Physics 2D Lecture Slides
Lecture 10: Jan 24th 2005

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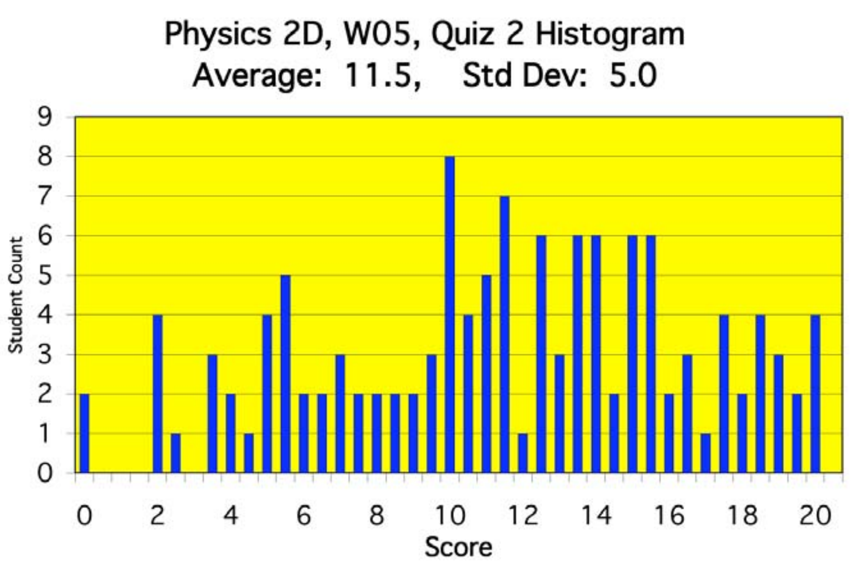


Conservation of Mass-Energy: Nuclear Fission

$M \rightarrow M_1 + M_2 + M_3$ **Nuclear Fission**

$$Mc^2 = \underbrace{\frac{M_1 c^2}{\sqrt{1-\frac{u_1^2}{c^2}}}}_{<1} + \underbrace{\frac{M_2 c^2}{\sqrt{1-\frac{u_2^2}{c^2}}}}_{<1} + \underbrace{\frac{M_3 c^2}{\sqrt{1-\frac{u_3^2}{c^2}}}}_{<1} \Rightarrow M > M_1 + M_2 + M_3$$

Loss of mass shows up as kinetic energy of final state particles

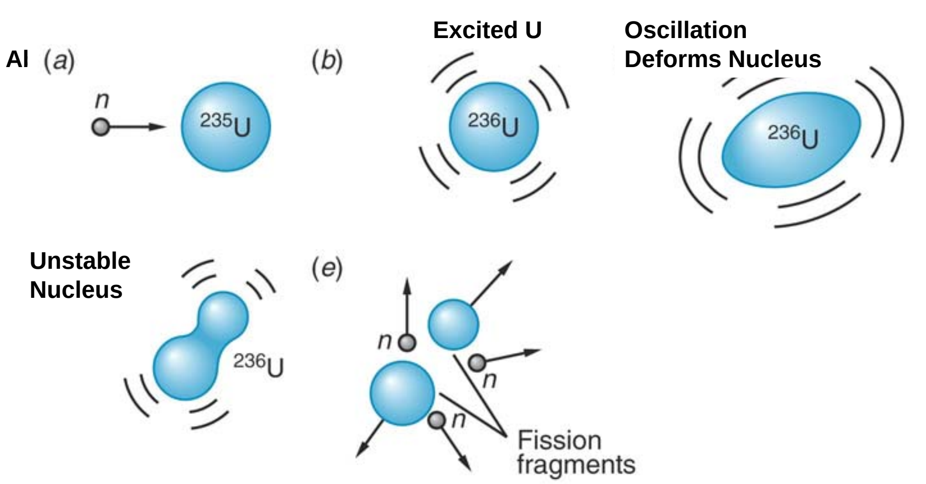
Disintegration energy per fission $Q=(M-(M_1+M_2+M_3))c^2 = \Delta Mc^2$

$^{236}_{92}U \rightarrow {}^{143}_{55}Cs + {}^{90}_{92}Rb + 3\,{}^{1}_{0}n$ $\quad$ (1 AMU$= 1.6605402\times10^{-27}kg = 931.49$ MeV)

$\Delta m = 0.177537u = 2.9471\times10^{-28}kg = 165.4$ MeV$=$ energy release/fission =peanuts

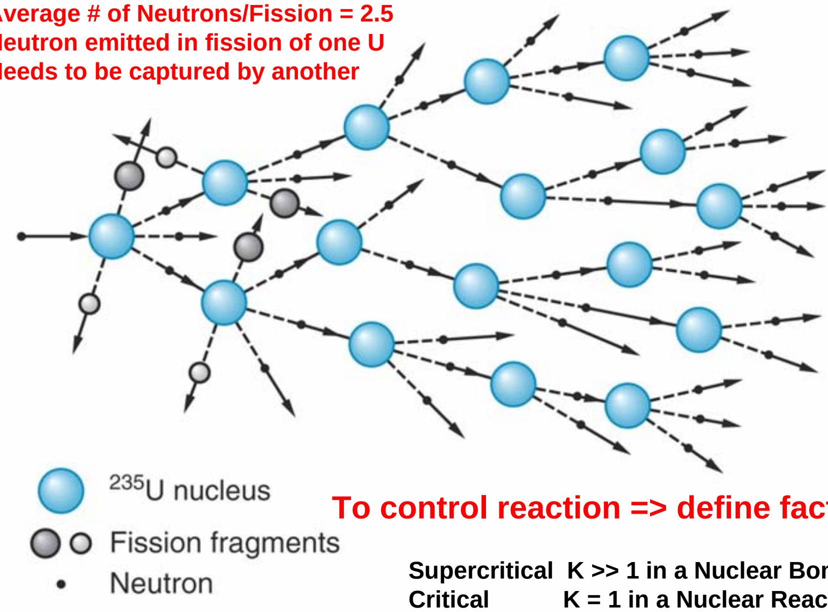
What makes it explosive is 1 mole of Uranium = 6.023 x 10^{23} Nuclei !!

Nuclear Fission Schematic : "Tickling" a Nucleus



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

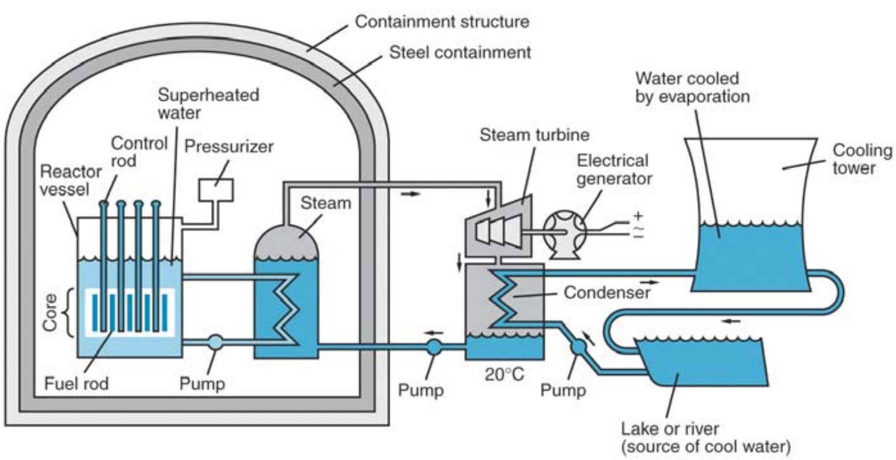


To control reaction => define factor K

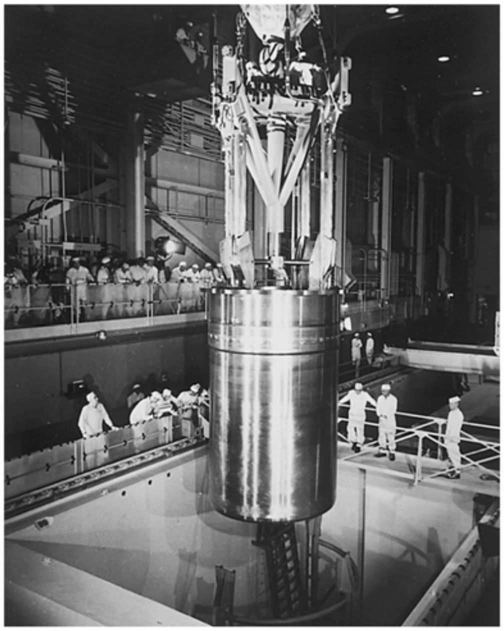
Supercritical K >> 1 in a Nuclear Bomb
Critical K = 1 in a Nuclear Reactor

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 Nuclearr 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:

$$Mc^2 + BE = \sum_{i=1}^{n} m_i c^2$$

$${}^2_1H \quad + \quad {}^2_1H \quad = \quad {}^4_2He \quad + \quad 23.9\text{ MeV} \quad =$$

Deuterium Deuterium = Helium + Released Energy

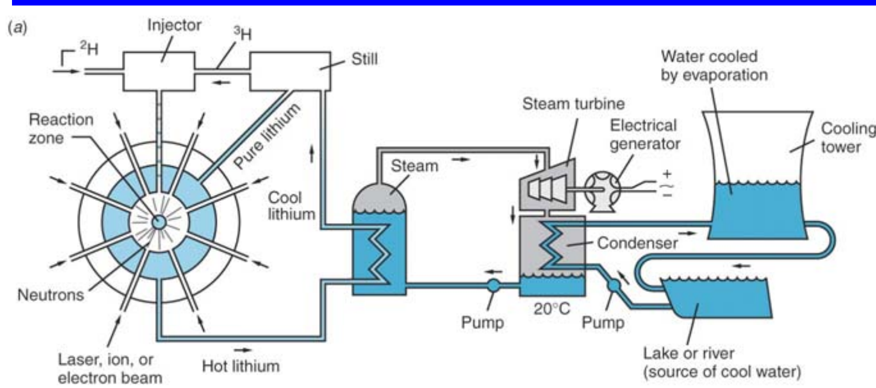
Think of energy released in Fusion as Dissociation energy of Chemistry

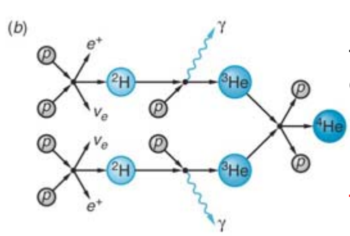
Sun's Power Output = 4×10^{26} Watts $\Rightarrow 10^{38}$ Fusion/Second !!!!

Nuclear Fusion: Wishing For The Star

- Fusion is eminently desirable because
  - More Energy/Nucleon
    - (3.52 MeV in fusion Vs 1 MeV in fission)
    - $^{2}H + ^{3}H \rightarrow ^{4}He + n + 17.6$ 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 → fusion
    - Need to
      - heat particle to high temp such that thermal energy $E = kT \approx 10$keV → tunneling thru coulomb barrier
      - Implies heating to $T \approx 10^{8}$ 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^{6} Joules lasting 10^{-8} S

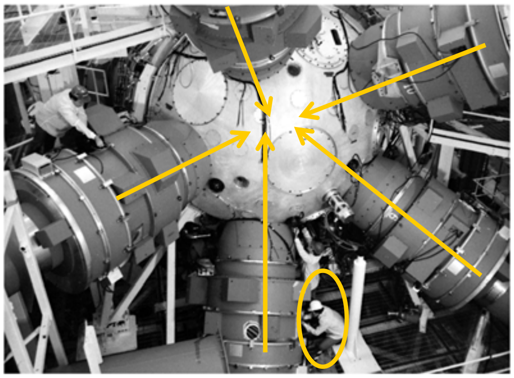
Momentum imparted by laser beam compresses pellet by 1/10000 of normal density and heats it to temp $T \approx 10^{8}$ K for 10^{-10} S

Burst of fusion energy transported away by liquid Li

A Powerful Laser : NOVA @ LLNL

Size of football field, 3 stories tall

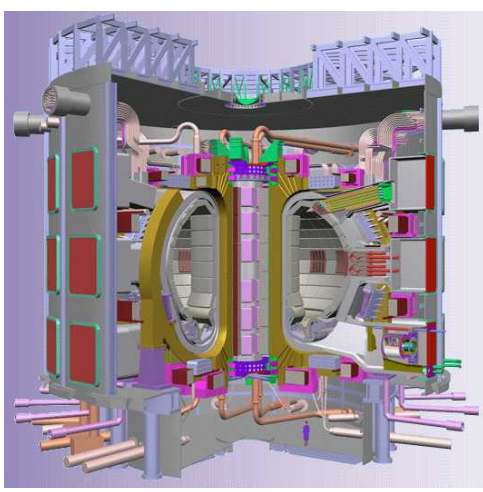
Generates 1.0 x 10^{14} watts (100 terawatts)



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 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:

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\epsilon_0}$$

$$\oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

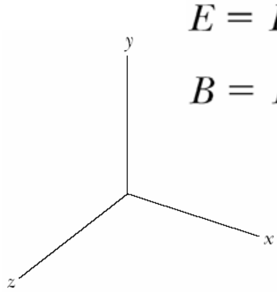
$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}$$

$$E = E_{\max} \cos(kx - \omega t)$$

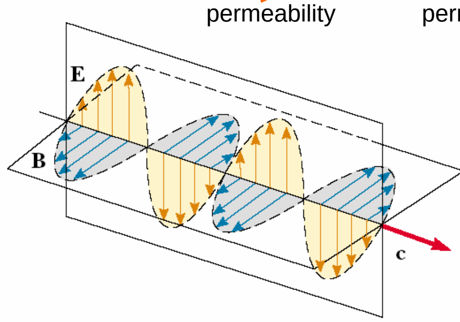
$$B = B_{\max} \cos(kx - \omega t)$$



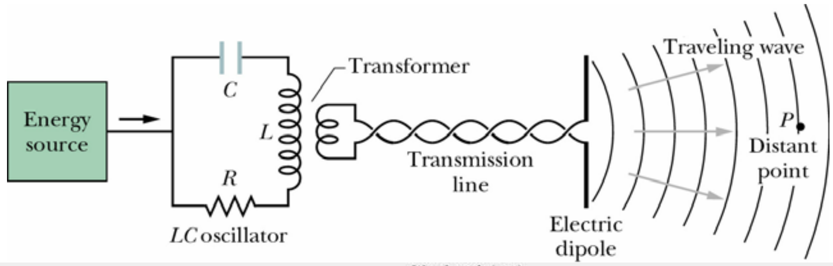
$$\boxed{c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}}$$

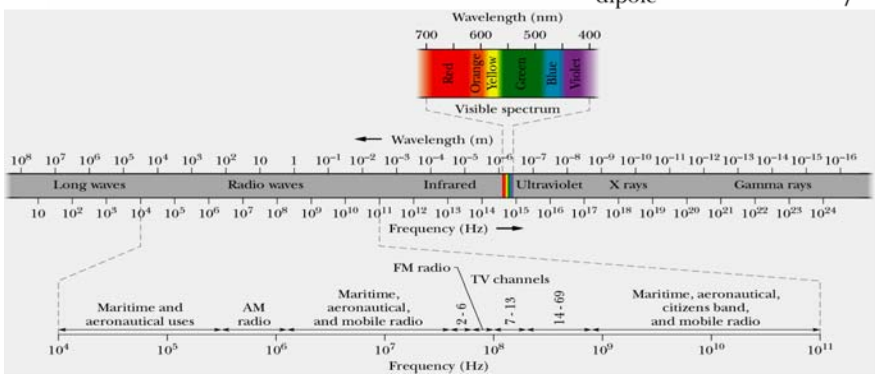
permeability

permittivity

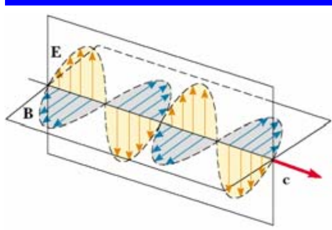


Hertz & Experimental Demo of Light as EM Wave





Properties of EM Waves: Maxwell's Equations



Energy Flow in EM Waves :

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

$\boxed{\text{Power incident on an area A}} = \vec{S}.\vec{A} = \frac{1}{\mu_0}\left(AE_0B_0Sin^2(kx - \omega t)\right)$

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

Larger the amplitude of Oscillation
More intense is the radiation

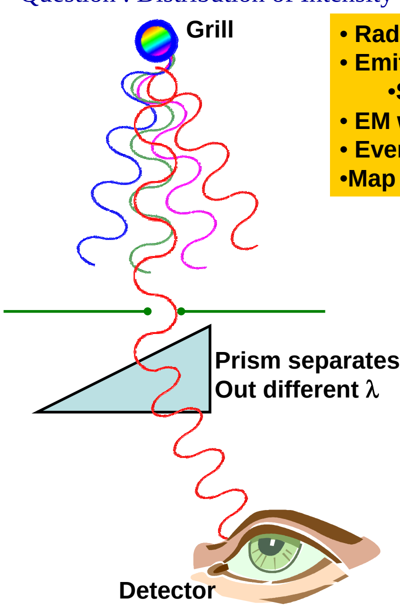
If all this discussion of properties of EM waves looks unfamilar to you, pl. visit the Physics Tutorial Center on 2nd floor of Mayer Hall

Disasters in Classical Physics (1899-1922)

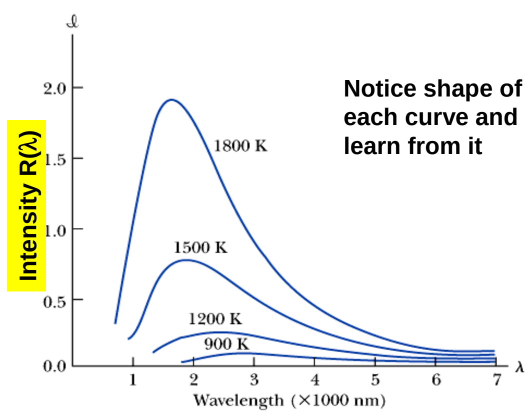
- Disaster ➔ Experimental observation that could not be explained by Classical theory (Phys 2A, 2B, 2C)
  - Disaster # 1 : Nature of Blackbody Radiation from your BBQ grill
  - Disaster # 2: Photo Electric Effect
  - Disaster # 3: Scattering light off electrons (Compton Effect)
- Resolution of Experimental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

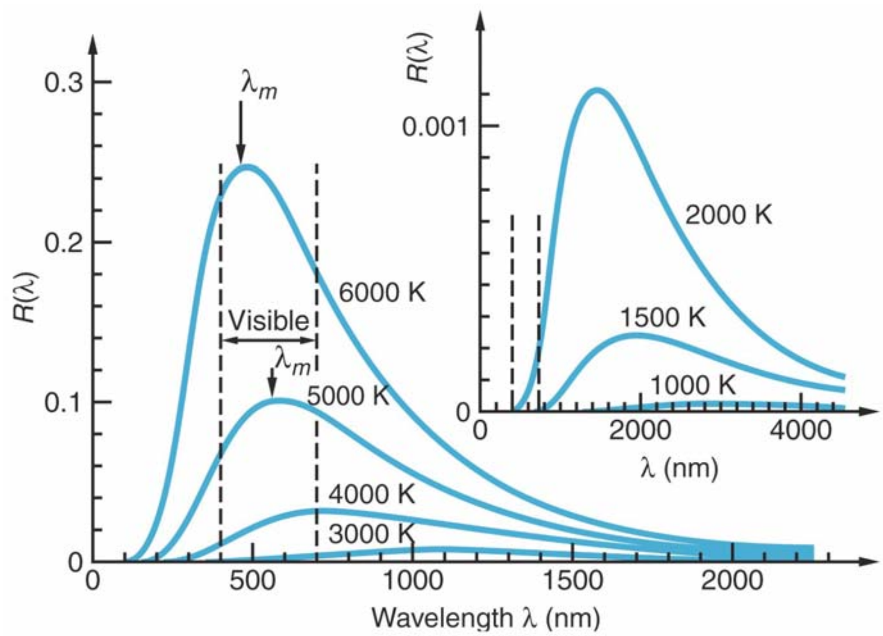


- Radiator (grill) at some temp T
- Emits variety of wavelengths
  - Some with more intensity than others
- EM waves of diff. λ bend differently within prism
- Eventually recorded by a detector (eye)
- Map out emitted Power / area Vs λ



Notice shape of each curve and learn from it

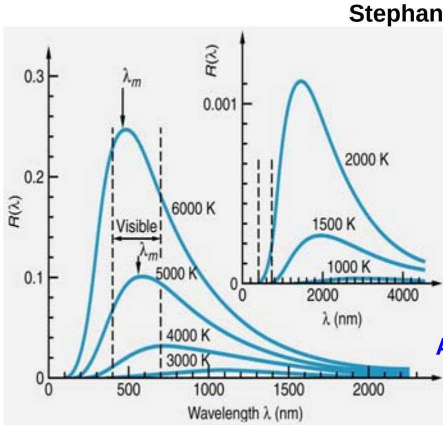
Radiation from A Blackbody



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

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

Stephan-Boltzmann Constant $\sigma = 5.67\ 10^{-8}\ \mathrm{W / m^2 K^4}$



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

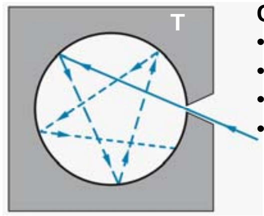
$$\lambda_{MAX} \propto 1 / T$$

Wein's Law $\lambda_{MAX}\, T = \text{const} = 2.898\ 10^{-3}\ \text{mK}$

As a body gets hotter it gets more RED then White

Reason for different shape of R(λ) Vs λ for different temperature?
Can one explain in on basis of Classical Physics (2A,2B,2C) ??

Blackbody Radiator: An Idealization



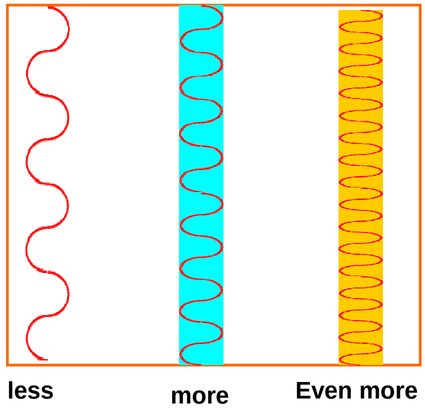
Classical Analysis:
- Box is filled with EM standing waves
- Radiation reflected back-and-forth between walls
- Radiation in thermal equilibrium with walls of Box
- How may waves of wavelength λ can fit inside the box ?

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

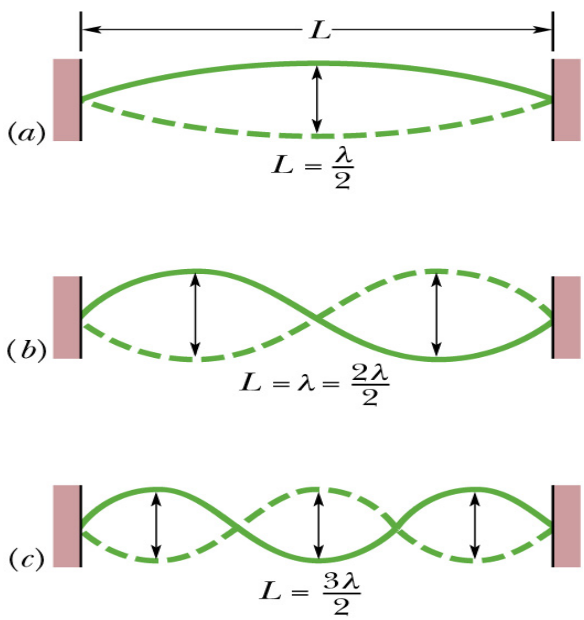
Cavity in equilibrium T w.r.t. surrounding. So it radiates everything It absorbs

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

Predict nature of radiation inside Box ?



Standing Waves



The Beginning of The End ! How BBQ Broke Physics

Classical Calculation

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

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

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

Energy density $u(\lambda)$= [# of standing waves/volume]× Energy/Standing Wave

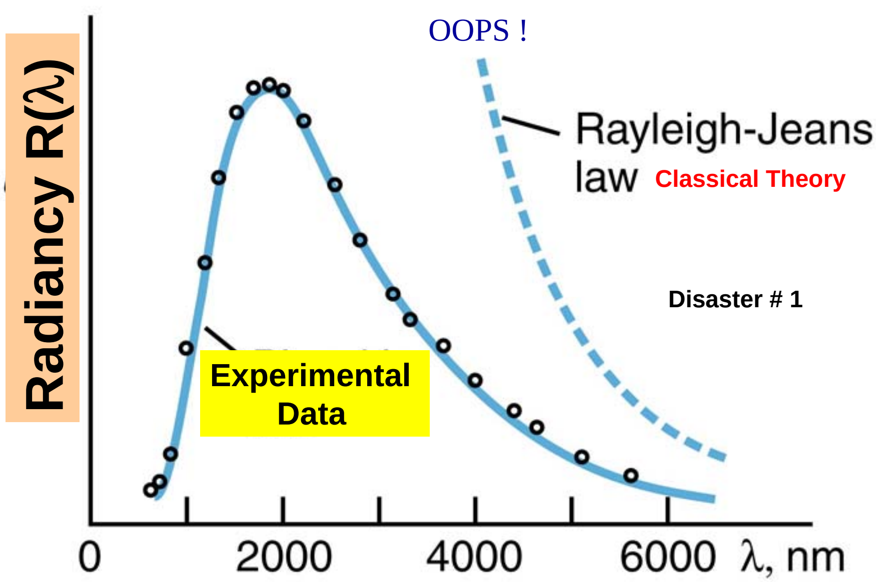
$$= \frac{8\pi V}{\lambda^4} \times \frac{1}{V} \times kT = \frac{8\pi}{\lambda^4} kT$$

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

Radiancy is Radiation intensity per unit λ interval: Lets plot it

Prediction : as $\lambda \rightarrow 0$ (high frequency) $\Rightarrow R(\lambda) \rightarrow$ Infinity !
Oops !

Ultra Violet (Frequency) Catastrophe

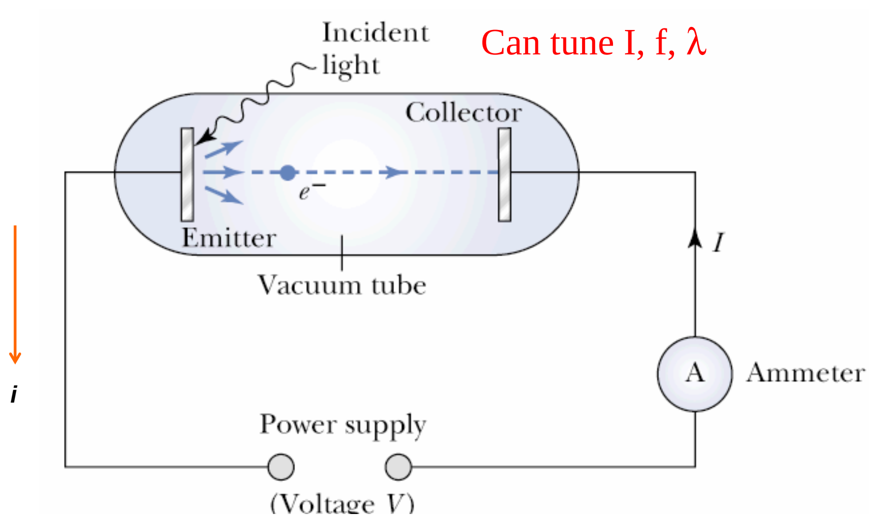


That was a Disaster ! (#1)

Disaster # 2 : Photo-Electric Effect

Light of intensity I, wavelength λ and frequency ν incident on a photo-cathode

Can tune I, f, λ

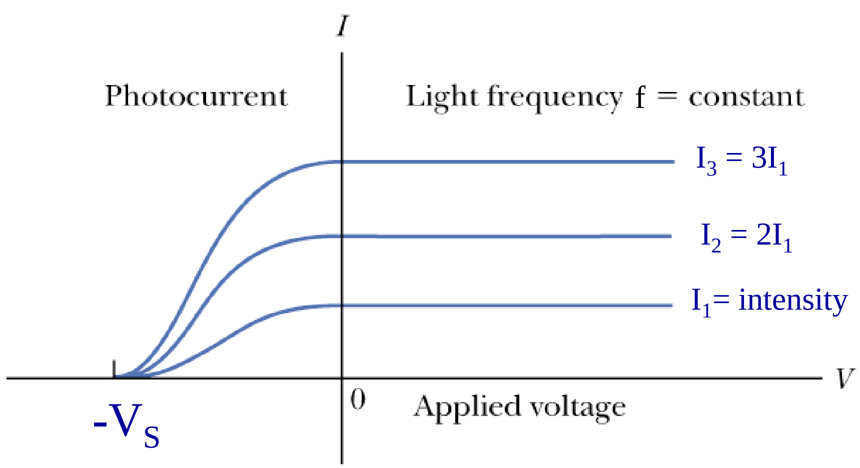


Measure characteristics of current in the circuit as a fn of I, f, λ

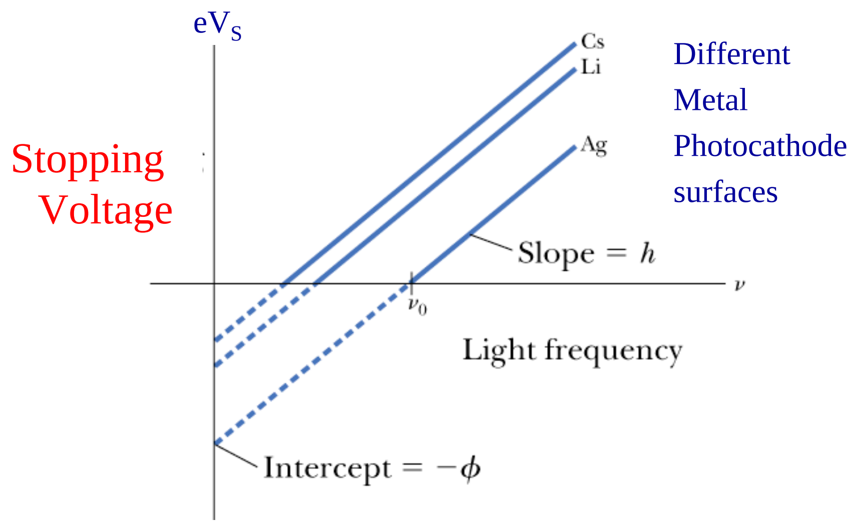
Photo Electric Effect: Measurable Properties

- 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
    - **$K_{MAX} = eV_S$ (V_S = Stopping voltage)**
    - **Stopping voltage → no current flows**
- Effect of different types of photo-cathode metal
- Time between shining light and first sign of photo-current in the circuit

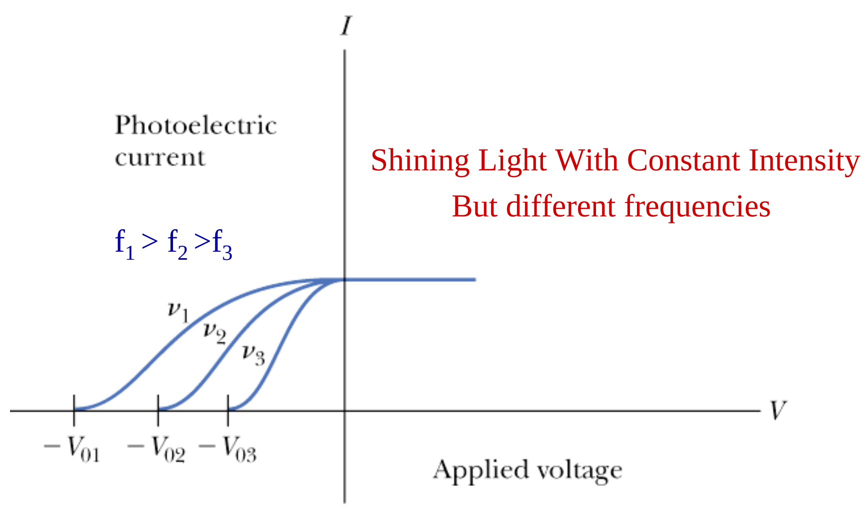
Observations : Current Vs Frequency of Incident Light



Stopping Voltage V_s Vs Incident Light Frequency



Retarding Potential Vs Light Frequency



Conclusions from the Experimental Observation

- Max Kinetic energy K_{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 !