Exploring energy and equilibrium through simple experiments

Explorant l'energia i l'equilibri mitjançant experiments senzills

Prof. Dr. Klemens Koch / Didactics of chemistry, Pedagogical University Berne and Gymnasium Biel-Seeland, Switzerland

abstract

Energy moves us and entropy determines the direction, e.g. of chemical equilibria. They are behind chemistry, they accompany us through chemistry lessons and many everyday problems, such as the climate debate. This article aims to get to the bottom of the energy concepts in chemistry and their application in chemistry teaching by looking at about a dozen phenomena in ten experiments. The role of entropy is only touched on in passing; dealing with it explicitly would be a topic in itself.

keywords

Experiments, energy, heat and work, collision theory, catalysis, chemical equilibrium.

resum

L'energia ens mou i l'entropia en determina la direcció, per exemple dels equilibris químics. Aquests termes químics ens acompanyen en les classes de química i de molts problemes quotidians, com el debat climàtic. Aquest article pretén arribar al fons d'aquests termes i la seva utilització en l'ensenyament de la química analitzant una dotzena de fenòmens en deu experiments.

paraules clau

Experiments, energia, calor i treball, teoria de col·lisions, catàlisi, equilibri químic.

1. Introduction: Energy, entropy and equilibrium

Energy is an abstract quantity with accordingly great potential to explain much in the world. Energy is the ability to work or transfer heat. Energy can be stored: A 100 g bar of chocolate 1 m above a surface has a potential energy of 1 joule, but also a chemical energy of about 2.300.000 joule!

Energy can be converted, e.g. the chemical energy of chocolate can be converted into kinetic energy during sport. Energy can also be transferred, e.g. electromagnetically, as light when a candle burns. Much of this is put into a framework by the first law of thermodynamics.The direction in which a chemical reaction proceeds and how it relates to its counter-reaction in a chemical equilibrium is described by entropy and the second law of thermodynamics.

This article is less about the basics of thermodynamics than about related experiments. The special significance of work and heat, light energy, electrical energy, activation energy and catalysis as well as the effect on the course of chemical reactions and the dynamic chemical equilibrium, will be shown.

Table 1 lists the experiments included in this article. The experiments can be carried out individually or in combination:

Experiments 1 to 3 show the basics of the energy concept: Experiment 1 the distinction between work and heat, regarding entropy and description with the GIBB equation. Experiment 2 shows the importance of volume-pressure work in chemical reactions. Experiment 3 shows the quantisation of energy at the atomic level with great significance in chemistry. The use of electrical energy in chemistry and electromagnetic phenomena are shown in experiment 4.

The collision theory and the role of activation energy is shown in experiments 5 to 7 and continued to a "reaction at a distance" in batteries. Catalysis is discussed

DOI: 10.2436/20.2003.02.251 https://revistes.iec.cat/index.php/EduQ/index
ISSN 2013-1755, SCQ-IEC Educació Química EduQ número 32 (2023), p. 45-54

exemplarily in experiment 8 and in the model in experiment 9. The chemical equilibrium of a system of everyday reactions with carbonates and carbonic acid is shown in a "rainbow" in experiment 10.

thermal energy. This is demonstrated by stretching and releasing the neck of a rubber balloon. It is also shown how heat is absorbed or released, which makes interesting connections to changes of state and refrigerators.

Experiment	Title
1	Work and heat, hot and cold with a rubber balloon
2	Pressure-volume work: The expanding and inverted glove
3	Energy of light in different colours and quanta
4	Water electrolysis multiplied and magnetically influenced
5	Smashing thermite - collision theory
6	Silvering by rubbing - activation energy with the thumb
7	Aluminium-air battery – reaction energy without collision?
8	Ethanol oxidation on a copper spiral - similar to biochemistry?
9	Connecting paper clips with a trick - a model for catalysis?
10	Chemical rainbow - equilibria in series

Table 1. Experiments to construct and relate the ideas of energy, entropy, links to chemistry and equilibrium.

2. Exp. 1. Work and heat, hot and cold with a rubber balloon

Thermodynamics is about heat and work transfer and entropy.

There is a fundamental difference between work and

How to proceed

Take a rubber balloon by the neck. Stretch the neck and release it.

– Predict the energetic changes by the stretching and the releasing of rubber, work and heat.

– In the released state: Feel with your upper lip or measure the temperature of the balloon skin with an IR thermometer.

– Stretch the neck of the balloon and feel or measure the temperature of the balloon skin again in the stretched state.

– Keep the neck of the balloon stretched and let it adjust to room temperature.

– Release the neck of the balloon and feel or measure the temperature of the balloon skin again.

Explanations

Stretching needs work and means approaching the molecules and aligning them in parallel. This releases energy as heat (figure 1).

It is analogous to the liquefaction of gases, e. g. for gas lighters. When a gas is compressed, the molecules are brought closer together. This releases energy in the form of heat (figure 2).

The expansion and release of a balloon is analogous to the change of the state of aggregation (figures 1 und 2).

Releasing the balloon requires energy in the form of heat (-> cold), like the evaporation from liquid to gas.

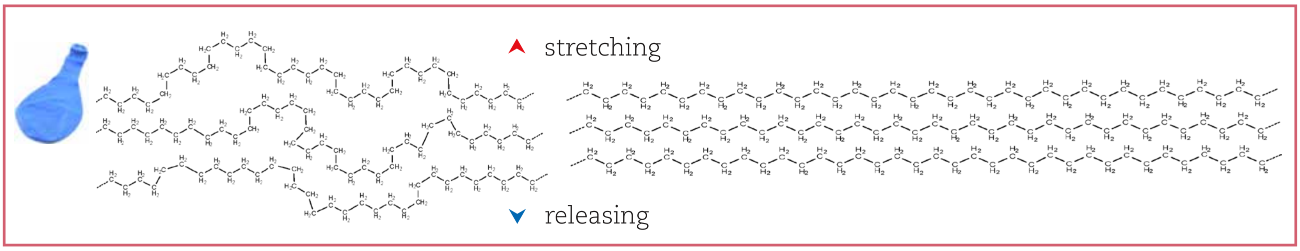

Figure 1. Molecular representation of the released (left) and the stretched (right) state.

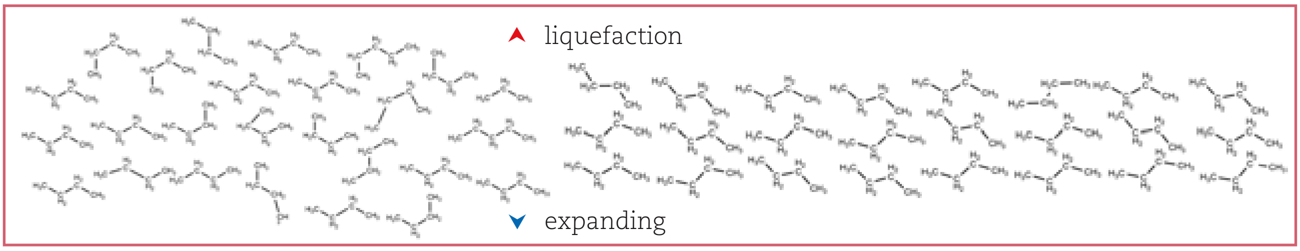

Figure 2. Molecular representation of Butane in the gaseous (left) respectively in the liquid (right) state. Note the similarity with figure 1.

When stretching, the molecules approach each other like in the condensation process. This releases energy in the form of heat.

It is a model for a refrigeration machine where heat is absorbed by evaporation of a liquid and released outside the refrigerator by condensation of the gas. As the condensation is not spontaneous, the refrigeration machine has to do the work by compressing the gas.

Inversely, it is a model of a heat pump. With work, a gas is condensed, and heat is released in one place and absorbed in another place when the liquid evaporates.

When the balloon is stretched using work, the molecules are forced to approach and align in parallel. As they come closer, energy is released in the form of heat.

The phenomena can be well understood with the GIBBS equation:

Stretching (non-spontaneous):

$$\Delta G = \Delta H - T \cdot \Delta S$$

>0 (work!) <0 >>0 (<<0)

Release means to let the molecules spontaneously separate and work. It absorbs energy as heat, which makes it cold.

But why do the molecules move away from each other if there is an attraction between them? The explanation implies entropy. The entropy in the rubber increases.

Releasing (spontaneous):

$$\Delta G = \Delta H - T \cdot \Delta S$$

Further activities

You can hang a weight on a rubber band. Look at the GIBBS equation and predict what should happen when you heat the rubber band with a hair dryer.

3. Exp. 2. Pressure-volume work: The expanding and inverted glove

Pressure-volume-work makes the difference between energy and enthalpy.

This experiment shows why enthalpy describes chemical reactions more appropriately than energy:

Expand a glove by producing carbon dioxide and reverse the process by absorbing carbon dioxide. The pressure-volume work adds to the energy.

The reaction between sodium carbonate and citric acid produces carbon dioxide gas. The gas must create space in a certain volume against the air pressure; energy is converted by pressure-volume work.

In the reverse reaction with a base, carbon dioxide gas is absorbed; the same amount of pressure-volume work is converted back.

How to proceed

Expanding Glove (figure 3a)

Put a heaped teaspoon sodium hydrogen carbonate (≈ 7 g $NaHCO_3$) and citric acid (≈ 6 g $C_6H_8O_7$) in the empty glass jar (minimum height 20 cm, opening 8 - 12 cm). Fill the glove with about 15 ml of water, put it over the rim of the jar and let the fingers hang outwards. To start the reaction, pour the water into the glass jar and move the jar to start the reaction.

Observation

As the water mixes with the powders a gas starts to evolve. The glove expands and straightens. Let the gas at the top escape once or twice.

Explanation

The sodium hydrogen carbonate dissolved in water and the citric acid carry out a chemical reaction that produces carbon dioxide. The gas expands the glove. The reaction is endothermic.

$$3\ NaHCO_3 + C_6H_8O_7 \rightleftarrows Na_3C_6H_5O_7 + 3\ CO_2 + 3\ H_2O$$

Reverse glove (figure 3b)

Add sodium hydroxide solution (approx. 4 g in 10 ml water, alternatively calcium oxide or or calcium hydroxide solution) to the glass vessel and put the glove back on.

Observation

The glove is reversed and pushed into the glass jar.

Explanation

The sodium hydroxide solution absorbs the carbon dioxide, and the pressure goes below atmospheric pressure. The atmospheric pressure pushes the glove into the glass bowl.

$$CO_2\ g + H_2O\ l \rightleftarrows H_2CO_3\ aq$$

$$H_2CO_3\ aq + 2\ NaOH\ aq \rightleftarrows Na_2CO_3\ aq\ \text{(sodium carbonate, soda)} + 2\ H_2O$$

$$\text{(or } H_2CO_3 + Ca(OH)_2\ aq \rightleftarrows CaCO_3\ \text{(calcium carbonate, lime)} + 2\ H_2O)$$

Figure 3. Expanding glove (a) against the air pressure and inverted glove (b) driven by the air pressure.

4. Exp. 3. Energy of light in different colours and quanta

The following experiment arranges LEDs according to light energy: Which ones need a high electrical voltage, which ones also shine with less voltage?

How to proceed

First connect one and then several LEDs (Light Emitting Diodes) to a lithium button battery. To do this, slide the connecting wires over the battery so that the longer wire is on the positive terminal.

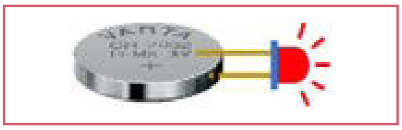

Figure 4a. How to connect an LED to the lithium button battery.

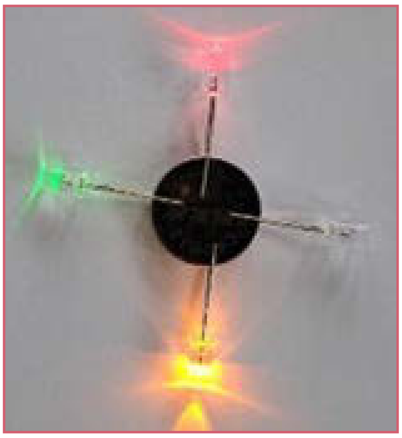

Figure 4b. Multiple LED on one button cell.

Depending on the colour, the LEDs need 2- 3.5 V voltage. The lithium battery generates approx. 3 V open-circuit voltage. The battery is also a resistor and prevents too much current from flowing.

Explanation

Light energy: LEDs emit light when electrons fall from a higher to a lower energy level and give off (light) energy in the process. The higher the fall, the more energy the light has, the more electrical energy it needs to bring the electrons to the higher level. The voltage drops as more LEDs are connected and is then no longer sufficient for the one with the greatest energy difference in light generation (figure 5).

In the follow-up experiment, the photoelectric effect in LED is used to show the quantum nature of light during emission and absorption and thus the discrete energy states in the atoms.

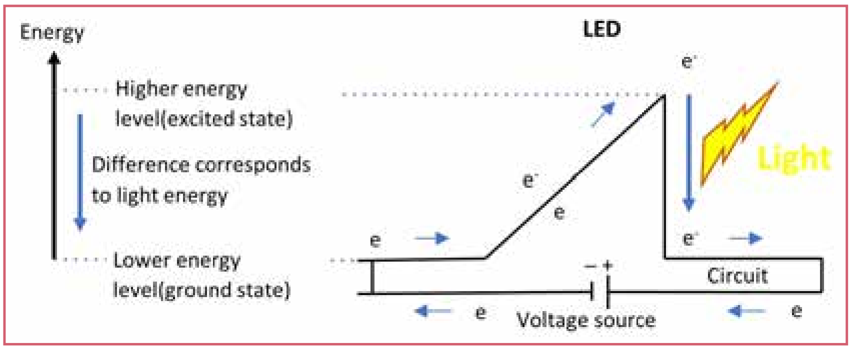

Figure 5. Simple model of an LED: A voltage source transports electrons to a higher energy level. From there they fall to a lower level, emit (light) energy and flow back in the circuit.

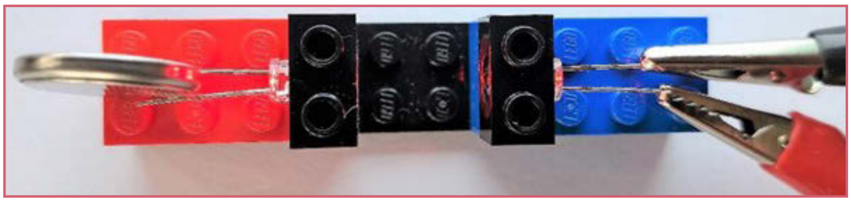

Figure 6. Juxtaposition of an emitting and a receiving LED with a LEGO construction.

How to proceed

Illuminate different receiver LEDs with different coloured emitting LEDs. Make sure that they are aligned straight, e.g. with the help of matching Lego® components.

Use a voltmeter to measure the voltage that is generated in the receiver LED after absorption. This is the counter-reaction to the generation of light in the emitting LED and shows the conversion of light into electrical energy.

For example:

– When a red, emitting LED illuminates a blue, absorbing LED.

– Or vice versa when a blue LED illuminates a red LED.

– Or when a red LED illuminates a red LED.

With coloured solutions or foils between equally coloured emitting and absorbing LEDs, we have a simple spectrometer.

Explanation

The absorbing LED only reacts when the right "energy portion" or the right light quantum or photon from a certain wavelength arrives. A blue LED does not react to red light, even if it is very intense. But it does react to blue light or UV light (figure 7).

A coloured solution or foil absorbs a proportion of the photons; this proportion can be linked to the concentration by the Beer-Lambert law. It is a model of a simple spectrometer.

5. Exp. 4. Water electrolysis multiplied and magnetically influenced

The introductory experiment shows the chemical reactions, especially acid/base effects, when the current flows from the electrode to the electrolyte and vice versa.

How to proceed

A sodium sulphate electrolyte solution 0.1M is mixed with universal indicator and set to neutral with calcareous, slightly basic tap water or with a little sodium bicarbonate. It is electrolysed with two carbon electrodes and a voltage of 9 V - 18 V. Red cabbage juice can also be used as

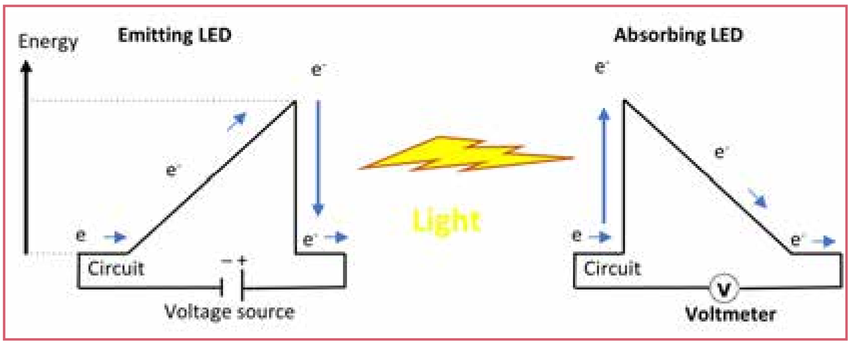

Figure 7. Model of energy transfer by quanta in the juxtaposition of an emitting and a receiving LED.

a “universal indicator”. The carbon electrodes are short sections of carbon rods, such as those used in model making or for kites. Pencil leads also work. Sodium sulphate is used because this salt is inert to electrolysis in water.

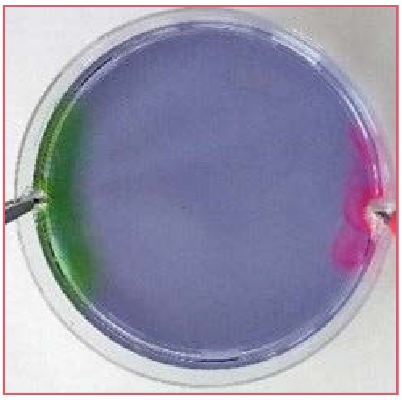

Figure 8. The colours change at both poles, here with red cabbage juice.

Explanation

Minus pole - cathode $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

Water is reduced at the cathode (negative pole) and H_2 g and OH^- aq are released.

The solution becomes basic. The solution becomes purple with the universal indicator and green with the red cabbage juice (figure 8).

Positive pole + anode $2\ H_2O \rightarrow O_2 + 4\ H^+ + 4\ e^-$

Water is oxidised at the anode (positive pole) and O_2 g and H^+ aq are released.

The solution becomes acidic. The solution turns red with both indicators (figure 8).

Total reaction (cathode reaction double): $6\ H_2O \rightarrow O_2 + 2\ H_2 + 4\ OH^{--} + 4\ H^+$

after neutralisation: $6\ H_2O \rightarrow O_2 + 2\ H_2 + 4\ H_2O$

simplified: $2\ H_2O \rightarrow O_2 + 2\ H_2$

When stirring the reaction mixture, the neutralisation of equal amounts of hydrogen cations H^+ aq and hydroxide anions OH^- aq always results in a neutral green solution.

Double electrolysis with a carbon bipolar electrode

The electrolysis experiment becomes more impressive when the current enters and leaves the electrolysis several times. This is technically used for high-voltage electrolysis instead of high-current electrolysis.

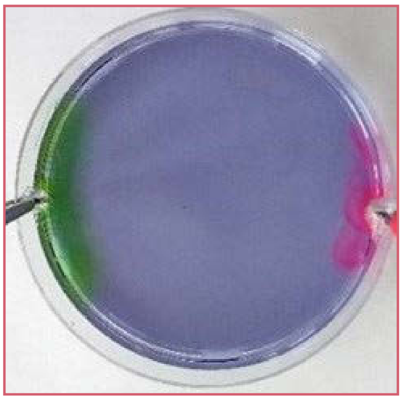

Figure 10. Colour change of the red cabbage juice during electrolysis with a bipolar electrode.

How to proceed

For this purpose, another carbon rod, approx. 5 cm long, is placed in the centre of the Petri dish. The neutral sodium sulphate electrolyte solution with universal indicator is electrolysed with two carbon rods and 13-18 V.

Observations

The same colour changes occur as in the previous experiment, but in addition, a red and a violet spot form again on the carbon rod placed in the centre (figure 10).

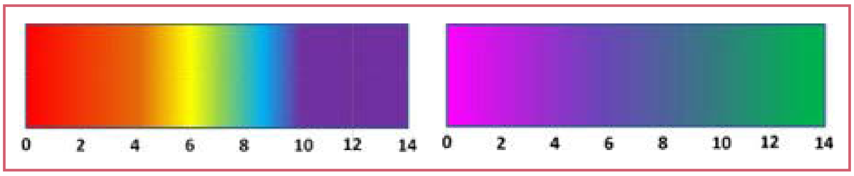

Figure 9. Colours of a universal indicator dye solution (left) and red cabbage juice (right, at high pH values a slow secondary reaction to yellow dyes is going on) at different pH values.

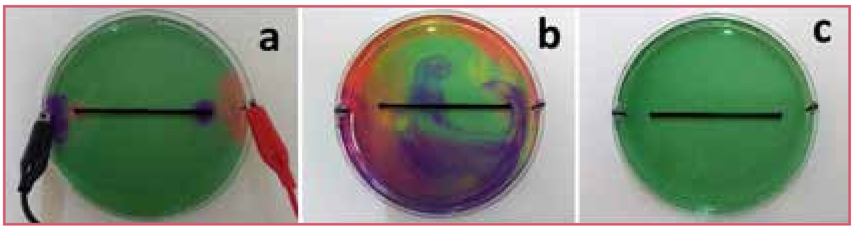

Figure 11. Colours of the universal indicator. a: after electrolysis with bipolar electrode; b: during mixing of the reaction solution; c: after mixing of the reaction solution.

When mixing the reaction solution after the end of electrolysis, a wonderful range of colours is produced in between and a green solution again at the end (figure 11).

Explanation

Part of the current flows through the bipolar electrode. At the ends of the bipolar electrode, there is again a "current translation" from ion current to electron current and vice versa, associated with the reduction or oxidation of the water and the corresponding colour appearances.

Variation with an LED as bipolar electrode

The proof that current flows through the bipolar electrode in the solution can also be provided by an LED: The feet of an LED are bent flat sideways, and it is placed in the electrolyte solution. The solution is electrolysed with two movable carbon rod electrodes and 13-18 V. The electrodes are immersed in the electrolyte solution and moved closer and closer to the terminals of the LED from the edge, without touching them, until the LED starts to light up. The cathode must approach the short terminal of the LED (negative pole), the anode the long terminal (positive pole).

Observations and discussion

The LED lights up and electrolysis starts at the electrodes with the familiar colour change of the universal indicator where ion current translates into electron current at the LED wire ends after electrolysis and vice versa (figure 12).

Variation: Electrolyte current in the magnetic field - Rotation of the electrolyte

The Petri dish with the neutral sodium sulphate electrolyte solution mixed with universal

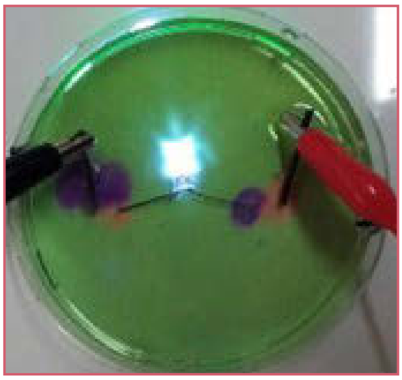

Figure 12. Electrolysis with an LED as bipolar electrode.

indicator is placed on a strong disc magnet. The solution is electrolysed with 9-18 V and two carbon rods, which are positioned to the left and right of the disc magnet.

Observation

The solution starts to rotate in two opposite directions (figure 13).

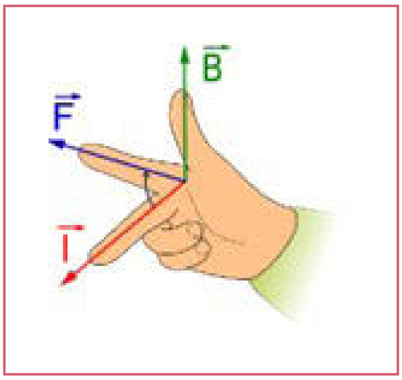

Figure 14. Right-hand rule for magnetic field, current and Lorentz force.

aurora, generator, electric motor, etc.

Variation with salt and pepper

In a petri dish or other shallow vessel, dissolve some table salt in water and sprinkle a little fine pepper powder on the surface. Place the vessel on a disc-shaped super magnet and electrolyse the

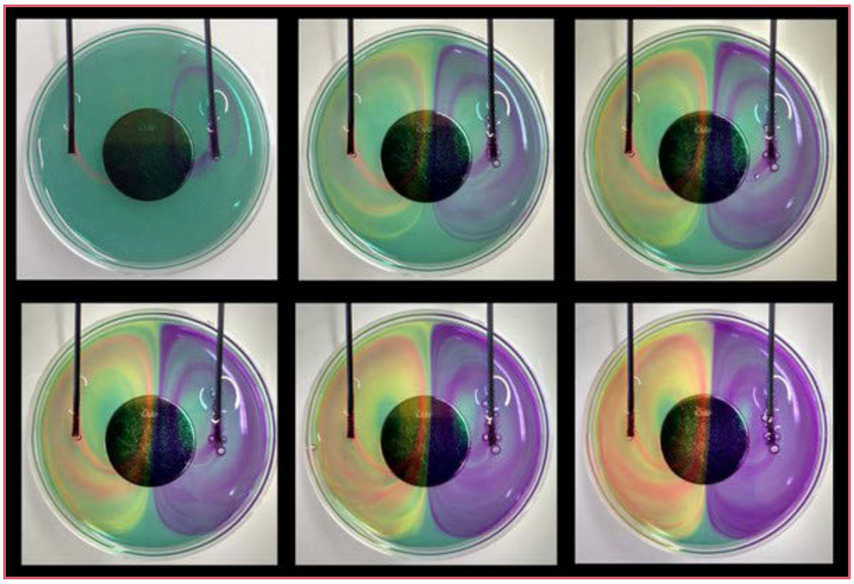

Figure 13. Development of water electrolysis with universal indicator in the magnetic field in 90s steps.

Explanation

The three physical quantities: magnetic field, electric current and force are causally connected and are oriented in the three spatial directions according to the right-hand rule (figure 14).

This physical phenomenon has great importance and many applications in electromagnetic effects: Electromagnetic radiation,

solution with two carbon rods and 9-18 V as above. The pepper powder shows a circular movement of the electrolyte.

6. Exp. 5. Smashing thermite - collision theory

Reactions start when particles with sufficient activation energy meet in suitable alignment (collision theory), which is nicely illustrated by the following experiment.

If two rusty iron balls collide in the macro world, their particles also collide in the micro world; if there is aluminium foil between them, this leads to a thermite reaction.

How to proceed

Wear safety goggles and hearing protection. A rusty iron ball of approx. 5 cm diameter is struck tangentially with a second rusty ball wrapped in aluminium foil. There is a bang and sparks fly.

Explanation

Hot iron particles are produced in a strongly exothermic thermite reaction.

$$2\ Al + Fe_2O_3 \rightarrow Al_2O_3 + 2\ Fe$$

Subsequently, the hot iron particles burn up.

$$3\ Fe + 2\ O_2 \rightarrow Fe_3O_4$$

Figure 15. Sparks when the balls collide with aluminium foil in between.

7. Exp. 6. Silvering by rubbing - activation energy with the thumb

Particles can overcome the activation energy with friction.

With the following solid-state reaction, metals containing copper such as brass, bronze, aluminium bronze or copper itself can be coated with silver by rubbing.

How to proceed

Rub-on silver plating: Clean and degrease the surface. Take up some silvering mixture with a damp cloth and rub the slurry onto the non-ferrous metal surface until it is completely coated. Then rinse the surface with water and polish with lime powder.

To prepare the silvering mixture: Pulverise finely: 3 parts silver chloride AgCl, 15 parts sodium chloride NaCl (not iodised!) and 20 parts potassium hydrogen tartrate ($KC_4H_5O_6$) (mass fractions).

Mix the powders and store them away from light.

Explanation

Silver(I) is reduced to silver, which forms a coating. Copper and the other less noble metals are oxidized.

$$Cu + 2\ AgCl \rightarrow 2Ag + CuCl_2$$

8. Exp. 7. Aluminium-air battery – reaction energy without collision?

(Redox) reactions can also take place without collision of particles if the electrons flow via an electrical conductor.

A lot of energy is released in the two following redox reactions:

$$4\ Al\ s + 3\ O_2\ g/aq \rightarrow 2\ Al_2O_3\ s$$

Oxygen in the air oxidises aluminium

or

$$4\ Al\ s + 12\ H^+\ aq \rightarrow 6\ H_2\ g$$

Acid oxidises aluminium

The energy can be released as heat, but also as electrical work if the reactions take place at different locations, e.g. in a battery:

How to proceed

About 40 ml of granulated activated carbon is placed on a piece of aluminium foil (approx. 15 cm x 15 cm) and moistened with semi-saturated saline solution. A graphite plate electrode (approx. 70 mm x 40 mm) is placed on top. The voltage of approx. 0.9 V between the aluminium foil and the graphite electrode operates an LED lamp or an electric motor with a low starting voltage (solar electric motor) for a long time. The activated carbon must be moistened regularly. The activated carbon can be returned to the storage vessel, even when moist, and reused. The aluminium foil

Figure 16. Silver-plated copper- and brass-plated coins.

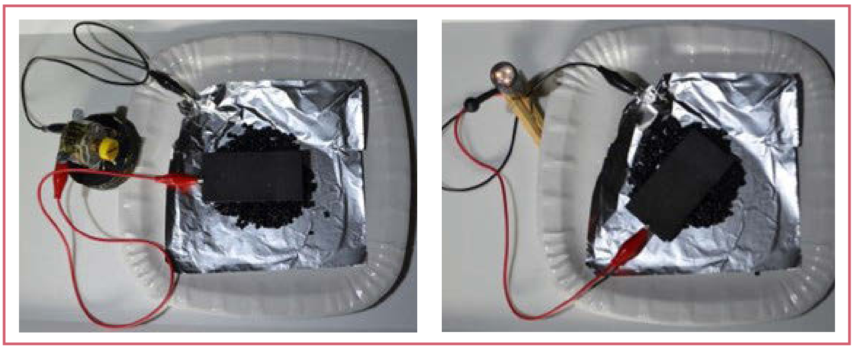

Figure 17: Aluminium/air battery with electric motor (left) or low-voltage LED lamp (right).

shows a fractal corrosion pattern after the experiment.

Explanation

The reactions take place in separate locations, at the anode (negative pole) and the cathode (positive pole) of the battery. The energy of the electron flow is used for a lamp or a motor. The ions move in the water (electrolyte) and close the circuit.

Minus pole: $4\ Al \rightarrow 4\ Al^{3+} + 12\ e^-$

Plus pole: $3\ O_2 + 12\ e^- \rightarrow 6\ O(-II)$ resp. Plus pole: $12\ H^+ aq + 12\ e^- \rightarrow 6\ H_2\ g$

9. Exp. 8. Ethanol oxidation on a copper spiral - similar to bio-chemistry?

Many reactions save activation energy thanks to catalysts - this is also a characteristic of the phenomenon of life.

Alternately, copper is oxidised in air and copper oxide is reduced in ethanol vapour. The transition from these reaction steps to continuous ethanol oxidation with oxygen shows that and how copper acts as a catalyst.

Caution: Ethanal and ethanol are flammable and hazardous to health (e.g. causes headaches). Work in a fume cupboard or with good ventilation.

Preparation

A piece of copper wire (length approx. 40 cm, diameter approx. 1 mm) is wound in a spiral around a pencil or similar, leaving about 25 cm free end. This free end is bent so that it can be hung in a wide-necked 200 mL Erlenmeyer flask and the copper spiral hangs about 4 cm above the bottom. It is advantageous if it does not hang at the same height everywhere (figure 18a).

How to proceed

The bottom of a wide-necked 250 mL Erlenmeyer flask is heated and approx. 5 mL ethanol is added so that ethanol vapours are produced. The copper wire spiral is heated to glowing with a gas burner, hung in the Erlenmeyer flask still glowing, pulled out, hung in again, pulled out, etc. It is finally hung in. Finally, it is hung in and left hanging.

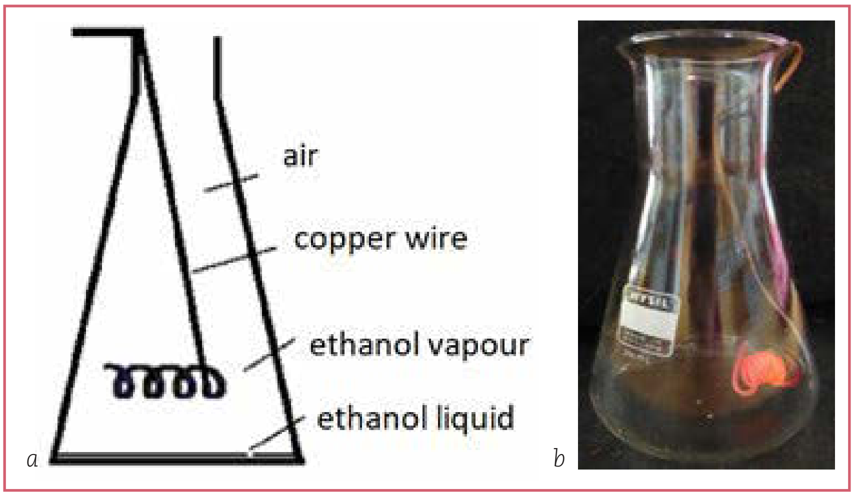

Figure 18: Copper wire in spiral form in ethanol vapours (a: preparation scheme and b: photo of the final reaction).

Observation and explanation

Oxygen in the air oxidises copper in the flame to copper oxide:

$$Cu\ s + ½\ O_2\ g \rightarrow CuO\ s$$

Ethanol vapours reduce copper oxide and are oxidised to ethanal:

$$CuO\ s\ +\ CH_3CH_2OH\ g \rightarrow Cu\ s\ +\ CH_3CHO\ g\ +\ H_2O\ g$$

If the spiral hangs where oxygen and ethanol vapours are present, the reaction happens in one step and the copper spiral glows due to the reaction energy and a grass-like aldehyde smell is perceived (figure 18b). The two reactions occur together. Copper is a catalyst or oxidation mediator (via the intermediate CuO):

$$CH_3CH_2OH\ g\ +\ ½\ O_2\ g \xrightarrow{Cu} CH_3CHO\ g\ +\ H_2O\ g$$

Compare the reaction and the system with processes in living organisms!

10. Exp. 9. Connecting paper clips with a trick - a model for catalysis?

Reactions run more easily with catalysis - is there a magic trick behind it?

Starch molecules are long chains of condensed α-glucose molecules and are hardly accessible purely synthetically. Nature produces billions of tons every year. How does it do it? Does it have a trick?

All large nutrient molecules of carbohydrates, fat and proteins are built up from small molecular building blocks by condensation and broken down again during digestion.

Monosaccharides (e.g. glucose or fructose) condense into disaccharides (e.g. sucrose) or polysaccharides (e.g. starch), amino acids condense into proteins. This requires synthase enzymes and triphosphates, similar to ATP, as an energy source.

How an enzyme can combine two small molecules into a larger one is complex and cannot be observed directly. To better understand the mechanism, we describe it with models.

How to proceed

Take a paper strip of approx. 20 x 5 cm. Fold a few centimetres in an S-shape in the middle. The fold has three layers. Put a paper clip over the front two layers of the fold on the left and one over the back two layers on the right (figure 19 a-c). Pull on both ends of the paper strip so that the fold comes loose and the paper clips join.

or worse. They stop working when they are poisoned, or they stop working when it is too hot, when they lose their natural structures and denaturate. Enzymatic condensation is not a magic trick, it is more sophisticated!"

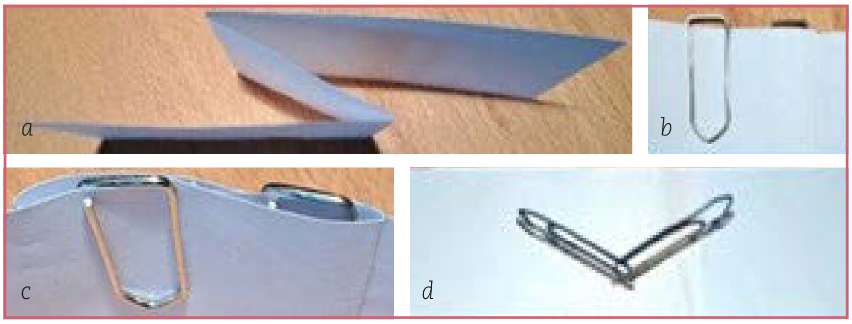

Figure 19. a-c : Folding the paper strip and attaching the paper clips. d: Connected paper clips after pulling up the paper strip.

Does the paper clip-paper strip model fit for enzymatic condensation?

Understanding the world means recognising connections. Models are all the more useful for this purpose, the more appropriately they depict the complex processes of nature. Compare the process of enzymatic reactions in living organisms with the model of the paper clip and the strip of paper? Find equivalents for the words in bold.

"Enzymes catalyse, for example, the combination of two monosaccharides to form a disaccharide. This connection requires energy supply from ATP molecules. Enzymes have active sites where the substrates fit in (lock-and-key principle) and first form an enzyme-substrate complex. For starch, thousands of glucose molecules are joined, not simultaneously, but step by step. The joining step takes place in the enzyme according to an optimised reaction mechanism. Understanding chemistry often means elucidating reaction mechanisms. With allosteric inhibition, enzymes work slower

Explanation

An astonishing number of aspects of enzyme action can be associated (~) with the paper-clip model:

enzyme ~ folded paper strip

Monosaccharide ~ one paper clip; disaccharide two linked paper clips etc.

energy supply ~ mechanical work to connect two paper clips

active site ~ the locations where you attach the two paper clips to the paper strip

etc.

A model can never explain everything, but discussion and comparison reveal important aspects of the modelled situation.

11. Exp. 10. Chemical rainbow - equilibria in series

Enthalpy is exchanged in reactions; entropy ensures that dynamic chemical equilibria are formed.

In the following aqueous solution with a sodium carbonate/acetic acid concentration gradient, different equilibria occur. Which equilibria occur in which pH value and which carbonic acid-derived particles (species CO_3^{2-}, HCO_3^-, H_2CO_3 bzw. H_2O/CO_2 (aq/g) are involved?

How to proceed

Fill a test tube with acetic acid solution CH_3COOH aq 0.1M to ¾ of its height. Add universal indicator dye solution. Hold the test tube at an angle and let the saturated sodium carbonate solution flow with the pipette along the test tube wall to the bottom until some colourless sodium carbonate solution has collected at the bottom.

Observation and explanation

A rainbow of colours appears in the test tube (figure 20).

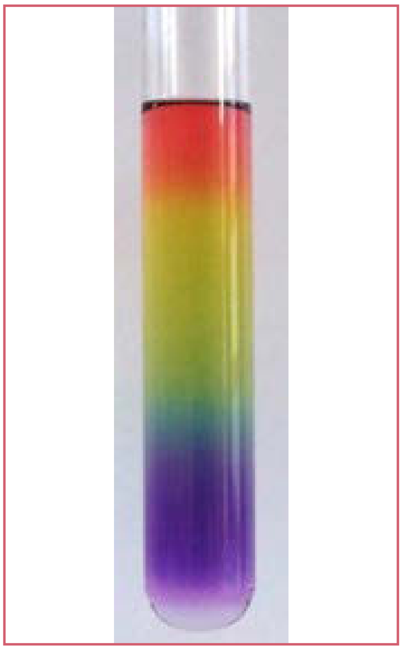

Figure 20. Test tube with acetic acid, universal indicator dye solution and sodium carbonate solution.

Determine the different pH values at different heights of the test tube using Figure 21. Also, use the height of the bubble formation of carbon dioxide to link it to a specific pH value.

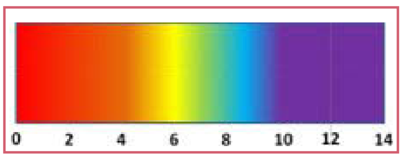

Figure 21. Colours of a universal indicator dye solution at different pH values.

Explanation

At the corresponding pH values, there are two main reactions that influence the transformation of the dyes of the universal indicator and the formation of gas bubbles.

1: In the "purple part" around pH 10.4

$$CO_3^{2-}\ aq + CH_3COOH\ aq \rightleftharpoons CH_3COO^-\ aq + HCO_3^-\ aq$$

2: In the "yellow-green part" around pH 6.4

$$HCO_3^-\ aq + CH_3COOH\ aq \rightleftharpoons CH_3COO^-\ aq + H_2CO_3\ aq$$

The carbon dioxide gas bubble formation of CO_2 g shows the pH value as a "gas indicator" together with the "colour indicator" of the universal indicator. This pH value corresponds approximately to the $pK_A = 6.4$ of carbonic acid.

At a pH value of about 6.4, we can therefore observe:

$$H_2CO_3\ aq \rightleftharpoons \mathbf{CO_2\ g} + H_2O\ aq$$

Final considerations

The ten experiments show very aesthetic and most surprising phenomena. Their use in chemistry lessons by myself and colleagues shows how this stimulates interest and motivation in the students. The experiments are easy and safe to perform. But on reflection, they reveal complex scientific ideas. They start from the phenomena of everyday life and methodically lead to the fascinating scientific concepts behind them.

The ten experiments show very aesthetic and most surprising phenomena. Their use in chemistry lessons by myself and colleagues shows how this stimulates interest and motivation in the students.

Acknowledgement

The text was translated from German into English with the help of deepl.com.

References

Experiment 2. Variation of a demonstration by W. Schatz and H. Wachtler seen at the Chemietage 2016 in Linz, Austria.

Experiment 3. E. V. Kvittingen, L. Kvittingen, B. J. Sjursnes, R. Verley: Simple and Inexpensive UV-Photometer Using LEDs as Both Light Source and Detector, J. Chem. Educ. 2016, 93, 1814–1817, DOI: 10.1021/acs.jchemed.6b00156

Experiment 4. Kyle N. Knust. Milkin University, USA. Electrolysis with bipole electrodes. Oral communication 2016

Overview of bipolar electrochemistry: S. E. Fosdick, Kyle N. Knust, K. Scida, R. M. Crooks, Bipolar Electrochemistry, Angew. Chem. Int. Ed. 2013, 52, 10438–10456, DOI: 10.1002/anie.201300947

Figure 14: Par Jack maderivative work: Canarris — Travail personnel Rechte-Hand-Regel.svgMano-2.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=46400799, 15.05.2023

Experiment 5. Larry Peck. Texas A&M University. experiment shown at the BCCE 2000 Balls can be purchased at Flinn Scientific or at www.kugel-winnie.de (cannon balls 50 mm, hardened, material 1.3505, Quality G500)

Photo: https://www.chem-page.de/experimente/smashing-thermit.html, 25.05.2023)

Experiment 7. M. Tamez, J. H. Yu: Aluminum–Air Battery, Journal of Chemical Education, 84/12, p. 1936A, Dec. 2007, K. Koch: LED-Lampen mit einfachen galvanischen Zellen betreiben, c+b, Bulletin of the Swiss Science Teacher Association (VSN), www.vsn.ch, 1/13, spring 2013.

Experiment 9. Thomas Brezinza «Tolle Experimente». Ravensburger Buchverlag. Ravensburg. 2005. Adrian Allen: Workshop «It's not magic, it's science we don't see». ASE Conference, 6 January 2023, Sheffield UK . Internet: «paper clip linking», e.g. https://www.youtube.com/watch?v=f3R0wOYom1E (13.1.23)

Experiment 10. http://www.rsc.org/eic/2016/05/rainbow-fizz-ph-demonstration (22.5.16)

Prof. Dr. Klemens Koch

Didactics of chemistry, Fabrikstrasse 8, Sekundarstufe II, PH Bern, 3012 Bern, Switzerland, klemens.koch@phbern.ch, https://www.phbern.ch/ueber-die-phbern/personen/klemens-koch) and chemistry teacher at the Gymnasium Biel-Seeland, Switzerland.

Research field: Experiments and didactics for an extended understanding of the everyday world, e.g. in introductory chemistry, redox chemistry, thermodynamics and quantum chemistry.