Conservation of Mass-Energy: Nuclear Fission

\[ Mc^2 = M_1 c^2 + M_2 c^2 + M_3 c^2 \]

\[ \Rightarrow M > M_1 + M_2 + M_3 \]

Loss of mass shows up as kinetic energy of final state particles
Disintegration energy per fission \( Q = (M - (M_1 + M_2 + M_3))c^2 = \Delta Mc^2 \)

\[ {}^{235}_{92}U \rightarrow {}^{141}_{55}Cs + {}^{90}_{43}Rb + 3n \] (1 AMU = 1.6605402 \times 10^{-27} kg = 931.49 MeV)

\( \Delta m = 0.177537u = 2.9471 \times 10^{-28} \text{kg} = 165.4 \text{ MeV} = \text{energy release/fission = peanuts} \)

What makes it explosive is 1 mole of Uranium = 6.023 x 10^{23} Nuclei !!

Nuclear Fission Schematic: “Tickling” a Nucleus

Absorption of Neutron
Excited U
Oscillation
Deforms Nucleus
Unstable Nucleus
Fission fragments
Sustaining Chain Reaction: 1st three Fissions

Average # of Neutrons/Fission = 2.5
Neutron emitted in fission of one U
Needs to be captured by another

To control reaction => define factor K

Supercritical  K >> 1 in a Nuclear Bomb
Critical           K = 1 in a Nuclear Reactor

Schematic of a Pressurized-Water Reactor

Water in contact with reactor core serves as a moderator and heat transfer Medium. Heat produced in fission drives turbine
**Lowering Fuel Core in a Nuclear Reactor**

First Nuclear reactor: Pennsylvania 1957

Pressure Vessel contains:
- 14 Tons of Natural Uranium
- + 165 lb of enriched Uranium

Power plant rated at 90MW, Retired (82)

Pressure vessel packed with Concrete now sits in Nuclear Waste Facility in Hanford, Washington

---

**Nuclear Fusion: What Powers the Sun**

Opposite of Fission

Mass of a Nucleus < mass of its component protons + Neutrons

Nuclei are stable, bound by an attractive "Strong Force"

Think of Nuclei as molecules and proton/neutron as atoms making it

Binding Energy: Work/Energy required to pull a bound system (M) apart leaving its components (m) free of the attractive force and at rest:

\[ Mc^2 + BE = \sum_{n=1}^{2} m_i c^2 \]

\[ _1^2 \text{H} + _1^2 \text{H} = _2^4 \text{He} + 23.9 \text{ MeV} = \]

Deuterium + Deuterium = Helium + Released Energy

Think of energy released in Fusion as Dissociation energy of Chemistry

Sun's Power Output = 4×10^{38} Watts ⇒ 10^{38} Fusion/Second !!!!
Nuclear Fusion: Wishing For The Star

- Fusion is eminently desirable because
  - More Energy/Nucleon
    - (3.52 MeV in fusion Vs 1 MeV in fission)
    - $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + \text{n} + 17.6 \text{ MeV}$
  - Relatively abundant fuel supply, No danger like nuclear reactor going supercritical
- Unfortunately technology not commercially available
  - What’s inside nuclei => protons and Neutrons
  - Need Large KE to overcome Coulomb repulsion between nuclei
    - About 1 MeV needed to bring nuclei close enough together for Strong Nuclear Attraction $\rightarrow$ fusion
    - Need to
      - heat particle to high temp such that thermal energy $E = kT \approx 10 \text{keV} \rightarrow$ tunneling thru coulomb barrier
      - Implies heating to $T \approx 10^8 \text{ K}$ (like in stars)
      - Confine Plasma (± ions) long enough for fusion
        - In stars, enormous gravitational field confines plasma

Inertial Fusion Reactor: Schematic

Pellet of frozen-solid Deuterium & tritium bombarded from all sides with intense pulsed laser beam with energy $= 10^8 \text{ Joules lasting } 10^{-8} \text{ S}$

Momentum imparted by laser beam compresses pellet by 1/10000 of normal density and heats it to temp $T = 10^8 \text{ K for } 10^{-10} \text{ S}$

Burst of fusion energy transported away by liquid Li
A Powerful Laser: NOVA @ LLNL

Size of football field, 3 stories tall
Generates $1.0 \times 10^{14}$ watts (100 terawatts)

10 laser beams converge onto H pellet (0.5mm diam)
Fusion reaction is visible as a starlight lasting $10^{-10}$ S
Releasing $10^{13}$ neutrons

ITER: The Next Big Step in Nuclear Fusion

Visit [www.iter.org](http://www.iter.org) for Details of this mega Science & Engineering Project
This may be future of cheap, clean Nuclear Energy for Earthlings
Ch 3 : Quantum Theory Of Light

• What is the nature of light?
  – When it propagates?
  – When it interacts with Matter?

• What is Nature of Matter?
  – When it interacts with light?
  – As it propagates?

• Revolution in Scientific Thought
  – Like a firestorm of new ideas (every body goes nuts!..not like Evolution)
    • Old concepts violently demolished, new ideas born
      – Interplay of experimental findings & scientific reason

• One such revolution happened at the turn of 20th Century
  – Led to the birth of Quantum Theory & Modern Physics

Classical Picture of Light: Maxwell’s Equations

• Maxwell’s Equations:

\[ \oint E \cdot ds = \frac{Q}{\varepsilon_0} \]
\[ \oint B \cdot ds = 0 \]
\[ \oint E \cdot ds = -\frac{d\Phi_B}{dt} \]
\[ \oint B \cdot ds = \mu_0 I + \mu_\varepsilon_0 \frac{d\Phi_E}{dt} \]

\[ \frac{\partial^2 E}{\partial x^2} = \frac{\mu_0 \varepsilon_0}{\partial t^2} \]
\[ \frac{\partial^2 B}{\partial x^2} = \frac{\mu_0 \varepsilon_0}{\partial t^2} \]

\[ E = E_{\text{max}} \cos(kx - \omega t) \]
\[ B = B_{\text{max}} \cos(kx - \omega t) \]

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \]
Hertz & Experimental Demo of Light as EM Wave

Energy source

LC oscillator

Transformer

Electric dipole

Traveling wave

Power incident on an area $A$

Energy Flow in EM Waves:

Poynting Vector $\vec{S} = \frac{1}{\mu_0} (\vec{E} \times \vec{B})$

$\vec{S} \cdot \vec{A} = \frac{1}{\mu_0} (AE_0 B_0 \sin^2 (kx - \omega t))$

Intensity of Radiation $I = \frac{1}{2\mu_0 c} E_0^2$

Larger the amplitude of Oscillation

More intense is the radiation

If all this discussion of properties of EM waves looks unfamiliar to you, pl. visit the Physics Tutorial Center on 2nd floor of Mayer Hall
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

Nature of Radiation: An Expt with BBQ Grill

Question: Distribution of Intensity of EM radiation Vs T & λ

- Radiator (grill) at some temp T
- Emits variety of wavelengths
  - Some with more intensity than others
- EM waves of diff. λ bend differently within prism
- Eventually recorded by a detector (eye)
- Map out emitted Power / area Vs λ

Notice shape of each curve and learn from it
**Radiation from A Blackbody**

(a) Intensity of Radiation \( I = \int R(\lambda) d\lambda \propto T^4 \)

\[ I = \sigma T^4 \text{ (Area under curve)} \]

Stephan-Boltzmann Constant \( \sigma = 5.67 \times 10^{-8} \text{ W} / \text{m}^2 \text{K}^4 \)

(b) Higher the temperature of BBQ
Lower is the \( \lambda \) of PEAK intensity

\[ \lambda_{\text{MAX}} \propto \frac{1}{T} \]

Wein’s Law \( \lambda_{\text{MAX}} T = \text{const} = 2.898 \times 10^3 \text{ mK} \)

As a body gets hotter it gets more RED than White

Reason for different shape of \( R(\lambda) \) Vs \( \lambda \) for different temperature? Can one explain in on basis of Classical Physics (2A,2B,2C) ??
Blackbody Radiator: An Idealization

Classical Analysis:
- Box is filled with EM standing waves
- Radiation reflected back-and-forth between walls
- Radiation in thermal equilibrium with walls of Box
- How may waves of wavelength $\lambda$, can fit inside the box?

Blackbody Absorbs everything
Reflects nothing
All light entering opening gets absorbed (ultimately) by the cavity wall

Cavity in equilibrium $T$ w.r.t. surrounding. So it radiates everything it absorbs

Emerging radiation is a sample of radiation inside box at temp $T$

Predict nature of radiation inside Box?

Standing Waves

(a) $L = \frac{\lambda}{2}$

(b) $L = \lambda = \frac{2\lambda}{2}$

(c) $L = \frac{3\lambda}{2}$
The Beginning of The End! How BBQ Broke Physics

Classical Calculation

# of standing waves between Wavelengths $\lambda$ and $\lambda + d\lambda$ are

$$N(\lambda)d\lambda = \frac{8\pi V}{\lambda^4} d\lambda; \ V = \text{Volume of box} = L^3$$

Each standing wave contributes energy $E = kT$ to radiation in Box.

Energy density $u(\lambda) = \frac{\# \text{ of standing waves/volume}}{\text{Energy/Standing Wave}}$

$$u(\lambda) = \frac{8\pi V}{\lambda^4} \times \frac{1}{V} \times kT = \frac{8\pi}{\lambda^4} kT$$

Radiancy $R(\lambda) = \frac{c}{4} u(\lambda) = \frac{c}{4} \frac{8\pi}{\lambda^4} kT = \frac{2\pi c}{\lambda^4} kT$

Radiancy is Radiation intensity per unit $\lambda$ interval: Let's plot it.

Prediction: as $\lambda \to 0$ (high frequency) $\Rightarrow R(\lambda) \to \infty$ !

Oops!

Ultra Violet (Frequency) Catastrophe

![Graph showing the comparison between Radiancy R(\lambda) and Experimental Data, with a Classical Theory line labeled Rayleigh-Jeans law and a dashed line labeled Ultra Violet (Frequency) Catastrophe.]
That was a Disaster! (#1)

Disaster #2: Photo-Electric Effect

Light of intensity $I$, wavelength $\lambda$, and frequency $\nu$ incident on a photo-cathode

Can tune $I$, $f$, $\lambda$

Measure characteristics of current in the circuit as a function of $I$, $f$, $\lambda$
Photo Electric Effect: Measurable Properties

- Rate of electron emission from cathode
  - From current $i$ seen in ammeter

- Maximum kinetic energy of emitted electron
  - By applying retarding potential on electron moving towards Collector plate
    $$K_{\text{MAX}} = eV_S \quad (V_S = \text{Stopping voltage})$$
    $$\text{Stopping voltage} \rightarrow \text{no current flows}$$

- Effect of different types of photo-cathode metal

- Time between shining light and first sign of photocurrent in the circuit

Observations: Current Vs Frequency of Incident Light

<table>
<thead>
<tr>
<th>Photocurrent</th>
<th>Light frequency $f = \text{constant}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_3 = 3I_1$</td>
</tr>
<tr>
<td></td>
<td>$I_2 = 2I_1$</td>
</tr>
<tr>
<td></td>
<td>$I_1 = \text{intensity}$</td>
</tr>
</tbody>
</table>

- $I_3 = 3I_1$
- $I_2 = 2I_1$
- $I_1 = \text{intensity}$
- $-V_S$
- $0$ Applied voltage
- $V$
**Stopping Voltage $V_s$ Vs Incident Light Frequency**

Stopping Voltage

Different Metal Photocathode surfaces

Slope = $h$

Intercept = $-\phi$

**Retarding Potential Vs Light Frequency**

Shining Light With Constant Intensity But different frequencies

Photoelectric current $f_1 > f_2 > f_3$

Applied voltage

$V$

$I$
Conclusions from the Experimental Observation

• Max Kinetic energy $K_{\text{MAX}}$ independent of Intensity $I$ for light of same frequency

• No photoelectric effect occurs if light frequency $f$ is below a threshold no matter how high the intensity of light

• For a particular metal, light with $f > f_0$ causes photoelectric effect IRRESPECTIVE of light intensity.
  – $f_0$ is characteristic of that metal

• Photoelectric effect is instantaneous !...not time delay

  Can one Explain all this Classically !