PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

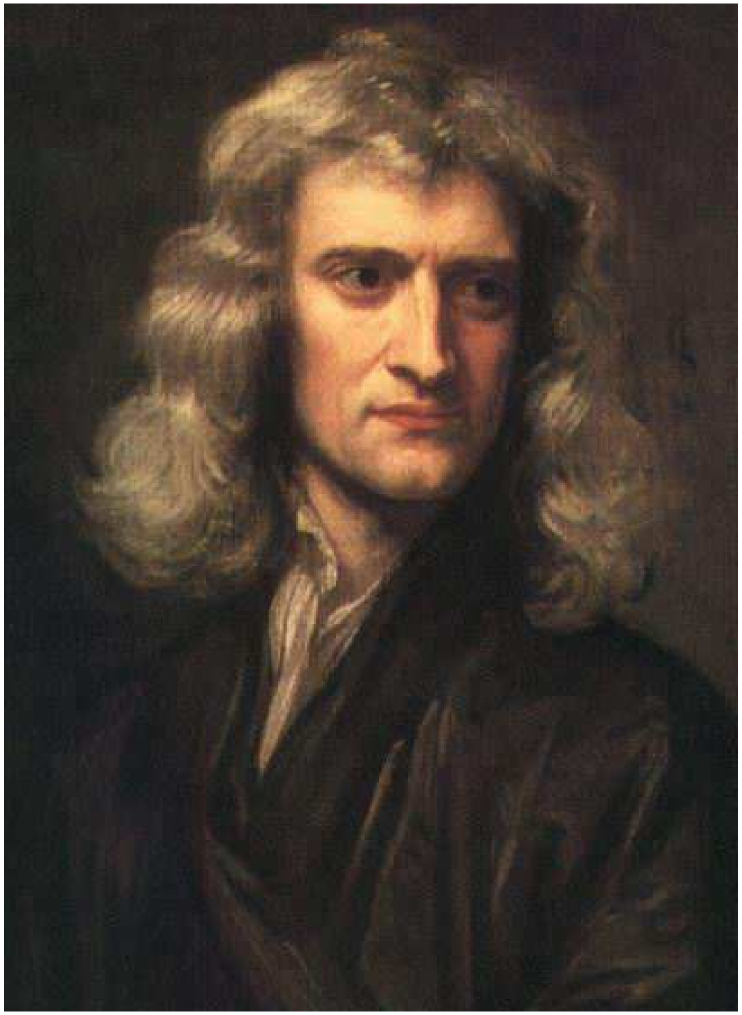
Radioactivity and Ionizing Radiation

QuarkNet

summer workshop

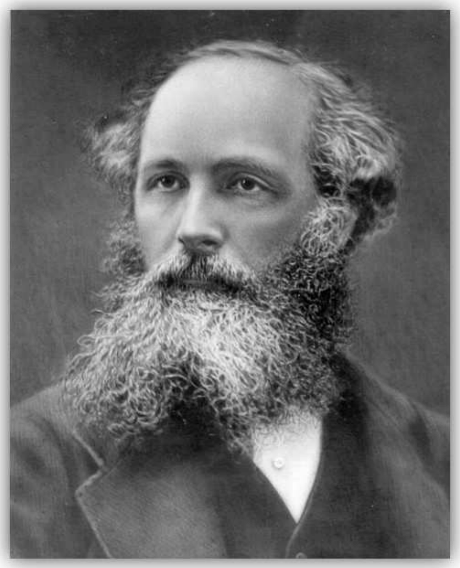
June 24-28, 2013

“Recent” History



- Most natural phenomena can be explained by a small number of simple rules.
- You can determine what these rules are by *observation* and by doing *experiments*.
- This is how science has progressed since the 1700’s.

Maxwell's Equations (1864)



$$\oint_S \hat{\boldsymbol{n}} \cdot \vec{\boldsymbol{E}}\, d\boldsymbol{A} = \frac{\boldsymbol{Q_{inside}}}{\boldsymbol{\epsilon_0}}$$

$$\oint_S \hat{\boldsymbol{n}} \cdot \vec{\boldsymbol{B}}\, d\boldsymbol{A} = \boldsymbol{0}$$

$$\oint_C \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{\ell}} = -\frac{d\boldsymbol{\phi_m}}{d\boldsymbol{t}}$$

$$\oint_C \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{\ell}} = \boldsymbol{\mu_0 I} + \boldsymbol{\mu_0 \varepsilon_0} \frac{d\boldsymbol{\phi_e}}{d\boldsymbol{t}}$$

A solution to these equations in the absence of sources corresponded to oscillating $\vec{\boldsymbol{E}}$ and $\vec{\boldsymbol{B}}$ fields propagating at the speed of light.

Discovery of Radio Waves

ELECTRIC WAVES

BEING

RESEARCHES ON THE PROPAGATION OF ELECTRIC
ACTION WITH FINITE VELOCITY
THROUGH SPACE

BY

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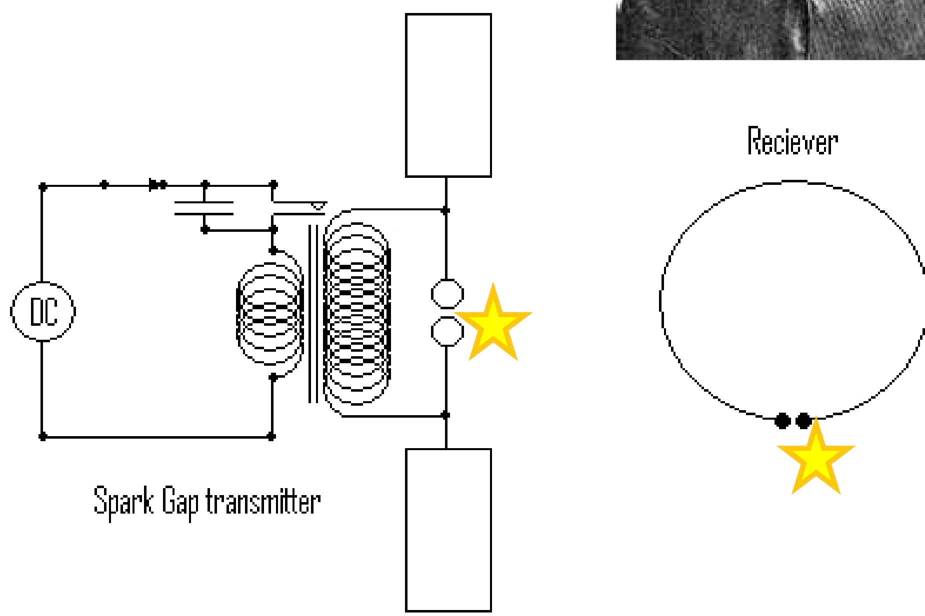
AUTHORISED ENGLISH TRANSLATION

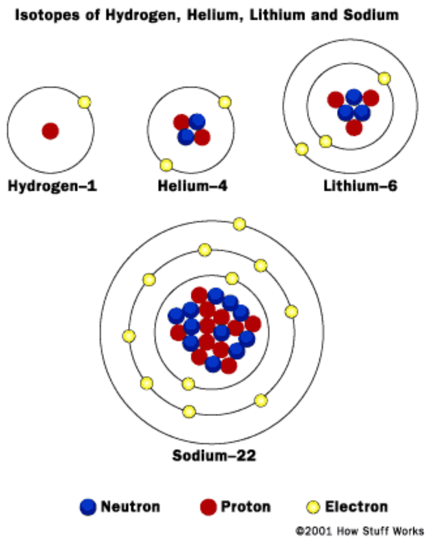
BY D. E. JONES, B.Sc.
DIRECTOR OF TECHNICAL EDUCATION TO THE STAFFORDSHIRE COUNTY COUNCIL
LATELY PROFESSOR OF PHYSICS IN THE UNIVERSITY COLLEGE OF WALES, ABERYSTWYTH

WITH A PREFACE BY LORD KELVIN, LL.D., D.C.L.
PRESIDENT OF THE ROYAL SOCIETY, PROFESSOR OF NATURAL PHILOSOPHY
IN THE UNIVERSITY OF GLASGOW, AND FELLOW OF ST. PETER'S
COLLEGE, CAMBRIDGE

London
MACMILLAN AND CO.
AND NEW YORK
1893



More Recent History



- Nils Bohr described atomic structure using early concepts of Quantum Mechanics
- Albert Einstein extends the laws of classical mechanics to describe velocities that approach the speed of light.

All matter should obey the laws of quantum mechanics and special relativity.

The Birth of Particle Physics

- In 1896, Thompson showed that electrons were particles, not a fluid.

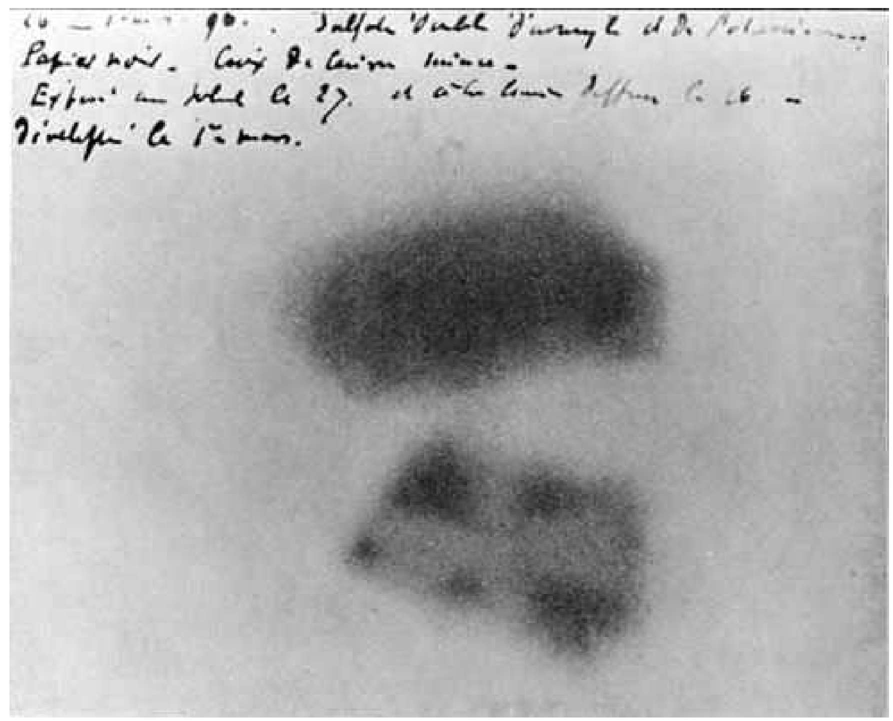
- In 1905, Einstein argued that photons behave like particles.

- In 1907, Rutherford showed that the mass of an atom was concentrated in a nucleus.

Particles that should obey the laws of quantum mechanics and relativity.

Something Totally New

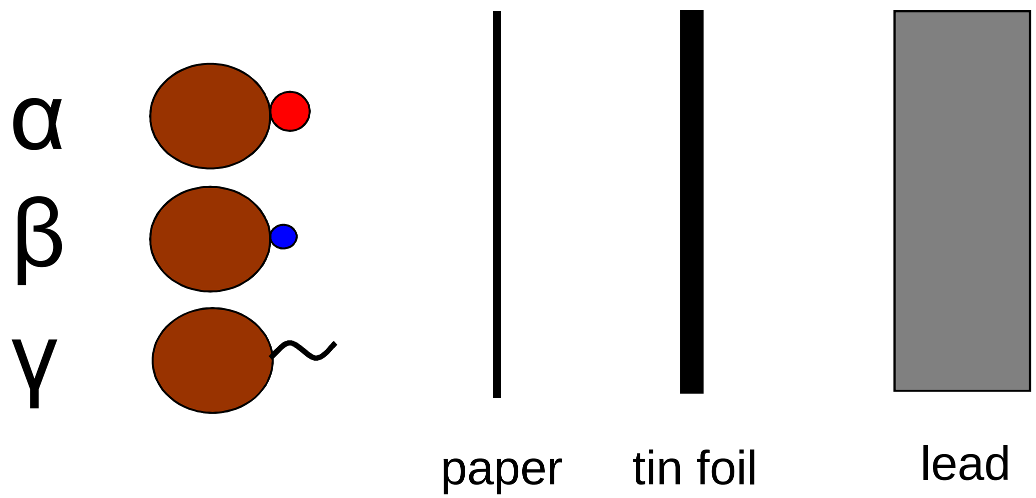
- In 1896, Becquerel discovers "uranium rays":



This did not correspond to any known type of "particle". It was sort of like x-rays, but the source of their energy was unclear.

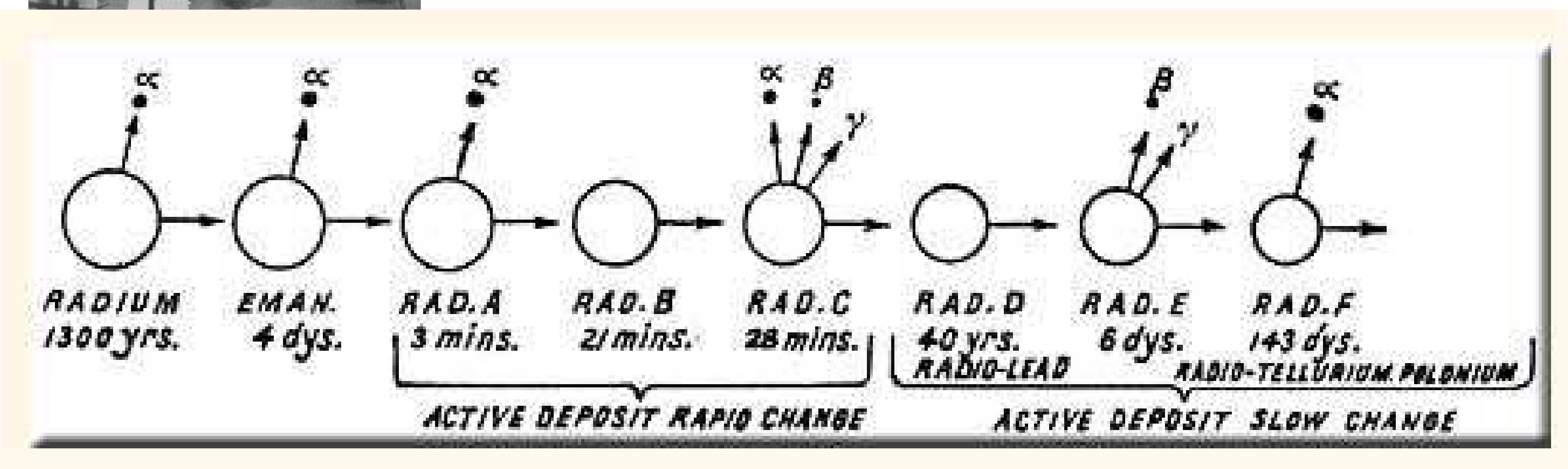
Something Totally New

- Rutherford classifies types of radiation:



Something Totally New

- Marie Curie determines that radioactivity has nothing to do with chemistry...
- Nobel prizes in 1903 *and* 1911!



“Rays” are particles

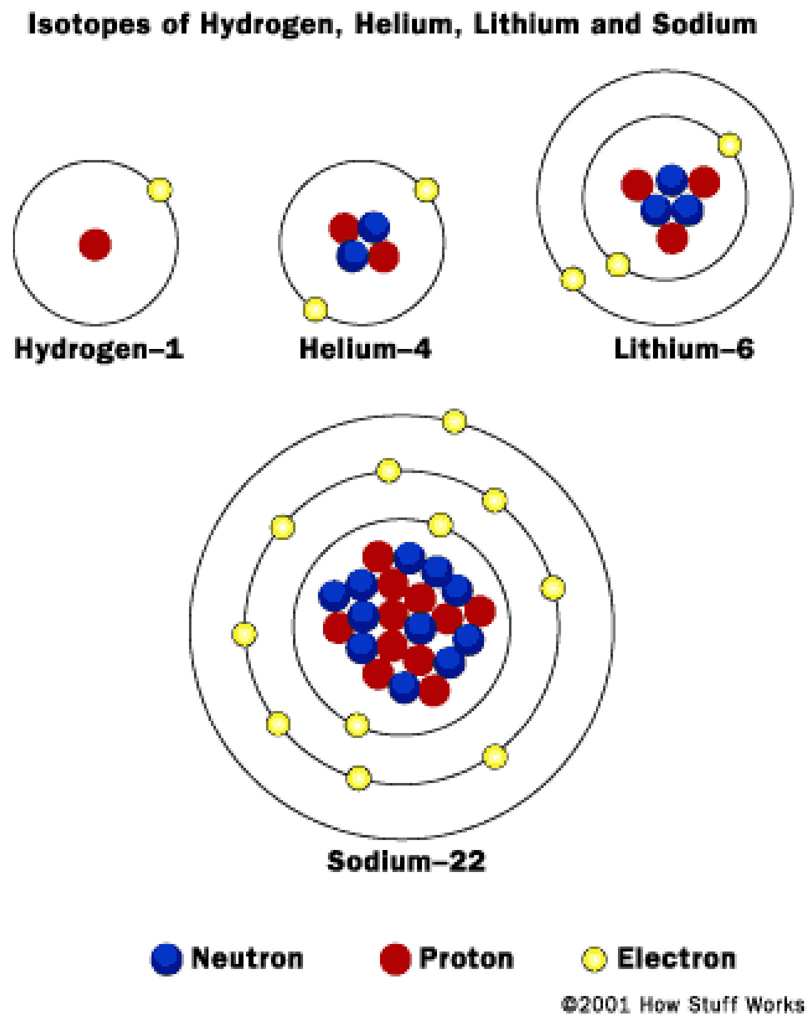
- The α-ray is just a helium nucleus – a very stable configuration of 2 protons and 2 neutrons.
- A β-ray is just an electron – but it is emitted from the nucleus with a lot of energy
- A γ-ray is just a photon – but it is also emitted from the nucleus with a lot of energy

Detecting Ionizing Radiation

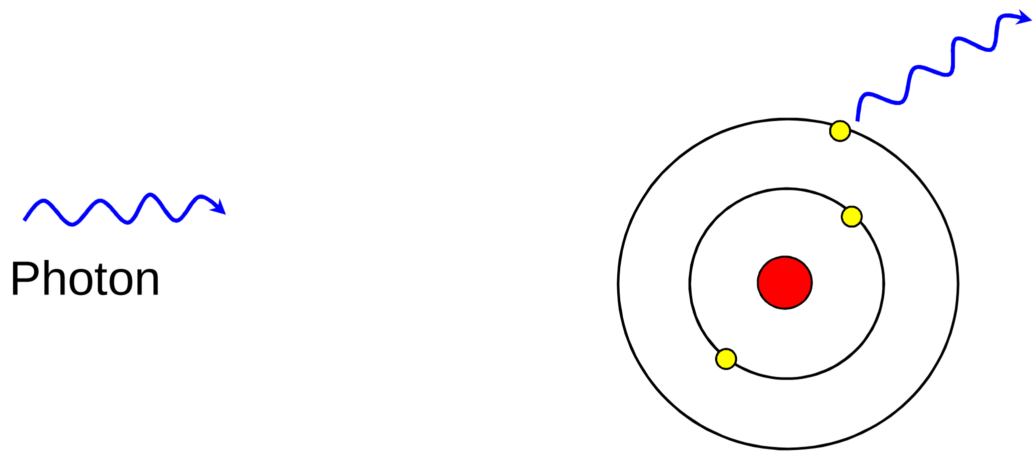
- We can only detect “rays” when they deposit energy in a medium that induces an observable change
  - Break chemical bonds, initiating chemical reactions (for example, exposing photographic film)
  - Ionize material, liberating mobile charge carriers
- Particles with electric charge (α and β) have electric fields around them that extend over lots of electrons in the medium
- Photons have no electric charge so they only have “short range” interactions.

Bohr’s Model for Atomic Structure

Nils Bohr, 1885-1962



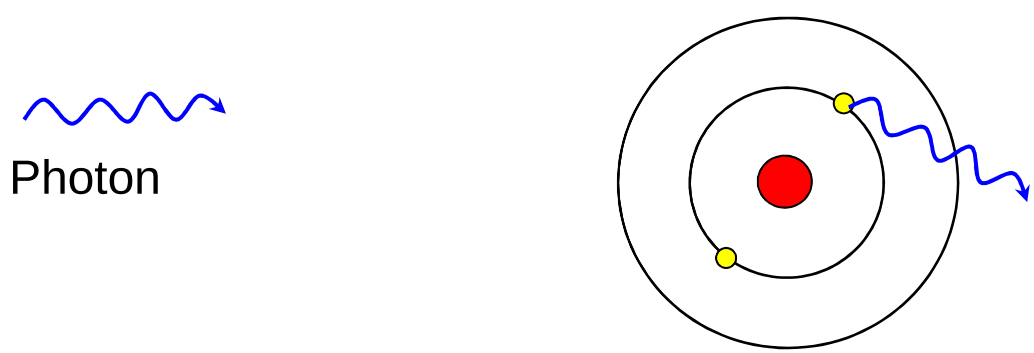
Photons Interacting with Atomic Electrons



The photon is absorbed, increasing the energy of the atom.

This energy is later released by the emission of another photon.

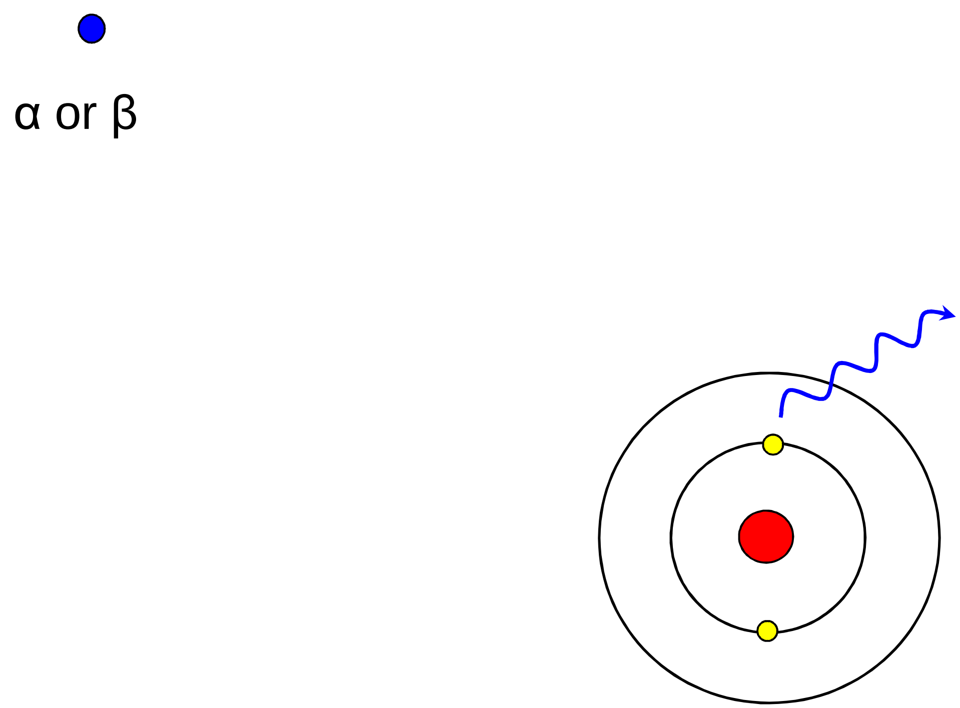
Photons Interacting with Atomic Electrons



The photon is interacts with the electron, ionizing the atom.

This electron loses energy by ionizing the medium.

Charged Particle Interacting with Atomic Electrons

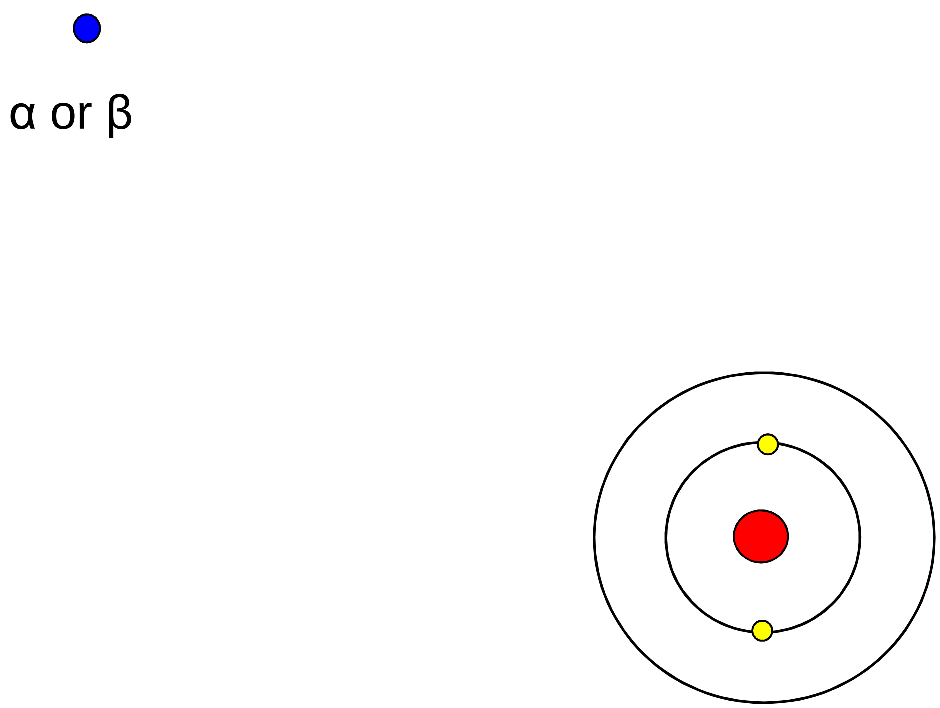


The electric field of the α or β ray transfers energy to the atom.

This energy is later released by the emission of a photon.

(this animation does not accurately reflect the quantum mechanical nature of this process)

Charged Particle Interacting with Atomic Electrons



The α or β transfers enough energy to the electron to ionize the atom.

The electron then loses its energy in the detector material and is eventually reabsorbed.

Energy Units

- We like to use eV, keV, MeV, GeV to measure energy
  - This is the energy gained by an electron as it moves through a potential difference of $1, 10^3, 10^6, 10^9$ volts
- We also like to measure mass in energy units:

$$E = mc^2 \text{ so } m = E/c^2$$

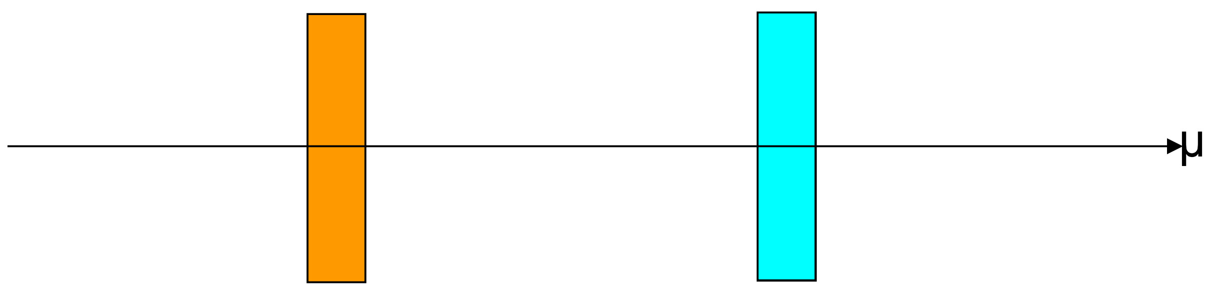
- An electron has a mass of about $0.5\ MeV/c^2$
- A proton has a mass of about $1\ GeV/c^2$
- Typical energies released in nuclear decays are hundreds of keV to a few MeV

How Fast is Energy Lost?

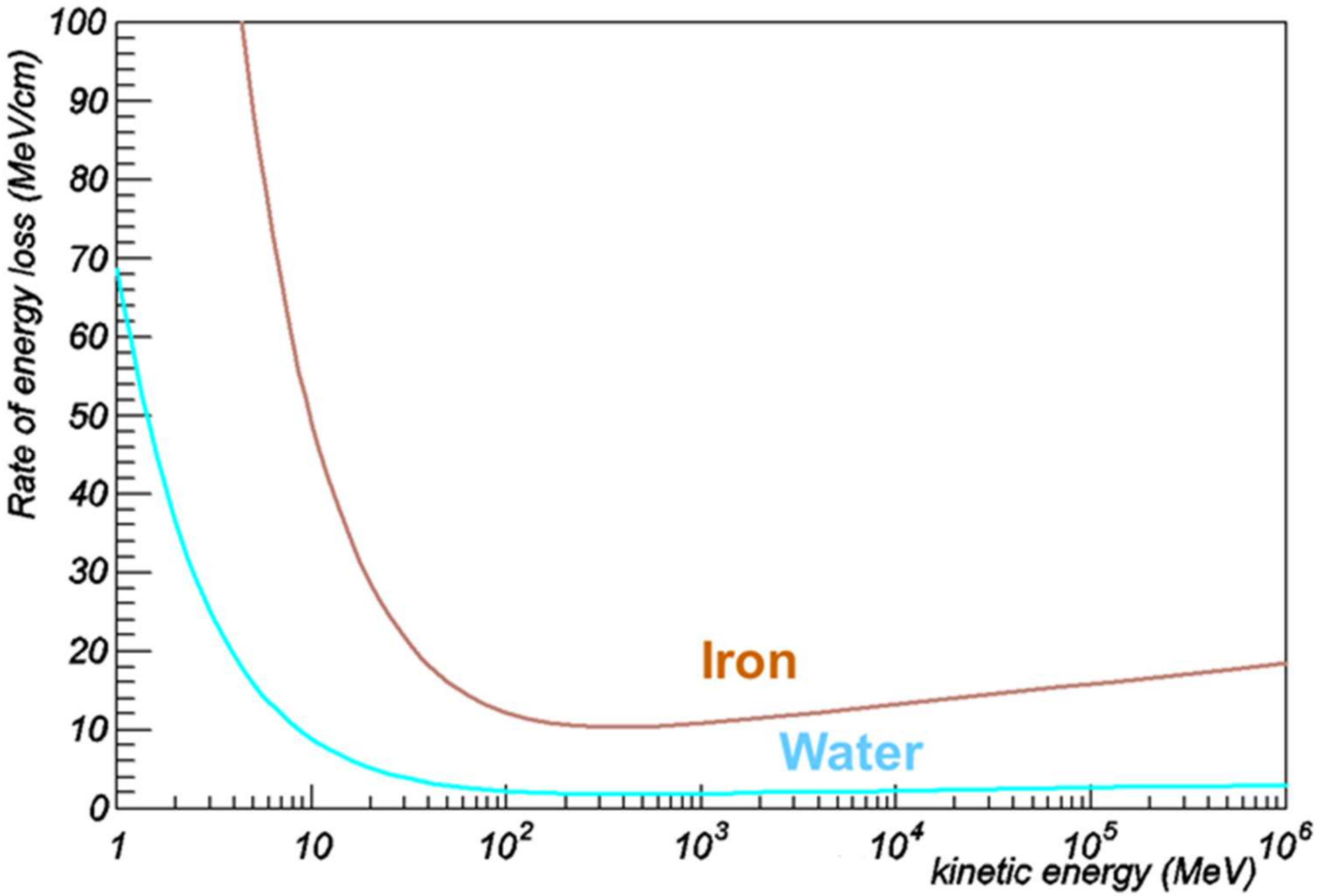
- Low energies, less than 1 MeV
  - Electric field increased by relativistic Lorentz effects.
- Moderate energies, 1 MeV to 1 GeV
  - As velocity increases, the interaction time decreases.
- At high energies, greater than 1 GeV
  - Although energy increases, the velocity plateaus at the speed of light.

The Universal Energy Loss Curve

- Energy loss depends ONLY on:
  - Charge of the incident particle (squared)
  - Velocity of incident particle
  - Density of electrons in the material
  - Depends weakly on the type of material
- For example, consider a muon that passes through a thin piece of iron or water:

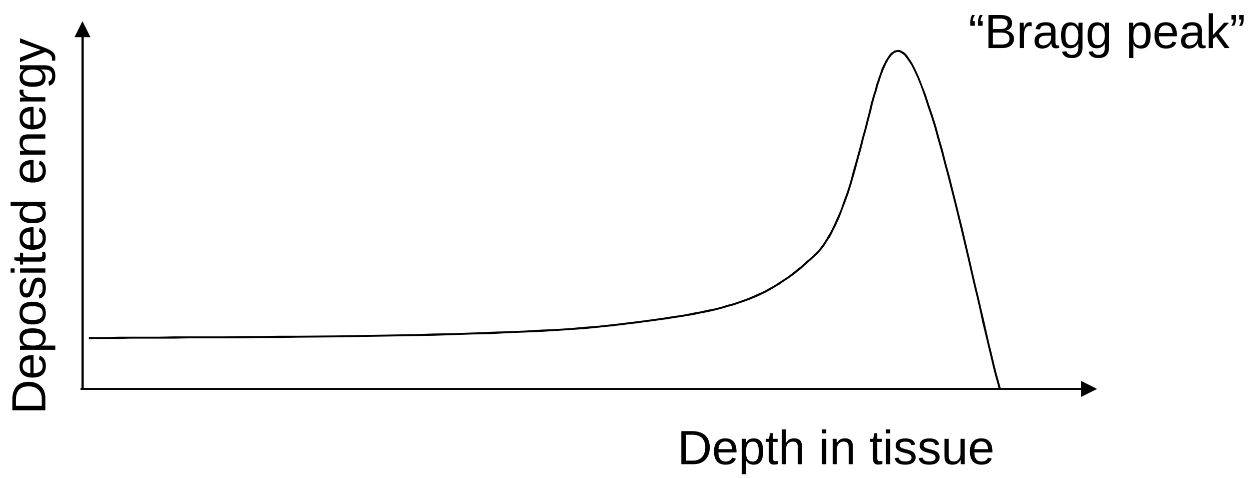


Universal Energy Loss Curve



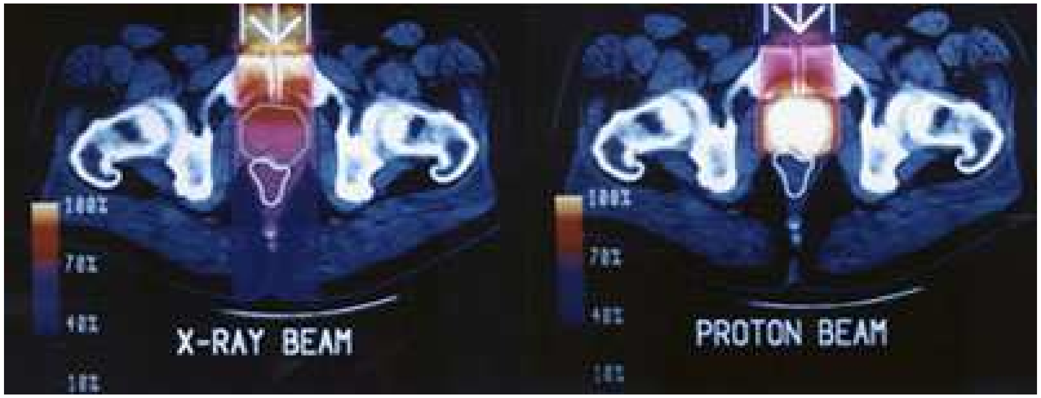
Apply What You Just Learned

- In 1946, Robert Rathbun Wilson recognized that protons could be used for cancer therapy:



- Low energy charged particles deposit most of their energy at the end of their path through some material.

Proton Therapy



Detecting Ionizing Radiation

Geiger Counters

Ion Chambers

Wire Chambers

GEM Detectors

An electric field does WORK on ionized gas atoms to produce a voltage pulse.

Solid State Detectors

Radiation creates electron/hole pairs in silicon or germanium that allow a current to flow.

Photographic Film

Photographic Emulsion

Ionization initiates a chemical reaction.

Cloud Chamber

Bubble Chamber

Ionization initiates a physical change in a gas or liquid.

Crystal Scintillator

Organic Scintillator

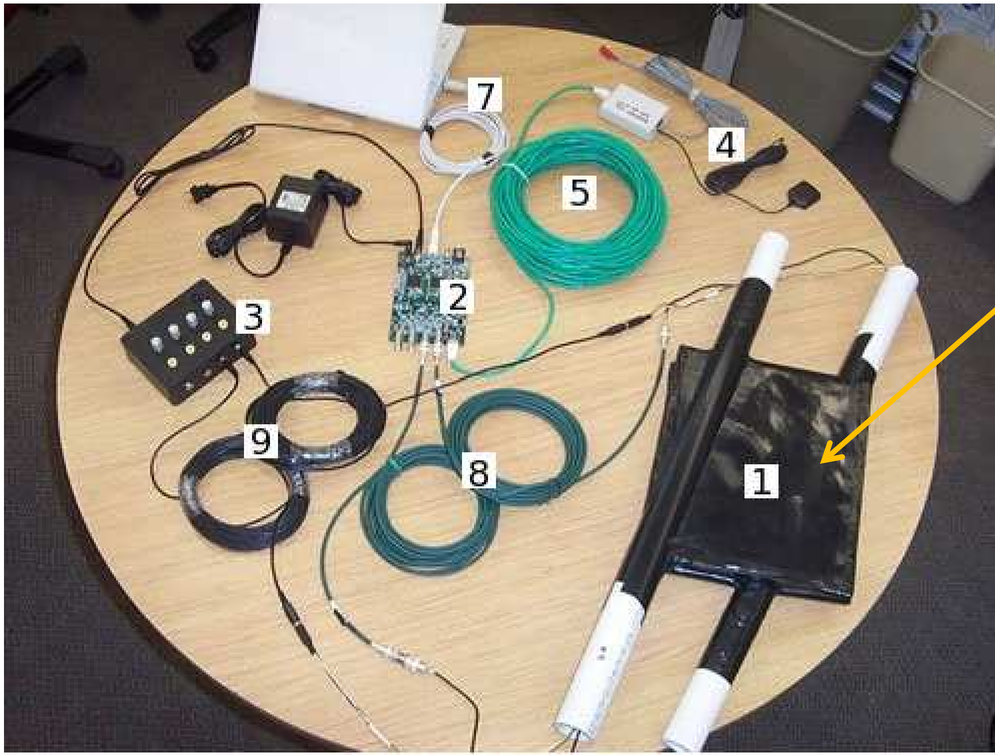
Recombination of electrons and ions produces light!

Plastic Scintillator

Plastic Scintillator

- See, for example, Saint-Gobain, Inc.
- Clear plastic traps light by total internal reflection.
- Doped with a secret chemical that emits light when ionized, but does not re-absorb it.
- Easy to cut, polish, bend, glue…
- How much light is produced?
  - A typical charged particle travelling through 1 cm of plastic scintillator might produce about a thousand photons
  - Most of them would be blue
  - They bounce around inside the scintillator until they either escape or are absorbed
- Usually wrapped in tin foil or white paper and then in black plastic or opaque paper to keep other light out.

The Cosmic Ray Detector



Plastic scintillator wrapped in white paper and black plastic.

- Next… how do you detect the light?
  - A few hundred photons at a time…

Photomultiplier Tubes

- Photoelectric Effect:
  - A photon kicks an electron out of the surface of a metal (usually an alkali like K or Cs)
- A photoelectron is accelerated in an electric field
  - If its in a vacuum it can gain a lot of energy
- If it hits a metal surface, it might eject another electron
  - If the metal is coated with a secret chemical it might eject two or three…
- These can be accelerated and can eject more, etc…
- The multiplication factor (we call this the "gain") can be large: $3^{12} = 0.5 \times 10^6$
- The pulses are FAST… typically lasting about 50 ns or less.

Photomultiplier Tubes

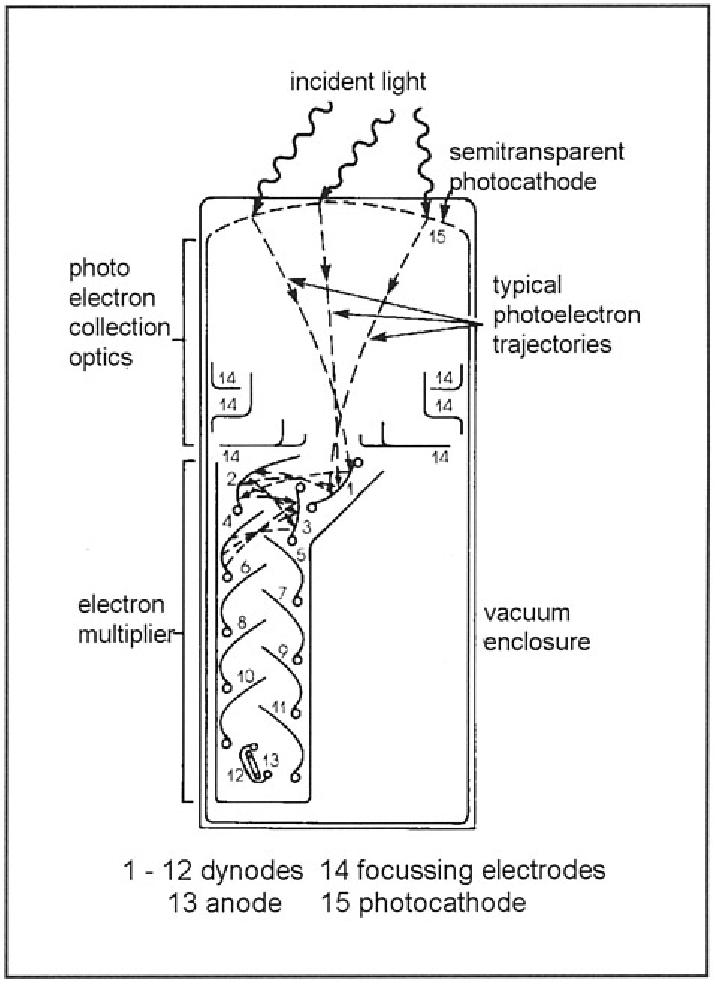
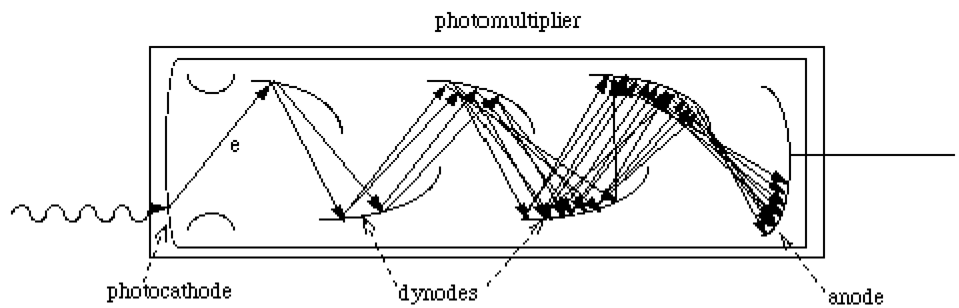


Fig. 4.1 ***Schematic of a photomultiplier tube.***



The electric field between the anode and the last dynode accelerates many, many electrons: it does WORK on them.

This induces a voltage pulse at the anode.

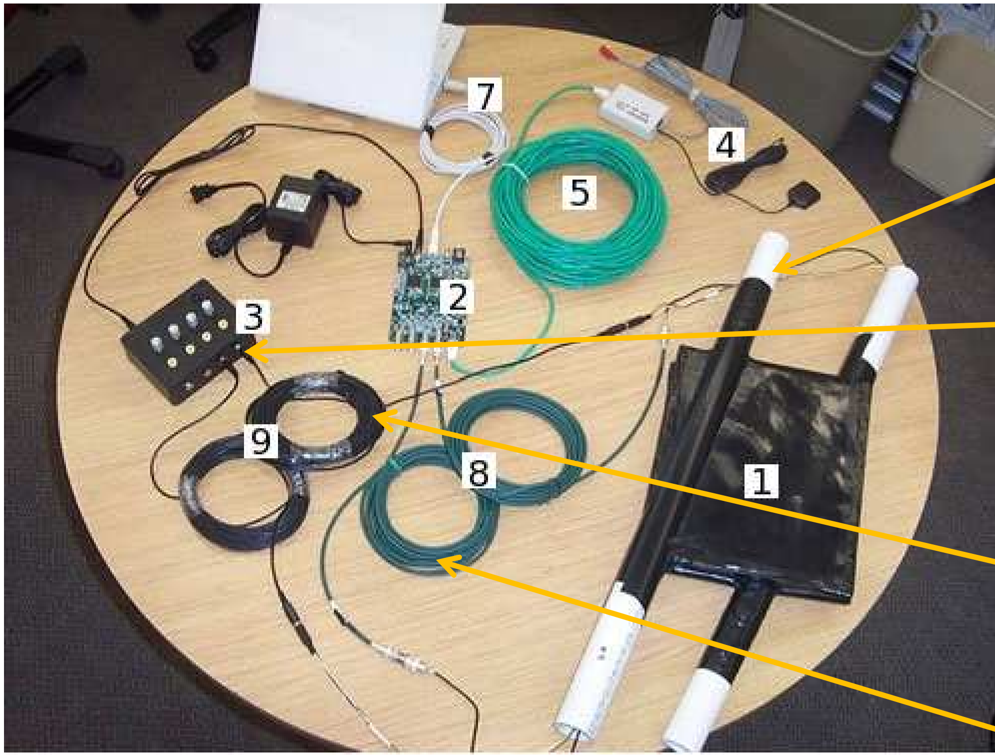
A stronger electric field produces more secondary electrons, and produces a bigger pulse.

Technical point: How do you generate the right voltages on each of the dynodes? Starting from only 5 volts?

Photomultiplier Tubes

- The electrons in the photocathode don't need much energy to escape the metal
  - That's why a photon can knock them out
- Sometimes they get energy from other sources
  - Thermal energy, radioactive decay (eg, potassium-40) , cosmic rays
- These produce pulses at *random* times
- We call these pulses "noise" or "dark current"
- More voltage usually means more noise…

The Cosmic Ray Detector



Photomultiplier tubes (PMT's) are inside the white plastic things.

This box lets you adjust the voltage on the PMT's.

Two cables come out:

- One set of wires provides power to the PMT and sets the voltage
- The other cable carries the signal to the electronics.

- Next, how do you detect the voltage pulses?

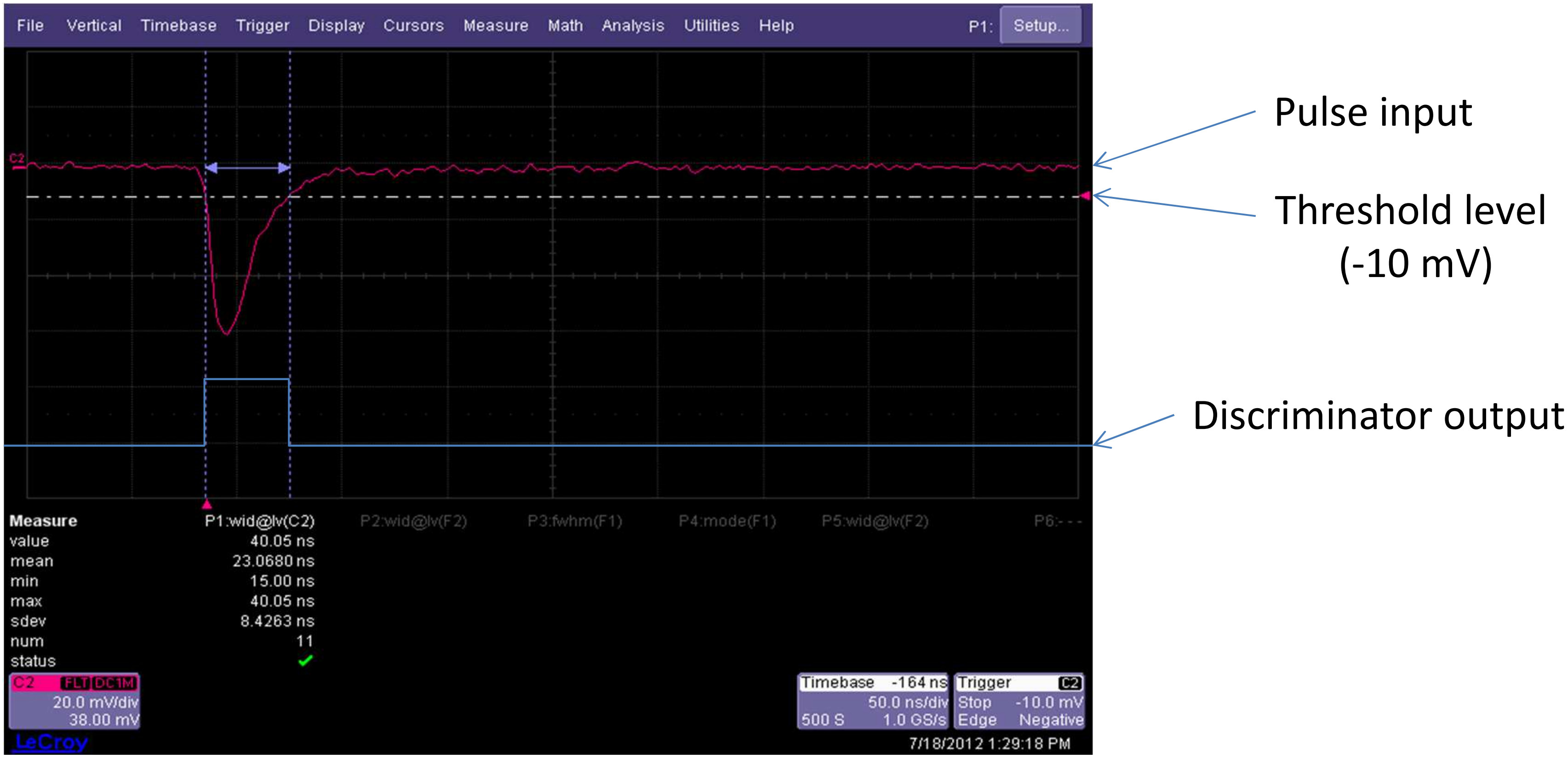
Cables

- Coaxial cables carry the signals from the PMT to the DAQ board with very little distortion
  - Exactly the same physics as a pulse propagating down a rope…
- Speed of signal propagation: ~20 cm/ns
  - Two thirds the speed of light
- The black cables are about 50 feet long
  - Propagation delay is about 75 ns
- Sometimes, some fraction of the energy in the pulse is reflected from connectors in the cable…
  - Would this ever show up as a second pulse?
  - If it did, when would it arrive?

Discriminator

- A “discriminator” is an electronic circuit that compares an analog input signal to a reference voltage
  - You can usually adjust the reference voltage
- The output is a digital logic level
  - zero volts when $V_{in} < V_{ref}$
  - 3.3 volts when $V_{in} > V_{ref}$
- They usually switch very quickly.
- You can see this using an oscilloscope…

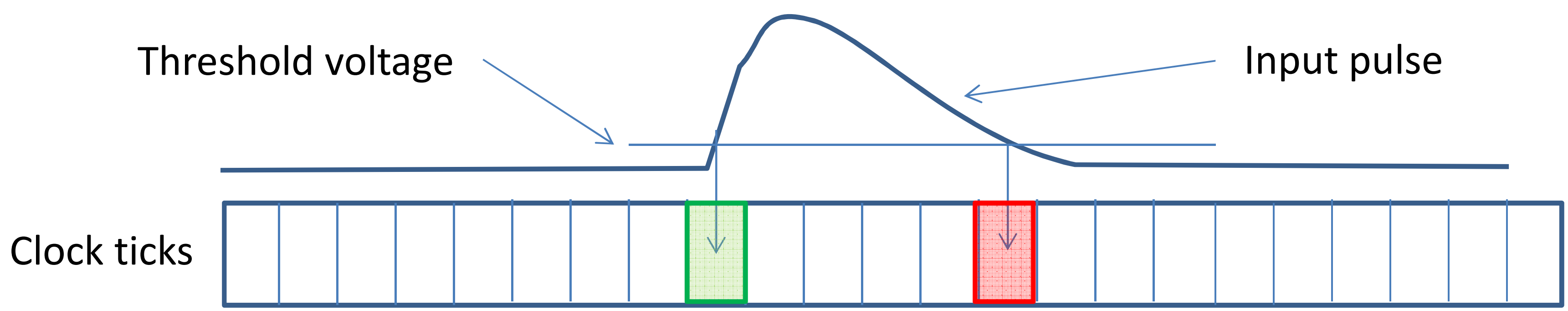
Example



- Once you have a digital logic pulse, you can analyze it using digital electronics (a “computer”).

Detector Electronics

- Measures the times of the leading and trailing edge of the discriminator pulses.
  - The difference is called “Time Over Threshold”
  - Larger pulses have a larger time-over-threshold
  - We don’t measure the pulse height directly
- The electronics has an internal clock that “ticks” every 1.25 ns
  - This determines how precisely times can be measured



What Can We Measure So Far?

- Two main types of measurements:
  - Count rates: how many leading edges in a fixed period of time (eg, 1 minute, 5 minutes, etc…)
  - Times of leading and trailing edges
- Important problem:
  - Do you know that each pulse is from something you are trying to detect?
  - It might be from noise in the PMT…
  - How can we tell the difference?
- We can’t read every pulse and analyze all the data fast enough.
- Solution: ***a coincidence trigger!***

Tomorrow

- With this understanding of how the detectors work, we will tune them up for optimal performance!
- We will adjust the high voltage to see how it affects the amount of noise…
- We will make a discovery worthy of a Nobel prize (just 100 years late).