Solar Cell Experiment

The California NanoSystems Institute
University of California, Los Angeles
Science Outreach Program

May Leung Chiu, Amar Flood, Steve Joiner, Alshakim Nelson, and Rob Ramirez

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Overview

Students prepare solar cells – devices which convert light energy into chemical / electrical energy – from simple starting materials and measure their electrical output in the light and dark using a multimeter.

Outline

Day One
- Teacher Pre-Lab – 45 minutes
  - Prepare TiO_2 Suspension
  - Distribute Supplies to Work Areas
- Student Procedure – 30 minutes
  - Coat one glass slide with TiO_2 and allow to cook for 20 minutes
- Teacher Post-Lab – 5 minutes
  - Collect Supplies
  - Turn off hot plate after slides have cooked for 20 minutes

Day Two
- Teacher Pre-Lab – 15 minutes
  - Prepare Raspberry Juice (Anthocyanin Dye Solution)
  - Distribute Supplies to Work Areas
- Student Procedure – 45 minutes
  - Dye slide from previous period with anthocyanin solution
  - Coat second slide with carbon
  - Assemble and test solar cell
- Teacher Post-Lab – 5 minutes
  - Collect Supplies and Clean Up

For the latest update to the manuals, visit
http://voh.chem.ucla.edu/outreach.php3
Discussion board password: **nano**
or email: **tolbert@chem.ucla.edu**

California State Science Standards Grades 9-12
Addressed by the Solar Cell Experiment

Physics

2. *The laws of conservation of energy and momentum provide a way to predict and describe the movements of objects.*

4a. *Students know waves carry energy from one place to another*

5b. *Students know how to solve problems involving Ohm's law.*

5c. *Students know any resistive element in a DC circuit dissipates energy. Students can calculate the power (rate of energy dissipation) in any resistive circuit element by using the formula Power =* I^2R

5o. *Students know how to apply the concepts of electrical and gravitational potential energy to solve problems involving conservation of energy*

Light, which can be modeled as a wave carrying energy, is converted into electrical energy (the movement of electrons) and energy is conserved. Students may be asked to calculate the "light" and "dark" resistances of their solar cell and class average solar cells using $R = V / I$. Students may be asked to calculate the power of their solar cell and class average solar cells using $P = I^2R$. Students may also be asked to relate these concepts to energy and to discuss conservation of energy in this respect.

Discussion Questions 5, 6, 7, and 8 all deal with conservation of energy in various ways. Calculations involving Ohm's Law and Power would need to be assigned by the teacher. Teachers may wish to try several activities in Further Exploration including Sources and Intensities of Light (demonstrates that intensity (net energy) of light affects the electrical energy output by the solar cell), Colors of Light (can discuss how different wavelengths of light affect the solar cell's performance), and Circuits (discuss many principles of electrical circuits and plan and test a circuit design to increase Power output by varying both voltage and current input).

Chemistry

1j. *Students know that spectral lines are the result of transitions of electrons between energy levels and that these lines correspond to photons with a frequency related to the energy spacing between levels by using Planck's relationship (*$E = h\upsilon$*).*

3g. *Students know how to identify reactions that involve oxidation and reduction and how to balance oxidation-reduction reactions.*

7f. *Students know how to use the Gibbs free energy equation to determine whether a reaction would be spontaneous.*

10b. *Students know the bonding characteristics of carbon that result in the formation of a large variety of structures ranging from simple hydrocarbons to complex polymers and biological molecules*

Anthocyanin is a complex organic molecule based on carbon, and is colored because it absorbs a specific wavelength (related to spectral lines) of light, resulting in the transition of an electron into a higher energy state, according to $E = h\upsilon$. This kicks off a series of spontaneous ($\Delta G < 0$) oxidation-reduction reactions that result in electrical energy equal to the energy of the light absorbed.

Discussion Questions 5, 6, 7, and 8 all deal with conservation of energy in various ways. Question 8 also discusses redox reactions and all of the chemical reactions after the first one are spontaneous due to the progressive decrease in Gibb's Free Energy. Discussion Topic 9 in the teacher's manual shows the structure of anthocyanin, the organic molecule that absorbs the photon of light. Teachers may wish to try several activities in Further Exploration including Colors of Light (different energies (colors) of light result in different levels of electrical output because the orbitals in the dye molecule are quantized and only specific energies of light can be absorbed) and Different Dyes (different organic molecules can also produce an electrical effect, but with differing quantitative (and qualitative, if discussing colors of light) results), due to the difference in atomic structures and therefore energy levels of the organic molecules involved.

Biology/Life Sciences

1f. *Students know that usable energy is captured from sunlight by chloroplasts and is stored through the synthesis of sugar from carbon dioxide.*

See Discussion Question 5 for a thorough discussion. The Different Dyes experiment in the Further Exploration section is strongly recommended to further demonstrate the connection of this experiment to photosynthesis.

Earth Sciences

4b. *Students know the fate of incoming solar radiation in terms of reflection, absorption, and photosynthesis.*
7a. *Students know the carbon cycle of photosynthesis and respiration and the nitrogen cycle.*

Solar radiation is absorbed by the molecules in the solar cell converting light energy into electrical energy. For a complete discussion and its relationship to photosynthesis, see Discussion Questions 5, 6, 7, and 8. The Different Dyes experiment in the Further Exploration section can be used to further demonstrate the connection of this experiment to photosynthesis.

Investigation and Experimentation

1a. *Select and use appropriate tools and technology (such as computer-linked probes, spreadsheets, and graphing calculators) to perform tests, collect data, analyze relationships, and display data.*
1b. *Identify and communicate sources of unavoidable experimental error.*
1c. *Identify possible reasons for inconsistent results, such as sources of error or uncontrolled conditions.*
1d. *Formulate explanations by using logic and evidence.*
1f. *Distinguish between hypothesis and theory as scientific terms.*
1g. *Recognize the usefulness and limitations of models and theories as scientific representations of reality.*
1j. *Recognize the issues of statistical variability and the need for controlled tests.*
1k. *Recognize the cumulative nature of scientific evidence.*
1l. *Analyze situations and solve problems that require combining and applying concepts from more than one area of science.*
1m. *Investigate a science-based societal issue by researching the literature, analyzing data, and communicating the findings. Examples of issues include irradiation of food, cloning of animals by somatic cell nuclear transfer, choice of energy sources, and land and water use decisions in California.*
1n. *Know that when an observation does not agree with an accepted scientific theory, the observation is sometimes mistaken or fraudulent (e.g., the Piltdown Man fossil or unidentified flying objects) and that the theory is sometimes wrong (e.g., the Ptolemaic model of the movement of the Sun, Moon, and planets).*

Discussion Questions 1, 2, 3, and 4 are specifically designed to help students to realize many of these key concepts, particularly 1a, b, c, d, and j. Question 4 can serve as a lead in to class discussions on 1f, g, k, and n. Class discussions on 1l can be based on the discussions outlined above for each of the disciplines – physics, chemistry, life sciences, and earth sciences. Discussion Question 7 can be used as a research prompt to encourage students to understand the science-based societal issue of choice of energy sources as outlined in 1m. Various energy sources (nuclear, solar, wind, hydroelectric, coal, oil, hydrogen, ethanol, etc.) are all hot topics of debate. Cutting edge nanotechnology research is currently underway in areas of methanol catalysis, hydrogen storage, and solar harvesting, and all of these are directly applicable to future sources of energy. Students can be assigned one specific energy source to research or may be asked to compare and contrast two or more.

*****Tip for Teachers*****

Read the entire teachers manual before you begin this experiment with your students! There are a number of ways in which students may be assessed on this experiment. You may choose to assign some of the discussion questions from the student manual for credit, you may ask the students to keep a lab notebook, or you may ask the students to prepare a lab report.

Solar Cell Supplies List

Reusable Supplies Included in Kit:

- 40 Plates of Conductive Glass
- Mortar & Pestle
- 2 Dropper Bottles for TiO_2
- 2 Dropper Bottles for Iodide Solution
- 10 Petri Dishes with Lids
- 25 Pasteur Pipettes
- Multimeter
- 2 Alligator Clips
- 40 Binder Clips
- 1 Cloth (for squeezing raspberry juice)
- 1 Copy of Student Manual (to be photocopied for students)
- 1 Copy of Teacher's Manual (this is it)

Consumable Supplies Included in Kit:

(Reorder requests: http://voh.chem.ucla.edu/outreach.php3)

- 20 g nanocrystalline TiO_2
- 2 mL Triton X
- 200 mL Aqueous Acetic Acid Solution (pH 3-4 in deionized water)
- 200 mL Iodide Solution (0.5M KI & 0.05M I_2 in ethylene glycol)

Supplies to be Obtained by Teacher:

- Frozen Raspberries (allow to thaw in refrigerator overnight)
- Ethanol (Rubbing Alcohol may be substituted)
- Distilled or Deionized Water
- Scotch Tape
- Absorbent Tissue or Cotton Swabs
- Hot Plate
- Overhead Projector

Kit contains materials for 20 solar cells (40-60 students working in groups of 2-3) to be made at a time.

Each Group of 2-3 Students Will Need:

- 2 Glass Plates
- 2 Binder Clips
- 1 Pasteur Pipette
- 1 Petri Dish (either top or bottom cover)

Day One – Teacher Pre-Lab – 45 Minutes

Prepare the TiO_2 Suspension

1. In 1 mL increments, add 9 mL of the provided acetic acid solution (pH 3-4 in deionized water) to 6 g of TiO_2 powder in a mortar and pestle while *grinding*.

   The grinding process mechanically separates the aggregated TiO_2 particles due to the high shear forces generated.

2. Add each 1 mL addition of the dilute acid solution only when the previous mixing and grinding has produced a uniform and lump-free suspension with a consistency of a thick paint.

   The grinding process requires about 30 minutes and should be done in a well-ventilated area.

3. To the TiO_2 paste, add a drop of Triton X (a surfactant similar to dish detergent) and swirl.

   This allows the final suspension to more uniformly coat the glass plates. So as not to produce foam, the TiO_2 suspension should not be ground or agitated after the surfactant is added.

4. Transfer half of the TiO_2 suspension in to each of the 2 provided small dropper bottles and allow it to equilibrate for at least 15 minutes (if not overnight) for best results. These bottles will need to be shared with the entire class.

Distribute the Supplies

Each Group of 2-3 Students Should Have:

- 2 conductive Glass Plates
- 1 Pasteur Pipette
- Scotch Tape

Set Up a Glass Plate Washing Station (Near Sink or Waste Container) With:

- Ethanol (Rubbing Alcohol May Be Substituted)
- Distilled or Deionized Water
- Absorbent Tissue or Cotton Swabs

Set Up a Multimeter Station With:

- Multimeter set to ohms

Set Up an Annealing Station in a Hood or Well Ventilated Area With:

- Hot Plate – Set On High and Post Clear Warning Signs – "**HOT**"

*****Tip for Teachers*****

Before the students start the experiment, make sure that you know how the multimeter works! If you have doubts, set the meter to ohms and touch the two leads to something that DOES conduct electricity – the alligator clips for example – and see what the display looks like. Then touch the leads to something that DOES NOT conduct electricity – a sheet of paper, for example – and see what the display looks like.

Day One – Student Procedure – 30 Minutes

Note: Procedure contains more detail and advanced terminology than the student manual

Preparation of the TiO_2 Coated Glass Plate

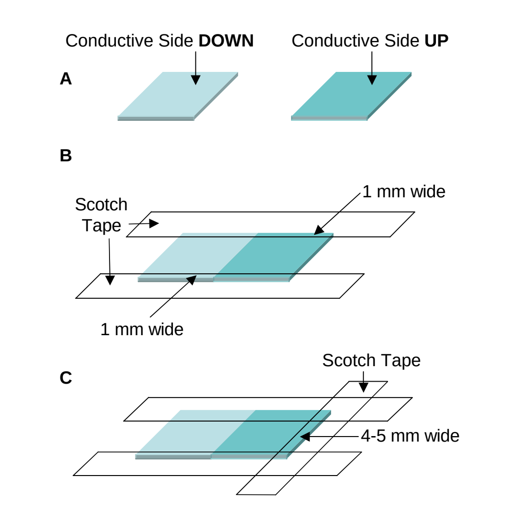


Figure 1

1. Obtain and clean two conductive glass plates by rinsing them in ethanol and then drying with a soft tissue—use the same technique as with cleaning a pair of eyeglasses. Once you have cleaned the glass plates, do not touch the faces of the plates, as the oils in your hand will contaminate these surfaces.

2. Use a multimeter, set to ohms, in order to check which side of the glass is conductive; the reading should be between 10 to 30 ohms.

3. Orient one glass plate with the conductive side up. This plate will be coated with the TiO_2 suspension. Turn over another glass plate, so that the conductive side is face down. Place it adjacent to the glass slide that is to be coated. When the assembly is completed, one glass plate will be conductive side up and the other with its conductive side down (keep track of the plate that is conductive side up). See **Figure 1A**. At this stage, the second piece of glass merely aids in the coating process.

4. Apply two pieces of Scotch (3M) adhesive tape (6-7 cm in length) to the top faces of the glass plates in order to mask a strip NO MORE than 1 mm wide on the two longer edges (**Figure 1B**).

5. Apply another piece of adhesive tape along the top of the glass to be coated so as to mask a 4 to 5 mm strip (**Figure 1C**). The three pieces of tape should extend from the edge of the glass to the table in order to secure the plates to the table.

   This tape controls the thickness of the TiO_2 layer, forming a 40-50 μm deep channel for the TiO_2 suspension. The tape also masks a strip of the conductive glass so that an electrical contact can later be made.

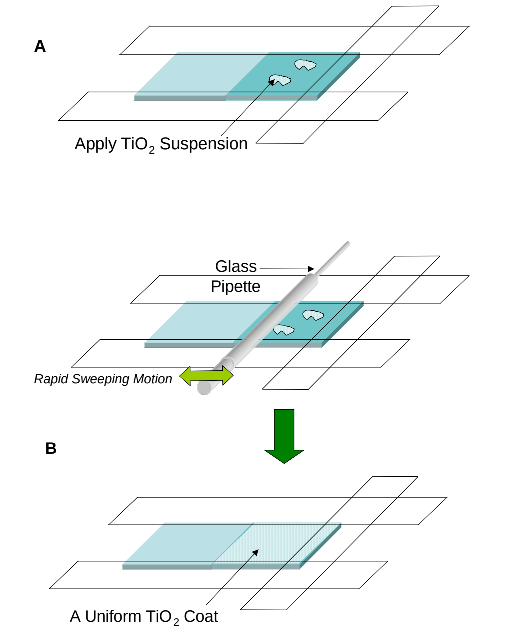


Figure 2

6. To coat the glass, add 2-3 drops of the TiO_2 suspension to the conductive-side-up glass slide using the dropper bottle (**Figure 2A**). The amount of solution needed is only 5 μL per square cm.

7. Within five seconds after application of the TiO_2 suspension, slide (DO NOT ROLL) a clean glass pipette (held horizontally) over the plate to spread and distribute the material (**Figure 2B**). The most successful technique for achieving a uniform film is to use a rapid sweeping motion of the pipette towards the tape end of the setup and then back over the film in the opposite direction, sweeping the excess TiO_2 off onto the second plate.

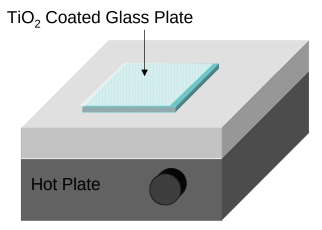


Figure 3

If the coating looks non-uniform, then the material can be wiped off the plate and the pipette with a dampened tissue and the deposition procedure repeated.

8. After deposition of the TiO_2 suspension, carefully remove the tape. Allow the TiO_2 film to dry for one minute. Wash and dry the plate that was conductive side down and set it aside for the next lab period. Clean the glass pipette, and allow the teacher to collect it for future use.

9. Anneal the TiO_2 film on the conductive glass by placing the glass plate on a hot plate that has been set on high (**Figure 3**). KEEP TRACK OF WHERE YOU PUT YOUR GLASS SLIDE!!! You will need to identify your glass slide tomorrow.

*****Tip for Teachers*****

Since students will need to remember which glass plate belongs to which group of students the following day, you may wish to place a sheet of paper with a sketch of the top of the hot plate adjacent to the heating station. Have each team of students draw a square on this sheet to represent where their glass plate is located on the hot plate and initial the square.

NOTE: During the heating of the films, the plates will initially turn brown (as the acetic acid burns off) and will then return back to white. If the tape is not fully removed from the glass slides, dark burned areas will appear on the edges of the glass slides. This is generally okay.

Alternate Procedure

If you have longer lab periods (block schedules, for example), have the students time their heating process, and, using tweezers, remove the glass slides after 20 minutes on the hot plate. DO NOT PUT THE GLASS SLIDES DIRECTLY ON A COLD SURFACE – they will crack. Instead, put them on a cloth or kitchen hot pad to allow them to cool for about 15 minutes. The glass slide must be cool enough to hold comfortably in your hand before carrying on to the next step, or the TiO_2 is likely to peel off the surface and the glass may even crack. **If you plan to do the entire experiment in one day, be sure that you complete both of the teacher pre-lab sections before your lab period!

Day One – Teacher Post-Lab – 5 Minutes

Turn Off the Hot Plate 15-20 Minutes After Lab Period

Do not move the glass slides. Allow them to slowly cool atop the hot plate until the next lab period.

Place Frozen Raspberries in Refrigerator Overnight

Moving the raspberries from your freezer to your refrigerator allows them to thaw overnight, so that you can squeeze the juice the following day.

Day Two – Teacher Pre-Lab – 15 Minutes

Prepare the Anthocyanin Dye Solution

CAUTION: MESSY!

1. Collect enough Petri dishes (tops or bottoms) so that each team of students will get one (you may wish to prepare one or two extra, just in case) and arrange them side-by-side on a tray, plate, etc. to make it easy to distribute one to each group once they are filled.

2. Empty a package of frozen raspberries (thawed in the refrigerator overnight) into the provided cloth and squeeze through the cloth (to filter out pulp and solid material) so that the bottom of each Petri dish is just covered in juice.

3. Dilute the raspberry juice in each dish by adding distilled or deionized water so that the volume of the liquid in each dish is approximately doubled.

4. Distribute one Petri dish to each student work station.

Alternate Procedure

Give each group of students 5-6 raspberries, a Petri dish, and a piece of cloth (a scrap from an old T-shirt, etc.) and allow them to squeeze and dilute their own juice. Fun, but potentially messy and time-consuming at the start of the lab!

Fill the 2 Iodide Dropper Bottles

Use the iodide solution provided with the kit. The class will have to share these two dropper bottles.

Distribute the Supplies

Each Group of 2-3 Students Should Have:

- 2 Glass Plates from previous period – 1 clean and 1 coated, now-cooled, on the hot plate
- 1 Petri dish with anthocyanin dye (prepared above)
- 2 binder clips

Set Up a Glass Plate Washing Station (Near Sink or Waste Container) With:

- Ethanol (Rubbing Alcohol May Be Substituted)
- Distilled or Deionized Water
- Absorbent Tissue or Cotton Swabs

Set Up a Multimeter Station With:

- Multimeter with 2 alligator clips attached to leads
- Overhead Projector (light source) nearby

Day Two – Student Procedure – 45 Minutes

Note: Procedure contains more detail and advanced terminology than the student manual

Staining of the TiO_2 Coated Glass with Anthocyanin Dye & Preparing the Carbon Coated Glass Plate

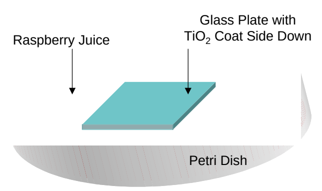


Figure 4

1. Retrieve the cooled TiO_2-coated glass plate from the hot plate and place it into the raspberry juice solution face down (**Figure 4**). Soak the TiO_2-coated glass plate for 10 minutes in the dye. If any of the white color of the TiO_2 can be seen upon viewing the stained film from either side of the glass plate, then the film should be placed back in the dye for an additional 5 minutes. Adsorption of anthocyanin to the surface of TiO_2 and complexation to Ti(IV) sites is rapid.

   Do not remove the glass plate from the raspberry solution until you are ready to assemble the solar cell in the next section.

2. While the TiO_2 electrode is being stained in the berry juice, the carbon-coated counter electrode can be made from the other conductive glass plate.

3. Clean your second glass plate (the one that is not soaking in raspberry juice) by rinsing it in ethanol and then drying with a soft tissue—use the same technique as with cleaning a pair of eyeglasses. Once you have cleaned the glass plate, do not touch the face of the plate, as the oils in your hand will contaminate the surface.

4. Use a multimeter, set to ohms, in order to check which side of the glass is conductive; the reading should be between 10 to 30 ohms.

5. Hold the conductive glass plate by the edges or with tweezers. Using a graphite (carbon) rod or soft № 2 pencil lead, apply a carbon film to the entire conductive side of the plate (**Figure 5**). Be careful not to miss any spots. This thin carbon layer serves as a catalyst for the electron transfer resulting in the triiodide to iodide regeneration reaction. No tape is required for this electrode, and thus the whole surface is coated with the catalyst.

6. The catalyst coating on the counter electrode should not be touched. It should not be rubbed or slid against the TiO_2 electrode or any other surface. The counter electrode should be picked up at the edges and carefully placed where it is desired.

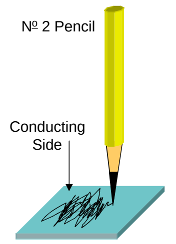


Figure 5

Assembly of the Solar Cell

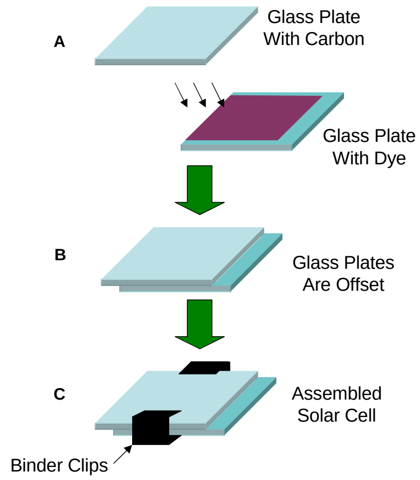


Figure 6

1. Remove glass plate (which is stained a dark purple) from the raspberry juice and rinse it with deionized water, then with ethanol.

   It is important to dry the stained glass plate and to remove the water from within the porous TiO_2 film before the iodide electrolyte solution is applied to the film. One way to ensure the TiO_2 film is dry is to rinse it with ethanol and place it on a tissue with the film side up.

2. Gently blot the TiO_2 film dry with a tissue.

3. Place the dried and stained electrode on a flat surface so that the TiO_2 film is face up; the carbon-coated counter electrode (from section III) is placed on top of the TiO_2 film such that the conductive side of the counter electrode faces the TiO_2 film (**Figure 6A**). To avoid excessive exposure of the stained film to air, steps 1-3 should be completed *within 1 minute*.

4. Gently lift the counter electrode and offset the two plates so that all of the TiO_2 is covered by the carbon-coated counter electrode, and the uncoated 4-5 mm strip of each glass plate is exposed (**Figure 6B**).

   At each end, 4-5 mm of each plate is exposed. The two exposed sides of the device will later serve as the contact points for the negative and positive electrodes.

5. Carefully pick up the assembly while it is in this orientation. Place two binder clips on the longer edges to hold the plates together (**Figure 6C**).

6. The iodide electrolyte solution consists of 0.5 M KI mixed with 0.05 M I_2 in ethylene glycol. Carefully place two drops of this liquid I^-/I_2 solution at one edge of the plates. Keeping the plates sandwiched together, alternately remove and replace each binder clip. This creates a small space between the plates into which the solution is drawn by capillary action. Continue alternating between the clips until all of the stained area is contacted by the electrolyte.

7. Wipe off the excess electrolyte from the exposed areas of the glass using cotton swabs and tissues dampened with ethanol. It is important that the electrolyte is completely removed from the two exposed sides of the cell.

Measuring the Electrical Output

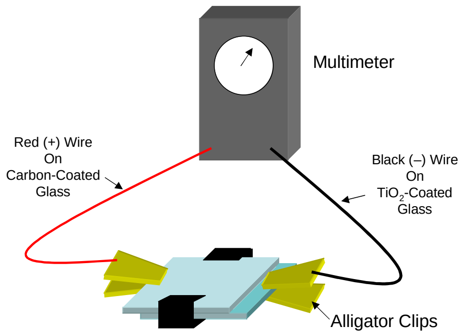


Figure 7

1. Fasten alligator clips to the two exposed sides of the solar cell to make electrical contact to the finished device (**Figure 7**).

2. Attach the black (–) wire of the multimeter to the TiO_2 coated glass plate (negative electrode).

3. Attach the red (+) wire of the multimeter to the carbon coated glass plate (positive electrode).

4. Place the solar cell on top of an overhead projector.

5. Measure the current (set to mA) before and after the overhead projector has been turned on.

6. Measure the voltage (set to volts) before and after the overhead projector has been turned on.

Did you make a successful solar cell?

*****Tip for Teachers*****

If you run out of time to test the solar cells at the end of your class period, or if you wish to do further experiments with the solar cells (see Further Exploration, at the end of this manual), you can use the solar cells again by following these simple instructions:

1. Store the solar cells in a sealed container (Ziploc bag, Tupperware, etc.) and place them in a cool, dark location (a refrigerator is ideal).

2. To regenerate the solar cells, simply add new iodide solution (steps 6 & 7 of the "Assembly of the Solar Cell" section in this manual).

3. If this simple process does not work, the solar cell can be taken apart, and both glass slides can be rinsed with ethanol and blotted dry with a tissue, and then the Solar cell can be reassembled and new iodide solution can be added (steps 3-7 of the "Assembly of the Solar Cell" section of this manual).

Day Two – Teacher Post-Lab – 5 Minutes

Collect and Store Reusable Supplies

Refer to page 2 of this manual to determine which supplies are considered reusable.

Clean Glass Slides for Future Use

If you have finished all experiments that you plan to do with the solar cells, the glass slides should be cleaned by scrubbing them with a soft tissue, using ethanol and water to take off the TiO_2 and other residues. It is nearly impossible to remove the carbon (pencil) from the second glass slide, so future teams of students should be given 2 slides – one that is clean, and one that has previously been used as the carbon-coated slide – and instructed to coat the clean one with TiO_2.

Suggested Topics for Discussion

1. Did your solar cell work? How can you tell? If it didn't work, why do you think this might have happened? If it did work, how might you be able to improve it?

   Students should see noticeably higher values for both current and voltage when the overhead projector is turned on than when it is turned off. If they do not see any change, then their solar cell did not work. Students will compare how WELL their solar cell worked in question two.

   If the solar cell did not work, the MOST COMMON cause for this is that one or both of the conductive slides is upside down – conductive side out!! This can be easily tested with the multimeter without disassembling the cell. Most other causes of a failed solar cell can be determined by visual inspection as well (students forgot a step or missed an ingredient). Occasionally, a solar cell will fail for "undetermined reasons". This is VERY rare, and it is still likely due to a missed step (such as failing to clean one of the slides or contaminating one of the surfaces with a fingerprint), but students will swear that they did not miss any steps or make any mistakes. In these rare cases, the reason for the solar cell's failure will have to be chalked up as "undetermined"

   There are two key areas for improvement of a working solar cell: First, the dye is made from berry juice and as such is subject to degradation. The use of a synthetic dye will make the solar cells last longer (and may also be more efficient at converting light energy to electrical energy). The second area for improvement is the electrolyte, which is prone to evaporation and to "leaking" from the solar cell. This can be addressed by sealing the edges of the solar cell so that the electrolyte is trapped, or by using a solid, polymer, or gel-based electrolyte.

2. How did your solar cell compare to the class average solar cell in each of the four categories tested?

   Answers will vary, but students should provide qualitative answers ("lower voltage than the class average in the light") and quantitative answers ("0.21 mA less current than the average in the dark").

3. Looking at the data for the entire class, which solar cells didn't work? Eliminate these solar cells and recalculate the class averages in all four categories tested. How does your solar cell compare to the class average solar cell now?

   Students should be able to pick out which solar cells did not show a significant increase in current and voltage when exposed to the light and eliminate these data points. However, different students may choose to ignore different sets of data, and this may lead to a good class discussion on where to draw the line about solar cells that did and did not work. For example, is there a threshold that must be crossed before a solar cell can be considered to have worked? What happens if you set this value VERY high (eliminating most of the class data)? What if you set this threshold VERY low (keeping virtually all of the class data, including solar cells that clearly did NOT work)? This discussion can lead nicely into question four.

4. Scientists make predictions, design experiments, and then collect and analyze data. As such, they may have to decide which data they choose to analyze and which data they choose to ignore. When is it ethical to ignore scientifically collected data as you may have done in question three?

   Answers will vary, but students should recognize that science is a discipline of facts and not opinions, so data (even if it is contrary to what you expected) is still data. If data is to be ignored, a rigorous definition of "good data" and "bad data" should be determined, and this definition must be included when the data is reported. For example, "bad data" in this case might be defined as solar cells that had less than a 0.1 V increase when measured with the light on after an initial measurement with the light off. Even though you have chosen to ignore these data points, you MUST still report a yield in your final experimental report ("16 of the 20 solar cells worked, according to our definition").

5. Photosynthesis is a process in which plants generate chemical energy from light energy. How is this similar to what happens with your solar cell? How is it different?

   In both cases, a dye molecule (anthocyanin in our experiment, chlorophyll in photosynthesis) is excited by a photon of light and releases an electron. Energy is conserved – the energy of the light is converted into chemical energy – an excited molecule, which then transfers its electron to another structure, resulting in electrical energy. In photosynthesis, the electron goes on to react in the Calvin-Benson cycle ultimately transforming raw materials (carbon dioxide and water) into sugar, storing the energy as food for the plant. In the solar cell, the electron travels out through the TiO_2 into the electrode, where the energy can be used to produce electrical work (in our case, the work is measured by the multimeter).

6. What is the function of each part of the solar cell that you built (**Figure 8**)?

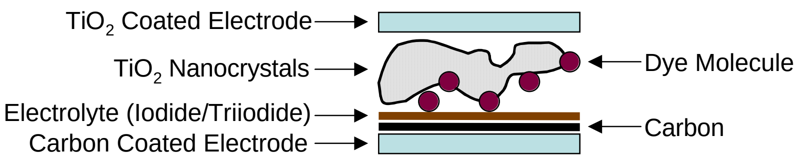


Figure 8

Dye Molecule – absorbs a photon of light, exciting an electron from its ground-state orbital into an excited-state orbital, making it easy for the electron to come free from the molecule and travel through the electrical circuit.

TiO_2 Nanocrystals – are very small, so they have a high surface area. When annealed (cooked) they fuse to form a very rough (and therefore very large) surface area. The dye molecules react with this surface, forming bonds so that they can stick to it. The larger the surface area, the more dye molecules can be attached to the surface and therefore the more electrons can be excited at any given time. The TiO_2 is a semi-conductor, so it enables the electrons to move away (conduct) from the dye molecules and into the circuit.

Electrodes – conduct the electrons from the cell into the electrical circuit. This allows the electrons to flow through the circuit (in our case, a multimeter). Flowing electrons are called electricity! Tin oxide (SnO_2) coated glass is used because it is both conductive and transparent, and we want light to pass through the electrodes into the solar cell.

Electrolyte – when the dye loses an electron, it becomes positively charged, and needs obtain another electron to be re-neutralized. (It will then be able to react again when another photon comes along!) The iodide ion (I^-) is able to provide the required electron, thereby neutralizing both the iodide and the dye molecule. Iodine is not stable as a single neutral atom, so two neutral atoms of iodine react with an additional iodide ion to form triiodide (I_3^-).

Carbon – Recall that electrons are flowing OUT through the TiO_2-coated electrode and IN through the carbon-coated electrode. The carbon acts as a catalyst, allowing two incoming electrons to react with one molecule of triiodide to form three iodide ions, thus completing the cycle.

7. What are other sources of energy? How do these sources of energy compare to solar energy?

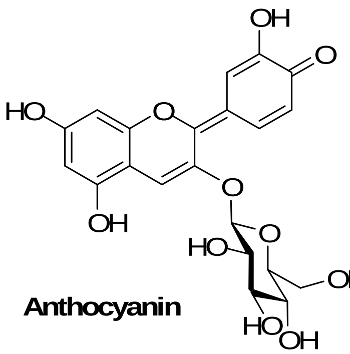
   Answers will vary.

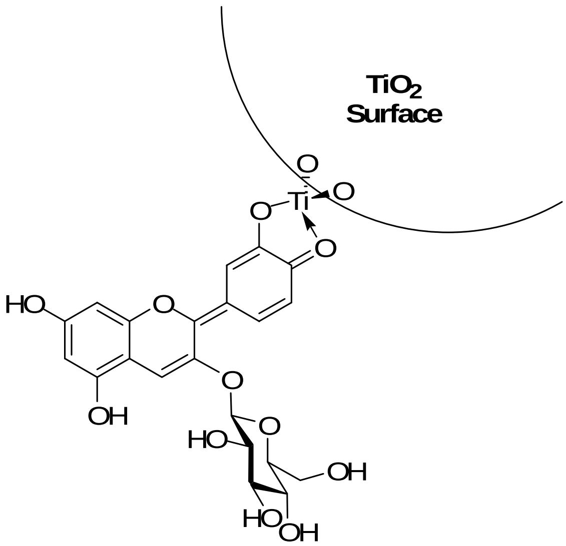
8. ADVANCED: Write balanced equations for each of the (electro)chemical processes that happen in the solar cell.

*anthocyanin + photon → anthocyanin**
anthocyanin + TiO_2 → e^- (in TiO_2 lattice) + anthocyanin$^+$*
e^- (in TiO_2 lattice) + neg. electrode → TiO_2 + e^- (in neg. electrode)
e^- (in neg. electrode) → e^- (in pos. electrode) + electrical energy
anthocyanin$^+$ + 3/2 I^- → anthocyanin + 1/2 I_3^-
1/2 I_3^- + e^- (in pos. electrode) → 3/2 I^- + pos. electrode

NET REACTION:
photon (light energy) → electrical energy

9. Chemistry classes may wish to discuss that anthocyanin is an organic molecule. It is shown below, and is also shown chelated to the TiO_2.


Anthocyanin



Adapted from
The Institute For Chemical Education
Department of Chemistry
University of Wisconsin, Madison
http://ice.chem.wisc.edu

Further Exploration

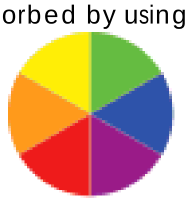
Additional Activities for Advanced Students

Sources and Intensities of Light

Measure the voltage and current output from the solar cell while it is exposed to a number of sources of light (suggestions include: dark box; classroom with lights out; classroom with fluorescent lights on; overhead projector light; direct sunlight; outdoors, but in the shade of a tree or building, etc.). How does the solar cell respond in each situation? Can you relate the apparent intensity of light (how bright each light source appears to you) to the electrical output from the solar cell?

Colors of Light

Recall that when a substance is exposed to white light, some of the light is absorbed and the rest is reflected. Thus, an object which appears white is absorbing very little light, an object which appears black is absorbing a lot of light, and an object which appears blue is absorbing light that is not blue. We can predict the color of light that is being absorbed by using a color wheel:



The color that an object reflects is opposite from the color that is being absorbed, so we can determine that an object which appears blue is absorbing orange light. What color does your solar cell appear to be? What color light must it absorb? To test this, obtain several different colored (we recommend red, green, and blue) gels – transparent sheets of plastic that are used to change the color of light sources. You can get these from any theatrical supply store. Alternatively, print several sheets of transparency film using a color printer, each with different solid colors. Cover the overhead projector with each sheet, so that a colored light source is projected onto your solar cell, and measure the voltage and current outputs for each color. Which color produces the most electrical energy? The least? How does this compare with your prediction? NOTE: If you use a chlorophyll solar cell from the “Different Dyes” experiment, you can test the light response of solar cells that appear very different in color.

Different Dyes

There are a number of different dyes that can be used to make the solar cells. You can use the same procedure described in this manual, but instead substitute the juice from blackberries, pomegranate seeds, Bing cherries, red hibiscus tea leaves, or cranberries (all contain anthocyanin).

In addition, you can make a chlorophyll dye using green leaves (we’ve found that spinach leaves work well, but others may also work): On day one of the two-day experiment, grind the leaves in acetone (nail polish remover) in the mortar and pestle until the solution is dark green. Filter off the solution into a GLASS container, and immerse the annealed (20 minutes) and COOLED TiO_2-coated glass slide in the solution. Seal the container to prevent evaporation and wrap it in aluminum foil so that the interior of the container is dark. Allow the glass slide to soak in the solution for 24 hours dying the TiO_2 surface light-green. Store the glass slide in the solution until you are ready to assemble the solar cell, following the original directions. How do the solar cells made with each type of dye compare to each other?

Circuits

Solar cells behave similarly to batteries when placed into a circuit. Recall that when batteries are connected in series, their voltages are added, but their currents remain constant and when batteries are placed in parallel, their currents are added, but their voltages remain constant. Number a class set of solar cells so that you can keep track of each one. Record in a table the current and voltage values for each numbered cell in both the light and the dark. Using a number of alligator clips, wire up 2, 3, 4, etc. solar cells (noting which ones you use) in series and measure the voltage and current. Now, wire them up in parallel and measure. Do they respond as you would predict? Can you design and build a single circuit with solar cells in both series AND parallel to increase both the voltage and the current output?