Title: Splitting Water With Electricity

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Subject: Physics & Chemistry
Grade Level: 9 – 12
Standards: New York State – Intermediate science (http://www.p12.nysed.gov/ciai/)
Standard 1 – Analysis, Inquiry, and Design
Standard 3 – Mathematics
Standard 4 – The Physical Setting
Standard 6 – Interconnectedness: Common Themes
Standard 7 – Interdisciplinary Problem Solving

Schedule: One 40-minute class period

Description:

The purpose of this activity is to investigate the concept of electrolysis by using tools developed through the study of electrostatics. We will determine the energy necessary to remove oxygen and hydrogen atoms from a water molecule, dissociate water into its constituent elements, and check the identity of these elements by determining the ratio in which these elements are produced.

Objectives:

- Students will use the electrostatic potential equation to calculate the amount of energy stored inside a water molecule.
- Using the operational definition for voltage, students will determine how much voltage would be necessary to separate water into hydrogen and oxygen components.
- Students qualitatively measure the ratio of oxygen and hydrogen bubbles to assess H_2O
- Students will be able to explain conceptually (based upon charge, energy, electric field concepts) how this experiment works.

Vocabulary:

- Electrostatic potential energy
- Voltage
- Electric field
- Anode
- Cathode
- Electrolyte

Materials:

- 4 - 1.5V batteries (D cell)
- Battery holder
- Voltmeter
- Alligator clips
- Graphite leads (mechanical pencil lead works best)
- Deionized water
- Baking soda
- Small bowl or beaker.

Safety:

Small risk of electrocution and gaseous build-up of combustible products. See **Safety** section for more information.

Science Vocabulary:

Electrostatics: A branch of physics that studies the properties of stationary charge or moving charge with no acceleration present.

Potential Energy: Stored energy within a system due to the arrangement of the object.

Coulomb's Law: An inverse-square law that relates the force a pair of charges experience if held a certain distance. $F = \frac{kq_1q_2}{r^2}$

Joules: A unit of energy, named after James Prescott Joule. 1 J = 1 N·m

Voltage: The electrical potential difference, or work per unit charge of an electrical system.

Volt: The unit of Voltage, named after Alessandro Volta. 1 V = 1 J/C.

Electrolyte: A compound that ionizes when dissolved in a solvent.

Anode: The positively charged electrode by which the electrons leave a device.

Cathode: The negatively charged electrode by which positively charge ions leave a device.

Electrolysis: Chemical decomposition produced by passing an electric current though a liquid or solution containing ions.

Multimeter: An instrument designed to measure electric current, voltage, and usually resistance, typically over several ranges of value.

Electrical leads: A conductor by which one circuit element is electrically connected to another

Deionized water: Pure water that has had impurities physically removed.

Conductivity: The degree to which a specified material conducts electricity.

Electric field: The region around a charged particle or object within which a force would be exerted on other charged particles or objects.

Threshold: A point of entry or beginning.

Electrochemistry: The branch of chemistry that deals with the relations between electrical and chemical phenomena.

Science Content for the Teacher:

From the perspective of physics, if energy is conserved, then one can determine the amount of energy required to disassociate a single water molecule by considering how much energy is required to assemble the molecule. From electrostatics, we know Coulomb's Law plays a dominant role in explaining whether or not (and to what degree) two charges sense an attractive or repulsive force. The amount of work required to bring two charges together (from infinity to some distance r_{12}) is equal to the *opposite* of the energy stored within the charges (see Figure 1.a,) or:

$$W = \Delta U_e = -\int_{\infty}^{r} \vec{F} \cdot \overrightarrow{dr} \quad = -\int_{\infty}^{r_{12}} \frac{kq_1q_2}{r^2}\, dr$$

When one evaluates the above integral, one can determine the amount of stored *electric* potential energy between two charges as:

$$U_e = U_{12} = \frac{kq_1q_2}{r_{12}},$$

Where U_e, is the stored potential energy (in units of Joules,) k is Coulomb's constant, q_1 and q_2 are charges (in units of Coulombs) and r_{12} is the distance between the charge pair.

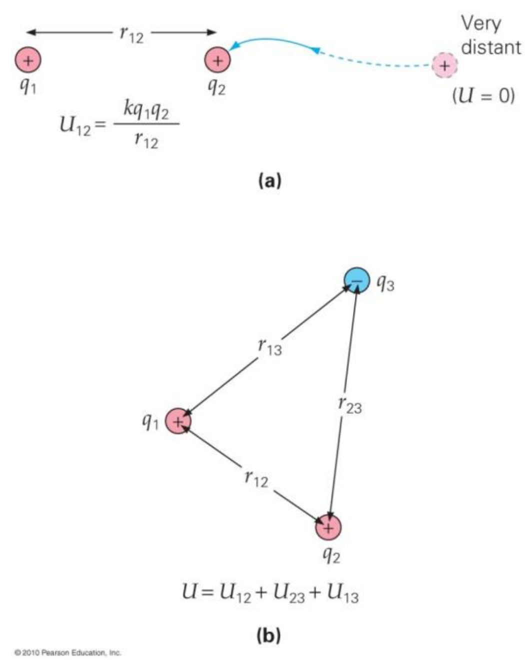

Figure 1. Electrostatic potential energy diagram. (a) For a pair of charges. (b) For an ensemble of charges.

To determine the total electric potential energy for an ensemble of charges, you simply sum the amount of energy required to assemble the charges as pairs (see Figure 1.b,) or:

$$U_{Total} = \sum_{j=1}^{N(j\neq i)} k\frac{q_iq_j}{r_{ij}} = U_{12} + U_{23} + U_{13} + \cdots$$

Lastly, we must consider the concept of *voltage* and how this factors into our experiment. The operational definition of voltage is the amount of work per unit charge, or:

$$V = \frac{W}{q} = \frac{U_{Total}}{q}$$

Where the unit *Volt* is used for voltage and 1 V = 1 J/C.

For a single water molecule (H_2O,) the following physical properties are experimentally verified as:

$r_{13} = r_{23} = 9.6 \times 10^{-11} m$
$\theta = 104°$
$q_1 = q_2 = 5.2 \times 10^{-20} C$
$q_3 = -10.4 \times 10^{-20} C$

To determine the total energy, one must first solve for r_{12}:

$\sin(52°) = \frac{r_{12}}{2 \cdot r_{13}}$, or $r_{12} = 1.5 \times 10^{-11} m$.

Next, we determine the energy of each charge pair:

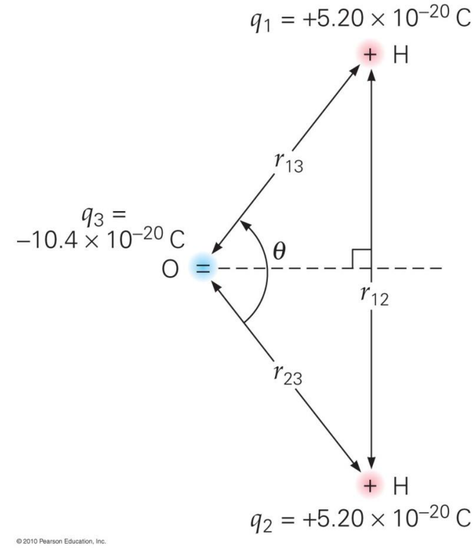

Figure 2. Charge configuration for a water molecule.

$$U_{12} = \frac{kq_1q_2}{r_{12}} = \frac{\left(9.0 \times 10^9 \frac{N \cdot m^2}{C^2}\right)(5.2 \times 10^{-20} C)(5.2 \times 10^{-20} C)}{1.5 \times 10^{-11} m} = 1.6 \times 10^{-19} J$$

$$U_{13} = \frac{kq_1q_3}{r_{13}} = \frac{\left(9.0 \times 10^9 \frac{N \cdot m^2}{C^2}\right)(5.2 \times 10^{-20} C)(-10.4 \times 10^{-20} C)}{9.6 \times 10^{-11} m} = -5.07 \times 10^{-19} J$$

$$U_{23} = \frac{kq_2q_3}{r_{23}} = \frac{\left(9.0 \times 10^9 \frac{N \cdot m^2}{C^2}\right)(5.2 \times 10^{-20} C)(-10.4 \times 10^{-20} C)}{9.6 \times 10^{-11} m} = -5.07 \times 10^{-19} J$$

The total energy to assemble the molecule is simply the sum of the energy of each charge pair:

$$U_{Total} = U_{12} + U_{23} + U_{13} = -8.54 \times 10^{-19} J$$

The negative implies that energy is stored within this particular arrangement as bond energy. In order to remove the atoms from the bonds, an equal (but opposite) amount of energy would be needed.

In this experiment, the *electric field* performs work on the molecule. In order to establish an electric field, we must have a potential difference, or *voltage*.

The operational definition of voltage is the work per unit charge. Just how much voltage would be required to perform this task? In this case, our unit charge is the charge of an electron, which is defined as $e^- = -1.6 \times 10^{-19} C$. However, the electric field is doing work on *four* charges:

$$V = \frac{W}{q} = \frac{8.54 \times 10^{-19} J}{4 \cdot (-1.6 \times 10^{-19} C)} = -1.33\ V$$

According to electrostatic theory, **-1.33 V** is the *threshold voltage* necessary to observe the electrolysis of water.

Experimental Setup:

The setup process for this experiment is fairly straightforward and is intended to be a qualitative investigation concerning the electrochemical properties of water. See the chemistry section for more information.

1. Gather the following supplies for your students (supplies are per group, no more than 3 students per group.) Make sure all of the electrical components are functional prior to initiating the investigation.

- Four 1.5 Volt D cell batteries
- Battery holder for D cell batteries
- Digital Multimeter
- Alligator clips with wire
- Graphite leads (mechanical pencil lead works best)
- Deionized water
- Baking soda (or tap water if baking soda is unavailable)
- Small bowl, beaker, or petri dish.
- Graduated cylinder

2. Students will need to add 25 mL of deionized water into a small bowl.

3. Add 1 mg of baking soda to the water. Since water is a poor conductor, adding baking soda (an *electrolyte*) assists in the creation of a uniform electric field by making the solution slightly conductive. Increasing the conductivity of the solution assists the flow of charge between the graphite leads.

4. Connect your power supply to your solution. Do this by inserting batteries into the battery holder and connecting the battery holder to the graphite leads with alligator clips. Make sure the graphite leads are on opposite ends of the bowl. As a suggestion, have students plug in one D cell battery (at a time) into the circuit and have them comment on what they observe. As they systematically reach the threshold voltage, have them comment on how the dynamics of the system change.

Things to consider:

Chemistry:

A reduction reaction occurs at the negatively charged cathode, where electrons are being given to hydrogen cations, forming hydrogen gas:

Cathode: $2H^{+}(aq) + 2e^{-} \rightarrow H_2\ (g)$

Meanwhile, an oxidation reaction is taking place at the positively charged anode, and (as a result) oxygen gas is being generated:

Anode: $2H_2O(l) \rightarrow O_2\ (g) + 4H^{+}\ (aq) + 4e^{-}$

In short, the reaction that is taking place is

$2\ H_2O \rightarrow 2H_2(g) + O_2(g)$,

which highlights that (if pressure and temperature is constant) **twice** the volume of hydrogen gas (with respect to the volume of oxygen gas) is produced. This effect should be visible to your students.

It should be noted that **-1.48 V** is a more accurate threshold voltage value for the electrolysis of water. The derivation of this value considers the thermodynamic properties and pH fluctuations of the system, which is beyond the scope of this exercise.

Safety:

Hydrogen gas is combustible, and while oxygen gas is not, oxygen-rich environments accelerate the rate at which combustion occurs. Be mindful that your students are generating oxygen and hydrogen gas when performing this experiment. The risk of starting a fire (although small) exists.

To minimize the risk of gaseous buildup, perform this experiment in a well-ventilated room. Make sure students do not leave the experiment running. When students have made their observations and acquired the necessary data, have your students disconnect the circuit.

Have students practice smart and safe laboratory décor by wearing googles and gloves. Be firm and make sure they are taking this experiment seriously.

In some cases, students have been known to cross the graphite leads, which creates a small spark and (consequentially) combustion of the gas. Additionally, some students (who have accidentally placed their fingers into the solution) have claimed to feel a slight electric shock. Note that while the current and voltage values are low, only a benign surface shock could best explain any sense of electric shock. To avoid the possibility of a surface shock and discomfort, have students wear latex gloves while performing the experiment.

Lastly, avoid the use table salt (NaCl) as the electrolyte, as chlorine gas (rather than oxygen,) is produced in a competing half-reaction. Chlorine in gaseous form is toxic. Using tap water can be used if an electrolyte can't be found.

Disposal of equipment: Feel free to dispose of the solution down the drain. Please consider the environment when disposing your electrical equipment (this includes the D cell batteries.) D cell batteries should not be thrown in the garbage.

Approximate cost of equipment:

Item	Quantity	Item Number	Cost
1.5V D cell batteries (www.batteryjunction.com)	4	PC-1300	$ 4.40 ($ 1.10 each)
Battery holder (www.radioshack.com)	1	270-396	$2.99 (holds 4 D cell batteries)
Multimeter (www.harborfreight.com)	1	98025	$5.29
Alligator clip and wire (www.cnaweb.com)	2	603472	$2.90 (pk of 10)
Graphite (1.3mm) (www.staples.com)	1	56544 – 1868816	$0.99 (refill pack)
Baking Soda (www.walmart.com)	1	48665-009278866	$2.18 (16 oz)
Small bowl (petri dish) (www.carolina.com)	1	741250	$5.95 (20 pack)

Consult the CCMR lending library of experiments website. Materials can be requested and mailed to you free of charge.

http://www.ccmr.cornell.edu/education/lendinglibrary/

Assessment:

Things to consider when grading your student's lab findings:

1. Did the student complete the pre lab assignment?

Theoretical calculations for electrolysis

2. Did the student calculate the correct value and or show all of the work?

3. Did the student correctly address the question, "Why is this (electric potential energy) value negative?

4. Did the student correctly determine the necessary voltage needed to separate the water molecule into its components?

Experimental setup

5. Does the student sufficiently answer the question: How is an electric field established in this setup?

6. Does the student provide a coherent diagram (with labels) of the apparatus used?

Analysis and reflection of the experiment

7. Does the student thoughtfully consider the ratio between the number of bubbles formed from one terminal to another?

8. Does the student provide a cohesive conclusion and offer thoughtful suggestions on things to avoid?

Acknowledgements:

A special thank you to Mrs. Nevjinder K. Singhota, whose infinite patience is truly inspirational. I must also extend my sincere gratitude to Mr. Lee Cook, Ms. Rebecca Gorla, Mr. Tim Williamson, and Mrs. Alia Jackson for their unyielding camaraderie and professionalism throughout our RET experience at Cornell.

Name: Date: Section:

Splitting Water with Electricity Pre Lab Exercise

Please read the laboratory handout and complete the vocabulary list prior to conducting the experiment.

1. Electrostatics:

2. Potential Energy:

3. Coulomb's Law:

4. Joules:

5. Voltage:

6. Electrolyte:

7. Anode:

8. Cathode:

9. Electrolysis:

10. Multimeter:

11. Leads:

12. Deionized water:

13. Conductivity:

14. Electric field:

15. Threshold value:

16. Electrochemistry:

Name: Date: Section:

Splitting Water with Electricity Lab

The purpose of this activity is to investigate the concept of electrolysis by using tools developed through our study of electrostatics. We will determine the energy necessary to remove oxygen and hydrogen atoms from a water molecule, dissociate water into its constituent elements, and check the identity of these elements by determining the ratio in which these elements are produced.

Step one – Theoretically determine the amount of energy necessary for electrolysis.

The water molecule is the foundation of life. Many of its properties (such as the reason it is a liquid on Earth) are related to the fact that it is a permanent polar molecule.

The distance from each hydrogen to the oxygen atom is 9.60 x10^{-11} m, and the angle between the two hydrogen-oxygen bond directions is 104^{o}.

1. What is total electrostatic energy of the water molecule? (Show all work to receive full credit.)

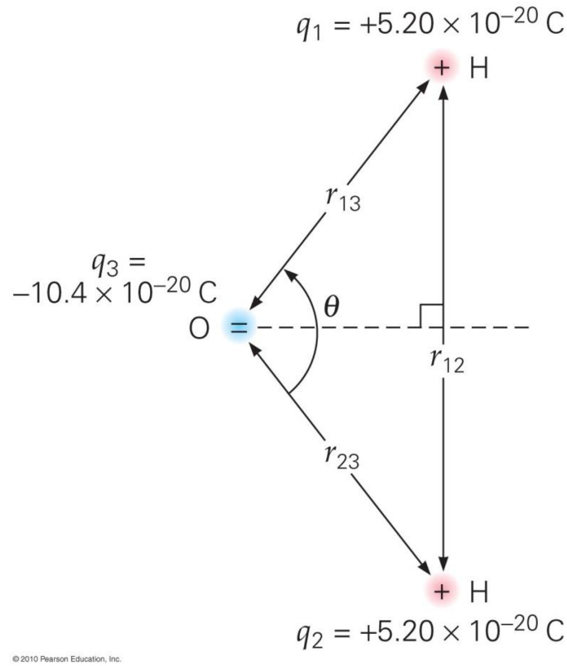

Figure 1. Charge configuration for a water molecule.

2. Why is the electrostatic energy value *negative*?

3. What potential difference (voltage) would be required to separate this molecule into constituent atoms?

Step two – Experimental setup.

Collect the following items: Four 1.5V D cell batteries, two alligator clip wires, a small piece of graphite (mechanical pencil stick), small container filed with 25 mL of water and a small amount of salt.

4. Propose an experimental setup that could demonstrate the decomposition of water (electrolysis of H_2O) into its constituent components. How is an electric field used in this setup?

5. Provide a diagram of your apparatus and a short explanation below. Do not run the experiment until you've completed this part.

Step three – Run the experiment.

You will need to determine the operating voltage of your battery before running the experiment. Using a digital multimeter, set the dial to VDC +20V (this means direct-current voltage, 20V readout maximum value).

6. With the space provided below, report the actual voltage of your battery and compare it to the nominal voltage (label on battery.) Connect the batteries to your circuit (one at a time, so as to linearly increase our overall voltage) and comment on what you observe.

Battery number	Nominal voltage	Actual voltage	Observations on reaction

7. Consider the space between both graphite pieces. Conceptualize what you think the electric field looks like. Be sure to label all parts (anode, cathode, electrolyte, and direction of electric field) and consider the direction of the electric field as a vector field.

Step four – Analyze the experiment.

8. Perform the experiment and provide a 1-paragraph reflection on what you've observed.

9. Provide a diagram of what your graphite pieces look like while the experiment is running. Which graphite piece has more bubbles, the one connected to the positive terminal, or the one connected to the negative terminal?

10. Using your best judgment, what is the ratio between the number of bubbles formed from one terminal to another?

11. What happens when you connect the two graphite terminals together? What could be causing what you see?

12. Conclusion: Provide a 1-paragraph reflection of your findings. What should one avoid when running this experiment? Are there any safety issues one should consider when running this experiment?