

Light Quanta

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Particle-Wave History

- 1700's
  - Corpuscular Model -- Newton
  - Wave Model - Huygens
- 1801 - Thomas Young's double slit experiment → waves
- 1862 - Maxwell's prediction that light carried energy as oscillating electric and magnetic fields

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Particle-Wave Nature Continued

- 1887-- Hertz demonstrated electromagnetic waves (radio frequency) with sparking electric circuits
- 1905 - Einstein - Nobel prize-winning paper - photoelectric effect -
  - Light interacts with matter in tiny packets of energy
  - Now called photons
  - Light is **both wave and particle**

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### Quantization & Planck's Constant



Max Planck (1858-1947)

- Amount of energy in any system is quantized
- Assumed energy in matter was quantized but that radiant energy (light) is continuous
- Planck's constant - number that results when energy of photon is divided by its frequency
- $E = hf$

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### Energy of Photons

- How much total energy is in a monochromatic beam composed of n photons of frequency f?
- $E = nhf$

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### Quantum

- What does the term quantum mean?
- A quantum is the smallest elemental unit of a quantity. Radiant energy, for example, is composed of many quanta, each of which is called a photon. So the more photons in a beam of light, the more energy in that beam.

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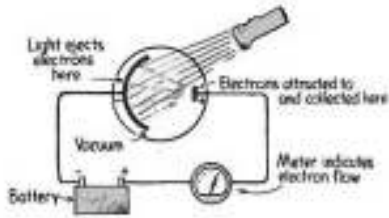
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### Photoelectric Effect



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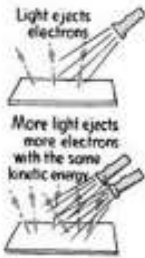
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### Photoelectric Effect



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### Photoelectric Effect



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## Difficulties With Wave Explanation

- The time lag between turning on the light and the ejection of the first electrons was not affected by the brightness or frequency of the light.
- The effect was easy to observe with violet or ultraviolet light but not with red light.
- The rate at which electrons were ejected was proportional to the brightness of the light.
- The maximum energy of the ejected electrons was not affected by the brightness of the light. However, there were indications that the electron's energy did depend on the frequency of the light.

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## Time Lag

- According to wave model, an electron in dim light should, after some delay, build up enough vibrational energy to fly out, while an electron in bright light should be ejected almost immediately.
- However, electron is usually observed being ejected immediately, even under the dimmest light

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## Energy of Electrons

- brightness of light in no way affected the energies of ejected electrons -- puzzling
- more electrons were ejected in brighter light, but not at greater speeds
- weak beam of ultraviolet light produced a smaller number of ejected electrons but at much higher speeds.

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### Einstein's Photons

- light encountering a surface or any detector as a succession of corpuscles, or photons
- number of photons in a light beam controls the brightness of the whole beam
- frequency of the light controls the energy of each individual photon.

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### Millikan Verifies

- Experimental verification of Einstein's explanation of the photoelectric effect was made 11 years later by the American physicist Robert Millikan
- Einstein won the Nobel prize for explaining the photoelectric effect

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### Photoelectric Effect

- Will brighter light eject more electrons from a photosensitive surface than dimmer light of the same frequency?
- Yes. The number of ejected electrons depends on the number of incident photons.

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## Photoelectric Effect

- Will high-frequency light eject a greater number of electrons than low-frequency light?
- Not necessarily. The energy (not the number) of ejected electrons depends on the frequency of the illuminating photons. A bright source of blue light, for example, may eject more electrons at a lower energy than a dim violet source.

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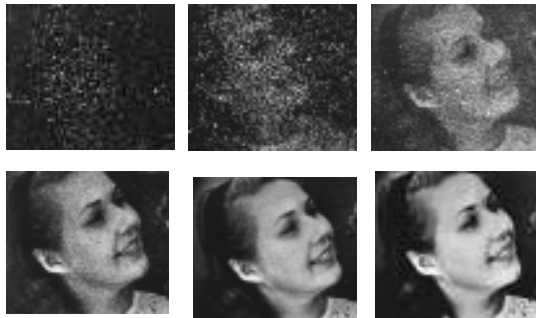
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The approximate numbers of photons at each stage are (a)  $3 \times 10^3$ , (b)  $1.2 \times 10^4$ , (c)  $9.3 \times 10^4$ , (d)  $7.6 \times 10^5$ , (e)  $3.6 \times 10^6$ , and (f)  $2.8 \times 10^7$ .

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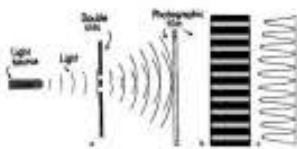
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## Double Slit Experiment



- What the Bleep Clip on Double Slit

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### Interference Pattern Develops



- Stages of two-slit interference pattern.
- The pattern of individually exposed grains progresses from (a) 28 photons to (b) 1000 photons to (c) 10,000 photons.
- As more photons hit the screen, a pattern of interference fringes appears.

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### Single Slit Diffraction



- If we cover one slit so that photons hitting the photographic film can only pass through a single slit, the tiny spots on the film accumulate to form a single-slit diffraction pattern

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### How Do They "Know"

- photons hit the film at places they would not hit if both slits were open!
- If we think about this classically, we are perplexed and may ask how photons passing through the single slit "know" that the other slit is covered and therefore fan out to produce the wide single-slit diffraction pattern.

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### How Do They "Know?"

- Or, if both slits are open, how do photons traveling through one slit "know" that the other slit is open and avoid certain regions, proceeding only to areas that will ultimately fill to form the fringed double-slit interference pattern?

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### Modern Answer

- modern answer is that the wave nature of light is not some average property that shows up only when many photons act together
- Each single photon has wave as well as particle properties. But the photon displays different aspects at different times.

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### Wavicle?

- photon behaves as a particle when it is being emitted by an atom or absorbed by photographic film or other detectors
- photon behaves as a wave in traveling from a source to the place where it is detected
- photon strikes the film as a particle but travels to its position as a wave that interferes constructively

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### Electrons?

- act that light exhibits both wave and particle behavior was one of the interesting surprises of the early twentieth century.
- even more surprising was the discovery that objects with mass also exhibit a dual waveparticle behavior

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### Particles as Waves



Louis de Broglie  
(1892-1987)

- According to de Broglie, every particle of matter is somehow endowed with a wave to guide it as it travels
- Under the proper conditions, then, every particle will produce an interference or diffraction pattern

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### DeBroglie Wavelength

- All bodies—electrons, protons, atoms, mice, you, planets, suns—have a wavelength that is related to the body's momentum by

$$\text{Wavelength} = \frac{h}{\text{momentum}}$$

- A body of large mass and ordinary speed has such a small wavelength that interference and diffraction are negligible

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### Uncertainty Principle



Werner Heisenberg  
1901 -- 1976

- act of measuring something affects the quantity being measured
- Quantum uncertainties stem from the wave nature of matter
- Arthur Young video

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### Heisenberg Uncertainty

- wave by its very nature occupies some space and lasts for some time
- it cannot be squeezed to a point in space or limited to a single instant of time
- inherent "fuzziness" of a wave gives a fuzziness to measurement at the quantum level.

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### Heisenberg Uncertainty

- experiments show that any measurement that in any way probes a system necessarily disturbs the system by at least one quantum of action,  $h$ , Planck's constant.
- any measurement that involves interaction between the measurer and what is being measured is subject to this minimum inaccuracy.

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### Heisenberg Uncertainty

$$\Delta x \Delta p \geq \frac{h}{2\pi} \quad \Delta E \Delta t \geq \frac{h}{2\pi}$$

- Quantum uncertainties are significant only in the atomic and subatomic realm.

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