



The Karlsruhe Physics Course

for the lower secondary school

Volume 3

Note to the reader

We have chosen a *one-section-one-page* layout. The advantage is that figures, tables and equations stay where they are supposed to be. Moreover, it is easy to update the text. For reading we recommend the Adobe reader or the GoodReader.

Friedrich Herrmann

The Karlsruhe Physics Course

*A Physics Text Book for the Lower Secondary School
Volume 3*

With the collaboration of Karen Haas, Matthias Laukenmann, Lorenzo Mingirulli, Petra Morawietz, Dieter Plappert and Peter Schmäzle

Illustrations: Friedrich Herrmann

Translation: GETS (German English Translation Services)
Robin Fuchs, Winterthur



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Rate of Reaction and Chemical Potential

To begin with, here is a definition of chemistry: Chemistry deals with the transformation of substances. For example, it describes the reaction of gasoline and oxygen producing carbon dioxide and water, i.e., the burning of gasoline:

Gasoline, oxygen \rightarrow carbon dioxide, water

This definition of chemistry is somewhat tentative because chemists do not deal exclusively with the transformation of substances and because there are substance transformations that are not considered chemical but belong to the area of nuclear physics. However, for the time being, the definition above suffices.

Chemistry and physics are closely related and could reasonably be considered a single field of science. However, they have been split into two separate school and university subjects, and physicists and chemists have different jobs. There is a practical reason for this: Chemistry and physics combined into one subject would simply be too extensive for one person to master.

Physicists and chemists use many closely similar methods. The same theoretical tools are used in chemistry that are applied in physics. Chemical reactions can be described by use of physical quantities and the relation between them. The part of chemistry that is especially oriented toward physics is called *physical chemistry*.

You already know some of the quantities used in physical chemistry from the physics you have learned: temperature, pressure, and entropy. There are some new quantities that will be added as well.

When we were dealing with thermodynamics we introduced a quantity for measuring *amount* of heat called entropy S , Table 24.1. Likewise, in electricity there is a quantity that measures the *amount* of electricity called electrical charge or electricity Q . The quantity in mechanics that measures the *amount* of motion or momentum of a body is momentum p .

Mechanics	p = momentum (amount of motion)
Electricity	Q = electric charge (amount of electricity)
Thermodynamics	S = entropy (amount of heat)
Chemistry	n = amount of substance

Table 24.1

Overview of some physical and chemical quantities

In the same manner we will now use a quantity in chemistry with which we can measure the *amount* of a substance. It is called *amount of substance* and is abbreviated to n .

Each of the parts of physics just mentioned has yet another quantity characteristic of it that describes from where to where the quantity in question flows.

Temperature tells us in what direction entropy flows, namely from higher to lower temperature. Electric potential tells us in what direction electricity flows, and the velocity of bodies allows us to see from which body to which body momentum flows in the process of friction.

We will find a corresponding “chemical” quantity that shows in what direction a chemical reaction proceeds. This quantity is the *chemical potential*, abbreviated to the Greek letter μ . The chemical potential tells us, for example, whether the following reaction runs by itself from left to right or from right to left:

Hydrogen, nitrogen $\overset{?}{\rightleftharpoons}$ ammonia

meaning whether ammonia is produced from hydrogen and nitrogen or whether ammonia decomposes into hydrogen and nitrogen.

24.1 Amount of substance and currents of substance

As the name indicates, the quantity called amount of substance measures the amount of a substance. The unit of amount of substance is the *mole* (symbol: *mol*). A one mole portion of substance contains $6.022 \cdot 10^{23}$ particles.

It is not always easy to decide what these particles of a substance are.

The smallest particles are often molecules. 1 mol of hydrogen gas contains $6.022 \cdot 10^{23}$ H₂ molecules. The smallest particles of some substances are atoms. Helium gas is an example of this. One mole of helium is composed of $6.022 \cdot 10^{23}$ He atoms. The situation is somewhat more complicated with most solid substances. A common salt crystal could actually be described as one gigantic molecule. This crystal is made up of just one “smallest” particle. In this case it is common, however, to describe the smallest particle as a single Na ion together with one Cl ion. Such a “NaCl unit” is not, in the strictest sense, a molecule at all. In the future, when we refer to 1 mol of common salt, we will always mean $6.022 \cdot 10^{23}$ of such NaCl units.

Instead of saying that a substance is composed of smallest particles, we can say that it has a smallest possible amount of substance that can be expressed in moles. The smallest amount of a substance is called the *elementary quantity*. The following is valid:

$$6,022 \cdot 10^{23} \text{ particles: } 1 \text{ mol} \\ 1 \text{ particle: } \frac{1}{6,022 \cdot 10^{23}} \text{ mol} = 1,66 \cdot 10^{-24} \text{ mol}$$

or:

$$\text{elementary quantity} = 1,66 \cdot 10^{-24} \text{ mol.}$$

Chemists measure the quantity of substances in moles. Why do they do this? Why don't they do what any reasonable person would do and measure a portion of substance in kilograms or liters? Chemistry is much simpler when quantities of substance are given in moles and when amount of substance is used and not mass or volume.

Here is a discussion between a musician, a physicist and a chemist that will illustrate this point:

There is powdered iron in one test tube and sulfur in another.

Musician: What are those, iron and sulfur?

Physicist: Yes, that is obvious.

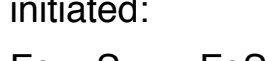
Musician: Aha. There is more sulfur than iron, just about twice as much. That is easy to see.

Physicist: That's ridiculous. Hold them in your hands. Can't you feel that the iron is heavier? Now look, the scale shows that the iron weighs 14 g and the sulfur weighs only 8 g.

Chemist: What are you talking about? I see it very differently. Look. (*She mixes the two substances and heats up the mixture with a bunsen burner. By the glowing of the mixture we can see that a reaction is taking place.*) There is neither iron nor sulfur left over after the reaction. This is the proof that exactly the same amounts of iron and sulfur were present. By the way, they were each exactly 1/4 mol.

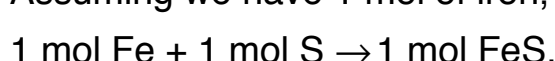
From this conversation you probably noticed that the classification of “more” or “less” depends upon what measure of amount is being used as the basis.

In order to better understand the discussion of the three persons let us consider the reaction equation for the reaction that the chemist initiated:

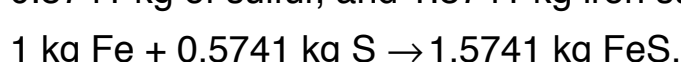


This equation makes a simple statement about the balance of the reaction, assuming that the substances are being measured in moles. The equation states that the amount of the reacting iron is exactly equal to the amount of reacting sulfur, and that the resulting amount of substance of iron sulfide is equal to the vanishing amount iron (and therefore also to the amount of vanishing sulfur).

Assuming we have 1 mol of iron, then:



If the amount of substance is measured in kg, meaning that mass is being measured, then the balance appears more complicated. For example, we let 1 kg of iron react. In order to do this, we need 0.5741 kg of sulfur, and 1.5741 kg iron sulfide is the result:



The values of mass of sulfur and iron sulfide are “odd numbers.”

We will use another example to make clear what the reaction equation is saying. We consider the reaction of hydrogen with oxygen which produces water. You know from chemistry class that the corresponding equation is



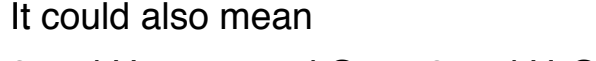
This equation tells us what the proportion of each of the reacting substances is, assuming that the amounts are being measured in moles (and not, say, in kg). It is:

$$n(\text{H}_2) : n(\text{O}_2) : n(\text{H}_2\text{O}) = 2 : 1 : 2.$$

Equation (1) only tells us something about the *ratio* of the quantities $n(\text{H}_2)$, $n(\text{O}_2)$, and $n(\text{H}_2\text{O})$. The equation doesn't necessarily have to mean:



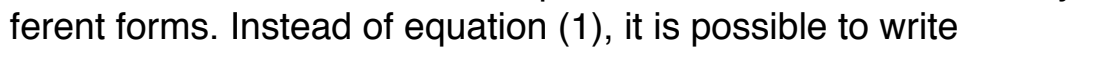
It could also mean



or



Because the reaction equation only expresses the ratios of the amounts of substance, such equations can be written in many different forms. Instead of equation (1), it is possible to write



All three equations, (1), (2), and (3), make the same statement. Generally, however, one writes reaction equations so that the smallest possible integer numbers are before the substance symbols. In our case, equation (1) would be the one to use. This form of the equation is called the *standard form*.

In the following we will use the quantity n , i.e., the amount of substance, as the measure of the quantity of a substance. However, we do not have a measuring device for determining values of amounts of substance that is as simple as the one for determining mass values. (Mass is determined with a scale.) In order to determine the amount of substance, a detour needs to be taken. In the periodic table (see Appendix), the mass of one mole for every basic chemical substance is listed. The number at the right hand side below the element symbol is the mass per amount of substance, meaning the quotient m/n . Please note that this value is not given in kg/mol but in g/mol. For example in copper:



Therefore, for copper,

$$m/n = 63.5 \text{ g/mol.}$$

This means that 1 mol of copper weighs 63.5 g or in other words: One substance portion of copper with an amount of substance of 1 mol has a mass of 63.5 g.

In order to determine the mass of a mole of a chemical compound, one simply adds the m/n values of the basic substances making up the compound. If a type of atom appears twice or three times in a molecule, the corresponding m/n values have to be counted twice or three times.

Example:

What is the mass of 1 mol Fe₂O₃?

In the periodic table, we find for iron



and for oxygen



Therefore, the mass of 1 mol is Fe₂O₃ is

$$m = 2 \cdot 55.8 \text{ g} + 3 \cdot 16.0 \text{ g} \approx 159.6 \text{ g.}$$

Reactions often run continuously. Examples of this are the burning reaction in the flame of a candle or the burner of an oil fueled central heating unit. Most reactions in the chemical industry are continuous as well. In order to tell someone how much of a substance is produced in such a reaction, it is not possible to give an amount of substance because the amount of substance, as a product of the reaction, increases continuously. A reasonable measurement in this case would be amount of substance per time. This would be, for instance, the number of moles which are produced per second, or the number of moles flowing per second out of the reactor.

We call this quantity the current of amount of substance I_n . Therefore

$$I_n = \frac{n}{t}.$$

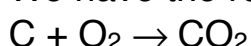
The unit of current of amount of substance is mol/s.

Exercises

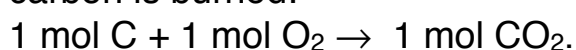
1. What is the mass of one mole of each of the following substances?
H₂O (water)
O₂ (oxygen)
CO₂ (carbon dioxide)
Ag₂S (silver sulfide)
Pb(NO₃)₂ (lead nitrate)
C₁₂H₂₂O₁₁ (cane sugar)
2. How many moles of sugar are in 100 g of candy? (The candy is just about 100% cane sugar.)
3. What is the amount of substance of 1 l of water?
4. A gas bottle contains 12 kg of propane (C₃H₈). How many moles is that?

24.2 Conversion and rate of conversion

We have the reaction



(the burning of carbon), take place twice. The first time, 1 mol of carbon is burned:



The second time, we burn 5 mol of carbon:



Larger amounts of substance were converted the second time. We can say that the *conversion* resulting from the reaction was five times as great the second time around than the first time.

Now we will compare two completely different reactions with each other: The burning of aluminum



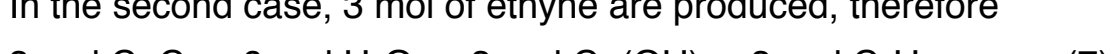
with the production of ethyne and calcium hydroxide from calcium carbide and water



Let us assume that, in the first case, 8 mol of aluminum are oxidized, meaning that



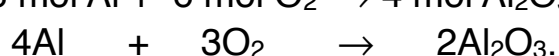
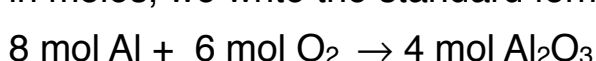
In the second case, 3 mol of ethyne are produced, therefore



Which reaction converted more? If the reactants are compared, the first reaction appears to convert more: 14 mol. The amount of reactant in the second reaction is only 9 mol. If, however, the end product of the conversion is measured, the second one wins. The second reaction produces 6 mol, the first one only 4.

It would certainly be advantageous if we had a clearly defined measure for conversion.

Let us consider the reaction of equation (6). Below the reaction equation that describes the conversion of the individual substances in moles, we write the standard form of the equation:



We will choose an arbitrary substance appearing in the reaction equation, for instance aluminum. We divide the amount of aluminum being converted by the number that is before the Al in the standard form:

$$\frac{8 \text{ mol}}{4} = 2 \text{ mol}$$

If we do this for another substance taking part in the reaction, we obtain the same result. For oxygen, the result is:

$$\frac{6 \text{ mol}}{3} = 2 \text{ mol}$$

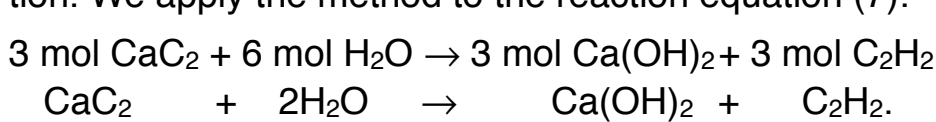
and for aluminum oxide, it is

$$\frac{4 \text{ mol}}{2} = 2 \text{ mol}$$

This result, which we obtained in three different ways, is called the conversion of the reaction, and we use the symbol $n(R)$. Therefore:

$$n(R) = \frac{\text{amount of X being converted}}{\text{number before X in standard form}}$$

Here X stands for an arbitrary substance participating in the reaction. We apply the method to the reaction equation (7):



We randomly choose H₂O as our substance. This results in

$$n(R) = 6 \text{ mol}/2 = 3 \text{ mol}.$$

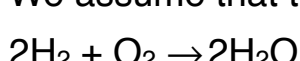
Again, the result is the same as with the other substances.

We now wish to compare continuous reactions with each other. It is no longer possible to describe such reactions by their conversion because it increases continuously. What needs to be measured is the conversion per time span, the *conversion rate* $I_{n(R)}$

$$I_{n(R)} = \frac{n(R)}{t}$$

The unit is mol/s.

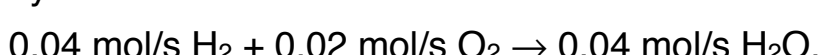
We assume that the reaction



proceeds with a conversion rate of

$$I_{n(R)} = 0,02 \text{ mol/s}.$$

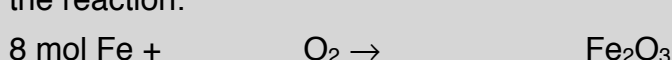
The equation is multiplied in its normal form (which it is already in) by 0.02 mol/s:



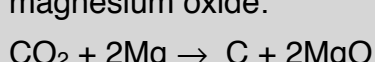
At a conversion rate of 0.02 mol/s, 0.04 mol of hydrogen react per second with 0.02 mol of oxygen resulting in 0.04 mol of water.

Exercises

1. Complete the following reaction equation and give the conversion of the reaction:



2. Carbon dioxide can react with magnesium resulting in carbon and magnesium oxide:



a) 4 g of carbon are produced. Write the reaction equation with the pertaining amounts of substance.

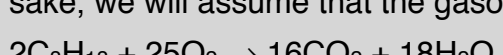
b) How many grams of carbon dioxide react with how many grams of magnesium?

c) How many CO₂ molecules disappear?

d) What is the conversion of the reaction?

3. 0.1 mole of water is produced per second in a methane flame. What is the rate of conversion?

4. Gasoline is burned in the cylinders of a car engine. For simplicity's sake, we will assume that the gasoline is composed of pure octane:

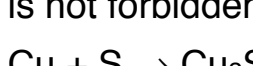


What is the rate of conversion when a distance of 100 km is driven, producing 10 l of water, and the car is driven at 50 km/h?

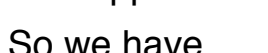
24.3 Chemical potential

The substances A1, A2, A3, ... should be able to react with each other in principle, producing B1, B2, B3, The expression “be able to react with each other in principle” means that the reaction is not forbidden by the reaction equation.

(So the reaction



is not forbidden in principle but in the reaction



the copper balance does not add up.)

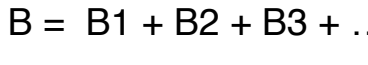
So we have



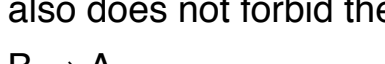
We write this reaction in the abbreviated form:



This means that



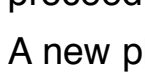
and



Now when the reaction balance does not forbid reaction (8), then it also does not forbid the reverse reaction:



Which of the two reactions (8) and (9) is taking place, though? Is it the combination of substances in A transforming into the combination of substances in B, or is it the reverse? What direction does the reaction



proceed in? From left to right or from right to left?

A new physical quantity gives us information about the direction of a reaction: the *chemical potential* μ . μ has a certain value for each of the two combinations of substances. If the chemical potential $\mu(\text{A})$ of the combination of substances A is greater than the chemical potential $\mu(\text{B})$ of the combination of substances B, the reaction proceeds from left to right. If $\mu(\text{A})$ is smaller than $\mu(\text{B})$, then the reaction proceeds from right to left. If $\mu(\text{A})$ and $\mu(\text{B})$ are equal, there is no reaction. We have a state of *chemical equilibrium*.

$\mu(\text{A}) > \mu(\text{B})$: A disappears, B is produced;
 $\mu(\text{A}) < \mu(\text{B})$: B disappears, A is produced;
 $\mu(\text{A}) = \mu(\text{B})$: no reaction, chemical equilibrium

This is a little less exact, but easier to remember:

A reaction runs by itself from a higher to a lower chemical potential.

The difference $\mu(\text{A}) - \mu(\text{B})$ is called the *chemical tension* of the reaction $\text{A} \rightarrow \text{B}$. In order for the reaction $\text{A} \rightarrow \text{B}$ to take place, the chemical tension must be greater than zero. This can also be expressed by:

Chemical tension represents a drive for a reaction.

The unit of the chemical potential is the *Gibbs*, abbreviated to G and named for J. W. Gibbs who introduced the chemical potential.

Every substance has a specific chemical potential. For now we will deal with the chemical potential of pure substances and not combinations of substances.

The chemical potentials of pure substances can be found in tables. The chemical potential changes with pressure and temperature of the substance. Tables usually contain the chemical potential for standard conditions, or in other words, a pressure of 1 bar and a temperature of 25 °C. The tables in the appendix contain the potential values for about 800 different substances.

Measuring the chemical potential of a substance can be rather involved. Later on we will see how to go about doing this. For now, we will take the potentials directly from the table.

We are looking for the chemical potential of ethanol. We need to look under the empirical formula $\text{C}_2\text{H}_6\text{O}$. We find:

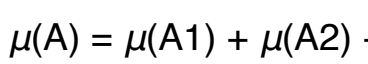
$$\mu(\text{C}_2\text{H}_6\text{O}) = -174.89 \text{ kG}.$$

The unit kG means kilogibbs. The chemical potential for water is found under OH_2 :

$$\mu(\text{OH}_2) = -237.18 \text{ kG}.$$

It is not possible to do much with the chemical potential of pure substances alone. Our problem was to see whether or not one combination of substances transforms into another combination of substances. What we actually need is the chemical potential of a combination of substances.

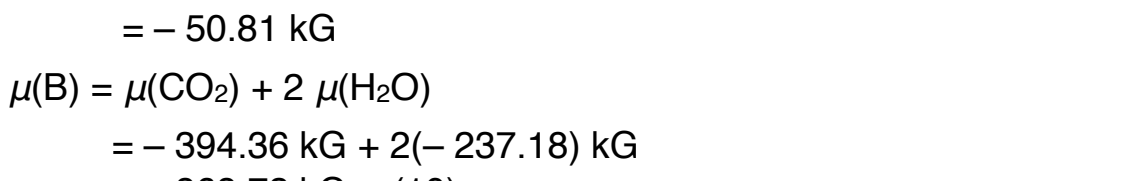
The chemical potential of a combination of substances



is now easy to calculate when the chemical potentials of the pure substances A1, A2, A3... are known. It is

$$\mu(\text{A}) = \mu(\text{A1}) + \mu(\text{A2}) + \mu(\text{A3}) + \dots$$

If a substance appears with a factor, this factor is applied in the sum of chemical potentials. Here is the burning of methane (the main component in natural gas) as an example:



$$\mu(\text{A}) = \mu(\text{CH}_4) + 2 \mu(\text{O}_2)$$

$$= -50.81 \text{ kG} + 2 \cdot 0 \text{ kG}$$

$$= -50.81 \text{ kG}$$

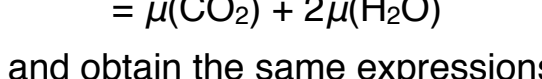
$$\mu(\text{B}) = \mu(\text{CO}_2) + 2 \mu(\text{H}_2\text{O})$$

$$= -394.36 \text{ kG} + 2(-237.18) \text{ kG}$$

$$= -868.72 \text{ kG} \quad (10)$$

The values of $\mu(\text{CH}_4)$, $\mu(\text{O}_2)$, $\mu(\text{CO}_2)$ and $\mu(\text{H}_2\text{O})$ were taken from the table.

The fact the factors multiplying a substance have to be applied in the formula for the chemical potential of a combination of substances can be easily understood. It is possible to write the reaction equation (10) in the form



We now generate the chemical potentials $\mu(\text{A})$ and $\mu(\text{B})$ by adding up the chemical potentials of the parts of the combinations of substances A and B:

$$\mu(\text{A}) = \mu(\text{CH}_4) + \mu(\text{O}_2) + \mu(\text{O}_2)$$

$$= \mu(\text{CH}_4) + 2\mu(\text{O}_2)$$

$$\mu(\text{B}) = \mu(\text{CO}_2) + \mu(\text{H}_2\text{O}) + \mu(\text{H}_2\text{O})$$

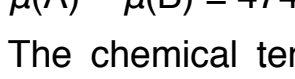
$$= \mu(\text{CO}_2) + 2\mu(\text{H}_2\text{O})$$

and obtain the same expressions as before.

We are now able to decide in which direction the chemical reaction can run. We consider reaction (10). Does methane react with oxygen into carbon dioxide and water or is the reverse true? We have already determined that the chemical potential of the combination of substances A is greater than that of the combination of substances B. Therefore, the reaction runs from A to B or from left to right.

In order to get used to this new method, we will apply it to some reactions where you already know in which direction they run.

Detonating gas reaction



$$\mu(\text{A}) = 2\mu(\text{H}_2) + \mu(\text{O}_2) = 0 \text{ kG}$$

$$\mu(\text{B}) = 2 \mu(\text{H}_2\text{O}) = 2(-237.18) \text{ kG}$$

$$= -474.36 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = 474.36 \text{ kG}$$

The chemical tension is positive, as expected. The reaction runs from left to right. Hydrogen burns to water.

Burning of carbon



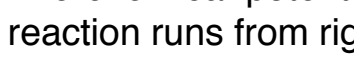
$$\mu(\text{A}) = \mu(\text{C}) + \mu(\text{O}_2) = 0 \text{ kG}$$

$$\mu(\text{B}) = \mu(\text{CO}_2) = -394.36 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = 394.36 \text{ kG}$$

There are no surprises here either. The reaction runs from left to right.

Rusting of iron



$$\mu(\text{A}) = 2 \mu(\text{Fe}_2\text{O}_3) = 2(-742.24 \text{ kG})$$

$$= -1484.48 \text{ kG}$$

$$\mu(\text{B}) = 4 \mu(\text{Fe}) + 3 \mu(\text{O}_2) = 0 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = -1484.48 \text{ kG}$$

The chemical potential of A is smaller than that of B. Therefore, the reaction runs from right to left. Iron rusts, as everybody knows.

Gold does not oxidize



$$\mu(\text{A}) = 2\mu(\text{Au}_2\text{O}_3) = 2 \cdot 163.30 \text{ kG}$$

$$= 326.60 \text{ kG}$$

$$\mu(\text{B}) = 4 \mu(\text{Au}) + 3 \mu(\text{O}_2) = 0 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = 326.60 \text{ kG}$$

This reaction runs from left to right. Gold oxide decays by itself. Gold does not “rust.”

The zero point of the chemical potential

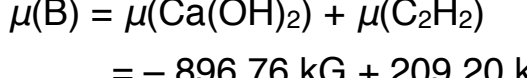
When you were looking for chemical potential values you certainly noticed that the chemical potential of the chemical elements is always 0 kG. This is not by chance, they have been so assigned. This is done in just the same way that the zero point of the electric potential, the temperature, and the speed have been arbitrarily assigned.

What is special about the chemical potential is that there are as many zero points as there are chemical elements.

We must bear one thing in mind though: the chemical potential of a substance is 0 kG when the substance is in its most stable form. For example, the chemical potential $\mu(\text{H})$ of the strongly unstable atomic hydrogen is not set at zero, but at the chemical potential $\mu(\text{H}_2)$ of molecular hydrogen is.

Producing substances with high chemical potential out of substances with low chemical potential.

A reaction runs by itself from high to low chemical potential. It “runs down the potential hill.” However, if one is not careful, the following wrong conclusion could be drawn: Every product of a reaction has a lower chemical potential than every reactant. The following example will show that this is not necessarily so. As an example we will use the production of ethyne from calcium carbide and water.



$$\mu(\text{A}) = \mu(\text{CaC}_2) + 2 \mu(\text{H}_2\text{O})$$

$$= -67.78 \text{ kG} + 2(-237.18) \text{ kG}$$

$$= -542.14 \text{ kG}$$

$$\mu(\text{B}) = \mu(\text{Ca}(\text{OH})_2) + \mu(\text{C}_2\text{H}_2)$$

$$= -896.76 \text{ kG} + 209.20 \text{ kG}$$

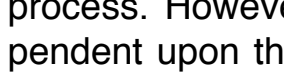
$$= -687.56 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = 145.42 \text{ kG}$$

The chemical potential of the combination of substances A is greater than that of B so the reaction runs from left to right. However, one of the products, ethyne, has a higher potential than either of the two initial substances. This high potential is balanced out by the very low chemical potential of the other product, calcium hydroxide.

Dissolving as a reaction

The dissolving of one substance in another one is also a chemical reaction. An example of this is the dissolving of table salt in water.



The table also contains the chemical potentials of ions making it possible for us to calculate the chemical tension of a dissolving process. However, the chemical potential of a dissolved ion is dependent upon the concentration of those ions. The potential values of ions shown in the table are for 1 M solutions in water (1 mol of solute in 1 kg of water). From this we can determine whether it is possible to produce a 1 M solution in water.

The result for our table salt solution is:

$$\mu(\text{A}) = \mu(\text{NaCl}) = -384.04 \text{ kG}$$

$$\mu(\text{B}) = \mu(\text{Na}^+) + \mu(\text{Cl}^-)$$

$$= -261.89 \text{ kG} + (-131.26 \text{ kG})$$

$$= -393.15 \text{ kG}$$

$$\mu(\text{A}) - \mu(\text{B}) = 9.11 \text{ kG}$$

$\mu(\text{A})$ is greater than $\mu(\text{B})$. This means that a 1 M salt solution can be produced: 1 mol of table salt per 1 liter of solution. Of course it is also possible to dissolve less NaCl. However, the values in our table do not allow us to see whether or not it is possible to dissolve more than this.

Exercises

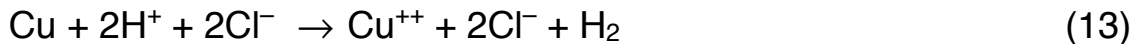
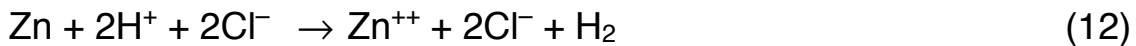
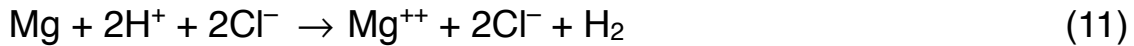
- Determine the chemical tensions for the following reactions and indicate whether or not the reaction can take place under standard conditions.
 - $2\text{Mg}(\text{solid}) + \text{O}_2(\text{gaseous}) \rightarrow 2\text{MgO}(\text{solid})$
 - $2\text{Hg}(\text{liquid}) + \text{O}_2(\text{gaseous}) \rightarrow 2\text{HgO}(\text{red, solid})$
 - $\text{C}_5\text{H}_{12}(\text{liquid}) + 8 \text{O}_2(\text{gaseous}) \rightarrow 5\text{CO}_2(\text{gaseous}) + 6\text{H}_2\text{O}(\text{liquid})$
 - $12\text{CO}_2(\text{gaseous}) + 11\text{H}_2\text{O}(\text{liquid}) \rightarrow \text{C}_{12}\text{H}_{22}\text{O}_{11}(\text{solid}) + 12\text{O}_2(\text{gaseous})$
 - $\text{CuO}(\text{solid}) + \text{Zn}(\text{solid}) \rightarrow \text{Cu}(\text{solid}) + \text{ZnO}(\text{solid})$

- Show reactions where CuO is reduced. Calculate the chemical tensions.

- Which of the following substances allow the production of a 1 M solution in water?
 - I_2 , KOH , NH_4Cl , NH_3 , AgCl .

24.4 Chemical potential and rate of conversion

We compare three related reactions: dissolving of three bivalent metals in hydrochloric acid.



First we calculate the chemical tensions:

$$\text{for (11)} \quad \mu(\text{A}) - \mu(\text{B}) = 456,01 \text{ kG}$$

$$\text{for (12)} \quad \mu(\text{A}) - \mu(\text{B}) = 147,03 \text{ kG}$$

$$\text{for (13)} \quad \mu(\text{A}) - \mu(\text{B}) = -65,52 \text{ kG}$$

The tension in the first reaction is high, the second one is lower, and the third one is negative.

We attempt to carry out the reactions. The magnesium dissolves quickly while hydrogen is produced rather violently. Zinc takes very long to dissolve and the production of hydrogen takes place much less violently than with magnesium. Nothing at all happens with copper.

The higher the chemical tension, the greater the rate of conversion.

We draw the following conclusion:

Although this sentence is correct, it is incomplete and could lead to some wrong conclusions. Conversion rate depends upon more than just chemical tension. This is true in the same way that an electric current is not only dependent upon voltage and an entropy current is not just dependent upon temperature difference.

24.5 Reaction resistance

If we only take chemical tension into account, a reaction sometimes does not go like it should. Gasoline can be in an open container without burning. Hydrogen and oxygen can be mixed without an explosion taking place. You might say that it doesn't burn because it must first be ignited, and you would be correct. However, why don't the substances react unless they are ignited? Why don't the reactions run from high to low chemical potential?

We see that the availability of a driving force for a reaction may not be enough. This is basically not surprising, as could have been expected from the outset. After all, the air in a tire doesn't usually flow out of it although the pressure outside is lower than inside. Although a driving force exists, the wall of the tire hinders it from flowing, Fig. 24.1

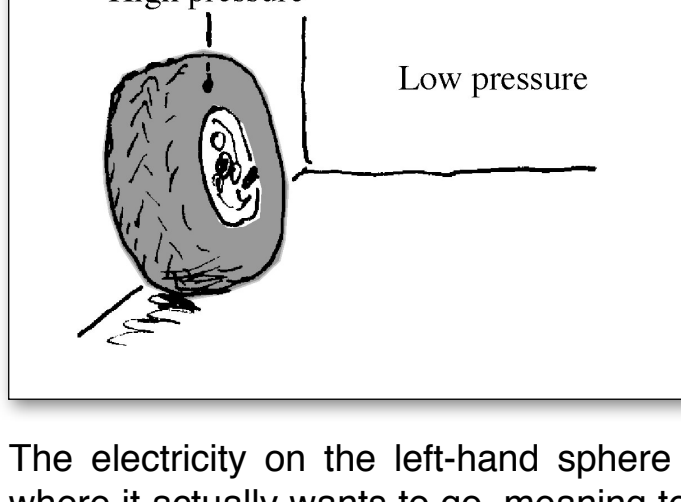


Fig. 24.1
Air does not flow from the place of high pressure (inside the tire) to where the pressure is lower (outside the tire).

The electricity on the left-hand sphere in Fig. 24.2 does not flow where it actually wants to go, meaning to the right-hand sphere. The electric resistance of the air between the two spheres is too high.

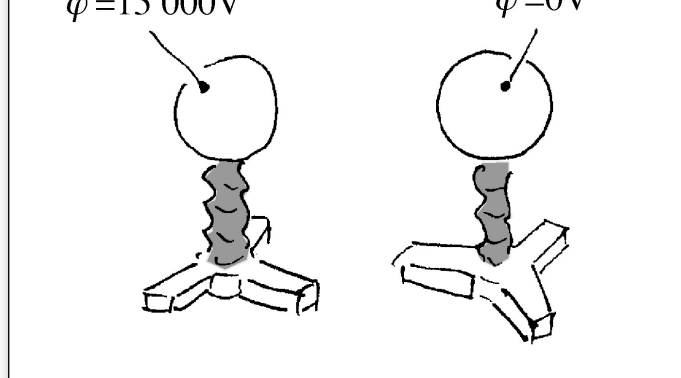


Fig. 24.2
The electricity does not flow from where the electric potential is higher (left-hand sphere) to where the electric potential is low (sphere on the right).

When a chemical reaction does not take place although there is a chemical tension, it is due to a resistance that is too high. We say that the *reaction resistance* is too high and the reaction is *inhibited*.

Reaction resistance can be high or small or even very high or very small. Two reactions with the same chemical tension can run very differently. They can have very different conversion rates depending upon how high the reaction resistances are.

The higher the reaction resistance of a reaction, the smaller the conversion rate.

A simplified description of what chemists do would go like this: They want to allow certain reactions to take place, and to hinder others.

One way of influencing the process of a reaction is to set up an appropriate resistance—smaller or higher—depending upon what is needed.

It is similar in electrical engineering. In this case, connections are established through a wire made of a material with low resistance.

Currents are prevented from flowing by materials which are bad conductors.

What does the resistance of a chemical reaction depend upon? How can this resistance be influenced?

Fig. 24.3a shows a glass of hydrochloric acid with a piece of magnesium next to it. If it really only depended upon chemical tension, the two substances would have to react with each other. Naturally they don't do this. The reaction is inhibited. In this case, it is very simple to lower the reaction resistance. It is enough to put the two substances together by tossing the piece of magnesium into the glass of hydrochloric acid, Fig. 24.3b, or to pour the hydrochloric acid over the magnesium.

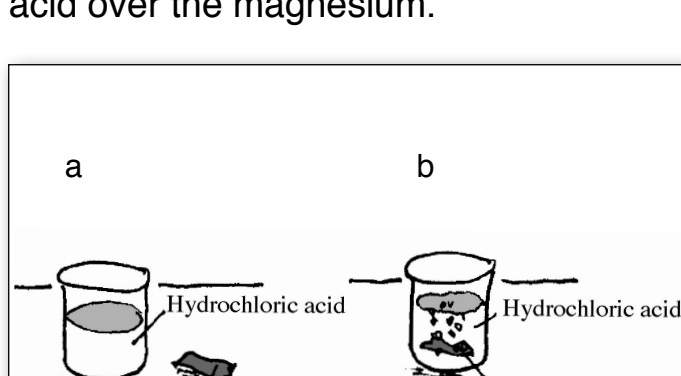
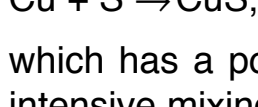


Fig. 24.3
(a) Magnesium and hydrochloric acid do not react because the reaction is inhibited. (b) Magnesium and hydrochloric acid react.

The reaction resistance can be further lowered by improving the contact between the reacting substances. Mixing them well with each other is a way of doing this. Solid substances must be well pulverized before doing so. A large NaCl crystal lying quietly in water will dissolve very slowly. The reaction resistance is very high. However, if the crystal is made into powder, poured into the water and well stirred, the resistance to the dissolution process is much less and the conversion rate is much greater.

Mixing lessens reaction resistance.

Often, though, even good mixing doesn't help. The reaction



which has a positive chemical tension, just doesn't happen despite intensive mixing. Heating it (raising its temperature) finally gets it going.

It suffices to ignite the reactants at a single location. As soon as the reaction has started, entropy is produced. The temperature in the vicinity increases, and the reaction is initiated here as well. Thus the reaction progresses. We can conclude:

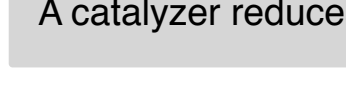
Raising temperature reduces reaction resistance.

There are many reactions of this type that only begin to run when the initial substances are ignited. Burning of all fuels—heating oil, coal, gasoline, natural gas, hydrogen—all belong to this class of reactions.

There are other, more elegant, ways of reducing the reaction resistance. A *catalyzer* can be added to the substances that are supposed to react. The catalyzer causes the reaction to proceed. Its amount does not change during reaction. In other words, adding a catalyzer turns a reaction on and removing it turns the reaction off.

A catalyzer reduces the reaction resistance.

Here is a simple example. The tension of the reaction



is positive. If only chemical tension counted, hydrogen peroxide H_2O_2 should dissolve by itself in water but it doesn't because the reaction is inhibited. We now put a type of catalyzer used in cars into the test tube with the hydrogen peroxide. Gas immediately begins to form, Fig. 24.4. Testing with a glowing wood of a piece of wood shows that this gas is oxygen. In this reaction, the amount of the catalyzer doesn't change. The reaction runs as long as there is hydrogen peroxide left.

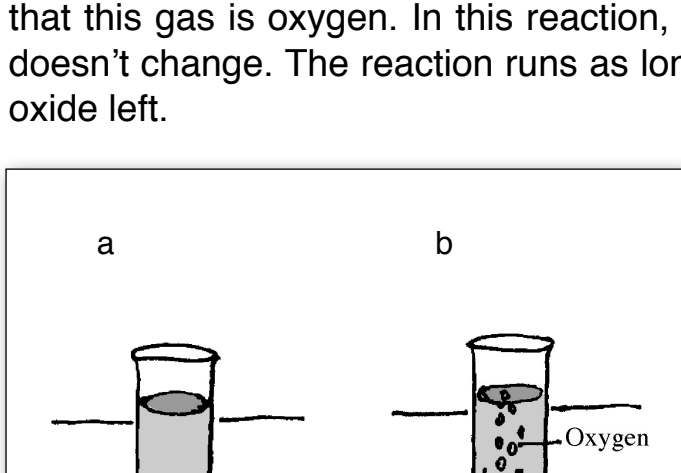
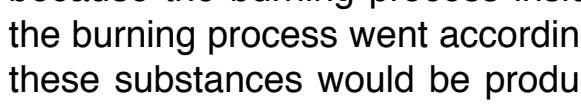
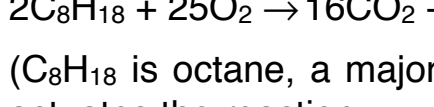


Fig. 24.4
(a) Hydrogen peroxide does not decay. (b) The reaction is switched on by adding a catalyzer.

There are pollutants in the exhaust fumes of gasoline engines. These are mainly nitrogen monoxide NO, carbon monoxide CO, and unburned gasoline. These substances are contained in the exhaust because the burning process inside the engine is not completed. If the burning process went according to the chemical tension, none of these substances would be produced. For this reason, the exhaust fumes are let flow through a catalyzer. This causes the rest of the gasoline to burn:



(C_8H_{18} is octane, a major component of gasoline.) A catalyzer also actuates the reaction



in which the poisonous substances CO and NO are transformed into non-toxic N_2 and CO_2 . By the way, CO_2 also has damaging effects upon the environment in that it contributes to warming of the atmosphere.

Catalyzers are especially important to reactions in biological systems. Thousands of reactions can take place in such systems, and if it only depended upon chemical tension, they would all actually take place. As a result, after a short period of time, an organism would transform into only carbon dioxide and water. However, most of these reactions are inhibited and would never take place on their own. They are only made possible by catalyzers, and each reaction needs a different catalyzer. These catalyzers are called *enzymes*. A biochemical reaction is controlled by enzymes that function like a complicated system of chemical switches.

In this and the previous section we have seen that the conversion rate of a reaction depends upon two things:

1. chemical tension and
2. reaction resistance.

We have also investigated what a reaction resistance depends upon. In Fig. 24.5 all of these dependencies are summarized.

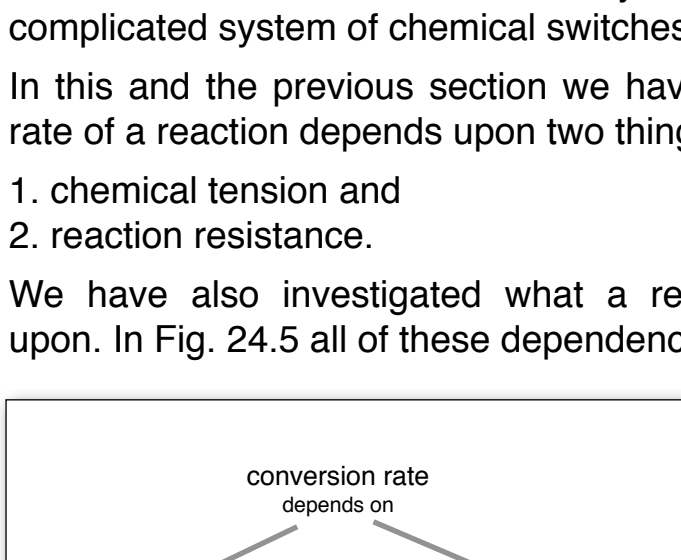


Fig. 24.5
Relation between Conversion rate, Chemical tension, and Reaction resistance

Exercises

1. Name some reactions that, even when well mixed, have a high reaction resistance.
2. Name some reactions that have a small reaction resistance if the reacting partners are brought into contact with each other.
3. An explosive is a substance that can decay by itself into other substances. Its chemical potential is higher than that of the products of decay. What can be said about the resistance to the reaction?

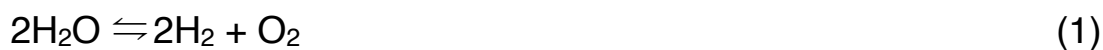
25

Amount of Substance and Energy

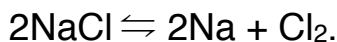
25.1 Reaction pumps

We have found that “A reaction runs by itself from high to low potential”. Sometimes, however, it is desirable to have a reaction run in the opposite direction. We want to let run a reaction so that the chemical potential of the combination of products is greater than that of the initial combination of substances.

For example, one might wish to decompose water into hydrogen and oxygen. The reaction



should run from left to right, meaning against its natural drive. Another example would be to produce sodium out of cooking salt by



The reaction runs by itself from right to left, but we want it to run from left to right.

Actually, the problem we want to solve is one we have seen earlier: Sometimes it is desirable to have air flow against its natural inclination from low to high pressure. This can be accomplished by using an air pump or compressor, Fig. 25.1.

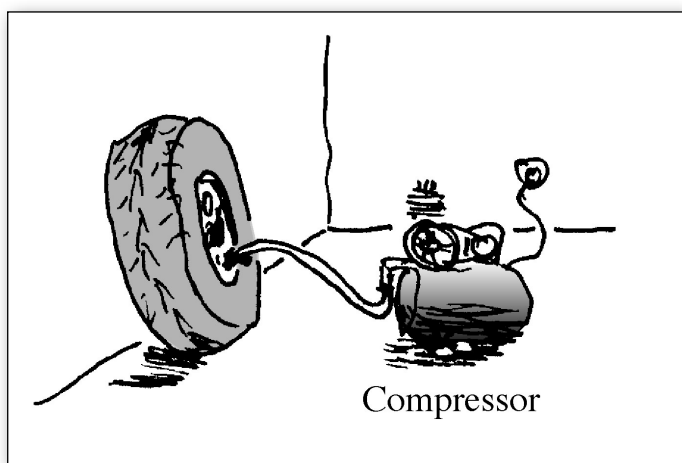


Fig. 25.1

An air pump transports air from places of low pressure to places of high pressure.

Another example would be to transport entropy from a lower to a higher temperature. This can be done with a heat pump, Fig. 25.2. What we need to have a reaction run from a lower to a higher potential is also some kind of pump: a *reaction pump*.

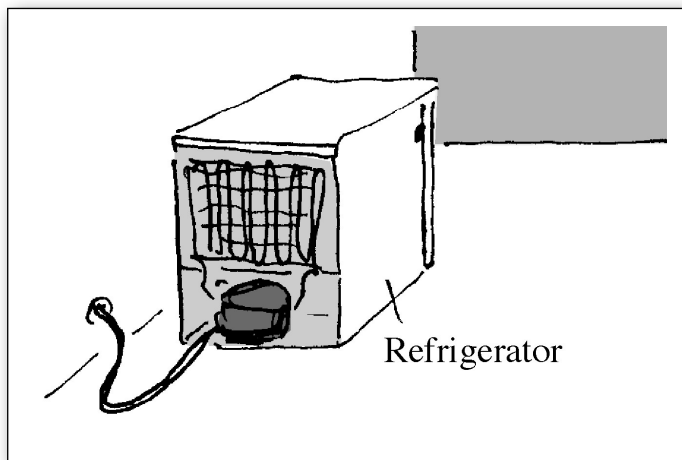


Fig. 25.2

The heat pump transports entropy from places of lower to places of higher temperature.

Such pumps actually do exist and they play an important role in chemical technology. They are called *electrochemical cells*.

Fig. 25.3 shows an electrochemical cell that can decompose water. It is a reaction pump for reaction (1). The process of decomposing a substance with a reaction pump is called *electrolysis*.

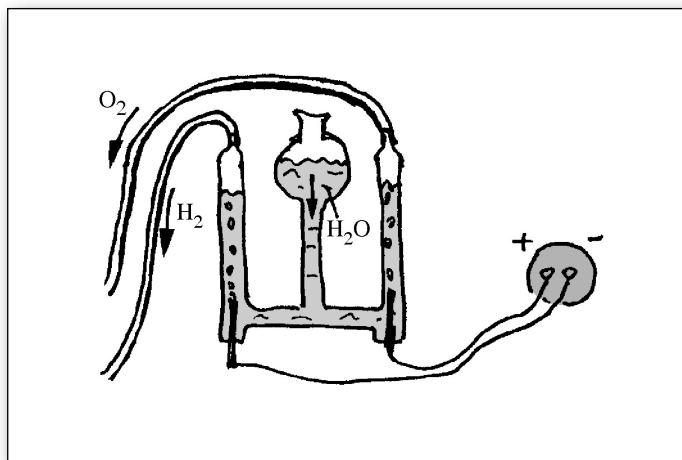


Fig. 25.3

An electro-chemical cell functions as a “reaction pump”.

A reaction pump must be plugged into an electric energy source in order to function, just as an air pump or a heat pump must be.

25.2 Conversion rates and energy currents

Fig. 25.4 shows the energy flow diagram of the electrochemical cell in Fig. 25.3.

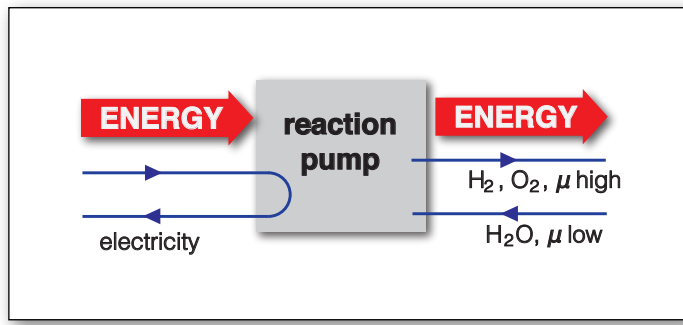


Fig. 25.4
Energy flow diagram of a reaction pump

For comparison, the flow diagram of a water pump is shown in Fig. 25.5.

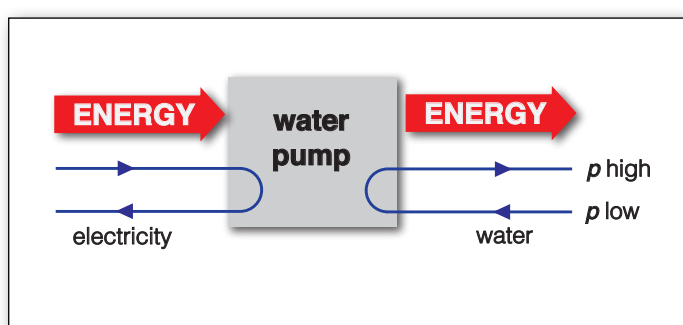


Fig. 25.5
Energy flow diagram of a water pump

Fig. 25.6 shows the flow diagram of a heat pump. We see that a reaction pump is an energy exchanger. It receives energy with the carrier electricity and gives it up again with the reaction products.

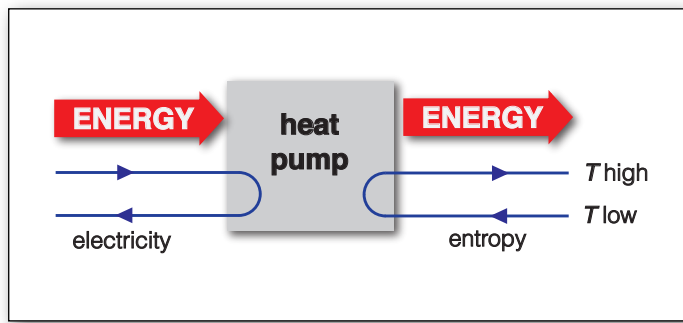


Fig. 25.6
Energy flow diagram of a heat pump

Energy enters the cell along with the initial reaction substances. More energy flows out with the products than went in with the reactants. The difference is equal to the energy taken over from the electricity.

Clearly, the more energy introduced into the cell, the greater the amount of substance that is converted. Because the energy that flows into the cell comes out again, we can say that the more energy flowing *through* the cell, the greater the amount of conversion.

This statement can also be formulated quantitatively. Fig. 25.7a shows an electrochemical cell. An energy current with a given strength flows through this cell, and the reaction has a certain conversion rate. Fig. 25.7b shows two cells connected in parallel. Both of them are identical to the one in Fig. 25.7a. An electric current naturally flows through them that is twice the one in Fig. 25.7a and twice as much is converted. The two cells connected in parallel could be considered as one large cell, Fig. 25.7c. From the comparison of the small cell in Fig. 25.7a and the large one in Fig. 25.7c, it follows that the rate of conversion of a cell is proportional to the strength of the energy current flowing through it:

$$P \sim I_{n(R)} \quad (2)$$

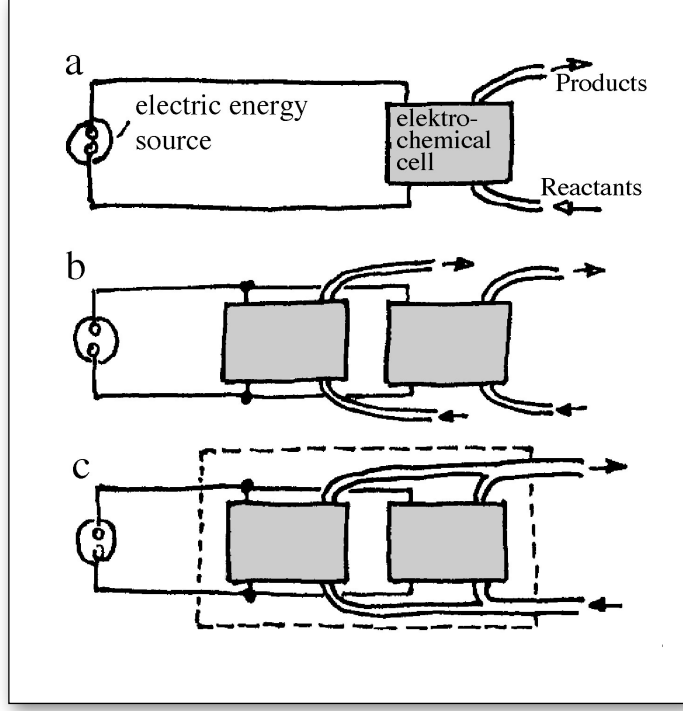


Fig. 25.7
(a) An electro-chemical cell.
(b) The rate of conversion and the energy current in two cells connected in parallel are twice that of just one.
(c) The cells connected in parallel are considered just one large cell.

We are still missing the proportionality factor. Let us consider two cells in which different reactions occur. In one, water is being decomposed, and in the other, hydrogen and chlorine are being produced from hydrochloric acid. The reactions run so that the rates of conversion in both cells are the same. We find that the cells use different amounts of energy: For the same $I_{n(R)}$, P is different. The proportionality factor that would turn (2) into an equation is dependent upon what reaction is taking place in the cell. It has different values for different reactions.

We know that different reactions differ from each other in their chemical tension. Indeed, the relation between rate of conversion and the strength of the energy current is simply this:

$$P = (\mu(A) - \mu(B)) \cdot I_{n(R)} \quad (3)$$

This means that the factor of proportionality is the chemical tension. There is a simple reason why the chemical tension is given here: The chemical tension, and the chemical potential with it, are defined by Equation (3). This means that the equation can be used to measure a chemical tension. The energy current P and the conversion rate $I_{n(R)}$ are measured, and their ratio is determined:

$$\mu(A) - \mu(B) = \frac{P}{I_{n(R)}} \quad .$$

$\mu(A)$ is the higher and $\mu(B)$ is the lower chemical potential.

If the chemical tension of a reaction is known, equation (3) can be used to calculate how much energy per second is being transferred from the electricity to the products of the reaction.

In equation (3), we use

$$P = \frac{E}{t}$$

and

$$I_{n(R)} = \frac{n(R)}{t}$$

and obtain

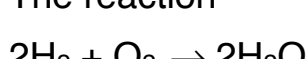
$$E = (\mu(A) - \mu(B)) \cdot n(R)$$

This equation tells us how much energy is necessary per converted mole so that the reaction $A \leftrightarrow B$ runs against its nature.

Example:

How much energy is needed to electrolyze 1 kg of water?

The reaction



should “be pumped” from right to left. For water,

$m/n = 0.018 \text{ kg/mole}$.

1 kg of water contains 55.56 mole. The reaction conversion is

$$n(R) = n(\text{H}_2\text{O})/2 = 55,56 \text{ mol}/2 = 27,78 \text{ mol}.$$

We calculated the chemical tension of the reaction earlier:

$$(\mu(A) - \mu(B)) = 474.36 \text{ kG}.$$

We obtain

$$\begin{aligned} E &= (\mu(A) - \mu(B)) \cdot n(R) \\ &= 474.36 \text{ kG} \cdot 27.78 \text{ mol} = 13\,178 \text{ kJ} \approx 13 \text{ MJ} \end{aligned}$$

You remember that we used a formula very similar to (3) in order to calculate how much energy per second is transferred from the electricity to the entropy in a heat pump:

$$P = (T(A) - T(B)) \cdot I_S$$

(T = absolute temperature, I_S = entropy current)

We also know another formula of this type. In order to calculate the strength of an energy current transported by an electric cable, the following formula is used:

$$P = (\phi(A) - \phi(B)) \cdot I$$

(ϕ = electric potential, I = electric current)

Exercises

1. How much energy is needed to get 1 kg of sodium from cooking salt?
2. How much energy is needed to get 2 moles of lead from lead chloride?

25.3 Reversing a reaction pump

A reaction pump transfers energy from one carrier to another. The energy goes into the cell with electricity and leaves it with the reaction products. Just as with every other energy exchanger, reaction pumps can be reversed. Such a device is well known to you and you encounter it in many different versions and under many different names: Battery, rechargeable battery, mono cells, fuel cells, etc.

These devices are also called electro-chemical cells. Electro-chemical cells can run in two directions: either as “reaction pumps”—see the last section—or as “electricity pumps”.

Figs. 25.8a and b show the energy flow diagrams of two electro-chemical cells. The one in Fig. 25.8a works as the reaction pump for the reaction $B \rightarrow A$. The cell in Fig. 25.8b acts as an electricity pump. In this case, the reaction runs from A to B, meaning in the natural direction. Therefore, electricity is transported from lower to higher potential.

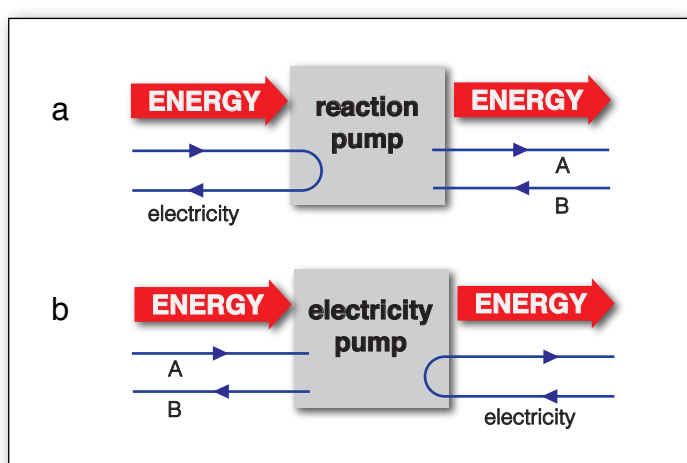


Fig. 25.8
Energy flow diagram of a reaction pump (a) and an electricity pump (b)

There are many technical terms for electricity pumps.

Fuel cells

If the reactants are continuously fed into a cell and the products are continually extracted, the cell is called a fuel cell. One example would be a hydrogen fuel cell where hydrogen and oxygen react into water.

A fuel cell essentially does what a thermal power plant does. It receives energy with the combination of substances “fuel + oxygen” and emits it with electricity. A fuel cell has great advantages over a thermal power plant: It has less energy loss and it works silently. Despite this, fuel cells for supplying electric energy are not in use yet because they cannot be run using coal or heating oil which are the most common fuels.

Mono cells, baby cells, and button cells

Here, the initial substances for the reaction are already in the cell and the reaction products are not discharged. When the initial substances are used up, the cell becomes unusable.

Such cells are often called batteries. This term is, as we will soon see, incorrect.

Accumulator

An accumulator or rechargeable battery is a cell that can run both ways, as a reaction pump and as an electricity pump. The initial substances and reaction products stay in the accumulator.

For this reason, an accumulator can be used as an energy storage unit. When it is being charged with energy, a chemical reaction is pumped from low to high chemical potential which is opposite to the natural direction. During the process of discharging, the reaction runs from high to low chemical potential. In the process, electricity is transported from low to high electric potential. The most well known accumulator is the lead storage battery in a car, the car battery.

Batteries

When several cells are connected in series, we call it a battery. A 12 V car battery is made up of six 2-V cells connected in series and a 4.5 V flat battery is composed of three 1.5 V cells connected in series.

The relation between energy current and rate of conversion in chemical electricity pumps is naturally the same as with reaction pumps. This means that here, too

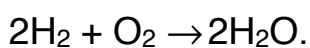
$$P = (\mu(A) - \mu(B)) \cdot I_{n(R)}.$$

Again, $\mu(A)$ is the higher and $\mu(B)$ the lower potential. P is the energy current flowing into the cell with the substances and out again with the electricity. Here, as well, the following holds for the relation between amount of energy and converted amount of substance:

$$E = (\mu(A) - \mu(B)) \cdot n(R).$$

Example

We consider the reaction taking place in a hydrogen fuel cell:



How much energy does the electricity carry out of the cell when 1 kg of water is produced?

We have already performed the calculation in the last section when we asked how much energy is needed to electrolyze 1 kg of water. The result was $E = 13 \text{ MJ}$.

Exercises

- In a fuel cell, methane reacts with oxygen producing carbon dioxide and water. How many joules does the cell produce per second at a conversion rate of 1 mole/s?
- The following reaction is taking place in a lead storage battery (accumulator):

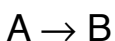
$$\text{Pb} + \text{PbO}_2 + 4\text{H}^+ + 2\text{SO}_4^{2-} \rightleftharpoons 2\text{PbSO}_4 + 2\text{H}_2\text{O},$$
 It runs to the left during charging and to the right while discharging.
 - What is the conversion rate when the accumulator emits 100 joules per second?
 - While charging, 2 kg of lead sulfate is transformed into lead and lead oxide. How much energy is stored in the process?

26

Heat Balance of Reactions

26.1 Entropy production in chemical reactions

We wish to let the chemical reaction



run continuously and steadily. The substances are chosen so that $\mu(A)$ is greater than $\mu(B)$. We know that energy can be gained from this reaction. Energy is released in the process of converting the substances A into B. The energy current is calculated by

$$P = (\mu(A) - \mu(B)) \cdot I_{n(R)}.$$

Two different things can be done with this energy. It can be used for pumping something from low to high potential, electricity for example. This was just discussed in detail in the last section.

The reaction could also be allowed to run freely without pumping or driving anything. In this case, all of the energy would be used to produce entropy. In order to produce an entropy current of $I_{S \text{ produced}}$, it is necessary to have an energy current of

$$P = T \cdot I_{S \text{ produced}}.$$

If all the energy produced by a chemical reaction were used to create entropy—or better: were wasted—the following would be valid:

$$(\mu(A) - \mu(B)) \cdot I_{n(R)} = T \cdot I_{S \text{ produced}}.$$

We can use this to calculate the amount of entropy produced per second:

$$I_{S \text{ produced}} = \frac{\mu(A) - \mu(B)}{T} I_{n(R)}$$

We insert

$$I_{S \text{ produced}} = S_{\text{produced}} / t$$

and

$$I_{n(R)} = n(R) / t$$

and get

$$\frac{S_{\text{produced}}}{t} = \frac{\mu(A) - \mu(B)}{T} \cdot \frac{n(R)}{t}$$

If we multiply both sides by t , we obtain

$$S_{\text{produced}} = \frac{\mu(A) - \mu(B)}{T} \cdot n(R). \quad (1)$$

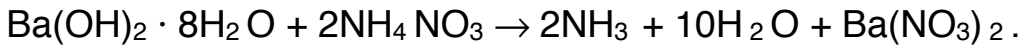
This equation tells us how much entropy is produced when a certain chemical conversion $n(R)$ takes place.

When a reaction releases energy that is used for nothing else but the production of entropy, it is said to run freely.

Every freely running reaction produces entropy.

This might lead us to the following conclusion: In every freely running reaction the substances become warm because we know that as entropy increases, so does temperature. This conclusion would, however, be wrong. We will see this by doing an experiment.

We mix two solid substances: Barium hydroxide that contains a rather large amount of water of crystallization, and ammonium nitrate. The substances react, producing ammonia gas, liquid water and barium nitrate:



The remarkable thing about this reaction is that the products are very cold. When the temperature is taken, it is found to be minus 10 degrees Celsius. What happened? Did the reaction possibly run in the wrong direction, from low to high chemical potential? Could entropy possibly have been destroyed? That would be a sensation. We will now see that this is not the case.

In order to understand what happened here, we need to investigate the balance of entropy in reactions more carefully.

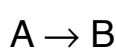
Exercises

1. How much entropy is produced by burning 1 kg of gasoline? (Calculate using octane C_8H_{18} , one of the main components of gasoline.)
2. When 1 kg of iron rusts, how much entropy is produced?

26.2 The entropy balance of chemical reactions

There is an important point that we have not dealt with yet.

Consider the reaction



and assume, at first, that no entropy is produced (as in an electrochemical cell). During the reaction, the reactants disappear and the products are created.

The initial substances contain a given amount of entropy that must be taken over by the products. Generally, for the same amount of entropy, the temperature belonging to the initial substances is different from the temperature of the products. In some reactions, the temperature of the products is lower than and in other cases higher than the initial substances.

This is similar to putting the air of a container A into an empty container B. The air in B will generally not have the same pressure as it had in A, Fig. 26.1.

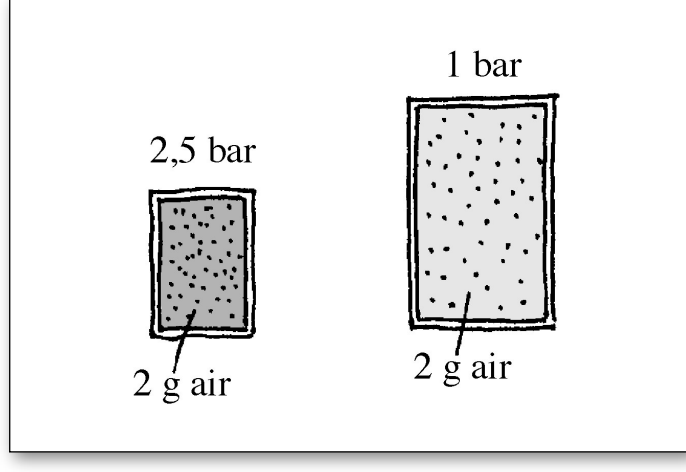


Fig. 26.1
The same quantity of air has different pressures in different containers.

The last column of the table in the Appendix shows the entropy contained in every substance at standard temperature. The values are based upon 1 mole of the substance. The table therefore contains the quantity S/n . For water, we find in the table that

$$S/n = 69.91 \text{ Ct/mol},$$

meaning that 1 mol of water at standard temperature contains an entropy of 69.91 Carnot.

For carbon dioxide we have

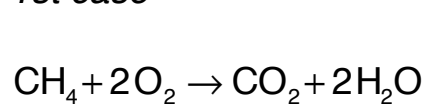
$$S/n = 213.64 \text{ Ct/mol},$$

meaning that 1 mole of carbon dioxide at a standard temperature contains 213.64 Ct.

We now have the means to establish the complete entropy balance of reactions.

Three different cases can occur during balancing. We will look at one example for all three of these cases. Each time, we will make a balance for 1 mole.

1st case



Using the table, we find how much entropy the initial and final substances have at standard temperature:

$$S(A) = S(\text{CH}_4) + 2S(\text{O}_2) = 186.10 \text{ Ct} + 2 \cdot 205.03 \text{ Ct} = 596.16 \text{ Ct}$$

$$S(B) = S(\text{CO}_2) + 2S(\text{H}_2\text{O}) = 213.64 \text{ Ct} + 2 \cdot 69.91 \text{ Ct} = 353.46 \text{ Ct}.$$

It turns out that the products have less entropy (at the same temperature) than the initial substances. If the initial substances had the temperature of the surroundings before the reaction, the end substances must take over 596.16 Ct of entropy. However, their temperature becomes higher than standard temperature because at normal temperature, the end substances contain an amount of entropy of 353.46 Ct. We could also say that the amount of entropy

$$S(A) - S(B) = 596.16 \text{ Ct} - 353.46 \text{ Ct} = 242.7 \text{ Ct}$$

is left over.

Entropy is also produced by the reaction. We calculate the quantity of produced entropy by Equation (1):

$$S_{\text{produced}} = \frac{\mu(A) - \mu(B)}{T} \cdot n(R)$$

For our reaction:

$$\mu(A) - \mu(B) = 817.91 \text{ kG}.$$

We had assumed that

$$n(R) = 1 \text{ mol},$$

and

$$T = 298 \text{ K},$$

so that

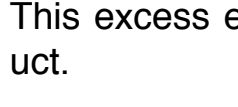
$$S_{\text{produced}} = \frac{817.91 \text{ kG}}{298 \text{ K}} \cdot 1 \text{ mol} = 2744.7 \text{ Ct}$$

So we see that during the reaction process, 2744.7 Ct is produced. This entropy is added to the excess entropy just calculated. This results in a total excess entropy of

$$S(A) - S(B) + S_{\text{produced}} = 242.7 \text{ Ct} + 2744.7 \text{ Ct} = 2987.4 \text{ Ct}.$$

This excess entropy leads to a strong warming up of the end product.

2nd case



$$S(A) = S(\text{C}) + S(\text{O}_2) = 5.74 \text{ Ct} + 205.03 \text{ Ct} = 210.77 \text{ Ct}$$

$$S(B) = 213.64 \text{ Ct}$$

$$S(A) - S(B) = -2.87 \text{ Ct}.$$

This time, the amount of entropy in the products is greater than that of the initial substances (both at standard temperature). There is no excess entropy. If no entropy were produced, the products would be colder than the reactants. Produced entropy is added, though.

Using

$$\mu(A) - \mu(B) = 394.36 \text{ kG}$$

we obtain

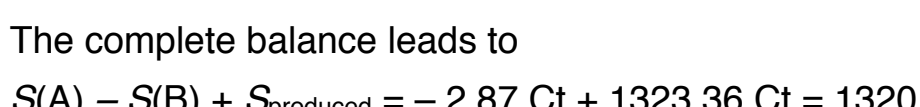
$$S_{\text{produced}} = \frac{394.36 \text{ kG}}{298 \text{ K}} \cdot 1 \text{ mol} = 1323.36 \text{ Ct}$$

The complete balance leads to

$$S(A) - S(B) + S_{\text{produced}} = -2.87 \text{ Ct} + 1323.36 \text{ Ct} = 1320.5 \text{ Ct}.$$

So once again, there is excess entropy. The products of the reaction are therefore warmer than the initial substances.

3rd case



$$S(A) = S(\text{Ba}(\text{OH})_2 \cdot 8\text{H}_2\text{O}) + 2S(\text{NH}_4\text{NO}_3) = 426.77 \text{ Ct} + 2 \cdot 151.08 \text{ Ct} = 728.93 \text{ Ct}$$

$$S(B) = 2S(\text{NH}_3) + 10S(\text{H}_2\text{O}) + S(\text{Ba}(\text{NO}_3)_2) = 2 \cdot 192.34 \text{ Ct} + 10 \cdot 69.91 \text{ Ct} + 213.80 \text{ Ct} = 1297.58 \text{ Ct}$$

$$S(A) - S(B) = -568.65 \text{ Ct}.$$

In this case, the amount of entropy in the products is much greater than that in the initial substances (both at standard temperature). With no entropy being produced, the end substances would therefore be much colder than the initial substances. We will check to see whether or not this lack of entropy can be compensated for by the entropy production.

With

$$\mu(A) - \mu(B) = 38.46 \text{ kG}$$

we obtain

$$S_{\text{produced}} = \frac{38.46 \text{ kG}}{298 \text{ K}} \cdot 1 \text{ mol} = 129.1 \text{ Ct}$$

and the total balance is

$$S(A) - S(B) + S_{\text{produced}} = -568.65 \text{ Ct} + 129.1 \text{ Ct} = -439.55 \text{ Ct}.$$

In order to bring the reaction products up to standard temperature, we need the missing 439.55 Ct. For this reason, the temperature of the final substances lies well below that of the initial substances.

The last case we just investigated is one that arises fairly seldom. Even if $S(A)$ is smaller than $S(B)$, the entropy that is produced is usually enough to even out the difference $S(A) - S(B)$ so that, in total, there is excess entropy.

Reactions where excess entropy exists (Cases 1 and 2), are called *exothermic*. Reactions where entropy is missing so that the initial temperature cannot be maintained (Case 3), are called *endothermic*.

Exercises

- When iron rusts, is entropy absorbed or emitted? How much is absorbed or emitted?
- Extra CaCl_2 is added to a watery 1 M CaCl_2 solution, and dissolved. Does the solution become warmer or cooler?
- Extra NaBr is added to a watery 1 M NaBr solution, and dissolved. Does the solution become warmer or cooler?
- Extra KNO_3 is added to a watery 1 M KNO_3 solution, and dissolved. Does the solution become warmer or cooler?

27

Relativity

27.1 Mass is energy

The following story is not exactly factual but something can be learned from it anyway.

Columbus and his crew reach a new land and find it is a very beautiful, fertile place with many trees and flowers. They assume they are on an island and name it Florida. However, after a long search they determine that there are no mineral resources there.

Columbus undertakes a second journey and again discovers a land that he assumes to be an island. This new place appears to be desert because nothing is growing there. However, this place is very rich in mineral resources and because of the beautiful colors of its rock formations, they name it Colorado.

Years later, Vespucci sails to the area in which Florida and Colorado are found and makes a surprising discovery: Both of these lands are actually one and the same island. Columbus had approached it from two different sides.

The story ends here. It was told in order to make something that takes place in physics clear to you. It has happened that the same thing has been discovered twice without people being aware at first that the two discoveries were actually one and the same thing. We will look at an example of this in the following.

You already know the two physical quantities mass and energy. One of them, mass, was already known in ancient times as weight. The other one, energy, was established around 1850 by Joule, Mayer, and Helmholtz. A little more than 50 years later, in the year 1905, Einstein discovered that both these quantities are actually the same. Mass and energy are simply different names for the same physical quantity. Because mass and energy were considered different quantities, different units were used for them.

Einstein published his “Theory of Relativity” in 1905 stating that the following relation between mass m and energy E is valid:

$$E = k \cdot m$$

where

$$k = 9 \cdot 10^{16} \text{ J/kg}$$

is a constant.

In our story when it was discovered that Florida and Colorado were the same island, two things became clear:

- Agriculture is possible on the island called Colorado.
- There are natural resources on the island known as Florida.

When it was discovered that mass is the same quantity as energy, two things became clear:

- The quantity formerly called energy, must also have the characteristics of mass: energy must have weight and it must also have inertia.
- The quantity earlier known as mass must also have the characteristics of energy. It must be possible to drive or heat something with mass.

These are astounding, almost unbelievable statements of the theory of relativity. In the next sections, we will see what their consequences are. We will also see why no one really noticed them before 1905.

Mass and energy are the same physical quantity.

27.2 Energy has the characteristics of mass

According to Einstein's discovery, energy has weight. The following equation tells us how many Joules correspond to a kilogram:

$$E = k \cdot m$$

If this statement were true, then in Fig. 27.1:

- A battery would be heavier when it is full than when it is empty;
- A car driving fast would be heavier than when it goes slowly or is standing still;
- Water in a bucket would be heavier when it is warm than when it is cold.

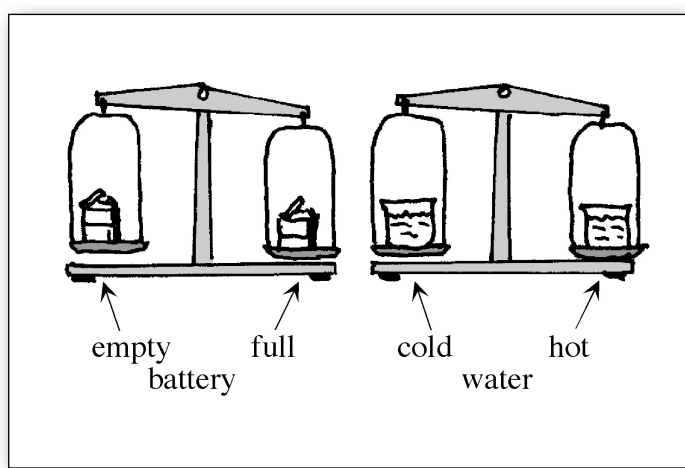


Fig. 27.1

A fully charged battery weighs more than an empty one, and warm water is heavier than cold water.

The reason that this is generally unnoticeable can be understood when you calculate by how many kilograms the mass of the objects in question changes.

We will consider a monocrystal for example. A monocrystal discharges about 10 kJ of energy. How much lighter is it because of this?

We calculate

$$m = \frac{E}{k} = \frac{10 \text{ kJ}}{9 \cdot 10^{16} \text{ J/kg}} = 1.1 \cdot 10^{-13} \text{ kg}$$

The battery's mass decreases less than the mass of a dust particle. A typical dust particle weighs about 10^{-12} kg. There is no scale that can measure this.

There are similar tiny differences in mass between a slow and a fast car or between cold and hot water.

Is there any situation at all where the difference in mass can be perceived? If not, the assertion could not be proved. There are such situations, though. For example, when a body is charged with lots of momentum.

You know that the energy of a body increases when it is charged with momentum. Fig. 27.2 shows the relation between energy and momentum for an arbitrary body as described by the theory of relativity. Energy and mass are the same so this is also the relation between mass and momentum. The mass of the body at rest, meaning when it has no momentum, is labeled with m_0 . When momentum increases, the mass also increases, thereby making the body heavier and more inert.

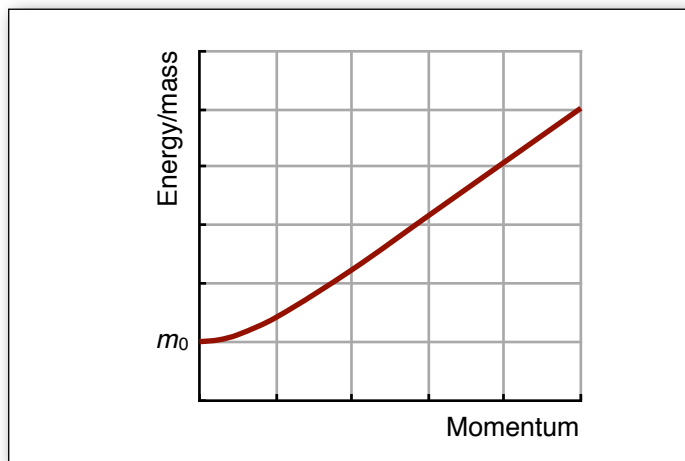


Fig. 27.2

The relation between energy and momentum and, equally, the relation between mass and momentum.

The mass m_0 the body has when it is at rest is called the *rest mass*.

A distinct increase of the mass of a body takes place in *particle accelerators*.

A particle accelerator is a very large facility that functions similarly to a television tube. In a television tube electrons are charged with momentum to create a beam.

In a particle accelerator, electrons or other particles are charged with momentum. The particles in an accelerator receive much more momentum than those in a television tube. When two particle rays are aimed directly against each other, new particles are created at collision. Such reactions help us learn a lot about the make-up of matter.

Particle acceleration goes very fast. We will let it happen much more slowly in our thoughts. The electrons are charged uniformly with momentum in the accelerator. As expected, they go faster at first. However, although momentum continues to be added, the speed increases more and more slowly until it finally does not increase at all even though more momentum is being transferred to the electrons. Fig. 27.3 shows the relation between velocity and momentum.

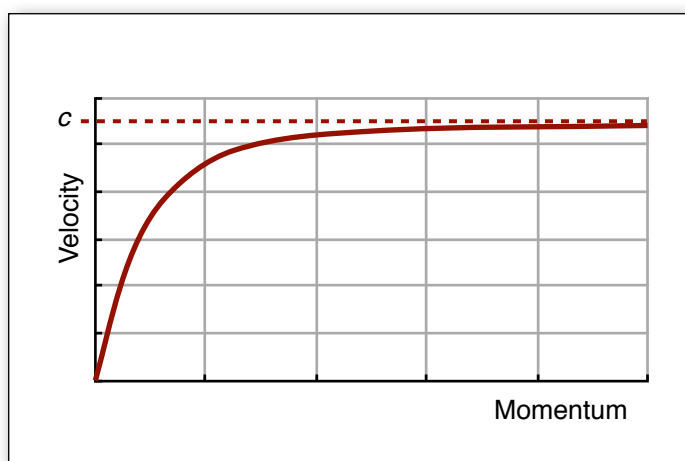


Fig. 27.3

The relation between velocity and momentum. At high speeds, a body approaches the limiting velocity c .

Why does the velocity stop increasing? The explanation is found in Fig. 27.2. When the particles are charged with momentum, the mass increases. Because of this, the particles become increasingly inert. This means that it becomes increasingly difficult to change their speed. Finally, the mass becomes so great that it is just about impossible to increase its velocity anymore.

The particle's velocity approaches a limiting value that cannot be exceeded. This *limiting velocity* is

$$c = 300\,000 \text{ km/s.}$$

This is the same speed at which light moves. It is impossible to make the electrons faster than light.

This same limiting velocity also exists for all other bodies. Cars, airplanes or rockets cannot exceed this velocity. (Of course, there are other reasons why cars and airplanes cannot reach this speed.)

No body can move faster than the speed of light.

In the equation

$$E = k \cdot m$$

the constant k is equal to the square of the limiting velocity c . Therefore, we can also write the equation in this form

$$E = m \cdot c^2.$$

Exercises

1. About 500 kJ of energy is needed to bring a car up to 100 km/h. How much heavier is the car then? Gasoline is burned at acceleration, which decreases the weight of the car. Estimate how much weight the car either loses or gains in all.
2. The sunlight falling perpendicularly upon one square meter every second transports energy of about 1000 Joule. How heavy is the corresponding amount of light? (Light has no rest mass.) How long would you have to wait until 1 gram of light has fallen upon the square meter?
3. Along with the light being emitted by the sun, it also emits energy of $3.8 \cdot 10^{26}$ J. How much lighter does it become?

27.3 Mass has the characteristics of energy

If mass is a measure of the same property as energy, then it must be possible to do all the useful things with it that are done with energy. It should be possible to drive vehicles and machines with any substance as well as to heat buildings with it. The substance need not be a special fuel or propellant. It should be enough that it has mass – and every substance has that.

For example, it should be possible to use sand as a fuel. We will calculate how much sand would be needed to fuel a car.

The equation

$$E = k \cdot m$$

tells us that 1 kg of sand (or 1 kg of any other substance) contains the following amount of energy:

$$E = 9 \cdot 10^{16} \text{ J/kg} \cdot 1 \text{ kg} = 9 \cdot 10^{16} \text{ J.}$$

In a normal engine, 1 kg of gasoline yields $4.3 \cdot 10^7$ J. One kilogram of sand is equal to two billion times that amount of energy, because $2\,000\,000\,000 \cdot 4.3 \cdot 10^7 \text{ J} \approx 9 \cdot 10^{16} \text{ J}$.

Is this actually possible? Isn't there some mistake here?

The calculation is indeed correct. The only mistake is concluding that a car can be fueled by sand. That energy is not always useful for driving something is not unusual.

One example is that in order to heat a house, it is not enough to just have enough heating oil. Oxygen is also necessary for burning the heating oil. If there were no oxygen, the heating oil would be worthless. It would not be possible to transfer the energy to another carrier—and this is what it is all about. In addition to the heating oil, an appropriate reaction partner is also needed.

The behavior of the huge amount of energy contained in every substance due to its mass is very similar. Here, as well, in order to make use of the energy, i.e., to transfer it to another energy carrier, an appropriate reaction partner is necessary.

The reaction partner needed in this case is so-called *antimatter*. Antimatter is a form of matter that does not exist in nature.

Antimatter can be artificially produced, but to do so, huge amounts of energy are needed. The same amount of energy is needed as corresponds to the mass. Nothing is gained by this.

In addition, it is almost impossible to store antimatter for more than a fraction of a second. It reacts very, very quickly with normal matter.

It has been speculated that the parts of the universe far away from us could be made up of antimatter but no one knows for sure yet.

28

Waves

Waves in water are well known to us, Fig. 28.1: they are deformations of the water's surface that move by themselves.

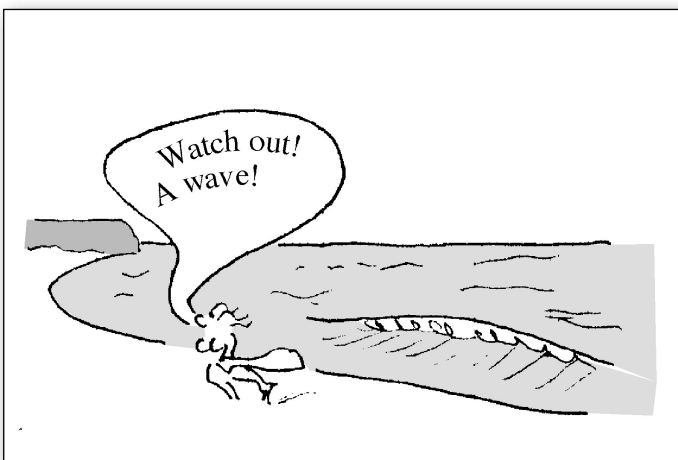


Fig. 28.1
Water wave

Sound waves are another wave phenomenon. These are very small displacements of air that move through the air.

Waves in water and sound waves are interesting enough in themselves to warrant our attention.

However, waves are also very important in the sciences because many phenomena, even ones where it would not be expected, can be described as waves.

There is a large class of waves known as electromagnetic waves. Waves such as radio and television waves belong to this category, as do the microwaves used in microwave ovens. An entire range of phenomena called radiation—infrared and ultraviolet as well as X-rays and gamma rays and light in general—are also electromagnetic waves. Later on we will see what all these different types of electromagnetic radiation have in common. We will also deal with the question of what the medium is through which these waves move. If we want to compare these waves with water waves, we should ask: What corresponds to the water and what corresponds to the deformation of the water?

You certainly understand now that it is really worthwhile to investigate waves.

In our list of wave phenomena, you may have noticed that some waves are used for data transmission. Sound, light, and radio waves all appear in nature as well as in technology as data carriers. There are also other types of waves or “radiation” that are used as data carriers. Perhaps you have already heard of infrared cameras. You certainly know about X-rays that are used to look inside the human body, i.e., to bring out data from inside the body.

28.1 Wave carriers

We will begin our investigation with an especially simple representative of waves—waves along ropes.

A long rope is laid upon the floor and one end is flipped up and immediately down again with a short strong movement. A wave moves away from the end that was snapped. Fig. 28.2 shows 3 snapshots of this wave as it moves.

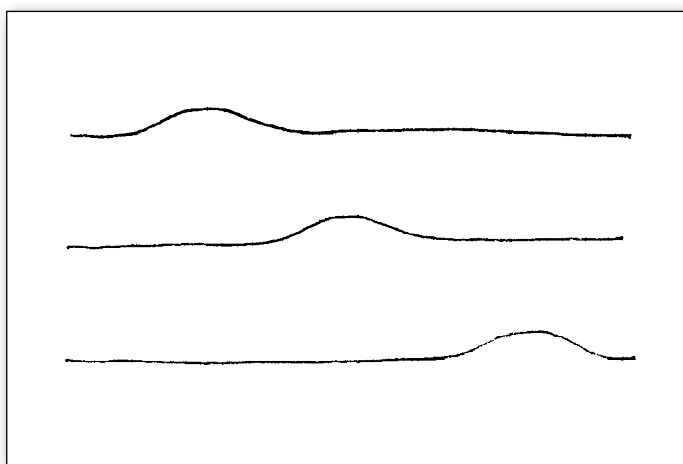


Fig. 28.2

Three snapshots of a wave along a rope

We describe this deformation as a wave moving through the rope. It is obvious that without a rope, no wave can be created.

We can generalize this observation: for a wave to exist, there must be an entity through which it can move. We call this entity the wave carrier (in this case, the rope is the carrier). At first, the carrier is in its ground state (lying in a straight line on the floor). A “source” at a certain place (in this case, the left end) goes through a short change of its ground state (the rope is snapped at this end). This change of ground state then travels through the carrier.

We consider a second type of wave from the same angle: a water wave in a long channel. The wave carrier is the water. In its initial state, the water’s surface is a flat horizontal surface, Fig. 28.3a. We dip an object into one end of the water and out again with a quick short movement, Fig. 28.3b. In the process, a deviation from the ground state occurs: a bump is created on the water’s surface which moves away from its source, Fig. 28.3c.

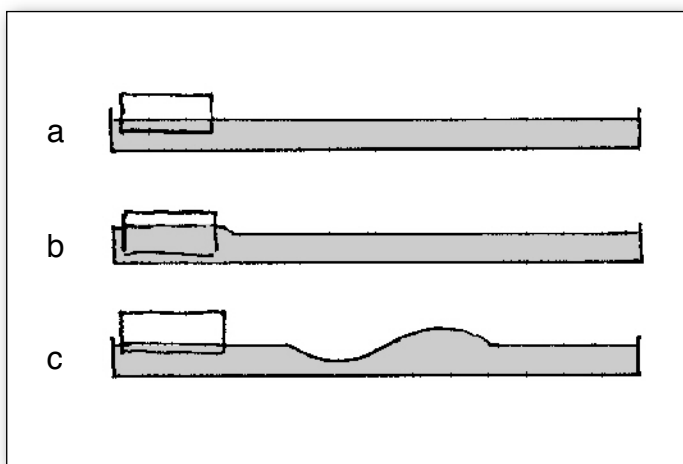


Fig. 28.3

The object floating on the water is suddenly pressed down and lifted again

A third example of a wave is shown in Fig. 28.4. The carrier of the wave is a long, somewhat tensed, steel spring. The change from its ground state is this: The left end of the spring is moved to the left with a short strong movement, and back again to its original position. This disturbance of the initial state also moves by itself away from the source.

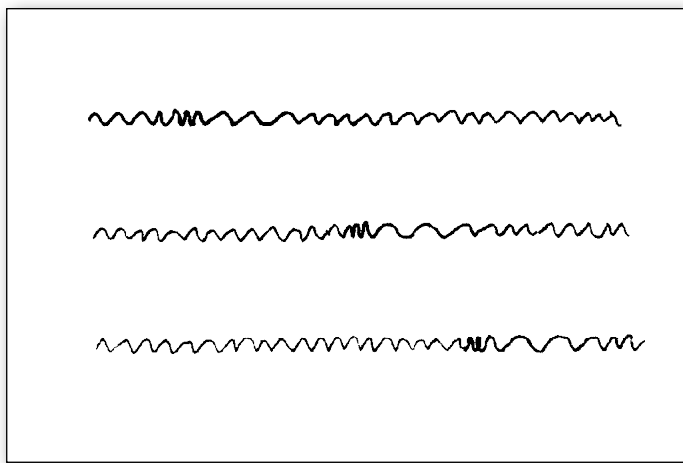


Fig. 28.4

Three snapshots of a longitudinal wave in a steel spring

We conclude that:

A wave needs a carrier. The ground state of the carrier is altered quickly at some location. This disturbance from the ground state moves by itself away from the source.

In all of the examples considered, not only did the wave move, but the carrier did as well. Remember to distinguish between these two different motions!

Sometimes the movement of the wave carrier is transverse to the wave’s direction of movement, for example in the case of the rope. Such waves are called *transverse waves*.

Sometimes the wave carrier makes a back and forth movement in the direction of the wave movement. The wave in the steel spring is an example of this. Such waves are called *longitudinal waves*.

Sometimes the movement of the carrier is more complicated. In the case of a water wave, for example, the carrier (the water) moves on a closed curve.

Sometimes nothing moves at all, as in the case of electromagnetic waves.

Do not confuse the motion of a wave with the motion of the wave carrier.

28.2 Transporting energy with waves

Let us consider the concrete example of the water wave in Figure 28.3.

We submerge the floating object at one end very, very slowly. The water level in the whole channel rises. Energy is used to press the object down into the water. We then allow the object to emerge from the water very, very slowly. In the process, the water level goes down again and we regain the energy we put into the water before. No wave is created during all this. We repeat the exact same process, but this time, very quickly. More energy is used to submerge the object than was used the first time and it is not all regained when the object is removed from the water. A part of the energy moves away with the wave. The wave transports energy.

This energy can be absorbed at another place and used to drive something. If you have been swimming in the ocean, you have probably already found out for yourself that water waves carry energy. There are experimental power plants that receive their energy from the ocean's waves.

Now back to our experiment. When a floating body is moved quickly, a wave is created that carries energy away with it. If it is moved very slowly, (almost) no wave is created and (almost) no energy moves away. In other words:

The faster the change of state at the source location, the more energy the wave carries away.

28.3 The velocity of waves

Try to make a rope wave faster or slower by moving the end of the rope in different ways. The only thing you will accomplish is to change the form of the wave or the size of the deformation. You will have no influence upon its speed. Throwing a stone is different. The stone's speed depends upon how much momentum it received at the "source". What does the speed of a wave depend upon, then?

The answer to this question is somewhat complicated. However, we can answer it to a certain extent:

The speed of a wave depends upon the carrier through which it moves.

This means that a wave on the surface of water has a different speed than one on the surface of alcohol, gasoline or mercury. A wave moving through a hard spring has a different speed than one moving through a soft one. Sound waves move through the air at about 300 m/s and through water at 1480 m/s. (The water waves we just looked at are not sound waves. It is easy, though, to produce sound waves in water. Just go to a swimming pool, put your head under water and scream!)

Light moves in so-called empty space (later on we will see that empty space isn't really so empty) at a speed of 300,000 km/s. In glass, it moves at only 200,000 km/s.

Exercise

A large number of dominoes are placed upright close to each other. When the first one is knocked over, it falls against the second one so that it also falls, etc. A change of state is moving through the series of dominos. What does this process have in common with a wave? How is it different from a wave?

28.4 Oscillations

In order to get ahead with the subject of waves, we will make a little detour and take a look at another phenomenon called oscillations.

When a physical quantity periodically changes its value, this is called oscillation.

The child on the swing in Fig. 28.5 is periodically changing her location, she is performing an oscillation.

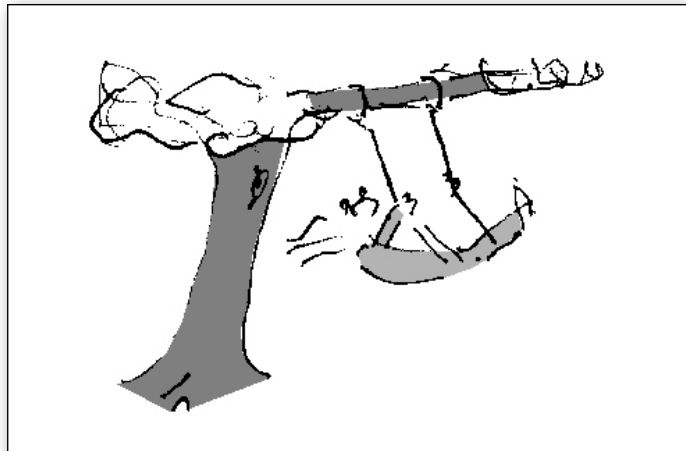


Fig. 28.5
The child and the swing are oscillating.

Press one end of a ruler strongly down upon the edge of a desktop, move the other end downward and then let it go. The ruler will oscillate, Fig. 28.6.

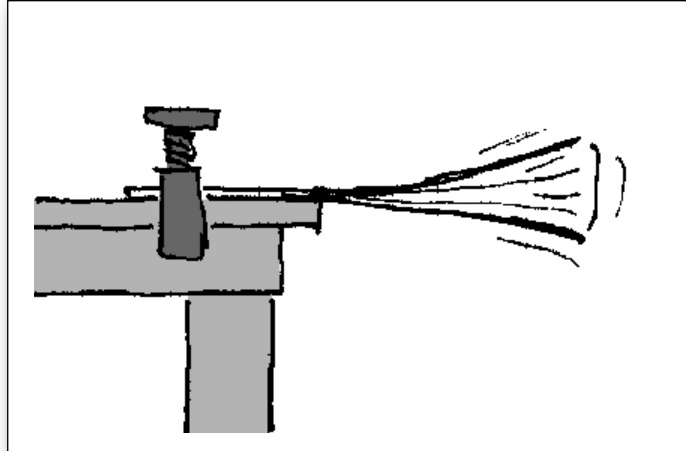


Fig. 28.6
The ruler is oscillating.

Fig. 28.7 shows a container that is hung so that it can tilt forward. A constant flow of water comes out of the faucet into the container. When the level of water in the container reaches a certain height, it tilts forward and the water flows out. Because it is now empty, it tilts back to its original position and the process starts over again. The container is oscillating.

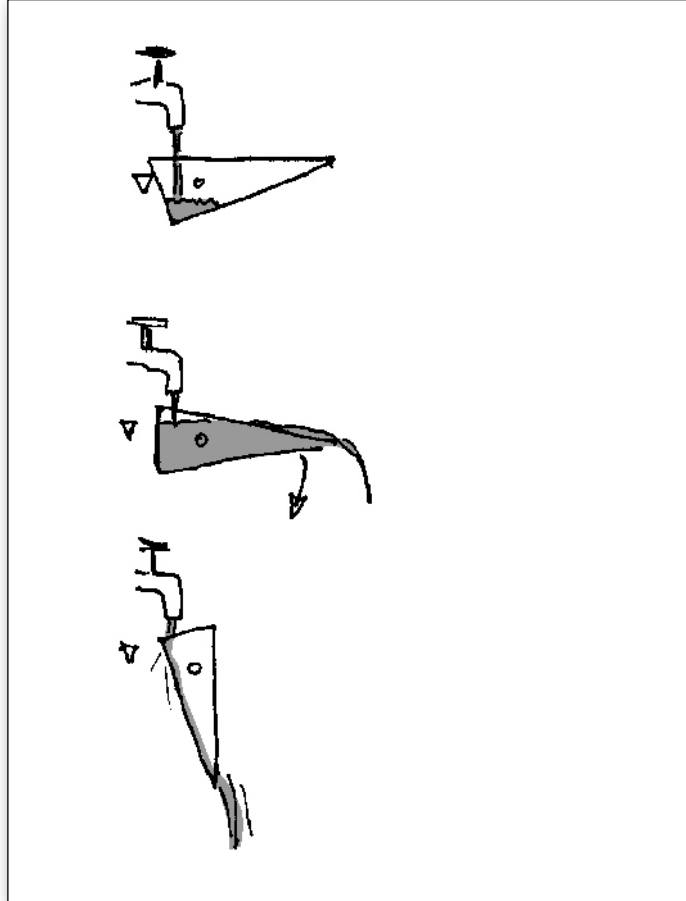


Fig. 28.7
The water container is oscillating.

We wish to represent an oscillation graphically. We put in the values of the quantity that changes periodically over time.

Fig. 28.8 shows the mass of water in the container in Fig. 28.7 as a function of time. At first, the amount of water increases uniformly. As soon as the container tilts, it decreases very fast and then fills up again at a constant rate, etc.

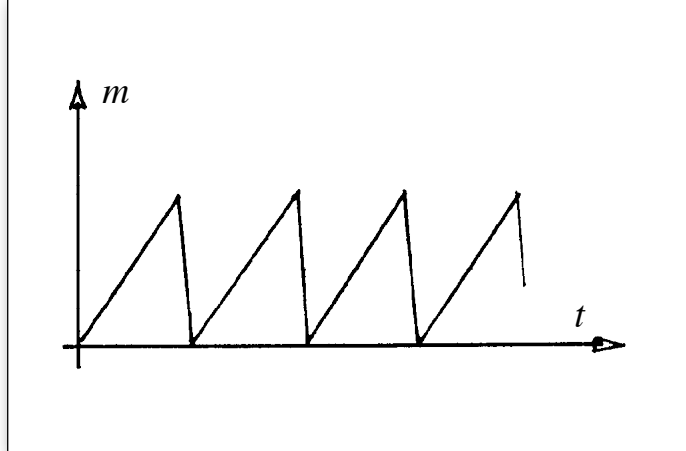


Fig. 28.8
The mass of water in the container in Fig. 28.7 as a function of time

A special type of oscillation is a *sinusoidal oscillation*. In this case, the physical quantity being considered changes according to a so-called *sine-function*. For example, the right end of the ruler in Fig. 28.6 is performing a sinusoidal oscillation. In Fig. 28.9, the location x of this end is shown as a function of time.

You will learn in your math class how a sine-function is defined. For our purposes, it is enough to know that it is a smooth oscillation without jerking motion and without sudden changes of direction.

By the way, you can obtain the values of the sine-function with a pocket calculator.

The time needed for an oscillating entity to go from a chosen initial state and to return to this state, is called the *period of oscillation*. It is symbolized by T .

If

$$T = 0.2 \text{ s}$$

is valid for the oscillating ruler, this means that the ruler needs 0.2 s for a complete up and down motion calculated from the lowest turnaround point.

The period of oscillation can also be seen in Fig. 28.9.

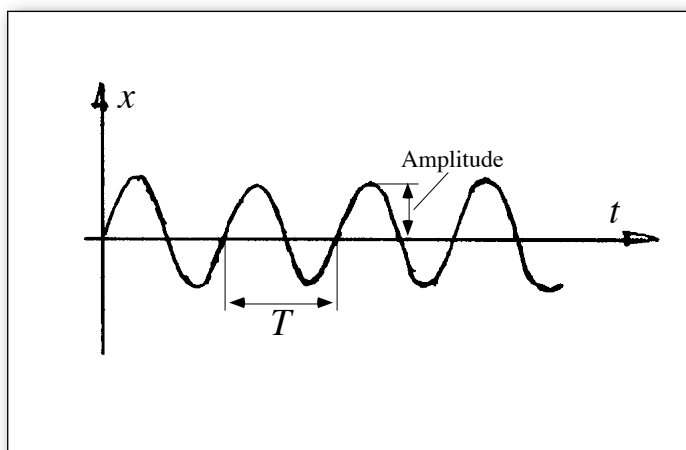


Fig. 28.9
Position x of the right end of the ruler in Fig. 28.6 as a function of time.

Instead of the period of oscillation T , the frequency f is often used as a measure of how fast something oscillates:

$$f = \frac{1}{T}$$

f indicates how many oscillations take place per second.

If, for example, the period of oscillation is

$$T = 0.5 \text{ s,}$$

then

$$f = \frac{1}{0.5 \text{ s}} = 2/\text{s}.$$

This means two oscillations per second. This makes sense because one oscillation needs exactly one half second.

The unit 1/s, or “per second” is also called Hertz, abbreviated to Hz. In our example, we have

$$f = 2 \text{ Hz.}$$

The maximum displacement of a sinus oscillation is called its *amplitude*, Fig. 28.9.

Exercises

1. Name some examples of oscillations. What physical quantities change their values periodically?
2. In mechanical clocks, a clock balance wheel carries out the oscillations and causes the ticking sound. If you have a mechanical alarm clock at home, measure the time for ten oscillations by using another clock with a second hand. What is the alarm clock's period of oscillation? What is its frequency?
3. Hang an object from a string of 1.5 meters length. Start it oscillating and measure the period of oscillation. Replace the object with another, heavier one and measure the period of oscillation again. Compare.

28.5 Sine waves

Now back to waves.

It isn't enough for us that only a single wave moves across water. We want the transport process to be continuous. How can we accomplish this? By sending off numerous waves in a so-called wave train. It is not enough to move the object sending off the wave train up and down only once. It must be moved up and down again and again, meaning periodically. The source must *oscillate*.

In our examples, the sender had to carry out some sort of movement in order to send waves on their way. An up and down motion was necessary to generate water waves, a back and forth motion was necessary for the wave in the steel spring. Now, in order to create a periodic wave, these movements must be oscillatory.

When the movement of the source of a wave is a sinusoidal oscillation, a *sine wave* is produced.

A sine wave in a rope is easy to recognize. A snapshot of the rope has the form of a sine-function, Fig. 28.10.

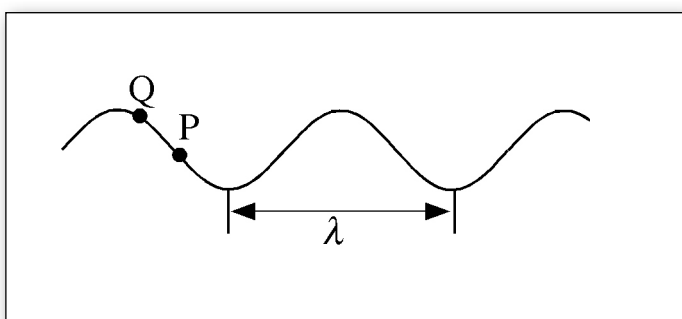


Fig. 28.10

Snapshot of a rope with a sine wave moving through it

Let us imagine that we have taken several snapshots of the rope in rapid succession, Fig. 28.11. The first picture shows a sinusoidal shape, as does the second, third, etc. However, all the pictures are shifted. The entire sine-function has moved to the right.

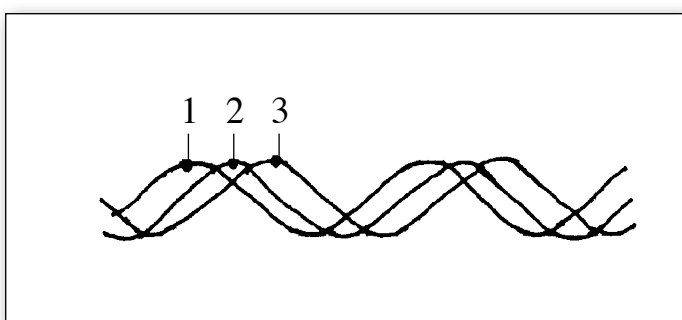


Fig. 28.11

Three snapshots of a sine wave in short time intervals

Now we will take a snapshot of a sinusoidal longitudinal wave, a sine wave in a steel spring, for example, Fig. 28.12. At first no sinusoidal shape can be seen. However, if the deviation of each point of the spring from its ground state is taken in the course of time, the image of a sine-function emerges.

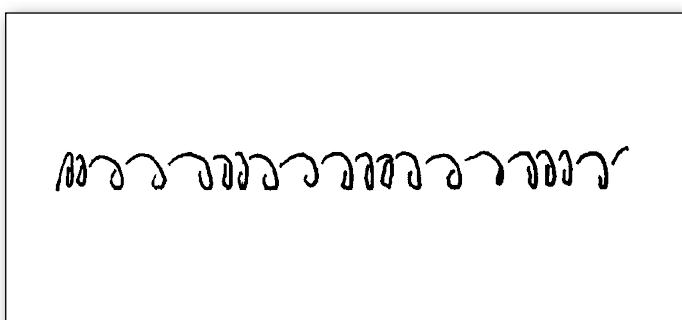


Fig. 28.12

Snapshot of a sinusoidal longitudinal wave

In Fig. 28.10, the distance between two neighboring “wave valleys” is marked. This distance is called the *wavelength* and is indicated by the Greek letter lambda, λ . The distance between two neighboring “wave crests” is, of course, also λ .

In order for a sine wave to move through a rope, the end of the rope must make a sinusoidal *oscillation*. When a sine wave moves in a rope, not only does the beginning of the rope make a sinusoidal oscillation, but so does every other part of it. Point P in Fig. 29.10 shows sinusoidal oscillation, and so does point Q. However, the oscillations of each point are shifted in time.

Exercises

1. Show the displacement of a point on a rope through which a wave moves as a function of time. In the same coordinate system, plot the displacement of a neighboring point on the rope.
2. Water waves on the ocean or on a pond show almost sinusoidal motion. What are the wavelengths observed?

28.6 The relation between velocity, frequency, and wavelength

Let us consider how wave crests and valleys emerge from the source. One complete wave crest and one complete wave valley emerge per oscillation period T . This is a section of the wave having length λ . This means that the wave moves forward by λ in the time T .

We can use this to give the speed of the wave. Because the speed is equal to the distance covered divided by the time needed to cover it, we have

$$v = \frac{\lambda}{T}$$

Now we will replace the period of oscillation T by the frequency f . With $T = 1/f$ we obtain

$$v = \lambda \cdot f.$$

An example: If a wave has a wavelength of $\lambda = 2$ m, and every part of the wave carrier oscillates with a frequency of 4 Hz, the resulting wave velocity is

$$v = 2 \text{ m} \cdot 4 \text{ Hz} = 2 \text{ m} \cdot 4/\text{s} = 8 \text{ m/s}.$$

Exercises

1. The speed of sound waves in air is about 300 m/s. What is the wavelength of the wave of standard pitch? Standard pitch has a frequency of 440 Hz.
2. Radio waves have a velocity of $v = 300\,000$ km/s. A radio station transmits with a frequency of 98.4 MHz. What is the wavelength of the waves?

28.7 Sound waves

Air is the carrier of sound waves. Air is invisible, so sound waves are invisible as well. It is easy to see that sound is actually waves in the air if we observe the way that sound waves are produced in loudspeakers. What we need is a loudspeaker with a visible “membrane”, a loudspeaker without its casing.

Fig. 28.13 shows how a loudspeaker is constructed. The membrane is mounted so that it can move perpendicularly to the loudspeaker. There is a solenoid mounted to the back of the membrane. This solenoid is inserted into a permanent magnet. One pole of the magnet is on the outside of the inner part of the magnet, the other pole is on the inner part of the outside of the magnet. When an electric current flows through the solenoid, the solenoid is pressed forward or backward by the magnetic field, depending on the direction of the current. The whole membrane moves along with it.

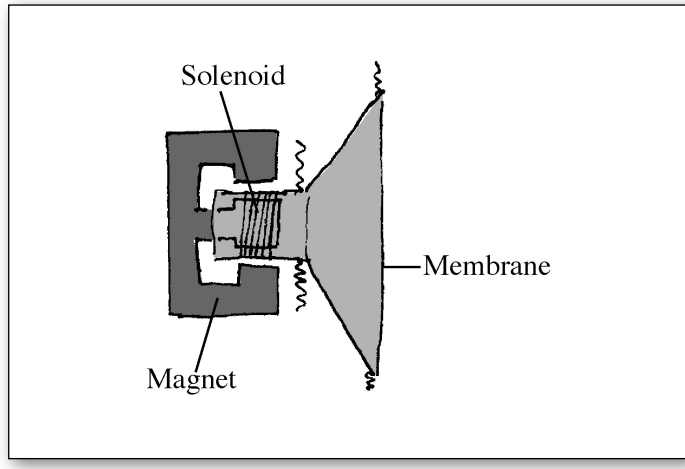


Fig. 28.13
Loudspeaker

We attach the loudspeaker to a battery through a switch, Fig. 28.14. If the switch is closed, a click is heard. When it is opened, it makes a click again. Turning on moves the membrane out of its initial state, turning off moves it back again.

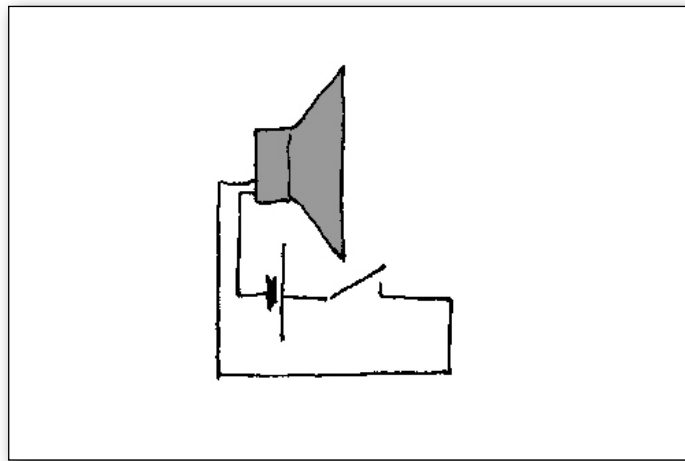


Fig. 28.14
When the switch is opened or closed a clicking sound is heard.

The sudden shifting of the membrane causes a quick displacement of the air on the surface of the membrane. This displacement separates from the membrane and moves away. This moving displacement of air is a sound wave.

The air moves back or forth in the direction in which the sound wave moves. Thus, sound is a longitudinal wave.

Another, simple experiment will demonstrate that air is the carrier of sound, Fig. 28.15. A bell is attached to a battery and put under a glass dome. While the bell rings, the air inside the dome is pumped out. As the air is pumped out, the sound of the bell gets quieter and quieter until it almost cannot be heard. When air is let into the dome again, the ringing becomes louder again.

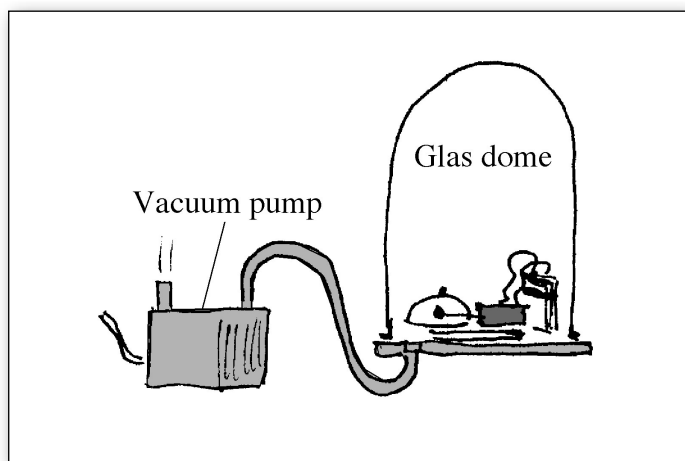


Fig. 28.15
When there is no more air under the glass dome, there is (almost) no sound from the bell anymore.

Despite a lack of air, something could still be heard. This is because solid materials also transport sound. In this case, it was the base the bell was mounted upon.

Sound is a longitudinal wave. The usual carrier of sound waves is air.

We attach the loudspeaker to a power supply that periodically turns the voltage on and off. Fig. 28.16 shows the voltage as a function of time. The power supply should be of the type where the frequency can be altered. We first choose a very low frequency: about 1 Hz. Two clicks per second can be heard: one turn on click and one turn off click.

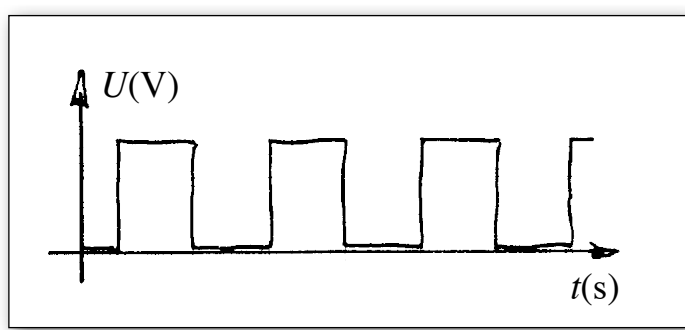


Fig. 28.16
“Square wave voltage”

We slowly increase the frequency. The clicks are now closer together. At about 20 Hz, we cannot hear the individual clicks anymore. What we hear is a *tone*, a continuous, stable sound.

The sound that is perceived is a low tone. When the frequency is raised, the tone becomes higher.

Instead of a “square wave signal,” we now put a sine wave signal on the loudspeaker. Again, we begin with a very low frequency. This time we hear absolutely nothing under 20 Hz. There are two reasons for this.

First, no wave is produced at very low frequencies. It is just like the example we had where no water wave was generated when an object is submerged very slowly in the water. Secondly, our hearing is only sensitive to waves within a certain frequency range: about 20 Hz to 20,000 Hz. As we age, this range becomes noticeably smaller.

Our hearing is sensitive to sine waves with frequencies between about 20 Hz and 20 kHz. The higher the frequency, the higher the sound.

We wish to measure the velocity of a sound wave, Fig. 28.17. The wave is produced by someone clapping their hands.

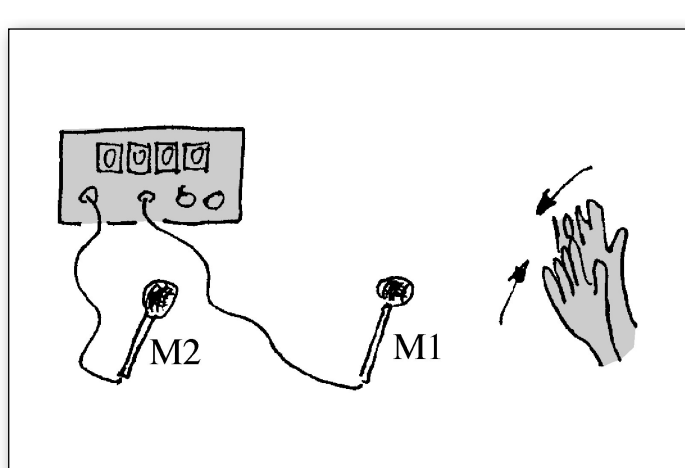


Fig. 28.17
Measuring the speed of a sound wave

The wave moves successively past microphones M1 and M2. The microphones are attached to an electronic stopwatch. When a signal comes from M1, the stopwatch starts. When the signal comes from M2, the stopwatch stops. It measures the time needed by the wave to cover the distance between M1 and M2.

The speed of the wave is obtained by dividing the distance between the microphones by the time needed by the wave to cover the distance between them. This is not a very precise experiment. A more precise method would show that the speed of sound is dependent upon temperature. Keep in mind, though that 300 m/s is generally close enough.

The speed of sound waves in the air is about 300 m/s.

Exercises

1. Name different sources of sound waves.
2. What is the frequency of a tone whose wavelength is 2 m.
3. What are the wavelengths of the lowest and highest tones that are possible to hear?
4. The speed of sound increases with increases in temperature. A sinusoidal sound wave goes from a colder location to a warmer one. What happens to the frequency? What happens to the wavelength?
5. During a thunderstorm, you see a bolt of lightning and hear the thunder 10 seconds later. How far away is the storm from you?

28.8. Electromagnetic waves

We wish to generate an electromagnetic wave. To do this, we orient ourselves to how other kinds of waves are generated by making the state of a carrier go through a sudden change. We will begin with a wire that has an electric current flowing through it. As you know, the wire is surrounded by a magnetic field. This means that the state of the surroundings of the wire has been changed because if no current were flowing, no magnetic field would be there, Fig. 28.18. We will now look in slow motion at the process of creating the field. Starting at 0 A, we slowly increase the current strength. The stronger the current, the denser the field becomes. If the current is decreased again, the field disappears. When the current is increased, energy flows into the field. If the current is reduced, energy flows back into the wire producing heat.

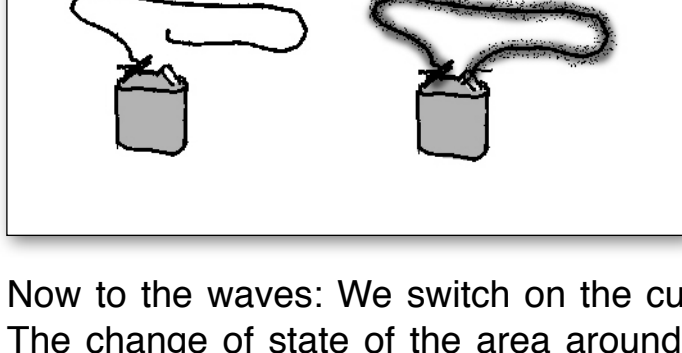


Fig. 28.18
The vicinity of an electric cable at two different states. Left: without a magnetic field; right: with a magnetic field.

Now to the waves: We switch on the current by closing the switch. The change of state of the area around the wire is very sudden. It separates from the wire and moves away by itself, Fig. 28.19. This change of state is a change in the magnetic field. The entity moving away is a magnetic field. This “electromagnetic” wave moves away during the process of switching on. If the current flows at a constant rate, nothing more moves away.

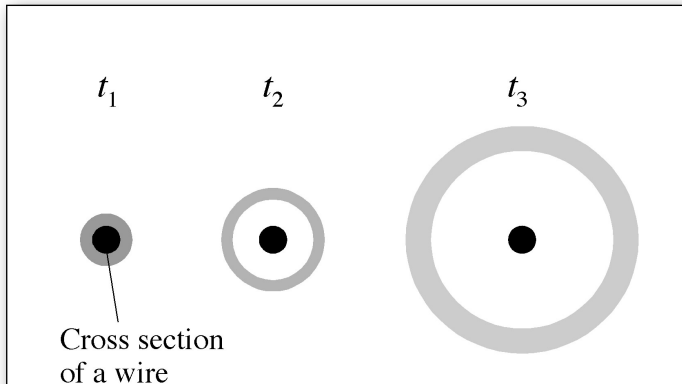


Fig. 28.19
Cross-section of a wire at three different points in time. When the electric current is suddenly turned on, an electromagnetic wave moves away from the wire.

If the current is (suddenly) switched off again, it causes a sudden change of state. This means that an electromagnetic wave moves away again.

The wire in which we have suddenly changed the current plays the role of a transmission antenna.

When the electric current in a wire is switched on or off, an electromagnetic wave separates from it.

It isn't easy to switch an electric current on or off quickly. If the usual type of switch is used, it would be too slow for our purposes. This is because when the contact is first touched, a weak current begins to flow that only “slowly” increases. Correspondingly, the current does not decrease as quickly when the switch is opened as we need it to. A better method is to produce a spark-over with the help of very high voltage. This spark-over is related to a very, very fast change of current.

There is another way to produce an electromagnetic wave. One takes a permanent magnet and moves it very quickly. The magnetic field changes in this case, too. This method is not effective though, because it is not possible to move the magnet fast enough.

How do we know whether or not a wave has been generated at all? A device is necessary that reacts to the arrival of a wave: a receiving antenna. The simplest way is to turn on a radio and set it to short, medium or long wave (FM is not good for this). Each time one of the waves we have generated arrives, we hear a disturbance, a click. It is also possible to make the arrival of waves visible by attaching the two ends of a wire to the input of an oscilloscope, Fig. 28.20. The wire forms a solenoid with one single turn. The arrival of the wave causes a change in the magnetic field of this solenoid. This change in the field in the solenoid creates a voltage between the ends of the solenoid. We called this process induction. The change lasts for a very short instant so that a very short “voltage surge” is produced. This can be seen on the oscilloscope's screen.

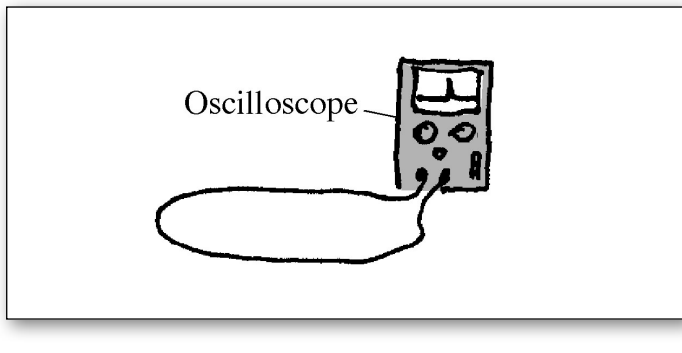


Fig. 28.20
The loop of wire is the receiving antenna. A voltage is induced in the receiving antenna by the incoming wave. The voltage is shown on the oscilloscope.

An important question is still unanswered: Through which medium does the electromagnetic wave actually travel? What is its carrier? It cannot be the air because electromagnetic waves can also move through matter free space. Light, which is an electromagnetic wave, has no problem crossing the 150 million km from the Sun to the Earth. This space is practically empty air and other matter. (The air around the earth is only a few kilometers thick.)

It can be assumed then, that so-called empty space must contain something that plays the role of carrier for electromagnetic waves. When it was discovered that light is a wave, this medium was called “ether.” It was believed that light was a mechanical wave in this ether, a wave with which the carrier also moved—just like sound waves do in air. Only later was it discovered that the change of state of the carrier of electromagnetic waves is not a deformation. This carrier has other surprising characteristics as well.

It was then given a new name because there were too many misconceptions connected to the name “ether.” The new name is “vacuum.” In plain English this means “empty space.”

The carrier of electromagnetic waves is called the “vacuum.”

This name should not be misunderstood. “Empty space” is something different from “nothingness” which would mean really nothing at all. However, there can still be something in an empty container. An empty coke bottle can still contain air after it has been emptied of coke. An empty gum dispenser which contains no more gum, still contains the entire mechanism for dispensing. Another example is an empty battery from which no more electric energy can be obtained. It is still full of lead and sulfuric acid.

When a part of space is said to be a vacuum, this means that no matter can be found there, but something else can. This something else is the carrier of electromagnetic waves. As long as no electromagnetic waves are moving through the vacuum, it is in its “ground state.”

The electromagnetic waves we generated were short pulses similar to the way we sent short shocks through the air with the loud-speaker. In order to produce a continuous wave, we must switch the electric current in our transmission antenna on and off in rapid succession. If an electromagnetic sine wave is desired, a sinusoidal alternating current must be sent through the wire. In order for the antenna to emit a wave, the frequency needs to be very high. The 50 Hz of normal alternating currents is too low.

You already know the velocity of electromagnetic waves: In a vacuum, it is 300,000 km/s.

Electromagnetic waves are everywhere and they all have different wavelengths. There are natural sources for electromagnetic waves of different wavelengths. There are also technical applications for waves of various wavelengths.

The range of nanometers that can be generated or observed, go from millions of nanometers to kilometers long, Fig. 28.21. Although all of these waves are of the same nature and, although they only differ in their wavelengths, there are great differences in how they are created. In addition, totally different things happen when waves of different wavelength hit matter. This is why they can be used for very different applications. This is also why waves of different lengths have different names: Gamma rays, X-rays, ultraviolet radiation (or ultraviolet light), (visible) light, infrared radiation (or infrared light or heat radiation), microwaves, and radio waves.

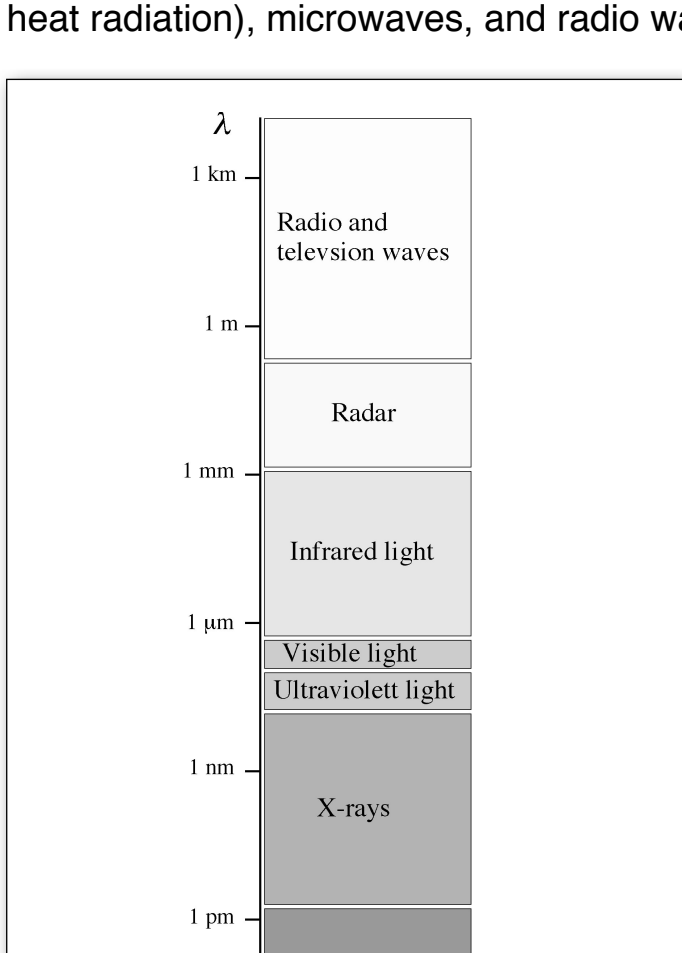


Fig. 28.21
Electromagnetic waves having different names and uses according to their wavelengths.

The most important applications can be put into two categories: Electromagnetic waves serve as data carriers and they serve as energy carriers.

Electromagnetic waves as data carriers

Light carries information (data) about our surroundings into our eyes, or into a camera or a television camera. Radio and television waves bring data from a transmission antenna to the receiving antenna of a radio or television set.

Even shorter waves are used for data transmission to and from satellites. They are sent and received by parabolic antennas. Transmission of radio and television between transmission towers is also done with electromagnetic waves within this range. Radar works with waves of this wavelength as well.

Space research and astronomy are done almost exclusively with the help of electromagnetic waves. Waves of the most diverse wavelengths come to Earth from space, ranging from gamma rays to radio waves. Each kind of radiation brings us different data about far away planets, stars, galaxies, quasars, and other strange celestial bodies.

Electromagnetic waves are also used to research the microworld. Here, X-rays play a very important role. Most of what has been discovered about the composition of solid matter has been done using X-rays.

Electromagnetic waves as energy carriers

All electromagnetic waves carry energy. Often, it is the transport of energy that we want, but sometimes this transport of energy is damaging.

The most important energy transport by electromagnetic waves is with the sunlight. It is the energy source for life on Earth.

Another important energy transport is by means of infrared radiation. A heater emits its energy (and its entropy) with this kind of radiation. The earth, too, emits as much energy with infrared light back into space as it receives with visible light from the Sun.

The food in a microwave oven is cooked or thawed by the energy of waves of 12 cm wavelength. Energy transport with radiation of very short wavelength is mostly undesirable because X-rays and γ -rays are dangerous. They destroy the molecules in living creatures.

Exercises

1. Why does a thunderstorm disturb television reception?
2. Name some different sources of electromagnetic waves.

28.9 Standing waves – interference

We wish to investigate what happens when two waves meet each other. Is there a collision?

1. Two single wave pulses

The best example are waves along ropes. We have a long rope lying stretched out on the floor. We send a wave pulse out from each end at the same instant, Fig. 28.22. The waves move toward each other. Waves then move back over the rope in both directions from the point where they meet. What has happened? Have the two waves bounced off each other? Were they reflected from each other?

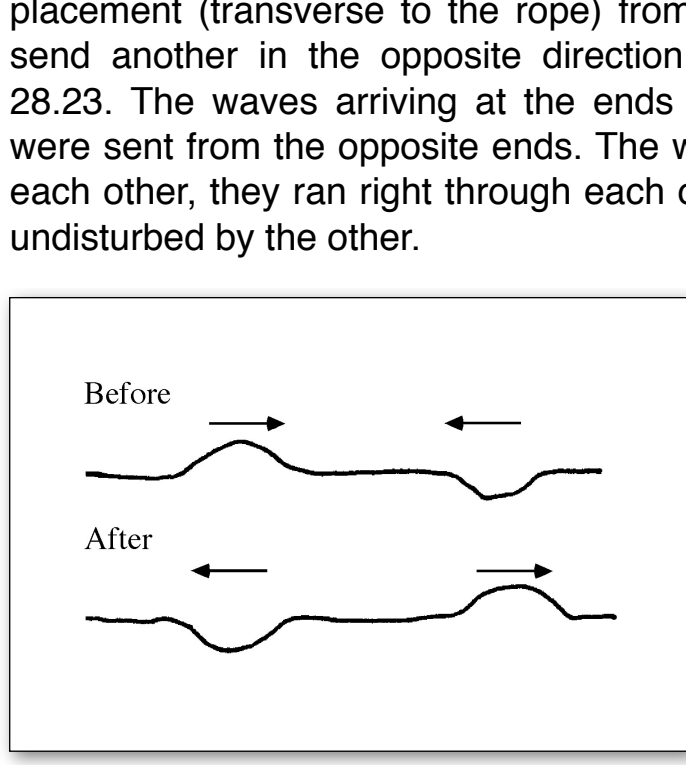


Fig. 28.22
Have the two waves bounced off each other?

We will now change the experiment somewhat. We send a displacement (transverse to the rope) from one end of the rope, and send another in the opposite direction, from the other end, Fig. 28.23. The waves arriving at the ends of the rope are those that were sent from the opposite ends. The waves were not reflected by each other, they ran right through each other. One wave was totally undisturbed by the other.

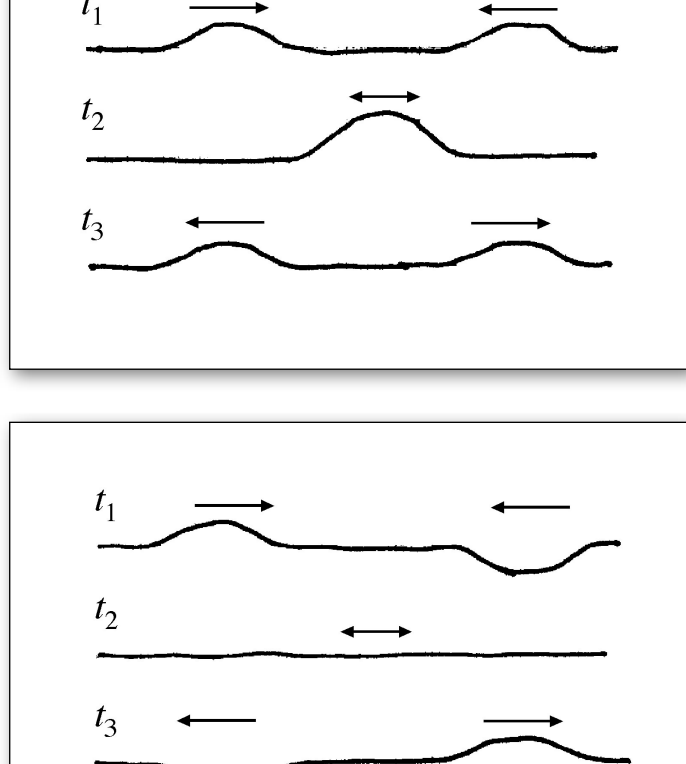


Fig. 28.23
The waves move through each other.

Each wave moved through the entire rope as if the other one wasn't there.

Here is what couldn't be seen in our experiment because it happened too fast:

At the instant the two waves meet in the middle, the displacements add up. For the wave in Fig. 28.22, this means that for an instant, there was just one wave in the middle of the rope with twice the displacement, Fig. 28.24. With the waves as in Fig. 28.23 the rope was absolutely straight for an instant: The displacements add up to zero, Fig. 28.25.

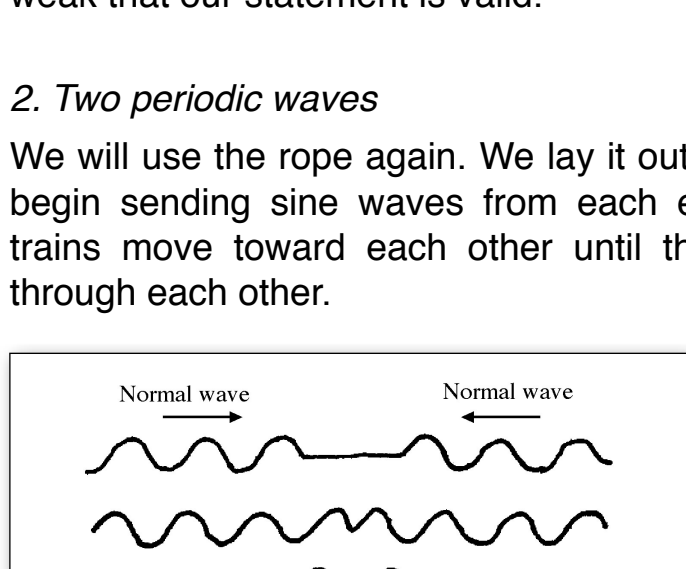


Fig. 28.24
At time t_2 , there is a wave crest in the middle with double displacement.

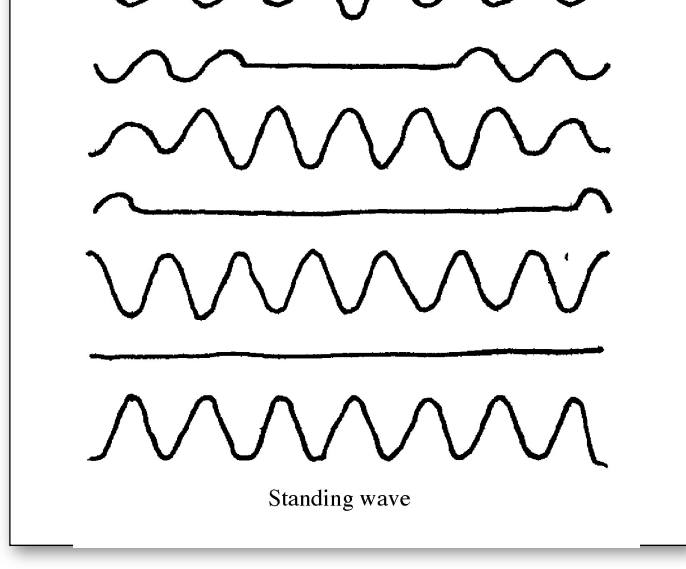


Fig. 28.25
At time t_2 , the rope is totally straight.

In summary:

Waves move through each other undisturbed.

As with so many rules, this one does not always hold true. It is no longer valid if the displacements of the waves are too great. An example: When two very large waves in the ocean that are about to break hit each other, they do not go through each other undisturbed. Most of the waves that we are dealing with here, however, are so weak that our statement is valid.

2. Two periodic waves

We will use the rope again. We lay it out straight upon the floor and begin sending sine waves from each end, Fig. 28.26. The wave trains move toward each other until they meet and continue on through each other.

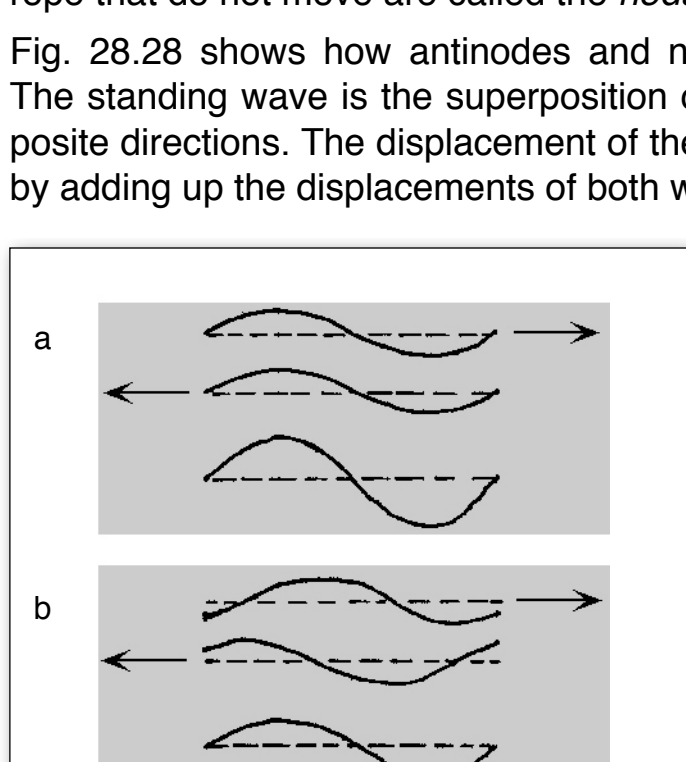


Fig. 28.26
Two sine waves move toward each other and through each other. The process is shown at 9 consecutive points in time.

What can be seen here is remarkable. There is no movement to be seen in any direction on the rope. Fig. 28.27 shows a segment of the rope where both waves are running, at five different points in time. The rope is sinusoidal in form, but the heights of the crests and valleys change. The places where the rope is not deflected to either side, stay still. They don't move in one direction or the other as would be the case in a normal wave.

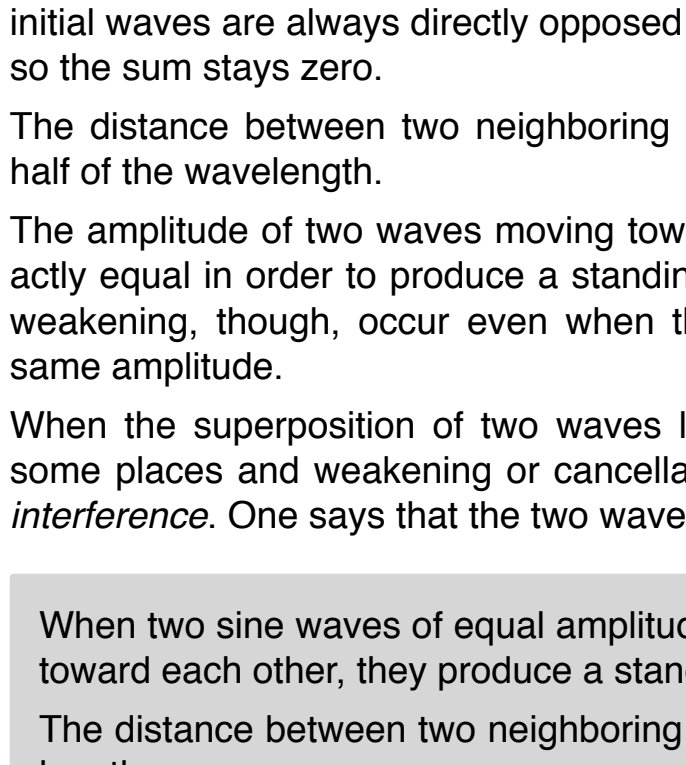


Fig. 28.27
The various dotted and dashed lines correspond to the forms of the standing wave at five different points in time.

This phenomenon is called a *standing wave*. The places of strongest movement or displacement are the *antinodes*, and the places on the rope that do not move are called the *nodal points*.

Fig. 28.28 shows how antinodes and nodal points are generated. The standing wave is the superposition of two waves moving in opposite directions. The displacement of the standing wave is obtained by adding up the displacements of both waves.

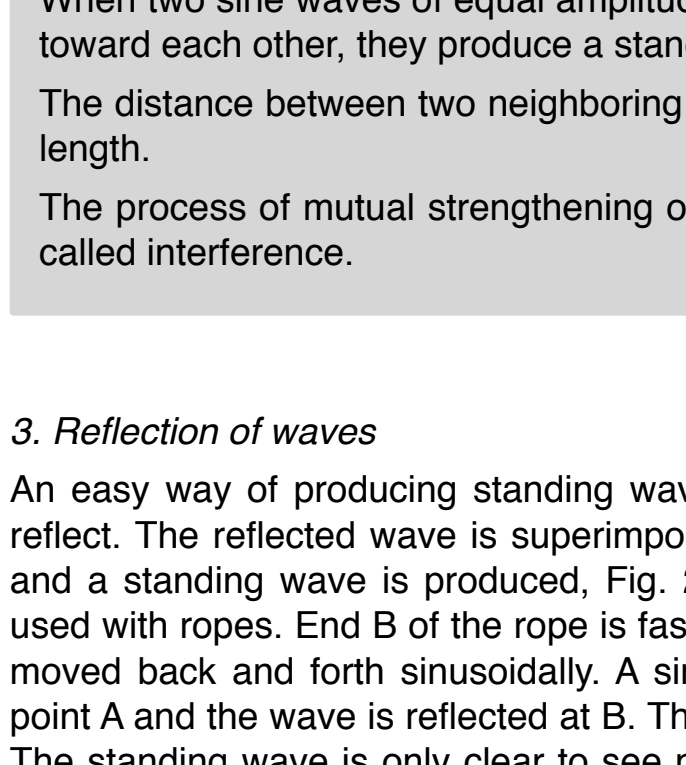


Fig. 28.28
The standing wave is produced by adding up the displacements of two waves moving toward each other. Parts a, b, and c of the Figure show the addition for three consecutive points in time.

Fig. 28.28 also shows the two initial waves for three different points in time at the top, and below the actual wave generated by addition. We see that the amplitude in the antinodes is twice that in standing waves as in either one of the two initial waves. Two displacements in the same direction come together here. The displacements of the initial waves are always directly opposed where the nodal points are, so the sum stays zero.

The distance between two neighboring nodal points is always one half of the wavelength.

The amplitude of two waves moving toward each other must be exactly equal in order to produce a standing wave. Strengthening and weakening, though, occur even when the waves do not have the same amplitude.

When the superposition of two waves leads to a strengthening in some places and weakening or cancellation in others, we speak of *interference*. One says that the two waves interfered.

When two sine waves of equal amplitude and wavelength move toward each other, they produce a standing wave.

The distance between two neighboring nodes is half of a wavelength.

The process of mutual strengthening or weakening of waves is called interference.

3. Reflection of waves

An easy way of producing standing waves is to have a sine wave reflect. The reflected wave is superimposed with the one coming in and a standing wave is produced, Fig. 28.29. This method can be used with ropes. End B of the rope is fastened somehow. End A is moved back and forth sinusoidally. A sine wave moves away from point A and the wave is reflected at B. The result is a standing wave. The standing wave is only clear to see near end B, because that is where both the initial waves have equal amplitude. The wave at A that moves toward B is much stronger than the one coming from B because something of every wave always gets lost along the way.

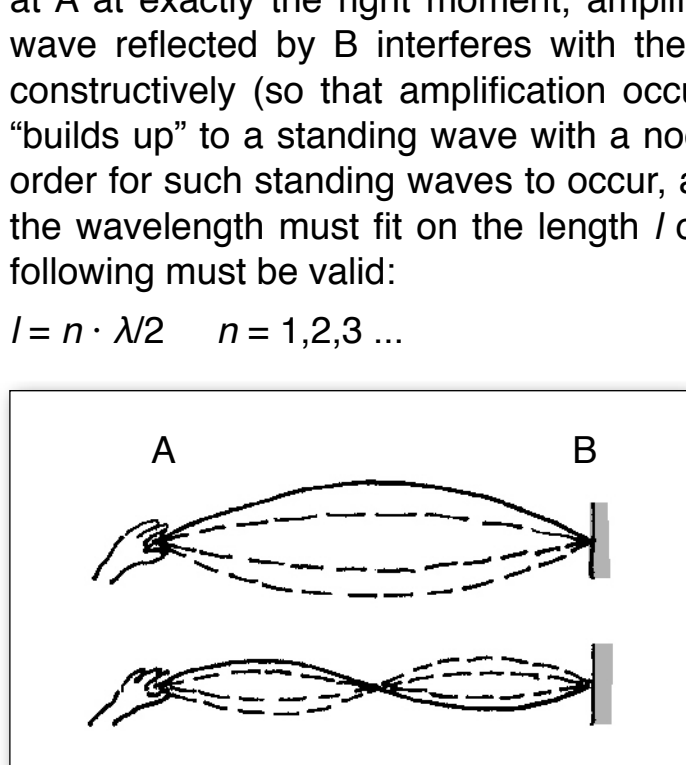


Fig. 28.29
The incoming wave interferes with the reflected wave.

Our method of generating standing waves also works with sound waves. In Fig. 28.30, the loudspeaker sends a sine wave against the wall. The wave is reflected by the wall. The incident wave and the reflected wave interfere with each other and a standing sound wave is produced.

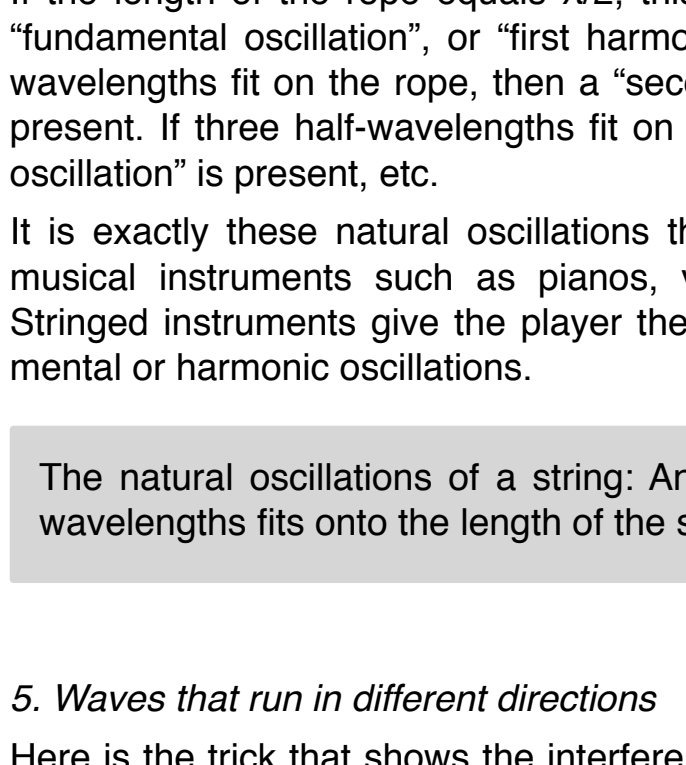


Fig. 28.30
Producing standing sound waves by reflection on a wall.

We attach a microphone to an oscilloscope and move it back and forth between the loudspeaker and the wall. The oscilloscope clearly shows the places of amplification and the points of weakening. While a wave on a rope is a one-dimensional entity, a sound wave is three-dimensional. It runs in one direction and extends in the two directions perpendicular to it. In this case, the nodes are not points as they are with the rope, but entire planes.

The idea might arise to try producing standing light waves by this method. One could take light of a single color (meaning sine light waves) and shine it upon a mirror. Indeed, nodes and antinodes are produced in front of the mirror. The wavelength of the light is so small, however, and the nodes lie so close together, that it is very difficult to prove the standing waves are there at all. Later on we will learn a trick that allows us to increase the distances between the nodes.

4. Caged waves

Again, we attach end B of our rope to something, but this time we hold end A up in the air and pull the rope taut. It never touches the floor. Because of this, friction is less than in the previous experiments and the waves in the rope are much less weakened. If we now generate a sine wave, it will be reflected not only at B. It will move back to A and be reflected again. When the wave crests arrive at A at exactly the right moment, amplification occurs because the wave reflected by B interferes with the one produced at A constructively (so that amplification occurs). The rope's movement "builds up" to a standing wave with a node at A and a node at B. In order for such standing waves to occur, an integer multiple of half of the wavelength must fit on the length l of the rope, Fig. 28.31. The following must be valid:

$$l = n \cdot \lambda/2 \quad n = 1, 2, 3, \dots$$

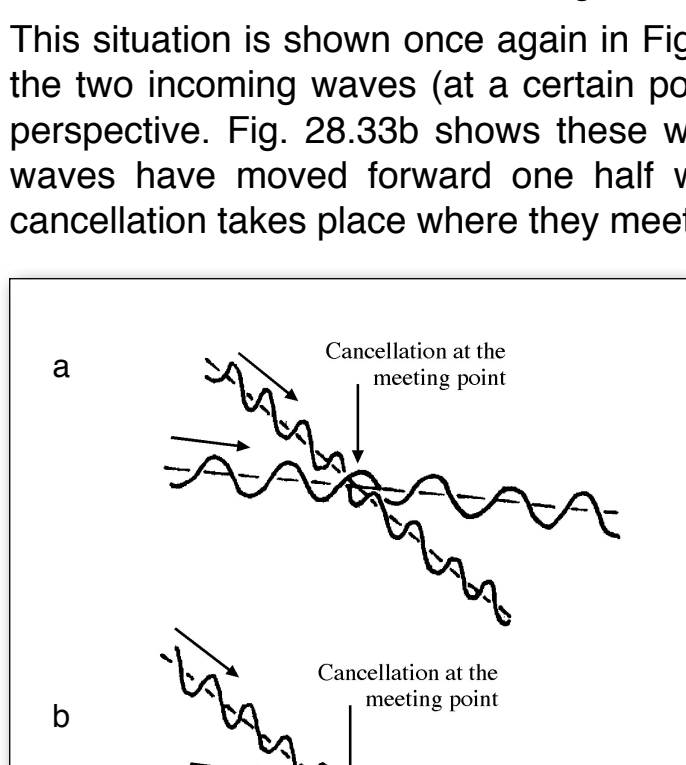


Fig. 28.31
Natural oscillation of a rope: An integer multiple of a half wavelength fits on the length of the rope.

Because each wavelength belongs a certain frequency, the end of the rope must be moved at a given frequency in order to produce a standing wave. This motion is called the *natural oscillation* of the rope. If the end of the rope is moved with an inappropriate frequency, a complex, non-periodic movement is generated in the rope. If the length of the rope equals $\lambda/2$, this means $n = 1$, we have a "fundamental oscillation", or "first harmonic oscillation". If two half-wavelengths fit on the rope, then a "second harmonic oscillation" is present. If three half-wavelengths fit on the rope, a "third harmonic oscillation" is present, etc.

It is interesting these natural oscillations of strings of musical instruments such as pianos, violins, cellos and guitars. Stringed instruments give the player the possibility to excite fundamental or harmonic oscillations.

The natural oscillations of a string: An integer multiple of half wavelengths fits onto the length of the string.

5. Waves that run in different directions

Here is the trick that shows the interference of light. We will explain it using a two-dimensional wave, a wave upon the surface of water, for example, because it is easy to sketch, Fig. 28.32.

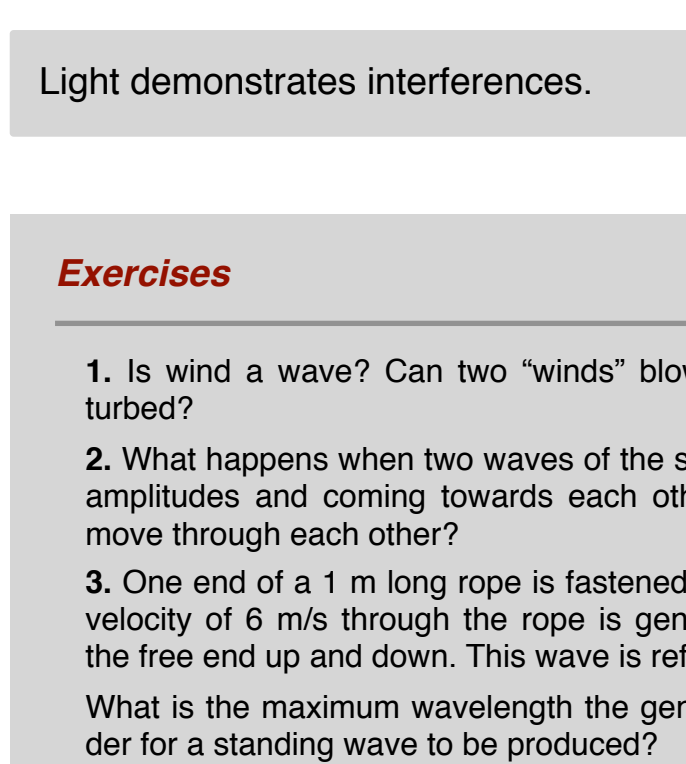


Fig. 28.32
(a) The waves move toward each other. The interference fringes are very close to each other.
(b) The waves are no longer moving toward each other, the interference fringes are further apart.
(c) The waves are moving in almost the same direction. The interference fringes are very far apart from each other.

Fig. 28.32a shows two waves that move toward each other. In the picture, one is coming from above, and the other one from below. The points of cancellation are shown by the horizontal lines.

We now turn the directions of the two waves, one to the right and one to the left, Fig. 28.32b. The points of cancellation are, again, horizontal lines, however, they are further apart.

We turn the directions of the waves even more, Fig. 28.32c, and the points of cancellation move even further apart.

Finally, when the waves move toward each other at an acute angle, the lines of cancellation have a large distance.

This situation is shown once again in Fig. 28.33a. Cross sections of the two incoming waves (at a certain point in time) are sketched in perspective. Fig. 28.33b shows these waves a moment later: both waves have moved forward one half wavelength. In both cases, cancellation takes place where they meet.

Fig. 28.33
Two "snapshots" of two interfering waves. Cancellation happens at the same place both times.

Now let us return to light. If two rays of light cross each other at a very acute angle, cancellation occurs on the planes that lie parallel to the bisecting lines of the angles between the light rays. The more acute the angle between the light rays, the further apart the planes are. The distance between the places of cancellation can be made as large as necessary in order to see them well.

Fig. 28.34 shows an experiment. The two light rays shining toward each other have been created in the following way: One ray falls at a very acute angle upon a mirror with two sections. The two sections of the mirror are tilted at a very small angle relative to each other. One half of the beam of light falls upon one half of the mirror and the other half falls upon the other half of the mirror. The direction of the reflected halves of the beam create an acute angle. The two half-rays run through each other and interfere.

Fig. 28.34
Experiment with interference of light

Because the angle between the two half-rays is very small, the planes of cancellation are far apart from each other. If a white screen (not sketched in Fig. 28.34) is put into the area of interference, an "interference pattern" of light and dark stripes appears.

This experiment was first conducted at the beginning of the 19th century. It was considered to be concrete proof that light is a wave.

Light demonstrates interferences.

Exercises

1. Is wind a wave? Can two "winds" blow through each other undisturbed?
2. What happens when two waves of the same wavelength but differing amplitudes and coming towards each other from opposite directions, move through each other?
3. One end of a 1 m long rope is fastened to something. A wave with a velocity of 6 m/s through the rope is generated by constantly moving the free end up and down. This wave is reflected at the ends.
What is the maximum wavelength the generated wave can have in order for a standing wave to be produced?
At what frequency does the free end need to be moved up and down to produce a standing wave with two nodes (in addition to the nodes at the ends)?
Sketch how the rope would move in this case.
4. What happens when two waves with the same amplitude and wavelength and moving in the same direction, superimpose?

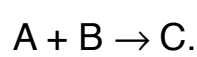
29

Photons

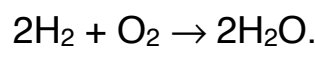
29.1 Chemical reactions with light

Light participates in some chemical reactions. These types of reactions are called *photochemical reactions* (from the Greek word phos for light).

You know how to describe reactions with reaction equations. The reaction of a substance A with a substance B resulting in a substance C is written as



A concrete example of this is the reaction of hydrogen and oxygen resulting in water:



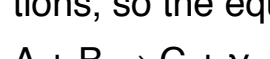
The substances hydrogen and oxygen disappear during the reaction, and the substance water is created. There are also reactions where light is produced or disappears along with other substances. Here are some examples.

Fluorescent bars

So-called fluorescent or luminescent bars are available at auto shops. A luminescent bar is made up of a transparent plastic tube containing two liquids A and B. At first, they are separate from each other. When the plastic bar is bent somewhat, the dividing wall between the two liquids is broken. The liquids mix and begin to react with each other, producing a liquid C and, along with it, light.

A luminescent bar is a light source that works without batteries or an electrical outlet. It is used as a signal lamp when a car breaks down or has an accident in the night. Anglers use luminescent bars attached to buoys in order to find them in the dark.

The Greek letter γ is used as the symbol for light in reaction equations, so the equation for the reaction in a fluorescent bar is



A reaction equation can also be more complicated. More than two substances can be produced, or the reaction can take place in several steps creating intermediate products. The point here is that light behaves like a normal substance.

The substances in the luminescent bar are chosen so that they don't react with each other all at once, but gradually. It can take several hours for substances A and B to completely disappear, ending the reaction. Naturally, light is produced only as long as the reaction is taking place.

Ozone in the Earth's atmosphere

Ozone (O_3), which is contained in the Earth's atmosphere, absorbs ultraviolet light coming from the Sun with a wavelength of 200-320 nm. As a result, almost no UV light of these wavelengths reaches the Earth's surface. This is very important because this light can destroy the cells of living creatures. It is the main cause of sunburn and skin cancer.

Ozone in the atmosphere ensures that the UV light coming from the sun with wavelengths of 200-320 nm does not reach the surface of the Earth.

Ozone is created by the reaction between O_2 with light of a different wavelength: UV light with a wavelength of 150-200 nm.



However, ozone can disappear again by reacting with the monatomic oxygen produced in the previous reaction:



Equations (1) and (2) tell us that we have what we previously had called a steady state. According to (1), ozone is produced at a constant conversion rate. The rate of reaction (2) depends upon how much O_3 and O are already present. It adjusts so that the production rate according to (1) is exactly equal to the rate of destruction of ozone according to equation (2).

The hole in the ozone layer of our atmosphere is the result of reaction (2) being accelerated by a catalyst. Introducing a catalyst to reaction (2) causes it to run more quickly at first. More ozone is destroyed than is produced, thereby breaking down the steady state. The ozone content of the atmosphere decreases. This results in a further slowing down of reaction (2) which continues until the rate of destruction again equals the rate of production and we have a steady state again. However, the amount of ozone is now lower than it was originally.

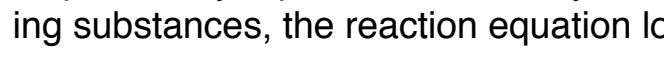
One catalyst that can speed up reaction (2) causing a lessening of ozone in the atmosphere, is chlorine. Chlorine goes into the atmosphere mainly as a component of chlorofluorocarbons, so-called CFCs. Chlorine is produced by the decay of CFC in the atmosphere.

CFCs are used as coolants in refrigerators and freezers, as propellants in spray bottles, and for foaming plastics as insulation materials. In the last few decades, there has been a strong increase in the production of CFCs meaning that more and more of these substances have ended up in the atmosphere. The result is a decrease in the amount of ozone in the atmosphere which leads to more UV light reaching the surface of the Earth—with the results for life on Earth that we have already discussed.

Photosynthesis

Photosynthesis in plants is a photochemical reaction that is of great importance for all life on Earth. In this reaction, plants produce glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) and oxygen (O_2) from carbon dioxide (CO_2), water (H_2O), and light. Plants use glucose as building materials for their cells and to store energy.

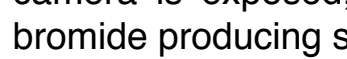
Photosynthesis is a complicated reaction with many intermediate steps. If we jump over these and just look at the starting and resulting substances, the reaction equation looks like this:



The parts of the plants where this reaction takes place are green. The reason for this is that green light plays almost no role in the process of photosynthesis. All the other parts of sunlight do, though. Green is left over.

Photographic film

Photographic film contains silver bromide, AgBr . When the film in a camera is exposed, the light falling upon it reacts with the silver bromide producing silver and bromide:



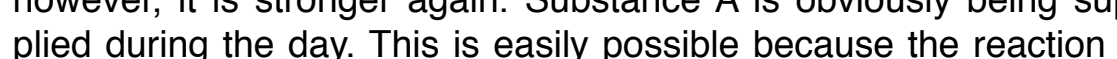
After the exposure, there is silver on the film where it was hit by light. During the developing process, the silver bromide at points where silver was created reacts with the developer, producing more silver. This silver combines with the silver already there, making clumps. Accumulations of such clumps absorb light, and those points are black. No silver is produced at places that light does not hit, so there are no clumps of silver produced. The film remains transparent.

Luminescent numbers and hands

The numbers and hands of some clocks glow at night. The luminescent substance A on the numbers and hands changes into a substance B and into light:



As soon as A has totally transformed into B and γ , the reaction comes to a standstill. If A is not supplied continuously, the glowing will eventually stop. Indeed, the glowing of the numbers and hands of a clock really does get weaker during the night. The next evening, however, it is stronger again. Substance A is obviously being supplied during the day. This is easily possible because the reaction is reversible:



When does reaction (3) take place? When does reaction (4)? If little light is available in the dark, then A decays according to equation (3). If a lot of light is available, then the regeneration of A proceeds according to equation (4).

In the examples we have just looked at, you see that:

In photochemical reactions, light behaves like a substance.

29.2 Photons

Every substance is made up of smallest parts called atoms and molecules. If light behaves like any other substance, we could expect “smallest portions” of light to exist. We could call them light “atoms”. The following experiment will confirm this assumption.

Light “atoms” are as invisible to the naked eye as the atoms of other substances. We need a very sensitive device that measures light, a so-called photo multiplier. When the sensor of a photo multiplier is held up to light, it reacts with the light, absorbing it. A display shows how much light is absorbed by the photo multiplier per time span.

We will investigate the light of an everyday light bulb. If this light were allowed to fall directly upon the photo multiplier, the device would be immediately destroyed. It would be similar to trying to weigh an elephant on a letter scale. The light bulb’s light needs to be dimmed before hitting the photo multiplier. This can be done with a gray filter that allows very little light through.

The light bulb is connected to an adjustable power supply. We slowly increase the electric current through the light bulb so that it begins to glow slightly. It emits just enough light for our eyes to perceive. Although the photo multiplier is behind the gray filter, it “sees” the slightly glowing light bulb through the filter: the display deflects.

Fig. 29.1 shows the deflections of the display in a time span of 5 ms (5 thousandths of a second). It is surprising that the display does not indicate a constant value. It pulses irregularly, and in between the display reads zero. The photo multiplier doesn’t “see” a uniformly glowing lamp but weak bursts of light that follow each other in short and irregular time intervals. In other words: The reaction of light with the photomultiplier’s sensor does not happen continuously, but in portions. These are the “light atoms”. They are called *photons*.

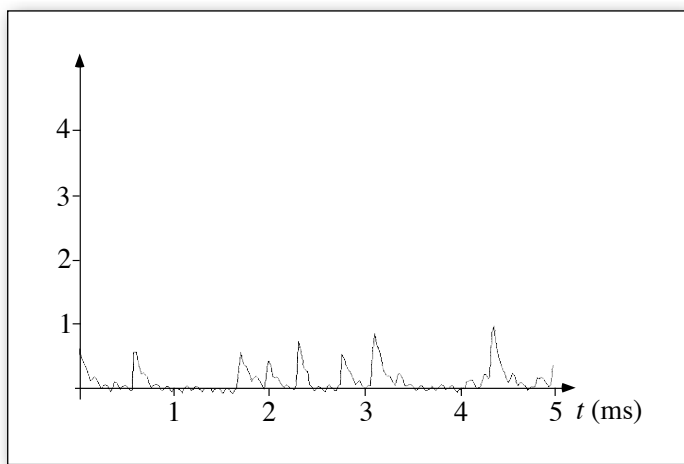


Fig. 29.1
The measuring device shows irregularly spaced pulses.

When the current through the lamp is raised making it glow brighter, the deflections happen more closely together, Fig. 29.2. Sometimes two photons come almost simultaneously. When this happens the display deflects more strongly. The frequency at which the light portions arrive at the photo multiplier depends upon the brightness of the lamp.

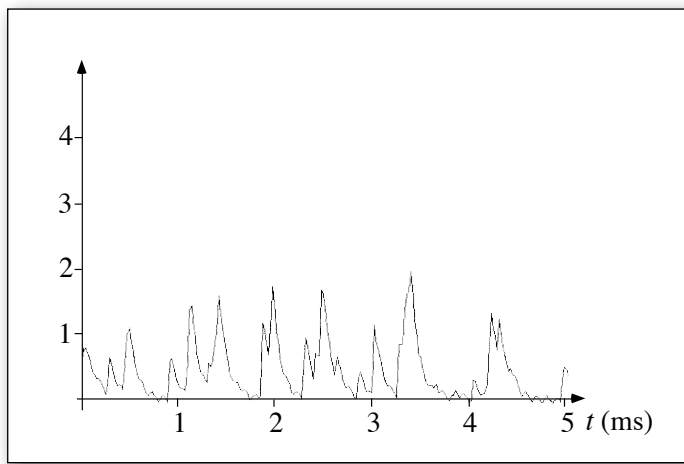


Fig. 29.2
The lamp glows brighter and the measuring device responds more frequently.

Light reacts in portions with other substances. These portions of light are called photons.

We raise the brightness of the lamp even more. The deflections of the display get closer and closer together until they merge, Fig. 29.3.

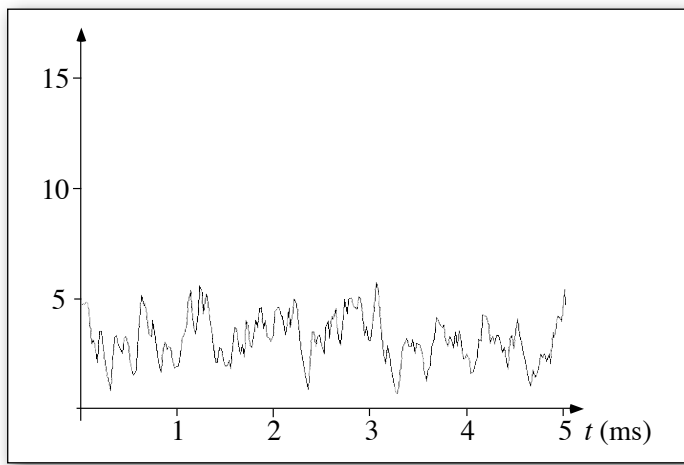


Fig. 29.3
The lamp shines so brightly that the measuring device deflects continuously.

A further increase of brightness results in a general increase of the now continuous deflection, Fig. 29.4. The measuring device does not see individual bursts of light anymore, but a continuous glowing.

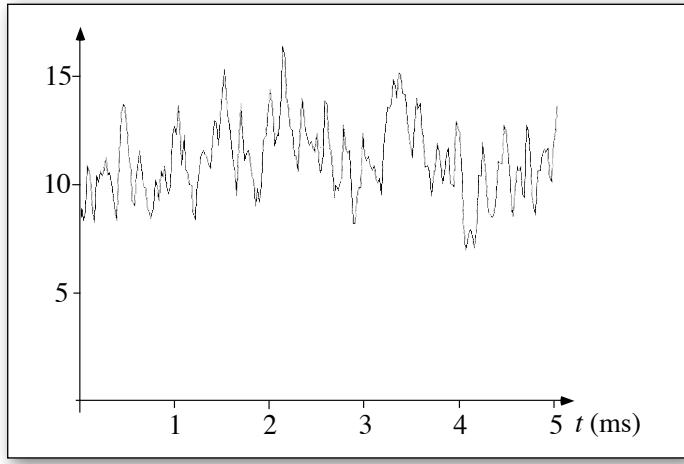


Fig. 29.4
When the lamp becomes even brighter, the amplitude is raised overall.

If we use a laser as our light source instead of a light bulb, the result is the same. As long as a very weak laser beam hits the photo multiplier, the display registers only irregular pulses. When the laser beam is made stronger, the pulses move together and finally merge.

Of course, photons move at the speed of light. In the air and in a vacuum, this is 3000,000 km/s.

The “discovery” of photons (which are also called *light quanta*) in the early years of the 20th century caused a great revolution in physics. Maybe you have already heard the expression *quantum physics*. Quantum physics is a result of this revolution and is the basis for much of modern physics.

29.3 The size of photons

Photons do not have a standard form. Their size and shape are dependent upon the source of the light. They also change after leaving the light source.

The photons produced by a normal laser used in school labs are about 10 cm long and have the same diameter as the light beam itself, about 5 mm. They are similar in size and form to a pencil. There are lasers that produce photons that are much longer, though. A laser photon can even be several kilometers long.

The photons of sunlight are much shorter. Their length is approximately the same as their wavelength, about 600 nm. Their diameter is about 0.06 mm (but only when the sunlight is not scattered by clouds or fog; in that case it is much smaller). The diameter is about 100 times the length. The photons of sunlight resemble a pancake.

The photons of a laser are relatively large, with the result that, in a normal undimmed laser beam they overlap. They are not separate from each other. However, even though we have a continuous “light soup” here, fractions of the light portions cannot be picked out by absorption, but only entire photons can.

The photons of sunlight, as well as of everyday light bulbs, are so small that they do not melt into each other. They are spatially separate from each other like the drops of water in a rainfall.

Although light is made up of photons, we perceive the light that hits our eyes as a continuous flow of light. This is due to the temporal resolving power of our eyes. The retina is too slow to register photons hitting it at very short intervals separately.

29.4 Energy and momentum of photons

Light transports energy, so every photon also transports energy. However, the amount of energy transported is not the same for every photon. It depends in a very simple way upon the frequency of the light:

$$E_{\text{Photon}} \sim f.$$

The energy of a photon is proportional to the frequency of the light.

The factor of proportionality is called *Planck's constant* h (named for Max Planck, whose work led to the discovery of the photon). Its value is

$$h = 6,6 \cdot 10^{-34} \text{ J} \cdot \text{s}.$$

Therefore

$$E_{\text{Photon}} = h \cdot f. \tag{5}$$

This equation allows you to calculate the energy of photons, if their frequency is known.

It is often the wavelength of light that is known, rather than its frequency. However, the frequency can be calculated from the wavelength. We remember the relation between wavelength λ , frequency f and velocity c :

$$c = \lambda \cdot f.$$

It follows that

$$f = \frac{c}{\lambda}.$$

High frequency means small wavelengths, and vice versa. We insert the expression into Equation (5) and obtain

$$E = \frac{h \cdot c}{\lambda}.$$

We conclude: The longer the wavelength of light, the smaller the amount of energy of its photons.

We calculate the energy of photons of red light ($\lambda = 8 \cdot 10^{-7} \text{ m}$):

$$E_{\text{red}} = \frac{h \cdot c}{\lambda_{\text{red}}} = \frac{6,6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{8 \cdot 10^{-7} \text{ m}} \approx 2,5 \cdot 10^{-19} \text{ J}$$

and of blue light ($\lambda = 4 \cdot 10^{-7} \text{ m}$):

$$E_{\text{blue}} = \frac{h \cdot c}{\lambda_{\text{blue}}} = \frac{6,6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{4 \cdot 10^{-7} \text{ m}} \approx 5 \cdot 10^{-19} \text{ J}$$

Compared to the amounts of energy we deal with on a daily basis, these amounts are tiny. However, in normal situations we have to do with many photons. A flashlight produces about 10^{15} photons per second. The sunlight hitting one square meter of the Earth's surface per second is made up of about 10^{21} photons.

The momentum transported by a photon is also proportional to the frequency of the light in question. It is

$$p = \frac{h}{c} \cdot f.$$

Or expressed in terms of the wavelength

$$p = \frac{h}{\lambda}.$$

The momentum of a photon of red light is

$$p_{\text{red}} = \frac{h}{\lambda_{\text{red}}} = \frac{6,6 \cdot 10^{-34} \text{ Js}}{8 \cdot 10^{-7} \text{ m}} \approx 8,25 \cdot 10^{-28} \text{ Hy}.$$

The momentum of a photon of blue light is twice as great:

$$p_{\text{blue}} = 16,5 \cdot 10^{-28} \text{ Hy}.$$

For example, a momentum current of $3 \cdot 10^8$ Huygens per second (= 300 million Newton) flows to the Earth with the sunlight that reaches it. The sunlight presses against the Earth like a water jet hitting a ball.

Up until now, we have only discussed visible and UV light. What holds for these two types of light also holds for all other types: For radio and television waves, microwaves, infrared, X-rays and gamma rays. All these kinds of radiation behave not only like waves but like substances as well. The relations between wave frequency, and energy and momentum of photons are the same as those of visible light. In Fig. 29.5 you will find an overview of the typical values of frequency and wavelength for various types of electromagnetic waves, and of the energy of the corresponding photons.

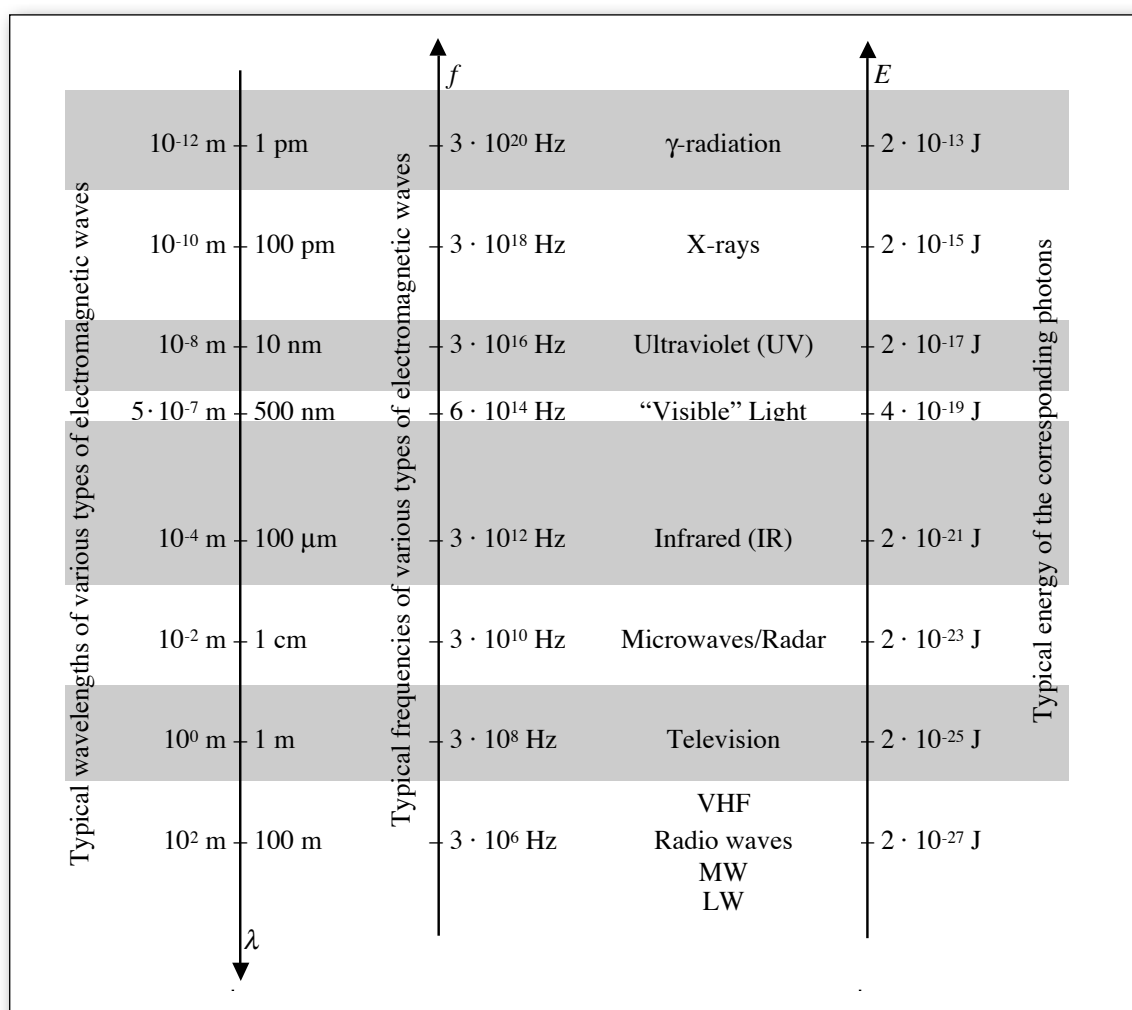


Fig. 29.5

Overview of the typical values of wavelengths and frequencies of different types of electromagnetic waves, and the energy of the corresponding photons.

γ radiation has the shortest wavelength and the highest frequency. It follows that the photons of γ radiation have the most energy. In contrast, radio waves have a large wavelength and low frequency. Therefore a radio photon contains very little energy. Note in the Figure that the energy values differ from one type of photon to another mostly by a factor of 100.

Exercises

- Calculate the energy and momentum of the photons of your favorite radio station.
 - Calculate the energy and momentum of X-ray photons with a wavelength of 150 pm.
 - Compare the values calculated in a) and b) with the energy and momentum of a photon of visible light.
- A ball is held up by the water jet of a fountain. Why doesn't the ball fall down considering that a momentum current is flowing out of the gravitational field into it?
 - A small sphere floats upon a light beam directed upward. Why doesn't the ball fall considering that a momentum current flows out of the gravitational field into it?
 - How many photons per second need to hit the sphere in part (b) of the exercise if the momentum current coming out of the gravitational field is $7 \cdot 10^{-11} \text{ N}$? (The wavelength of the light is 800 nm.)

29.5 Photons and interference

Earlier we had an experiment where a laser beam hit two mirrors oriented at a slight angle to each other, Fig. 29.6, thereby creating two laser beams running at an acute angle into each other. If a sheet of paper is held at the place where the two beams cross each other, an interference pattern can be seen on it.

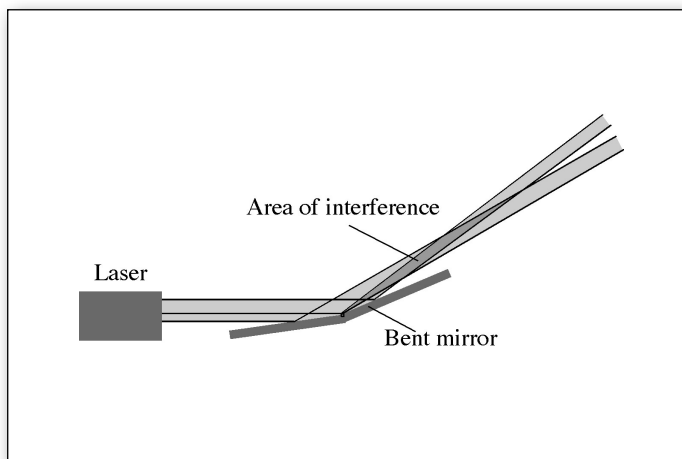


Fig. 29.6

On a bent mirror, the laser beam divides into two beams that cross each other at an acute angle.

We will now replace the paper with a digital camera. Now the interference pattern is created on the image sensor of the camera.

We had previously interpreted this phenomenon: In the dark places, the light waves cancel each other out, in light areas they reinforce. We now see, however, that it may not be quite so simple.

One photon is absorbed by *one* pixel of the sensor. Thus a single photon cannot cause an interference pattern, even if it is part of two intersecting laser beams. It only makes a contribution to the total pattern. The interference pattern comes from the fact that many photons fall on the sensor. The photons are distributed randomly in such a way that the interference pattern results. Figure 29.7 shows how the pattern builds up gradually (a \rightarrow b \rightarrow c).

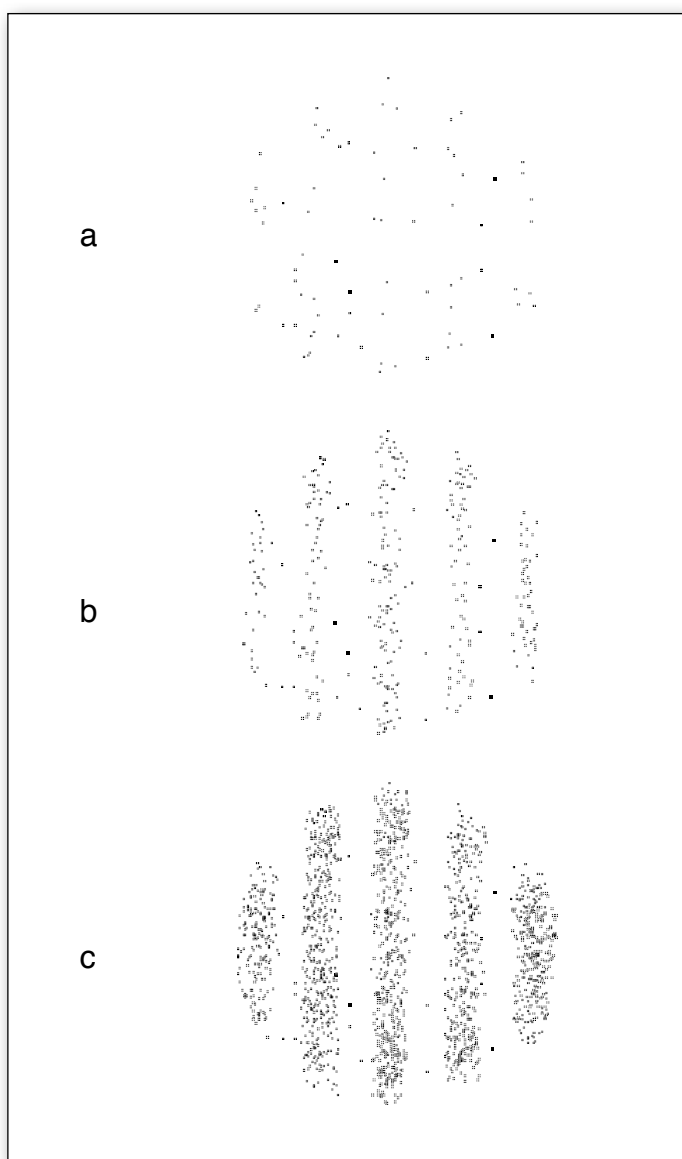


Fig. 29.7

An interference pattern gradually forms with increases exposure time.

A single photon cannot produce an interference pattern on a sensor. Photons distribute randomly so that an pattern is produced.

30

Atoms

Many different substances make up the things around you. Some of these are cement, wood, plastics, metals, glass, pigments, adhesives, and air. There are many more.

Most of these substances are mixtures of so-called pure substances. For instance, air is made up of nitrogen and oxygen, but also contains water vapor, carbon dioxide, and various noble gases. We know of several million pure substances but there are still many unknown to us.

It is easy to understand why such a great number of pure substances exists.

Each portion of a pure substance is made up of small identical particles similar to the many identical grains in a bag of wheat.

Among the pure substances, there is a small group of substances that are special: the *elements*, which number about 100. The smallest particles of an element are the atoms. There are as many kinds of atoms as there are elements.

A *molecule* is combined from several atoms. This molecule is the building block of a new pure substance, but is no longer an element itself.

Molecules can be built in many different ways similar to the way that different things can be built from a few kinds of Lego blocks. This explains the huge number of different kinds of molecules and of pure substances made of these molecules.

In the following, we will deal with questions about atoms such as: What forms do they have? What is their structure? We will find that it is possible to deform atoms to store energy in them.

Atoms are much too small to be seen with the naked eye, and even the best light microscope cannot make them visible. There are devices, however, that are able to do this: Fig. 30.1 shows a very small section of a piece of silicon recorded by a *scanning tunneling microscope*. The small bumps in the picture are the atoms on the surface of the silicon crystal.

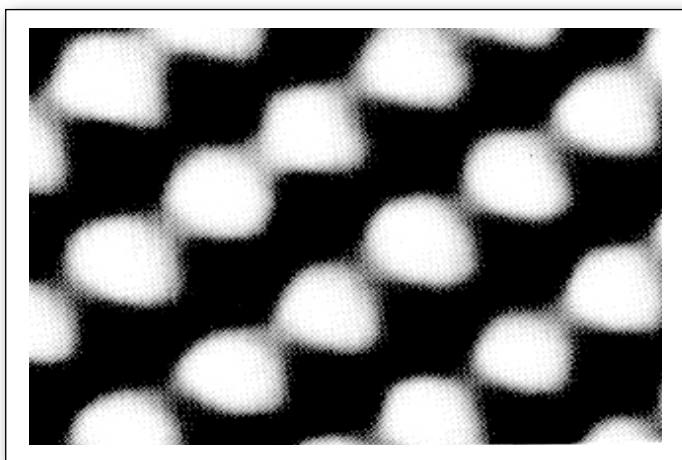


Fig. 30.1

The surface of silicon as seen through a scanning tunneling microscope.

Exercise

What proof for the existence of atoms do you know or can find in books (Internet, chemistry books, lexicons)?

30.1 The structure of atoms

Atoms are spherical. They are made up of a tiny, heavy nucleus and a light, relatively big shell.

The diameter of the nucleus is about one fifty-thousandth of the atom's diameter (the diameter of the shell). The mass of the nucleus makes up about 99.9% of the total atomic mass. Both the nucleus and the shell are electrically charged: The nucleus positively and the shell negatively. The absolute values of the charges of the nucleus and the shell are equal. This means that, as a whole, the atom is electrically neutral because the total charge is zero.

Atoms are made up of a small, heavy nucleus with a positive charge and a large negatively charged shell.

You have probably learned that the shell of an atom is made up of point-like electrons that move around the nucleus. This is the image of atoms that was created at the beginning of the 20th century. It is very different from how the atom is conceived of in modern physics.

It makes more sense to consider the atomic shell to be made up of a substance that is continuously distributed around the nucleus. We call this substance *electronium*.

The density of the electronium is not the same everywhere. It is greatest right next to the nucleus. With increasing distance from the nucleus, it decreases very quickly at first, and then more and more slowly. The atomic shell is spherical in shape but has no sharp edge where it ends, Fig. 30.2.

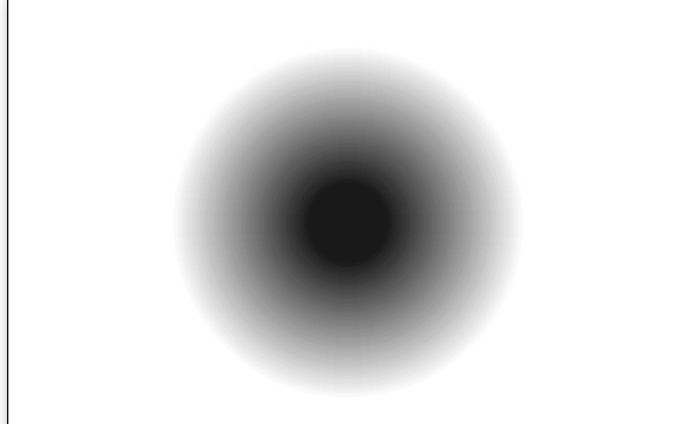


Fig. 30.2
The distribution of electronium in an atom

This characteristic of electronium shows a certain similarity to the Earth's atmosphere. The atmosphere also becomes thinner with increasing distance from the Earth's surface, and it has no sharp edge where it ends.

In order to specify the size of an atom, we take the radius which covers 90% of the electronium. Different kinds of atoms have different radii. A typical value for a radius is 10^{-10} m.

The shell of an atom is made up of electronium. The electronium is spherically symmetric around the nucleus. Its density decreases outwards.

If one tries to remove some electronium from the shell, a surprising characteristic of the atom crops up. At the moment we will not worry about how this is actually done. We will simply imagine the atom to be so large that we can put our hands into it. We imagine putting our hand in there to take a portion of electronium out of it. We take our handful of electronium and put it aside and reach in for more. To our surprise, we find the second portion is exactly equal to the first one. Again, we take a handful out and see that this portion of electronium is exactly equal to the first two. We concentrate on trying to take out a larger portion and we see that we obtain double, triple, or quadruple, etc. amounts but never amounts that lie in between. Now we try to remove smaller amounts of electronium from the atom. This is unsuccessful. We either obtain the same portions we already had or nothing at all.

Only well defined amounts of electronium, so-called *elementary portions* or multiples of them, can be removed from an atom. Just as the smallest portions of light or chemical substances have names, so does the smallest portion of electronium. It is called an *electron*. The general term for such elementary portions is *particle*.

As long as the electronium is left in the atomic shell, the elementary portions are unnoticeable. It forms a continuous "soup" in the shell, and no boundaries between the portions are detectable.

Here are the characteristics of an electron: It has a mass of 10^{-30} kg, an electric charge of minus $1.6 \cdot 10^{-19}$ C, and behaves like a little permanent magnet with a specific strength.

An electron is an elementary portion of electronium. The elementary portions of a substance are called particles.

Like the atomic shell, the atomic nucleus is made up of a substance. In contrast to the density of the shell which varies from point to point, the density of this nuclear material is uniform. This is similar to the density of steel in a compact steel ball.

Just like in the case of the shell, only certain portions can be taken out of the nucleus. However, there are two somewhat different portions whose names you are probably aware of: *Protons* and *neutrons*.

Protons and neutrons have much greater mass than electrons. They are about 1800 times as heavy. The electric charge of a proton is $+1.6 \cdot 10^{-19}$ C. It is the same as that of an electron, but has the opposite sign. Neutrons have no charge. Protons and neutrons are also magnetic but much less so than electrons.

The values of the quantities characterizing electrons, protons and neutrons are compiled again in Table 30.1.

	Mass	Electric charge	Magnetism
Electron	$0.9 \cdot 10^{-30}$ kg	$-1.6 \cdot 10^{-19}$ C	strong
Proton	$1700 \cdot 10^{-30}$ kg	$+1.6 \cdot 10^{-19}$ C	weak
Neutron	$1700 \cdot 10^{-30}$ kg	0 C	weak

Table 30.1

The nucleus of every atom contains positively charged protons, and the shell is made up of negatively charged electronium. However, as a whole, the atom is uncharged. Because the charges of electrons and protons are equal and opposite, we can conclude that the number of electrons in the atom's shell must be equal to the number of protons in the nucleus.

The number of protons in the nucleus is the criterion for distinguishing types of atoms. For instance, hydrogen atoms have one proton in the nucleus, helium atoms have two, lithium atoms have three, etc. The periodic table (see Appendix) shows the atoms listed according to the number of protons in the nucleus (their atomic numbers).

The nuclei of atoms contain the number of protons typical for each type of atom.

Electrons, protons, and neutrons are all magnetic. However, with the exception of iron, almost all substances that appear in our environment are non-magnetic. Even iron is only magnetic under certain special circumstances (iron nails are normally not magnetic).

The reason for this is that the effects of magnets can be canceled by other magnets. In about one quarter of all types of atoms, among them the atoms of noble gases, the magnetic effects of the electrons are cancelled completely. (The magnetic effects of protons and neutrons are so small that they make no noticeable contribution to the magnetism of a material.) Such atoms are magnetically neutral, thus the substances made up of them are neutral as well.

The other three quarters of atoms have individual magnetic atoms, but the substances formed by these atoms are usually non-magnetic. The atoms combine to form molecules and their magnetic effects cancel each other. For example, hydrogen, whose atoms have one electron in the shell and are therefore magnetic, appears in nature only as H_2 molecules. The magnetic effects of the two electrons of each molecule cancel each other, however, so that the molecule is magnetically neutral.

Molecules with uncompensated magnetic effects of the participating atoms, often form into larger non-magnetic groups of molecules. The magnetic effects of these groups are again cancelled out. Only in exceptional cases, when magnetic atoms or molecules in matter are so arranged that their magnetic effects do not compensate for each other, is the material magnetized. Such matter appears very rarely in nature but can be easily manufactured. Permanent magnets are made up of these materials.

The magnetic effects of electrons can compensate for each other

- inside the atomic shell;
- inside a molecule;
- inside groups of molecules.

Exercise

If an atom could be enlarged so that it was the size of the Earth (diameter about 12 000 km), what would the diameter of the nucleus be?

30.2 Size and density of atomic shells

The amount of electronium in the shell of an atom increases with increasing number of protons. For instance, the shell of a mercury atom (atomic number 80) has 80 times as much electronium as the shell of a hydrogen atom. It might be expected that the mercury atom would be substantially larger than a hydrogen atom, but their sizes are actually about the same.

This means that the density of the electronium in a mercury atom must be much higher than in a hydrogen atom.

As a kind of thought experiment, we will gradually construct various chemical elements out of protons, neutrons and electrons and ask the question of how the sizes and densities of the atoms change. Neutrons have no effect upon the size of an atom so we will not mention them anymore. We will begin with a hydrogen atom which is made up of a proton as the nucleus and one elementary portion of electronium as the shell.

We raise the number of protons by one and obtain a positively charged helium *ion*. Because two positively charged protons are now pulling on the negatively charged electronium, the electronium shifts closer to the nucleus. The helium ion is smaller than the hydrogen atom. This means that the electronium of the helium ion has higher density.

To obtain a helium *atom*, we next add an electron. The shell inflates like a balloon getting extra air blown into it. The two portions of electronium in a helium atom need more space than the one in a helium ion – the helium atom is larger than the ion.

Addition of a further proton results in a positively charged lithium ion, Fig. 30.3, and again, the electronium shrinks around the nucleus. The completion of the shell to produce a lithium atom has the same effect as with helium: The shell with the three electrons needs more space, so the lithium atom is larger than the lithium ion.

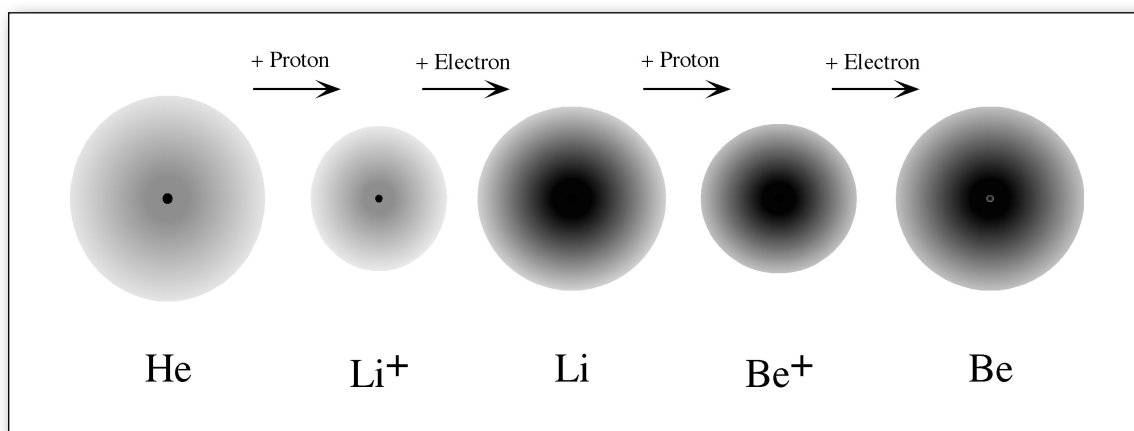


Fig. 30.3

We construct heavy atoms by alternately adding protons and electrons. (Neutrons are also added, but they have no influence upon the size of the atom or ion.)

Two opposing tendencies became noticeable during this step-by-step construction of atoms: The addition of a proton causes a shrinking of the shell, adding an electron causes it to become larger.

Figure 30.4 shows the radii of atoms as a function of their proton numbers. One sees that sometimes the tendency to shrink takes precedence, and sometimes the tendency to grow does. The radius of most atoms does not vary much from the typical value of somewhat more than 10^{-10} meters. The largest atoms are about twice as large as this and the smallest are about half as large.

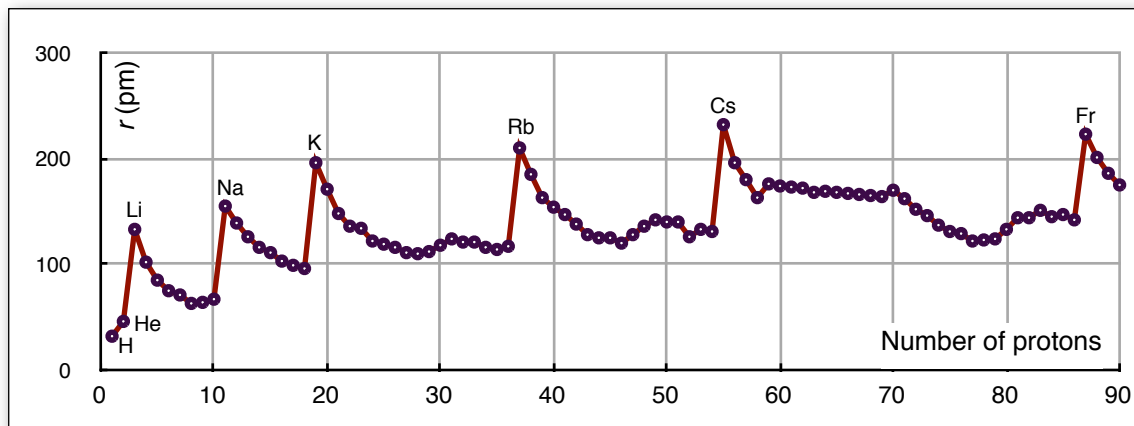


Fig. 30.4

The radii of various atoms

The radius of most atoms varies only a little from 10^{-10} Meters. However, there are great differences in the density of the electronium of an atomic shell.

30.3 Different states of atoms

An inflated balloon has a certain shape. This shape can be changed by pushing against it or by pulling on it. When it is left alone again it reverts to its original form. It has this normal shape only when it is left untouched.

Atoms react similarly. Everything we have said until now about the size and shape of an atom is valid only as long as the atom is “left alone.” There can be nothing near the atom which could deform it: No other atoms and no electric or magnetic fields. If this condition is fulfilled, an atom will have its normal spherical form.

This condition is fulfilled in gaseous substances where the distances between the individual atoms are relatively large. In the following, we will consider such free atoms. In solid and liquid substances atoms lie densely packed. We will deal with the forms of these atoms in a later chapter.

Whether it is a balloon or an atom, energy is always needed to deform it.

Energy can be supplied to a balloon in other ways than pressing. For instance, a tennis ball could be thrown against it. At impact, the tennis ball changes the form of the balloon. In this case the energy for the deformation comes from the tennis ball which is stopped at impact. The faster the tennis ball travels before the collision, meaning the more energy it has, the more strongly the balloon deforms. Of course, the balloon does not retain the deformation but returns immediately to its original shape. In the process, the tennis ball is catapulted away.

Atoms deform in a similar way. Other particles such as photons or electrons can be shot against them.

However, when this happens, atoms behave very oddly. They can “lock into” certain forms. If an atom is brought into this form by collision with another particle, it remains in this form at first. Only after a while does it spring back into its non-deformed shape. Figure 30.5 shows some of the forms a hydrogen atom can lock into.

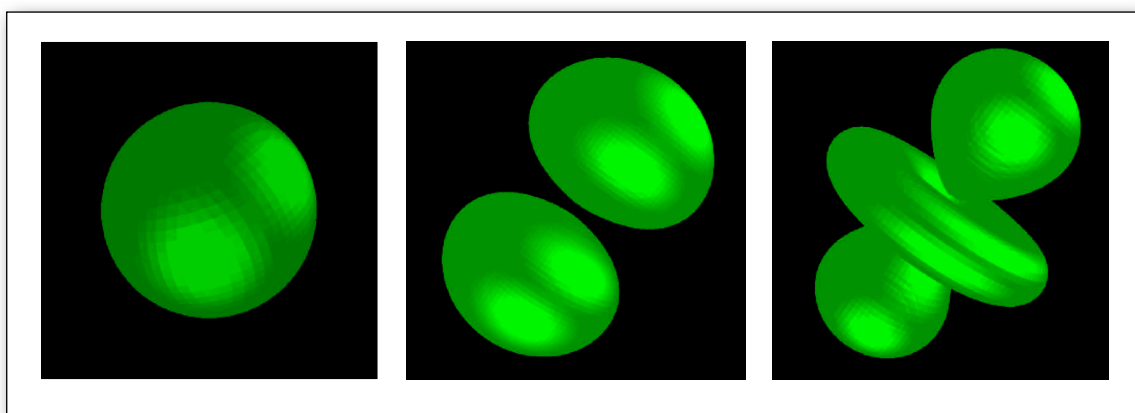


Fig. 30.5

(a) Hydrogen atom in its ground state. (b) and (c), Hydrogen atoms in two excited states.

An atom that is locked into a form is said to be in an *excited state*. The state of the non-deformed shell (Fig. 30.5a) is called the *ground state* of the atom. The process of deformation, or the changeover from the ground state to an excited state, is called *excitation*.

Atoms can be deformed. Atoms retain some of these deformations.

When an atom locks into these forms, it stores the energy used for the change of form. Because the atom can only retain certain forms, it can only store certain amounts of energy. In other words, the atom’s energy can only take certain values. Fig. 30.6 shows the *energy ladder* of an atom.

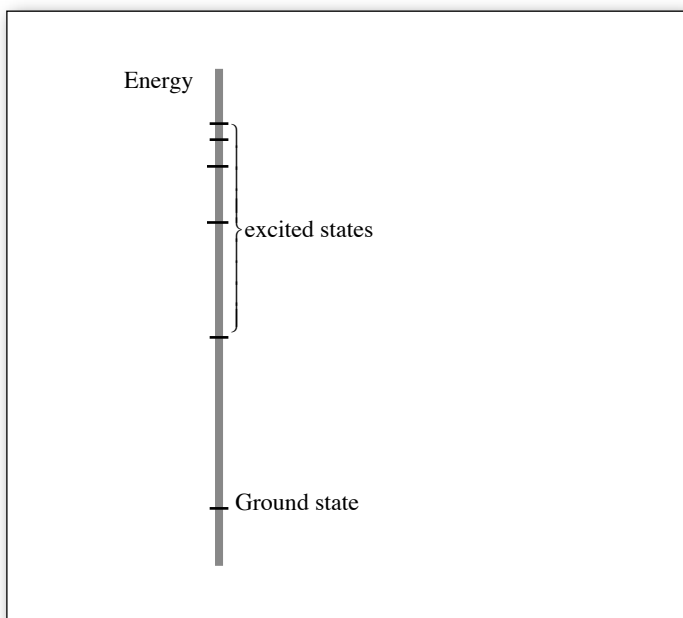


Fig. 30.6

The energy ladder of an atom: The energy of an atom can take only certain values.

We will not deal here with the fact that an atom can be set in motion whereby its energy could be changed arbitrarily. We will consider only motionless atoms.

The energy of an atom is at its lowest when the atom is in its ground state. The energy in an excited state is equal to the amount of energy taken up by excitation.

A motionless atom can only store certain amounts of energy.

How can an atom actually be excited, though? We need to shoot other particles, i.e., photons, electrons, ions, or other atoms, against the atom. Depending upon what kinds of particles are used, there are distinctively different results.

30.4 Excitation of atoms by photons

In order for a photon to excite an atom, the photon's energy must be exactly equal to the amount of energy the atom needs to go from its ground state to an excited state. If the photon does not have this much energy, the atom will, of course, not be excited. However, if the photon has more energy than this, excitation is also impossible.

Let us describe a concrete experiment. We will use a sodium atom as the atom to be excited. Sodium is good for observing what happens. Sodium is normally a solid substance but can be heated to easily produce sodium vapor.

We produce our photons with a lamp that creates a beam of white light, i.e., a mixture of all types of light with wavelengths between 400 and 800 nm. Because the energy of a photon does depend upon the wavelength of the light, we have a mixture of photons with very different energies.

The lamp's light beam is now focused on the sodium gas, Fig. 30.7. The energies of most of the photons do not correspond to what is needed for an excitation. These photons simply fly through the gas. Only a very small fraction of the photons have the appropriate amount of energy, and only these will be absorbed by the atoms. They deliver their energy to the atoms and disappear while the atoms change into an excited state.

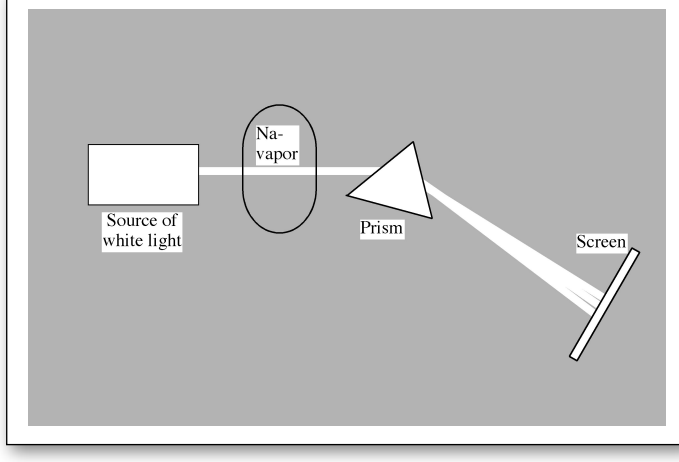


Fig. 30.7

The light from a light bulb passes through sodium gas. Afterwards, it is spectrally decomposed.

The absorbed photons are missing from the light beam after it passes through the gas. Their absence from the light beam goes unnoticed at first because they make up only a tiny part of the light. We will look more closely at the light beam after it has traveled through the gas by making a spectral decomposition of the light.

A prism deflects light with shorter wavelengths more strongly than light of longer wavelengths. We let a thin ray of the light that has passed through the gas fall upon a prism. A white screen is set up at some distance behind the prism. The light, sorted according to wavelengths, hits the screen. Light of different wavelengths evokes different color perceptions in our eyes so we see the colors of the rainbow on the screen.

By close examination it can be seen that a certain place on the screen, in the area of yellow light, remains dark, Fig. 30.8. The light of a certain wavelength is missing: Precisely the type of light whose photons are absorbed by the sodium atoms. A spectrometer shows the wavelength of the missing light: $\lambda = 589$ nm.

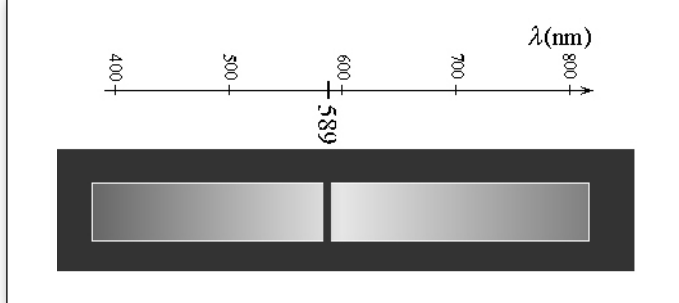


Fig. 30.8

Light with a wavelength of 589 nm is missing in the spectrum.

Hence, the energy of the absorbed photons is

$$E = \frac{h \cdot c}{\lambda} = \frac{6.6 \cdot 10^{-34} \text{ Js} \cdot 3 \cdot 10^8 \text{ m/s}}{589 \cdot 10^{-9} \text{ m}} \approx 0.3 \cdot 10^{-18} \text{ J}$$

This equals the energy difference between the ground state and the lowest excited state of the sodium atom, Fig. 30.9. In the process of absorbing a “yellow” photon, a sodium atom jumps from the lowest rung to the next higher one on its energy ladder.

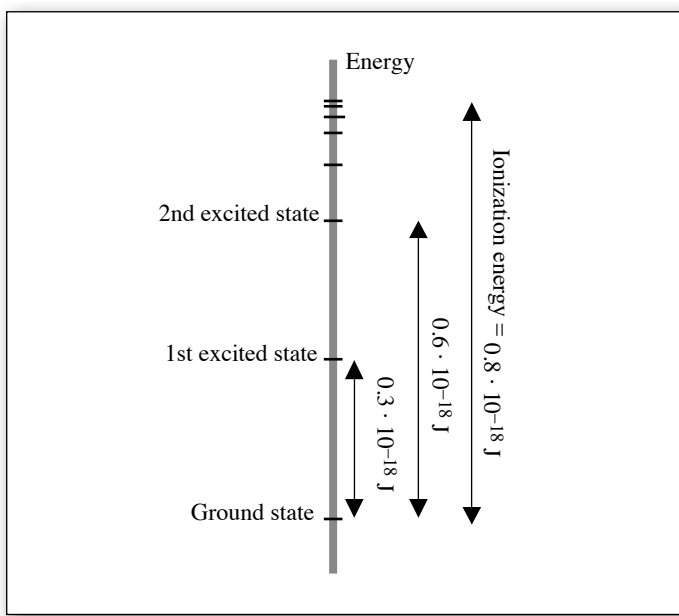
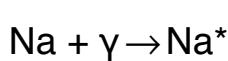


Fig. 30.9

Light with a wavelength of 589 nm is missing in the spectrum.

In an earlier chapter we saw that light behaves like a substance. Therefore, the absorption of light can be described as a reaction of substances. In our experiment, the reaction equation takes the form



Expressed in words: Sodium reacts with light into the substance written as Na^* . This substance is made up of sodium atoms in their first excited state. Sodium symbolized by Na is made up of sodium atoms in their ground state.

Photons with an energy of $E = 0.3 \cdot 10^{-18} \text{ J}$ are not the only ones absorbed by sodium. Sodium atoms can be brought into many other excited states. This is why there are other types of photons that can be absorbed. These photons have greater energies and shorter wavelengths than the ones we just investigated.

For example sodium atoms also absorb photons with an energy of $0.6 \cdot 10^{-18} \text{ J}$, Fig. 30.9. This corresponds to a wavelength of 330 nm which is ultraviolet light.

In summary:

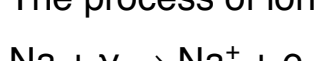
Photons with the appropriate energy can excite atoms. Photons are absorbed in the process.

We have seen that sodium atoms allow most photons of visible light to pass through unhindered. This is also true for all other gaseous substances. Their atoms or molecules absorb only very few or no visible photons. This explains something you already know about gases:

Gases are transparent.

The more energy is supplied to an atom by a photon, the more strongly the atom is deformed. If the photon energy is very high, the shell can deform so strongly that a portion of the electronium totally detaches from the atom. In the case of sodium, this happens when the photons have more than $0.8 \cdot 10^{-18} \text{ J}$. The detached electron is negatively charged, so the electric charge of the shell changes. A positively charged sodium ion is produced from the sodium atom. This process is called *ionization*. The least amount of energy needed to ionize an atom is called the *ionization energy*, Fig. 30.9.

The process of ionization can also be described as a reaction:



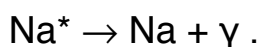
Na^+ describes the substance made up of positive sodium ions; e is the symbol for electronium.

Exercises

- Sodium atoms can be brought into the third excited state by light having a wavelength of $\lambda = 285 \text{ nm}$. Calculate the energy difference between the ground state and the third excited state.
- What is the maximum wavelength that light can have when it is used to ionize sodium atoms? What kind of light is this?

30.5 Returning to the ground state

Every reaction can run forward or backward. This is also true of the reaction of sodium with light into excited sodium. This means there is a reaction with the reaction equation



In the process of an excited sodium atom reverting to its ground state, one photon is emitted.

The experiment described in the previous section demonstrates that this is indeed the case. If one looks closely at the sodium gas container the beam of light passed through, a weak yellowish glow can be seen. A spectral analysis of the light shows that it has the same wavelength as the light which is missing on the screen. The sodium atoms emit the energy they absorbed with a photon by producing an identical photon.

The emission does not occur only in the direction in which the absorbed photons moved, but in all directions, Fig. 30.10. This is why the photons corresponding to the excitation are almost completely missing in the beam passing through.

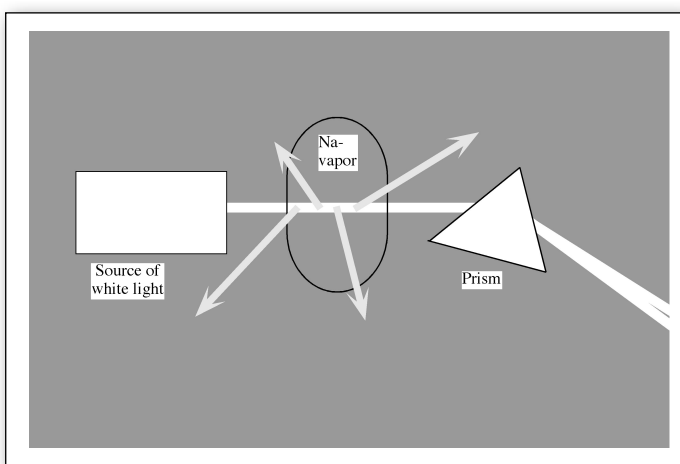


Fig. 30.10

The excited sodium radiates in all directions.

After it has absorbed the “yellow” photons, the sodium atom is in its lowest excited state. It can reach a higher excited state by absorbing a photon with more energy, Fig. 30.11a.

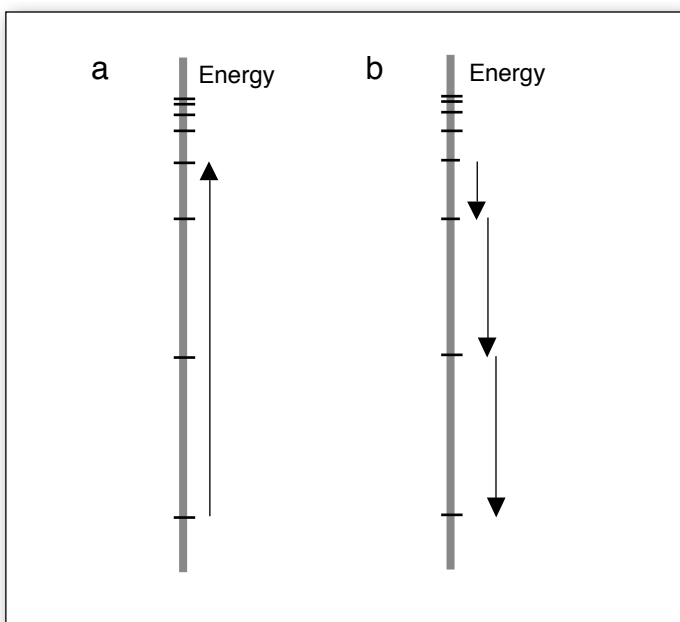


Fig. 30.11

The energy difference between various rungs of the energy ladder of a sodium atom.

Now, there are several ways for an atom to return to its ground state. It can jump directly to the ground state, emitting a photon that has the same energy as the one it absorbed during excitation. It can also climb down the energy ladder rung by rung, emitting several photons with smaller energies along the way, Fig. 30.11b.

In the process of returning to its ground state, an excited atom emits one or more photons.

30.6 The half life of the excited state

We have said that an atom lingers a while in an excited state and eventually jumps back into its ground state. How long does it remain in its excited state?

You might think this should be easy to find out: We could turn off the light source in the experiment in Fig. 30.7 and watch to see how long the gas would continue to emit yellow light. However, as soon as the white light is turned off, the yellow glow also stops. This leads us to conclude that the time it remains in the excited state is very short—so short that it cannot be perceived by simple observation. Exact measurement of the “lifetime” of an excited state of atoms yields about 10^{-8} seconds. Compared to the kinds of time intervals we deal with in everyday life, this is very short.

There is a particularly interesting aspect of this lifetime. Let us imagine that we excite a large number of atoms, say 100,000 of them, at the time t_0 . When the lifetime of their excited state runs out, we could expect them to jump back into their ground state all at once but they do not. They behave very differently.

It is impossible to predict when an individual atom will jump back to its ground state. It might be immediately after it has been excited or it may take quite a while. However, it is easy to say what the 100,000 atoms will do as a whole. A certain time after t_0 , say $2 \cdot 10^{-8}$ s later, about one half of the atoms or 50,000 have reverted to their ground state. The other 50,000 have not. After a further $2 \cdot 10^{-8}$ s, half of the 50,000 atoms still in the excited state have reverted to the ground state so that 25,000 stay in the excited state. Again, after another $2 \cdot 10^{-8}$ s, 12,500 of these atoms are still in the excited state, etc. Fig. 30.12 shows the number of atoms remaining in their excited state over time. One says that the number of atoms in the excited state decreases *exponentially*.

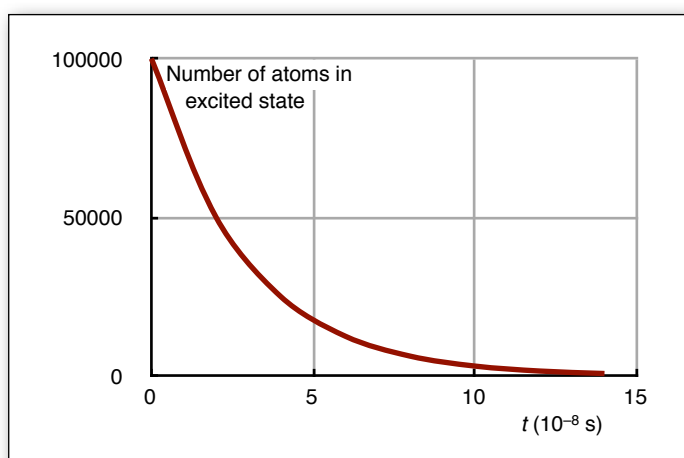


Fig. 30.12
The number of atoms in excited states as a function of time

The time it takes for half of the excited atoms to fall back into the ground state is called *half-life*. In the case we just discussed, the half-life is $2 \cdot 10^{-8}$ s.

Let us return to an individual atom in an excited state. We said that it is impossible to predict exactly when an atom will jump back to its ground state. This does not mean that we cannot say anything at all about its transition to the ground state. We can make the following statement: The *probability* that an atom will revert to its ground state within the next $2 \cdot 10^{-8}$ s is 0.5 or 50 %.

The exact value of the half-life is different for each kind of atom, and it varies for each possible excited state of any given atom. 10^{-8} seconds is a typical value. In most cases, values of half-life vary just a little from this.

It would seem that a time span as short as $2 \cdot 10^{-8}$ s would be hardly worth mentioning, but physicists who work in atomic and particle physics routinely deal with even much smaller time spans and it is not difficult to measure such time spans.

Processes where something decreases exponentially occur rather often in nature. Another example of this is light penetrating the surface of the water in a lake. Water absorbs light and the murkier the water, the more light it absorbs.

Let us assume that in a lake whose water is uniformly murky, only half of the light penetrates to a depth of 1 meter. You might assume that the next meter of water would absorb the rest of the light. Actually, one quarter of the light reaches a depth of 2 meters beneath the water's surface and one eighth of it reaches a depth of 3 meters, etc.

Another example for exponential reduction is air pressure in the atmosphere. At an altitude of 5 km, air pressure is just half of what it is at the surface of the Earth. At 10 km altitude, it is one quarter, at 15 km, one eighth, etc.

The number of atoms in an excited state decreases exponentially. The half-life tells us when the number of atoms in an excited state has decreased to half the original value.

A typical half-life value is 10^{-8} seconds.

It cannot be predicted when a particular excited atom will emit a photon.

It is equally impossible to predict whether an atom in a higher state of excitement will jump directly back to its ground state or will climb down the energy ladder rung by rung to its ground state. However, we can give probabilities. We consider an atom in the second excited state. It has two possibilities for reaching its ground state: either through the first excited state, or directly. Each of these possibilities occurs with a given probability. For example, one has a 35 % probability and the other a 65 % probability. (Together they must equal 100 %.) If 100,000 atoms are in this state, about 35,000 of them will use one way, and 65,000 will use the other.

30.7 Exciting atoms with electrons

Photons are not the only particles that can be used to excite atoms. Electrons, ions, protons, atoms, and molecules can all do this. Electrons are very often used, so we will deal with them here.

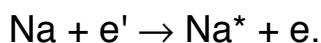
In order for an electron to excite an atom it needs – in addition to its rest energy – the amount of energy needed for excitation. The energy of an electron can be easily raised by putting it into fast motion, this means by charging it with momentum. It receives energy along with the momentum. This way of charging an electron with momentum and energy is not difficult to achieve.

All we have to do is bring an electron into an electrical field. Electrons carry electric charge so the field pulls on them. Their momentum and energy increase. When the fast moving electrons collide with atoms, the atoms deform and can get into an excited state.

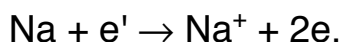
If an electron has received more energy than is needed for excitation, it takes the excess energy with it after colliding with the atom. It differs from a photon in this. The photon disappears at excitation so there is nothing that could take the left-over energy.

Atoms can be excited by fast moving electrons.

This process can also be described as a reaction. For example, sodium can react with electronium. The symbol for electronium is e ; the accelerated and electrically charged electronium we will write as e' . The reaction equation takes the form



If an electron with a lot of energy (and momentum) collides with an atom, the atom can deform so strongly that a portion of the shell's electronium detaches. The atom becomes ionized:



30.8 Gases as light sources

One of the most commonly used artificial light sources is the *gas discharge lamp*.

The main advantage these lamps have over light bulbs is their low energy requirement. A normal light bulb needs four to five times the energy of a gas discharge lamp to produce the same amount of light. In addition, a gas discharge lamp has a much longer lifetime.

An electric current makes the metal wire in a light bulb glow by heating it up. In a gas discharge lamp, it is a gas that glows. We can use our knowledge about the excitation of atoms to understand how the gas can be made to glow.

The gas is in a closed glass tube. There is a metal electrode mounted on each end of the tube, Fig. 30.13. One of these electrodes is positively charged, and the other negatively. The negatively charged one is heated which causes it to emit electrons. (Solid substances are mostly made up of electronium which can be so deformed by heating that electrons detach from it). Because the electrons are negatively charged, they are pulled by the electric field between the metal electrodes to the positively charged electrode.

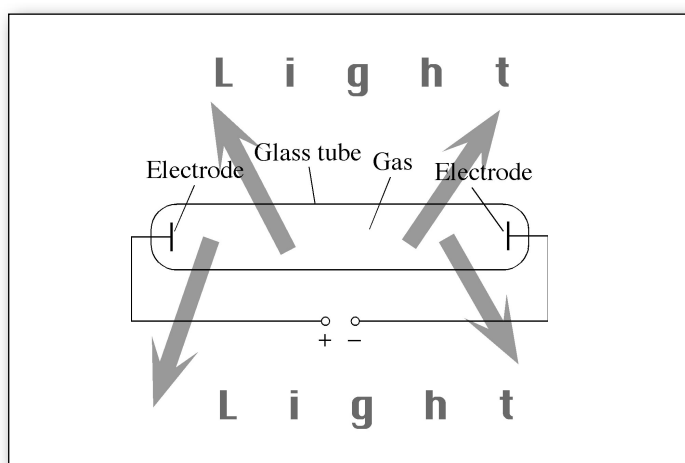


Fig. 30.13
Gas discharge tube

On their way there they encounter atoms, and two things happen:

(1) The atoms which are hit by fast electrons are ionized. This means that more electrons are produced.

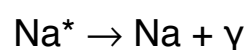
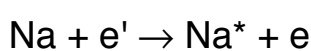
(2) Atoms which collide with slower electrons become excited.

The additional electrons obtained in case (1) are accelerated by the field and can ionize more atoms, etc. Starting from the electrons emitted by the metal electrodes, a large number of electrons are produced in the fluorescent light tube.

Because of this, the frequency of process (2) increases, and many atoms become excited by collision with electrons. These excited atoms emit photons when returning to their ground states, and the gas glows.

Atoms in gas discharge tubes become excited by electrons. The atoms emit photons when returning to their ground states.

Pedestrian walkways, tunnels, and traffic intersections are frequently lit by incandescent lamps containing sodium vapor. The production of light in such *sodium lamps* can be described by the reactions we know:



Sodium atoms emit “yellow” photons, creating the typical yellow light of a sodium lamp.

Sodium lamps use the least amount of energy of all gas discharge lamps. Their disadvantage is a very limited color spectrum. They emit light of only one wavelength, so everything they shine upon appears to be the same color which, in this case, is a more or less pale yellow. In order to counteract this effect, gases that emit light of other wavelengths are often added to the sodium lamps. This improves the color rendering a little.

A somewhat different type of a light source is the *fluorescent lamp*. These lamps are probably used in your school to light your classroom. Energy saving lamps are of the same type.

In these lamps, mercury vapor is excited by electrons. The energy difference between the ground state and the first excited state is about $0.8 \cdot 10^{-18} \text{ J}$. Photons with this energy correspond to light with a wavelength of about 250 nm. At first, the mercury vapor emits invisible UV light. The inner surface of the glass tube that contains the mercury vapor is coated by a white, *fluorescent substance*. The UV light emitted by the mercury reacts with this fluorescent substance, producing the desired visible light, Fig. 30.14.

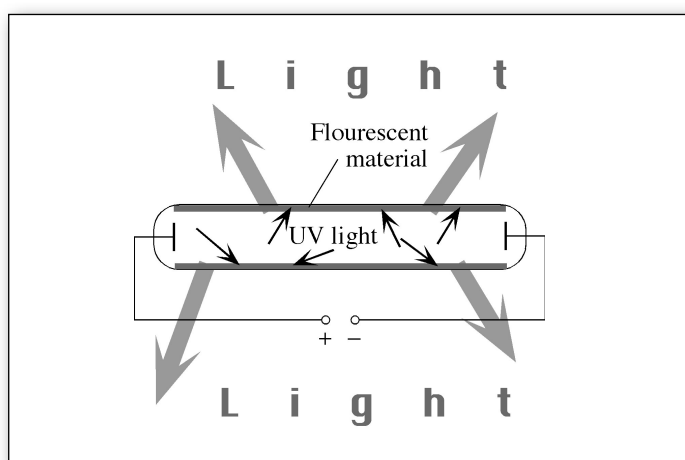


Fig. 30.14
Fluorescent tube

These fluorescent lamps use a little more energy than sodium lamps but have much better color rendering.

30.9 Spectra of gases

A gas discharge tube filled with hydrogen emits a pink light. When this light is investigated by using a spectrometer, we see that it is actually made up of four types of light. They have the wavelengths

$$\lambda_1 = 410 \text{ nm (violet),}$$

$$\lambda_2 = 434 \text{ nm (violet),}$$

$$\lambda_3 = 486 \text{ nm (blue) and}$$

$$\lambda_4 = 656 \text{ nm (red).}$$

How is this light mixture produced?

The energies of the corresponding photons are

$$E_1 = 0.48 \cdot 10^{-18} \text{ J,}$$

$$E_2 = 0.46 \cdot 10^{-18} \text{ J,}$$

$$E_3 = 0.41 \cdot 10^{-18} \text{ J and}$$

$$E_4 = 0.3 \cdot 10^{-18} \text{ J.}$$

These energy values can be found on the energy ladder of hydrogen atoms: They correspond to the energy differences between the first and second through fifth excited states, Fig. 30.15.

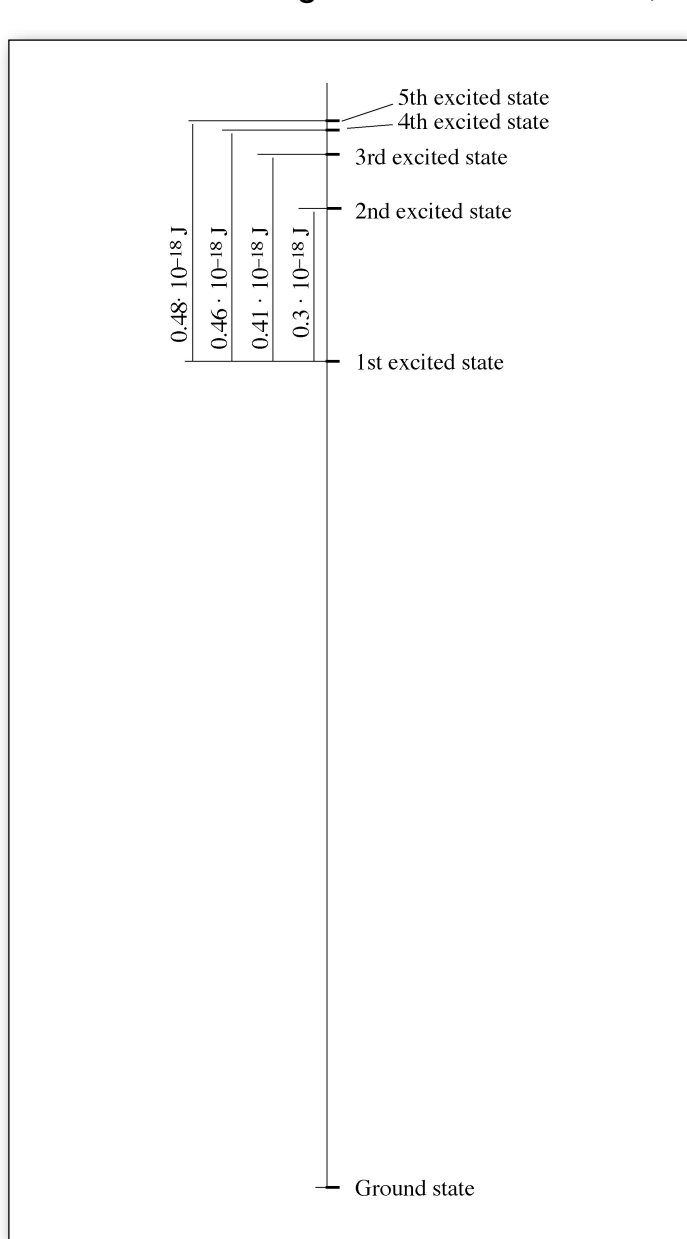


Fig. 30.15
The energy ladder of a hydrogen atom

In gas discharge tubes, hydrogen atoms are not only transferred to the first excited state, but to higher states of excitation as well.

There are, as we have seen, various possibilities for the atom to revert to its ground state from a higher state of excitation. It can jump directly back to its ground state, or it can climb step by step down the energy ladder. For example, it could first go to the first excited state and then to its ground state.

This is the reason why excited atoms can emit various kinds of photons. The light emitted by gas discharge lamps is made up of different kinds of light with different wavelengths.

Fig. 30.16 shows the *emission spectrum* of hydrogen. This is not a complete picture, however. In order to show the entire spectrum of the light emitted by hydrogen, the wavelength scale would need to be extended because hydrogen also emits UV and infrared light.

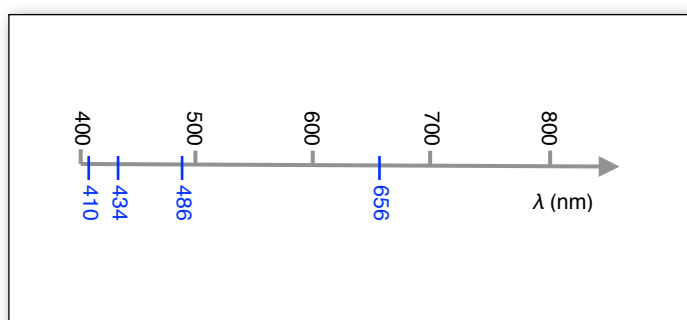


Fig. 30.16
Emission spectrum of hydrogen

We already know the emission spectrum of sodium vapor for the wavelengths between 400 and 800 nm: sodium emits only one sort of light here, Fig. 30.17a.

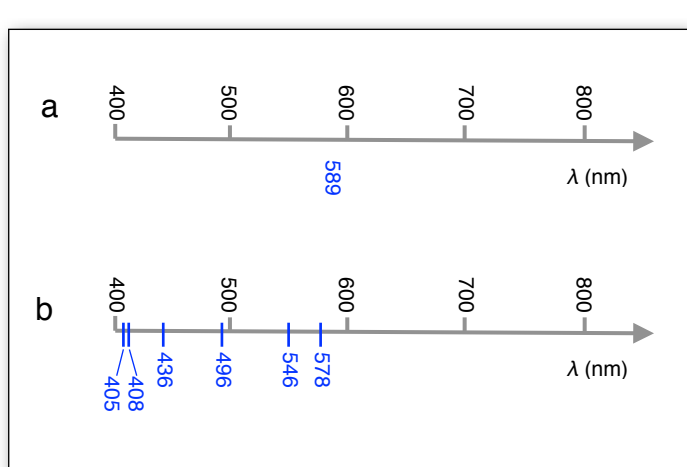


Fig. 30.17
Emission spectrum of sodium (a) and mercury (b)

In the last section, it was mentioned that mercury vapor emits mostly UV light. However, Fig. 30.17b shows that mercury also emits visible light. Light with wavelengths of 405 nm, 408 nm, 436 nm (all violet), 496 nm (turquoise), 546 nm, and 578 nm (both yellow) can all be found. We perceive this mixture of light as blue-green.

The spectrum in red neon lamps used in advertising is shown in Fig. 30.18. Other colors are obtained by using other gases or mixtures of gases.

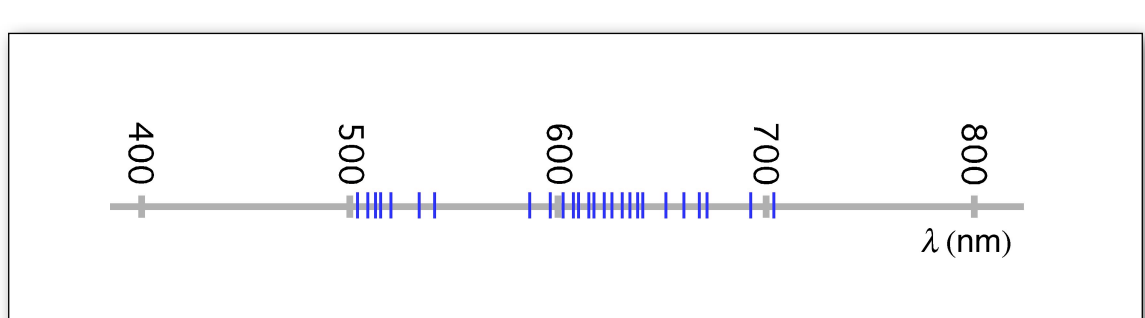


Fig. 30.18
Emission spectrum of neon

A comparison of Figs. 30.16, 30.17, and 30.18 shows that the spectra of different gases can be easily distinguished. The spectrum of a gas is very specific for the substance. It is like a “finger print” of the gas.

Every gas emits light with its own characteristic wavelengths. It is easy to distinguish the different spectra of gases because of this.

Spectral analysis is actually a very useful method in chemistry for identifying substances. The process calls for exciting the atoms of the substance or mixture of substances under investigation. The light emitted is then analyzed by a spectrometer.

A somewhat different procedure for spectral analysis is to examine the *absorption spectrum* of a substance. Light of a wide range of wavelengths is passed through the gas. A spectrometer is then used to find out which wavelengths of the spectrum are missing. Atoms absorb the same photons that they emit, so the absorption spectrum yields the same data as the emission spectrum.

Spectral analysis plays an especially important role in astrophysics. Stars are much too far away for us to simply fly to and take samples of what they are made out of. However, we have access to the electromagnetic radiation emitted by the stars. It is possible, for example, to determine the composition of the gaseous shell at the surface of the sun by finding out exactly which wavelengths are missing in the visible part of sunlight. The atoms in the shell absorb the photons of the white light produced in the interior of the sun. The spectrum produced is the absorption spectrum of the gaseous shell of the sun.

Everything we know about the evolution and composition of stars, comes from spectroscopic analysis of their radiation. Not only is the visible light investigated, but radiation of all other wavelengths as well, from radio waves to gamma radiation.

30.10 Why flames radiate

If the air supply to the flame of a candle, a lighter, a wood fire, or a Bunsen burner is reduced, it will radiate a strong yellow. When the air supply to a Bunsen burner is opened up to allow the flame to burn with a hiss, the yellow glow disappears. The flame then radiates with a weak bluish light, similar to that of the flames of a gas stove. A hydrogen flame has almost no light. If a little sodium (cooking salt will do) or lithium is sprinkled into the flame, it will become a strong yellow or a strong red. How are these different flame colors created?

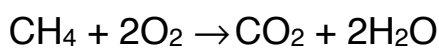
The atoms and molecules of a gas fly to and fro and collide with each other in the process. When the atoms or molecules collide, the atomic shells deform. Normally, there is not enough energy to cause excitation. If the gas is heated, the atoms become faster and their energy increases. When the temperature is high enough, excitation can finally occur.

There are many gases (for example, hydrogen along with the other gases found in hydrogen flames such as oxygen and nitrogen) that need a relatively large amount of energy to excite their atoms and molecules so that they emit visible photons. The flame cannot reach the temperature necessary for this. Hence, a hydrogen flame does not radiate.

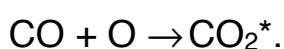
There is enough energy, however, in the atoms and molecules of the flame to bring lithium or sodium to the first excited state. If some lithium is put into a hydrogen flame, the atoms are brought to the first excited state and emit “red” photons when they revert to their ground state. The flame shines red. The flame shines yellow when some cooking salt, and therefore sodium, is put into the flame. A spectral analysis of the emitted light shows what substance in the flame is radiating.

Atoms can be excited by colliding with other atoms or molecules. This can happen in a flame.

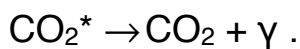
The weak bluish light that the flame of a Bunsen burner emits when it has enough oxygen comes from the CO_2 molecules going from their excited states down to their ground state. In this case, the CO_2 molecules are not excited by collision with other atoms and molecules. In the flame of the Bunsen burner, hydrocarbons (made up mostly of methane CH_4) are burned to produce carbon dioxide (CO_2) and water (H_2O). The overall reaction



takes place in steps. One of these steps is the burning of carbon monoxide:



This reaction produces carbon dioxide in an *excited* state. When it reverts to the ground state, the CO_2^* molecules emit photons:



These photons produce the blue light in the flames of Bunsen burners and gas stoves.

Excited atoms and molecules can be produced by chemical reactions.

The light emitted by fireflies is produced according to the same principle. A firefly does not glow like a piece of hot iron glows. A chemical reaction is taking place at the rear end of the firefly where excited molecules are produced that emit visible photons.

When the air supply to a Bunsen burner is curbed, there is not enough oxygen available for complete oxidation. Some carbon atoms are left over which combine to form carbon grains. These grains are the constituents of soot. These grains of soot *glow* in the high temperatures of the flame, meaning they emit light.

The relatively strong yellow radiation of the flame of a throttled Bunsen burner, candle, or lighter does not come from the gases in it, but from the glowing soot. This is why the spectrum of this flame is similar to that of a light bulb. The emitted light is composed of light of all the wavelengths between 400 and 800 nm. In the next chapter we will look into how glowing occurs.

31

Solids

Before continuing with solid substances or solids in short, let us sum up what the essential differences are in the arrangement of atoms in gases, liquids and solids, as well as what they have in common.

31.1 The arrangement of the atoms in gases, liquids, and solids

The atoms or molecules of a gas fly around in it, criss-crossing and colliding at random. Mostly, however, they are far apart from each other.

In contrast, the atoms of liquids and solids are not separated but lie touching each other, similar to tennis balls in a basket.

There are two ways of packing tennis balls. They can either be put into ordered piles, Fig. 31.1, or they can be piled randomly, Fig. 31.2. This is also true of the atoms in liquids and solids.

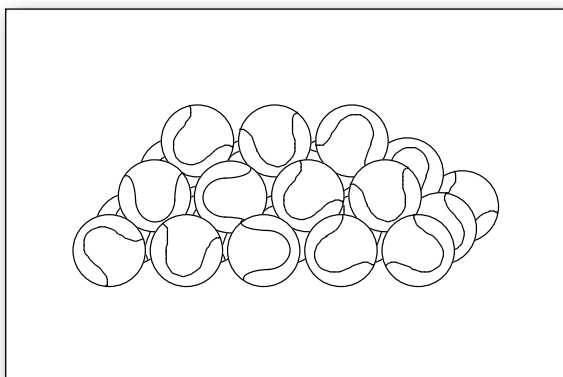


Fig. 31.1

Tennis balls can be piled up in a regular pattern...

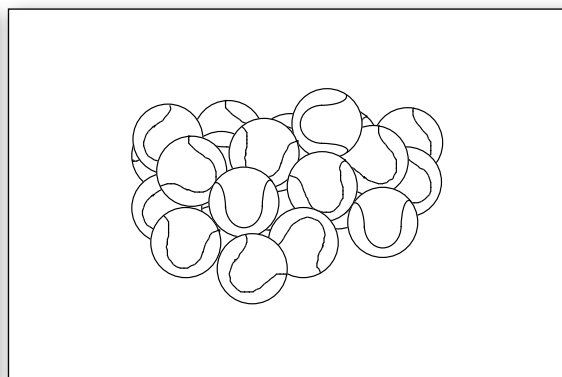


Fig. 31.2

...or irregularly.

The atoms of solid substances are usually in an orderly arrangement. Fig. 31.3 shows an example of a solid substance made up of two kinds of atoms. This kind of substance is called a *crystalline substance*, or a *crystal*. Metals, most types of stone, salt, sugar, sulfur, and diamond are all crystalline.

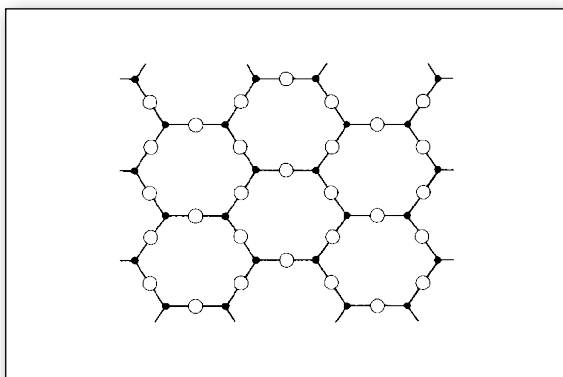


Fig. 31.3

Solid crystalline substance. The white and black circles mark the locations of the two types of atoms the crystal is made up of.

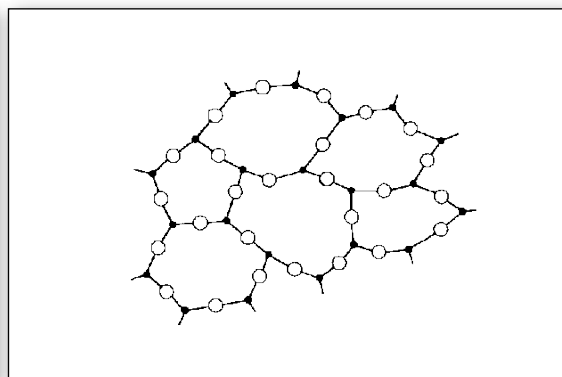


Fig. 31.4

Arrangement of atoms in an amorphous solid substance

There are, however, many substances that have an atomic structure more similar to the tennis balls in Fig. 31.2. Glass and most plastics are examples of this, Fig. 31.4. The structure of these kinds of materials is called *amorphous* structure.

As a rule, liquids have an amorphous structure. The most common liquid of all, water, is amorphous. Crystalline liquids are used in the liquid crystal displays of pocket calculators and flat television screens. Maybe you already know the abbreviation LCD which stands for *liquid crystal display*.

Table 31.1 gives an overview of the differences and similarities in the arrangement of atoms or molecules in gases, liquids and solids.

	Distance of atoms or molecules	Arrangement of atoms or molecules
Gases	Large	Disordered motion
Liquids	Densely packed	Usually amorphous, rarely crystalline
Solids	Densely packed	Crystalline or amorphous

Table 31.1

31.2 The distribution of the electronium in solid substances

Fig. 31.5 shows how we might imagine the interior of a solid substance, in this case a crystal, to look. The darker the gray color in the figure, the denser the electronium. At the points of maximum density are the atomic nuclei. At first, the density of the electronium decreases with increasing distance from a nucleus—until it comes close to the neighboring nucleus, where it begins to increase again.

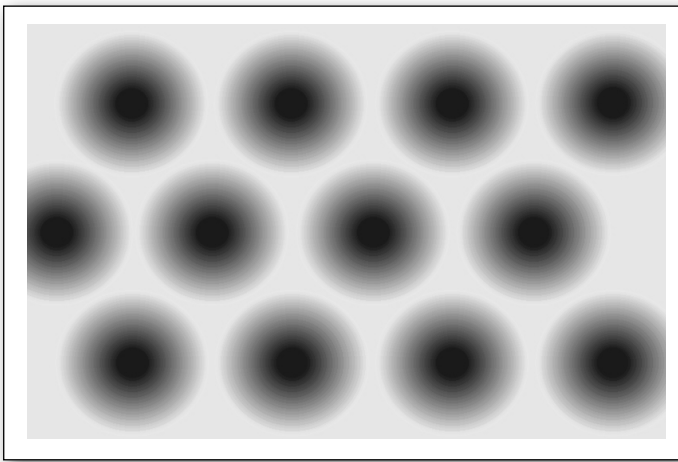


Fig. 31.5

Distribution of electronium in a solid substance

Similar to individual atoms, most electronium is found close to the nuclei. However, there are no empty spaces between the individual atoms like the ones we saw in the pyramid of tennis balls, Fig. 31.1. The entire space between the nuclei is filled with electronium. There is also no clear boundary between the end of one atom and the beginning of another. The electronium of the individual atoms merges into one continuous substance.

Fig. 31.6 also shows the distribution of electronium in a solid substance, in this case a crystal of table salt NaCl. The density of the electronium is represented by lines of constant density. The higher the number that labels a line in the figure, the higher the density of the electronium where the line is. These lines are comparable to the altitude lines on a map. The higher the label of an altitude line, the higher the altitude of the corresponding location.

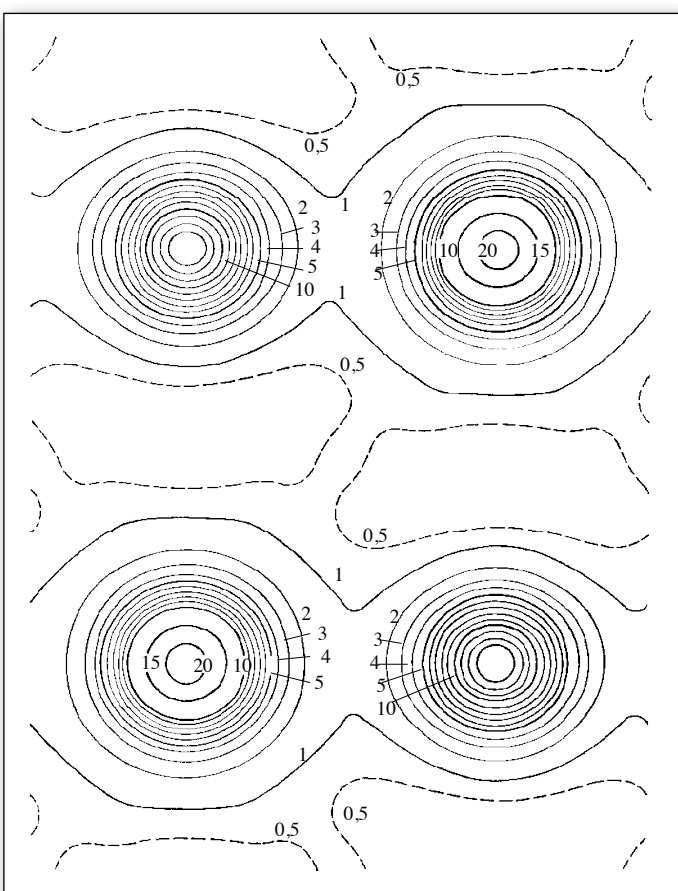


Fig. 31.6

Distribution of electronium in table salt

Fig. 31.6 shows four areas of especially high electronium density: At the top left and bottom right around the nuclei of the sodium, and at the top right and bottom left around the chlorine nuclei. In between, there are areas where the density is very low, but it never equals zero.

The electronium of solids forms a continuous substance which fills the entire space between the nuclei.

The atoms of a gas can move almost freely in the space where the gas is. The higher the temperature of the gas, the more quickly they move.

The atoms of solid substances, on the other hand, are confined to a given location. They cannot leave their place in the crystal lattice. However, they are not immobile. They oscillate around a middle position. The higher the temperature, the faster this oscillatory motion is.

Exercise

How many atoms does a crystal of cooking salt with an edge length of one millimeter contain?

31.3 The energy ladders of solid substances

We have seen that the electronium in the shell of an atom can deform and that it can also lock into certain forms. This applies to the electronium in solid substances as well.

In this case, deforming means that the electronium is shifted from one location to another exactly as it happens in individual atoms. The distribution of the electronium is changed: the density of the electronium decreases in one location and correspondingly increases in another.

Fig. 31.7 shows electronium in a non-deformed state. For the sake of clarity, we show it at a constant density. In Fig. 31.8, you can see how a deformation might look. The density at one location has decreased (lighter area) and it has increased at another (darker area). A *rarefaction* and a *compression* have occurred.



Fig. 31.7
Electronium in a non-deformed state
...

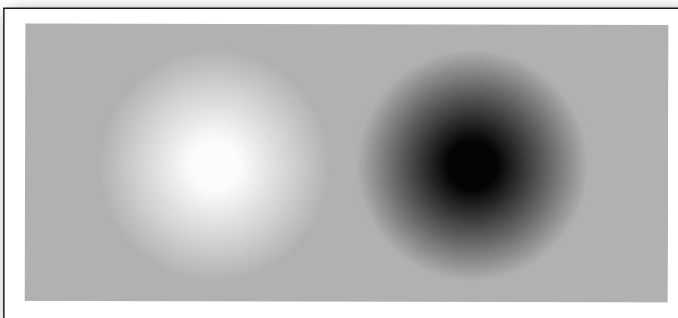


Fig. 31.8
... and in a deformed state (schematic)

The electronium in a solid substance can be brought into many forms. The deformations are not limited to the space of individual atoms but can extend over many atoms.

The electronium in solid substances can be deformed. Electronium can keep some of these deformations for a time.

As we did with atoms, we call the non-deformed state of the electronium the ground state. A state with deformed electronium is called an excited state.

Because different amounts of energy are necessary for exciting different kinds of deformation, solid substances have energy ladders just as atoms do. There is, however, one basic difference between the energy ladders of individual atoms and those of solid substances. The rungs of an atom's energy ladder are very narrow (because it can only store very specific amounts of energy) while those of a solid substance are much wider. The energy that can be stored by solid substances correspond to entire ranges on the energy scale.

The energy ladders of solid substances can be divided into two groups. There is a basic difference between these two types of energy ladders. In the first type, the excited states immediately follow the ground state, Fig. 31.9a. All metals have this type of energy ladder. It takes very little energy to excite the electronium of metals.

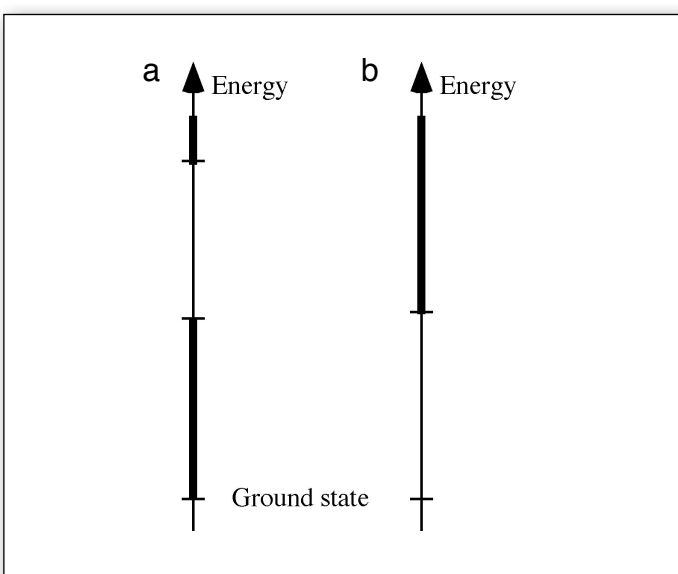


Fig. 31.9
Energy ladders of metals (a) and non-metals (b)

The second type of energy ladder has an *energy gap* between the ground state and the lowest rung, Fig. 31.9b. This is typical for the energy ladders of non-metals. Excitation, in this case, is only possible when there is enough energy to overcome the gap between the ground state and the lowest rung.

31.4 When light hits a metal

Light that hits a very smooth metal surface is mostly reflected. For this reason, the reflecting layer of a mirror is made up of aluminum. However, this aluminum does not reflect all the light which hits it. This can be clearly seen by performing the experiment shown in Fig. 31.10. Two large mirrors face each other close together. If one looks past the edge of mirror A into mirror B, the image of mirror A can be seen. In this image one sees the image of mirror B, in it the image of A, etc. A kind of hallway can be seen whose walls are formed by the edges of the mirrors. The light which appears to come from very far down this hallway is the light that has been reflected back and forth several times by the mirrors. It is interesting for us to see that this hallway becomes progressively darker as it recedes. This means that some light gets lost at every reflection. Indeed, about 10% of the light gets absorbed at each reflection.

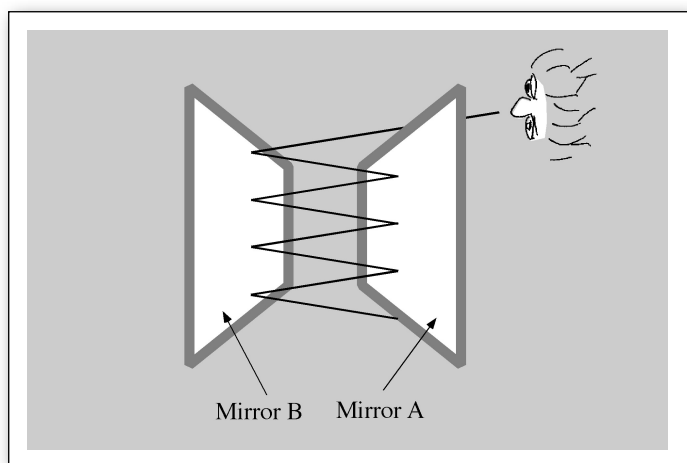


Fig. 31.10
The observer receives light that has been reflected between the mirrors many times.

We can conclude from this that the mirror, and every other metal, not only reflects light but absorbs it as well. Because of reflection, very little light penetrates the metal; therefore, only very little light is absorbed.

Absorption of light in metals agrees with the ladder in Fig. 31.11. The three bars next to the energy ladder correspond to the photons of red, green and blue light. None of the three reaches above the first rung of the ladder. This means that the photons of visible light can excite the electronium in metals.

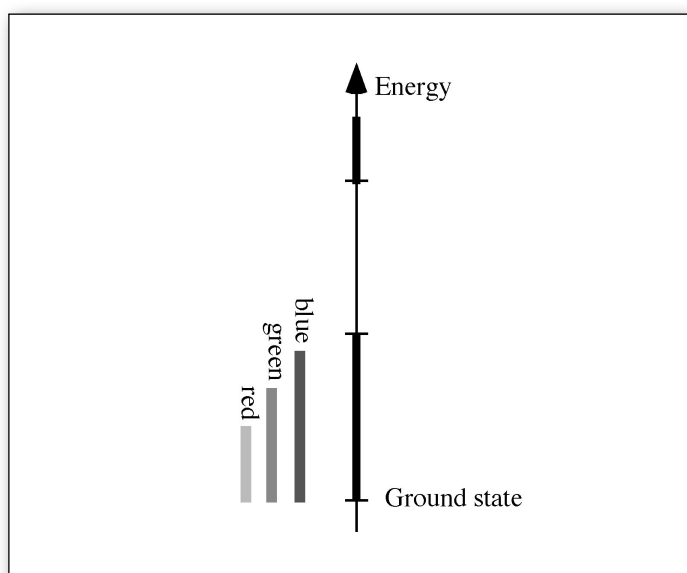


Fig. 31.11
The energies of photons corresponding to visible light cannot reach above the first rung of the energy ladder of a metal.

Photons of visible light can excite the electronium of metals and are absorbed in the process.

It is not difficult, however, to get a metal to absorb all of the light hitting it, and not only 10% of it. It is enough to make it into fine particles. Any metal powder will almost totally absorb light. Metal powders are black. How can this be explained?

When light hits metal powder, it is not just reflected once but many times—from one powder grain to the next, Fig. 31.12. After the first reflection, only 90% of the original amount of light remains. After the second reflection about 81% remains, and after the third, 73%, etc. After 25 reflections about 7% remains and after 50 reflections, about 0.5% or almost nothing is left of the light. The finer the metal powder, the higher the number of reflections and the blacker the powder. The light runs into a dead-end in the powder.

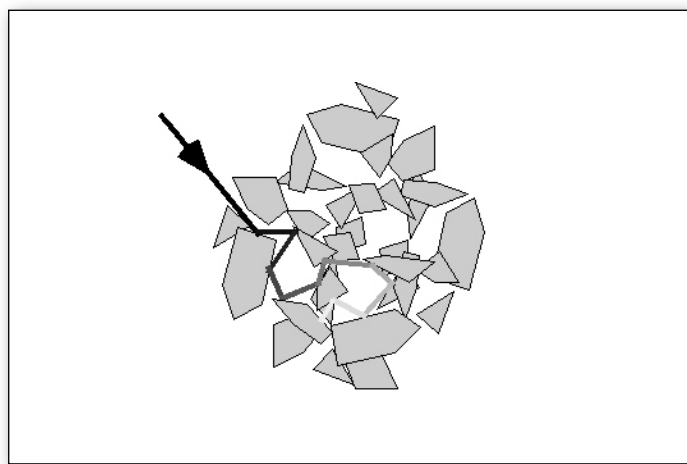


Fig. 31.12
Light in a metal powder is reflected back and forth numerous times.

Just about everyone has experienced powdery metal absorbing light. When a white metal cleaner is rubbed on the surface of clean, shiny aluminum, the cleaner turns black. The cause of this blackness is the aluminum powder that is rubbed off.

Another, very simple, experiment can demonstrate how light gradually disappears when it is reflected numerous times. A small hole is cut into a box, a shoe box for example, Fig. 31.13. The inside of the box should be white so that it does not absorb much light. The hole appears to be black. Light reaches into the carton through the hole, but does not find its way out again. Each time the light hits the wall of the shoe box, some of it is absorbed, and after it has gone back and forth several times, there is nothing remaining of it.

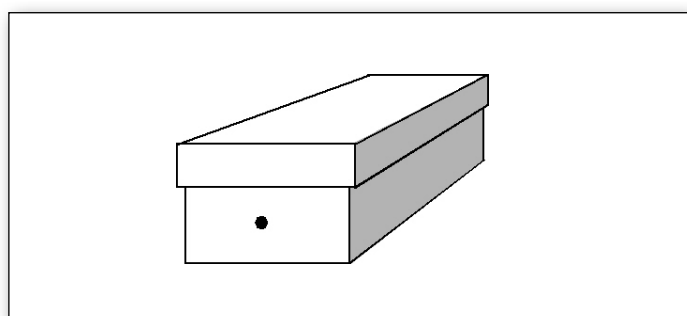


Fig. 31.13
The hole in the shoe box is black.

The blackness of every black object around us comes about in this way, for instance the black letters in any book. If you look closely at the paper, you will see that it has a rough surface. The light hitting it takes a zig-zag path upon it before it comes out again and reaches your eyes. If there is a place on the paper with a substance that absorbs a part of the light at every reflection, it will appear black there.

In black objects, light runs into a dead-end.

31.5 When light hits non-metals

Fig. 31.14 shows an energy ladder typical to many non-metals. The bars correspond to the photons of visible light. None of them reach up to the first rung of the energy ladder. The photons of visible light cannot deform the electronium of this substance. They are not absorbed but pass right through it. The substances with this kind of energy ladder are transparent. Examples of this are glass, salt, sugar, ice, cellulose (the chief ingredient in paper), most minerals (for example, quartz and feldspar), diamond, and plastic.

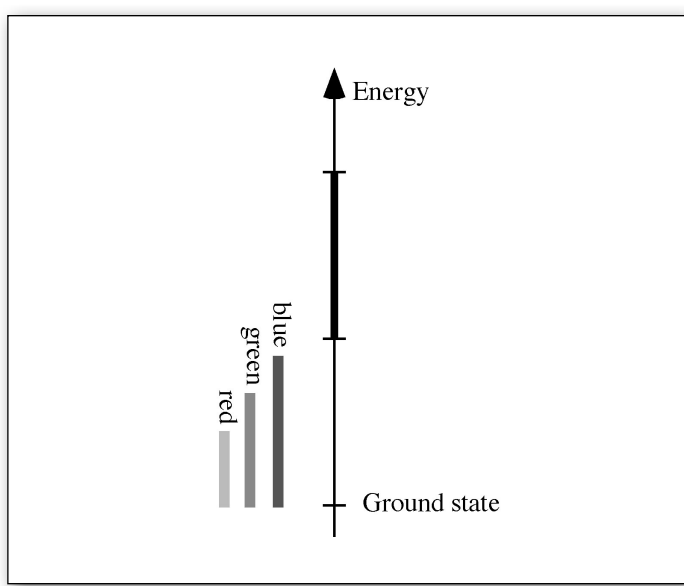


Fig. 31.14

The energies of the photons of visible light do not reach even the first rung of the energy ladder of a non-metal.

Possibly you are thinking about objects that are made of the substances just mentioned that are not transparent but white. Some of these would be table salt, powdered sugar, paper, ground glass, and snow. All of these substances or things are made up of small particles: grains or fibers. The smaller the particles, the whiter the white. Powdered sugar is whiter than granulated sugar.

The white that is perceived here is not in the individual small particles. By closely examining snow crystals, grains of salt, grains of sugar, and glass splinters, we find that the individual grains or fibers are transparent (for paper, a microscope is necessary to see this). The color impression white results from an accumulation of many transparent particles.

White objects are composed of many small transparent particles.

The light hitting such an object from the side is not absorbed by the particles, but is *refracted*. The direction of the light is altered. After being refracted several times, the light comes out again at the same side it went in. It does not pass through the substance, meaning the substance is opaque.

The white color of clouds also comes about in this way. A cloud is made up of numerous small transparent particles, namely water drops.

Non-metals are by no means always either white or transparent. Colored glass, colored stones, and colored plastics also exist. In these cases, color is created by other substances mixed into the transparent non-metals. These substances absorb visible light of certain wavelengths.

There is also another reason why a non-metal would have color or even be black. In the case of the energy ladder represented in Fig. 31.15, the energy gap (the distance between the ground state and the lowest rung on the ladder) is smaller than the energy of the photons of blue light. An example of a substance with such an energy ladder is cadmium sulfide. The longest of the three bars (corresponding to blue light) reaches into the area of allowed energy. The energy of these photons is sufficient to jump over the energy gap and to excite the electronium. The photons of the blue light are absorbed in the process.

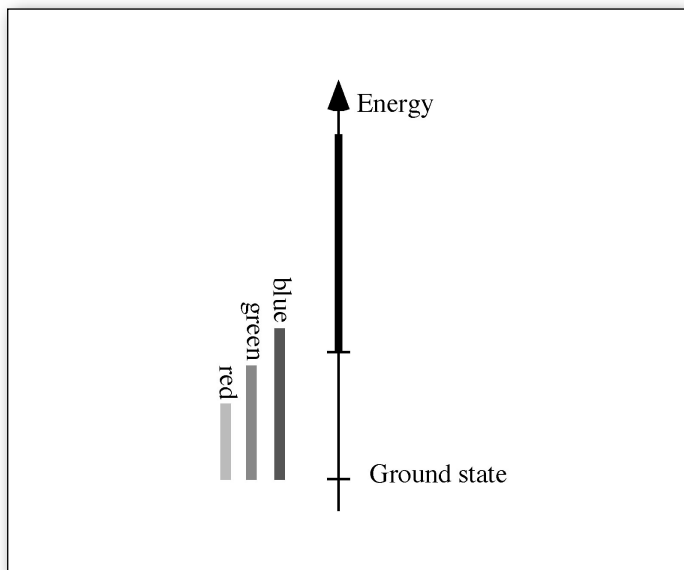


Fig. 31.15

The energy ladder of cadmium sulfide. Next to it, the energy of the photons of red, green, and blue light.

No other photons are absorbed. The blue light is then missing in the light that passes through and the mixture of the rest results in yellow. This is why a piece of cadmium is transparent yellow.

In the cases of silicon, germanium, and graphite, the gap between the ground state and the lowest rung is even smaller than that of cadmium sulfide, Fig. 31.16. The energies of all photons of visible light are enough to jump over the energy gap, resulting in no visible light being allowed to pass through. The part that is not allowed through is absorbed. Because a greater part of the light seeps into the material than it does with metals, smooth surfaces are non-reflective but have a black gloss. These substances are called *semi-conductors*.

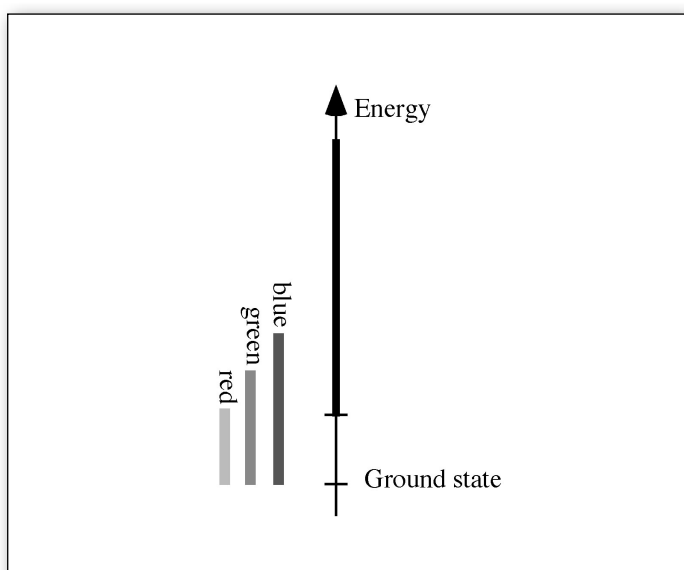


Fig. 31.16

Energy ladder of a semi-conductor

Semiconductors in powdered form are also deep black because the light runs into a dead end after numerous reflections in the grains of the powder. Soot is such a substance. It is mostly made up of tiny particles of graphite. It is used in printer's ink and to color plastics black.

The energies of infrared photons do not reach to the lowest rung of the energy ladder, so semiconductors allow infrared light to pass through—in contrast to metals.

Silicon is used for manufacturing the lenses of infrared cameras. Infrared light is allowed through these lenses and is refracted. Visible light, on the other hand, which would expose the film and should not be allowed into the infrared camera, is not allowed through.

31.6 Solids as a light source

The light of a light bulb comes from a glowing tungsten filament. The light of a candle comes from the glowing soot particles. How is this light produced?

In a solid substance, the nuclei and the electronium around them move around a central position. The higher the temperature, the more forceful the movement. The faster the movement is, the more energy is contained in the atoms.

In a metal, the energy of this movement is enough to excite the electronium even at normal temperature. However, the electronium absorbs only very little energy with this excitation. For this reason, the photons that are emitted in the process of returning to the ground state have only small energies as well. They are infrared photons and not the photons of visible light, Fig. 31.17.

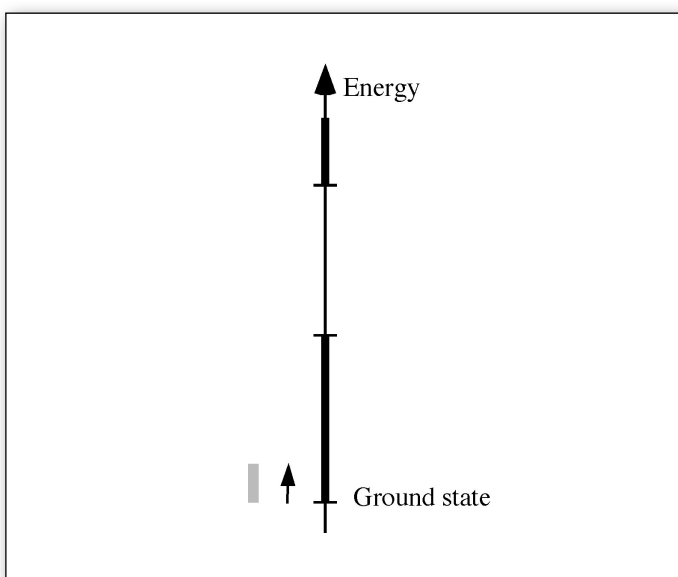


Fig. 31.17

At normal temperatures, the energy produced by the movement of the atoms of metals is only enough for slight deformations.

When the metal is heated, the motion of the atoms becomes more intense and their energy increases. The electronium becomes more strongly deformed, and the photons that are produced in the process of returning to the ground state are richer in energy, Fig. 31.18. Finally, at even higher temperatures, photons of visible light are produced and the metal glows.

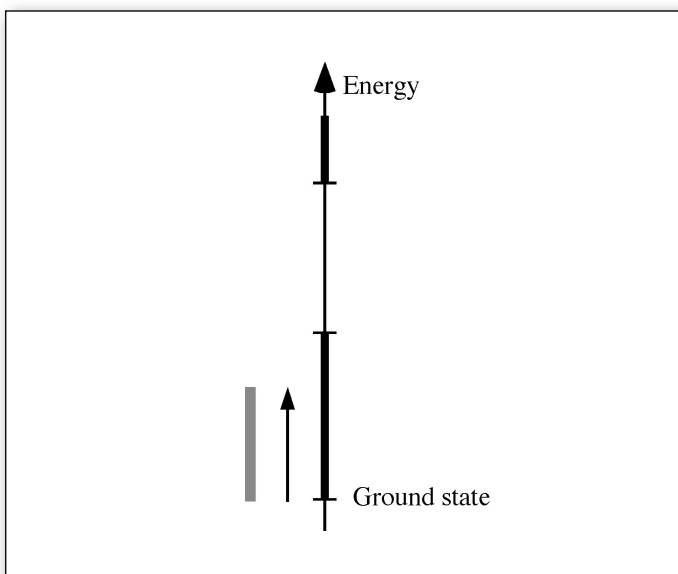


Fig. 31.18

At higher temperatures, the electronium is more strongly excited. Photons of visible light are produced as it returns to the ground state.

All black non-metals, i.e., semiconductors, begin to glow as well when they are heated.

Metals and semiconductors can glow, i.e., at high temperatures they can produce visible light.

This is not the case with transparent and colorless non-metals. Their energy gap is so great that even at high temperatures, the electronium cannot be excited, so photons of visible light are not produced.

Objects made up of transparent non-metals do not glow.

31.7 How solids conduct electricity

Cables are used to conduct electricity. They are made up of metal wires (mostly copper) and a plastic sheath. Metal is used because it conducts electricity well, and plastic is used because it (and most non-metals in general) does not conduct electricity. It keeps the electricity in the conductor from flowing out into the surroundings.

Electricity always sits upon particles, namely the negatively charged electrons and the positively charged protons of atomic nuclei. When electricity is to flow through a copper wire, either the nuclei or the electronium must move with it. Nuclei are bound to their places in the crystal grid so they cannot move through the copper wire. This leaves only the electronium.

One might imagine that the electric current is produced by the electronium flowing through the solid substance past the nuclei. However, the electronium is bound to the nuclei so tightly that it cannot shift in this way.

The situation is similar to the following problem: A large, heavy rug needs to be moved, Fig. 31.19. We grab one end and try to pull it across the floor. However, because it is large and heavy, it does not budge. We try another possibility. We create a wrinkle or fold in the rug, Fig. 31.20. This fold allows itself to be easily pushed through the rug and in the end, the whole rug has shifted position.

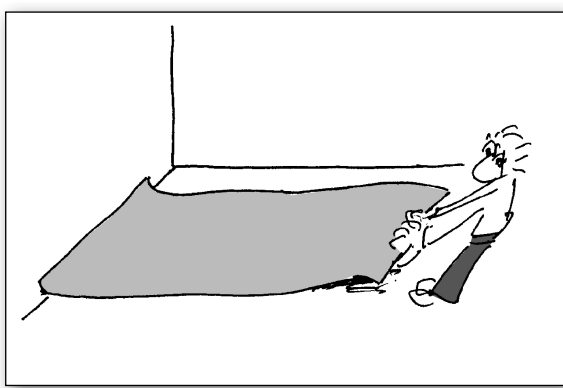


Fig. 31.19
One possibility for moving a rug

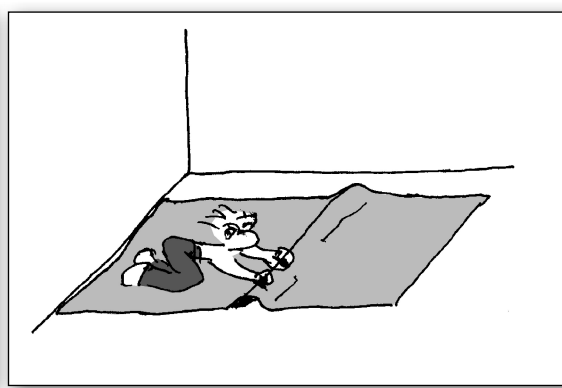


Fig. 31.20
... and another possibility

The electronium in a solid substance behaves similarly to the rug. As a whole, the electronium is very difficult to move. However, small deformations can be pushed through the solid. A solid substance is able to conduct electricity if its electronium can be easily deformed.

If an electric voltage between two sides of a solid body exists, for instance by connecting one side of it to the positive terminal of a battery and the other side to the negative terminal, compressions runs in the direction of the positive terminal and rarefactions in the direction of the negative terminal, Fig. 31.21. Just as the shifting of the whole rug is a result of shifting the fold in the rug, there is a net transport of electronium as a result of the movement of compressions and rarefactions in the electronium.

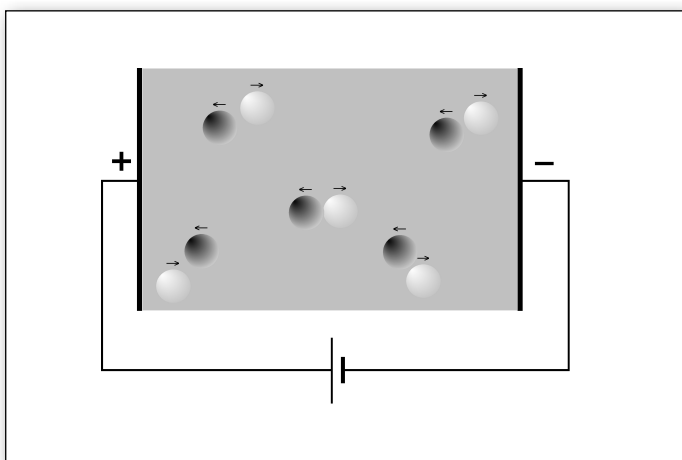


Fig. 31.21
If a battery is connected, the rarefactions move toward the negative terminal, and the compressions move toward the positive terminal.

As a result of compression, the electronium moves in the direction of the positive terminal. The shifting of the rarefaction in the direction of the negative terminal also results in electronium moving in the direction of the positive terminal. It is like the bubble that moves upwards from the bottom of a water glass. Where air was before the bubble started to rise (i.e., at the bottom), water will now be found. Water has gone from above to below, Fig. 31.22.

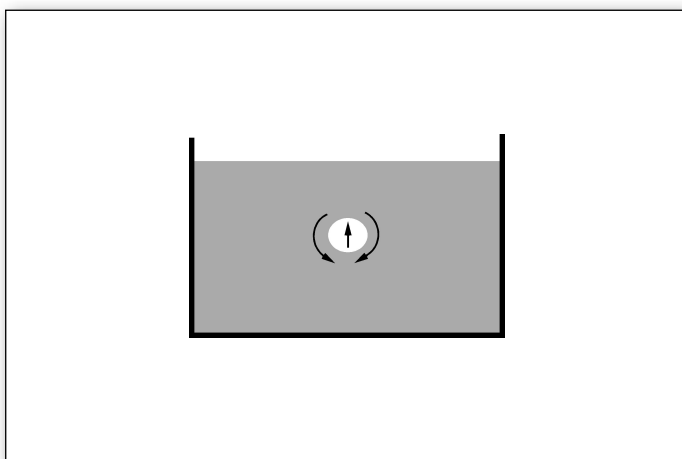


Fig. 31.22
The rising of an air bubble corresponds to the sinking of water.

Electricity is transported through solid substances by the movement of deformations of the electronium.

You already know that the electronium of metals can be easily deformed, while rather a lot of energy is necessary to excite the electronium in non-metals. The energy of a battery is enough to excite the electronium in metals. Hence, there are deformations that can move through the metal and carry electricity with them. Metals are good conductors of electricity.

A battery will not manage to excite the electronium in non-metals. There will be no deformations and no electricity can be transported. Non-metals do not conduct electricity.

31.8 How non-metals can be made to conduct

We will consider a non-metal whose energy gap is not too big, cadmium sulfide, for example. Blue photons have enough energy to overcome the gap. The electronium will be excited if it is illuminated by white light which contains photons of blue light. Deformations are produced. If the crystal of cadmium sulfide is a part of an electric circuit, electricity can flow. The crystal has become electrically conductive as a result of the excitation. When the illumination is stopped, no more deformations are produced in the electronium and the conductivity disappears.

Substances that become conductive when illuminated are called *photoconductors*. The more light that hits a photoconductor, the smaller its resistance. Photoconductors are used to measure intensity of light, which they do this in cameras, for example.

Just warming up a semiconductor is enough to excite the electronium and improve its conductivity. This explains the name “semiconductor”.

Non-metals with narrow energy gaps can be made conductive by lighting or heating them.

There is also another way to improve the conductivity of non-metals. A small part of the atoms of the substance can be replaced by the atoms of another substance. These “foreign atoms” are chosen so that they have either one electron more or one electron less in their shells than the atoms of the solid substance they are being inserted into.

The atoms of arsenic are inserted into germanium in this way. The extra electron of each arsenic atom behaves like a compression of the electronium. When an electric voltage is applied between two sides of the germanium crystal, the compressions move in the direction of the positive pole and a current flows.

If an atom with one electron less in the shell than the germanium atoms, i.e., a gallium atom, is inserted into the crystal lattice, it produces rarefactions. When the battery is connected, these move toward the negative pole.

Non-metals can be made conductive by inserting foreign atoms into them.

The most important electronic components—diodes and transistors—are produced from germanium or silicon which have been made conductive in this way. We shall discuss these in the next two sections.

31.9 Diodes

A diode is an electronic component with two connections. When inserted into an electric circuit, it allows the electricity to flow in one direction only. A diode is for electricity what a bicycle tire valve is for air.

A diode is made up of a semiconductor, usually germanium or silicon. One half of the material contains compressions, the other half contains rarefactions, Fig. 31.23. The compressions and the rarefactions are due to foreign atoms, that have been inserted previously. The ends are connected to the electric ports of the diode.

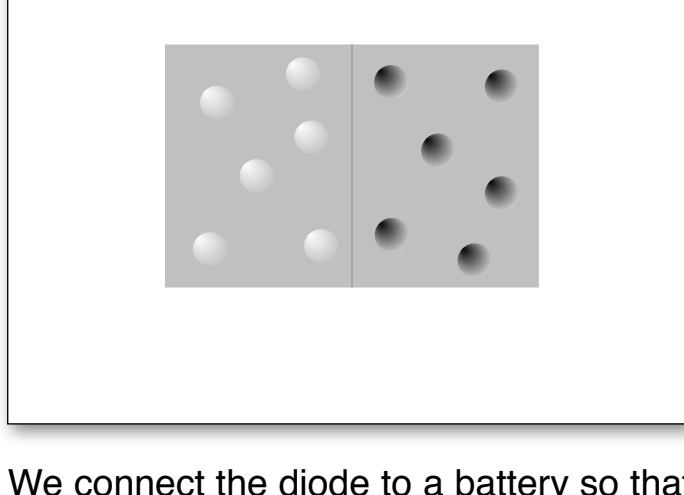


Fig. 31.23
The rarefactions are in the left side of the diode, and the compressions are in the right side.

We connect the diode to a battery so that the positive terminal of the battery is connected to the side with the rarefactions, and the negative terminal is connected to the side having the compressions. The rarefactions move toward the minus terminal, meaning towards the middle, and the compressions move in the direction of the positive terminal, also toward the middle, Fig. 31.24. At the same time, rarefactions are supplied from the cable on the left, and compressions from the one on the right. This is because the rarefactions move toward the negative terminal in the metal wires of the cable, and the compressions move towards the positive terminal.

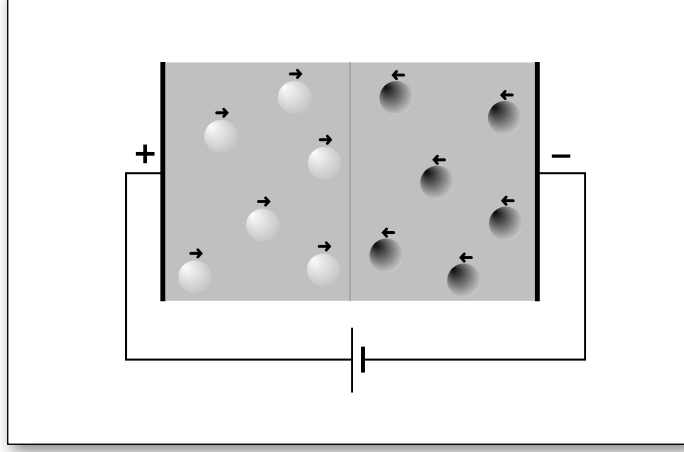


Fig. 31.24
Compressions and rarefactions move toward the middle of the diode.

The compressions and the rarefactions meet in the middle of the diode where the compressions “fall” into the rarefactions. They cancel each other at the rate that they are supplied from the ports of the diode. When a battery is connected to the diode, an electric current flows through it.

Now we connect the diode to the battery in just the opposite way. The negative terminal is connected to the side with rarefactions, and the positive terminal is connected to the side having compressions. The rarefactions move left toward the negative pole from the middle of the diode, and the compressions move to the right from the middle of the diode, Fig. 31.25. No rarefactions or compressions can be supplied from the middle of the diode, so the process soon comes to a standstill. Even though the battery is connected to it, there is no electric current through the diode.

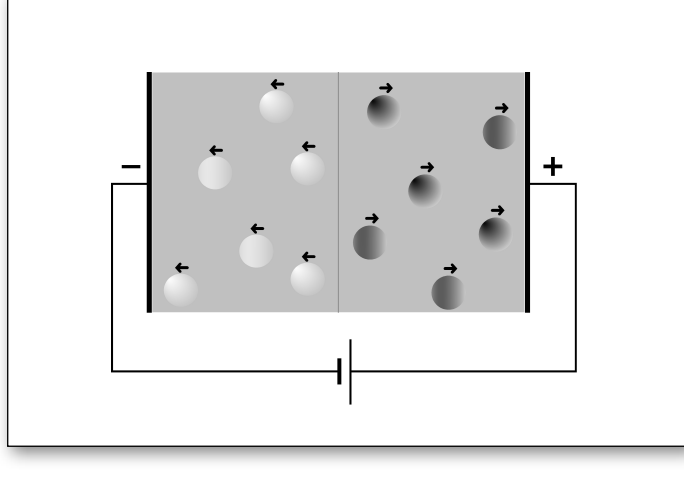


Fig. 31.25
Compressions and rarefactions move outward away from the middle.

The diode allows the electricity to pass through in one direction but not the other. When a diode is inserted into an electric circuit supplied with an alternating voltage source, Fig. 31.26, no alternating current will flow. The diode allows the electric current to flow in only one direction. The current is *rectified*. The diode acts as a *rectifier diode*.

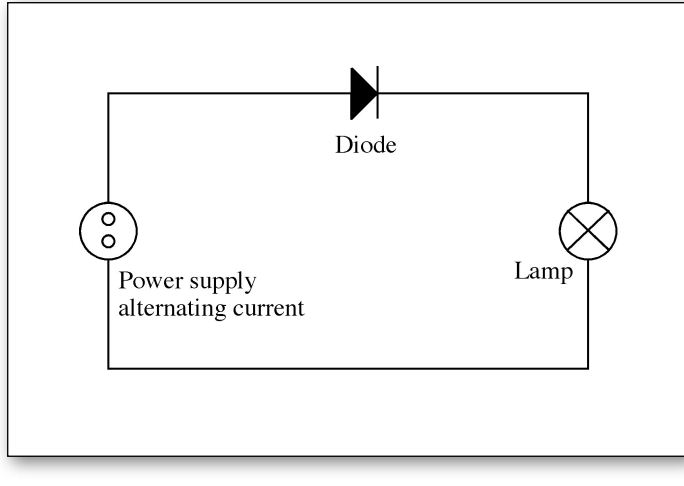


Fig. 31.26
The rectifier diode allows an electric current to flow in only one direction.

Diodes have other interesting characteristics. If a diode is connected to a battery like in Fig. 31.24, the compressions and rarefactions move to the middle and destroy each other there. In the process, the energy stored in the compressions and rarefactions must be released. This is accomplished by creating photons, Fig. 31.27. A diode that produces visible light is called a *light emitting diode* (LED).

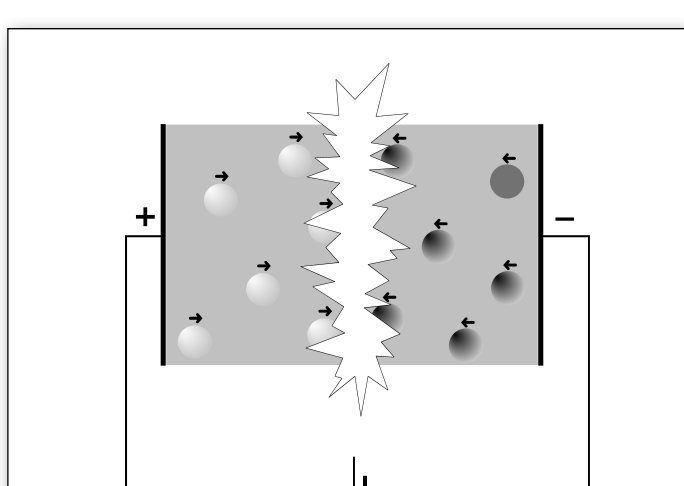


Fig. 31.27
When the compressions meet the rarefactions, photons are produced and the diode emits light.

There are many uses for diodes. They are used for the illuminated numbers or letters on electric appliances or as the source of self-luminous advertising boards where moving text or entire pictures are represented.

If a diode is connected to a battery such as in Fig. 31.25, it blocks. The electric current cannot flow. There is a way, though, to make this diode conduct.

Rarefactions and compressions are produced when photons are absorbed by a solid substance. If the diode is illuminated, the rarefactions and compressions that are extracted by the battery are resupplied. They move to the right or left, respectively, meaning that an electric current is flowing through the diode, Fig. 31.28. The strength of the current depends upon the illumination. If the illumination is strong, the current is strong, if the light is weak, the current is weak. If the diode is not illuminated at all, no current flows. This kind of diode is called a *photodiode*. Similar to photoconductors, photodiodes are used to detect or measure light.

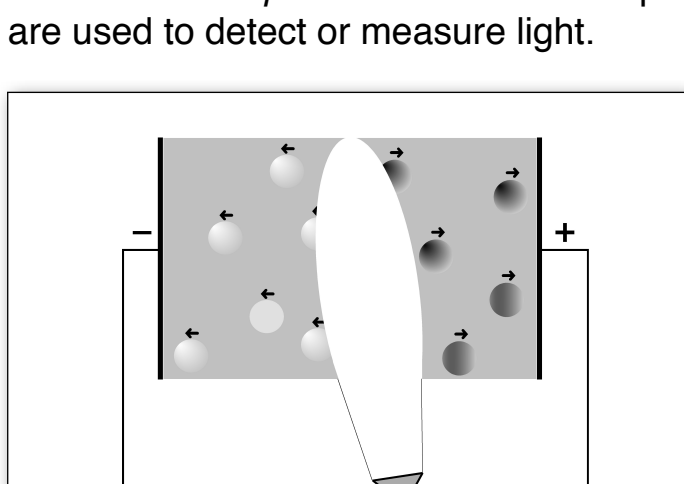


Fig. 31.28
During illumination, compressions and rarefactions are produced.

A diode can also be used as an electricity pump.

Instead of a battery, we connect a photodiode to a small electric motor, Fig. 31.29. If the diode is illuminated, extra rarefactions and compressions are produced. In the process, the already existing rarefactions are pressed to the left and the compressions to the right. They are pressed right out of the diode and through the electric motor. The diode is pumping electricity through the electric circuit.

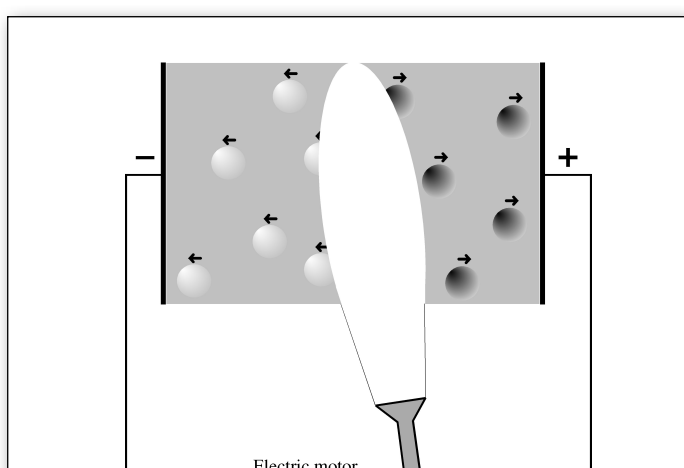


Fig. 31.29
The diode works as an electricity pump.

A diode that has been optimized for this purpose is called a *photoelectric cell*.

Diodes are used as

- electric current valves (rectifier diodes);
- light sources (light emitting diodes, LEDs);
- detectors of light (photodiodes);
- electricity pumps (photoelectric cells).

Exercise

Graphically represent the electric current in the electric circuit of Fig. 31.26 as a function of time.

31.10 Transistors

A transistor is a switch for an electric current that can be opened or closed electrically. It essentially fulfills the function of a relay, but has some advantages that a relay does not have. It needs a much smaller current and it reacts much more quickly. Moreover, it is much smaller. Finally, it not only turns on and off, but its “conductivity” for the electric current can be set to intermediate values.

Transistors are mostly used in electronic devices such as televisions, video cameras, stereo players, and smart phones. Above all, there are millions of them in every computer.

Fig. 31.30 shows the composition of a transistor. The current to be controlled is sent through a semiconductor which contains electronium compressions (due to impurities).

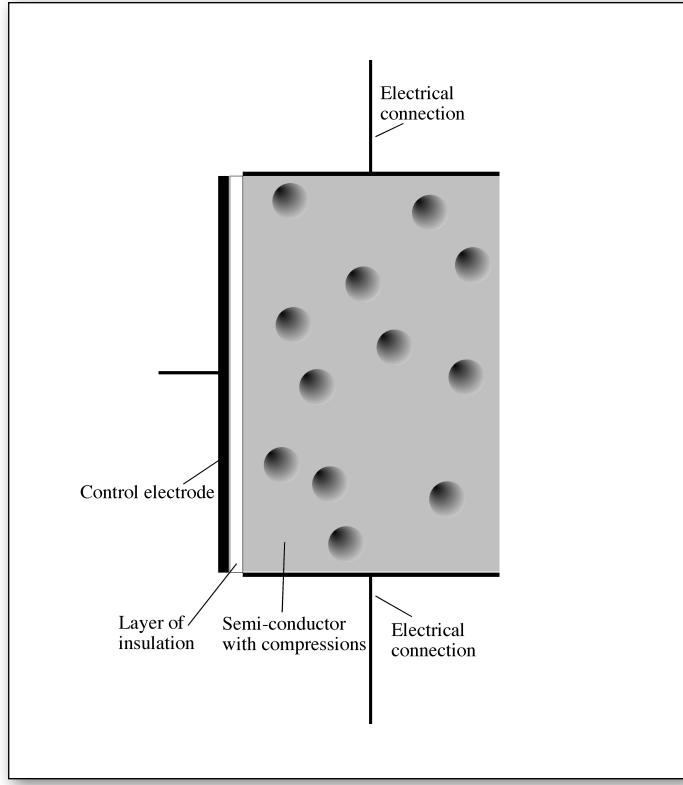


Fig. 31.30
Structure of a transistor

There is a thin insulating layer on the side of the semiconductor. On top of this is a layer of metal, the control electrode. The semiconductor, insulating layer, and control electrode together make up a capacitor. This capacitor can be charged by applying a voltage between the control electrode and the semiconductor. One terminal of the voltage source is connected to the control electrode, and the other one is connected to one of the terminals of the semiconductor.

When the capacitor is charged, the amount of electronium on one plate increases and on the other, it decreases.

If the voltage source is connected as shown in Fig. 31.31, compressions of electronium will be removed from the semiconductor. However, the semiconductor contains so few compressions that the loss by charging the capacitor strongly inhibits the conductivity. Even a small voltage is enough to cause the semiconductor to lose practically all its compressions. It turns into a non-conductor. The semiconductor cannot conduct electricity any longer, it behaves like an open switch.

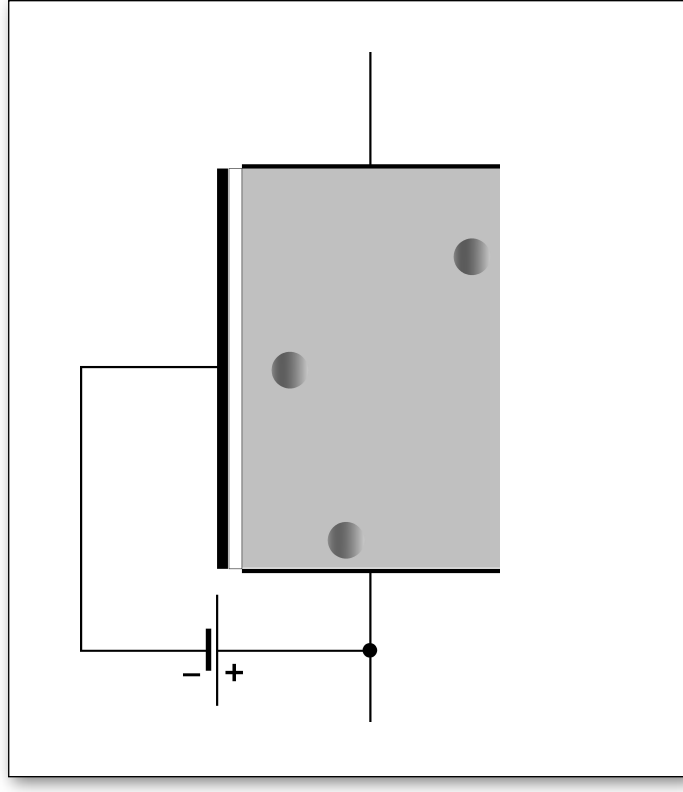


Fig. 31.31
The battery draws compressions out of the semi-conductor.

If, in contrast, the negative terminal of the voltage source is connected to the semiconductor and the positive terminal to the control electrode, Fig. 31.32, the semiconductor receives extra compressions. It conducts the electric current very well, behaving like a closed switch.

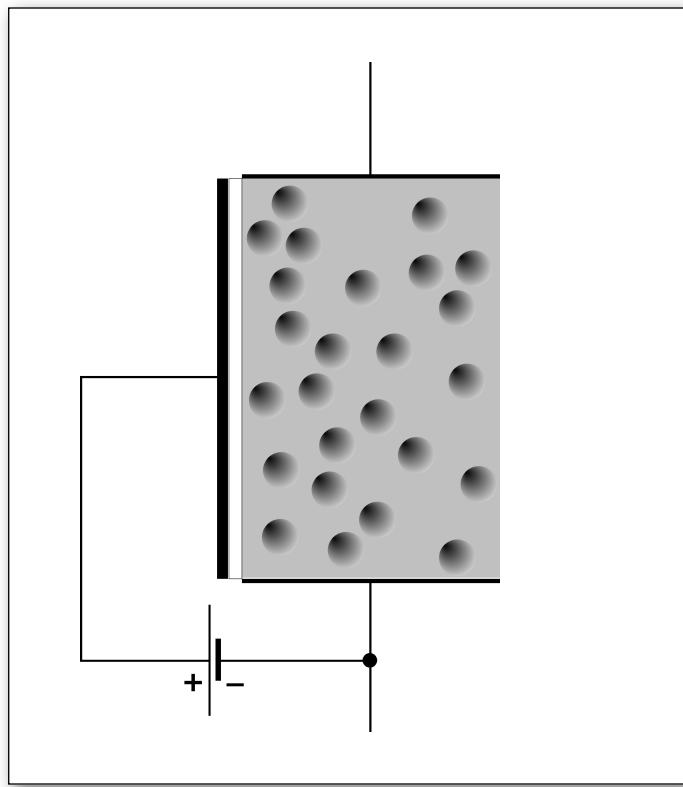


Fig. 31.32
The battery presses compressions into the semi-conductor.

Fig. 31.33 shows a complete electric circuit with a transistor. If the electric potential of the control electrode is lower than that of the semiconductor, the semiconductor will not conduct. The lamp will therefore not burn, Fig. 31.33.

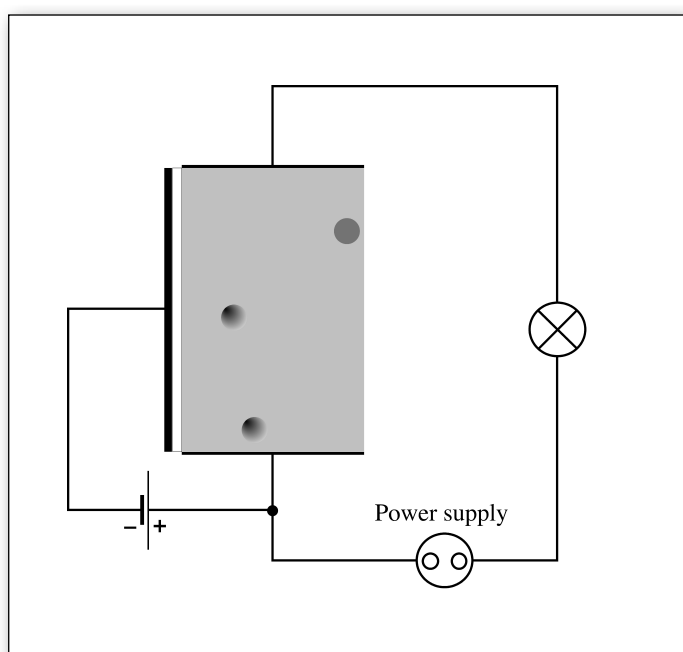


Fig. 31.33
The electrical circuit of the lamp is interrupted.

However, if the electric potential of the control electrode is higher, the semiconductor will conduct and the lamp will burn, Fig. 31.34.

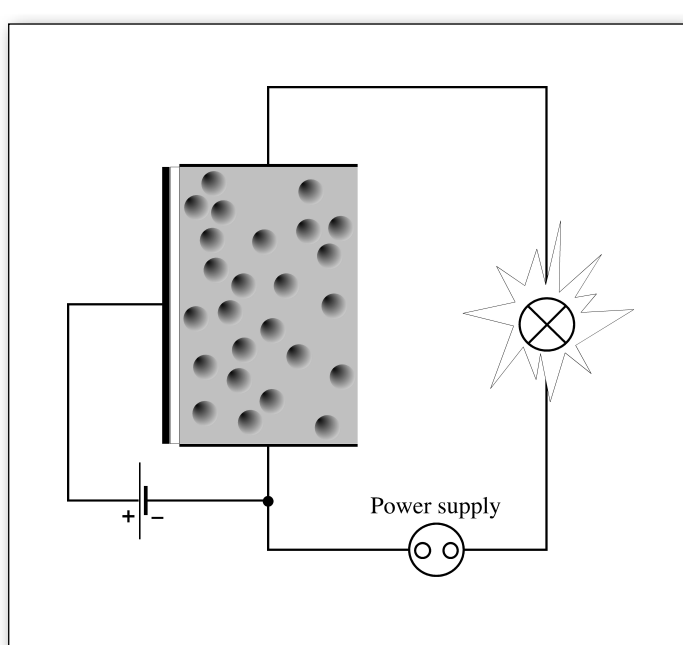


Fig. 31.34
The lamp's electric circuit is closed.

Exercise

There are transistors, that are made conductive by rarefactions. How does the battery need to be connected to the transistor so that the transistor behaves like an opened switch?

32

Nuclei

In our study of atoms we have dealt mostly with the electronium of atomic shells. So far, we have considered the nucleus mainly in its role of holding the electronium together. There are processes in nature, however, that can be understood only if atomic nuclei are better known: Processes in which atomic nuclei go through changes. These processes are called nuclear reactions.

Nuclear reactions take place to a minor degree here on Earth, but the nuclear reactions that go on in the Sun are of much greater importance. They are responsible for the Sun emitting light and so providing the Earth with energy. Nuclear reactions are also used in technology. This usage is both profitable as well as detrimental to humans. Such nuclear reactions are found in atomic reactors, fusion reactors, in atomic bombs, and in hydrogen bombs.

In studying the structure of nuclei, you will reencounter many of the things you learned about the composition of atomic shells. In addition, you will be able to apply a lot of what you have learned in chemistry class about normal chemical reactions.

32.1 The structure of atomic nuclei

In our discussion about the composition of atoms we have already learned that:

The diameter of an atomic nucleus is about 1/100,000th of the diameter of the atom. Despite this tininess, almost the entire mass of an atom is in the nucleus. The mass of the shell makes up only about 1/4000th of the mass of the nucleus.

In addition to mass and size, there is another remarkable difference between the shell and the nucleus.

You remember that the density of electronium gradually decreases outwards so that the atomic shell has no sharp edge – similar to the atmosphere around the Earth. You have also seen that the shells of heavy and light atoms do not differ so much by size, but mainly by density. A gold atom and a lithium atom are approximately the same size, but the density of the electronium of the gold atom is much greater than that of the lithium atom.

Atomic nuclei are rather different. The density of the nucleus is the same everywhere, unlike the Earth's atmosphere, but like a ball made of glass. In addition, the density of the nuclear matter is the same for all nuclei. The nucleus of a lithium atom has about the same density as that of a gold atom. The difference between the nuclei of lithium and of gold lies in their sizes, Fig. 32.1.

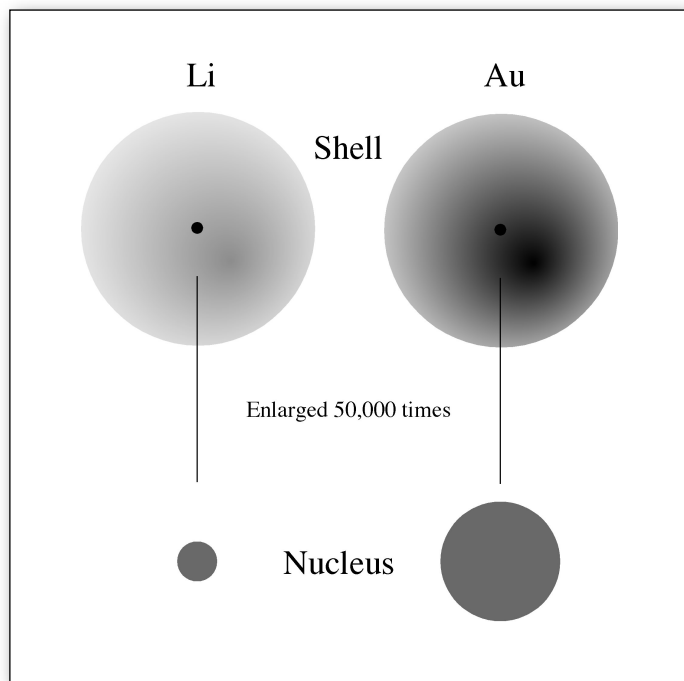


Fig. 32.1
The shell of a gold atom is the same size as that of a lithium atom but it is much denser. The nucleus of a gold atom is as dense as that of a lithium atom, but it is much bigger.

The density in an atomic nucleus is the same everywhere. The densities of different nuclei are the same.

As far as the shape is concerned, nucleus and shell are very similar. Nuclei are almost spherical. Some vary slightly from this spherical form, appearing flattened like a tangerine or slightly elongated like a kiwi fruit.

Density is measured in g/cm^3 . For example, water has a density of $\rho = 1 \text{ g/cm}^3$.

This means that 1 cm^3 of water weighs 1 g, or 1 liter of water weighs 1 kg. Because almost the entire mass of an atom is in the nucleus, the density of the nucleus takes enormous values. Nuclear matter has a density of

$$\rho = 10^{14} \text{ g/cm}^3.$$

If it were possible to collect 1 cm^3 of nuclear matter, it would have a mass of

$$10^{14} \text{ g} = 100,000,000 \text{ tons}.$$

In order to learn more about the remarkable substance that nuclei are made up of, we will perform an experiment. We already did this before when we were investigating atomic shells: We reach in and scoop out a portion of it. You shouldn't take the expression of reaching in too literally. It would be impossible to put a hand into the shell or the nucleus. It is, however, possible to do something that approximates reaching in. The nucleus can be bombarded by other small particles causing some of the nuclear matter to catapult out of it. At the moment, it is not important exactly how this would be done.

So we reach into the nucleus, scoop out a portion of it and look at what we now have in our hands. It won't surprise you that, similar to what happened with the electronium of the shell, we manage to only remove well defined portions. However, one thing is different: There are two kinds of smallest portions. Sometimes we hold something that has a positive electric charge in our hands, and sometimes we obtain something that is electrically neutral. If we reach for even more, we might end up with twice the charged portion or twice the amount of neutral elementary portion. Maybe we will get exactly one charged and one neutral portion together. You can imagine what can happen when we take out even more.

You already know what these portions are called. A positive elementary portion is called a proton and a neutral one is called a neutron. A nucleus has an integer number of positively charged portions, and a generally different integer number of neutral portions. In other words, a nucleus contains a well defined number of protons and of neutrons.

Keep in mind, though, that the protons and neutrons are not spatially separated from each other. If you imagine the proton substance to be a red colored pudding and the neutron substance to be a white colored pudding, the nucleus pudding would not be made up of red and white areas, it would be pink.

Table 32.1 shows the electrical charge and mass of protons, neutrons, and electrons. The masses of protons and neutrons are almost, but not quite, the same. The neutron is somewhat heavier. Later on, we will see that this difference is important for certain nuclear reactions. Note that both particles are about 1800 times as heavy as the electron.

	Electric charge	Mass
Proton	$1.6 \cdot 10^{-19} \text{ C}$	$1672.5 \cdot 10^{-30} \text{ kg}$
Neutron	0 C	$1674.8 \cdot 10^{-30} \text{ kg}$
Electron	$-1.6 \cdot 10^{-19} \text{ C}$	$0.91 \cdot 10^{-30} \text{ kg}$

Table 32.1

An electron's charge is exactly equal and opposite to a proton's. There are exactly as many electrons in the shell as there are protons in the nucleus. This means that the atom contains no electrical charge; it is electrically neutral.

Nuclear matter can be broken down into

- positively charged portions and
- electrically neutral portions.

A positively charged portion is called a proton, a neutral portion a neutron.

Exercises

1. The total number of protons and neutrons in a nucleus A is eight times that of a nucleus B. By what factor is the volume of A greater than that of B?

By what factor is the radius of A greater than the radius of B?

2. There are celestial bodies called *neutron stars* that are made up of nuclear matter. A typical neutron star has a diameter of 10 km. What is its mass?

32.2 Elements, nuclides, and isotopes

The atoms of different chemical elements vary from each other by the number of protons in their nuclei. The atomic number indicates this proton number and, as long as the atom is not ionized, the atomic number also indicates the number of electrons.

Atomic number = number of protons in the nucleus

If we judge nuclei by their numbers of protons only, there are as many different nuclei as there are elements, namely about 100. However, a nucleus with a certain number of protons can contain a larger or smaller number of neutrons. For instance, there are potassium nuclei (with 19 protons) with a number of neutrons between 20 and 33. This means there are various types of potassium nuclei, so-called *isotopes*. Chemically, there is almost no difference between the various isotopes of an element. The common natural potassium is a mixture of different isotopes. All other elements also have various isotopes.

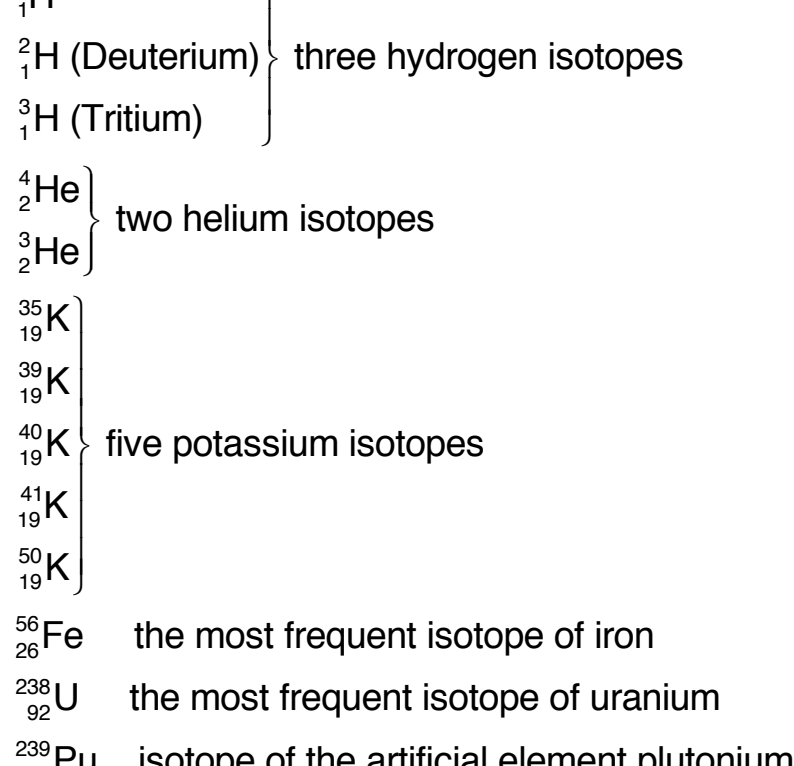
The isotopes of an element differ in the number of neutrons in their atomic nuclei.

If the different types of each chemical element were individually counted, the number of basic substances would not be about 100, but roughly 2000. As you know, the 100 basic chemical substances are called elements. The 2000 basic substances obtained when the different numbers of neutrons are taken into account, are called *nuclides*.

The following form of notation is used to represent a nuclide:

- the letter symbol from the periodic table of chemical elements;
- on the left above, the total number of protons and neutrons, and below, the atomic number, or number of protons.

Here are some examples of this form of notation

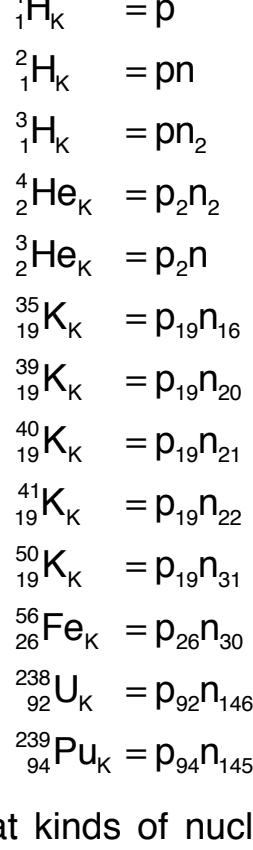


As you can see, the two heavy isotopes of hydrogen even have their own names. The isotope with one neutron is called deuterium, and the isotope with two neutrons is called tritium.

When nuclear reactions are investigated, usually only the nuclei are of interest. It is therefore practical for the nucleus of a nuclide to be given its own symbol. Therefore, the letter K is added to the nuclide symbol as an index. While the symbol ${}^{25}_{12}\text{Mg}$ represents the complete atom of a certain magnesium nuclide, the symbol ${}^{25}_{12}\text{Mg}_K$ represents only the nuclei of this nuclide.

Another symbolic representation of nuclides is more appropriate to some purposes. It derives from the representation used in chemistry to characterize molecules.

The formula Al_2O_3 gives us the aluminum and oxygen components of aluminum oxide. Correspondingly, the nuclide can be characterized by indicating the number of protons p and neutrons n . Here are some examples of this form of notation:



What kinds of nuclides do exist? We have already said that there are about 2000. This means that not just any component formula will correspond to an existing nuclide. For example, there is no pn_3 , meaning hydrogen with 3 neutrons. There is also no oxygen isotope p_8n_{17} or zinc isotope $p_{30}n_{50}$.

The question of which nuclides exist, meaning what combinations of nuclear matter p and nuclear matter n are possible, is similar to the question of which chemical compounds of hydrogen and oxygen exist. Which of the hydrogen-oxygen compounds in the following series can exist?

O, H, H₂, O₂, HO, H₂O, HO₂, O₃, H₂O₂, H₃O, H₃O₂, HO₃, ...

Some of these are old acquaintances: Molecular hydrogen H₂, molecular oxygen O₂, and water H₂O. Some members of the list obviously do not exist. Maybe you have encountered hydrogen peroxide H₂O₂. This substance exists, but it is unstable. The same is true of ozone O₃. Atomic hydrogen H is even more unstable.

The case of nuclides is similar. Most conceivable combinations of p, n don't exist. Of those that can exist, only a small fraction are stable.

Fig. 32.2 shows the map of nuclides, a diagram containing all the known nuclides. The number of protons is shown on the horizontal axis, and the number of neutrons is given on the vertical axis. Each circle corresponds to a nuclide discovered or manufactured up to now. Only the filled in circles represent stable nuclides. The empty circles correspond to unstable ones which gradually decay by themselves. Some have very short half-lives, others have long ones.

There are about 100 different elements and 2000 different nuclides.

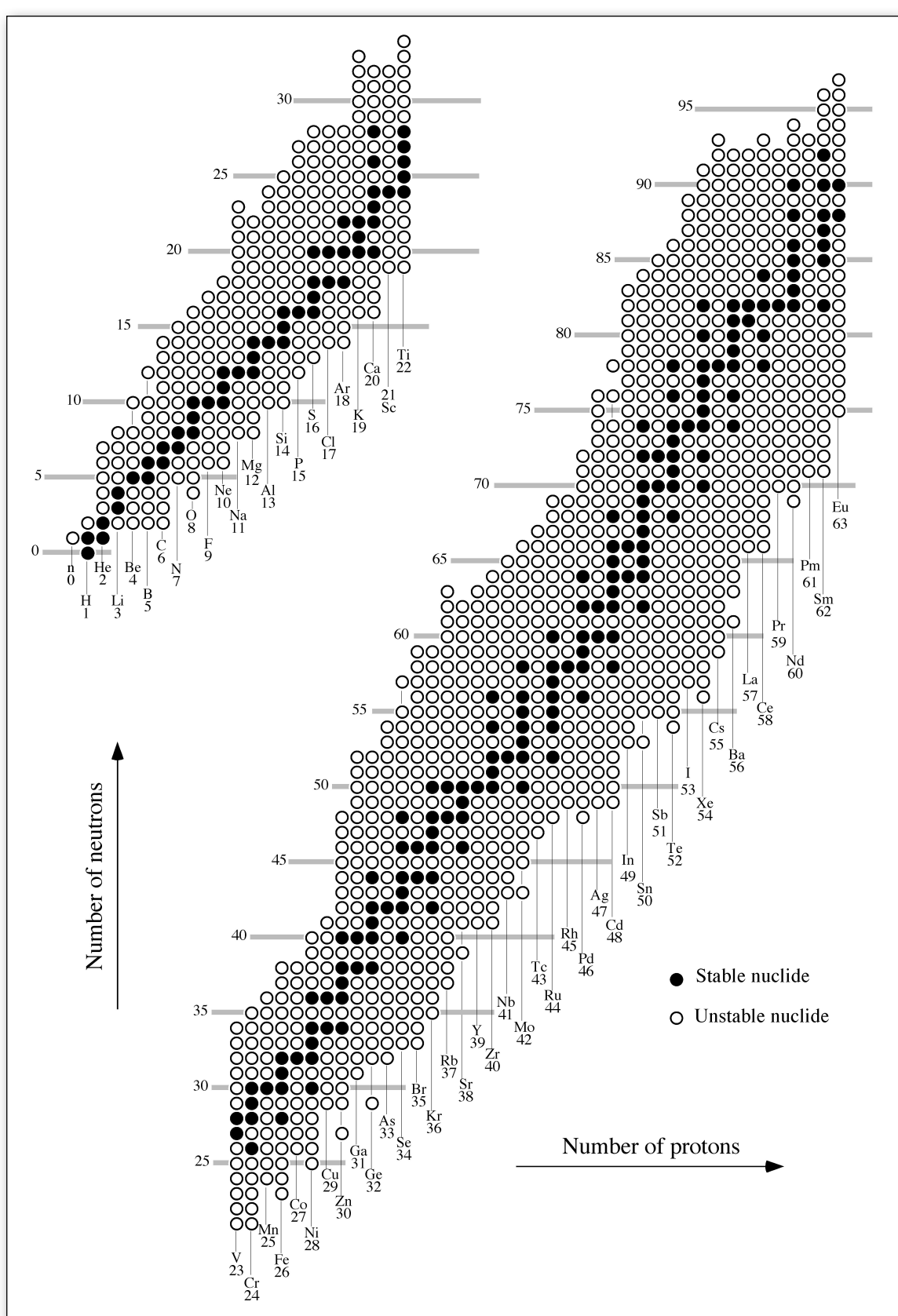


Fig. 32.2a
Nuclide map: Hydrogen to Europium

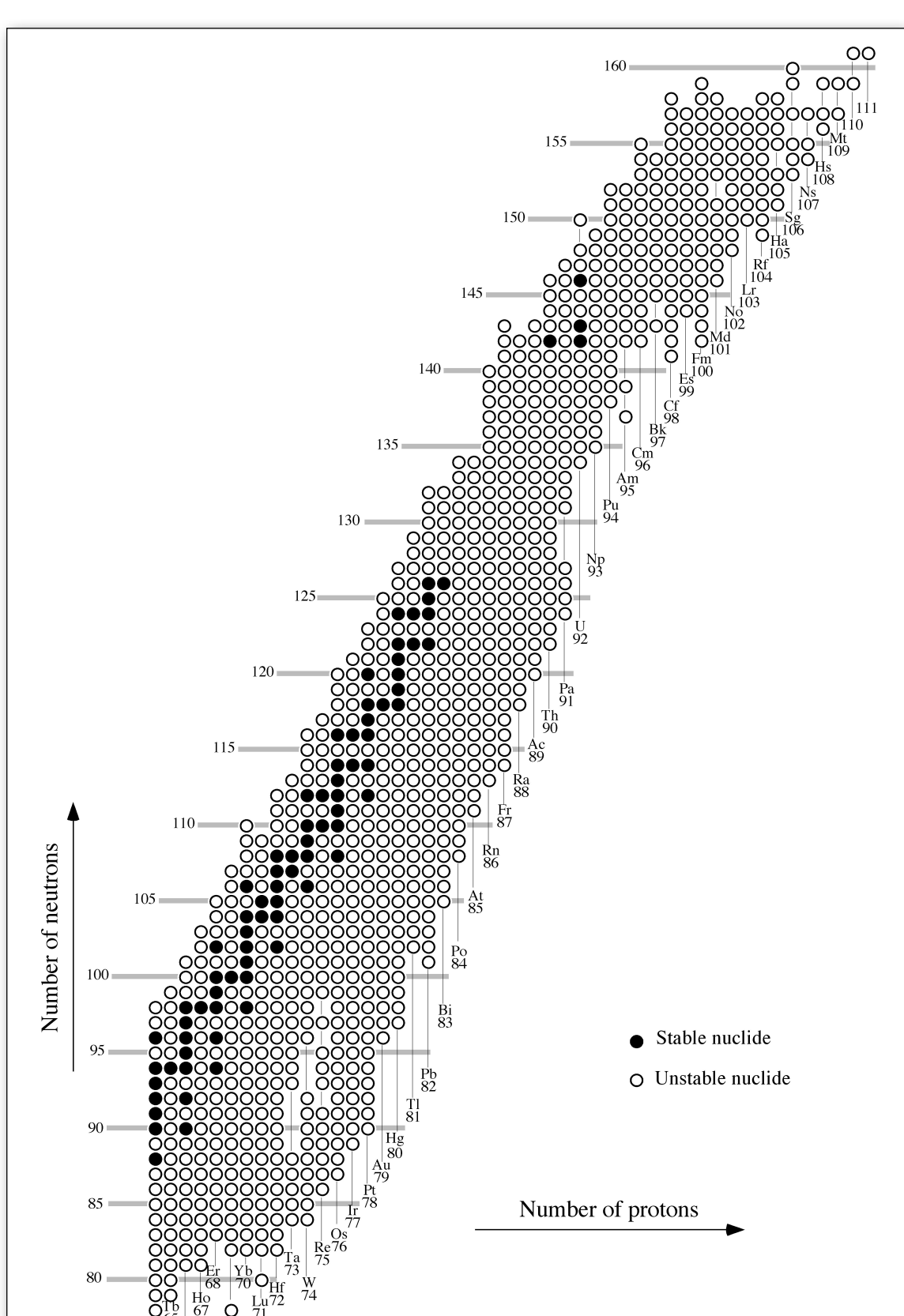


Fig. 32.2b
Nuclide map: Gadolinium to Element 111

Exercises

1. Choose six nuclides with different atomic numbers from the nuclide map, Fig. 32.2, and represent them symbolically using the two methods described in the text.
2. Formulate a general rule for the ratio of the number of protons and neutrons for existing nuclides of light elements (of up to 20 protons). Do the same for heavy elements as well. Use the nuclide map of Fig. 32.2.
3. How many stable nuclides exist?
4. Which is the heaviest stable nuclide?
5. Which are the stable isotopes of neon?
6. Which is the lightest element with no stable isotope?
7. Which element has the most isotopes? How many does it have? How many of these are stable?

32.3 Excitation of nuclei

Not only the atomic shell can deform. The nucleus can be deformed as well. Like the shell, the nucleus also snaps into certain forms. The most important difference is that about one million times the energy is necessary to deform an atomic nucleus than is needed to deform an atomic shell. Another great difference is that the lifetime of the excited state of a nucleus is, on average, only one millionth that of the excited state of the shell, Table 32.2.

	Typical excitation energy	Typical half-life
Atomic shell	10^{-19} J	10^{-8} s
Atomic nucleus	10^{-13} J = 0.1 pJ	10^{-14} s

Table 32.2

In the following, we will deal a lot with energies of the magnitudes of 10^{-12} to 10^{-15} Joule. It is therefore practical to use the abbreviation “pico” for 10^{-12} . Therefore, 10^{-12} J = 1 pJ. Fig. 32.3 shows the energy ladder of a thallium isotope.

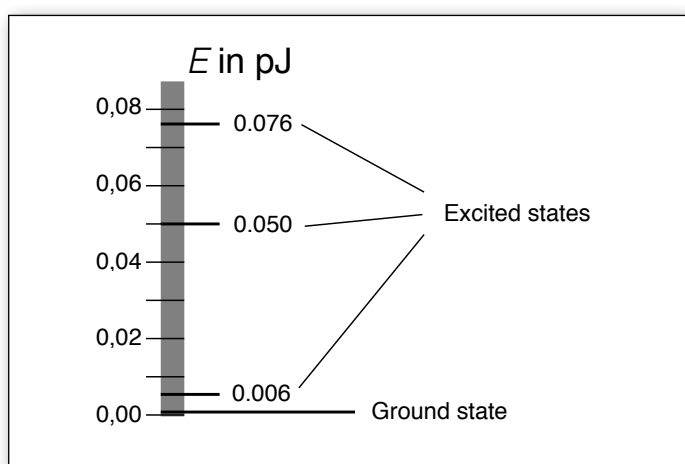
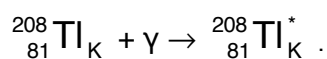


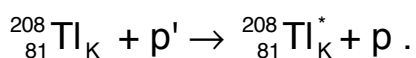
Fig. 32.3 Energy ladder of the thallium isotope $^{208}_{81}\text{Tl}$

The methods used for exciting nuclei are, in principle, the same as those used for the shell.

It is possible to excite a nucleus using photons. They must have exactly the amount of energy equal to what is needed for the change from the ground state to the excited state. There cannot be too little energy, but there cannot be too much either. As stated above, much more energy is needed than for exciting a shell. The photons must be those of γ radiation. An example of such a process is the excitation of a thallium nucleus:

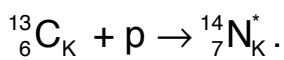


Nuclei can also be excited using particles with a rest mass, such as electrons, protons or neutrons. (There are corresponding processes for the excitation of the shell.) In this case, the particle used for excitation must bring enough energy. However, it can also have more than the amount of energy needed for the excitation. The particles that fly off can take the extra energy with them. As an example we again consider the thallium nucleus:



In this example, p' represents a fast proton, and p represents a slow one.

The third method for producing a nucleus in an excited state also has its analog in the atomic shell: The reaction products of some chemical reactions are in an excited state. One such example is a gas flame. The reaction products of nuclear reactions are often in an excited state too. We will discuss nuclear reactions in much more detail later on. However, here is a first example: A certain carbon isotope reacts with a proton to produce an excited nitrogen isotope.



An atomic nucleus can be excited just as an atomic shell can. The nucleus has a different form in its excited state than it has in its ground state. During the process of excitation, a well defined amount of energy is stored in the nucleus.

You remember that mass and energy both are the same physical quantity. If this quantity is measured in kg, we call it mass. It is called energy when it is measured in Joule. It is easy to convert one unit into the other. Mass and energy are interconvertible.

Conversion is done according to the formula:

$$E = k \cdot m$$

$k = 9 \cdot 10^{16}$ J/kg is the constant conversion factor.

When we deliver energy to a system, it becomes heavier. In many cases, the increase of energy, when compared to the total amount of energy of the system, is so small that we cannot detect that the system has become heavier. When the shell of an atom is excited, its mass changes so little that it is virtually unnoticeable.

The situation is quite different when an atomic nucleus is excited. We will consider the excitation of the thallium isotope $^{208}_{81}\text{Tl}$ (whose energy ladder is shown in Fig. 32.3) to the second excited state. An amount of energy of 0.05 pJ must be added. We convert to kg:

$$m = \frac{E}{k} = \frac{0.05 \cdot 10^{-12} \text{ J}}{9 \cdot 10^{16} \text{ J/kg}} = 0.56 \cdot 10^{-30} \text{ kg}$$

Compared to the total mass of the thallium atom, this is still very little. However, it is almost as much as the mass of an electron ($0.9 \cdot 10^{-30}$ kg).

A nucleus becomes heavier when it is excited.

Exercises

- The mass of a thallium atom is $350 \cdot 10^{-27}$ kg. By what fraction of the total mass is the atom heavier:
 - if the shell is excited?
 - if the nucleus is excited?
- Is it possible to tell the difference between the mass of 1 mole of a substance whose nuclei are excited and the same amount of the same substance in the ground state by using a scale?

32.4 Separation energy

Energy is necessary to separate magnets that stick to each other. This means that when separated, the magnets have more energy than when they are connected. Energy equals mass, so the separated magnets are heavier than the connected ones, Fig. 32.4. However, this effect is so minuscule, that it could never be detected in an experiment such as in Fig. 32.4.

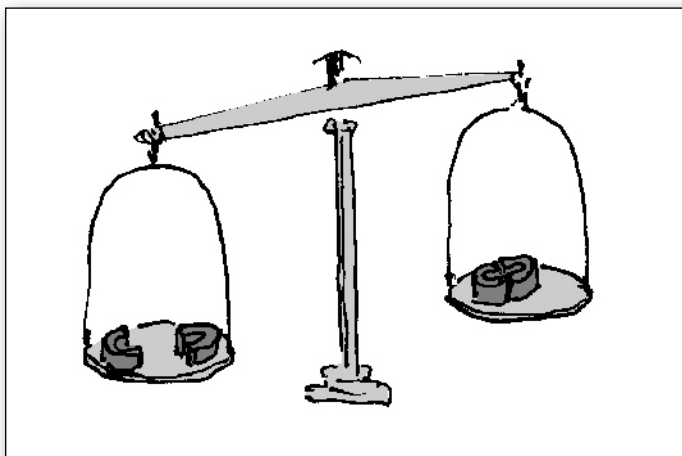


Fig. 32.4

The separated magnets have more energy than the attached ones. The effect is so slight, however, that it cannot be detected by the scale.

Energy is also necessary to remove a proton from a nucleus. Therefore, nucleus and proton together have less energy than nucleus and proton apart. If a proton is removed from a ${}^{14}_7\text{N}$ nucleus, a ${}^{13}_6\text{C}$ nucleus is created. The ${}^{14}_7\text{N}$ nucleus is lighter than the ${}^{13}_6\text{C}$ nucleus and the proton together, Fig. 32.5. In this case, the effect is considerably larger than in the example of the magnets and can be detected.

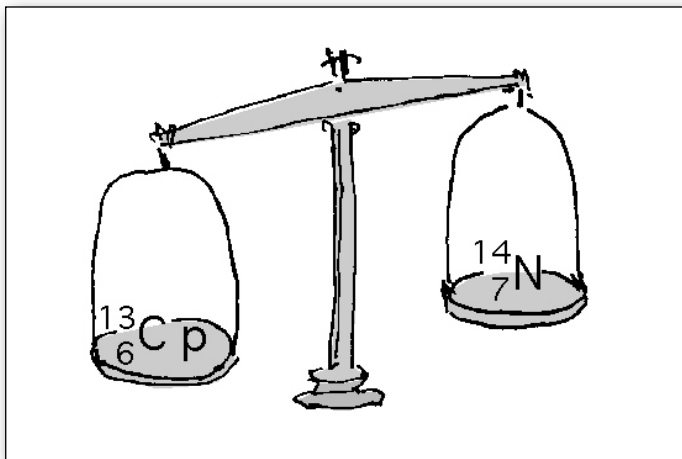


Fig. 32.5

A ${}^{14}_7\text{N}$ nucleus is lighter than a ${}^{13}_6\text{C}$ nucleus and a proton together.

The same holds for a nucleus from which a neutron is removed. A system becomes heavier because energy is needed for separating a neutron from it.

Now, in a thought experiment, we will gradually split an atomic nucleus into its protons and neutrons. A certain amount of energy is necessary for totally disassembling a nuclide nucleus. This amount of energy is called the *separation energy*. This energy has a different value for each nuclide. Later on we will be using these energy values for determining in which direction a nuclear reaction runs. The table in the Appendix shows the separation energies for about 1000 nuclides.

Energy is necessary for splitting a nucleus into its protons and neutrons. This energy is called separation energy. The components of the nucleus together are therefore heavier than the nucleus.

Exercises

1. The separation energy is approximately proportional to the total number of protons and neutrons. Choose 5 nuclides from the Table in the Appendix and graphically represent the separation energy as a function of the total number of protons and neutrons.
2. If a neutron is separated from a ${}^{15}_6\text{C}$ nucleus, a ${}^{14}_6\text{C}$ nucleus is obtained. If a neutron is again removed from it, a ${}^{13}_6\text{C}$ nucleus is obtained. When a third neutron is removed, a ${}^{12}_6\text{C}$ nucleus is the result, etc.
How much energy is needed for removing a neutron? Represent this energy graphically as a function of the total number of protons and neutrons of the particular carbon isotope.
Do this also for the helium isotopes. What do you notice here?

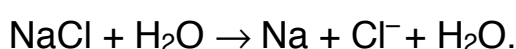
32.5 Conserved quantities

Our goal is to predict what kinds of nuclear reactions are possible. You already know the method we are going to use—at least in principle. We will make use of the fact that, in a reaction, the values of certain substance-like quantities cannot be changed.

You have already been introduced to such quantities. They are called *conserved quantities*.

Energy is a conserved quantity. In every process, the total amount of energy must be conserved. The same holds for electric charge.

Consider the process described by the following reaction equation:

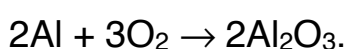


Such a reaction cannot actually take place because the conservation of electric charge is violated. The starting materials (left side) are, in total, neutral. In total, the products (right side) carry a negative electric charge. In contrast, a permitted reaction would be:

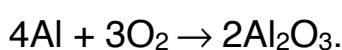


In this case, the balance of charge is as it should be.

Another forbidden process is:



Another law of conservation is being violated here: In chemical reactions, the number of atoms is a conserved quantity, and the numbers of atoms on the left and right sides do not match. However, a possible reaction might be:



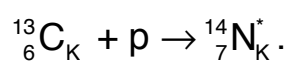
In chemical reactions, the number of atoms is a conserved quantity.

So, in order to set up a chemical reaction equation, we make use of the conservation of electric charge and of the number of atoms.

There is yet another aspect of the conservation of numbers of atoms: This law of conservation is not always valid. It has been emphasized that it is valid in “chemical reactions.” We will soon see that it is not valid for nuclear reactions. Therefore:

Some laws of conservation are valid only under certain circumstances.

We have already looked at an example of a nuclear reaction:



Notice that there is an atomic nucleus of carbon on the left, but none on the right. There is also a proton on the left (meaning an atomic nucleus of hydrogen) and none on the right. However, on the right there is an atomic nucleus of nitrogen and none on the left. The number of atoms in this nuclear reaction is not conserved.

We now have a problem: We have no rule anymore for setting up a reaction equation. Would just any reaction equation be permitted? Experience shows that this is absolutely not the case. Investigations of nuclear reactions have shown that there are other, formerly unknown, quantities for which a law of conservation holds. These are the so-called *baryonic charge* and *leptonic charge*. The baryonic charge and the leptonic charge both have a definite value for each nucleus and for each and every particle. The baryonic charge of the particles on the left side of the reaction equation (of the starting materials) must always equal that on the right side (the products). The leptonic charge of starting materials and products must be equal as well.

Baryonic charge cannot be produced or destroyed.
Leptonic charge cannot be produced or destroyed.

Before we undertake to set up a reaction equation taking this new aspect into account, we must broaden our knowledge of elementary portions somewhat.

Exercise

Which substance-like quantities do you know? Which of them are conserved quantities? Which ones are not?

32.6 Particles and antiparticles

In our analysis of shells and nuclei we have encountered three different kinds of elementary matter, i.e., of elementary particles. These are electrons, protons and neutrons. Most of the matter around us is made up of only these particles. Other kinds of particles have been discovered, but they are mostly artificially produced.

The existence of these other particles seems to make nuclear reactions more complicated at first. However, all of these particles can be combined very systematically and concisely. Table 32.3 shows them along with some of their characteristics. We will discuss this table in more detail.

Name, Symbol	Rest energy	Charge		
		Electric*	Baryonic	Leptonic
Photon γ	0 pJ	0	0	0
Electron e	0,0819 pJ	-1	0	1
Antielectron \bar{e}	0,0819 pJ	1	0	-1
Neutrino ν	fast 0 pJ	0	0	1
Antineutrino $\bar{\nu}$	fast 0 pJ	0	0	-1
Proton p	150,3277 pJ	1	1	0
Antiproton \bar{p}	150,3277 pJ	-1	-1	0
Neutron n	150,5349 pJ	0	1	0
Antineutron \bar{n}	150,5349 pJ	0	-1	0

* Multiples of the elementary charge

Table 32.3

Old acquaintances

The names of the particles are on the left side. Four of these particles are old acquaintances: Photon, electron, proton, and neutron.

Neutrinos

Actually, these should also be old acquaintances, as well, because the world is full of them. These are particles that fly around in great numbers. They mostly come from the Sun. They are produced in the same reaction that is responsible for sending sunlight to us. Neutrinos are unnoticeable to us because they go through matter almost unhindered. There are hardly any reactions that would allow us to detect them. Most of the Sun's neutrinos penetrate and pass through the Earth without reacting with any other particles, or without even being deflected.

Neutrinos help us to learn more about the reactions taking place deep inside the Sun. Experiments for measuring neutrinos are time consuming and complex because neutrinos react so little. The device for detecting them must be very large for the probability of a neutrino to get caught in it to be great enough. In addition, the experiment must be shielded from all other particles which would be produced in any kind of nuclear reaction or that come from space. This is why such experiments are set up deep underground in tunnels or mines.

The existence of neutrinos was already suspected way back when such complex experiments were unthinkable. How was this possible? It happened by use of an often applied method in microphysics. A certain reaction is investigated, and it is discovered that some law of conservation that was previously believed to be valid, appears to be violated. In the case of neutrinos, it was determined that the energy of a certain reaction was not conserved. This led to the conclusion that another, unknown and unnoticeable particle must have participated.

Neutrinos react only very weakly with other particles.

Antiparticles

The Table also shows four other particles. The names of these particles all begin with the prefix "anti": antielectron, antineutrino, antiproton, and antineutron. It is easy to see that they are quite similar to their corresponding un-prefixed particles. They are exactly the same except for the signs of the three charges. For example, a proton has a positive electric and a positive baryonic charge while an antiproton has a negative electric and negative baryonic charge.

One says that the antiproton is the *antiparticle* to the proton and that the proton is an antiparticle to the antiproton. A particle and an antiparticle form a couple made up of two very similar partners.

Particles and antiparticles differ from each other by the signs for their electric, baryonic, and leptonic charge.

Electrons and neutrinos, as well as their antiparticles, carry leptonic charges.

Protons and neutrons, as well as their antiparticles, carry baryonic charge.

Photons have no antiparticles.

32.7 Balance of charges

We are now able to set up a nuclear reaction. First we will consider some simple examples.

Is there a reaction

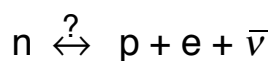


where a neutron transforms into a proton and into an electron? The balance of electric, baryonic and leptonic charge is:

	n	p + e
Electric charge	0	1 + (-1)
Baryonic charge	1	1 + 0
Leptonic charge	0	0 + 1

The electric charge of starting materials and products is the same: zero. Conservation of electric charge is adhered to. The baryonic charge is also the same on both the left and the right; it is equal to 1. However, the leptonic charge is not conserved in this reaction: it is zero on the left and 1 on the right. Therefore, the reaction cannot take place either from left to right or right to left.

It is possible to make a slight repair to the equation by inserting an antineutrino into the right side of it:



This time it balances out:

	n	p + e + $\bar{\nu}$
Electric charge	0	1 + (-1) + 0
Baryonic charge	1	1 + 0 + 0
Leptonic charge	0	0 + 1 + (-1)

Now the leptonic charge is the same on the left as on the right. It is zero. This reaction actually does take place: A free neutron decays by itself into a proton, an electron, and an antineutrino.

Equation (1) can also be made to satisfy all laws of balance by inserting a neutrino into the left side of it:



This reaction is also allowed, as the following balance table shows:

	n + ν	p + e
Electric charge	0 + 1	1 + (-1)
Baryonic charge	1 + 0	1 + 0
Leptonic charge	0 + 1	0 + 1

Exercise

Set up an equation describing the reaction of a proton with an antiproton. There are several possibilities.

32.8 Direction of reactions

One important question is still unanswered: In what direction does the reaction we have set up run?

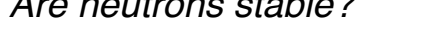
We can find the answer to this by applying a law of conservation again. Up to this point, we have not taken energy conservation into account. The energy balance of a reaction must be correct as well. The energy of the starting materials and products must be equal. If the rest energy of the particles on one side of the reaction equation is compared with that of the other side, we find it will never be exactly equal. However, the rest energies never actually need to be equal.

If the original nuclei or particles are at rest, their energy is the sum of their rest energies. The total rest energy of the produced particles may not be greater than that of the original particles. It can be smaller, though. When this happens, there is energy left over from the original particles. This left over energy can always be disposed of: It can be given to the particles being produced by making them move fast. The faster the produced particles move, the more energy they have in addition to their rest energy. We conclude that a nuclear reaction runs so that the rest energy of the participating nuclei and particles decreases.

In order to decide in which direction a reaction runs, the total rest energy of the particles on the left side must be compared with that on the right. The reaction runs from the higher to the lower rest energy.

A nuclear reaction where the original particles are at rest, always runs in the direction of decreasing rest energy.

Now let us put our new tools to work. We will investigate in which direction a reaction runs:



Are neutrons stable?

The reaction



is all right as far as the balance of electric, baryonic and leptonic charges are concerned. We have determined that. The balance of energy is still missing, though. We insert it into the Table with the balances of charges: The sum of the rest energies on the left side and the sum of the rest energies on the right side. We find the rest energies of the individual particles in Table 32.3.

	n	p + e + $\bar{\nu}$
Electric charge	0	1 + (-1) + 0
Baryonic charge	1	1 + 0 + 0
Leptonic charge	0	0 + 1 + (-1)
Rest energy (pJ)	n 150.5349	p 150.3277 e 0.0819
Sum (pJ)	150.535	150.410

The neutron's rest energy is greater than that of the proton, electron and antineutrino together. Therefore, the reaction runs from left to right. We subtract the smaller sum from the greater sum and obtain:

$$\Delta E = 150.525 \text{ pJ} - 150.402 \text{ pJ} = 0.123 \text{ pJ}.$$

Indeed, it can be observed that free neutrons (neutrons that are not bound to a nucleus) decay by themselves. Neutrons can be produced artificially but they decay within a few minutes even when they are carefully conserved. Their lifespan is commonly even shorter than this because they react very easily and attach themselves very quickly to the various atomic nuclei that they encounter.

Are protons stable?

You already know that protons do not decay. Let us convince ourselves that our nuclear physics tool also produces this result. As far as the balances of the three charges are concerned, the following reaction would be allowed:



We create a table with the balances:

	p	n + \bar{e} + ν
Electric charge	1	0 + 1 + 0
Baryonic charge	1	1 + 0 + 0
Leptonic charge	0	0 + (-1) + 1
Rest energy (pJ)	p 150.3277	n 150.5349 \bar{e} 0.0819
Sum (pJ)	150.328	150.617

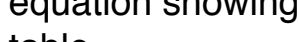
The rest energy of a proton is smaller than that of a neutron and an antielectron together. The reaction can only run from right to left: The proton cannot decay.

Is tritium stable?

We will test the decay into a helium nucleus, an electron, and an antineutrino:



For clarity, we will in future always enter the reaction formula as an equation showing the components of the nuclei and particles into the table.



The balances of charges are all right.

	pn ₂	p ₂ n + e + $\bar{\nu}$
Electric charge	1	2 + (-1) + 0
Baryonic charge	1	3 + 0 + 0
Leptonic charge	0	0 + 1 + (-1)
Rest energy (pJ)	p 150.3277 n 2 · 150.5349	p 2 · 150.3277 n 150.5349 e 0.0819
- E_s (pJ)	- 1.359	- 1.2346
Sum (pJ)	450.0385	450.0358

We calculate the rest energy of a nucleus by subtracting the separation energy E_s from the rest energy of the particles the nucleus is made up of.

$E_s(pn_2)$ and $E_s(p_2n)$ were taken from the table. The sum on the left is greater than the sum on the right. The reaction can run from left to right.

Indeed, tritium is unstable. Normal water generally contains a very small trace of tritium. This tritium decays according to the reaction we have just investigated. About 45 tritium nuclei decay in one kg of water per minute. How does water come to contain tritium at all? Wouldn't the tritium that somehow gets into the water have decayed long ago?

Tritium not only decays, it is also continuously reproduced in a reaction with so-called *cosmic rays*. The Earth is continually bombarded by a continuous flow of particles of very high energy – mostly protons and helium nuclei. These particles cause numerous nuclear reactions in the atmosphere. This is how many unstable nuclides are created.

The decay of ${}^{14}_6\text{C}$

The unstable carbon isotope ${}^{14}_6\text{C}$ is produced by cosmic rays. It decays according to



or, equivalently, according to



From now on we will not write the contributions of the balance of energy which cancel anyway: The rest energies of the particles that appear both on the left and the right sides of the component equation. In the case of equation (2), we no longer include:

- 6 protons

- 7 neutrons

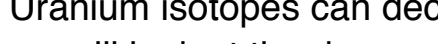
The table of balances now looks like this:

	p ₆ n ₈	p ₇ n ₇ + e + $\bar{\nu}$
Electric charge	6	7 + (-1) + 0
Baryonic charge	14	14 + 0 + 0
Leptonic charge	0	0 + 1 + (-1)
Rest energy (pJ)	n 150.5349	p 150.3277 e 0.0819
- E_s (pJ)	- 16.87	- 16.77
Sum (pJ)	133.66	133.64

The sum on the left is greater than that on the right so the reaction can take place.

The decay of uranium

Uranium isotopes can decay in many different ways. As an example, we will look at the decay of ${}^{235}_{92}\text{U}_K$ into barium and krypton:



	p ₆ n ₈	p ₇ n ₇ + e + $\bar{\nu}$
Electric charge	92	56 + 36 + 0
Baryonic charge	235	141 + 92 + 2
Leptonic charge	0	0 + 0 + 0
- E_s (pJ)	- 285.80	- 188.09 - 129.78
Sum (pJ)	- 285.80	- 317.87

This is one of many reactions in a nuclear reactor that are used to release energy.

Carbon synthesis

We will investigate a reaction that takes place in stars and that is responsible for the creation of carbon in the universe:

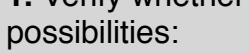
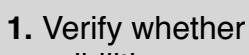
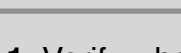


This reaction almost never takes place on Earth due to a high reaction resistance. This resistance can be lowered using methods common in chemistry: Raising of temperature or use of a catalyst. This is a nuclear reaction, so the temperature at which the reaction begins to take place is very high. It needs to be above 100 million Kelvin. This temperature is reached in stars.

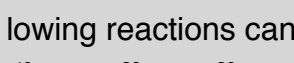
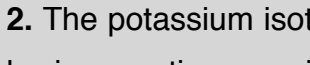
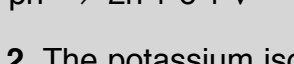
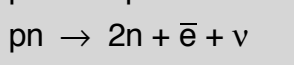
	3p ₂ n ₂	p ₆ n ₆
Electric charge	3 · 2	6
Baryonic charge	3 · 4	12
Leptonic charge	0	0
- E_s (pJ)	- 3 · 4.53	- 14.77
Sum (pJ)	- 13.59	- 14.77

Exercises

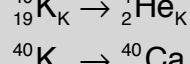
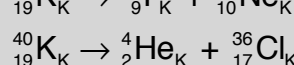
1. Verify whether deuterium can decay according to one of the following possibilities:



2. The potassium isotope ${}^{40}_{19}\text{K}$ is unstable. According to which of the following reactions can it decay?



3. Check which of the following two reactions can take place:



4. In the Sun, four protons react into one ${}^4_2\text{He}$ nucleus. Which particles are produced in addition? Show the reaction's balance of energy.

32.9 Nuclear radiation

In order to decide whether a particular nuclide is stable or not, all its possibilities for decay must be investigated. In the process of doing this, one would find that there are numerous possibilities for many of the nuclides.

Observations often show, however, that a nuclide is stable. It doesn't decay although the balance of the three charges and energy would allow this to happen. The reason is that the resistance to the reaction is too high. This is a phenomenon we know from chemistry.

Something else is observed as well: Most decay reactions that actually do take place, can be put into a few classes. These classes will be investigated in the following. The aspect these typical reactions have in common is that one of the reaction products is a very small particle: an electron, an antielectron, a neutrino or a ${}^4_2\text{He}$ nucleus.

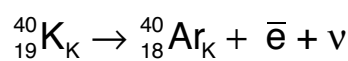
The most common decay reactions produce a small particle as one of the reaction products.

Creation of an electron

An example is the decay of the carbon isotope ${}^{14}_6\text{C}$, which we investigated in the previous section, see equation (2).

Creation of an antielectron

Another common type of reaction has an antielectron as one of its reaction products. The isotope ${}^{40}_{19}\text{K}$ can decay like this:



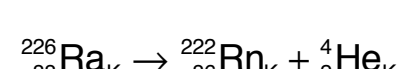
We check to see if this reaction is actually allowed:

	$p_{19}n_{21}$	$p_{18}n_{22} + \bar{e} + \nu$
Electric charge	19	18 + 1 + 0
Baryonic charge	40	40 + 0 + 0
Leptonic charge	0	0 + (-1) + 1
Rest energy (pJ)	p 150.3277	n 150.5349
- E_s (pJ)	- 54.72	\bar{e} 0.0819
Sum (pJ)	95.61	- 55.08
		95.54

The left side is larger than the right side, so the reaction is allowed.

Creation of a ${}^4_2\text{He}$ nucleus

An example of this type of reaction is the decay of the radium isotope ${}^{226}_{88}\text{Ra}$ into a radon isotope and the nucleus of a helium isotope ${}^4_2\text{He}$:



	$p_{88}n_{138}$	$p_{86}n_{136} + p_2n_2$
Electric charge	8	86 + 2
Baryonic charge	226	222 + 4
Leptonic charge	0	0 + 0
- E_s (pJ)	- 277.43	- 273.68 - 4.53
Sum (pJ)	- 277.43	- 278.21

In most nuclear reactions we encounter, only tiny amounts react. The conversion rate of the reaction is very small compared to the conversion rate of a typical chemical reaction. The amount of reaction products is so small that they cannot be detected with even the most sensitive scales. One might believe that detecting a nuclear reaction even took place at all would be very difficult. However, a nuclear reaction is often made evident when, for example, one of the particles produced is a light particle. A light particle takes with it a large part to the energy ΔE left over from a reaction. It flies off at great speed and can therefore be detected in various ways.

Typically, at least a billion molecules are necessary when chemical methods are used to detect a reaction, but nuclear decay reactions can be detected even if a single nucleus decays.

The fact that nuclear reactions occur at all was discovered in this way. It was realized that certain substances emitted an unknown "radiation," some kind of fast moving particles. These substances were said to be *radioactive*. The fast moving particles are produced by nuclear reactions, so we will call them *nuclear radiation*. The term "radioactive radiation" is often heard, too. The word radioactive means radiation-active (radius = ray). However, it is the decaying substance that is radioactive and not the radiation.

In the beginning, only three kinds of nuclear radiation were discovered. They differed from each other by their electric charge. (It was easy to determine the charge of the particles.) Even before it was known exactly what they were, these first three kinds of rays were given names. The particles which were later identified as helium nuclei were called α rays, and the fast moving electrons were called β rays. In addition, photons of high energy are emitted in many reactions. This always happens when the reaction product is initially in an excited state. These photons were called γ rays.

The names α , β and γ radiation have been kept in use until today even though we know that they are nothing more than some common, everyday reaction products. There are many other reaction products that have never received names.

While it is necessary to have large numbers of particles to detect a reaction using chemical methods, the decay of one nucleus in a nuclear reaction can be detected.

Earlier, it was stated that when most unstable nuclides decay, one of the reaction products will be an electron, an antielectron, or a helium nucleus. Figure 32.6 shows this very clearly. The figure is a strongly simplified version of the nuclide map of Fig. 32.2.

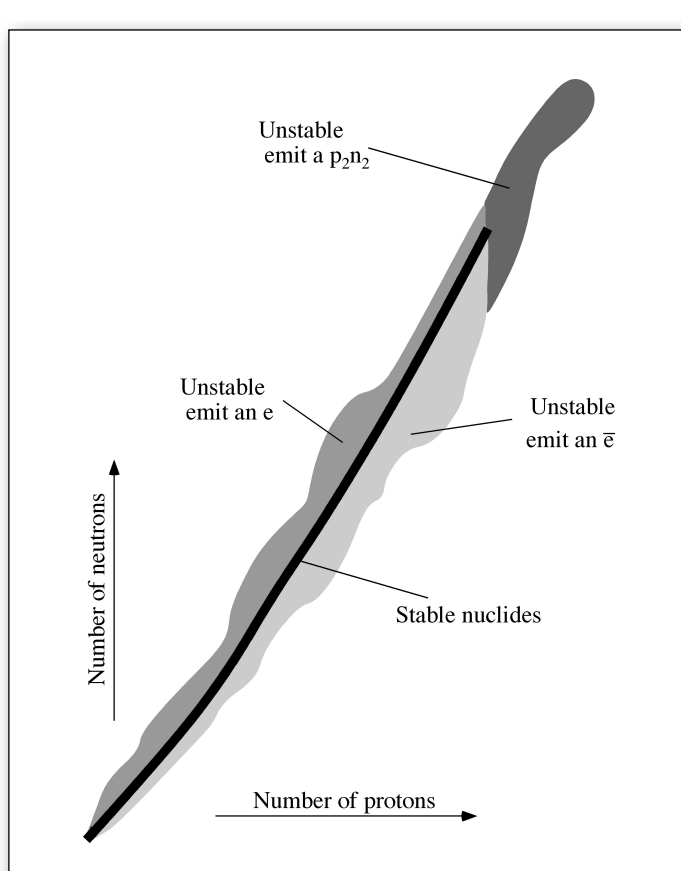


Fig. 32.6
Strongly simplified nuclide map

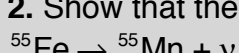
High intensities of nuclear radiation are dangerous to humans and other organisms. For this reason, there are strict safety regulations for dealing with radioactive substances. We are constantly exposed to a small dose of nuclear radiation because there are also radioactive substances in the environment all around us so.

Exercises

1. Which of the three particles e , \bar{e} and ${}^4_2\text{He}$ is produced in the decay of

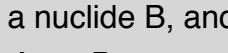
- ${}^{61}_{29}\text{Cu}$
- ${}^{66}_{29}\text{Cu}$
- ${}^{228}_{90}\text{Th}$

2. Show that the balance is all right for the three charges in the reaction



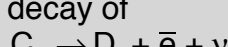
Remember that in this case, the symbols do not stand for nuclei, but for the entire atom including the shell. This reaction actually exists. Describe in words what happens. Establish the energy balance.

3. (a) We consider the decay of an unstable nuclide A, which produces a nuclide B, and an electron:

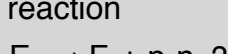


Where is nuclide A on the nuclide map? Where is A relative to B?

(b) Where on the map are the nuclides C and D which appear in the decay of



(c) Where on the map are nuclides E and F that appear in the decay reaction



32.10 The conversion rates of nuclear reactions

Nuclear reactions commonly proceed very slowly. That is why we do not notice them in daily life. The *conversion rate* (or simply *rate*) of a reaction tells us how fast it takes place.

$$\text{conversion rate} = \frac{\text{conversion}}{\text{time span}}$$

Symbolically:

$$I_n = \frac{n}{t}$$

The conversion n is a measure of the amount which is converted. In chemical reactions, it is given in the unit mole, so that mole/s is the unit of the conversion rate.

The rates of nuclear reactions are so small that even the well-known prefixes such as nano, pico, or femto are not small enough to describe them. For this reason, the conversion is no longer given in mole, but by the number of elementary reactions: the actual number of nuclei that have decayed or are newly created.

As is generally known, one mole is equal to $6 \cdot 10^{23}$ particles or “elementary amounts”:

$$1 \text{ mol} = 6 \cdot 10^{23} \text{ elementary amounts}$$

The conversion rate is therefore measured in elementary amounts per second, and we have

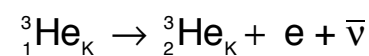
$$1 \frac{\text{mol}}{\text{s}} = 6 \cdot 10^{23} \frac{\text{elementary amounts}}{\text{s}}$$

The unit “Elementary amount per second” has been given its own name: Becquerel, abbreviated to Bq. Therefore:

$$1 \frac{\text{mol}}{\text{s}} = 6 \cdot 10^{23} \text{ Bq}$$

Example:

Earlier we have seen that the hydrogen isotope tritium makes up a small part of the hydrogen of common water. This tritium decays according to the reaction equation



The reaction rate in a cubic meter of everyday water is about

$$I_n = 750 \text{ Bq.}$$

For comparison, we will consider a chemical reaction that is considered slow: The rusting process of a car.

Assuming that 1 mole of rust is produced per year,

$$I_n = \frac{1 \text{ mol}}{1 \text{ year}} = \frac{1 \text{ mol}}{32 \cdot 10^6 \text{ s}} = \frac{1}{32 \cdot 10^6} \cdot 6 \cdot 10^{23} \text{ Bq} = 1.9 \cdot 10^{16} \text{ Bq}$$

This comparison shows a typical difference between chemical and nuclear reactions. Most nuclear reactions we have to do with have smaller conversion rates by far than typical chemical reactions. The quantities of the chemical elements on Earth change very little as a result of nuclear reactions.

The conversion rates of typical nuclear reactions are much smaller than those of chemical reactions.

When a chemical reaction needs to be accelerated in order to increase its rate, this can be achieved in two ways:

- by raising the temperature;
- by adding a catalyst (a substance whose amount does not change during the reaction).

This can also be done for nuclear reactions. The conversion rates can be increased by raising the temperature or using a catalyst.

However, several million Kelvin are necessary if we want to increase the conversion rate noticeably by raising the temperature. These conditions are found in the Sun and other stars. Actually, energy production in the Sun and stars happens through nuclear reactions. Another example of a way to increase the conversion rate using high temperatures is a *fusion reactor*. This is something still under development. It is hoped that such reactors will produce electric energy some day.

The catalytic acceleration of a nuclear reaction takes place in a nuclear reactor where neutrons act as catalyst.

We will be dealing more with nuclear reactions in a nuclear reactor and in the Sun later.

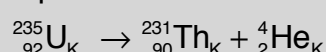
Nuclear reactions can be accelerated like chemical reactions by

- raising the temperature
- using a catalyst.

Exercise

Natural uranium contains 99.28 % of the isotope ${}^{238}_{92}\text{U}$ and 0.72 % of the isotope ${}^{235}_{92}\text{U}$. How many moles of the isotope ${}^{235}_{92}\text{U}$ are contained in one kg of uranium?

The isotope ${}^{235}_{92}\text{U}$ is used in nuclear reactors to produce energy. Even when it is not in the reactor yet, it decays according to the reaction equation



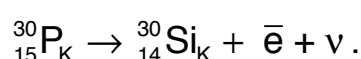
For this reaction, the conversion rate for 1 kg of the natural uranium isotope mixture is

$$I_n = 5,76 \cdot 10^5 \text{ Bq.}$$

Convert the conversion rate in mole/s. How long does it take until 1% of the ${}^{235}_{92}\text{U}$ has decayed?

32.11 Half-life

The phosphorus isotope $^{30}_{15}\text{P}_K$ is unstable. It decays according to



We will consider one nucleus of this phosphorus isotope. It can and will decay – but when? The answer to this question is the same as that to another question we asked (and answered) earlier. The time at which the reaction will take place is uncertain. However, this does not mean that it is absolutely arbitrary, because the probability with which a nucleus decays during a given time interval is well-defined. In the case of our reaction, there is a 50 % probability that the nucleus will decay within 2.5 minutes. It is as if the nucleus would toss a coin every 2.5 minutes. Depending upon whether the result is heads or tails, it will or will not decay within the next 2.5 minutes.

If a nucleus has several possibilities to decay – and most nuclei do – it will also “toss a coin” to see how the decay will happen.

We will now consider a large number of $^{30}_{15}\text{P}$ nuclei. Let us choose one million. We know that after 2.5 minutes, only half of these will remain. The other half will have decayed. After another 2.5 minutes, there are only 500,000 phosphorus nuclei remaining. After another 2.5 minutes, there are only 250,000 left, and again, after 2.5 minutes, only 125,000, etc., Fig. 32.7.

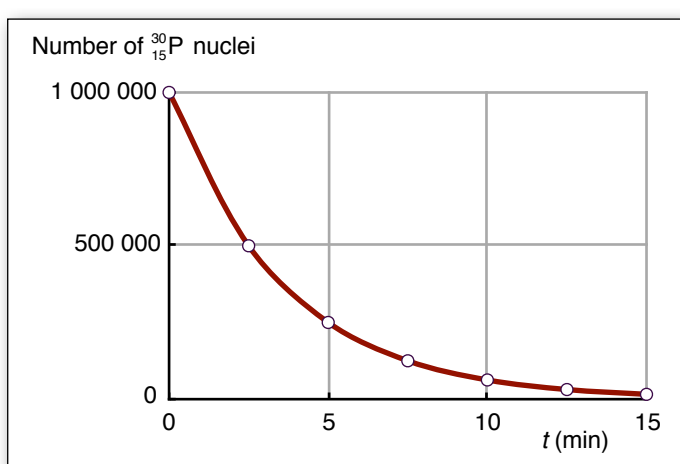


Fig. 32.7

In every 2.5 minute interval, the number of $^{30}_{15}\text{P}$ nuclei decreases by half.

The number of silicon nuclei or anti-electrons or neutrinos increases accordingly. After 2.5 minutes, there are 500,000, after 5 minutes 750,000, after 7.5 minutes, there are 875,000, etc., Fig. 32.8.

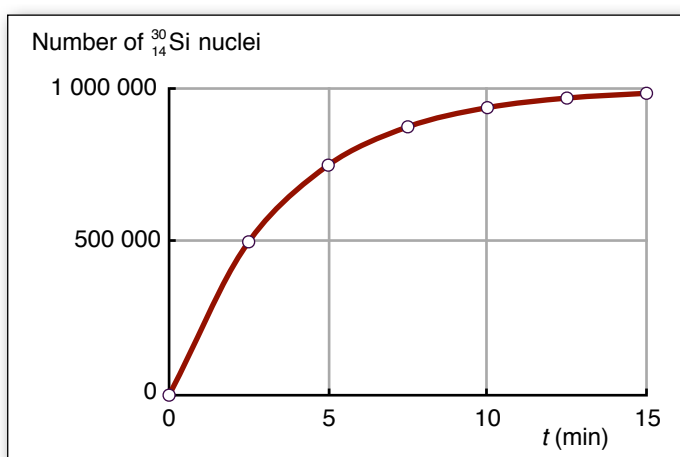


Fig. 32.8

The number of $^{30}_{14}\text{Si}$ nuclei increases.

As before, we call the time span needed for the amount of the reacting substance to decrease by half, the *half-life* $T_{1/2}$. The half-life of our phosphorus isotope is $T_{1/2} = 2,5$ min.

Half-life is the time span in which half of the amount of a substance decays.

Exercises

1. An unstable nuclide has a half-life of five minutes. How many of the original 400,000 nuclei are left over after 20 minutes?
2. The amount of a nuclide with a half-life of 2 years decreased from originally $8 \cdot 10^8$ to $1 \cdot 10^8$. How many years have passed?
3. In 4 months, the amount of a nuclide decreased to 1/16th of its original value. What is the half-life?
4. Nuclide A with a half-life of 2 days decays into nuclide B (plus two fast moving particles), and then further with a half-life of 120 years, into a nuclide C. There is pure A at time t_0 . What is the mixture in percent of the nuclei A, B, and C at the times
 - $t_0 = 0$ years,
 - $t_1 = 2$ years,
 - $t_2 = 1\,000\,000$ years?
5. You know that the amount of a substance whose nuclei are unstable decreases to half the original value during a period of one half-life. By what factor does the conversion rate (decay rate) decrease in the course of this period?

32.12 The sun

The Sun “functions” with the help of nuclear reactions. “Function” means that the energy that comes with the light from the sun is released by nuclear reactions.

The Sun is a star. There are innumerable other stars in the universe that are composed like the Sun, and in which the same processes take place. The Sun just looks larger to us than other stars because we are closer to it.

We will compare the Sun to the Earth in order to get a feeling for its size, temperature and composition. The most important data are compiled in Table 32.4.

	Earth	Sun
Mass	$6 \cdot 10^{24}$ kg	$2 \cdot 10^{30}$ kg
Radius	6000 km	700 000 km
Density Inside	17 g/cm ³	100 g/cm ³
Outside	3 g/cm ³	0.0001 g/cm ³
Temperature Inside	6000 K	15 000 000 K
Outside	300 K	6000 K
Composition (The percent values are based upon mass.)	35 % Fe 30 % O 15 % Si 13 % Mg 7 % other	75 % H 23 % He 2 % other

Table 32.4

The distribution of density in the Sun is especially interesting. Figure 32.9 shows that the density outside half of the Sun’s radius is very low. 90% of the Sun’s mass is in the inner half of the radius. It could be said that the Sun is only half as big as it looks.

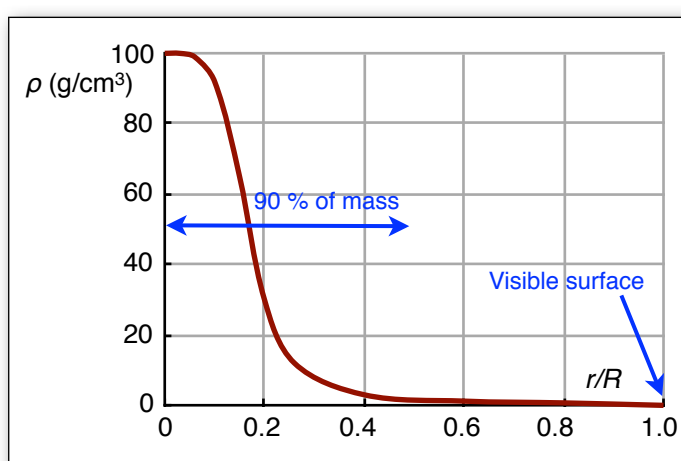


Fig. 32.9

The density of the Sun as a function of the distance from its center. The distance r is given in units of the Sun’s radius R . It can be seen that the largest part of the Sun’s mass is inside half of the radius. This means it is inside of $r/R = 0.5$.

Remember that the Sun is made up almost entirely of only hydrogen and helium.

The sun is made up almost entirely of hydrogen and helium.

The Sun emits light and with it, energy. The energy current that leaves the Sun in this way is very large. It is

$$P = 4 \cdot 10^{26} \text{ W.}$$

Only a two-billionths of it hits the Earth. However, this is still

$$P = 2 \cdot 10^{17} \text{ W.}$$

Where does the Sun get all this energy from? A nuclear reaction is taking place inside our star. Hydrogen is transforming into helium according to the reaction equation



We check the balance of the reaction:

	4p	$p_2n_2 + 2\bar{e} + 2\nu$
Electric charge	$4 \cdot 1$	$2 + 2 \cdot 1 + 0$
Baryonic charge	$4 \cdot 4$	$4 + 0 + 0$
Leptonic charge	0	$0 + 2 \cdot (-1) + 2 \cdot 1$
Rest energy (pJ)	2p 2 · 150.3277	2n 2 · 150.5349
– E_s (pJ)	0	2 \bar{e} 2 · 0.0819
Sum (pJ)	300.655	296.700

Per elementary conversion, there is $\Delta E = 3.955$ pJ of energy left over. There is entropy produced with this energy during the reaction. The material of the Sun gets hot.

Under normal circumstances – circumstances we on Earth would call normal – helium synthesis reactions do not take place because the reaction resistance is too high. It can only take place in the Sun because the temperature there is so high. Indeed, this reaction only happens inside the Sun where the temperature reaches about 15 million Kelvin. This is a staggering temperature for us on Earth. However, it is not so high for a nuclear reaction. The reaction we are considering runs fairly slowly even at 15,000,000 K. The reaction rate of 1 liter of the matter from inside the Sun, where it is hottest, is only about

$$I_n = 2,5 \cdot 10^9 \text{ Bq} \\ = 2,5 \cdot 10^9 \text{ elementary conversion per second.}$$

Compare this to the rusting car for which we calculated about $2 \cdot 10^{16}$ Bq.

After several decades, a car will have completely rusted. On the other hand, it is reassuring to know that the Sun has already “functioned” for about 5 billion years, and it has enough “fuel” (hydrogen) to still keep on shining that long again.

The amount of energy that one liter of Sun produces per second is not particularly large because of the small conversion rate. We obtain the energy current by multiplying the reaction rate I_n (in the unit Becquerel) with the energy that is emitted per elementary conversion. This is 3.956 pJ.

$$P = 2,5 \cdot 10^9 \cdot 3.956 \text{ pJ/s} \\ = 2,5 \cdot 10^9 \cdot 3.956 \cdot 10^{-12} \text{ J/s} = 0.01 \text{ W.}$$

The energy current flowing away from each liter of the Sun due to nuclear reactions is 0.01 W.

We compare this to other energy sources we are familiar with:

A normal flame with a volume of 1 liter produces about 1000 W. This is 100,000 times as much as 1 liter of Sun.

The fact that the Sun emits so much energy is due to the huge volume of its reactor.

One question has not yet been answered: How can such high temperatures be produced inside the Sun when the reaction runs so slowly?

Very high temperatures can be generated despite low conversion rates. An example of this phenomenon here on Earth is a haystack. Let us assume that the hay has been freshly stacked. A very slow reaction takes place in fresh hay which produces just a little entropy. The haystack begins to warm up very slowly. The heat insulation of the haystack is very good so the temperature inside eventually gets very high. At some point, however, the temperature stops increasing. Because of the high inner temperature, entropy begins to flow out. The temperature only rises until the energy flowing off is equal to that being produced at which point we have a steady-state. The longer the distance traveled by the entropy to the outside, the higher the temperature will be inside. This temperature can be so high that the hay begins to burn. For this reason, the temperature inside haystacks is measured from time to time.

Exactly this haystack-effect is also responsible for the high temperature inside the Sun. It is easy to see why the temperature inside the Sun is so very high. The Sun is gigantic so the path between the reaction zone near the center and the surface is huge. It is several hundred thousand km. In order for the entropy to travel these distances, a temperature difference of a few million Kelvin needs to be attained.

Helium nuclei are produced from hydrogen in a nuclear reaction inside the Sun. Despite the high temperature, the conversion rate is very low. The energy left over by the reaction is transported with entropy away from the reaction zone. In order for the steady-state to be sustained, the Sun must be much much hotter inside than further out.

Exercises

- How much energy is emitted by the Sun in producing 1 mole of helium? Compare this to how much is produced in the burning of 1 mole of hydrogen here on Earth (this means reacting with oxygen).
- Every human body produces heat: It emits energy and entropy. Estimate how much energy “one liter of human” emits. Compare this to the energy emitted by 1 liter of Sun.
- A star like the Sun forms by itself in space from evenly distributed hydrogen with an exceedingly low density. Try to describe this process of formation.

32.13 Nuclear reactors

A nuclear power plant

Fig. 32.10 shows a schematic of a nuclear power plant.

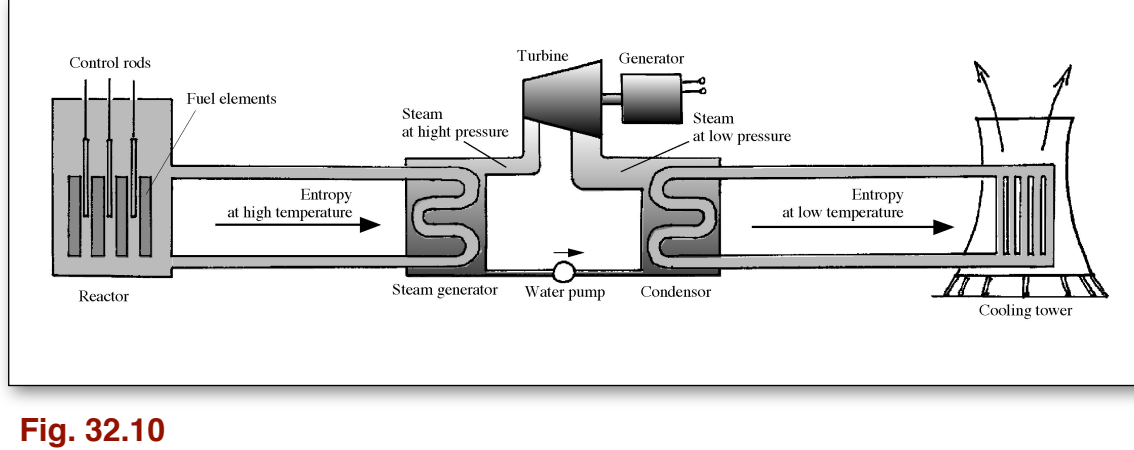


Fig. 32.10
Schematic of a nuclear power plant

A nuclear power plant functions very similarly to a coal-fired power plant. Both produce steam at high pressure and high temperature. Entropy at a high temperature is used for this. In a coal-fired power plant, entropy is produced by burning coal. The production of entropy in a nuclear power plant is accomplished in a *nuclear reactor*. The energy for this is released by a nuclear reaction.

The entropy is transported convectively with the water of the primary circuit from the reactor to the *steam generator*. The primary circuit works like a central heating unit where entropy, along with water, is brought convectively from one place (the boiler) to another (the radiators).

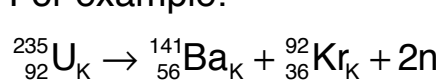
Steam is produced from the water of the secondary circuit in the steam generator. This generator has a high pressure – about 50 bar – and a high temperature – about 270 °C. The steam turbines are driven by the steam. At the exit of the turbine, the steam has a pressure of about 70 millibar and a temperature of about 40 °C. In the condenser, the expanded low-pressure steam gives its entropy to the water of the cooling circuit. The cooling water brings the entropy convectively to somewhere in the environment: Through another heat exchanger into a nearby river or through a cooling tower into the air.

Nuclear reactions

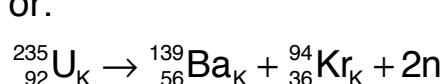
Now to the reactions taking place in a nuclear reactor. The nuclide responsible for the energy production is the uranium isotope $^{235}_{92}\text{U}_K$. It makes up only 0.7 % of natural uranium. The other 99.3 % is made up of the isotope $^{238}_{92}\text{U}_K$. For use in a nuclear reactor, the $^{235}_{92}\text{U}_K$ content of the uranium is enriched to 3 %.

The $^{235}_{92}\text{U}_K$ nucleus is unstable and can decay into two other nuclides.

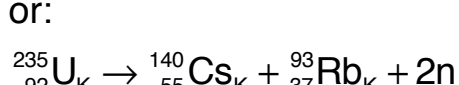
For example:



or:



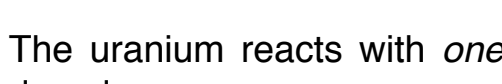
or:



and in many other ways as well.

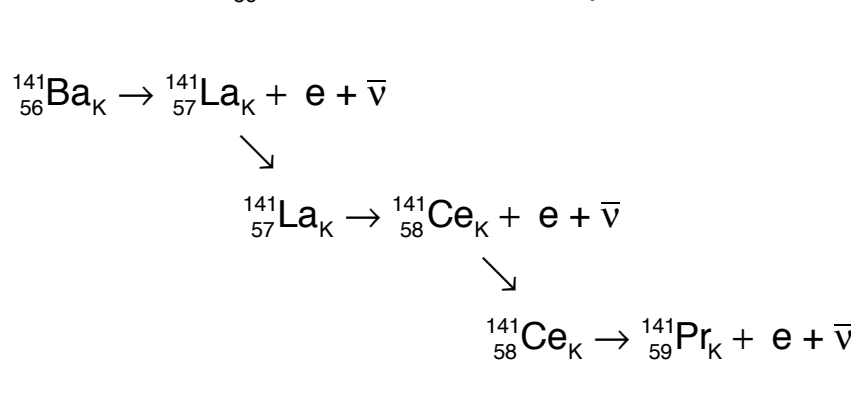
You see that in addition to the two large nuclides, two neutrons are produced as well. We will soon see that this is important. At first, all of these decay reactions have a high reaction resistance. The reaction rate is so small that it is totally inappropriate for releasing energy.

The reaction can be easily accelerated by a catalyst. Interestingly, neutrons (exactly the substance produced by the reaction itself) are a very good catalyst. Reactions in which the catalysts needed for acceleration are produced by the reactions themselves, are called *auto-catalytic reactions*. In order to clarify the role of catalysts, a neutron can be added to the left side of the reaction equation. Another neutron also appears on the right side of the equation. The result is, for example:



The uranium reacts with *one* neutron and *three* neutrons are produced.

This decay into two larger parts plus some neutrons is only the first step in the reaction. Not only the neutrons continue to react, but the two larger parts are unstable as well. They decay in a chain of consecutive reactions in which only small particles detach from the nucleus in question: electrons or ^4_2He nuclei. As an example, we will consider the $^{141}_{56}\text{Ba}$ nuclei which are produced as uranium decays:



At first, an unstable $^{141}_{57}\text{La}_K$ nucleus is produced from the $^{141}_{56}\text{Ba}_K$ nucleus which then produces an unstable $^{141}_{58}\text{Ce}_K$ nucleus. The resulting $^{141}_{59}\text{Pr}_K$ nucleus is stable.

All these reactions contribute to various degrees to the reactor's energy production. About 95 % of the total energy is released by the decay of the uranium (which is catalyzed by neutrons) and only 5 % by the subsequent reactions.

Despite their small importance to the reactor's balance of energy, the consecutive reactions play a very important role in the function of the reactor. They are the reason why a reactor needs very elaborate and expensive safety mechanisms.

In a nuclear reactor, $^{235}_{92}\text{U}_K$ nuclei decay into two almost equally large nuclides as well as some neutrons. The reaction is catalyzed by neutrons (auto-catalysis). All the resulting nuclides are unstable and continue to decay.

Controlling a reactor

First, a reminder about that the boiler of a coal-fired power plant is controlled just like an oil heater, a normal coal-burning stove, or a fire in the fireplace. In order to accelerate the reaction, more fuel and more oxygen are added. To reduce the conversion rate, the amounts of fuel and oxygen added are decreased. Since an auto-catalytic reaction takes place in a reactor, one can proceed differently here: The reactor is supplied with “fuel” once per year, i.e., with the amount of uranium needed for a year. The conversion rate can be controlled by influencing the amount of the catalyst (neutrons) the concentration of neutrons in a reactor can be reduced by inserting a control rod into the reaction zone. Control rods are rods made up of materials that absorb neutrons, meaning that they react well with neutrons.

Safety mechanisms

In the process of splitting uranium, very many different nuclides are produced. They are all unstable and continue to react. The consecutive reactions are not accelerated by any catalyst, though. They proceed with the various inherent speeds: some very fast, some very slowly.

We have seen that in these consecutive reactions, a light particle, an electron or ^4_2He nucleus, is always produced along with a heavy nuclide. We already know that in this case, almost all the energy released by the reaction is taken by this light particle. This means that the decay products of uranium are radioactive. Because of the high conversion rate in the reactor, the nuclear radiation emitted by the decay products is very intense and dangerous.

This is the cause of one of the problems in running a reactor. The decay products of uranium should not end up in the environment. Avoiding this wouldn't be a problem except for one thing. The energy production of a reactor cannot be stopped fast enough. The uranium decay process can be stopped very quickly with a control rod, but the consecutive reactions cannot be influenced. They only subside gradually. Table 32.5 shows how energy production continues after stopping uranium splitting.

Time after shutdown	Energy production (based upon normal operation of the plant)
5 seconds	5 %
1 minute	4 %
10 minutes	3 %
1 hour	1 %
1 day	0.7 %
2 days	0.5 %

Table 32.5

A large power plant normally produces about 1000 MW. If it is shut down, it will still produce 0.7 % of 1000 MW after one day. This is 7 MW. It is necessary for the energy to continue to be removed for some days after shutting down. If this were not to happen, the reactor would heat up so much that the reactor containers would melt.

The safety systems of power plants must be designed so that, even in an emergency, heat can be removed, making a melting of the reaction container unlikely. If this should happen anyway, further safety barriers must ensure that no radioactive substances make it into the environment.

A reactor needs an elaborate safety system due to the consecutive reactions of the decay products of uranium because

- the decay products of uranium are radioactive and may not end up in the environment;
- the energy production of consecutive reactions cannot be shut down.

Radioactive waste

When the reactor is given its new uranium a year, the reaction products of the previous year must be removed from the reactor. These reaction products are a mixture of the most various nuclides, many of which are unstable. One finds nuclides with half-lives that vary extremely.

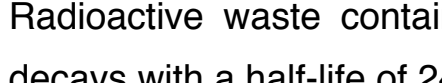
It is impossible to wait for all the nuclides to reach a stable state before removing them because some nuclides have half-lives of years, decades, centuries, and even millennia.

The reaction products that are removed once per year from a reactor are still radioactive and remain so for quite a while. For this reason, they need to be stored in a place where they cannot end up in the ecosystem.

Plutonium

The decay of uranium and the products resulting from it are the most numerous reactions in a nuclear reactor. In addition to these there are reactions of a different type, namely synthesis reactions.

$^{238}_{92}\text{U}$ reacts with neutrons into heavier nuclides. Among these, plutonium is especially important. Plutonium is an element which has no isotope existing in nature. In the reactor, the $^{239}_{94}\text{Pu}$ nuclide is produced out of $^{238}_{92}\text{U}$ in the following reaction

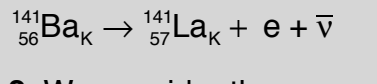


Radioactive waste contains plutonium, and $^{239}_{94}\text{Pu}$ is radioactive. It decays with a half-life of 24,000 years while emitting helium nuclei.

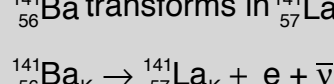
Just like $^{238}_{92}\text{U}$, neutrons catalyze the decay of $^{239}_{94}\text{Pu}$ into two parts of roughly equal size. It would therefore be possible to use $^{239}_{94}\text{Pu}$ as a reactor fuel, but it would first have to be separated from the other radioactive waste substances. This poses a new problem: It would be relatively easy to manufacture an atomic bomb from the separated pure plutonium.

Exercises

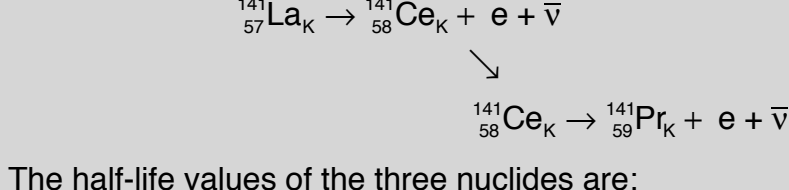
1. Compare the energy produced by the uranium decay reaction



with the energy produced by the subsequent reaction



2. We consider the consecutive reaction where, at first, $^{141}_{56}\text{Ba}$ transforms in $^{141}_{57}\text{La}$, then in $^{141}_{58}\text{Ce}$ and finally in $^{141}_{59}\text{Pr}$:



The half-life values of the three nuclides are:

$$T_{1/2}(^{141}_{56}\text{Ba}) = 18 \text{ minutes}$$

$$T_{1/2}(^{141}_{57}\text{La}) = 4 \text{ hours}$$

$$T_{1/2}(^{141}_{58}\text{Ce}) = 32 \text{ days}$$

We will begin at time t_0 with a certain amount of

$^{141}_{56}\text{Ba}$. Give a rough estimate of how much Ba, La, Ce, and Pr are present

(“a lot”, “medium”, “little”, “very little”):

a) after 30 seconds

b) after 18 minutes

c) after 5 days

d) after 1 year.

Periodic table of the elements

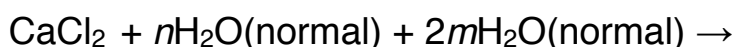
Main groups		Transition groups																Main groups																																							
I	II	III A	IV A	V A	VI A	VII A	VIII A	VIII A	VIII A	IA	II A	III A	IV	V	VI	VII	VIII																																								
1 H 1 1.0	2 Li 3 6.9	3 Na 11 23.0	4 Mg 12 24.3	5 K 19 39.1	6 Ca 20 40.1	7 Sc 21 45.0	8 Ti 22 47.9	9 V 23 50.9	10 Cr 24 52.0	11 Mn 25 54.9	12 Fe 26 55.8	13 Co 27 58.9	14 Ni 28 58.7	15 Cu 29 63.5	16 Zn 30 65.4	17 Ga 31 69.7	18 Ge 32 72.6	19 As 33 74.9	20 Se 34 79.0	21 Br 35 79.9	22 Kr 36 83.8	23 Rb 37 85.5	24 Sr 38 87.6	25 Y 39 88.9	26 Zr 40 91.2	27 Nb 41 92.9	28 Mo 42 95.9	29 Tc 43 97	30 Ru 44 101.1	31 Rh 45 102.9	32 Pd 46 106.4	33 Ag 47 107.9	34 Cd 48 112.4	35 In 49 114.8	36 Sn 50 118.7	37 Sb 51 121.8	38 Te 52 127.6	39 I 53 126.9	40 Xe 54 131.3	41 Cs 55 132.9	42 Ba 56 137.3	43 La 57 138.9	44 Hf 72 178.5	45 Ta 73 180.9	46 W 74 183.9	47 Re 75 186.2	48 Os 76 190.2	49 Ir 77 192.2	50 Pt 78 195.1	51 Au 79 197.0	52 Hg 80 200.6	53 Tl 81 204.4	54 Pb 82 207.2	55 Bi 83 209.0	56 Po 84 209	57 At 85 210	58 Rn 86 222
		Lanthanides		Ce 58 140.1	Pr 59 140.9	Nd 60 144.2	Pm 61 145	Sm 62 150.4	Eu 63 152.0	Gd 64 157.3	Tb 65 158.9	Dy 66 162.5	Ho 67 164.9	Er 68 167.3	Tm 69 168.9	Yb 70 173.0	Lu 71 175.0																																								
		Actinides		Th 90 232	Pa 91 231	U 92 238	Np 93 237	Pu 94 244	Am 95 243	Cm 96 247	Bk 97 247	Cf 98 251	Es 99 254	Fm 100 257	Md 101 258	No 102 259	Lr 103 260																																								

C ← Element symbol
 6 12.0 ← Mass/amount of substance in g/mol
 ↑ Atomic number

Table of chemical potentials and molar entropies

The values in the table are for substances under standard conditions, i.e., a temperature of 25 °C and a pressure of 1 bar. For dissolved substances they are based upon 1 mol of solute in one liter of solution.

The Table shows negative molar entropies for some of the dissolved substances. For instance, Ca^{++} : $S/n = -55,23 \text{ Ct/mol}$ can be found in the table. Of course, there are no negative entropies in nature. This is only the result of a mathematical trick. In watery solutions, ions are surrounded by so-called hydrate shells. This means that a number of water molecules are attached to each ion. The ion and the hydrate shell together form a kind of large molecule. During dissolving, for example of CaCl_2 , the reaction



takes place. CaCl_2 transforms into Ca^{++} - and Cl^- -ions, and “normal” water changes into water of hydrate shells. This reaction is usually written like this:



This means that the water on both sides of the reaction equation is left out. In order for the balance of entropy to be correct anyway, the entropy released by the formation of the hydrate shells is simply added to the entropy of the ions. Thus, in the table, in the place of Ca^{++} there is actually the molar entropy of



and in the place of Cl^- we find that of



If these values are used, the simplified reaction equation can be applied to set up the reaction's balance of entropy.

The molar entropy of normal water is much greater than that of the water of a hydrate shell so it can happen that the total amount of molar entropy of the ions is negative.

Ag ... Br (Silver to Bromine)

Formula	Name, phase	μ in kG	S/n in Ct/mol
Ag	Silver. gas	245.68	172.89
Ag	solid	0.00	42.55
Ag ⁺	Aqueous sol.	77.12	72.68
AgBr	solid	-96.9	107.11
AgCl	solid	-109.8	96.23
AgI	solid	-66.19	115.48
AgNO ₂	solid	19.08	128.2
AgNO ₃	solid	-33.47	140.92
AgN ₃	solid	376.14	104.18
Ag ₂ CO ₃	solid	-436.81	167.36
Ag ₂ O	solid	-11.21	121.34
Ag ₂ O ₂	solid	27.61	117.15
Ag ₂ O ₃	solid	121.34	100.42
Ag ₂ S	orthorhomb. solid	-40.67	144.01
Ag ₂ SO ₄	solid	-618.48	200.41
Al	Aluminum. gas	285.77	164.45
Al	liquid	6.61	35.23
Al	solid	0.00	28.32
Al ⁺⁺⁺	Aqueous sol.	-485.34	-321.75
AlBr ₃	solid	-505.01	184.1
Al(CH ₃) ₃	liquid	-10.04	209.41
AlCl ₃	gas	-570.05	314.29
AlCl ₃	solid	-630.06	109.29
AlF ₃	gas	-1192.75	276.77
AlF ₃	solid	-1431.15	66.48
AlI ₃	solid	-300.83	158.99
AlN	solid	-287.02	20.17
Al(NO ₃) ₃ · 6H ₂ O	solid	-2203.88	467.77
AlO(OH)	Böhmite. solid	-912.95	48.45
AlO(OH)	α -Diaspor. solid	-920.48	35.27
Al(OH) ₃	Hydrargillite. solid	-1143.91	70.12
AlPO ₄	Berlinite. solid	-1601.22	90.79
Al ₂ Cl ₆	gas	-1220.47	489.53
Al ₂ O ₃	liquid	-1483.14	99.28
Al ₂ O ₃	α . solid	-1581.88	50.94
Al ₂ O ₃	γ . solid	-1563.94	52.51
Al ₂ (SO ₄) ₃	solid	-3100.13	239.32
Al ₂ (SO ₄) ₃ · 6H ₂ O	solid	-4622.57	469.03
Al ₂ SiO ₅	Andalusite. solid	-2597.43	93.22
Al ₂ SiO ₅	Cyanite. solid	-2596.17	83.81
Al ₂ SiO ₅ · 2H ₂ O	Sillimanite. solid	-2625.88	96.19
Al ₂ Si ₂ O ₇ · 2H ₂ O	Halloysite. solid	-3759.32	203.34
Al ₂ Si ₂ O ₇ · 2H ₂ O	Kaolinite. solid	-3778.15	202.92
Al ₄ C ₃	solid	-196.23	88.95
Al ₆ Si ₂ O ₁₃	Mullite. solid	-6441.94	274.89
Ar	Argon. gas	0,00	154.73
Ar	Aqueous sol.	16.32	59.41
As	Arsenic. gas	261.08	174.1
As	grey. metall.. solid	0.00	35.15
AsCl ₃	gas	-248.95	327.06
AsCl ₃	liquid	-259.41	216.31
AsF ₃	liquid	-909.14	181.21
AsI ₃	solid	-59.41	213.05
As ₂ O ₃	monoclinic. solid	-577.02	117.15
As ₂ O ₅	solid	-782.41	105.44
As ₂ S ₃	solid	-168.62	163.59
As ₄ O ₆	cubic. solid	-1152.52	214.22
Au	Gold. gas	326.36	180.39
Au	solid	0.00	47.4
Au ₂ O ₃	solid	163.3	125,00
B	Boron. gas	511.67	153.34
B	liquid	19.35	14.78
B	solid	0,00	5.87
BBr ₃	gas	-232.46	324.13
BBr ₃	liquid	-238.49	229.7
B(CH ₃) ₃	gas	-35.98	314.64
BCl ₃	gas	-387.98	290.07
BCl ₃	liquid	-387.44	206.27
BF ₃	gas	-1120.35	254.01
BN	solid	-228.45	14.81
BO ₂ H	monoclinic. solid	-723.41	37.66
BO ₂ H	orthorhomb.. solid	-721.74	50.21
BO ₃ H ₃	gas	-928.43	295.14
BO ₃ H ₃	solid	-969.01	88.83
B ₂ Cl ₄	gas	-460.66	357.31
B ₂ Cl ₄	liquid	-464.84	262.34
B ₂ F ₄	gas	-1410.43	317.15
B ₂ O ₃	gas	-822.58	283.67
B ₂ O ₃	liquid	-1180.37	78.4
B ₂ O ₃	solid	-1193.7	53.97
B ₂ O ₃	amorphous	-1182.4	77.82
B ₃ N ₆ H ₆	liquid	-392.79	199.58
B ₄ C	solid	-71.13	27.11
Ba	Barium. gas	144.77	170.28
Ba	solid	0.00	66.94
Ba ⁺⁺	Aqueous sol.	-560.66	12.55
BaCO ₃	Witherite. solid	-1138.88	112.13
BaCl ₂	solid	-810.86	125.52
BaF ₂	solid	-1148.51	96.23
BaI ₂	solid	-598,00	167.4
Ba(NO ₃) ₂	solid	-794.96	213.8
BaO	solid	-528.44	70.29
Ba(OH) ₂ · 8H ₂ O	solid	-2793.24	426.77
BaS	solid	-456.06	78.24
BaSO ₄	solid	-1353.11	132.21
Be	Beryllium. gas	289.66	136.17
Be	liquid	9.96	16.54
Be	solid	0.00	9.54
BeCl ₂	gas	-366.1	251.04
BeCl ₂	α . solid	-446.26	82.68
BeF ₂	gas	-800.54	227.44
BeF ₂	solid	-979.38	53.35
Be(OH) ₂	gas	-625.37	247.69
Be(OH) ₂	α . solid	-814.51	49.37
Bi	Bismuth. gas	168.2	186.9
Bi	solid	0.00	56.74
BiClO	solid	-322.17	120.5
BiCl ₃	solid	-315.06	176.98
Bi ₂ O ₃	solid	-493.71	151.46
Bi ₂ S ₃	solid	-140.58	200.41
Br	Bromine. gas	82.43	174.91
Br ⁻	Aqueous sol.	-103.97	82.42
BrCl	gas	-0.96	239.99
BrF	gas	-109.16	228.86
BrF ₃	gas	-229.45	292.42
BrF ₃	liquid	-240.58	178.24
BrF ₅	gas	-350.62	320.08
BrF ₅	liquid	-351.87	225.1
BrH	gas	-53.43	198.59
Br ₂	gas	3.14	245.35
Br ₂	liquid	0.00	152.23

Ca ... Fe (Calcium to Iron)

Formula	Name, phase	μ in kG	S/n in Ct/mol
Ca	Calcium. gas	145.53	154.78
Ca	liquid	8.19	50.65
Ca	α . solid	0.00	41.55
Ca	β . solid	0.22	42.47
Ca ⁺⁺	aqueous sol.	-553.04	-55.23
CaBr ₂	solid	-656.05	129.7
CaCO ₃	Aragonite. solid	-1127.71	88.7
CaCO ₃	Calcite. solid	-1128.76	92.88
CaC ₂	solid	-67.78	70.29
CaCl	gas	-130.96	241.42
CaCl ₂	gas	-479.18	289.95
CaCl ₂	liquid	-732.16	123.88
CaCl ₂	solid	-750.19	113.8
CaCrO ₄	solid	-1277.38	133.89
CaF ₂	gas	-793.27	273.68
CaF ₂	solid	-1161.9	68.87
CaH ₂	solid	-149.79	41.84
CaI ₂	solid	-529.69	142.26
Ca(NO ₃) ₂	solid	-741.99	193.3
CaO	solid	-604.17	39.75
Ca(OH) ₂	solid	-896.76	76.15
CaPO ₄ H	solid	-1679.88	87.86
CaS	solid	-477.39	56.48
CaSO ₄	Anhydrite. solid	-1320.3	98.32
CaSO ₄ · 2H ₂ O	Gypsum. solid	-1795.73	193.97
CaSiO ₃	α -Wollastonite. solid	-1495.36	87.45
CaSiO ₃	β -Wollastonite. solid	-1498.71	82.01
Ca ₃ N ₂	solid	-368.61	104.6
Ca ₃ (PO ₄) ₂	α . solid	-3889.86	241.00
Ca ₃ (PO ₄) ₂	β . solid	-3899.49	235.98
Cd	Cadmium. gas	77.45	167.64
Cd	solid	0.00	51.76
Cd ⁺⁺	aqueous sol.	-77.58	-73.22
CdBr ₂	solid	-296.31	137.24
CdCO ₃	solid	-669.44	92.47
CdCl ₂	solid	-343.97	115.27
CdF ₂	solid	-647.68	77.4
CdI ₂	solid	-201.38	161.08
CdO	solid	-228.45	54.81
CdS	solid	-156.48	64.85
CdSO ₄	solid	-822.78	123.04
CdSO ₄ · 8/3 H ₂ O	solid	-1457.98	229.7
Cl	Chlorine. gas	105.03	165.1
Cl ·	aqueous sol.	-131.26	56.48
ClF	gas	-55.94	217.78
ClF ₃	gas	-123.01	281.5
ClF ₅	gas	-146.77	310.62
ClH	gas	-95.3	186.79
ClO ₂	gas	120.5	256.73
Cl ₂	gas	0.00	222.97
Cl ₂	aqueous sol.	6.9	121.34
Co	Cobalt. gas	380.33	179.41
Co	α . hexagonal. solid	0,00	30.04
Co	β . fcc. solid	0.25	30.71
Co ⁺⁺	aqueous sol.	-54.39	-112.97
Co ⁺⁺⁺	aqueous sol.	133.89	-305.43
CoCl ₂	solid	-269.87	109.16
CoF ₂	solid	-647.26	81.96
CoFe ₂ O ₄	solid	-1032.61	134.72
CoO	solid	-214.22	52.97
CoSO ₄	solid	-782.41	117.99
Co ₃ O ₄	solid	-774.04	102.51
Cr	Chromium. gas	351.87	174.39
Cr	solid	0.00	23.77
CrCl ₂	solid	-356.06	115.31
CrCl ₂ O ₂	Chromylchloride. liq.	-510.87	221.75
CrCl ₃	solid	-486.18	123.01
CrF ₃	solid	-1087.84	93.89
Cr ₂ O ₃	solid	-1058.13	81.17
Cs	Cesium. gas	49.72	175.49
Cs	liquid	0.03	92.07
Cs	solid	0.00	85.15
Cs ⁺	aqueous sol.	-282.04	133.05
CsBr	solid	-383.25	121.34
CsCl	gas	-257.85	255.96
CsCl	solid	-414.37	101.18
CsClO ₄	solid	-306.6	175.27
CsF	gas	-373.35	243.09
CsF	solid	-525.39	88.28
CsH	gas	101.67	214.43
CsI	solid	-333.46	129.7
Cu	Copper. gas	298.61	166.27
Cu	liquid	8.37	36.25
Cu	solid	0.00	33.11
Cu ⁺	aqueous sol.	50.00	40.58
CuBr	solid	-100.83	96.11
CuCO ₃ · Cu(OH) ₂	Malachite. solid	-893.7	186.19
CuCl	gas	63.5	237.09
CuCl	solid	-119.87	86.19
CuCl ₂	solid	-175.73	108.07
CuI	solid	-69.45	96.65
CuN ₃	solid	344.76	100.42
CuO	gas	216.93	234.6
CuO	solid	-129.7	42.63
Cu(OH) ₂	solid	-372.74	108.37
CuS	solid	-53.56	66.53
CuSO ₄	solid	-661.91	108.78
CuSO ₄ · H ₂ O	solid	-918.22	146.02
CuSO ₄ · 3H ₂ O	solid	-1400.18	221.33
CuSO ₄ · 5H ₂ O	solid	-1880.06	300.41
Cu ₂ O	solid	-146.02	93.14
Cu ₂ S	α . solid	-86.19	120.92
F	Fluor. gas	61.92	158.64
F -	aqueous sol.	-278.82	-13.81
FH	gas	-273.22	173.67
FH	aqueous sol.	-296.85	88.7
F ₂	gas	0.00	202.67
F ₂ O	gas	-4.6	247.32
Fe	gas	370.7	180.38
Fe	liquid	11.05	34.29
Fe	α . solid	0.00	27.28
Fe ⁺⁺	aqueous sol.	-78.87	-137.65
Fe ⁺⁺⁺	aqueous sol.	-4.6	-315.89
FeCO ₃	Siderite. solid	-666.72	92.88
Fe(CO) ₅	liquid	-705.42	338.07
FeCl ₂	gas	-159.62	287.48
FeCl ₂	solid	-302.34	117.95
FeCl ₃	gas	-247.87	344.1
FeCl ₃	solid	-334.05	142.26
FeCr ₂ O ₄	solid	-1343.9	146.02
FeO	gas	217.66	241.84
FeO	solid	-245.14	57.49
Fe(OH) ₂	gas	-306.63	282.75
Fe(OH) ₂	solid	-492.03	87.86
Fe(OH) ₃	solid	-705.56	104.6
FeS	Pyrrhotine. solid	-100.42	60.29
FeSO ₄	solid	-820.9	107.53
FeS ₂	Pyrite. solid	-166.94	52.93
Fe ₂ O ₃	Hematite. solid	-742.24	87.4
Fe ₂ (SO ₄) ₃	solid	-2263.05	307.52
Fe ₂ SiO ₄	Fayalite. solid	-1379.05	145.18
Fe ₃ C	Cementite. solid	20.08	104.6
Fe ₃ O ₄	Magnetite. solid	-1015.46	146.44

C (Carbon)

Formula	Name, phase	μ in kG	S/n in Ct/mol
C	Carbon. gas	669.58	157.99
C	Diamond. solid	2.9	2.38
C	Graphite. solid	0.00	5.74
CBr ₄	gas	66.94	357.94
CBr ₄	monoclinic. solid	47.7	212.55
CCl ₂ O	Carbonylchloride. gas	-204.6	283.42
CCl ₄	gas	-60.63	309.74
CCl ₄	liquid	-65.27	216.4
CF ₄	gas	-878.64	261.5
CH	gas	560.75	182.92
CHCl ₃	Chloroform. gas	-70.41	295.51
CH ₂	gas	371.87	181.04
CH ₂	Polyethylene. solid	4.4	25.34
CH ₂ Cl ₂	Dichlormethane. gas	-68.97	270.18
CH ₂ O	Formaldehyde. gas	-112.97	218.66
CH ₂ O ₂	Formic acid. gas	-350.03	251.6
CH ₂ O ₂	Formic acid. liquid	-359.57	129,00
CH ₂ O ₂	Formic acid. aqueous sol.	-372.38	163.18
CH ₃	gas	147.92	194.05
CH ₃ Br	Bromine methane. gas	-25.94	246.27
CH ₃ Cl	Chlorine methane. gas	-62.95	234.26
CH ₃ NO ₂	Nitromethane. gas	-6.92	275,00
CH ₃ NO ₂	Nitromethane. liquid	-14.55	171.9
CH ₃ NO ₃	Methylnitrate. liquid	-40.52	217,00
CH ₄	Methane. gas	-50.81	186.1
CH ₄ N ₂ O	Urea. solid	-196.82	104.6
CH ₄ O	Methanole. gas	-162.52	239.7
CH ₄ O	Methanole. liquid	-166.34	126.7
CO	gas	-137.15	197.56
CO ₂	gas	-394.36	213.64
CO ₂	Aqueous sol.	-386,00	113,00
CO ₃ ⁻	Carbonate ion. aqueous sol.	-527.9	-56.9
CO ₃ H ⁻	aqueous sol.	-586.85	91.21
CS	gas	184.1	210.46
CS ₂	gas	66.91	237.79
CS ₂	liquid	65.27	151.34
C ₂ Cl ₂	Dichloroethine. gas	198.41	271.96
C ₂ Cl ₄	Tetrachloroethene. gas	21.56	343.31
C ₂ Cl ₆	Hexachloroethane. gas	-50,00	397.77
C ₂ H ₂	Ethine. Acetylene. gas	209.2	200.83
C ₂ H ₄	Ethene. Ethylene. gas	68.12	219.45
C ₂ H ₄ O	Acetaldehyde. gas	-132.92	264.2
C ₂ H ₄ O	Epoxyethane. gas	-11.84	243.7
C ₂ H ₄ O ₂	Acetic acid. gas	-378.95	282.5
C ₂ H ₄ O ₂	Acetic acid. liquid	-389.95	159.83
C ₂ H ₄ O ₂	Acet. acid. aq. sol.	-396.56	178.66
C ₂ H ₅ Cl	Ethylchloride. gas	-60.46	275.89
C ₂ H ₅ Cl	Ethylchloride. liquid	-59.41	190.79
C ₂ H ₅ O ₂ N	Amino acetic acid. solid	-367.02	109.2
C ₂ H ₆	Ethane. gas	-32.62	229.5
C ₂ H ₆ O	Dimethyl ether. gas	-114.07	266.6
C ₂ H ₆ O	Ethyl alcohol. gas	-168.57	282,00
C ₂ H ₆ O	Ethyl alcohol. liquid	-174.89	160.67
C ₂ H ₆ O ₂	Ethanediol. Glycol. liq.	-327.07	179.5
C ₃ H ₄	Propadiene. gas	202.38	234.9
C ₃ H ₄	Propine. gas	194.16	248.1
C ₃ H ₆	Propene. gas	74.66	226.9
C ₃ H ₆	Cyclopropane. gas	104.11	237.9
C ₃ H ₆ O	Propanone. Acetone. gas	-151.82	294.9
C ₃ H ₆ O	Propanone. Acetone. liq.	-154.83	200.00
C ₃ H ₈	Propane. gas	-23.43	269.9
C ₄ H ₈	Butene-(1). gas	72.03	307.4
C ₄ H ₈ O ₂	Acet. acid ethylester. liq.	-323.19	259.00
C ₄ H ₁₀	Butane. gas	-15.62	310,00
C ₄ H ₁₀	2-Methylpropane. gas	-17.92	294.6
C ₅ H ₁₀	Cyclopentane. gas	38.67	292.9
C ₅ H ₁₀	Cyclopentane. liquid	36.49	204.1
C ₅ H ₁₂	Pentane. gas	-8.11	348.4
C ₅ H ₁₂	Pentane. liquid	-9.21	262.7
C ₆ H ₅ Cl	Chlorbenzene. liquid	93.65	194.1
C ₆ H ₅ NO ₂	Nitrobenzene. liquid	141.62	224.3
C ₆ H ₆	Benzene. gas	129.73	269.2
C ₆ H ₁₂	Cyclohexane. gas	31.75	298.2
C ₆ H ₁₂	Cyclohexane. liquid	26.83	204.1
C ₆ H ₁₄	Hexane. gas	0.3	386.8
C ₆ H ₁₄	Hexane. liquid	-4.26	296,00
C ₇ H ₈	Methylbenzene. Toluene. gas	122.39	319.7
C ₇ H ₈	Methylbenzene. Toluene. liq.	110.61	219.00
C ₈ H ₁₈	Octane. gas	17.44	463.7
C ₈ H ₁₈	Octane. liquid	6.41	361.2
C ₁₂ H ₂₂ O ₁₁	Saccharose. solid	-1543.52	360,00

Ga ... Li (Gallium to Lithium)

Formula	Name, phase	μ in kG	S/n in Ct/mol
Ga	Gallium. gas	238.91	168.95
Ga	solid	0.00	40.88
Ga ⁺⁺⁺	aqueous sol.	-158.99	-330.54
GaBr ₃	solid	-359.82	179.91
GaCl ₃	solid	-454.8	142.26
GaF ₃	solid	-1085.33	83.68
Ga(OH) ₃	solid	-831.36	100.42
Ga ₂ O ₃	rhomboedric. solid	-998.3	84.98
Ge	Germanium. gas	335.98	167.79
Ge	solid	0.00	31.09
GeBr ₄	liquid	-331.37	280.75
GeCl ₄	gas	-457.31	347.61
GeCl ₄	liquid	-462.33	245.6
GeH ₄	gas	113.39	217.02
GeI ₄	solid	-144.35	271.12
GeO	brown. solid	-237.23	50.21
GeO ₂	hexagonal. solid	-497.06	55.27
GeS	solid	-71.55	71.13
H	Hydrogen. gas	203.26	114.6
H ⁺	aqueous sol.	0.00	0,00
$\left. \begin{matrix} \text{HCO}_3^- \\ \text{HCl} \end{matrix} \right\} \text{see} \left\{ \begin{matrix} \text{CO}_3\text{H}_2^- \\ \text{ClH} \end{matrix} \right.$			
H ₂	gas	0.00	130.57
H ₂	aqueous sol.	18,00	49,00
$\left. \begin{matrix} \text{H}_2\text{CO}_3 \\ \text{H}_2\text{O} \\ \dots \end{matrix} \right\} \text{see} \left\{ \begin{matrix} \text{CO}_3\text{H}_2 \\ \text{OH}_2 \\ \dots \end{matrix} \right.$			
He	Helium. gas	0.00	126.04
He	aqueous sol.	19.25	55.65
Hg	Mercury. gas	31.85	174.85
Hg	liquid	0.00	76.02
Hg ⁺⁺	aqueous sol.	164.43	-32.22
HgBr ₂	solid	-153.13	171.54
HgCl ₂	solid	-178.66	146.02
HgI ₂	red. solid	-101.67	179.91
HgO	red. solid	-58.56	70.29
HgO	yellow. solid	-58.43	71.13
HgS	red. solid	-50.63	82.42
HgS	black. solid	-47.7	88.28
Hg ₂ ⁺⁺	aqueous sol.	153.55	84.52
Hg ₂ Br ₂	solid	-181.08	217.57
Hg ₂ CO ₃	solid	-468.19	179.91
Hg ₂ Cl ₂	solid	-210.78	192.46
Hg ₂ I ₂	solid	-111.00	233.47
Hg ₂ SO ₄	solid	-625.88	200.66
Hf	Hafnium. gas	576.56	186.78
Hf	solid	0.00	43.56
HfCl ₄	solid	-901.32	190.79
HfF ₄	monoclinic. solid	-1830.5	112.97
HfO ₂	solid	-1027.17	59.33
I	Iodine. gas	70.28	180.68
I ⁻	aqueous sol.	-51.59	111.29
ICl	gas	-5.44	247.44
ICl ₃	solid	-22.34	167.36
IF	gas	-118.49	236.06
IF ₇	gas	-818.39	346.44
IH	gas	1.72	206.48
I ₂	gas	19.36	260.58
I ₂	liquid	3.32	150.36
I ₂	solid	0.00	116.14
I ₂	aqueous sol.	16.4	137.24
In	Indium. gas	208.74	173.68
In	solid	0.00	57.82
In ⁺⁺⁺	aqueous sol.	-106.27	150.62
InBr	solid	-169.03	112.97
InI	solid	-120.5	129.7
In(OH) ₃	solid	-761.49	104.6
In ₂ O ₃	solid	-830.73	104.18
In ₂ (SO ₄) ₃	solid	-2439.27	271.96
Ir	Iridium. gas	617.98	193.47
Ir	solid	0.00	35.48
IrF ₆	solid	-461.66	247.69
K	Potassium. gas	61.17	160.23
K	liquid	0.26	71.45
K	solid	0.00	55.81
K ⁺	aqueous sol.	-283.26	102.51
KAl(SO ₄) ₂	solid	-2235.47	204.6
KBF ₄	solid	-1785,00	133.89
KBr	solid	-379.2	96.44
KBrO ₃	solid	-243.51	149.16
KCl	gas	-233.41	238.99
KCL	liquid	-395.11	86.65
KCl	solid	-408.32	82.68
KClO ₃	solid	-289.91	142.97
KClO ₄	solid	-304.18	151.04
KF	gas	-344.8	226.5
KF	solid	-533.13	66.57
KF ₂ H	solid	-852.41	104.27
KI	gas	-165.9	258.17
KI	solid	-322.29	104.35
KIO ₃	solid	-425.51	151.46
KH	solid	-34.04	50.21
KMnO ₄	solid	-713.79	171.71
KNO ₂	solid	-306.6	152.09
KNO ₃	solid	-393.13	132.93
KOH	gas	-235.46	244.35
KOH	liquid	-317.87	98.4
KOH	solid	-379.05	79.29
KSO ₄ H	solid	-1031.36	138.07
K ₂ CO ₃	liquid	-1049.44	170.37
K ₂ CO ₃	solid	-1064.59	155.52
K ₂ O	solid	-322.11	94.14
K ₂ O ₂	solid	-429.79	112.97
K ₂ CrO ₄	solid	-1295.78	200.12
K ₂ PtCl ₆	solid	-1109.18	333.88
K ₂ SO ₄	solid	-1316.37	175.73
Kr	Crypton. gas	0.00	163.97
Kr	aqueous sol.	15.06	61.5
La	Lanthan. gas	330.54	182.3
La	solid	0,00	57.32
La ⁺⁺⁺	aqueous sol.	-723.41	-184.1
Li	Lithium. gas	128.04	138.67
Li	liquid	0.93	33.94
Li	solid	0.00	29.1
Li ⁺	aqueous sol.	-293.8	14.23
LiCl	gas	-217.26	212.81
LiCl	solid	-384.03	59.3
LiF	gas	-361.57	200.16
LiF	solid	-588.67	35.66
LiH	gas	117.84	170.8
LiH	solid	-68.46	20.04
Lil	gas	-134.22	232.12
Lil	solid	-269.66	85.77
LiOH	gas	-252.42	217.57
LiOH	solid	-438.73	42.78
Li ₂ CO ₃	solid	-1132.44	90.37
Li ₂ CO ₃	liquid	-1105.55	127.29
Li ₂ O	gas	-187.31	229,00
Li ₂ O	solid	-562.11	37.89

Mg ... Ni (Magnesium to Nickel)

Formula	Name. phase	μ in kG	S/n in Ct/mol
Mg	Magnesium. gas	113.07	148.55
Mg	liquid	6.1	42.51
Mg	solid	0.00	32.69
Mg ⁺⁺	aqueous sol.	-456.01	-117.99
MgCO ₃	solid	-1029.26	65.69
MgCl ₂	gas	-398.8	276.91
MgCl ₂	liquid	-563.96	129.49
MgCl ₂	solid	-592.12	89.63
MgF ₂	gas	-731.5	258.3
MgF ₂	solid	-1071.12	57.24
MgI ₂	solid	-358.15	129.7
Mg(NO ₃) ₂	solid	-588.4	164.01
MgO	gas	-21.48	221.29
MgO	liquid	-502.46	50.35
MgO	solid	-568.96	26.94
Mg(OH) ₂	gas	-542.06	273.63
Mg(OH) ₂	solid	-833.69	63.18
MgS	solid	-341.72	46.02
MgSO ₄	solid	-1147.51	91.4
MgSiO ₃	liquid	-1415.39	92.52
MgSiO ₃	solid	-1462.07	67.77
Mg ₂ SiO ₄	liquid	-2003.19	123.04
Mg ₂ SiO ₄	solid	-2057.93	95.14
Mn	Manganese. gas	238.49	173.59
Mn	α . solid	0.00	32.01
Mn ⁺⁺	aqueous sol.	-228.03	-73.64
MnCO ₃	solid	-816.72	85.77
MnCl ₂	solid	-440.53	118.24
MnO	solid	-362.92	59.71
MnO ₂	solid	-465.18	53.05
Mn(OH) ₂	precipitated. amorph.	-615.05	99.16
MnS	green. solid	-218.4	78.24
MnSO ₄	solid	-957.42	112.13
MnSiO ₃	solid	-1240.56	89.12
Mn ₂ O ₃	solid	-881.15	110.46
Mn ₂ SiO ₄	solid	-1632.18	163.18
Mn ₃ O ₄	solid	-1283.23	155.64
Mo	Molybdenum. gas	612.54	181.84
Mo	solid	0.00	28.66
Mo(CO) ₆	solid	-877.8	325.93
MoF ₆	liquid	-1473.1	259.66
MoO ₂	solid	-533.04	46.28
MoO ₃	solid	-668.02	77.74
MoS ₂	solid	-225.94	62.59
N	Nitrogen. gas	455.58	153.19
NFO	gas	-51.04	247.99
NF ₃	gas	-83.26	260.62
NH ₃	gas	-16.48	192.34
NH ₃	aqueous sol.	-26.57	111.29
NH ₄ ⁺	aqueous sol.	-79.37	113.39
NH ₄ Cl	α .solid	-203.19	94.98
NH ₄ NO ₃	solid	-184.01	151.08
NH ₄ H ₂ PO ₄	solid	-1214.35	151.9
(NH ₄) ₂ SO ₄	solid	-899.9	220.3
NO	gas	86.57	210.65
NOCl	Nitrosylchloride. gas	66.11	261.63
NO ₂	gas	51.3	239.95
NO ₂ ⁻	aqueous sol.	-37.24	140.16
NO ₂ H	cis. gas	-42.97	248.66
NO ₂ H	trans. gas	-45.27	249.12
NO ₃ ⁻	aqueous sol.	-111.34	146.44
NO ₃ H	gas	-74.77	266.27
NO ₃ H	liquid	-80.79	155.6
N ₂	gas	0.00	191.5
Na	Sodium. gas	77.3	153.61
Na	liquid	0.5	57.85
Na	solid	0,00	51.45
Na ⁺	aqueous sol.	-261.89	58.99
NaBH ₄	solid	-127.11	101.39
NaBr	gas	-177.78	241.12
NaBr	solid	-349.26	86.82
NaCO ₃ H	Na-Hydrogencarb. solid	-851.86	102.09
NaC ₂ H ₃ O ₂	Na-Acetate. solid	-608.84	123.1
NaCl	gas	-201.32	229.7
NaCl	liquid	-365.68	95.06
NaCl	solid	-384.04	72.13
NaClO ₄	solid	-254.32	142.26
NaF	gas	-309.74	217.5
NaF	solid	-545.09	51.21
NaI	solid	-284.57	98.32
NaNO ₃	solid	-365.89	116.32
NaOH	gas	-215.93	236.4
NaOH	liquid	-375.13	74.17
NaOH	solid	-380.19	64.43
NaSO ₄ H	Na-Hydrogensulfate. solid	-992.86	112.97
Na ₂ CO ₃	liquid	-1031.88	155.39
Na ₂ CO ₃	solid	-1048.08	138.78
Na ₂ CO ₃ · 10 H ₂ O	solid	-3428.2	564,00
Na ₂ Cl ₂	gas	-565.94	325.52
Na ₂ O	solid	-379.11	75.04
Na ₂ O ₂	solid	-449.66	94.81
Na ₂ S	solid	-361.36	97.91
Na ₂ SO ₃	solid	-1002.07	146.02
Na ₂ SO ₄	Thenardite. solid	-1269.35	149.62
Na ₂ SO ₄ · 10H ₂ O	solid	-3647.4	592.04
Na ₂ S ₂ O ₃	solid	-1028.01	154.81
Na ₂ S ₂ O ₃ · 5H ₂ O	liquid	-2227.72	438.69
Na ₂ S ₂ O ₃ · 5H ₂ O	solid	-2230.07	372.38
Na ₂ SiO ₃	solid	-1467.38	113.85
Na ₂ Si ₂ O ₅	solid	-2324.25	164.05
Na ₃ AlF ₆	solid	-3114.1	238,00
Na ₃ PO ₄	solid	-1787.16	173.64
Nb	Niobium. gas	681.16	186.15
Nb	solid	0.00	36.4
NbBr ₅	solid	-510.45	259.41
NbC	solid	-136.82	35.4
NbCl ₃	solid	-518.82	146.44
NbCl ₃ O	solid	-782.41	142.26
NbCl ₄	solid	-606.68	184.1
NbCl ₅	solid	-683.25	210.46
NbF ₅	solid	-1699.12	160.25
NbN	solid	-205.85	34.52
NbO	solid	-378.65	48.12
NbO ₂	solid	-740.57	54.52
Nb ₂ O ₅	solid	-1766.07	137.24
Ne	Neon. gas	0.00	146.22
Ne	aqueous sol.	19.25	66.11
Ni	Nickel. gas	384.51	182.08
Ni	solid	0,00	29.87
Ni ⁺⁺	aqueous sol.	-45.61	-128.87
NiCO ₃	solid	-605.83	87.9
Ni(CO) ₄	gas	-587.27	410.45
Ni(CO) ₄	liquid	-588.27	313.38
NiCl ₂	solid	-259.06	97.65
NiF ₂	solid	-604.17	73.6
NiO	solid	-211.71	37.99
Ni(OH) ₂	solid	-447.27	87.86
NiS	solid	-79.5	52.97
NiSO ₄	solid	-759.81	92.05
Ni ₃ S ₂	solid	-197.07	133.89

O ... Se (Oxygen to Selenium)

Formula	Name. phase	μ in kG	S/n in Ct/mol
O	Oxigen. gas	231.75	160.95
OH ⁻	aqueous sol.	-157.29	-10.75
OH ₂	Water. gas	-228.59	188.72
OH ₂	liquid	-237.18	69.91
OH ₂	solid	-236.59	44.77
OH ₃ ⁺	Oxonium ion. aqueous sol.	-237.18	69.91
O ₂	gas	0.00	205.03
O ₂ H ₂	gas	-105.6	232.63
O ₂ H ₂	liquid	-120.42	109.62
O ₂ H ₂	aqueous sol.	-134.1	143.93
O ₃	gas	163.18	238.82
Os	Osmium. gas	744.75	192.46
Os	solid	0.00	32.64
OsO ₄	yellow. solid	-305.01	149.93
OsO ₄	white. solid	-303.76	167.78
P	Phosphorus. gas	280.02	163.09
P	liquid	0.09	42.89
P	red. solid	-12.13	22.8
P	white. solid	0.00	41.09
PBr ₃	liquid	-175.73	240.16
PCl ₃	gas	-267.78	311.67
PCl ₃	liquid	-272.38	217.15
PCl ₃ O	gas	-514.32	325.39
PCl ₃ O	liquid	-520.91	222.46
PCl ₅	gas	-305.01	364.47
PF ₃	gas	-897.47	273.13
PF ₅	gas	-1520.72	300.7
PH ₃	gas	13.39	210.12
PO ₄ ⁴⁻	aqueous sol.	-1018.8	-221.75
PO ₄ H ⁻	aqueous sol.	-1089.26	-33.47
PO ₄ H ₂ ⁻	aqueous sol.	-1130.39	90.37
PO ₄ H ₃	liquid	-1118.43	146.44
PO ₄ H ₃	solid	-1119.22	110.5
PO ₄ H ₃	aqueous sol.	-1142.65	158.16
P ₄ O ₆	gas	-2084.94	345.6
P ₄ O ₁₀	gas	-2669.85	403.76
P ₄ O ₁₀	hexagonal. solid	-2697.84	228.86
Pb	Lead. gas	161.92	175.26
Pb	liquid	2.22	71.72
Pb	solid	0.00	64.81
Pb ⁺⁺	aqueous sol.	-24.39	10.46
PbBr ₂	solid	-261.92	161.5
PbCO ₃	solid	-625.51	130.96
PbCl ₂	solid	-314.13	135.98
PbCl ₄	gas	-276.2	384.51
PbF ₂	solid	-617.14	110.46
PbI ₂	solid	-173.64	174.85
Pb(N ₃) ₂	monoclinic. solid	624.67	148.11
Pb(N ₃) ₂	orthorhomb.. solid	622.16	149.37
PbO	gas	26.36	239.94
PbO	liquid	-171.19	85.96
PbO	yellow. solid	-187.9	68.7
PbO	red. solid	-188.95	66.53
PbO ₂	solid	-217.36	68.62
Pb(OH) ₂	solid	-421.07	88.00
PbS	solid	-98.74	91.21
PbSO ₄	solid	-813.2	148.57
PbSiO ₃	solid	-1062.15	109.62
Pb ₃ O ₄	solid	-601.24	211.29
Pd	Palladium. gas	339.74	166.94
Pd	solid	0.00	37.57
Pd ⁺⁺	aqueous sol.	176.56	-117.15
PdCl ₂	solid	-125.1	104.6
PdI ₂	solid	-62.76	150.62
PdS	solid	-66.94	46.02
PdS ₂	solid	-74.48	79.5
Pt	Platinum. gas	520.49	192.3
Pt	solid	0.00	41.63
PtS	solid	-76.15	55.06
PtS ₂	solid	-99.58	74.68
Rb	Rubidium. gas	55.86	169.99
Rb	solid	0.00	69.45
Rb ⁺	aqueous sol.	-282.21	124.26
RbBr	solid	-378.15	108.28
RbI	solid	-325.52	118.03
Re	Rhenium. gas	724.67	188.83
Re	solid	0.00	36.86
ReCl ₃	solid	-188.28	123.85
ReO ₂	solid	-368.19	72.8
Re ₂ O ₇	solid	-1066.08	207.11
Rh	Rhodium. gas	510.87	185.7
Rh	solid	0.00	31.51
Ru	Ruthenium. gas	595.8	186.4
Ru	solid	0.00	28.53
RuO ₄	gas	-139.75	289.95
RuO ₄	liquid	-152.3	183.26
RuO ₄	solid	-152.3	146.44
S	Sulfur. gas	238.28	167.71
S	liquid	0.39	35.31
S	orthorhombic. solid	0.00	32.07
S	monoclinic. solid	0.04	32.75
S ⁻⁻	aqueous sol.	85.77	-14.64
SF ₆	gas	-1105.41	291.71
SH ₂	gas	-33.56	205.69
SH ₂	aqueous sol.	-27.87	121.34
SO	gas	-19.84	221.84
SO ₂	gas	-300.19	248.11
SO ₃	gas	-371.08	256.65
SO ₃	β . solid	-368.99	52.3
SO ₃ ⁻⁻	aqueous sol.	-486.6	-29.29
SO ₃ H ⁻	aqueous sol.	-527.81	139.75
SO ₃ H ₂	aqueous sol.	-537.9	232.21
SO ₄ ⁻⁻	aqueous sol.	-744.63	20.08
SO ₄ H ⁻	aqueous sol.	-756.01	131.8
SO ₄ H ₂	gas	-656.09	289.11
SO ₄ H ₂	liquid	-690.06	156.9
S ₂ Cl ₂	gas	-31.8	331.37
Sb	Antimon. gas	222.17	180.16
Sb	solid	0.00	45.69
SbBr ₃	solid	-239.32	207.11
SbCl ₃	gas	-301.25	337.69
SbCl ₃	solid	-323.72	184.1
SbCl ₅	gas	-334.34	401.83
SbCl ₅	liquid	-350.2	301.25
Sb ₂ O ₃	orthorhomb.. solid	-626.55	123.01
Sb ₂ O ₄	solid	-795.8	127.19
Sb ₂ O ₅	solid	-829.27	125.1
Sb ₂ S ₃	black. solid	-173.64	182.00
Sb ₂ Te ₃	solid	-55.23	234.3
Sb ₄ O ₆	cubic. solid	-1268.17	220.92
Sc	Scandium. gas	336.06	174.68
Sc	solid	0.00	34.64
ScF ₃	solid	-1555.61	92.05
Sc(OH) ₃	solid	-1233.44	100.42
Sc ₂ O ₃	solid	-1819.41	77.4
Se	Selenium. gas	187.07	176.61
Se	hexagonal. black. solid	0.00	42.44
SeF ₆	gas	-1016.71	313.76
SeH ₂	gas	15.9	218.91
SeO	gas	26.82	233.89

Si ... Zr (Silicon to Zircon)

Formula	Name. phase	μ in kG	S/n in Ct/mol
Si	Silicon. gas	411.29	167.86
Si	liquid	40.83	44.46
Si	solid	0.00	18.83
SiBr ₄	gas	-431.79	377.77
SiBr ₄	liquid	-443.92	277.82
SiC	α . hexagonal. solid	-60.25	16.48
SiC	β . cubic. solid	-62.76	16.61
SiCl ₄	gas	-617.01	330.62
SiCl ₄	liquid	-619.9	239.74
SiF ₄	gas	-1572.68	282.38
SiH ₄	gas	56.9	204.51
SiO	gas	-126.36	211.5
SiO ₂	gas	-306.93	228.86
SiO ₂	liquid	-850.21	47.93
SiO ₂	α -Cristobalite. solid	-853.67	50.05
SiO ₂	β -Cristobalite. solid	-854.54	43.4
SiO ₂	α -Quartz. solid	-856.67	41.84
SiO ₂	β -Quartz. solid	-856.48	41.46
SiO ₃ H ₂	solid	-1092.44	133.89
SiO ₄ H ₄	solid	-1333.02	192.46
Si ₂ O ₅ H ₂	solid	-1943.47	192.46
Si ₂ O ₇ H ₆	solid	-2425.88	330.54
Si ₃ N ₄	solid	-642.66	101.25
Sn	Tin. gas	267.36	206.03
Sn	α . grey. solid	0.13	44.14
Sn	β . white. solid	0.00	51.55
SnBr ₄	gas	-331.37	411.83
SnBr ₄	solid	-350.2	264.43
SnCl ₄	gas	-432.21	365.68
SnCl ₄	liquid	-440.16	258.57
SnH ₄	gas	188.28	227.57
SnO	solid	-256.9	56.48
SnO ₂	solid	-519.65	52.3
Sn(OH) ₂	precipitated	-491.62	154.81
SnS	solid	-98.32	76.99
Sr	Strontium. gas	110.04	164.54
Sr	solid	0.00	54.39
Sr ⁺⁺	aqueous sol.	-557.31	-39.33
SrCO ₃	Strontianite. solid	-1137.63	97.49
SrCl ₂	solid	-781.15	117.15
SrO	solid	-559.82	54.39
SrSO ₄	solid	-1334.28	121.75
Te	Tellurium. gas	157.11	182.63
Te	solid	0.00	49.71
TeO ₂	solid	-270.29	79.5
Ti	Titanium. gas	425.09	180.19
Ti	solid	0.00	30.63
TiBr ₃	solid	-523.84	176.56
TiBr ₄	solid	-589.53	243.51
TiC	solid	-180.75	24.23
TiCl ₂	solid	-464.42	87.45
TiCl ₃	solid	-653.54	139.75
TiCl ₄	liquid	-737.22	252.34
TiF ₄	amorphous	-1559.38	133.97
TiH ₂	solid	-80.33	29.71
TiI ₄	solid	-371.54	249.37
TiN	solid	-309.62	30.25
TiO	α . solid	-494.97	34.77
TiO ₂	Anatase. solid	-884.5	49.92
TiO ₂	Rutile. solid	-889.52	50.33
Ti ₂ O ₃	solid	-1434.28	78.78
Tl	Thallium. gas	147.44	180.85
Tl	solid	0.00	64.18
Tl ⁺	aqueous sol.	-32.38	125.52
Tl ⁺⁺⁺	aqueous sol.	214.64	-192.46
TlBr	solid	-167.36	120.5
TlCl	solid	-184.93	111.25
TlI	solid	-125.39	127.61
TlNO ₃	solid	-152.46	160.67
TlOH	solid	-195.76	87.4
Tl ₂ CO ₃	solid	-614.63	155.23
Tl ₂ O	solid	-147.28	125.52
Tl ₂ S	solid	-93.72	150.62
Tl ₂ SO ₄	solid	-830.48	230.54
U	Uranium. gas	478.82	198.52
U	solid	0.00	50.33
U ⁺⁺⁺	aqueous sol.	-520.49	-125.52
U ⁺⁺⁺⁺	aqueous sol.	-579.07	-326.35
UBr ₄	solid	-788.68	242.67
UC ₂	solid	-175.73	58.58
UCl ₄	solid	-962.32	198.32
UCl ₆	solid	-1010.44	285.77
UF ₄	solid	-1761.46	151.04
UF ₆	solid	-2033.42	227.82
UI ₄	solid	-527.6	271.96
UN	solid	-313.8	75.31
UO ₂	solid	-1075.29	77.82
UO ₃	solid	-1184.07	98.62
V	Vanadium. gas	453.21	182.19
V	solid	0.00	28.91
V ⁺⁺	aqueous sol.	-217.57	-129.7
V ⁺⁺⁺	aqueous sol.	-242.25	-230.12
VCl ₂	solid	-405.85	97.07
VCl ₃	solid	-511.28	130.96
VCl ₃ O	liquid	-668.6	244.35
VCl ₄	liquid	-503.75	255.22
VF ₅	liquid	-1373.19	175.73
VN	solid	-191.21	37.28
VO	solid	-404.17	38.91
VSO ₄	solid	-1169.85	108.78
V ₂ O ₃	solid	-1139.3	98.32
V ₂ O ₄	α . solid	-1318.38	102.51
V ₂ O ₅	solid	-1419.63	130.96
W	Tungsten. gas	807.09	173.84
W	liquid	43.07	45.7
W	solid	0.00	32.64
WCl ₆	α . solid	-455.65	238.49
WF ₆	gas	-1632.18	340.95
WF ₆	liquid	-1631.47	251.46
WO ₂	solid	-533.92	50.54
WO ₃	solid	-764.08	75.9
Xe	Xenon. gas	0.00	169.57
Xe	aqueous sol.	13.39	65.69
Zn	Zinc. gas	95.18	160.87
Zn	solid	0,00	41.63
Zn ⁺⁺	aqueous sol.	-147.03	-112.13
ZnBr ₂	solid	-312.13	138.49
ZnCO ₃	solid	-731.57	82.42
ZnCl ₂	solid	-369.43	111.46
ZnF ₂	solid	-713.37	73.68
ZnI ₂	solid	-208.95	161.08
ZnO	solid	-318.32	43.64
Zn(OH) ₂	solid	-555.13	81.59
ZnS	Zinc blende. solid	-201.29	57.74
ZnSO ₄	solid	-874.46	119.66
Zr	Zirconium. gas	566.51	181.25
Zr	solid	0.00	38.99
ZrC	solid	-199.58	32.17
ZrCl ₄	solid	-889.94	181.59
ZrF ₄	β . monoclinic. solid	-1810,00	104.6
ZrH ₂	solid	-128.87	35.02
ZrN	solid	-336.39	38.87
ZrO ₂	α . monoclinic. solid	-1042.82	50.38

Table of separation energies

Z = Number of protons
 N = Number of neutrons
 E_s = Separation energy (in pJ)

	Z	N	E _s
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H	1	0	0,00
		1	0,36
		2	1,36

He	2	1	1,24
		2	4,53
		3	4,39
		4	4,69

Li	3	2	4,22
		3	5,13
		4	6,29
		5	6,61
		6	7,26

Be	4	3	6,02
		4	9,05
		5	9,32
		6	10,41
		7	10,49

B	5	3	6,05
		4	9,02
		5	10,37
		6	12,21
		7	12,75
		8	13,53

C	6	3	6,25
		4	9,71
		5	11,77
		6	14,77
		7	15,56
		8	16,87

N	7	5	11,86
		6	15,08
		7	16,77
		8	18,50
		9	18,90
		10	19,84
		11	20,30

O	8	6	15,82
		7	17,94
		8	20,45
		9	21,11
		10	22,40
		11	23,03
		12	24,25

F	9	8	20,54
		9	22,01
		10	23,68
		11	24,74
		12	26,04
		13	26,87
		14	28,08

Ne	10	7	18,09
		8	21,17
		9	23,04
		10	25,74
		11	26,82
		12	28,48
		13	29,31
		14	30,74
		15	31,42

Na	11	9	23,39
		10	26,13
		11	27,90
		12	29,89
		13	31,01
		14	32,45
		15	33,35
		16	34,44

Mg	12	9	23,90
		10	27,01
		11	29,12
		12	31,76
		13	32,94
		14	34,72
		15	35,75
		16	37,11
		17	37,72

Al	13	11	29,41
		12	32,13
		13	33,95
		14	36,04
		15	37,28
		16	38,79
		17	39,71

Si	14	12	33,01
		13	35,14
		14	37,90
		15	39,25
		16	40,95
		17	42,01
		18	43,48
		19	41,23

P	15	13	35,48
		14	38,34
		15	40,15
		16	42,12
		17	43,39
		18	45,01
		19	46,02

S	16	14	39,04
		15	41,13
		16	43,54
		17	44,93
		18	46,76
		19	47,88
		20	49,46
		21	50,15
		22	51,44

Cl	17	16	43,91
		17	45,75
		18	47,78
		19	49,15
		20	50,80
		21	51,78
		22	53,08
		23	54,01
		24	55,28

Ar	18	16	44,66
		17	46,70
		18	49,14
		19	50,55
		20	52,45
		21	53,50
		22	55,08
		23	56,06
		24	57,57
		25	58,47
		26	59,81

K	19	18	49,44
		19	51,37
		20	53,47
		21	54,72
		22	56,33
		23	57,54
		24	59,09
		25	60,25
		26	61,68
		27	62,78
		28	64,12

Ca	20	18	50,17
		19	52,30
		20	54,80
		21	56,14
		22	57,98
		23	59,25
		24	61,04
		25	62,22
		26	63,89
		27	65,05
		28	66,65
		29	67,47
		30	68,49

Sc	21	21	56,83
		22	58,77
		23	60,32
		24	62,14
		25	63,54
		26	65,25
		27	66,57
		28	68,19
		29	69,16

Ti	22	21	57,55
		22	60,16
		23	61,68
		24	63,80
		25	65,22
		26	67,08
		27	68,39
		28	70,14
		29	71,16
		30	72,41
		31	73,28

V	23	23	62,54
		24	64,62
		25	66,31
		26	68,16
		27	69,66
		28	71,43
		29	72,60
		30	73,96
		31	74,94

Cr	24	22	61,20
		23	63,31
		24	65,92
		25	67,62
		26	69,70
		27	71,18
		28	73,11
		29	74,39
		30	75,94
		31	76,94
		32	78,27

Mn	25	25	68,35
		26	70,55
		27	72,23
		28	74,16
		29	75,60
		30	77,44
		31	78,24
		32	79,79
		33	80,81

Fe	26	25	69,13
		26	71,73
		27	73,44
		28	75,08
		29	77,07
		30	78,87
		31	80,09
		32	81,70
		33	82,76
		34	84,17
		35	85,06
		36	86,35

Co	27	27	74,14
		28	76,39
		29	78,01
		30	79,83
		31	81,21
		32	82,88
		33	84,08
		34	85,63
		35	86,57
		36	87,99

Ni	28	27	74,88
		28	77,54
		29	79,18
		30	81,14
		31	82,58
		32	84,41
		33	85,66
		34	87,36
		35	88,45
		36	90,00
		37	90,98
		38	92,42
		39	93,34

	Z	N	E _s
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Cu	29	30	81,69
		31	83,30
		32	85,18
		33	86,60
		34	88,34
		35	89,61
		36	91,20
		37	92,33
		38	93,79
		39	94,80

Zn	30
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