22.101 Applied Nuclear Physics (Fall 2006)

Lecture 21 (11/29/06)

Detection of Nuclear Radiation: Pulse Height Spectra

References:

W. E. Meyerhof, *Elements of Nuclear Physics* (McGraw-Hill, New York, 1967), Sec.3-6.

We have just concluded the study of radiation interaction with matter in which the basic mechanisms of charged particle, neutron and gamma interactions were discussed separately. A topic which makes use of all this information is the general problem of detection of nuclear radiation detection. Although this subject properly belongs to a course dealing with experimental aspects of applied nuclear physics, it is nevertheless appropriate to make contact with it at this point in the course. There are two reasons for this. First, radiation detection is a central part of the foundational knowledge for all students in the department of Nuclear Science and Engineering. Even though we cannot do justice to it due to the limited time remaining in the syllabus, it is worthwhile to make some contact with it, however brief. Secondly, an analysis of the features observed experimentally in pulse-height spectra of gamma radiation is timely given what we have just learned about the γ-interaction processes of Compton scattering, photoelectric effect and pair production.

We start by noting that regardless of the type of nuclear radiation, the interactions taking place in a material medium invariably result in ionization and excitation which then can be detected. Heavy charged particles and electrons produce ion pairs in ionization chambers, or light emission (excitation of atoms) in scintillation counters, or electron-hole pairs in semiconductor detectors. Neutrons collide with protons which recoil and produce ionization or excitation. In the case of gammas, all 3 processes we have just discussed give rise to energetic electrons which in turn cause ionization or excitation. Thus the basic mechanisms of nuclear radiation detection involve measuring the ionization or excitation occurring in the detector in a way to allow one to deduce the energy of the incoming radiation. A useful summary of the different types of detectors and methods of detection is given in the following table [from Meyerhof, p. 107].

Common Nuclear Detectors

Particle	Detector	Method of Detection	Remarks
Heavy charged particles; electrons	Ionization chamber and proportional counter	Total number of ion pairs determined by collecting partners of one sign, e.g. electrons.	Can be used to determine T_0 if particle stops in chamber. #
	Semiconductor detector	Ionization produces electron -hole pairs. Total charge is collected.	Used to determine T_0.
	Geiger counter	Ionization initiates brief discharge.	Good for intensity determination only.
	Cloud chamber or photographic emulsion	Path made visible by ionization causing droplet condensation or developable grains.	Can be used to determine T_0 from range. Type of particle can be recognized from droplet or grain count along path.
	Scintillation detector	Uses light produced in excitation of atoms.	T_0 proportional to light produced.
Neutrons	Any of the above using proton recoils from thin organic lining or nuclear reactions with appropriate filling gas	Ionization by recoiling protons.	T_0 from end point of recoil distribution.
		Ionization by reaction products.	Some reactions can be used to determine T_0.
	Organic scintillator and photomultiplier	Using light produced in excitation of atom by recoiling protons.	T_0 from end point of recoil distribution.
			The above methods for neutrons require $T_0 > 0.1$ Mev.
Gamma Rays	Geiger counter	Electrons released in wall of counter ionize gas and initiate discharge.	Good for intensity determination only.
	NaI scintillation detector	Light produced in ionization and excitation by electrons released in the three interaction processes.	T_e proportional to light produced; $h\nu$ inferred from electron energy distributions.
	Semiconductor detector	Electrons produced create electron-hole pairs. Total charge is collected.	$h\nu$ inferred from electron energy distributions.

The initial kinetic energy of the particle is called T_0.

Figure by MIT OCW.

We focus on detection of γ radiation. Suppose we are concerned with the problem of detecting two γ rays, at energies 1.37 Mev and 2.75 Mev, emitted from the radioactive Na^{24}. The measurements are in the form of pulse-height spectra, number of counts per channel in a multichannel analyzer plotted against the pulse height, as shown in Fig. 19.1. These are the results obtained by using a detector in the form of Na-I scintillation detector. The spectra are seen to have two sets of features, one for each incident γ. By a set we mean a photopeak at the incident energy, a Compton edge at an energy approximately 0.25 Mev ($m_e c^2/2$) below the incident energy, and two so-called *escape* peaks denoted as P1 and P2. The escape peaks refer to pair production processes where either one or both annihilation photons escape detection by leaving the counter.

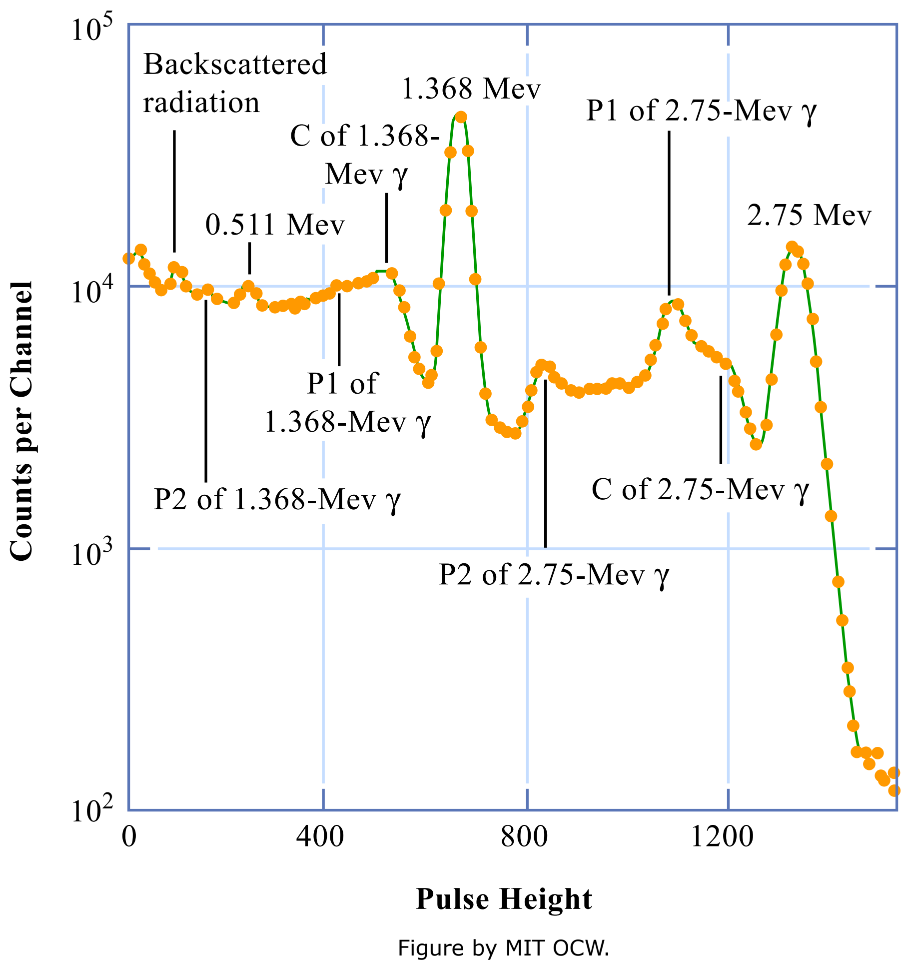

Fig. 19.1. Pulse-height spectra of 1.37 Mev and 2.75 Mev γ obtained using a Na-I detector. (from Meyerhof)

Thus, P1 should be 0.511 Mev below the incident energy and P2 should be 0.511 Mev below P1. The other features that can be seen in Fig. 19.1 are a peak at 0.511 Mev, clearly to be identified as the annihilation photon, a backscattered peak associated with Compton scattering at $\theta = \pi$ which should be positioned at $m_e c^2/2$, and finally an unidentified peak which we can attribute to x-rays emitted from excited atoms.

One can notice in Fig. 19.1 that the various peaks are quite broad. This is a known characteristic of the scintillation detector, namely, relatively poor energy resolution. In contrast, a semiconductor detector, such as Li-drifted Ge, would have much higher energy resolution, as can be seen in Fig. 19.2. In addition to the sharper lines, one should notice that the peaks measured using the semiconductor detector have *different* relative intensities compared to the peaks obtained using the scintillation detector. In particular, looking at the relative intensities of P1 and P2, we see that P1 > P2 in Fig. 19.1, whereas the opposite holds, P2 > P1, in Fig. 19.2.

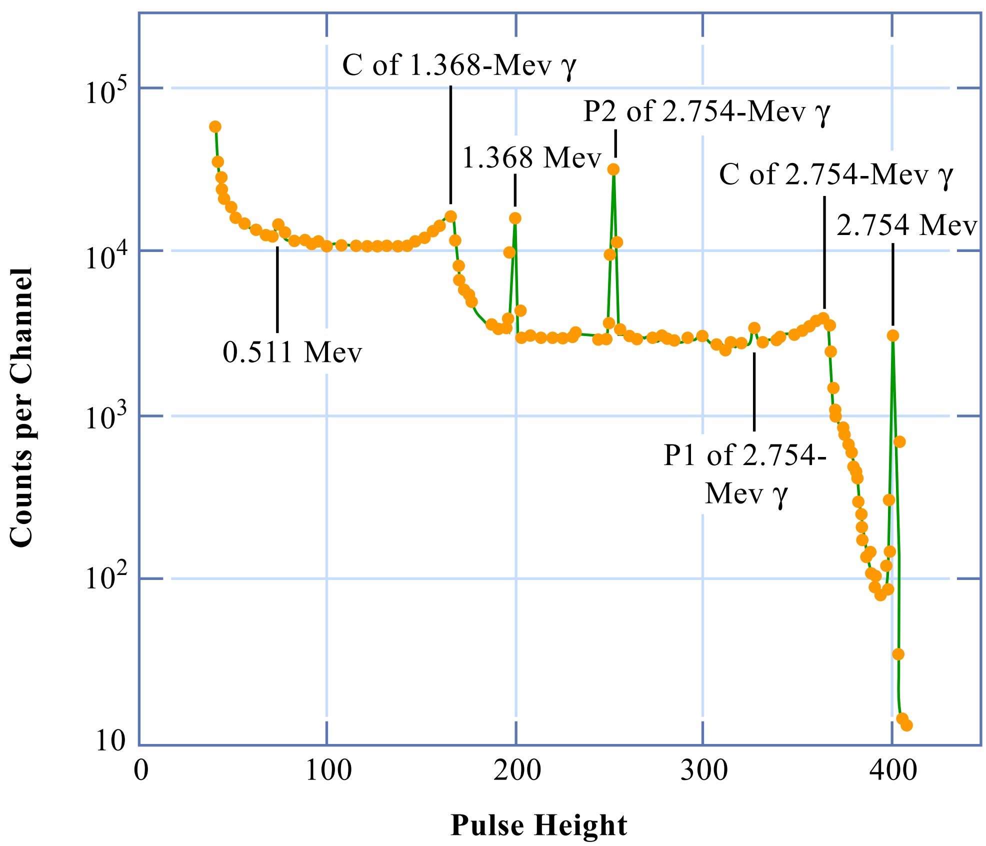

Figure by MIT OCW.

Fig. 19.2. Same as Fig. 19.1 except a semiconductor detector is used. (from Meyerhof)

This difference can be explained by noting that the scintillation detector is larger in physical size than the semiconductor detector. In this particular case the former is a cylinder 7.6 cm in diameter and 7.6 cm in length, whereas the latter is 1.9 cm in diameter and 0.5 cm in height. Thus one can expect that the probability that a photon will escape from the detector can be quite different in these two cases.

To follow up on this idea, let us define P as the probability of escape. In a one-dimensional situation $P \sim e^{-\mu x}$, where μ is the linear attenuation coefficient and x is the dimension of the detector. Now the probability that one of the two annihilation gammas will escape is P1 = 2P(1-P), the factor of 2 coming from the fact that either gamma can escape. For both gammas to escape the probability is P2 = P^2. So we see that whether P1 is larger or smaller than P2 depends on the magnitude of P. If P is small, P1 > P2, but if P is close to unity, then P2 > P1. For the two detectors in question, it is to be expected that P is larger for the semiconductor detector. Without putting in actual numbers we can infer from an inspection of Figs 19.1 and 19.2 that P is small enough in the case of the scintillation detector for P1 to be larger than P2, and also P is close enough to unity in the case of the semiconductor detector for P2 to be larger than P1.