Lesson 3:
How Sunscreens Block: The Absorption of UV Light

Teacher Materials

Contents

How Sunscreens Block: The Absorption of UV Light: Teacher Lesson Plan

Orientation

This lesson introduces students to the core science behind sunscreen absorption of UV light. This is an advanced topic that requires students to have a background in atomic energy levels, absorption and emission processes.

- The How Sunscreens Block: The Absorption of UV Light PowerPoint focuses on the details of how matter absorbs light. The slides start with the more familiar concept of the emission of light by atoms and progress to absorption of light by atoms, then absorption of light by organic molecules, and finally absorption of light by inorganic compounds. The Absorption Summary Student Handout should help students pull make connections between a chemical's structure and its absorptive properties.
- The Student Reading on Absorption provides more details about this key interaction between light and matter.
- The Reflecting on the Guiding Questions Worksheet asks students to connect their learning from the activities in the lesson to the overall driving questions of the unit.

Essential Questions (EQ)

What essential questions will guide this unit and focus teaching and learning?

1. What are the most important factors to consider in choosing a sunscreen?
2. How do you know if a sunscreen has "nano" ingredients?
3. How do "nano" sunscreen ingredients differ from most other ingredients currently used in sunscreens?

Enduring Understandings (EU)

Students will understand:

(Numbers correspond to learning goals overview document)

1. How the energies of different wavelengths of light interact differently with different kinds of matter.

Key Knowledge and Skills (KKS)

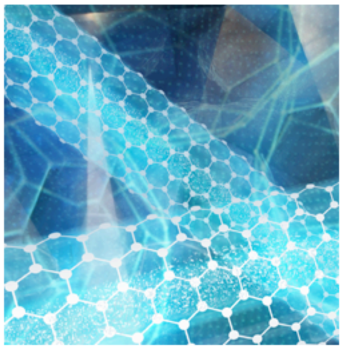
Students will be able to:

(Numbers correspond to learning goals overview document)

1. Describe the mechanisms of absorption and scattering by which light interacts with matter.

Absorption Timeline

Day	Activity	Time	Materials
	Homework: Absorption of Light by Matter: Student Reading	*20 min*	Copies of Absorption of Light by Matter: Student Reading
Day 1 (50 min)	Show How Sunscreens Block: The Absorption of UV Light PowerPoint Slides, using the embedded question slides and teacher's notes to start class discussion.	35 min	How Sunscreens Block: The Absorption of UV Light PowerPoint Slides & Teacher Notes
	Discuss the readings and any questions students have about the PowerPoint slides.		Copies of Absorption Summary: Student Handout Computer and projector
	Have students work individually or in small groups to fill out the Reflecting on the Guiding Questions: Student Worksheet.	5 min	Copies of Reflecting on the Guiding Questions: Student Worksheet
	Bring the class together to have students share their reflections with the class. This is also a good opportunity for you to address any misconceptions or incorrect assumptions from students that you have identified in the unit up till now.	10 min	Reflecting on the Guiding Questions: Teacher Instructions & Answer Key



How Sunscreens Block

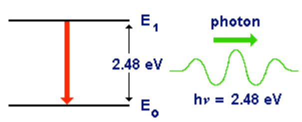
The Absorption of UV Light

NanoSense
the basic sense behind nanoscience

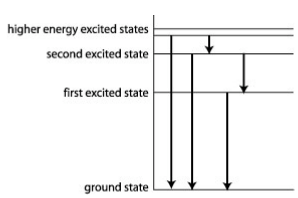
Prelude: Emission of Light by Atoms

- **An e^- falls from a higher energy state to a lower one**
  - A photon with the exact energy difference between the levels is released

Single electron falling from energy level E1 to E0



- **Each atom has characteristic energy level transitions which create an atomic spectrum**



Electronic transitions and visible emission spectrum for a Helium atom

Sources: Images adapted from http://members.aol.com/WSRNet/tut/absorbu.htm, http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

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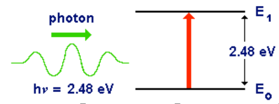
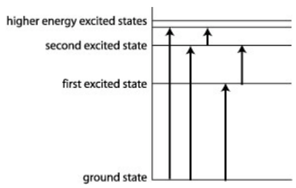
Prelude: Absorption of Light by Atoms

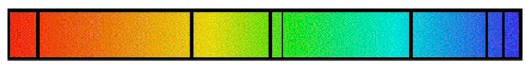
- **Absorption is just the reverse**
  - Only a photon with energy exactly corresponding to the energy of transition of an electron can be absorbed

Single electron transition From E_0 to E_1



- **The different transitions produce absorption spectrums of discrete lines**





Electronic transitions and visible absorption spectrum for a Helium atom

Sources: http://members.aol.com/WSRNet/tut/absorbu.htm, http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

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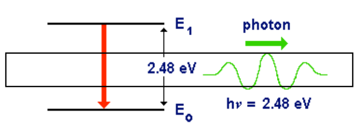
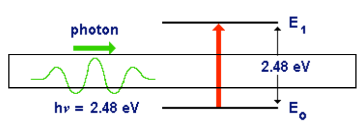
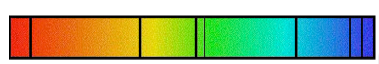
Prelude: Emission versus Absorption

Emission	Absorption
• Energy released at specific wavelengths	• Energy taken in from specific wavelengths





• Emission spectrum only shows wavelengths emitted	• Absorption spectrum shows all wavelengths except those absorbed

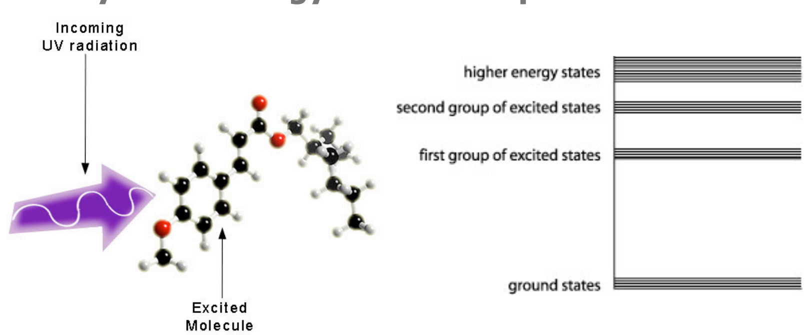


Sources: Images adapted from http://members.aol.com/WSRNet/tut/absorbu.htm, http://csep10.phys.utk.edu/astr162/lect/light/absorption.html

If atomic absorption produces absorption lines, what do you think molecular absorption look like?

Organic Molecules: Energy Levels

- **Molecules have multiple atoms which can vibrate and rotate in relation to each other**
  - Each kind of vibration / rotation = different energy state
- **Many more energy transitions possible**

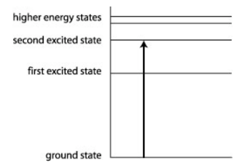


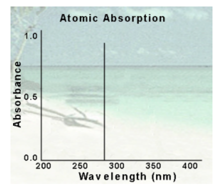
Source: Image adapted from http://www.3dchem.com/molecules.asp?ID=135#

Organic Molecules: Absorption

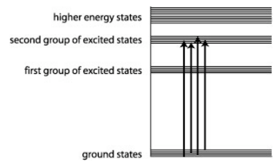
- **Many closely spaced energy transitions mean that instead of absorbing exact frequencies of light, molecules absorb groups of frequencies**

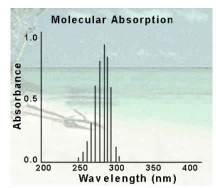
Atomic Absorption





Molecular Absorption



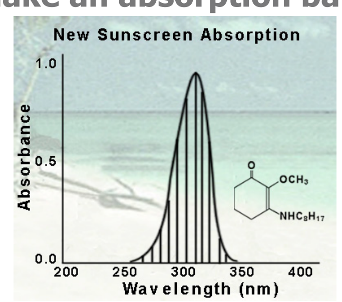


Source: http://www.nptel.iitm.ernet.in/courses/IITMadras/CY101/lecture16new/lecture16.htm

Organic Molecules: Absorption Curve

- **The many closely spaced absorption lines combine to make an absorption band:**

Absorption range for a new sunscreen molecule under testing



Range: 255 – 345 nm

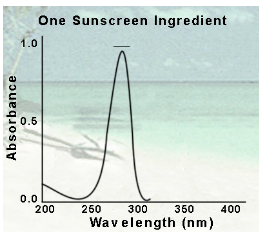
Peak: 310 nm

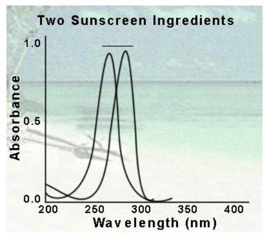
- **Peak absorption and absorption range vary by molecule**
  - Molecules are usually strong UVB or UVA absorbers but not both

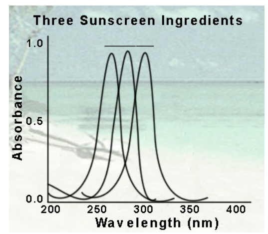
Source: http://www.aims.gov.au/pages/research/projects/sunscreens/images/graph02-2a.jpg

Organic Molecules: UV Protection

- Different ingredients are good for blocking different parts of the UV spectrum







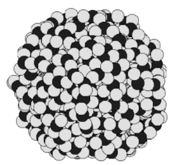
- Using more than one kind of molecule gives broader protection

Source: Graphs adapted from http://www.aims.gov.au/pages/research/projects/sunscreens/pages/sunscreens02.html

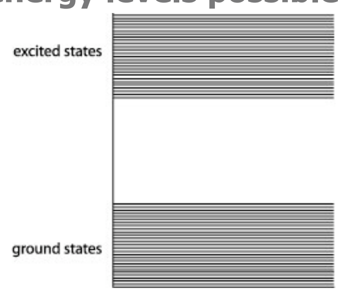
How do you think absorption by inorganic compounds might be different than absorption by molecules?

Inorganic Compounds: Energy Levels

- **Inorganic ingredients exist as particle clusters**
  - Very large number of atoms involved
  - Electrons' energy depends on their position in relation to all of them
- **Huge number of different energy levels possible**



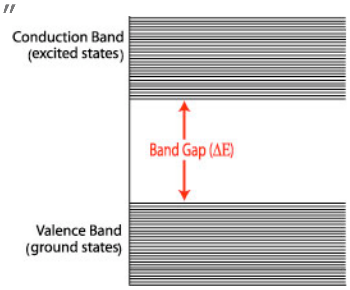
~200 nm TiO_2 particle



Source: Images adapted from http://www.cse.clrc.ac.uk/msi/projects/ropa.shtml

Inorganic Compounds: Absorption I

- **Because the energy levels are so closely spaced, we talk about them together as energy "bands"**
  - Normal energy band for electrons (ground states) is called the "valence band"
  - Higher energy band (electrons are more mobile) is called the "conduction band"
- **In each band, there are many different energies that an electron can have**
  - The energy spacing between the two bands is called the "energy gap" or "band gap"



Source: Original Image

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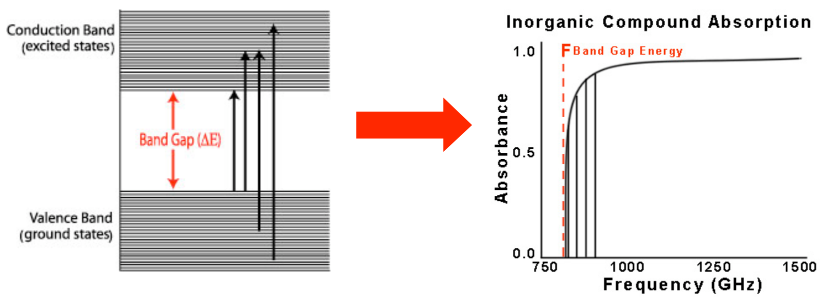
Inorganic Compounds: Absorption II

- **Electrons can "jump" from anywhere in the valence band to anywhere in the conduction band**
  - Inorganic Compounds are able to absorb all light with energy <u>equal to or greater than</u> the band gap energy



Source: Original Images

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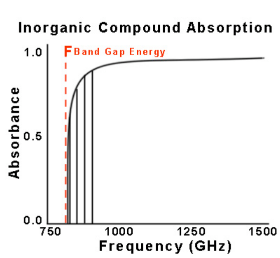
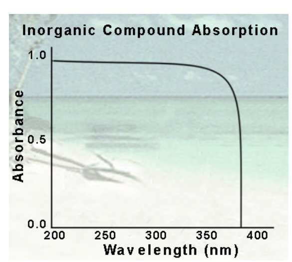
Inorganic Compounds: Absorption Curve

- **This is the same as saying that all light absorbed must have a wavelength equal to or less than the wavelength corresponding to the band gap energy**





- **Absorption curves have sharp cutoffs at this λ**
  - Cutoff λ is characteristic of the kind of compound
  - Doesn't depend on size of the cluster

Source: Graph adapted from http://www.aims.gov.au/pages/research/projects/sunscreens/pages/sunscreens02.html

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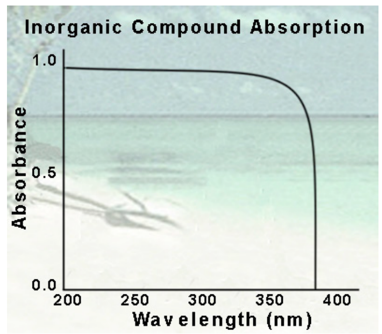
Inorganic Compounds: UV Protection

- **Inorganic Compounds with cut off wavelengths around 400 nm (ZnO and TiO_2) are able to absorb almost the whole UV spectrum**
  - Can be the only active ingredient in a sunscreen
  - Can also be combined with other ingredients for reasons such as appearance or cost
  - True for both nano and traditional forms (not dependant on size)



Source: Graph adapted from http://www.aims.gov.au/pages/research/projects/sunscreens/pages/sunscreens02.html

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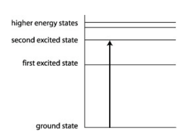
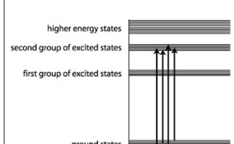
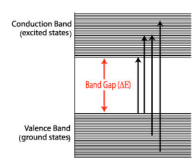
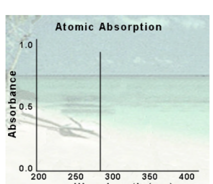
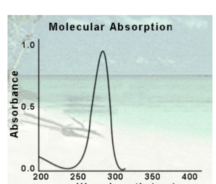
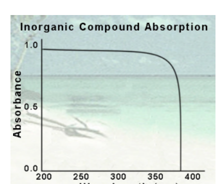
Absorption Summary

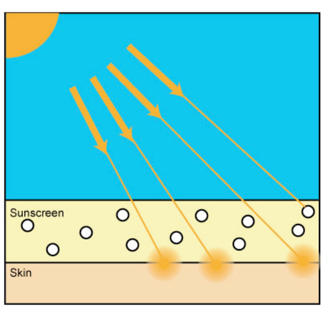
	Atoms	Organic Molecules	Inorganic Compounds
Energy Levels			
Absorption Spectrum			

Challenge Question:

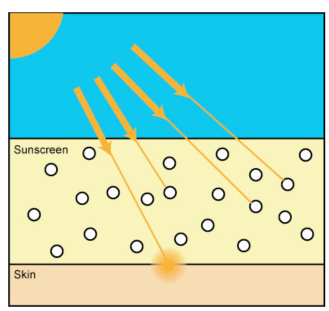
Can sunscreens absorb all of the UV light that shines on our skin?

Answer: It Depends I

- The amount of sunscreen applied influences how much of the incoming UV light is absorbed



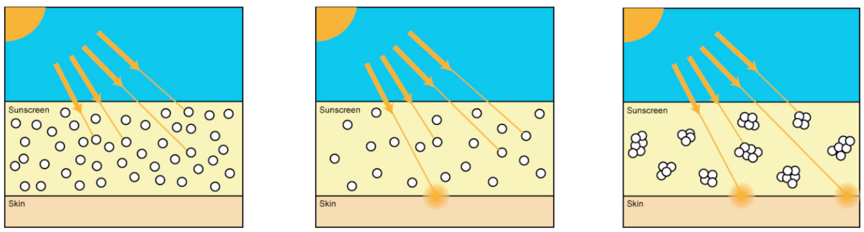
Thin Layer of Application



Thick Layer of Application

Answer: It Depends II

- **The concentration and dispersion of the active ingredients also influences how much of the incoming UV light is absorbed**



High Concentration High Dispersion | **High Dispersion Low Concentration** | **High Concentration Low Dispersion**

Summary

- **Active sunscreen ingredients absorb UV light**
  - Organic molecules each absorb a specific range of wavelengths determined by their energy level spacing
  - Inorganic compounds absorb all wavelengths less than a critical value (which corresponds to the band gap energy)
- **Several practical factors are important to ensure that a sunscreen provides the best possible protection against UV light**
  - High concentration of active ingredients
  - Wide dispersion of active ingredients
  - Applying an appropriate amount of sunscreen

How Sunscreens Block: The Absorption of UV Light: Teacher Notes

Overview

This set of slides focuses on the details of how matter absorbs light. The slides start with the more familiar concept of the emission of light by atoms and progress to absorption of light by atoms, then absorption of light by organic molecules, then absorption of light by inorganic compounds.

Slide 1: Title Slide

Slide 2: Prelude: Emission of Light by Atoms

The key concept in this slide is that the energy of the photon released is always equal to an energy difference between energy levels. The characteristic energy of the photon is related to its frequency and wavelength, and if the light is in the visible spectrum, a characteristic color.

The different energy levels relate to the position and movement of electrons with respect to the nuclei.

Slide 3: Prelude: Absorption of Light by Atoms

Absorption is the complementary process to emission. Instead of light being released by the atom, the atom captures the energy of light that shines on it.

In order for absorption to occur, the energy of the incoming photon must be exactly equal to the energy of an energy transition. This is the same principle that as for emission.

Since there are several possible electronic transitions, there are several energies of photons that can be absorbed. Each of these corresponds to a specific frequency of light ($E=hf$). Each frequency of light in the visible spectrum appears as a specific color to ours eyes. This produces the visible absorption spectrum for helium shown in the slide.

Important Note: Even though only the visible absorption is shown here, molecules can also absorb other kinds of radiation.

Common Student Question: What happens to the light energy after it is absorbed?

Answer: Some time after light is absorbed, the electron will fall back down to a lower energy state. This releases the energy which is re-emitted as a photon or group of photons, often of lower energy. After this happens, the electron is free to absorb a new photon of light.

Slide 4: Prelude: Emission versus Absorption

Note that the absorption and emission spectra have lines at the same frequencies since the photons emitted and absorbed correspond to the same electronic transitions (same difference in energy levels). The characteristic difference in energy levels depend on the kind on atom and these spectra can be thought of as atomic “fingerprints.”

Slide 5: If atomic absorption produces absorption lines, what do you think molecular absorption looks like? (Question Slide)

Have your students brainstorm ideas about how molecules are different from atoms and how this might relate to the absorption of light.

Slide 6: Organic Molecules: Energy Levels

Energy levels relate to the position and movement of electrons and nuclei with respect to each other. Since molecules have more than one nuclei (because they involve more than one atom), in addition to electronic energy levels, they can be in different rotational and vibrational modes based on the relative motion of the different nuclei. This creates multiple ground and excited energy levels for each electronic state.

Slide 7: Organic Molecules: Absorption

Since molecules have groups of energy levels, instead of only absorbing single frequencies of light, they absorb a set of closely spaced frequencies (and thus wavelengths). While this creates a curve and is referred to as an absorption range – it is really a set of discrete energy transitions that absorb similar frequencies of light.

Note that the absorption is the strongest in the middle of the range. This is because this is the wavelength that corresponds to the most common energy transition.

This is a good point in the presentation to give you students the Absorption Summary: Student Handout to refer to.

Slide 8: Organic Molecules: Absorption Curve

Note that molecule does not absorb evenly over its whole absorption range. The more peaked the absorption curve, the more quickly absorption drops off as you move away from the peak wavelength.

Student Check Question: What kind of UV light does the sunscreen molecule shown in the graph absorb?

Answer: Mostly UVB light. The UVB range is ~280-320 nm while the UVA range is ~320-400 nm. The absorption range runs from 255 nm to 345 nm and thus covers more of the UVB spectrum than the UVA one. In addition, from the peak at 310 nm the absorbance slope toward the shorter wavelengths is more gradual. You can demonstrate than there is more UVB than UVA being absorbed by drawing a vertical line at 320 nm and looking at the area under the curve on both sides (on the left you may want to draw a second cutoff line at 280 nm for the end of the UVB range). Students should notice that the area between the 280 and 320 nm lines (UVB region) is bigger than the area to the right of the 320 nm line (UVA region).

Slide 9: Organic Molecules: UV Protection

Different molecules have different peak absorption wavelengths, different ranges of absorption and differences in how quickly absorption drops off ("fat" curves as compared to "skinny" ones). It is important to realize that even within a molecule's absorption range, it does not absorb evenly and absorption at the ends of the range are usually low.

This is a good opportunity to refer back to the Summary of FDA Approved Sunscreen Ingredients: Student Handout which lists the absorption range for each FDA approved active ingredient.

Student Challenge Question: Which ingredients provide good UVA protection?

Answer: Avobenzone and Ecamsule are organic molecules that absorb in the UVA range. Zinc Oxide and Titanium Dioxide are inorganic compounds that absorb UVA light.

Student Challenge Question: The upper wavelength of absorption for Octocrylene and Zinc Oxide are both in the UVA range very similar. How can one provide little UVA protection and one provide good protection?

Answer: It has to do with the shape of the absorption curves. The absorption curve for inorganic compounds such as Zinc Oxide looks like a cliff, they absorb strongly up to the cutoff wavelength. The absorption curve for organic compounds is a peak, which means they absorb very weakly at the edge of their absorption range.

Slide 10: How do you think absorption by inorganic compounds might be different than absorption by molecules? (Question Slide)

Have your students brainstorm ideas about how the structure of inorganic compounds is different from that of molecules and how this might relate to the absorption of light.

Slide 11: Inorganic Compounds: Energy Levels

Energy levels relate to the position and movement of electrons and nuclei with respect to each other. Because of the large number of electrons and nuclei involved in the ionic clusters, there are many closely spaced possible energy states available in both the ground and excited states.

Slide 12: Inorganic Compounds: Absorption I

The difference in energy between ground states is so small that they are thought of as a continuous energy band. The same is true for the excited states. Within a band, very little energy is needed to change states.

This gap in energy between the ground states and the excited states, however, is comparatively large. This energy difference is called the band gap.

Slide 13: Inorganic Compounds: Absorption II

The band gap is basically an energy threshold. Light with any energy equal to or greater than the band gap energy can be absorbed because it will correspond to some transition between a ground state and an excited state.

The band gap energy tells us the smallest frequency of light that can be absorbed. All other transitions require more energy and thus will involve light with greater energy (and thus a higher frequency)

You may want to review the relationships between Energy and frequency (E=hf) and between frequency and wavelength (λ=c/f) with your students to help them understand the diagrams on this and the following slide.

Slide 14: Inorganic Compounds: Absorption Curve

These two graphs show the same absorption curve graphed first as a function of frequency and then as a function of wavelength. Remind students that frequency and wavelength are inversely related and a higher frequency corresponds to a smaller wavelength (c=f*λ).

Student Discussion Question: What would the graph look like if it had transmittance (instead of absorbance) on the y-axis?

Answer: The graph would be inverted; it would start low and then show a steep rise.

Slide 15: Inorganic Compounds: UV Protection

The energy of the band gap of ZnO corresponds to light of 380 nm meaning that it can absorb all light that has a wavelength of 380 nm or less. This includes almost the entire UVA range (~320-400 nm) and does include the entire UVB (~280-320 nm) range.

The energy of the band gap of $Ti0_2$ corresponds to a wavelength of ~365 nm.

The absorption properties are based on chemical structure and thus are not affected by the size of the inorganic cluster. Both traditional inorganic ingredients and nano inorganic ingredients have the same absorption curve and absorb strongly across both the UVB and UVA range.

Slide 16: Absorption Summary

This slide summarizes the three kinds of absorption introduced in this PowerPoint and replicates two of the rows of the Absorption Summary: Student Handout. The key concept to review with students is how the different structure of atoms, organic molecules and inorganic compounds leads to differences in energy level spacing which in turn leads to the difference absorption spectrum.

Slide 17: Can sunscreens absorb all of the UV light that shines on our skin? (Question Slide)

This slide transitions to the idea that many molecules (or inorganic clusters) are needed to protect our skin. Ask your students why they think applying a thin layer of sunscreen lowers its effectiveness.

Slide 18: Answer: It Depends I

In order for a molecule (or inorganic cluster) to absorb UV light, the UV light must come into contact with it. Sunscreens are colloidal suspensions which means that the active (absorbing) ingredients are embedded in a (non-absorbing) lotion.

The greater the amount of sunscreen applied, the greater the chance that UV light will come into contact with an active ingredient, and thus get absorbed.

Because the light absorbing clusters are suspended in another medium, a single layer application does not provide total protection. Imagine a clear sheet of plastic with some black dots on it. If you shine a light above it, you will see a shadow of the dots because only these specific areas block the light. If you put a second sheet with a different pattern of dots on it on top of the first and shone a light, you would start to see bigger patches of shadow. If you continue to do this with more and more sheets, eventually you will see a rectangular shadow as the full area of the plastic is blocked. The absorbing clusters suspended in the sunscreen work the same way, if you apply too thin a layer, it is like only having a few sheets of plastic.

Layer Demonstration: You may want to do an in-class demo of the concept described above by printing black dots onto sheets of acetate and having the class try predict how many sheets are required to get "total protection". The actual number will vary with the size of the dots you make, but it is generally many more than student expect.

Slide 19: Answer: It Depends II

In addition to the amount of sunscreen, there are two factors that sunscreen companies work with to make sunscreens as effective as possible. The first is the concentration of the active ingredients. The more active ingredient molecules or inorganic clusters you have, the greater the chance that light will come into contact with them.

Student Challenge Question: If a higher concentration of active ingredients makes sunscreens more effective, why are the concentrations listed on the bottle so low? (You may want to ask students if they remember the concentrations they saw in the sunscreen label activity)

Answer: Too much of any chemical can be harmful to the skin. When the FDA approves a sunscreen ingredient, they also give the maximum concentration that can be used. In addition, if too much of an ingredient is present, it can be hard to keep it dispersed.

Dispersion is a measure of how evenly distributed the active ingredients are throughout the sunscreen. If they are evenly spaced, this is good dispersion and leads to effective UV absorption. If the active ingredients clump together, it is easier for UV light to pass through the sunscreen without getting absorbed, and thus cause damage to our skin.

Slide 20: Summary

Key take-away points from this presentation are:

- Chemical structure determines energy level spacing, which in turn determines what wavelength(s) of light are absorbed.
- Organic sunscreen ingredients exist as discrete molecules and thus are good at absorbing narrow ranges of UV light.
- Inorganic sunscreen ingredients exist as ionic clusters and thus are good at absorbing the whole UV range (below the band gap wavelength)

Reflecting on the Guiding Questions: Teacher Instructions & Answer Key (Lesson 3)

You may want to have your students keep these in a folder to use at the end of the unit, or collect them to see how your students' thinking is progressing. You can also have a group discussion about what students learned from the activity that helps them answer the guiding questions.

Discussion Idea:

For each "What I still want to know" section, have students share their ideas and discuss whether their questions are scientific ones or questions of another sort. Scientific questions are questions about how the natural world operates that can be answered through empirical experiments. Other kinds of questions might be ethical in nature (e.g. do friends have a responsibility to persuade friends to use sunscreen?) or policy questions (e.g. should the FDA endorse the most effective sunscreens?).

Think about the activities you just completed. What did you learn that will help you answer the guiding questions? Jot down your notes in the spaces below.

1. What are the most important factors to consider in choosing a sunscreen?

What I learned in this activity:

Possible Answers:

Since inorganic ingredients absorb both UVA and UVB, sunscreens that include them have broadband protection

Organic ingredients each absorb a specific wavelength range that can be in the UVA or UVB range. To ensure broadband protection, it is important to choose a sunscreen that has a combination of ingredients that will absorb both kinds of light. Avobenzone and Ecamsule are the two FDA approved organic ingredients that absorb strongly across the UVA range.

Regardless of the ingredients, it is important to make sure that we use enough of the sunscreen we choose for it to be effective.

What I still want to know:

2. How do you know if a sunscreen has “nano” ingredients?

What I learned in this activity:

Possible Answers:

“Nano” ingredients are smaller versions of traditional inorganic ingredients. If a sunscreen contains Zinc Oxide or Titanium Dioxide, they may be in nanoparticle form.

What I still want to know:

3. How do “nano” sunscreen ingredients differ from most other ingredients currently used in sunscreens?

What I learned in this activity:

Possible Answers:

“Nano” ingredients are smaller versions of traditional inorganic ingredients which exist as ionic clusters. They are different from most ingredients currently used in sunscreens which are organic molecules.

While organic molecules absorb narrow bands of the UVA or UVB spectrum, all inorganic ingredients (including “nano” ingredients) absorb strongly in both the UVA and UVB range up to their cutoff wavelength: 380nm (ZnO) or 365 nm (TiO_2).

What I still want to know: