

Varieties of animal pupils



Round pupils

Animals like dogs, wolves and big cats have round pupils. They actively chase down prey, mostly in daylight. Round pupils mean that the field of view isn't spectacularly wide, but as top predators their vision isn't required to help them flee from attack.



Vertical slit pupils

The animals that sport these pupils are small ambush predators that hunt close to the ground: cats, foxes and even crocodiles. The slits allow a greater expansion of the pupil to let in much more light - an adaptation to predators hunting in a variety of light conditions.



Horizontal pupils

Horizontal, oblong-shaped pupils are a feature of prey animals - sheep, goats and horses. These curious-looking pupils provide a wide field of view, allowing the animals to scan for potential predators. The pupils also keep the ground in sharp focus to aid escape.



Horizontal slit pupils

These pupils are also a feature of prey-like animals, seen in some frogs, toads, snakes and octopuses. This pupil type allows the animal to spot the vertical motion of predators and therefore take evasive action. They also extend wide to let plenty of light in for day and night foraging.



Crescent pupils

This pupil type is shown in stingrays, flatfish and some catfish. Crescent pupils enhance vision by decreasing the effects of distortion in the water, providing a wide field of view to look out for any predators lurking nearby or spot potential prey. They also boost contrast.



W-shape pupils

Shown in cuttlefish, these pupils are a modified horizontal-slit pupil. In darkness the pupils are almost circular but form a W-shape in bright light. This allows light to enter the pupil from many different directions and boosts image contrast and distance vision.



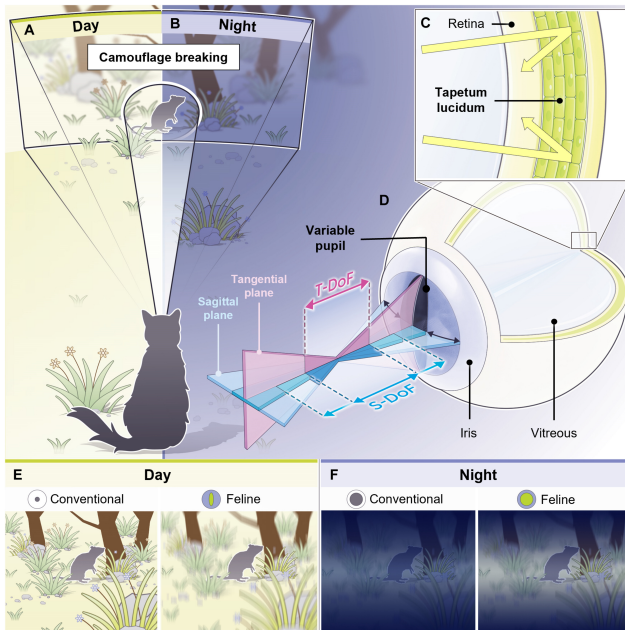
Vertical beaded pupils

Geckos (as well as some fish) have pupils that decrease to very thin vertical slits with multiple pinholes in bright light. These multiple 'beads' work together to help the lizard perceive distance as well as allow hunting in various environments.



Invertebrates' compound eyes do not feature pupils, but some have dark spots called pseudopupils

Cats eyes aid prey detection



- In bright light, cats' pupils constrict to vertical slits. This protects their eyes from too much light, and also helps detect prey by giving a narrow depth-of-field in the vertical direction, and a wide depth-of-field in the horizontal direction.
- The slits can be sharply focused on the prey, while leaving the surroundings blurry, therefore making it easier to detect prey in the presence of a confusing background.
- During twilight, the pupils become very wide and circular to allow more light in, and the reflective membrane at the back of the cat's eyes increases the amount of light collected.

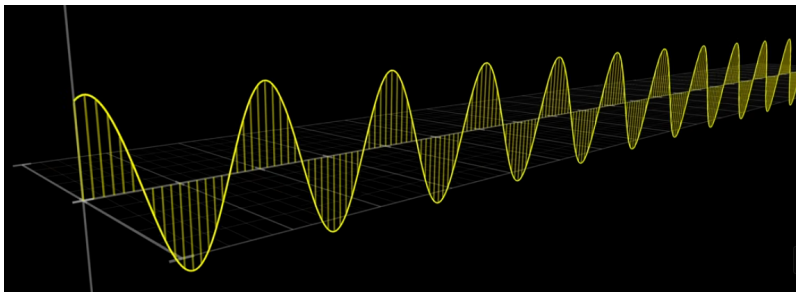
Lecture 14—learning outcomes

- Distinguish between polarized and unpolarised light.
- Describe what happens to unpolarized and polarized light when it passes through a polarizing sheet, calculate the resulting intensity of the light.
- Use a diagram to explain how unpolarised light can become polarized when reflected from an interface.
- Calculate Brewster's angle for different interfaces. Explain what this means.
- Describe different ways that light can become polarized.
- For photon absorption and emission, apply the relationship between energy, power, intensity, rate of photons, the Planck constant, and the associated frequency.
- Describe the photoelectric effect using words and equations. Explain the significance of the observation of the photoelectric effect.

Textbook chapters: 33.4, 33.7, 38.1–2

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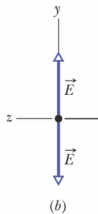
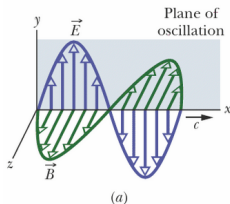
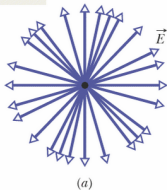
Polarised light—introduction



- Up until now we have imagined light as a wave with an E field as shown in the figure above, propagating towards the right.
- There is no reason for the E vectors (the thin lines in the figure) to point up and down, they could be at any angle provided they are perpendicular to the direction of propagation.
- The figure shows an example of **linearly polarised light**, which is a special case of **elliptically polarised light** as we shall see later.

Polarised and unpolarised light

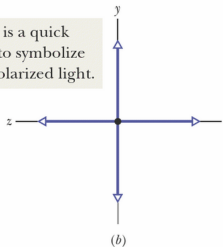
Unpolarized light headed toward you—the electric fields are in all directions in the plane.



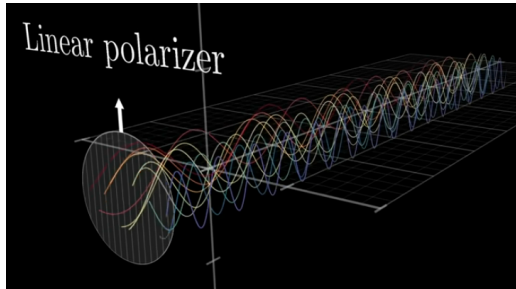
Vertically polarized light headed toward you—the electric fields are all vertical.

- The top figure shows linearly polarised light, with the direction of polarisation (determined by the E vector) being along the y axis.
- Panel (a) in the figure at left attempts to show unpolarised light (e.g., light from the Sun, to a good approximation), where the E vector changes its direction rapidly along the line of propagation.
- Panel (b) is a convenient shorthand for unpolarised light. Any light wave can be decomposed into two orthogonal polarisations in this way.

This is a quick way to symbolize unpolarized light.

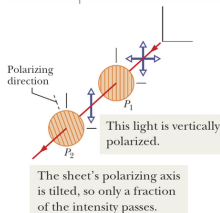
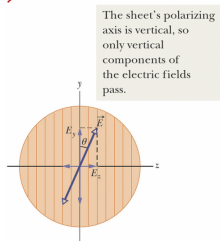
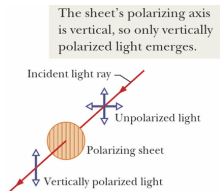


Unpolarised light passing through a linear polarisor



- Polarizing sheets, known commercially as Polaroid filters, were invented in 1932 by Edwin Land while he was an undergraduate student. Polarizing sheets consist of long molecules embedded in plastic. During the manufacturing process the sheets are stretched to align the molecules in parallel rows. When light is sent through a sheet, the electric field components along one direction pass through easily, while components perpendicular to that direction are absorbed by the molecules and disappear.
- The figure shows the light on the far side of a polarising sheet that is illuminated by unpolarised light coming in from the left.
- The figure shows the light further broken down into component colours. In fact, the E field is not multi-valued along the axis as this implies.

Intensity of transmitted polarised light



- In the top figure unpolarised light (with equal components in the vertical and horizontal directions) is passed through a vertically polarised sheet. The horizontal component is removed, so the light intensity is halved.

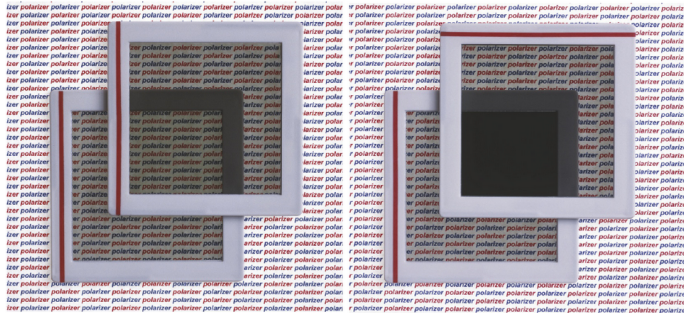
$$I = \frac{I_0}{2} \quad \text{one-half rule, for unpolarised light}$$

- Suppose now that the incoming light is already polarised along some direction θ as shown in the middle figure. We can resolve the E vector into horizontal and vertical components as shown. E_z is absorbed, and $E_y = E \cos \theta$ is transmitted. Recalling that the intensity of a wave is proportional to the square of the amplitude, we have

$$I = I_0 \cos^2 \theta \quad \text{cosine-squared rule, for polarised light}$$

- The bottom figure shows sheet P_1 (the polariser) producing polarised light from an unpolarised source, passing through sheet P_2 (the analyser). The intensity of the light on this side of P_2 will be given by the cosine-squared rule.

Overlapping polarising sheets



Richard Megna/Fundamental Photographs

(a)

(b)

- Overlapping polarising sheets transmit light fairly well if their directions of polarisation are aligned, as in panel (a).
- If the directions are crossed (i.e., at 90° to each other), the light is almost entirely blocked, as in panel (b).

Problem—polarisation and intensity with three polarising sheets

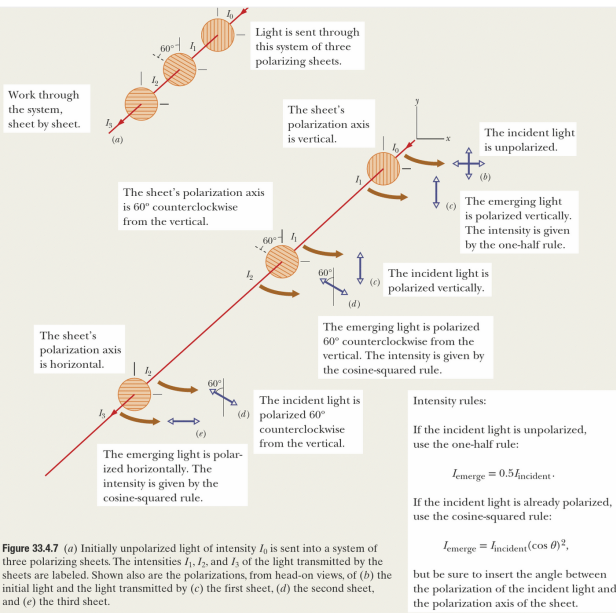


Figure 33.4.7 (a) Initially unpolarized light of intensity I_0 is sent into a system of three polarizing sheets. The intensities I_1 , I_2 , and I_3 of the light transmitted by the sheets are labeled. Shown also are the polarizations, from head-on views, of (b) the initial light and the light transmitted by (c) the first sheet, (d) the second sheet, and (e) the third sheet.

The figure, drawn in perspective, shows a system of three polarizing sheets in the path of initially unpolarized light. The polarizing direction of the first sheet is parallel to the y axis, that of the second sheet is at an angle of 60° CCW from the y axis, and that of the third sheet is parallel to the x axis. What fraction of the initial intensity of the light emerges from the three sheet system, and in which direction is that emerging light polarized?

Solution

Polarisation and intensity with three polarising sheets

Example 33.2 figure 1a, drawn in perspective, shows a system of three polarising sheets in the path of initially unpolarised light. The polarising direction of the first sheet is parallel to the y axis, that of the second sheet is at an angle of 60° counterclockwise from the y axis, and that of the third sheet is parallel to the x axis. What fraction of the initial intensity I_0 of the light emerges from the three-sheet system, and in which direction is that emerging light polarised?

KEY IDEAS

1. We work through the system sheet by sheet, from the first one encountered by the light to the last one.
2. To find the intensity transmitted by any sheet, we apply either the one-half rule or the cosine-squared rule, depending on whether the light reaching the sheet is unpolarised or already polarised.
3. The light that is transmitted by a polarising sheet is always polarised parallel to the polarising direction of the sheet.

First sheet: The original light wave is represented in example 33.2 figure 1b, using the head-on, double-arrow representation of figure 33.13. Because the light is initially unpolarised, the intensity I_1 of the light transmitted by the first sheet is given by the one-half rule (equation 33.48):

$$I_1 = \frac{1}{2}I_0.$$

Because the polarising direction of the first sheet is parallel to the y axis, the polarisation of the light transmitted by it is also, as shown in the head-on view of example 33.2 figure 1c.

Second sheet: Because the light reaching the second sheet is polarised, the intensity I_2 of the light transmitted by that sheet is given by the cosine-squared rule

(equation 33.50). The angle θ in the rule is the angle between the polarisation direction of the entering light (parallel to the y axis) and the polarising direction of the second sheet (60° counterclockwise from the y axis), and so θ is 60° . (The larger angle between the two directions, namely 120° , can also be used.) We have

$$I_2 = I_1 \cos^2 60^\circ.$$

The polarisation of this transmitted light is parallel to the polarising direction of the sheet transmitting it — that is, 60° counterclockwise from the y axis, as shown in the head-on view of example 33.2 figure 1d.

Third sheet: Because the light reaching the third sheet is polarised, the intensity I_3 of the light transmitted by that sheet is given by the cosine-squared rule. The angle θ is now the angle between the polarisation direction of the entering light (example 33.2 figure 1d) and the polarising direction of the third sheet (parallel to the x axis), and so $\theta = 30^\circ$. Thus,

$$I_3 = I_2 \cos^2 30^\circ.$$

This final transmitted light is polarised parallel to the x axis (example 33.2 figure 1e). We find its intensity by substituting first for I_2 and then for I_1 in the equation above:

$$\begin{aligned} I_3 &= I_2 \cos^2 30^\circ = (I_1 \cos^2 60^\circ) \cos^2 30^\circ \\ &= \left(\frac{1}{2}I_0\right) \cos^2 60^\circ \cos^2 30^\circ = 0.094I_0. \end{aligned}$$

Thus,

$$\frac{I_3}{I_0} = 0.094. \quad (\text{Answer})$$

That is to say, 9.4% of the initial intensity emerges from the three-sheet system. (If we now remove the second sheet, what fraction of the initial intensity emerges from the system?)

Problem—rotating the polarisation of a beam of light

We want to rotate the direction of a linearly polarised beam of light through 90° by sending the beam through one or more polarising sheets. (a) What is the minimum number of sheets required? (b) What is the resulting intensity of the light? (c) What is the minimum number of sheets required if the transmitted intensity is to be more than 60% of the original intensity? (d) Is it possible to have the transmitted intensity approaching arbitrarily close to the original intensity, assuming perfect polarising sheets?

Solution—rotating the polarisation of a beam of light

(a) 2, at 45° to each other,

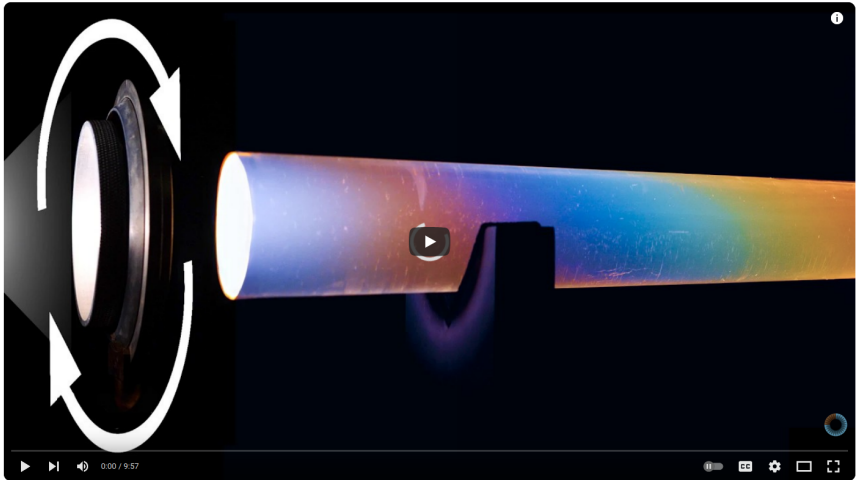
(b) $\cos^2(\pi/4) = 0.25$,

(c) 5, since $\cos^{2m}(\pi/2m) = 0.6054 > 0.6$ when $m = 5$,

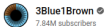
(d) yes.

Polarisation and scattering of light

The video linked below is an excellent introduction to polarisation, and is well worth watching more than once.



This tests your understanding of light | The barber pole effect



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<https://www.youtube.com/watch?v=QCX62YJCmGk>

Explanation of the previous video

The video linked below goes into more detail explaining the effects seen in the last video. Skip it if you don't have the time, but it is really interesting.

Why diagonal stripes?



How wiggling charges give rise to light



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51K



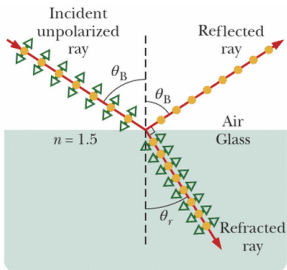
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Thanks



<https://youtu.be/aXRTczANuIs?t=688>

Polarisation by reflection



- Component perpendicular to page
- ↔ Component parallel to page

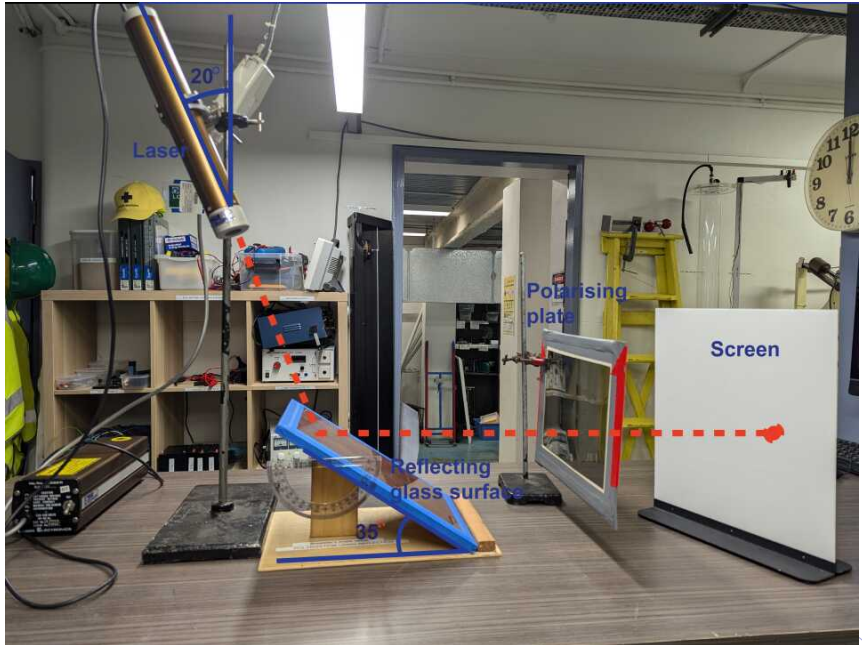
- The figure shows unpolarised light hitting an air glass interface. Firstly, consider the polarisation component parallel to the page, as shown with green arrows. This component causes electrons at the glass interface to oscillate in the direction of the arrows. If the reflected and refracted rays are at 90° as shown, then the electrons will be oscillating precisely along the direction of the reflected ray, and will produce no electromagnetic radiation in that direction. So, this polarisation component of the incoming light will not be reflected.
- The polarisation component perpendicular to the page is reflected and refracted without hindrance, since the motion of the electrons is perpendicular to the rays in both cases.
- The net result is that the reflected ray is perfectly polarised in the direction perpendicular to the page.
- The angle θ_B is known as the **Brewster angle** and can be calculated by combining the law of reflection, $\theta_B + \theta_r = 90^\circ$, and Snell's law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$, giving

$$\theta_B = \tan^{-1} \frac{n_2}{n_1}$$

which, in the special case of air, with $n_1 \approx 1$, becomes **Brewster's law**

$$\theta_B = \tan^{-1} n$$

Demo: Lb19—polarisation by reflection



Polaroid glasses block rays reflected at the Brewster angle

Polaroid glasses only pass the vertical component of light, so they block light reflected from water (or glass) at the Brewster angle, and partially block light at nearby angles.

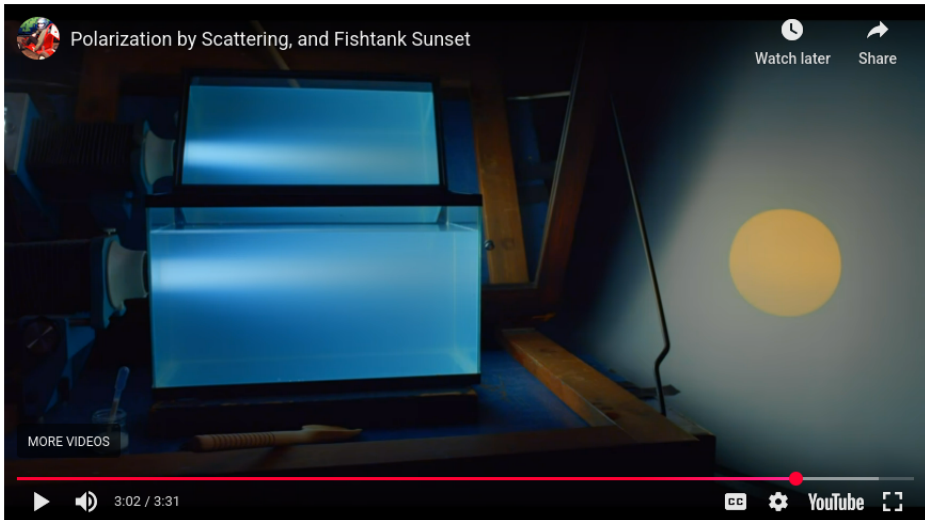


Without polarized glasses

With polarized glasses

Polarisation by scattering, and why the sky is blue

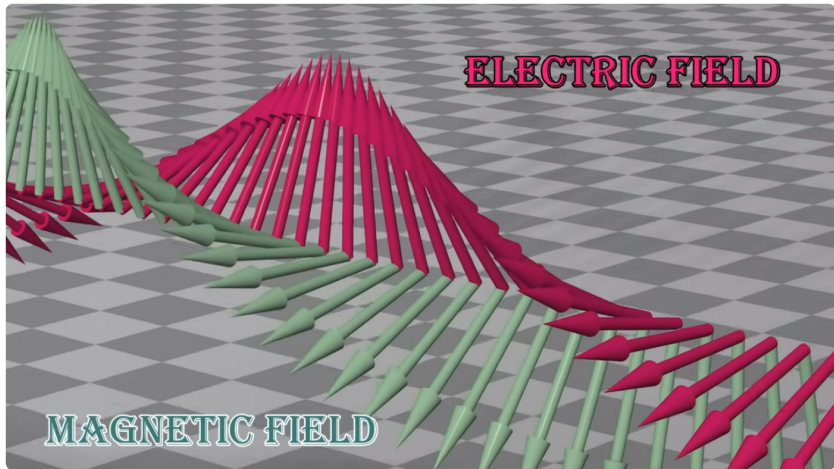
The video linked below has an excellent discussion of scattering of light by particles, and how it causes polarisation. This is also why the sky is blue (you also need to know that scattering intensity is proportional to λ^{-4} , so blue light is much more strongly scattered than red light) and shows strong polarisation when view through polaroid glasses.



<https://sciencedemonstrations.fas.harvard.edu/presentations/polarization-scattering>

Linearly (examinable) and circularly (non-examinable) polarised light

The video linked below will help you understand polarisation of light. Circularly polarised light results from combining light with linear polarisations at 90° to each other, with a 90° phase shift. If the phase shift is varied from 90° , elliptically polarised light is produced. Just as light can be decomposed into orthogonal linear components, it can instead be decomposed into left and right circular components.



Polarization of Light: circularly polarized, linearly polarized, unpolarized light.



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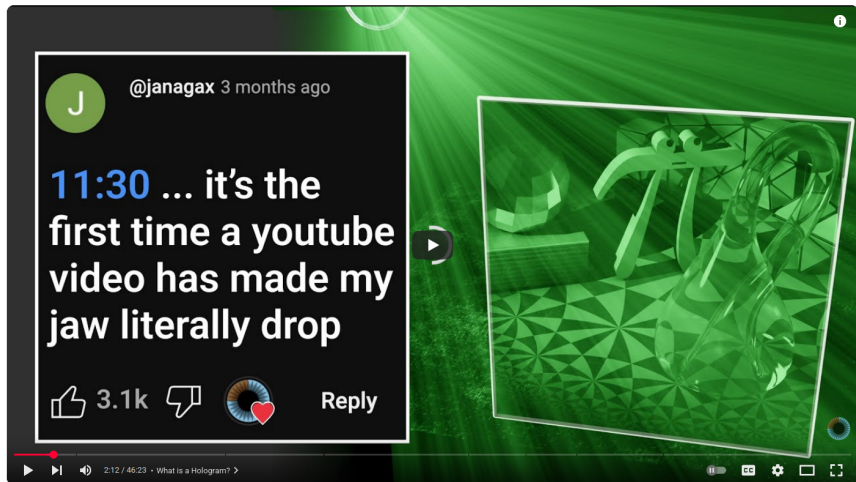


<https://www.youtube.com/watch?v=8YkfEft4p-w>

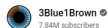


Holograms: how are they possible?

The video linked below on holography is absolutely fascinating, and helpful in understanding light and interference, but goes beyond the syllabus of PHYS1231.



How are holograms possible?



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142K



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Thanks



<https://www.youtube.com/watch?v=EmKQsSD1aa4>

The photon, the quantum of light

- In 1905, Einstein proposed the revolutionary idea that electromagnetic radiation (or simply *light*) is quantized and exists in elementary amounts (quanta) that we now call photons. His motivation was to explain the photoelectric effect (see upcoming slides). He received the Nobel Prize for this work.

- According to his proposal, the quantum of a light wave of frequency f has energy

$$E = hf \quad (\text{photon energy})$$

where $h = 6.63 \times 10^{-34}$ J s is Planck's constant.

- The smallest amount of energy that a light wave of frequency f can have is hf (i.e., one photon). If the wave has more energy than this, its total energy must be an integer multiple of hf .

- Einstein further proposed that when light is absorbed or emitted by an object, the absorption or emission event occurs in the atoms of the object.

- When light of frequency f is absorbed by an atom, the energy hf of one photon is transmitted from the light to the atom. After this absorption event the photon vanishes and the atom is said to have *absorbed* it.
- When light of frequency f is emitted by an atom, an amount of energy hf is transferred from the atom to the light. In this emission event, a photon suddenly appears, and the atom is said to have *emitted* it.

Problem—emission and absorption of light as photons

A sodium vapor lamp is placed at the center of a large sphere that absorbs all the light reaching it. The rate at which the lamp emits energy is 100 W; assume that the emission is entirely at a wavelength of 590 nm. At what rate are photons absorbed by the sphere?

Solution

Emission and absorption of light as photons

A sodium vapour lamp is placed at the centre of a large sphere that absorbs all the light reaching it. The rate at which the lamp emits energy is 100 W; assume that the emission is entirely at a wavelength of 590 nm. At what rate are photons absorbed by the sphere?

KEY IDEAS

The light is emitted and absorbed as photons. We assume that all the light emitted by the lamp reaches (and thus is absorbed by) the sphere. So, the rate R at which photons are absorbed by the sphere is equal to the rate R_{emit} at which photons are emitted by the lamp.

Calculations

That rate is

$$R_{\text{emit}} = \frac{\text{rate of energy emission}}{\text{energy per emitted photon}} = \frac{P_{\text{emit}}}{E}.$$

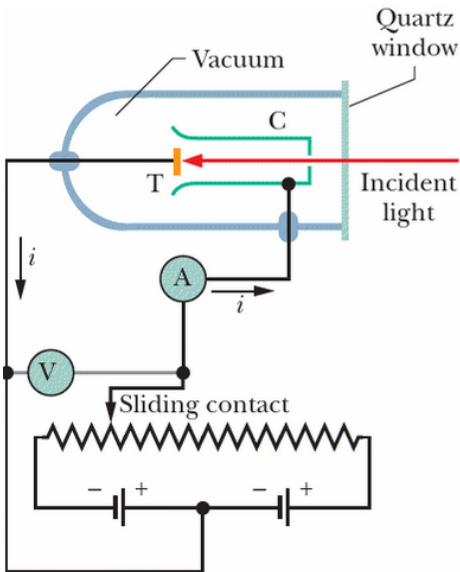
Next, into this we can substitute from equation 38.2 ($E = hf$), Einstein's proposal about the energy E of each quantum of light (which we here call a photon in modern language). We can then write the absorption rate as

$$R = R_{\text{emit}} = \frac{P_{\text{emit}}}{hf}.$$

Using equation 38.1 ($f = c/\lambda$) to substitute for f and then entering known data, we obtain

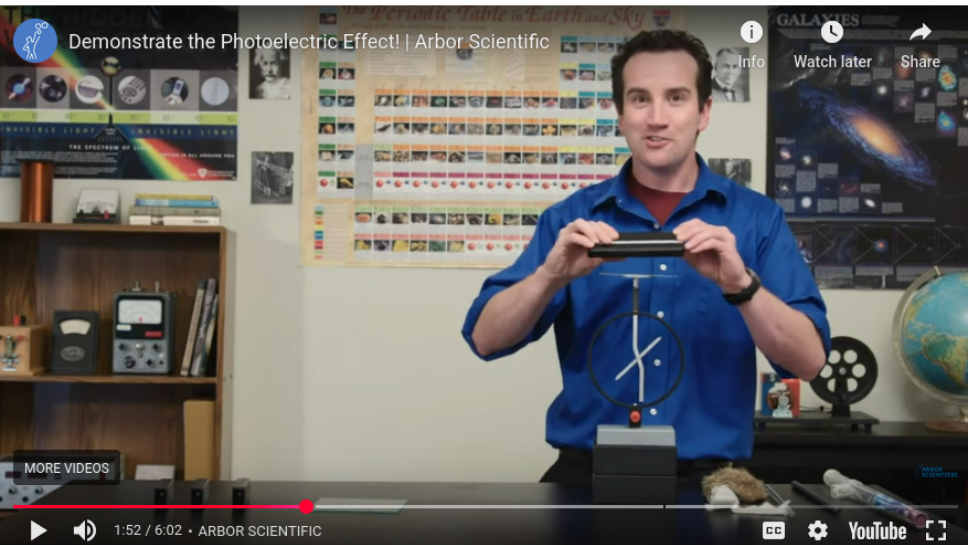
$$\begin{aligned} R &= \frac{P_{\text{emit}} \lambda}{hc} \\ &= \frac{(100 \text{ W}) (590 \times 10^{-9} \text{ m})}{(6.63 \times 10^{-34} \text{ J} \cdot \text{s}) (2.998 \times 10^8 \text{ m/s})} \\ &= 2.97 \times 10^{20} \text{ photons/s.} \end{aligned} \quad (\text{Answer})$$

The photoelectric effect



- The photoelectric effect is where a beam of light hitting a metal surface can cause an electron to be ejected from that surface. The effect can be investigated by the apparatus in the figure. A beam of light enters the evacuated chamber from the right and hits target T . Any electrons that are emitted are swept up by the positive voltage placed on the collector C . The ammeter A registers the current and you can plot this as a function of the intensity and wavelength of the incident light.
- The first experiment you can conduct is to adjust the potential difference V , making it slightly negative until the electron current drops to zero, at which point $V = V_{\text{stop}}$ and the most energetic electrons that are ejected are turned back before they reach the collector. The kinetic energy of the most energetic electrons is then $K_{\text{max}} = eV_{\text{stop}}$ where e is the elementary charge.
- This experiment shows that for light of a given frequency, K_{max} *does not depend on the intensity of the light source*. This result cannot be explained by the classical wave model of light but can be explained by the photon model.
- The second experiment is to vary the frequency f of the incident light and measure V_{stop} as a function of f . The result is that the photoelectric effect *does not occur if the frequency is below a certain cut-off frequency, no matter how intense the incident light is*. This cannot be explained by the wave theory, but can be explained by photons.

Demo: the photoelectric effect



Demonstrate the Photoelectric Effect! | Arbor Scientific

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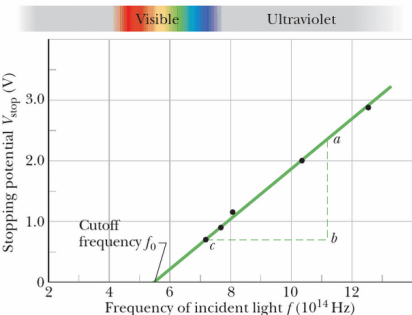
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The background features a large periodic table titled "The Periodic Table in Earth and Sky", a poster of "THE SPECTRUM OF LIGHT" showing visible and invisible light regions, and a "GALAXIES" poster. A wooden shelf on the left holds various electronic equipment, and a globe is visible on the right.

The photoelectric effect—the stopping potential

Electrons can escape only if the light frequency exceeds a certain value.

The escaping electron's kinetic energy is greater for a greater light frequency.



- The figure shows the results of the second experiment from the earlier slide, using sodium as the target.
- Photons with frequency less than f_0 cannot eject any electrons.
- Einstein summed up the results of such photoelectric experiments with the equation

$$hf = K_{\text{max}} + \Phi \quad (\text{photoelectric equation}).$$

where Φ is called the **work function** of the metal.

- The above equation is essentially a statement of the conservation of energy for a single photon absorption. We can rewrite this equation using the expression for V_{stop} from the last slide, and get

$$V_{\text{stop}} = \left(\frac{h}{e}\right) f - \frac{\Phi}{e}.$$

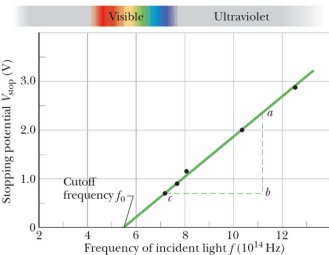
which is the equation of a straight line with slope h/e and y intercept $-\Phi/e$, agreeing with the experimental results in the figure.

Problem—photoelectric effect and work function

Find the work function Φ of sodium from the figure.

Electrons can escape only if the light frequency exceeds a certain value.

The escaping electron's kinetic energy is greater for a greater light frequency.



Solution

Photoelectric effect and work function

Find the work function Φ of sodium from figure 38.2.

KEY IDEAS

We can find the work function Φ from the cutoff frequency f_0 (which we can measure on the plot). The reasoning is this: at the cutoff frequency, the kinetic energy $K_{\max}$ in equation 38.5 is zero. Thus, all the energy hf that is transferred from a photon to an electron goes into the electron's escape, which requires an energy of Φ .

Calculations

From that last idea, equation 38.5 then gives us, with $f = f_0$,

$$hf_0 = 0 + \Phi = \Phi.$$

In figure 38.2, the cutoff frequency f_0 is the frequency at which the plotted line intercepts the horizontal frequency axis, about 5.5×10^{14} Hz. We then have

$$\begin{aligned}\Phi &= hf_0 = (6.63 \times 10^{-34} \text{ J} \cdot \text{s}) (5.5 \times 10^{14} \text{ Hz}) \\ &= 3.6 \times 10^{-19} \text{ J} = 2.3 \text{ eV.} \quad (\text{Answer})\end{aligned}$$