· **Final exam: Dec 20, 11.30am -1.30pm, here, cumulative**

Chs: 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14, 15, 19, 20, 22, 23, 24, 25, 26, 27, 31

· **Review Session Tue Dec 13**

Today:

Finish Color (Ch. 27)

Intro to Quantum Theory (Ch.31)

A little history behind origins of quantum mechanics…

- Theories on the nature of light (ca 400 BC):

    - Plato (and also Euclid): light = "streamers" emitted by the eye

    - Pythagoreans: light = fine particle emanating from luminous bodies

    - Empedocles: light = high-speed wave

    So, for more than 2000 years, people debated: is light a wave or particle?

- Newton (1700s) – light = stream of particles ("corpuscles"); Huygens = wave theory

- Young's experiment (1800) – double-slit – showed interference of light, so concluded, light must be a wave (recall earlier, only waves interfere, particles do not).

- Wave theory supported by Maxwell (light =electromagnetic wave, carrying energy), and Hertz's demo with sparks from electric circuits

- Einstein (1905): **light = wave and particle!** Dual nature, eg it travels with wave properties but interacts with matter as a particle would.

- Other key figures: Planck (*quanta*), de Broglie and later, Schroedinger, Heisenberg

Quantization

- Quantum physics says that the amount of energy in any system is *quantized*, i.e. can only take on certain values.

  Eg. Energy in a beam of laser light = an integer times a single energy quantum (see more shortly).

- But energy quantization would mean that a fire could only have certain temperatures – why don't we witness this?

  Because fires are "macroscopic" as are our thermometers, meaning that the quantum of energy in a fire is far smaller than we can measure (eg far smaller than a oC). So we effectively see continuous range of temps.

Quantization cont.

- The quantum world is thus "grainier" than the classical world of everyday life: everyday energies have very tiny quanta.

  Smoothness arises out of graininess is the same concept as that photos are made up of tiny colored dots; that materials are made up of tiny atoms…

- The quantum of light and of electromagnetic radiation in general, is called a **photon**. Energy of photon = hf *(more shortly).*

  - **Planck's constant = h = 6.63 x 10-34 J.s**
  - h is a "fundamental constant" of nature, that sets a lower limit on the smallness of things.

Other fundamental constants are Newton's grav constant G, and speed of light in vacuum c

Clicker Question

Which of the following is not quantized?

A)   Energy in a beam of laser light

B)   Number of people in a closed room

C)   Electric charge

D)   All are quantized

E)   More than one, but not all, above

Answer: D

For something to be quantized, means that it exists only in certain amounts – usually whole-number multiples of a certain amount (which would be the quantum for that thing).

Photon energy

· Energy of a photon: $E = h f$

· Depends on frequency, f – so a photon of higher frequency represents a higher amount of energy than a photon of lower frequency.

N photons have energy Nhf

· Note: brightness of a whole light beam depends on how *many* photons there are in the beam, *N*, whereas the energy of individual photon determined only by its frequency.

i.e. energy in a beam of light is $E = Nhf$

· $E = hf$ gives the smallest amount of energy that can be converted to a light of frequency *f*

Photon energy continued…

· So radiation of light is not continuous; rather emitted as photons with each photon "throbbing" at frequency f, carrying energy hf) – i.e. radiation is also quantized.

· Explains why microwave radiation doesn't cause damage to our living cells like higher-freq uv does: each photon carries too low energy.

· Emission of light from atoms is quantized – so the frequencies that a type of atom fluoresces at characterizes that atom. (The electrons in an atom are arranged in quantized energy levels, and it's the difference between these that are the frequencies seen in spectra…)

Clicker Question

What is the energy of a photon of white light?

A)   Zero

B)   Infinity

C)   It depends on the exact frequency of the white light

D)   It is a meaningless question

Answer: D

White light is a mixture of various frequencies and therefore a mixture of many photons. One photon of white light has no physical meaning.

Clicker Question

Which has more photons, a beam of red light or a beam of blue light of the same total energy?

A) Red

B) Blue

C) Both same

D) Cannot be determined without more information

Answer: A, red.

Since red light carries less energy per photon and both beams have the same total energy, there must be more photons in the beam of red light.
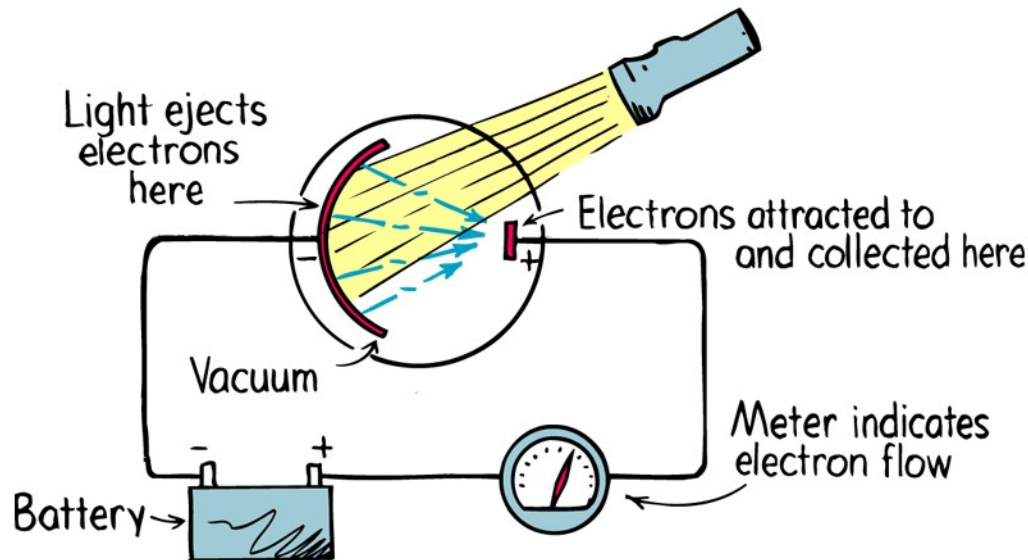
Analogy with two equally heavy bags, one of ping-pong balls and other of golf balls – must be more ping-pong balls.

Particle nature: Photoelectric Effect

· Is the effect that light incident on a metal, can eject electrons from it !
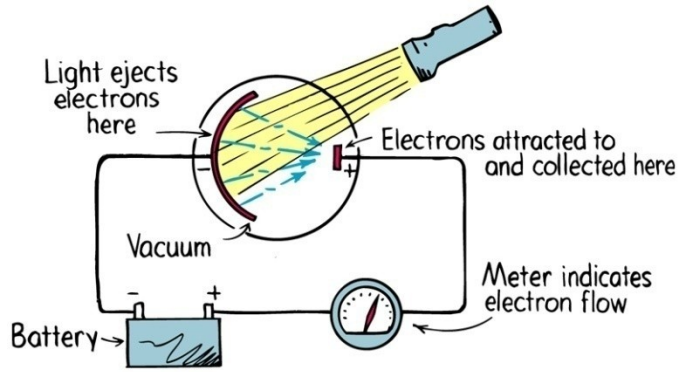
(this is used today eg. in electric eyes security devices, automatic door opening)

· Instrumental in supporting quantized nature of light in 1900's, and particle-like properties.

Light ejects electrons here

Electrons attracted to and collected here

Vacuum

Meter indicates electron flow

Battery →

Note that if there was no light shining on the curved plate, there would be no current.

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Particle nature: Photoelectric Effect cont.

Light ejects
electrons
here

Electrons attracted to
and collected here

Vacuum

Battery→

Meter indicates
electron flow

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· If instead, we charge the receiving plate with just enough negative charge so it repels electrons, the current can be stopped.

Measure potential difference across the plates at which current is just stopped – *tells you kinetic energy of the ejected electrons*.

· So far, said nothing that can't be explained by wave-model of light: incident light waves can build up an electron's vibration so much so that it breaks loose from surface. BUT there are aspects that can't be explained from wave-nature: (next slide)

Photoelectric effect cont.

· Observations that cannot be explained by wave-model of light:

(1) Time-lag between turning on light and ejection of first electron is *not* affected by brightness or frequency of light.

in dim light, wave theory would predict need more time for electron to build up enough energy to be ejected, whereas in bright light, expect it would be ejected almost immediately

(2) Can observe with violet or ultraviolet light but *no* ejection for red light, even if intense.

wave theory would predict any frequency, if intense enough can eject an electron.

(3) Maximum energy of the ejected electrons is *not* affected by the brightness of the light.

wave theory would predict brighter light with its stronger electric field, would give more energy to electrons.

Photoelectric effect cont.

(4) For each kind of metal, only light of frequencies higher than a certain threshold frequency, ejects electrons. Related to point (2)
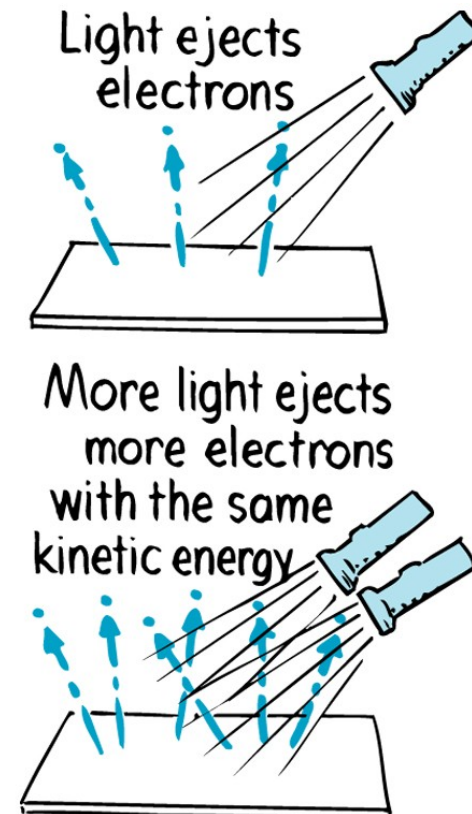
- NOT OK in a wave model
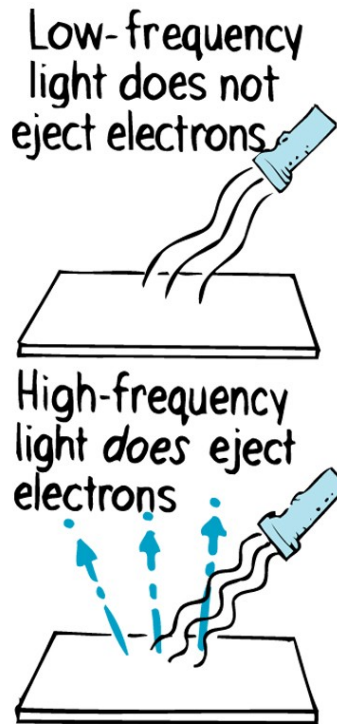
Note: Rate at which electrons ejected is proportional to brightness (intensity) of light

- OK in a wave model

Low-frequency light does not eject electrons.

High-frequency light *does* eject electrons

Light ejects electrons

More light ejects more electrons with the same kinetic energy

Photoelectric effect cont.

- Einstein explained all this in 1905, using Planck's quantum theory of radiation

- Planck's theory was that *emission* of light from excited atoms was quantized, i.e that energy in matter is quantized, but that radiant energy is continuous. (we didn't cover this in this course – see more in Ch.30)

- Einstein went further – said that *radiant energy is quantized itself*: light = hail of particles, called *photons.*

Photoelectric effect cont.

· So, in photoelectric effect: *each electron absorbs one photon.*

   - all or nothing effect, so no time-delay as no energy needs to build up (explains 1)

   - since $E = hf$, photon's energy for red light is not big enough to overcome forces attracting electron to metal so it can't be ejected. But f is greater for violet and uv, so photon has more energy to give to the electron – can be ejected. (explains 2 & 4)

   - the brighter the light, i.e more intense, means more photons, but not more energy per photon – so more electrons get ejected but each does not get more energy (max energy of ejected electron is that of one photon, i.e. hf) (explains 3)

· So photoelectric effect is conclusive proof for the particle nature of light.

· But light also has wave properties – eg interference :

   wave-particle duality (see shortly)

__Clicker Question__

In the photo-electric effect, is it brightness or frequency that determines the kinetic energy of the ejected electrons? How about the number of ejected electrons?

A) Brightness determines both KE and number

B) Brightness determines KE and frequency determines number

C) Frequency determines both KE and number

D) Frequency determines KE and brightness determines number

Answer: D

The electron's kinetic energy depends on the frequency of the illuminating light. With high enough frequency, the # of electrons ejected is determined by the number of photons incident, ie. on the brightness.

Another Question

Silver bromide (AgBr) is a light-sensitive substance used in some photographic film. Can you explain why this film may be handled without exposure in a darkroom illuminated with red light?

How about blue light? How about very bright red light compared to dim blue light?

(Hint: consider quantization of energy)

The energy of red light is too low per photon to trigger the chemical reaction in the photographic crystals.

Blue light does have enough energy.

Very bright red light simply means more photons that are unable to trigger a reaction. It is safer to have bright red light than dim blue light.

Wave nature of light: Interference

- **Recall** from Ch. 18, that adding, or "superposing", two identical waves in phase with each other produces a wave of the same frequency but twice the amplitude:
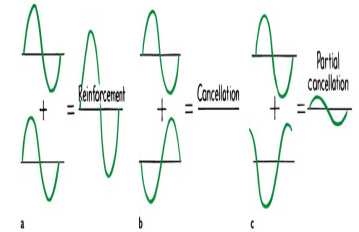
  Constructive interference

- If they are exactly one-half wavelength out of phase, superposition results in complete cancellation:
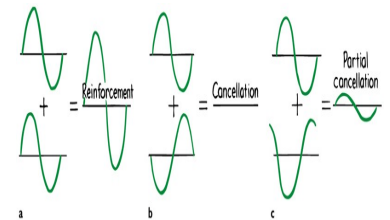
  Destructive interference

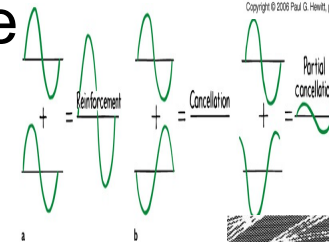- If they are out of phase by other amounts, partial cancellation occurs:

- **Recall** also the picture of water waves emanating from two nearby vibrating sources:
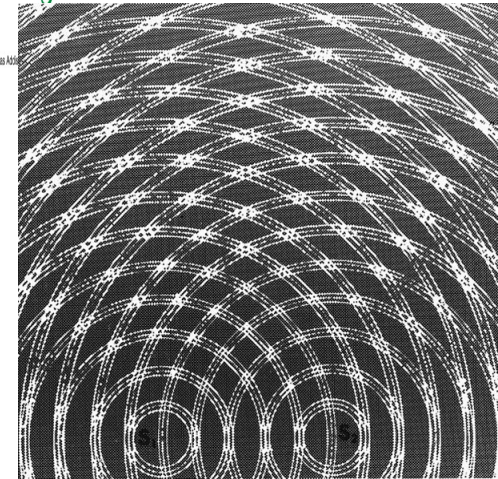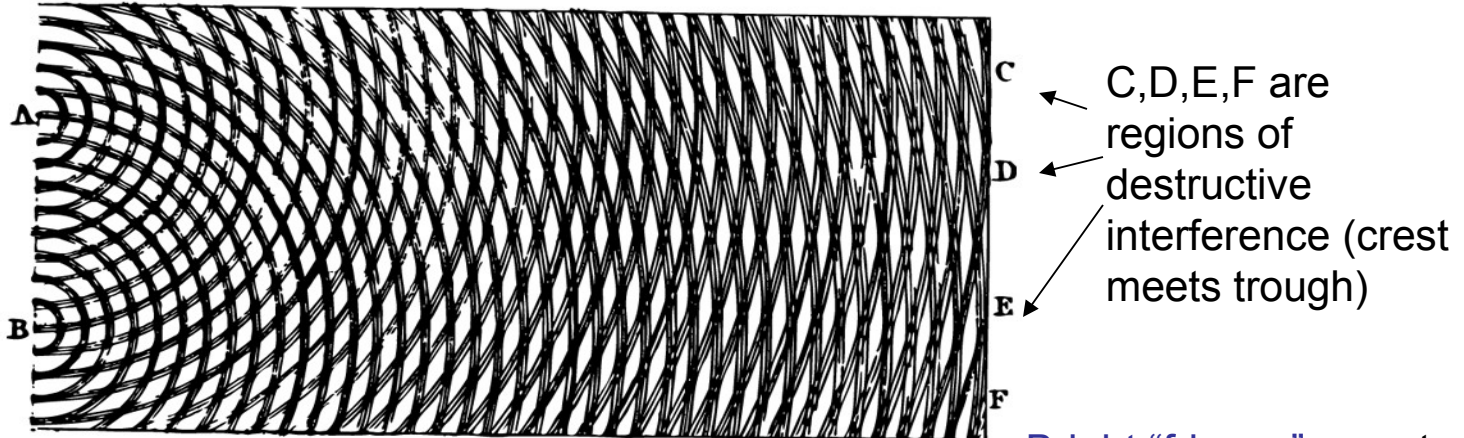
Very similar interference pattern results when *light* is directed through two closely spaced pinholes (A and B):

dark circles = crests

white spaces = troughs

Get constructive interference when crests overlap crests or troughs overlap troughs.

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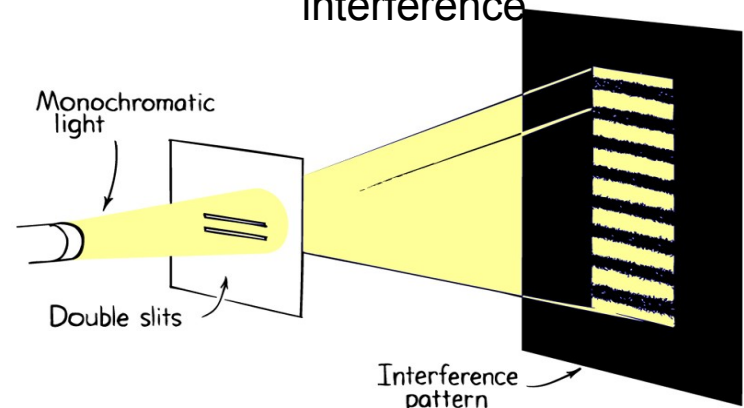
C,D,E,F are regions of destructive interference (crest meets trough)

Bright "fringes": constructive interference

Dark "fringes": destructive interference

Young's "double-slit" experiment (1801):

demonstrates the wave nature of light.

(Above figure is a representation of his original drawing to analyze this)

Monochromatic light

Double slits

Interference pattern

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Double-slit expt cont.

· *(Note that this and the previous slide are from Ch 29 in your book)*

· Extra Reading **(non-examinable):** What determines the spacing of the fringes?

Depends on the wavelength:

In the central bright fringe, paths from the two slits are the same length so waves arrive in phase ie. reinforce each other.

At neighboring dark fringe, one path is longer by half-wavelength c.f. other path, so waves arrive $\lambda/2$ out of phase ie. cancel each other.

Other bright fringes: path-lengths differ by integer x λ

Other dark fringes: path-lengths differ by 3λ/2, 5λ/2, 7λ/2 etc
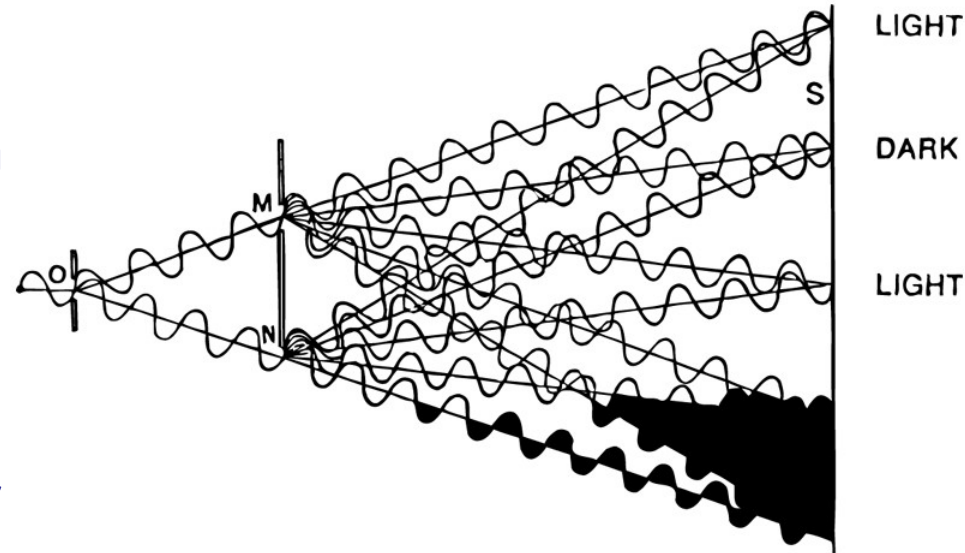
LIGHT
DARK
LIGHT

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· This also means that red-light interference fringes (longer λ) are more widely spaced than blue-light fringes.

Questions (non-examinable)

(1) Young's experiment is more effective with slits rather than with pinholes. Can you think of why?

The slits give a clearer fringe pattern because the pattern is parallel-line-shaped fringes, rather than the fringes of overlapping circles. Also, the slits let more light through so the pattern is brighter than with pinholes.

(2) Would one also get a fringe pattern when light passes through 3 parallel thin slits? How about thousands of such slits?

Yes! In fact an arrangement of multiple slits of identical spacings is called a *diffraction grating*.

Through interference, diffraction gratings disperse white light into colours, like prisms do, since bright fringes of each colour (ie wavelength) are at different locations.

Same effect for why see pretty rainbow-like spectra from CD surfaces. "Colourful" feathers of some birds – actually tiny grooves!
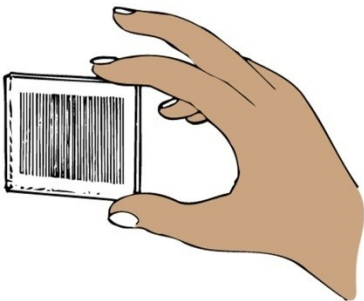
Wave-Particle Duality of light

- **Light behaves like a wave** when travelling from a source to the place where it is detected.

   -- cannot explain interference pattern using particles, since a stream of particles coming through each slit would come through independently of one another, striking the screen in two localized regions. No fringe pattern.

- **Light behaves as a particle** (photon) when it is being emitted or when being absorbed at a detector eg absorbed by a photographic film (next slide)

Wave-particle Duality cont.

· Shows up in optical images like photos:

wave nature explains how the light travels – light waves spread from each point of the object, bend through the lens system, obeying laws of waves

particle nature explains interaction with the photographic film. Film made up grains of silver halide crystals. Each photon gives up its energy *hf* to a single grain – triggers a photochemical process.

1.2 x 104 photons

· Can see image built up by individual photons:

3 x 103 photons

-very weak ie very few photons, arriving randomly at the screen

9.3 x 104 photons

2.8 x 107 photons

The double-slit experiment has been done with electrons!

Wave-particle duality holds for *any* particle, not just light!

- Any material particle (ie one with mass) also has both wave and particle properties: wave is a guide for how it travels.

- Discovered by de Broglie: $\boxed{\text{Wavelength} = \dfrac{h}{\text{momentum}}}$

· Usual bodies eg humans, books etc have large mass, and so at ordinary speeds, the wavelength is tiny (recall *h = 6.63 x 10-34 J.s*).

So the wave nature is not detectable, i.e. you can't see interference etc.

· Electrons are much tinier and they do demonstrate wave properties - eg used in electron microscopes.

· Typical wavelengths are thousands of times shorter than light, so can distinguish detail not visible with optical microscopes. Check out electron interference patterns in your book…

Clicker Question

The wave nature of matter is best illustrated by

A)   The photoelectric effect

B)   The double-slit experiment

C)   Neither

Answer: B

The interference pattern for an electron beam having gone through a double-slit shows that matter travels as a wave.

Uncertainty Principle

- Due to Heisenberg.

- Cannot simultaneously know the position *x and* momentum *p* of a quantum particle:

$$\Delta p \; \Delta x \; > h/2\pi$$

Δp = uncertainty in measurement of p,   means greater or equal to etc.

- Means that if we make a very accurate measurement of the position of a particle (small Δx), the uncertainty in its momentum will be very large.

And vice-versa, i.e. the sharper one of these quantities is, the less sharp is the other

- Also, energy-time uncertainty principle:

$$\Delta E \; \Delta t \; > h/2\pi$$

Clicker Question

If a proton and electron have identical speeds, which has a longer wavelength?

A) Proton

B) Electron

C) Both same

D) Need more information

Answer: B

A proton of same speed as electron has more momentum than the electron (p=mv). So, it has smaller de Broglie's wavelength = h/p. i.e. the electron has a longer wavelength.

More Questions

(1) If we are able to measure the momentum of an electron precisely, what do we know about its position?

Absolutely nothing! Measuring momentum exactly means $\Delta p = 0$, so to satisfy the uncertainty principle, must have infinite uncertainty in position.

(2) Imagine we try a "double-slit" experiment with baseballs. Whether we are able to discern fringes or not, depends on their spacing, which depends on the wavelength of the particle. If the baseballs travel at 20 m/s and have a mass of 0.2 kg, what is this wavelength?

$\lambda = h/p$ = (6.63 x 10-34 Js)/(0.2 kg x 20 m/s) = 1.66 x 10-34 m

So it's too small to resolve

i.e. everyday objects have too small a de Broglie wavelength for quantum effects to be noticeable