Photosynthesis Module

Structure and Thermal Motion of
LH2 Complex in Purple Bacteria

NGSS: Relevant Topics

- **HS-PS4-4:** Evaluate the effects that different frequencies of electromagnetic radiation have when absorbed by matter. Emphasis is on the idea that photons associated with different frequencies of light have different energies, and the (interaction with) living tissue from electromagnetic radiation depends on the energy of the radiation.
- **HS-LS1-5:** Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy. Emphasis is on illustrating inputs and outputs of matter and the transfer and transformation of energy in photosynthesis by plants and other photosynthesizing organisms.
- **MS-LS1-6:** Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms. Emphasis is on tracing movement of matter and flow of energy.

Introduction

In this module, we will explore how living systems harvest sunlight through the process of photosynthesis. Although there are numerous mechanics involved, we are going to start by highlighting only one of them in hopes of shedding light on this incredible phenomenon.

The creatures we are going to investigate are purple bacterium. These common single-cellular organisms are found at the bottom of aquatic habitats such as lakes and ponds. Similar to eukaryotic bottom feeders (such as shrimp), the bacterium secure the leftover light from the sun not blocked out or consumed by the plants and algae floating above. As the name suggests, purple bacteria are colored purple because they do *not* absorb in that range of the light spectrum. They were also the first bacteria observed to photosynthesize anaerobically, i.e., without oxygen.

Bacteria outnumber all eukaryotes combined in biomass, but are so small that they can not be seen by the naked eye. To give you an idea, there are approximately one million bacterial cells in a single milliliter of fresh water. If you were to lyse (break open) a single bacteria and examine its interior, you would find that within each cell is a spectrum of inner machinery giving rise to an amalgamation of properties - including the components responsible for photosynthesis.

It is safe to think of these operations as the inner workings of numerous abstract and almost alien-like machines - with all the inner parts cooperating as one to fuel the whole. Let us zoom in on just one of these apparatuses within the bacterial cell, where the operations necessary for photosynthesis originate.

Procedure

The entirety of today's lesson will be contained in VMD Lite. The following instructions will guide you through all of the visualizations and simulations we have prepared.

1. Under the "Extensions" tab in VMD, open the TkConsole window. Type in "package require vmdlite" and hit enter.
2. Then type "vmdlite" at the prompt and press enter to open VMD Lite.
3. Click "Lesson" on the welcome window that appears.
4. Select the main lesson folder named "lessons", then click "Load LH2".

Slide 1: Chromatophore

5. Before beginning the lesson, navigate to the “media” folder in the main LH2 directory, and play the video entitled **Chromatophore.mp4**. Set the video to play on a continuous Loop.

You should see an array of structures arranged on a rotating sphere. This structure is called a chromatophore, and it is known to come in a variety of other shapes such as tubules, folds, and small sacs. The chromatophore harbors numerous biological parts across its surface that together combine like a factory to perform the photosynthetic operations.

In size, each chromatophore averages around 70 nanometers in diameter, and consists of approximately 100,000,000 atoms. To give you an idea of this scale, a single nanometer takes up a billionth of a meter. This chromatophore is just one of hundreds like it within the bacterium. Its function is to absorb light from the sun and provide energy (ATP) for the cell. Through physical processes, this energy is translated into numerous operations to help the cell continue operating, to survive, repair, and divide.

6. Familiarize yourself with the structures present along the chromatophore’s surface. The red and teal rings around the outside of the chromatophore are called light-harvesting complex 1 and light-harvesting complex 2 (LH1 and LH2). Photosynthetic processes begin at the LH2, which acts like the cell’s antenna for incoming light. The purple structures are known as reaction centers (RC), while the magenta ones are bc1 dimers. The large yellow structures protruding well beyond the surface of the chromatophore are the ATP synthases, which produce the ATP used elsewhere in the cell. Although the actual chromatophore is entirely opaque, half of this sphere has been made transparent so that you can see inside of the individual structures.
7. Examine the chromatophore to see if you can get an idea for the total number of each of the structures present. **Which one of the structures listed is by far the most abundant? Why do you think this is?**
8. Click “Next” (slide 2) to proceed to the next section.

Slide 2: LH2 in Membrane

9. This slide contains a zoomed-in graphical representation of a single light-harvesting complex 2 from Slide 1 (seen previously in teal). This structure is just one of the numerous LH2’s previously seen arranged across the chromatophore’s surface.
10. Here we see the LH2 secured within the membrane of the chromatophore. **What do you predict the LH2 will do when embedded within the chromatophore’s surface?**
11. Drag the bar or press “Play” to watch the simulation. **What do you observe? Was your prediction accurate?**

Even though the atoms undergo chaotic movements, they are restrained by the balance of forces from their interactions with the rest of the protein and the membrane. Thus, the chromatophore not only serves to arrange the many photosynthetic processes to be in close proximity, but it also anchors them in place against the chaotic environment around them.

12. Next let’s examine the numerous structures present. Pause the simulation, and locate the rings of chlorophylls and carotenoids (seen in blue/magenta and green, respectively). These structures function as to channel energy from incoming light through the cell.
13. You should find that the chlorophylls are arranged in two separate rings. Take a moment to think about the geometry of these structures. **Why do you think the chlorophylls are oriented arranged in such a way?**

It turns out that the arrangement of the chlorophylls affects the wavelengths, i.e., colors, of light that can be absorbed. Therefore, the two distinct rings increases the range of useable light for purple bacteria. The magenta ring of chlorophylls are called “B850” because they absorb light primarily around a wavelength of 850 nanometers; the blue ring of chlorophylls are called “B800” for a similar reason. Both wavelengths are in the infrared region.

14. **How does this new information fit with your prediction from the question posed at the end of slide 1 (on the abundance of LH2 structures found across the surface of the chromatophore)?**

Each chlorophyll gains energy by absorbing incoming light particles (called photons) from the sun. All light in the universe is comprised of photons, which take on properties of both waves and particles. Einstein discovered that the total energy of these photons was not dependent on the light's intensity (total number of the incoming particles), but actually on their individual frequency via the relation:

$$E = hf$$

Here, E is the energy of the photon and f its frequency. The frequency of each photon is the inverse of its wavelength λ, such that $\lambda = c/f$, where c is the speed of light (3×10^8 m/s). Light having a longer wavelength (infrared light, for example) will have a lower frequency, while light having a shorter wavelength (such as ultraviolet light) will have a higher frequency. The colors that we humans experience (those within the so-called "visible spectrum") are in between these two extremes.

As can be seen from the above equation, individual photons with higher frequencies (more compact wavelengths) carry more intrinsic energy E than those having lower frequencies (more spread out wavelengths). Finally, you might be wondering what the h represents. This symbol is called the Planck constant, an incredibly small number (6.626×10^{-34} J·s) that occurs frequently in quantum mechanics.

15. Click "Next" (slide 3) to proceed to the next section.

Slide 3: LH2 in Water

As you may immediately notice, we have now prepared this system so that the key energy-absorbing molecules, the chlorophylls and carotenoids, are completely removed from their protein/membrane scaffolding, now surrounded only by water (not shown).

16. **How do you predict the chlorophylls will behave when isolated from the chromatophore's surface?**

Press play and observe what happens. As you can see, the special arrangement of chlorophylls is unable to sustain itself in the absence of the membrane and protein scaffold. The random motion of water molecules within the cell quickly disrupts their optimal structure, and thus eliminates the potential for any photosynthetic processes to take place. These random movements of the water and other molecules (called Brownian motion) are directly tied to the temperature of the system.

Given that temperatures as mild to us as 25°C (77°F) create such a chaotic environment on the molecular level, the cell has evolved structures capable of creating pockets of stability for some of its functions.

17. Click "Next" (slide 4) to proceed to the next section.

Slide 4: Bacteriochlorophyll

18. On this slide, we have isolated the chlorophylls from the rest of the LH2. At the center of each of the chlorophyll's rings is a single magnesium atom (blue). Use the display to find one. **What purpose do you think this metal particle could have in the ability of the chlorophyll to collect energy from its environment? Discuss your thoughts with your neighbor.**

As we know from studies of electricity and electrical circuits, metals make very good conductors. The properties that allow metals to conduct electrons (negatively charged subatomic particles) also make them useful in many biological reactions in which electrons need to be transferred from one molecule to another. While the chlorophylls shown on the screen do not directly transfer any electrons, they donate the energy they absorb from light to a "special" pair of chlorophylls in the Reaction Center (purple protein in the video), where an electron is transferred.

Problems

- **Problem 1:** Experiments on the bacteriochlorophyll have found that it absorbs photons having wavelengths of approximate length $\lambda = 800$ nanometers. **Given the relations provided, calculate the energy of a typical photon absorbed by a single chlorophyll and compare your answer with your neighbor.** The answer you find will be in the units of Joules (a unit of both energy and work).

- **Problem 2:** (*Challenge Problem*) As an example of the magnitude of your previous answer, a single Joule is the energy required to lift a typical apple a distance of one meter. **If you wanted to lift this same apple using only the energy from light, how many 800-nanometer photons would be required?**

Conclusion

This concludes our module describing the role of LH2 in photosynthesis. A few of the things we hope you learned in this module are:

- Although there is a great deal of chaos on the molecular level, cells have evolved ways to secure, arrange, and connect their interior biological molecules, thus creating a balance between order and disorder within their environment.

- Photons with different frequencies carry different energies, some of which can be absorbed by chlorophylls depending on their arrangement.

- Structures capable of photosynthetic operations carry the capacity to transform energy from one form to another (electromagnetic to chemical) and subsequently channel it for performing useful work across the cell. This work ultimately leads to the cell's fundamental abilities to survive, repair, and divide.

Solutions

Problem 1:

To calculate the energy of a typical photon absorbed by a single chlorophyll, use the equations supplied:

$$f = \frac{c}{\lambda} = 3.75 \times 10^{14} \text{ Hz}$$

$$E = hf = 2.48 \times 10^{-19} \text{ J}$$

Problem 2:

Now that you know that each photon carries an energy of 2.48×10^{-19} J, you want to know how many of these photons it would take to carry a total energy of 1 Joule. Thus, set up an equation multiplying the energy of one photon (E_γ) by the number of photons needed (n_γ):

$$1 \text{ J} = n_\gamma \cdot E_\gamma$$

$$1 \text{ J} = n_\gamma \cdot 2.48 \times 10^{-19} \text{ J}$$

and solve for n_γ to find that 4.02×10^{18} photons are required.