Disasters in Classical Physics (1899-1922)

• Disaster ➔ Experimental observation that could not be explained by Classical theory (Phys 2A, 2B, 2C)
  – Disaster # 1: Nature of Blackbody Radiation from your BBQ grill
  – Disaster # 2: Photo Electric Effect
  – Disaster # 3: Scattering light off electrons (Compton Effect)

• Resolution of Experimental Observation will require radical changes in how we think about nature
  – ➔ QUANTUM MECHANICS
    • The Art of Conversation with Subatomic Particles
Photo Electric Effect
Einstein’s Explanation of Photoelectric Effect

- Energy associated with EM waves in not uniformly distributed over wave-front, rather is contained in packets of “stuff” ⇒ PHOTON
- \( E = hf = \frac{hc}{\lambda} \) [but is it the same \( h \) as in Planck’s th.?]
- Light shining on metal emitter/cathode is a stream of photons of energy which depends on frequency \( f \)
- Photons knock off electron from metal instantaneously
  - Transfer all energy to electron
  - Energy gets used up to pay for Work Function \( \Phi \) (Binding Energy)
    - Rest of the energy shows up as KE of electron \( KE = hf - \Phi \)
- Cutoff Frequency \( hf_0 = \Phi \) (pops an electron, \( KE = 0 \))
- Larger intensity \( I \) ⇒ more photons incident
- Low frequency light \( f \) ⇒ not energetic enough to overcome work function of electron in atom
Einstein’s Explanation of PhotoElectric Effect

\[ V_Se = hf - \phi \]
Is “h” same in Photoelectric Effect as BB Radiation?

Slope \( h = 6.626 \times 10^{-34} \text{ JS} \)

Einstein \( \rightarrow \) Nobel Prize!

No matter where you travel in the galaxy and beyond…
..no matter what experiment You do

\( h \) : Planck’s constant is same

NOBEL PRIZE FOR PLANCK
<table>
<thead>
<tr>
<th>Element</th>
<th>$\phi$ (eV)</th>
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<tbody>
<tr>
<td>Na</td>
<td>2.28</td>
</tr>
<tr>
<td>C</td>
<td>4.81</td>
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<tr>
<td>Cd</td>
<td>4.07</td>
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<td>Mg</td>
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<tr>
<td>Ni</td>
<td>5.01</td>
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<tr>
<td>Se</td>
<td>5.11</td>
</tr>
<tr>
<td>Pb</td>
<td>4.14</td>
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</table>
Photoelectric Effect on some Iron Surface:

Light of Intensity \( I = 1.0 \mu \text{W/cm}^2 \) incident on \( 1.0 \text{cm}^2 \) surface of Fe

Assume Fe reflects 96% of light

further only 3% of incident light is Violet region (\( \lambda = 250\text{nm} \))

barely above threshold frequency for Ph. El effect

(a) Intensity available for Ph. El effect \( I = 3\% \times 4\% \times (1.0 \mu \text{W/cm}^2) \)

(b) how many photo-electrons emitted per second?

\[
\text{# of photoelectrons} = \frac{\text{Power}}{h \cdot f} = \frac{3\% \times 4\% \times (1.0 \mu \text{W/cm}^2) \lambda}{h \cdot c} = \frac{(250 \times 10^{-9} \text{ m}) (1.2 \times 10^{-9} \text{ J/s})}{(6.6 \times 10^{-34} \text{ J} \cdot \text{s})(3.0 \times 10^8 \text{ m/s})} = 1.5 \times 10^9
\]

(c) Current in Ammeter: \( i = (1.6 \times 10^{-19} \text{ C})(1.5 \times 10^9) = 2.4 \times 10^{-10} \text{ A} \)

(d) Work Function \( \Phi = hf_0 = (4.14 \times 10^{-15} \text{ eV} \cdot \text{s})(1.1 \times 10^{15} \text{ s}^{-1}) = 4.5 \text{ eV} \)
Photon & Relativity: Wave or a Particle?

- Photon associated with EM waves, travel with speed $=c$
- For light ($m=0$): Relativity says $E^2 = (pc)^2 + (mc^2)^2$
- $\Rightarrow E = pc$
- But Planck tells us: $E = hf = h(c/\lambda)$
- Put them together: $hc/\lambda = pc$
  - $\Rightarrow p = h/\lambda$
  - Momentum of the photon (light) is inversely proportional to $\lambda$

- But we associate $\lambda$ with waves & $p$ with particles ....what is going on??
  - A new paradigm of conversation with the subatomic particles: Quantum Physics
X Rays: “Bremsstrahlung”: Braking Radiation

Produced by bombarding a metal target with energetic electrons
Produced in general by ALL accelerating charged particles
X rays: very short \( \lambda \approx 60-100 \text{ pm (}10^{-12}\text{m)} \), large frequency \( f \)
Very penetrating because energetic

Useful for probing structure of sub-atomic Particles
The “High Energy Accelerator” of 1900s: produced energetic light : X-Ray , gave new optic to subatomic phenomena
X Ray Spectrum in Molybdenum (Mo)

(b)

$K_\alpha$

$K_\beta$

$\lambda_m$

$\lambda$, Å

$I(\lambda)$ (relative)

$V = 35$ kV
Bragg Scattering: Probing Atoms With X-Rays

Constructive Interference: $n\lambda = 2d\sin \theta$
Compton Scattering: Quantum Pool!

- 1922: Arthur Compton (USA) proves that X-rays (EM Waves) have particle-like properties (acts like photons)
  - Showed that classical theory failed to explain the scattering effect of
    - X rays on to free (not bound, barely bound electrons)
- Experiment: shine X-ray EM waves on to a surface with “almost” free electrons
  - Watch the scattering of light off electron: measure time + wavelength of scattered X-ray

(a) Classical model

![Diagram of Compton Scattering]
Compton Effect: what should Happen Classically?

- Plane wave \([f, \lambda]\) incident on a surface with loosely bound electrons \(\rightarrow\) interaction of E field of EM wave with electron: \(F = eE\)
- Electron oscillates with \(f = f_{\text{incident}}\)
- Eventually radiates spherical waves with \(f_{\text{radiated}} = f_{\text{incident}}\)
  - At all scattering angles, \(\Delta f \& \Delta \lambda\) must be zero
- Time delay while the electron gets a “tan” : soaks in radiation
Compton Scattering: Setup & Results

How does one explain this startling anisotropy?

\[ \Delta \lambda = (\lambda' - \lambda) \propto (1 - \cos \theta) \]

Scattered \( \lambda' \) larger than incident

\[ \Delta \lambda = \left( \frac{h}{m_e c} \right) (1 - \cos \theta) \]
Compton Effect: Quantum (Relativistic) Pool

(b) Quantum model
Compton Scattering: Quantum Picture

Energy Conservation:
\[ E + m_e c^2 = E' + E_e \]

Momentum Conservation:
\[ p = p'\cos\theta + p_e \cos\phi \]
\[ 0 = p'\sin\theta - p_e \sin\phi \]

Use these to eliminate electron deflection angle (not measured)

\[ (E - E') + m_e c^2 \]
\[ = \left[ p^2 - 2pp'\cos\theta + p'^2 \right] c^2 + (m_e c^2)^2 \]

For light \( p = \frac{E}{c} \) \[ \Rightarrow \]
\[ E^2 + E'^2 - 2EE' + 2(E - E')mc^2 = \left[ \frac{E^2}{c^2} - 2 \frac{EE'}{c^2} \cos\theta + \frac{E'^2}{c^2} \right] c^2 \]
\[ \Rightarrow -EE' + (E - E')mc^2 = -EE'\cos\theta \]
\[ \Rightarrow \frac{E-E'}{EE'} = -\frac{1}{m_e c^2} (1 - \cos\theta) \Rightarrow (\lambda' - \lambda) = \left( \frac{h}{m_e c} \right) (1 - \cos\theta) \]
Checking for $h$ in Compton Scattering

Plot scattered photon data, calculate slope and measure $h$

It’s the same $h$!!

\[
\Delta \lambda = (\frac{h}{m_e c})(1 - \cos \theta)
\]

Compton wavelength $\lambda_C = \frac{h}{m_e c}$

Energy Quantization is a UNIVERSAL characteristic of light (EM Waves)
Blindmen & an Elephant

touched the trunk of the elephant, said elephant was like a branch of a tree.

...touched the tail of the elephant, said elephant was like a snake.

touched an ear. He said elephant was a huge fan.

felt a leg of the elephant., elephant was like a pillar.

touched the side of the elephant, said the elephant was like a wall

Gentlemen, all five of you have touched only one part of the elephant ..elephant is all of above

LIKEWISE WITH LIGHT!
Next Question: What is the Nature of Matter

- Fundamental Characteristics of different forms of matter
  - Mass
  - Charge
  - Measure them

\[ \mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \]