Gamma Ray Spectroscopy

Week of Feb. 1, 2010

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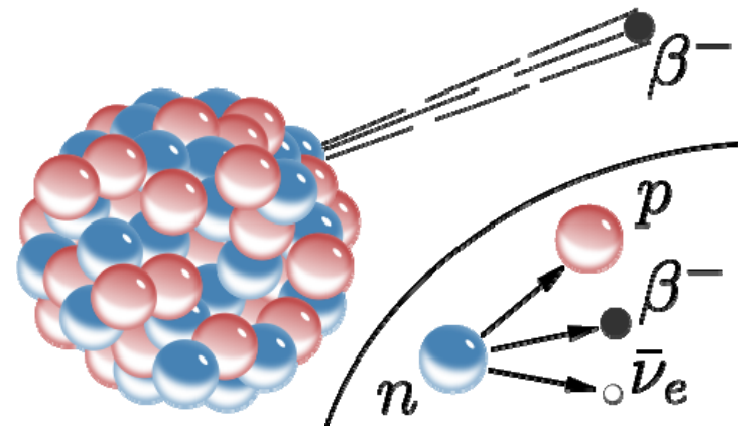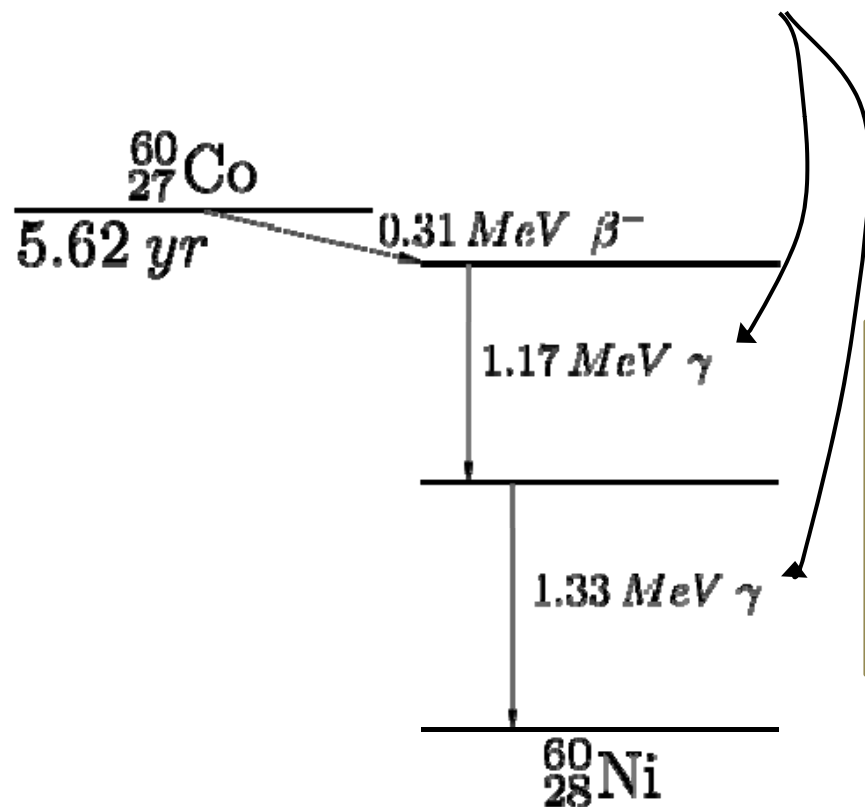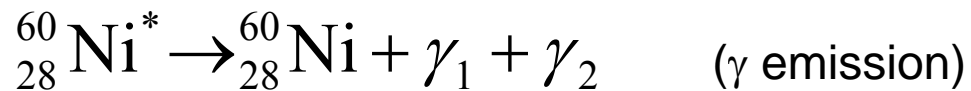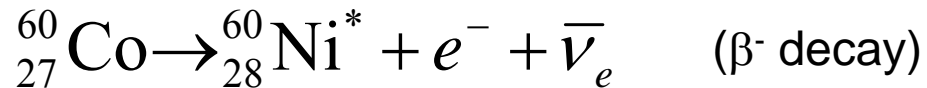**Modern Physics Laboratory
(Physics 6180/7180)**

The University of Toledo
Instructor: Randy Ellingson

Gamma Ray Production: Co-60

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni}^{*} + e^{-} + \overline{\nu}_{e}$$ (β⁻ decay)

$$^{60}_{28}\text{Ni}^{*} \rightarrow {}^{60}_{28}\text{Ni} + \gamma_{1} + \gamma_{2}$$ (γ emission)

$^{60}_{27}\text{Co}$
5.62 yr   0.31 MeV β⁻

1.17 MeV γ

1.33 MeV γ

$^{60}_{28}\text{Ni}$

β⁻

p

β⁻

n $\overline{\nu}_{e}$

In β⁻ decay, the weak interaction converts a neutron (n) into a proton (p) while emitting an electron (e⁻) and an electron antineutrino (ν_{e}):

$$\text{n} \rightarrow \text{p} + \text{e}^{-} + \overline{\nu}_{e}$$

Gamma Ray Spectroscopy

Gamma Rays?

High-frequency electromagnetic radiation.

Typical <u>visible light</u> frequency:

$\nu = c/\lambda = (3 \times 10^8 \text{ m/s})/(500 \times 10^{-9} \text{ m})$,

$\nu = 6 \times 10^{14} \text{ s}^{-1}$ (600 THz).

Typical gamma ray frequency: $\nu > 10^{19} \text{ s}^{-1}$

→ $\lambda < c/10^{19} \text{ s}^{-1}$ → $\lambda < 3 \times 10^{-11}$ m, or $\lambda < 30$ pm.

Energy for $\lambda = 30$ pm is ~40 keV, so typical gamma ray energies exceed ~50 keV (almost always < 10 MeV).

Note overlap between gamma ray and X-ray energies (e.g., 140 keV). X-rays are emitted by electrons outside the nucleus, while gamma rays are specifically emitted by the nucleus (that is, produced by gamma decay).

Gamma rays are produced by sub-atomic particle interactions such as electron-positron annihilation, neutral pion decay, radioactive decay, fusion, fission or inverse Compton scattering in astrophysical processes.
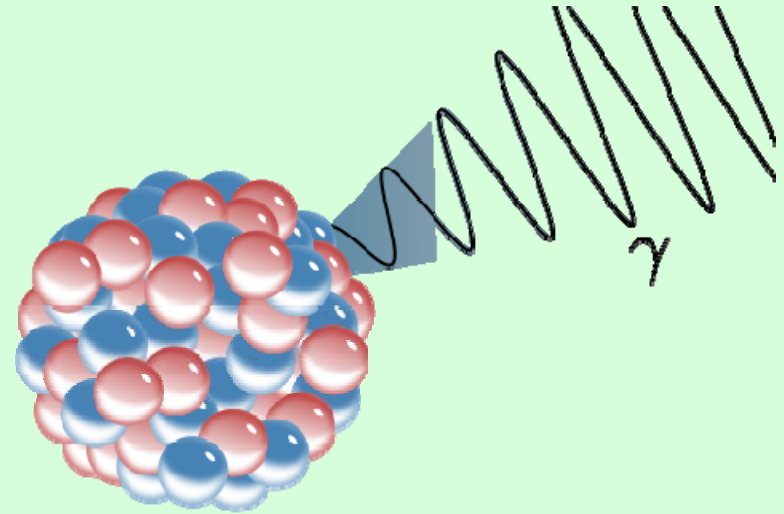
Health Effects of Gamma Rays

Gamma Rays – Health Effects

A health hazard since they result in ionization when interacting with living tissue (ionizing radiation).

Effects of ionizing radiation on living tissue depends on the amount of energy deposited rather than the charge generated in ionization. Total energy deposited is the **absorbed dose**:

The gray (Gy) has units of (J/kg) and is the SI unit of *absorbed dose*: given by the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.

Equivalent dose? Measures the biological effect of radiation on human tissue. For gamma rays, how does the *equivalent dose* differ from *absorbed dose*?

Shielding: Large amounts of mass. Most important: the total "areal mass density" in the path of the gamma rays. Pb shields only slightly better (20-30%) than an equal mass of another shielding material.

Note that the density (ρ) of lead is 11.35 g/cm^3; $\rho \cong 0.95$ g/cm^3 for polyethylene.

Gamma ray interactions with matter

Gamma Ray – matter interaction

When a gamma ray passes through matter, the probability for absorption in a thin layer is proportional to the thickness of that layer. This leads to an exponential decrease of intensity with thickness.

$$I(d) = I_0 e^{-\mu d}$$

Here $\mu = n\sigma$ is the linear attenuation coefficient (an absorption coefficient), measured in cm^{-1}, n the number of atoms per cm^3 in the material, σ the absorption cross section in cm^2 and d the thickness of material in cm.
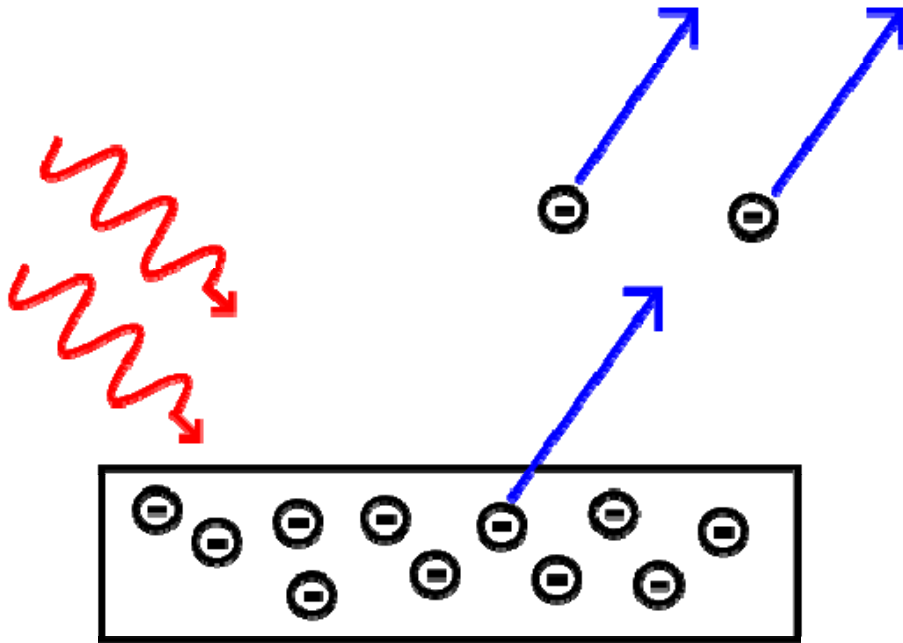
Note: the probability that a particle will travel no farther than distance d is given by $1-e^{-\mu d}$.

μ depends on both the gamma ray energy as well as the atomic number of the absorber.

Linear attenuation coefficient for lead

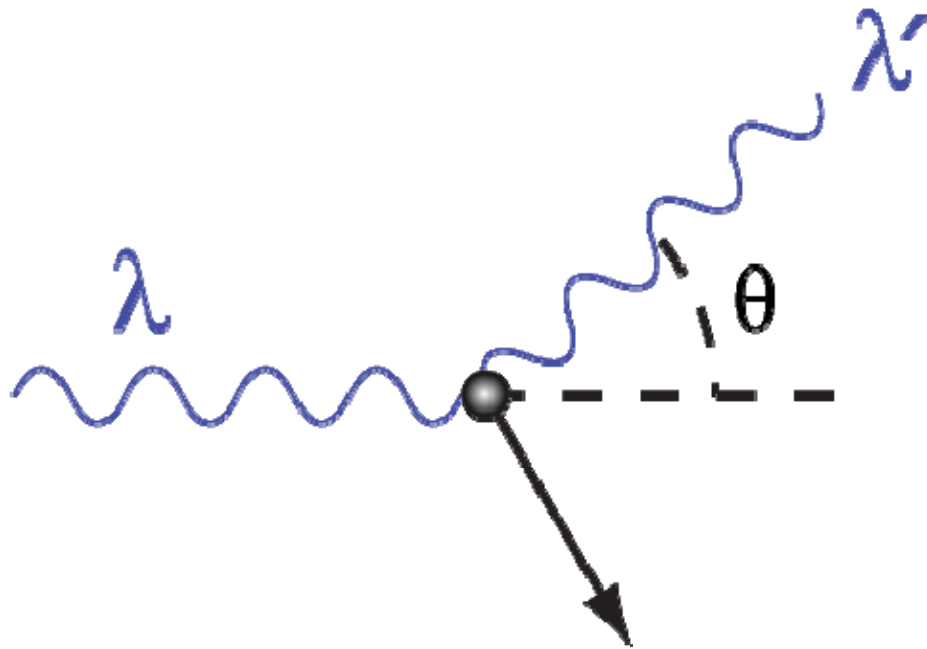From William J. Price, "Nuclear radiation Detection"
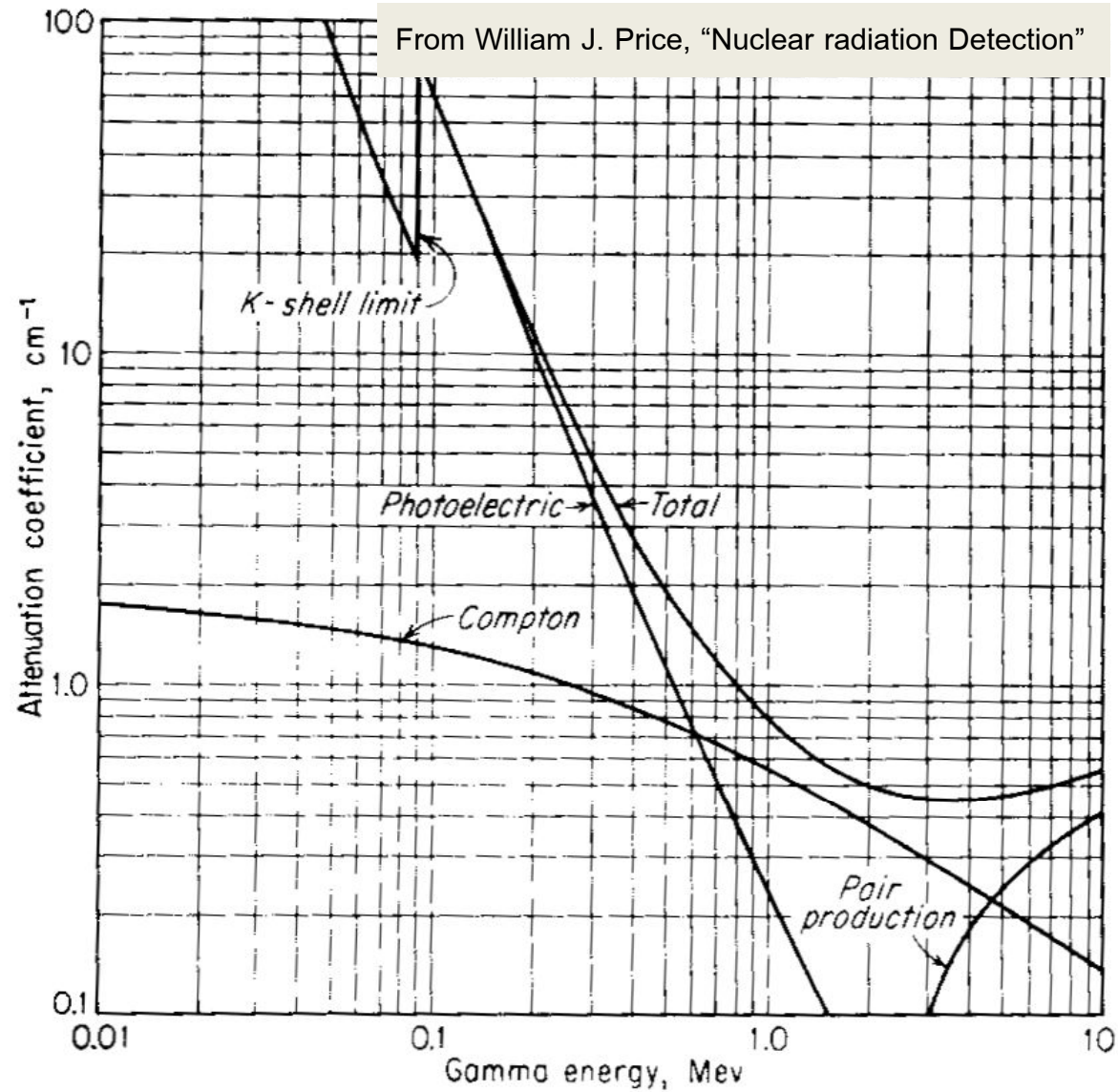
Photoelectric effect

- **Photoelectric effect:** A "gamma ray" photon can transfer its energy to an atomic electron and eject it from the atom by the photoelectric effect
- The electron ejected from the atom (the "photoelectron") ends up with a kinetic energy equal to the incident gamma photon's energy minus the binding energy of the electron. The gamma photon's energy is completely converted, and there is no residual photon.
- Photoelectric effect dominates the energy loss mechanisms gamma rays (and x-rays) with energies below 50 keV; importance falls off at higher energies.
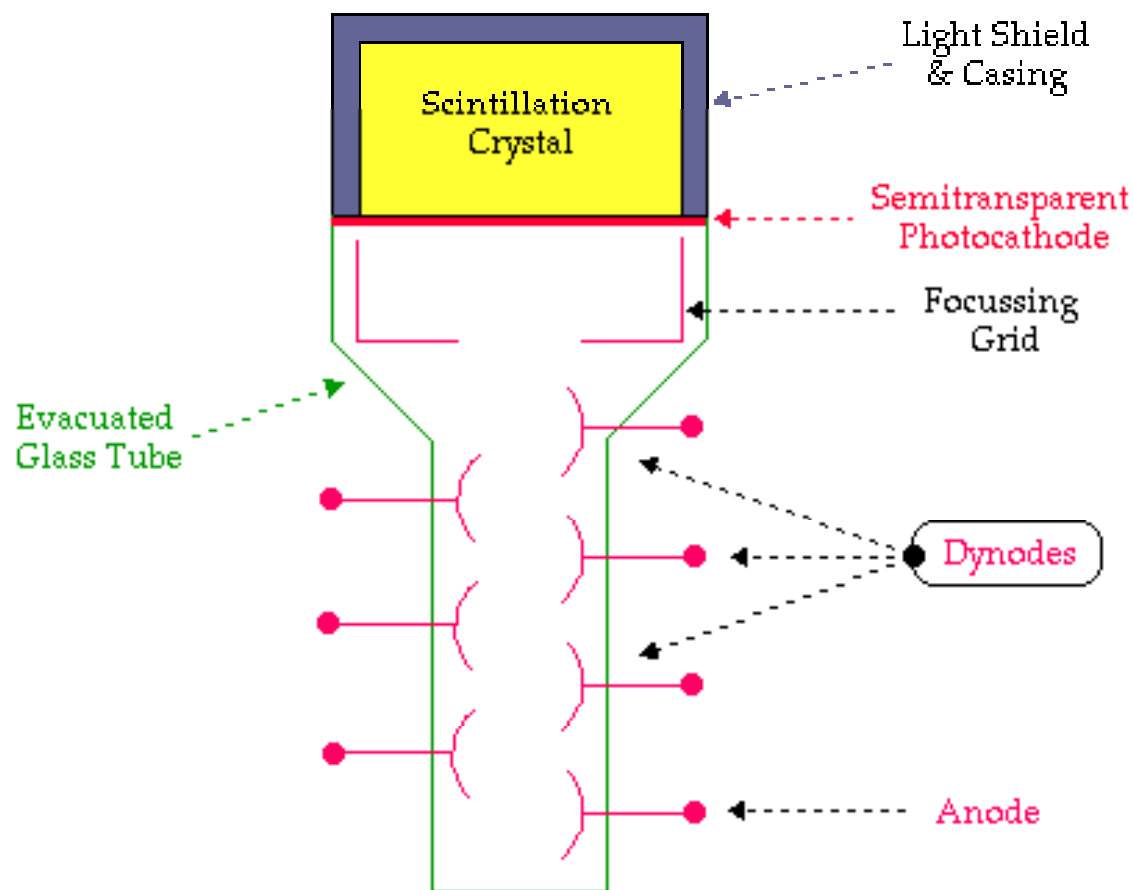
Compton Scattering of gamma rays

- **Compton scattering:** A Compton scattered gamma ray ejects an electron from an atom; in contrast to the photoelectric effect, Compton scattering results in a re-emitted gamma ray photon at some lower frequency and in a different direction. Based on energy dependences of the various gamma ray interactions, Compton scattering dominates for gamma photons in the energy range 100 keV to 10 MeV.
- Compton scattering depends weakly on the atomic number of the absorbing material, so while very dense shield material enables thinner shields, areal mass is the primary consideration in shielding.

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

Sodium Iodide scintillator + PMT

Light Shield & Casing

Scintillation Crystal

Semitransparent Photocathode

Focussing Grid

Evacuated Glass Tube

Dynodes

Anode

Public Domain: http://en.wikibooks.org/w/index.php?title=File:NM9_1.gif&filetimestamp=20060606092917

NaI:Tl emission following exposure to a ~ 300 R / hr x-ray field.

http://carlwillis.wordpress.com/2008/05/07/scintillation-crystals-and-x-rays/

Photomultiplier Tube (PMT)

- **Photomultiplier tube (PMT):** a PMT works on the principle of the *photoelectric effect*, in which an incident photon with sufficient energy frees an electron from a photocathode. PMTs multiply the current from incident light by as much as ~100 x 10^6 (gain), and can be used as single-photon detectors for very sensitive photon counting applications.

  Gain in a PMT follows from *secondary emission*, in which an energetic electron impacts an electrode, thereby freeing another electron to contribute to the current. The electrons are accelerated from electrode to electrode (called dynodes), and it is from this multi-state process that amplification (gain) occurs. PMTs can detect light in the ultraviolet (UV), visible (Vis), and near-infrared (NIR) spectral regions.
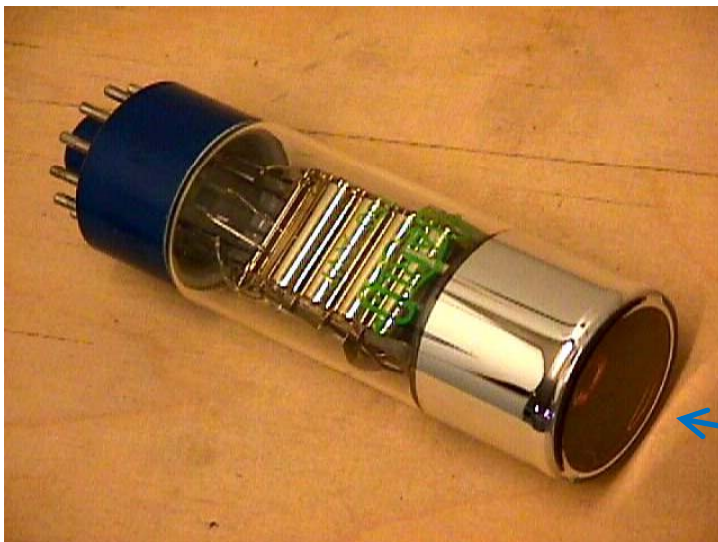
Typical PMT (end-on) detector.

Detector end

Lab Write-ups
(synopses or reports)

http://www.fringebloggers.com

- Show what you have learned – describe the experiment (background, what is measured, important steps, how things fit together, origins and magnitude of the uncertainties);

- Label your graphs carefully – ensure that the reader knows what is graphed. Include units on each axis label, and on other quantities.

- Internet age – *avoid plagiarism*: understand what you read, know the points you want to make, and restate the ideas in your own words. You'll learn more this way, and avoid potentially big problems.