University of Michigan
Physics 441-442: Advanced Laboratory
Notes on **"RADIOACTIVITY"**
January 2007

1. As usual in the lab, you are forced to learn in several categories at the same time. Your goals in this experiment are to

    - use a simple apparatus to detect something that you cannot otherwise see, and learn about it by inference
    - understand statistics and experimental uncertainties, in the context of a *counting experiment*
    - learn a bit about nuclear physics and the interaction of particles with matter

    The several categories of stuff to learn:

    Kinds of radiation: What are α, β, γ ? Read the Appendix to this note, and also in Knoll, Melissinos, or a Modern Physics text (Tipler, Serway, or Krane)

    The interaction of radiation with matter: α, β, γ have different interactions with matter, which affect how they are detected. γ 's interact once, *via* Compton scattering or photoelectric effect; this all-or-nothing interaction leads to the exponential range, characterized by an *attenuation coefficient.* Work this out. $\alpha' s$ and $\beta' s$ are charged, and interact by continuous energy loss, leading to a finite range. See Knoll, or Melissinos 5.2. (BTW, in case you think this is just some technical lab detail, note that the energy loss of charged particles was first worked out by N. Bohr, and he continued to work on it throughout his life. And: the nice discussion in Melissinos was cribbed from the lecture notes of E. Fermi!)

    Gieger-Muller counter: This is your transducer. It is not a black box. There is a whole physics behind the detection of ionization. See Melissinos 5.3. Understand the regimes of response as a function of high voltage.

    Statistics: If the bus comes once every 20 minutes, what is the probability that two busses will come together after you have been waiting 40 minutes? This can be calculated using the *Poisson* distribution, which describes the probability of finding r occurances of some event in an interval in time or space, given the average number μ per interval. It is the typical characterization for a *counting experiment.* In the limit where μ is large, the Poisson distribution becomes a Gaussian (the "bell curve"). You need to know these elements of statistics, and radioactive decay is a classic example. See Bevington, Taylor, Melissinos 10.5, Knoll, or the lab links on statistics.

    Experimental Uncertainty: A measurement is meaningless without an idea of how seriously one should take it. *THIS IS THE LAW*. Learn how to assign uncertainties. There are some quantitative techniques, see Bevington, Taylor, or Melissinos 10.4, but this is also an art form, if necessary a good guess at the error is way better than nothing.

2. If you want this to be a rewarding experience, you *must* consult outside materials. The lab write-up is just a rough guide, it’s up to you to dig in and learn about all the interesting details “under the hood”.Yes there is going to be a lot to read. Did you want to learn something, or just fool around?

3. Comments on the write-up and procedure.

    a. The important physics behind the characteristic curve and signal shape for the Gieger counter is well described in Melissinos. Understand this stuff. However, this is not much more than a kind of calibration, get it over with quickly,so you can get on with the physics! Plot a few points in big steps to see where the turn on is. Focus on a few points near the turn-on, after you know where it is.
    b. Absorption: this is the most interesting part of the lab. Read up on this in references. Take big steps in relative absorbing thickness until you can see the effects. Plot ln(counts) vs thickness. Get the right number for the absorption length!
    c. Regarding solid angle: plot your data as N vs d^{-2}, you should get a straight line that degenerates at one end. Why? The slope is K’. Plotting with this trick to make things linear can be very revealing
    d. In “Counting Statistics”: can you see the difference between the Poisson and Gaussian regimes. Thus small μ in part 1, large μ in Part 2. Read Bevington!
    e. Deadtime is an interesting detector detail, but hard to measure well with this setup. Do the simple thing and understand what you are doing, but don’t expect exactness on this.

4. References

P. Bevington, Data Reduction and Error Analysis for the Physical Sciences
R. Eisberg and R. Resnick, Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles
R.D. Evans, The Atomic Nucleus
Fraunfelder and Henley, Subatomic Physics
G. F. Knoll, Radiation Detection and Measurement
Leo, Techniques for Nuclear and Particle Detection
Melissinos, Experiments in Modern Physics

Appendix: The Origin of Gamma Rays and A Bit of Nuclear Physics

In Bohr's model for atomic line spectra, an electron makes a transition between quantized energy levels, and the energy lost by the electron appears in a photon of specific frequency, according to the deBroglie relation:

$$E_f - E_i = \Delta E = h\nu$$

Although we are accustomed to think of this as a change in state of a single electron, it is useful to think of the process as a change in the configuration of the whole atom: the nucleus and its collection of electrons find a lower energy state, and the excess energy is carried away by a photon. Now consider the nucleus, a multi-particle collection of protons and neutrons held together by the "strong" interaction, whirling about themselves in bound configurations with stationary wave-functions and quantized energies. There is no fixed attractive center (the nucleus does not have nucleus!), but the net effect of all the nucleons is to create an average nuclear potential in which the bound states of the individual nucleons are arranged in a shell scheme reminiscent of atomic structure. The configuration of all of the nucleons in this level structure is a collective nuclear state with a quantized energy. When a nucleus decays radioactively to a lower energy state, the excess energy is sometimes released as a photon, or "gamma-ray".

Several features of the nuclear environment make nuclear emission spectra far more complicated than the atomic case.

a. In the **nuclear system,** each particle feels the force of every other particle. For large nuclei, the spectrum of the multi-particle states can be very complicated. In addition, with two different kinds of fermions, the Exclusion Principle allows 4 particles in each state, and changes of state can therefore include changes in particle identity.

b. The **strong interaction** is independent of charge: the strong force between a neutron and a proton is the same as that between two neutrons or two protons. However, the electric Coulomb repulsion between the like signed protons is still there, and a net destabilizing force for the nuclear state. This is the reason that A > 2Z when Z is large: the excess of neutrons contributes enough strong binding energy to overcome the large internal Coulomb repulsion. In many heavy nuclei it is energetically favorable to emit a bound state of two neutrons and two protons (in effect a helium nucleus), reducing the Coulomb repulsion in the remainder nucleus, and gaining an additional binding energy contribution from the fact that helium is the most tightly bound nucleus. These changes of nuclear state are called radioactive **α decays,** and the emitted helium nucei are still called **α rays.**

c. The **weak interaction** can change a proton into a neutron and vice versa, moving the excess charge and energy into a positron/electron and a neutrino/anti-neutrino. A free neutron is unstable and decays to a proton in 887 sec as $n \rightarrow p + e^- + \overline{\upsilon}_e$. This happens to a free neutron because it has slightly more mass than the decay products, and thus the decay is energetically favorable. This does not happen, in general, to neutrons in the nucleus, because adding a proton would *raise* the energy due to the increased Coulomb repulsion. However, in some particular states, this is still energetically favorable because changing a particle identity circumvents a configuration restriction due to the Uncertainty Principle. Alternatively, in some particular states, the inverse process reduces the number of protons and the lowered Coulomb repulsion is more significant than the increase in mass, lowering the overall energy. These changes of nuclear state are called radioactive β **decays,** and the emitted electrons or positrons are still called β **rays.**

d. The **electromagnetic interaction** can mediate a nuclear transition where the collective system drops to a lower electrical potential, releasing the excess energy in the form of a high energy photon. These are called γ **decays**, and the photons are still called γ **rays**. The spectrum of nuclear gamma rays shows a rich line structure, and the situation is very remininscent of atomic transitions, with the salient difference that nuclear states are separated by MeV scale energies. In many cases, γ **decays** occur right after α or β **decays,** a kind of final electromagnetic cleanup rearrangement after the gross changes in atomic number and weight.

2. Interaction of Gamma-rays and Charged Particles with Matter

Becquerel first detected gamma-rays with film placed behind "solid" objects, proving that although they were very penetrating, they ultimately reacted with matter in a manner similar to light. To understand any technique for gamma detection, we have to start with the quantum interaction of light with matter, and the ways photo-energy is transferred to the detector. In all cases, the photon transfers energy to electrons, and detection relies on sensing the ionization created as the high energy electron moves through matter. We review the energy loss mechanisms here, and techniques for sensing the ionization in the next section. discuss how this happens in a scintillator, the nature of the nuclear gamma ray signals there, the detector response, and the methodology for measurements.

a. The Quantum Interactions of Light with Matter.

We describe briefly here the three main mechanisms by which a photon transfers energy to an electron. More detail on the interaction of light with matter can be found in the References. As is generally done in the description of a particle scattering, the probability of an interaction is quantified by using a *cross-section*, σ, which is an effective size of the target, as seen by the projectile. In some cases the cross section actually is related to the size of the target, in other cases it measures the range of the interaction between the scatterers. In all cases, though, just like throwing a ball at a barn, the bigger the cross section, the greater the likelihood of hitting the target. More detail on the derivation and meaning of cross-section can be found in Fraunfelder and Henley.

i) In the **photo-electric** effect, the photon transfers all of its energy to an electron and disappears.
In our case, the electron gains an energy equal to that of the gamma-ray minus the ionization energy of an atom of the scintillator. Since inner shell ionization potentials, typically KeV, are $O(10^{-3})$ of the gamma energy, we may consider that the electron energy measures the gamma energy. The cross section for the ejection of one electron from a K shell of an atom with nuclear charge Z is

$$\sigma_{photo} \propto \sigma_T Z^5 \left[\frac{h\nu}{mc^2} \right]^{-\frac{7}{2}}$$

where σ_T is the classic Thompson cross section for an EM wave incident on a free electron, which is independent of frequency. Therefore, we see that the probability of a photoelectric interaction is steeply falling with gamma energy above 511 KeV, and increases very strongly with the charge of the target nucleus. The above expression is true for energies above the K shell ionization level. For lesser energies, the K shell ionization "turns off", and the drop in the cross-section is known as the "K absorption edge".

ii) In **Compton scattering**, the photon is not absorbed, but instead scatters elastically with the electron, like a collision between billiard balls. In fact, the energy and momentum of the photon and electron after the scattering are exactly as if this is a collision between particles, and, as first measured by Compton, this was one of the early convincing evidences that light could behave as "a particle". The detailed calculation shows that if a photon of energy E is deflected from its original direction through an angle θ, the new photon energy E' is given by

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma / mc^2)(1 - \cos\theta)}$$

In our case, the scintillator records the energy of the recoiling *electron,* which obviously acquires the energy lost by the photon

$$E_e = E'_\gamma - E_\gamma .$$

Since there is a continuum of scattering angles, there is therefore a continuum of scattered electron energies, up to a maximum at $\theta = \pi$, when the photon bounces straight backwards, and the electron recoils in the original photon direction.

iii) In **pair-production**, a photon with energy greater than $2m_ec^2$ converts into an electron-positron pair. This does not happen in free space, as a single massless photon turning into two massive particles violates conservation of energy and momentum. However, in matter, a nearby nucleus can participate in the recoil, and the pair production process becomes dominant as the photon energy becomes greater than a few MeV.

b) The Interaction of Charged Particles with Matter

So, every gamma ray ultimately interacts with matter in a way that transfers energy to electrons, and detection of gamma-rays then becomes the problem of detecting of MeV electrons. When a high energy charged particle passes through bulk matter, it loses energy mainly by a succession of inelastic atomic collisions, leaving behind a trail of ionized atoms. The amount of ionized charge can be measured in many ways, and this is the primary means for the detection of particles. There is a rich experimental and theoretical body of work about this phenomena, and it all follows the original treatment of **Niels Bohr,** who wrote down the rate of energy loss as a function of distance, dE/dx. More discussion of dE/dx in Leo, Melissinos, or Knoll.