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Electrolysis of Water in School Experiments – Simple and Safe Model Experiment for Hydrogen Production Using Everyday Materials for Teaching Purposes

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Abstract Hydrogen is becoming increasingly important as a versatile energy source in society and industry across various sectors. It is obtained through the electrolysis of water, in which water is split electrolytically into oxygen and hydrogen. The production of hydrogen through electrolysis is an excellent way to teach students key aspects of modern energy storage and the energy transition in a clear and concise manner. However, simple, safe, and inexpensive experiments are particularly important in school lessons. The model experiment presented here shows how the electrolysis of water can be carried out successfully and safely using readily available everyday materials. Both technical fundamentals and safety-related aspects are taken into account.

Keywords: *Hydrogen, Electrolysis, Energy supply, Model tests, School experiments*

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1. Introduction

In the course of the energy transition and the future sustainable energy supply, hydrogen is increasingly gaining attention as a key resource. As a versatile energy carrier with low emissions, hydrogen is seen as a way of overcoming global challenges such as the changing climate and, above all, reducing dependence on fossil fuels. However, hydrogen is not only important in science and technology, it is also playing an increasingly important role in social, industrial and political contexts. Energy production, transportation, storage and use are particularly important in this context [1,2,3].

In industry, hydrogen is increasingly seen as a promising raw material for various production processes and as an energy source for transportation. Compared to conventional fossil fuels, hydrogen appears to be more environmentally friendly, as it does not produce any harmful emissions when burned [4]. The use of hydrogen offers a wide range of possible applications in areas such as industry, transportation and energy storage and contributes to the reduction of CO_2 emissions and the promotion of a sustainable energy supply. From steel production to the chemical industry, the implication of hydrogen is seen as opening up new avenues. The mobility sector is also focusing on hydrogen: hydrogen-powered vehicles, whether in local public transport or heavy goods vehicles, could play a central role in the decarbonization of the transport sector in the near future [5]. Even Airbus, with its ZEROe project, is pursuing various concepts for how aircraft can be based on hydrogen technology and plans to launch a commercial hydrogen-powered aircraft on the market by 2035 [6].

From a political perspective, hydrogen is a key topic for shaping future strategies. For example, the German government's last coalition agreement called for "the establishment of a European Union for green hydrogen" [7]. Germany should become the lead market for hydrogen technologies by 2030, for which the government wants to "develop an ambitious update of the national hydrogen strategy" [7]. In addition, the targets for electrolysis output are to be significantly increased and European and international climate and energy partnerships for climate-neutral hydrogen and its derivatives are to be promoted on an equal footing [7]. However, international cooperation in the field of hydrogen technology and ensuring security of supply and the development of corresponding infrastructure are complex.

The importance of hydrogen in the social and political debate extends beyond technical dimensions. It is seen as a symbol of the shift towards a more sustainable economy and a green future [8,9,10]. Such current social discourses must find their way into chemistry lessons and contribute to a critical and reflective understanding of the technologies. One way of promoting an understanding of the technology is the implication of simple and target group-oriented model experiments. The following article describes a simple experiment on the electrolysis of hydrogen. This makes the experiment ideal for introducing the topic of hydrogen chemistry.

2. Didactic Significance for Chemistry Teaching

In terms of scientific competence, an important task of chemistry teaching is to introduce students to current research and technologies in areas that are socially relevant now and will be in the future. Therefore, it is very important to develop suitable, easy-to-perform experiments and materials for chemistry teaching. The electrolysis of water is a key experiment for introducing electrochemical principles and illustrating hydrogen as an energy source. From a teaching perspective, the experiment is highly relevant as it ties in with the competence goals of chemistry lessons in several ways. On the one hand, the experiment enables learners to experimentally understand basic concepts of electrochemistry, such as the function of electrodes, ion migration, and the conversion of energy forms. The use of everyday materials demonstrates the relevance to the learners' everyday lives, which increases their motivation and interest in the topic and in experimenting. In addition, the electrolysis of water opens up access to current social issues such as the energy transition, sustainable mobility and industry, and energy storage from renewable sources. This allows technical content to be linked to interdisciplinary issues that are particularly important in terms of education for sustainable development. Seibert et al. have developed an innovative teaching concept for green hydrogen with a focus on environmental scientific media literacy for education for sustainable development based on social media content [11]. Venzlaff et al. and Kremer & Tausch have already published practical experiments for chemistry lessons on how green hydrogen can be produced using current research projects such as photoreforming [12] and photocatalysis [13,14]. This article joins these innovative teaching concepts and presents another experimentally guided possibility for producing hydrogen electrolytically using everyday materials. The experiment thus contributes to the promotion of knowledge acquisition and evaluation skills, in which the experimental opportunities and limitations of hydrogen as an energy source can be critically reflected upon. In addition, the methodological simplicity and high safety of the model experiment also allow for action-oriented teaching.

3. Experiments on Water Electrolysis

Green hydrogen is produced through water electrolysis, which uses renewable electrical energy for its sustainable production. However, due to the high stability of the water molecule, the energy requirement for the electrolysis of hydrogen is very high. Three technologies are currently being considered for large-scale electrolysis: alkaline, PEM and high-temperature electrolysis [15]. Water electrolysis consists of partial reactions: the hydrogen evolution reaction and the oxygen evolution reaction. The efficiency of the reactions depends on the pH value of the electrolytes and the electrode materials used. In particular, transition metals such as nickel, iron and cobalt appear to be very promising. Alkaline water electrolysis will be crucial for the successful implementation of green hydrogen in industry and society [16]. The efficiency of alkaline electrolysis is between 70 and 80 % and depends on factors such as the electrolyte solution, the temperature and the electrode material. Research is focusing on improving efficiency in order to optimize the production of green hydrogen [17].

In chemistry lessons, the classic demonstration experiment for water electrolysis and thus for hydrogen production using electrical energy is carried out using a Hofmann water decomposition apparatus. However, only very small quantities of gases are produced in this apparatus and it is very expensive for schools to purchase, meaning that there are often only very few apparatus available. In the following, experiments are therefore presented on how alkaline hydrogen electrolysis can be modeled using low-cost experiments with everyday materials. At the same time, the simple experimental set-up enables various adaptations and modifications for further experimental investigations, as are currently being discussed in research.

Based on an experiment on electrolysis presented by Brand [18], large syringes (100 mL) from medical supplies are used as the basis for the electrochemical half-cells.

A three-way stopcock and pieces of tubing are used for gas discharge and regulation in order to connect all the syringes to each other and a third syringe is used to collect the gases (Figure 1). An insulated, two-core copper wire is used as the electrode holder and cable material. This is stripped at both ends to create a conductive connection. Suitable copper sheets measuring 4.2 x 2.8 cm are attached to the stripped ends of the copper wires to create a larger electrode surface by pinching them with pliers. A commercially available 5 V USB-C power supply unit for cell phones and a suitably prepared USB-C cable with stripped ends of the live wires are used as the voltage source. Alternatively, a commercially available laboratory power supply unit can also be used. The live ends are connected to the copper wire using crocodile clips and cables (Figure 2). The design ensures safe operation, as the system is closed and hydrogen production is highly controlled. It is recommended that the experiment be carried out under a fume hood. However, thanks to the closed design, the experiment can also be carried out outside of a fume hood.

The low-cost experiments for alkaline water electrolysis using an alkaline solution of potassium hydroxide and water are described below, as is also used in large-scale alkaline electrolysis [19]. The first experiment below explains the setup and handling of the low-cost experiment and initially simulates large-scale electrolysis with 30-percent potassium hydroxide solution.

Figure 1. Model experiment with everyday materials

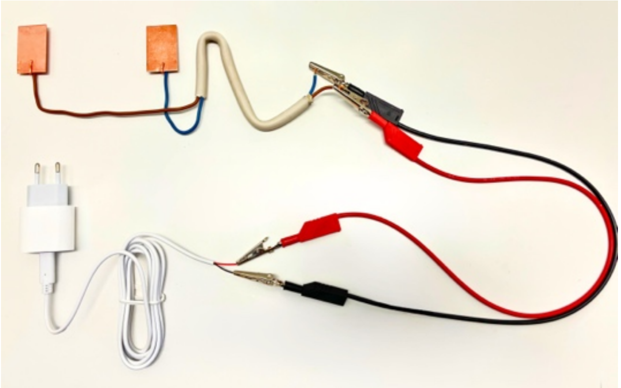

Figure 2. Clear representation of the electrodes and voltage source from everyday materials

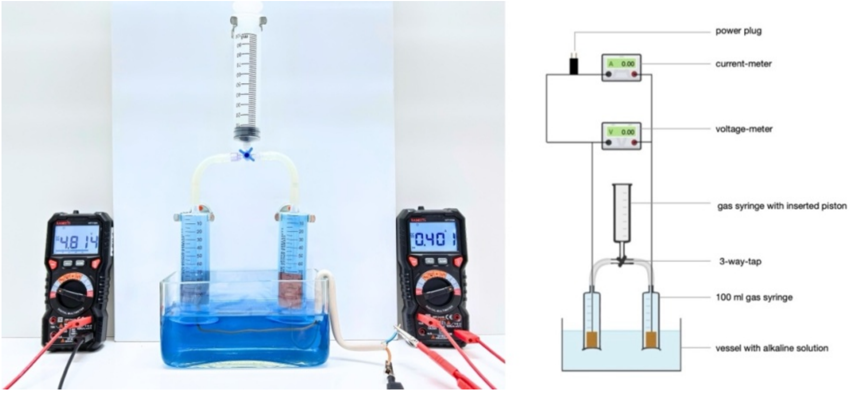

Figure 3. Experimental setup with schematic representation of the sketch

3.1. Electrolysis in a low-cost Experiment with Potassium Hydroxide Solution

Laboratory equipment: three 100 ml syringes, three-way stopcock with adapter, rubber hose, rigid insulated copper wires (eg. two-core copper c.able), USB-C power supply unit (5 V, 1 A), USB-C cable, stand material, 900 ml crystalliser bowl, multimeter as voltmeter and ammeter, cable material and crocodile clips

Chemicals: two copper sheets (4.2 x 2.8 cm each), potassium hydroxide solution ($\omega = 30$ %)

Conducting: The plungers of two syringes are removed and clamped in a stand with the tip pointing upwards. The lower opening is placed over the bottom of the vapor tray. The copper wires from the copper cable are stripped at the ends and the copper sheets are attached to each cable using pliers (Figure 2). These prepared electrodes are inserted into the syringes from below. The tips of the two prepared syringes are connected to each other with two pieces of tubing and a three-way stopcock. At the third outlet of the three-way stopcock, another syringe with a plunger is placed above the entire experimental setup. The three-way stopcock must be set to the shut-off position so that pneumatic filling can be successful. The evaporation dish and the syringes are filled with a 30 % potassium hydroxide solution (Figure 3).

The other two ends of the copper wires are each connected to a stripped end of a live wire of a USB-C cable using crocodile clips and cable material. The USB plug is plugged into the USB power supply unit (Figure 2). The voltage and current are measured using two multimeters (Figure 3).

Experimental observation: When the USB cable is connected to the USB power supply unit, electrolysis of the alkaline solution takes place immediately.At the beginning, the measured charging voltage is between 2.5-2.7 V and rises to around 3.4-3.5 V after a few seconds. These values may vary slightly depending on the power supply unit used. After a short time, gas development can be detected at both electrodes. The voltage with a value of 3.4 V and the current with a value of 0.41 A remain almost constant during the measurement (Figure 4). By minute 25, a total of 74 ml hydrogen is produced at the cathode and 28 ml oxygen at the anode.

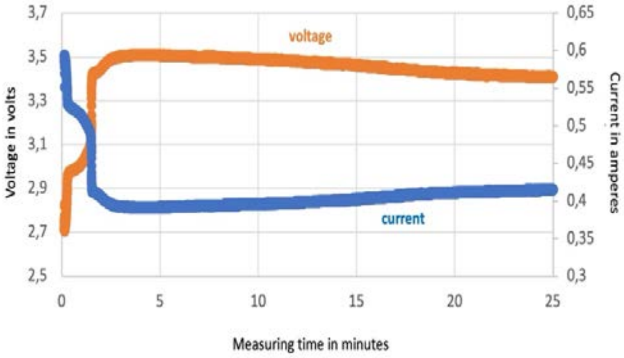

Figure 4. Time course of voltage and current during electrolysis (30 percent potassium hydroxide solution)

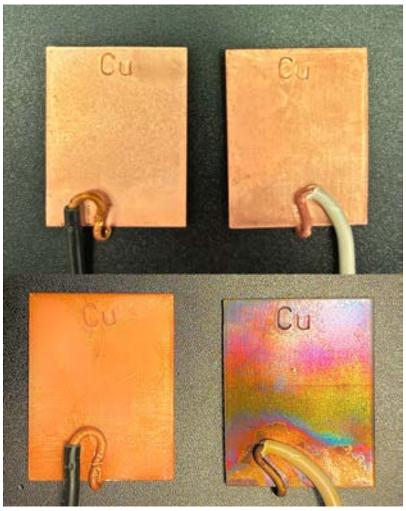

Figure 5. Copper electrodes before the experiment (top) and after the experiment (bottom)

After electrolysis is complete, a blue coloration of the solution can be observed. From a didactic point of view, however, the alkaline solution can be colored with universal indicator so that the gas development can be better observed. Once electrolysis is complete and the experiment has been secured, the electrodes can be removed from the syringes. If these are examined more closely, a discoloration of the copper sheets can be seen (Figure 5).

Electrolysis produces copper complexes, among other things. The solution must therefore be disposed of as heavy metal waste.

Analysis of the experiment: The ratio of gas evolution is 2: 1, with almost twice as much hydrogen being produced as oxygen in the following reaction.

At the cathode, water molecules are split into hydrogen and hydroxide ions by accepting electrons:

$$2OH^-\left(aq\right) \rightarrow \frac{1}{2}O_{2(g)} \uparrow + H_2O_{(l)} \tag{1}$$

At the anode, hydroxide ions are oxidized to oxygen and water by releasing electrons:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} \uparrow + 2OH^-_{(aq)} \tag{2}$$

Both gases can be detected experimentally. Safety note: Both gases must be detected separately from each other, as otherwise a dangerous explosive mixture may occur! The three-way valve allows the upper, third syringe to be filled with oxygen gas from the anode side and verified using the glow discharge test. To do this, the oxygen gas from the syringe is passed through a glow discharge. If this glows, the oxygen has been successfully detected. After successful detection, the oxygen is completely released from the syringe and it is placed back on the experimental apparatus.

Now the hydrogen gas can be passed from the cathode side into the syringe via the three-way valve and detected using the oxyhydrogen test. To do this, the hydrogen gas from the syringe should be directed into an upside-down test tube, which is ignited over an open flame. With pure hydrogen gas, a corresponding ‘pop’ sound can be heard as acoustic evidence.

The jumps in voltage and current in the first few minutes during the charging process and the slightly delayed gas formation at the anode can be explained by the formation of copper(II) oxide. These double peaks of the reaction of copper to copper(II) oxide to copper(I) oxide are also described in the literature [20]. The longer the electrolysis, the lower the influence of the initial side reactions on the efficiency. Without taking the first 5 minutes into account, the efficiency in this specific case is around 37.5 % compared to 35.7 %. In a series of measurements over 45 minutes, an efficiency of approx. 40 % was achieved with this setup.

With the help of the recorded measured values, the students can easily calculate the efficiency of the electrolysis in relation to the hydrogen produced. The efficiency η of an electrolysis describes the ratio of chemical energy to supplied electrical energy. The calculation is carried out using the following formula

$$\eta = \frac{E_{chemical}}{E_{electric}} \cdot 100 \tag{3}$$

The first step is to calculate the chemical energy of hydrogen. The energy density of hydrogen is 10,8 $\frac{J}{ml}$ [21].

$$E_{chemical} = m_{H_2} \cdot EnergydensityH_2 \quad (4)$$

$$E_{chemical} = 74ml \cdot 10,8\frac{J}{ml} \quad (5)$$

$$E_{chemical} = 799,2J \quad (6)$$

The electrical energy $E_{electrical}$ is then calculated using the recorded measured values of voltage U, current I and time t.

$$E_{electrical} = U \cdot I \cdot t \quad (7)$$

$$E_{electrical} = 3,4V \cdot 0,41A \cdot 1500s \quad (8)$$

$$E_{electrical} = 2.091J \quad (9)$$

Finally, the efficiency η is calculated using the formula mentioned at the beginning:

$$\eta = \frac{E_{chemical}}{E_{electric}} \cdot 100 \quad (10)$$

$$\eta = \frac{799,2J}{2091J} \cdot 100 \quad (11)$$

$$\eta = 38.22\% \quad (12)$$

In this test, an efficiency of 38.22 % was calculated for the electrolysis of the hydrogen produced. In a series of measurements lasting 45 minutes, an efficiency of approx. 40 % was achieved with this setup.

With this simple but safe experimental setup, a significant amount of hydrogen can be produced in a short time in a student experiment. At the same time, the students can observe the gas development very well. For use in chemistry lessons, this is an inexpensive, low-cost experiment that can be used several times in lessons and is therefore suitable as a student experiment.

Potassium hydroxide solution with a concentration of 30 % is not prohibited in schools, but is subject to a special substitute substance test. Below a concentration of 2 %, potassium hydroxide solution is only an irritant, not a corrosive, so that concentrations below 2 % are preferable in student experiments [22]. Therefore, an experiment will be tested below that allows the use of a low concentrated alkaline solution.

3.2. Experimenting Safely-electrolysis with 2% Caustic Potash Solution

Laboratory equipment: as in experiment 1

Chemicals: as in experiment 1, instead of a potassium hydroxide solution (ω = 30 %) a potassium hydroxide solution (ω = 2 %) is used

Conducting: The experiment is set up as described in experiment 1 and instead of the 30 % potassium hydroxide solution, a 2 % potassium hydroxide solution is used. The experiment is also carried out as in experiment 1.

Experimental observation: When using a 2% potassium hydroxide solution, the gas development on both electrodes is delayed, but can then also be clearly observed. The voltage and current are also very constant with this experimental change (Figure 6) and are 4.05 V and 0.26 A respectively.

Further tests confirm the same measured values of 4.18 V and 0.23 A. Depending on the power supply unit used, the values can also fluctuate slightly here. After 25 minutes, a total of 45 ml hydrogen and 15 ml oxygen have been produced. The copper electrodes also show clearly visible discoloration in this test.

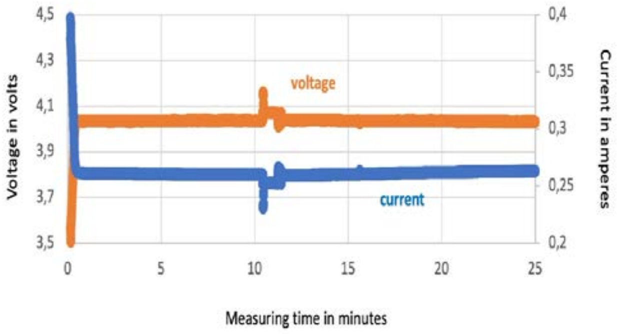

Figure 6. Time course of voltage and current during electrolysis (2% potassium hydroxide solution)

Analysis of the experiment: The reactions and discolorations that take place at the electrodes have already been explained in experiment 1. The ratio of gas development at the end of the 25-minute electrolysis is also 2:1 here.

The efficiency is around 31.4 % and is therefore slightly lower than with a 30 % solution. This can be explained by the lower conductivity. Due to the lower concentration of 2 % of the potassium hydroxide solution, the experiment can be used in chemistry lessons as a learner experiment and the gas development can still be clearly observed at the electrodes. At this point, the influence of the electrolyte solution on the efficiency can be discussed with the students. Electrolyte solutions seem to have an influence on the efficiency. The learners can now express ideas on how the efficiency of electrolysis can be influenced and the following experiment can be used as a check.

3.3. Caustic Soda Instead of Caustic Potash Solution: the Use of Caustic Soda to Investigate Electrolysis

Laboratory equipment: as in experiment 1

Chemicals: as in the experiment, instead of a potassium hydroxide solution (ω = 30 %) a sodium hydroxide solution (ω = 2 %) is used.

Conducting: The experiment is set up as described in experiment 1 and instead of the 30 % potassium hydroxide solution, a 2 % sodium hydroxide solution is used. The experiment is also carried out as in experiment 1.

Experimental observation: When using a 2% sodium hydroxide solution, the gas development on both electrodes starts immediately and can be clearly observed as in experiment 1.

The voltage and current are also very constant with this experimental change (Figure 7) and are 4.1 V and 0.24 A respectively. Depending on the power supply used, the values can also fluctuate slightly here. After 25 minutes, a total of 40 ml hydrogen and 15 ml oxygen have been produced. The copper electrodes also show clearly visible discoloration in this experiment.

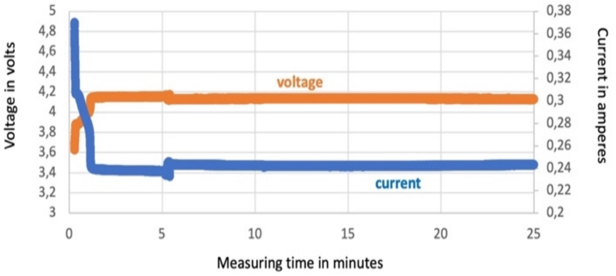

Figure 7. Time course of voltage and current during electrolysis (2% sodium hydroxide solution)

Analysis of the experiment: The reactions and discolorations that take place at the electrodes have already been explained in experiment 1 and the alkali metal ions are not directly involved in the reactions. The ratio of gas development at the end of the 25-minute electrolysis is around 2:1. However, the efficiency is only around 29.3 % and is therefore significantly lower than in the two experiments with potassium hydroxide solution. This can be analyzed and evaluated with the students at this point.

3.4. Experimental Adaptations: Extensions to the Model Experiment

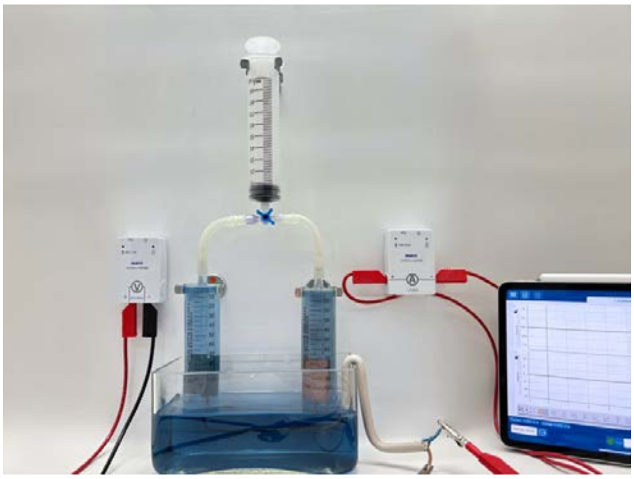

Figure 8. Extension of the model test with digital measurement sensors

In addition to the three experiments described, many other variations are possible with regard to the structure and use of electrolyte solutions and electrodes. For example, other electrode materials could be investigated with regard to their catalytic properties. Series of measurements with graphite foil and graphite felt as electrode materials were also investigated in the course of this work and are suitable for use in chemistry lessons. The influence of temperature on electrolysis can be easily implemented with this simple model experiment, as the evaporation dish with the entire experimental setup only needs to be placed on a hotplate. This means that reaction conditions can be simulated in large-scale electrolysis. The integration of digital measuring sensors in the model experiment is also simple and clear (Figure 8)

4. Conclusion and Outlook

The experimental setup is very suitable for use in schools due to its simplicity and relevance to everyday life. In addition, it has proven to be very robust (more than 70 measurements with one and the same experimental setup) and larger quantities of hydrogen can be obtained quickly with suitable electrodes.

The experimental setup can be used for further experiments, for example in fuel cell technologies.

In addition, the experimental setup has the experimental potential to investigate other electrolytes and electrode materials and to discuss their influence on the efficiency with the students in chemistry lessons. This means that further current research projects and discourses on water electrolysis can be quickly and easily implemented experimentally in school lessons.

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