Physics 3313 - Lecture 5

Wednesday February 3, 2010
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1. Finish Ch. 2
2. HW 1 still due 02/08, HW2 assigned this pm due 2/10
3. Quiz on Ch. 2
4. Particle Properties of Waves
5. Photoelectric Effect
Relativistic Energy and Momentum

• Combining $E = \gamma mc^2$ and $\vec{p} = \gamma mv$ one can obtain (2.12)

\[
E^2 = (mc^2)^2 + p^2 c^2 \quad \text{and} \quad E = \sqrt{(mc^2)^2 + p^2 c^2}
\]

• These expressions relate the $E$, $p$, and $m$ for single particles, but are only valid for a system of particles of mass $M$ if which need not be true

\[
\sum_i m_i c^2 = Mc^2
\]

• Since $mc^2$ is an invariant quantity, this implies is also an invariant

• If $m=0$ this implies $E = p = 0$, but what if $v = c$?

• Then $\gamma = 1/0$ and $E = p = 0/0$, which is undefined!

\[
E^2 - p^2 c^2
\]

• For a massless particle with $v = c$, then we could have $E = pc$ for example the photon (which unfortunately has the symbol $\gamma$)
Units

- Use $W=qV$ to define electron volt (eV) a useful energy unit
- $1\ eV = 1.6 \times 10^{-19}\ C \times 1\ V = 1.6 \times 10^{-19}\ J$
- Binding energy of hydrogen atom is 13.6 eV
- Uranium atom releases about 200 MeV when it splits in two (fission) (not a lot of Joules/fission, but there are a lot of atoms around…)
- Rest mass of proton ($m_p$) is $0.938\ GeV/c^2$ which is a fine unit for mass
- Units of momentum, $p$, MeV/c
Relativistic Energy Problems

From \( E = \gamma mc^2 \) we can multiply by \( v \) to obtain \( vE = \gamma mvc^2 \).

Simplifying gives \( vE = pc^2 \) which gives us a useful relation: \( \frac{v}{c} = \frac{pc}{E} \).

An electron and a proton are accelerated through 10 MV, find \( p \), \( v \), and \( \gamma \) of each (work problem on blackboard).

Electron: \( pc = \sqrt{E^2 - (mc^2)^2} = \sqrt{(10.51)^2 - (0.511)^2} = 10.50 \text{MeV} \)

\[ p_e = 10.5 \frac{\text{MeV}}{c} \]

\[ \gamma = 1 + \frac{KE}{m_e c^2} \]

\[ \frac{v}{c} = \frac{pc}{E} = \frac{10.50}{10.51} = 0.999 \]

Proton: \( pc = \sqrt{(948)^2 - (938)^2} = 137.4 \text{MeV} \)

\[ \gamma = 1 + \frac{E_k}{m_p c^2} = 1 + \frac{10}{938} = 1.01 \]

\[ \frac{v}{c} = \frac{pc}{E} = \frac{137.4}{948.3} = 0.145 \]
Chapter 3 Quantum Theory/Particle
Properties of Waves

• Classically we perceive particles and waves as different objects
• Particles: baseball, dust, electrons have properties such as charge, momentum and mass and can be counted as discrete objects
• Waves: vibrating strings, water, sound, light have wave properties such as superposition, diffraction, and interference, and are measured by wavelength, frequency, and intensity (not discrete objects)
• Modern Physics introduces wave-particle duality: in the microscopic world neither particles nor waves but aspects of both
Electromagnetic Waves

- 1864 James Clerk Maxwell suggested that accelerating charges generate coupled E+M waves that travel indefinitely through space, both perpendicular to each other and direction of motion.

- Changing magnetic field produces a current/electric field: Faraday’s Law:

\[ V = -N \frac{d\phi}{dt} \]

- From symmetry if \( \Delta B \Rightarrow E \) then \( \Delta E \Rightarrow B \) etc. implies traveling waves with a velocity \( c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \); visible light is an EM wave (not vice-versa).
Wave Properties of Light

- Superposition: adding wave amplitudes
- Constructive interference
- Diffraction: bending of light around corners
- All support wave nature of light
- Wavelength, period, frequency

Figure 2.4 Origin of the interference pattern in Young's experiment. Constructive interference occurs where the difference in path lengths from the slits to the screen is $\theta, \lambda, 2\lambda, \ldots$. Destructive interference occurs where the path difference is $\lambda/2, 3\lambda/2, 5\lambda/2, \ldots$
Photoelectric Effect

- Light illuminating a surface causes emission of “photo-electrons” (visible spectrum)—ironically first observed in Hertz experiment which posthumously validated Maxwell’s predictions
- Simple device for measuring photo-electric effect

\[ KE_{\text{max}} = \frac{1}{2} m v_{\text{max}}^2 = eV_0 \]

\( V_0 \) is retarding potential: voltage above which no p.e.’s reach collector plate
Properties of Photoelectric Effect

- Existence of photoelectric effect was not a surprise: light waves carry energy which could dislodge an electron (like an ocean wave moving a pebble), but the details were surprising
  1) Very little time (nanoseconds) between arrival of light pulse and emission of electron, whereas might expect time for accumulation of enough energy (several eV) to liberate electrons
  2) Electron energy observed to be independent of intensity of light (bright light liberates more photoelectrons, not more energetic ones). Classically intensity is proportional to square of amplitude, so expect higher energy with higher intensity.
Photoelectric Effect Properties (cont.)

3) At higher frequency $\nu$ get higher energy electrons (blue 400 nm initiates p.e.’s with more energy than red 700 nm—takes larger potential $V_0$ to stop then)

Minimum frequency ($\nu_0$) required for photoelectric effect depends on material:

$$\text{slope} = \Delta E / \Delta \nu = h \text{ (planck’s constant)}$$
Einstein Explains P.E. Effect

- Einstein 1905 (I had a good year) explained P.E. effect: energy of light not distributed evenly over classical wave but in discrete regions called quanta and later photons (draw)
  1) EM wave concentrated in photon so no time delay between incident photon and p.e. emission
  2) All photons of same frequency have same energy $E=\hbar\nu$, ($\hbar =$Planck’s constant) so changing intensity changes number ($I=\nuh$, where $N$ is rate/area) but not energy
  3) Higher frequency gives higher energy

$$h = 6.626 \times 10^{-34} \text{ J} \cdot \text{sec}$$

- Electrons have maximum KE when all energy of photon given to electron.
- $\phi$ is work function or minimum energy required to liberate electron from material ($\phi = h\nu_0$)

$$KE_{\text{max}} = h\nu - \phi = h\nu - h\nu_0$$
Photoelectric Energy Formulas

\[
E = h\nu = 6.626 \times 10^{-34} \text{J}\cdot\text{s} \times \frac{eV\cdot\nu}{1.6 \times 10^{-19} \text{J}} = 4.136 \times 10^{-15} \text{eV}\cdot\text{sec}\cdot\nu
\]

using \( c = \lambda \nu \)

\[
E = 4.136 \times 10^{-15} eV\cdot s \cdot \frac{2.998 \times 10^8 \text{m/sec}}{\lambda} = \frac{1.240 \times 10^{-6} \text{eV}\cdot\text{m}}{\lambda}
\]
Example for Iron

• a) Find $\phi$ given $\nu_0 = 1.1 \times 10^{15} \text{ Hz}$

$$\phi = h \nu_0$$

$$\phi = 4.14 \times 10^{-15} \text{ eV} \cdot \text{sec} \times 1.1 \times 10^{15} \text{ s}^{-1}$$

$$\phi = 4.5 \text{ eV}$$

• b) If p.e.’s are produced by light with a wavelength of 250 nm, what is the stopping potential?

$$KE_{\text{max}} = eV_0 = h \nu - \phi = \frac{1.24 \times 10^{-6} \text{ eV} \cdot m}{250 \times 10^{-9} m} - 4.5 \text{ eV}$$

$$= 4.96 - 4.5 = 0.46 \text{ eV}$$ (is this the answer?)

NO! it is $V_0 = 0.46 \text{ V}$ (not eV)
Speed of Person Revisited

- http://www.youtube.com/watch?v=HofoK_QQxGc