VII: Introduction to Nuclear Spectroscopy

I. References

Melissinos and Napolitano, Experiments in Modern Physics., 2nd edition (2003), Academic Press.

II. Preparatory Questions

(must be answered in lab book before experiment is started and signed by instructor or TA)

- A. What factors are to be taken into account in selecting the source-to-detector distance?
- **B.** Explain briefly how one calibrates the energy scale of the multichannel analyzer.
- C. Complete the detector efficiency problem described below in section VI.

III. Introduction

From the time of the Greeks until well into the 19th century, the atom was thought to be the smallest indivisible piece of matter (particle). The discovery of the electron (J. J. Thomson, 1897) and the proton (Rutherford, 1919) led relatively rapidly to the idea that the atom consists of a positively charged nucleus with negatively charged electrons around it, this idea being finally formulated by Bohr in 1913 (see Experiment II). Since the beginning of the 20th century, so much progress has been made in understanding the bonding of electrons to the nucleus to form an atom that it is reasonable to say that this part of the structure of the atom is fully understood, at least insofar as the electronic and chemical properties of an atom can be determined from electromagnetism. Regarding the structure of the nucleus, however, no such complete understanding can be claimed. Whereas the force holding electrons to the nucleus is known to be the electric force whose properties are described extremely well by Quantum Electrodynamics, the forces holding the protons and neutrons (Chadwick, 1932) together in the nucleus are not fully understood. Only recently, in the 1970's, has a fundamental theory in terms of quarks and gluons, called Quantum Chromodynamics (QCD), been established as the fundamental description of the strong force, but how the theory of QCD results in bound nucleons and nuclei is still very much an open question and active area of current research.

The diameter of an atom (the "electron cloud" for an atom) is of order 10⁻⁸ cm, whereas the diameter of the nucleus is of the order 10⁻¹² cm. The energy binding an electron to the atom varies in the range 5 to 100 eV and is attributed to the attraction of positive and negative charges. The energy binding a proton or a neutron to a nucleus is in the range of 1 to 10 MeV and the nuclear forces are not strongly charge-dependent. Since these forces are never detectable between particles separated by distances much greater than the nuclear diameter, they must be very "short range", on the order of the size of a nucleon, which is about 1 fm.

In 1914 it was discovered (by Rutherford and Andrade) that the positions of the nucleons in the nucleus are not rigidly fixed but that a nucleus may be excited, for instance, by bombardment with other particles, and when this "excited" nucleus returns to its "ground state" the excess energy may be released as a quantum of radiation (photon). Thus it became apparent that the particles in the nucleus can absorb and emit photons in a manner similar to the bound electrons in an atom. Just as the photon energy absorbed or emitted by an electron is a large fraction of its binding energy, so the photon energies emitted and absorbed by the nucleus are large fractions of their binding energies. These photons are known as gamma-rays and typically have energies ranging up to 10 MeV.

Our detailed knowledge of the electronic structure of the atom stems very largely from careful studies of the spectrum of photon energies emitted by excited atoms (atomic spectroscopy); similarly, nuclear spectroscopy, including γ -ray spectroscopy, has played an important role in the development of our understanding of the nucleus.

Experiment VII consists of two basic parts. (1) The first part is an introduction to the principles and apparatus involved in a γ -ray detection system in which the response of a NaI(TI) detector to a source of monoenergetic γ -rays will be studied. A cesium source should be used to find the response of the detector to the particular source. Energy calibration should be done using other sources listed in Table 1. (2) In the second part the detector efficiency will be measured and compared with calculations you did in pre-lab question C.

IV. Detection

A. The Nal(TI) Scintillation Detector

The detector used in this experiment is an encapsulated, thallium doped, sodium iodide crystal optically coupled to a photomultiplier (Fig. VII-1) by a layer of optical grease between the face of the photomultiplier and the crystal. The crystal used in this lab is a cylinder of 3 inches in diameter and 3 inches long.

When an incident γ -ray is absorbed in the crystal it interacts essentially totally with the atomic electrons, and a fixed fraction of its energy is converted into the production of photons of much lower energy. The spectrum of these photons peaks at about 410 nm, which is within the spectrum of visible light (blue). The processes for absorbing γ -rays are described in the next section. The crystal is encapsulated in a form-fitting container with a highly reflective interior surface, which diffusely reflects light back into the crystal. The photons produced in the γ -ray absorption may undergo one or more reflections at this surface until they eventually enter the photomultiplier (PMT) where they can liberate electrons from the photocathode through the photoelectric effect. These photoelectrons cause a pulse of electric current that is then greatly amplified in the PMT. The pulse height of the output signal is directly proportional to the initial number of photoelectrons and is therefore also proportional to the energy of the incident γ -ray. The ultimate energy resolution depends statistically on the number of photoelectrons liberated.



B. Energy Loss Processes

When a γ -ray photon enters the NaI(TI) crystal (or any matter) it can interact in one of three ways: photoelectric capture, Compton scattering or pair production. In the photoelectric effect all of the energy is absorbed by a bound electron and is converted into the kinetic energy of this electron (minus a small binding energy and recoil loss). In the Compton scattering process, you will recall that the incident photons are scattered by electrons that may be considered as free, since the electron binding energy is small compared to the γ -ray energy. The initial γ -ray energy, E_{γ} , is shared by the electron, E_e , and the scattered photon, E_{γ}' .



Figure VII-2

The amount of energy transferred to the electron is a function of the scattering angle, θ , and all energies from zero up to a certain maximum can be released in the crystal.

The difference in wavelength between the scattered and incident photons is

$$\lambda' - \lambda = \frac{h}{m_0 c} (1 - \cos \theta)$$
 where $E = \frac{hc}{\lambda}$ VII-1

Solving for the energy of the deflected photon we get:

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

and the energy given to the electron is:

$$E_e = E_{\gamma} - \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{mc^2}(1 - \cos\theta)}$$
 VII-3

The maximum energy given to the electron (and hence to the scintillator) occurs when $\theta = 180^{\circ}$.

These two processes (photoelectric and Compton) dominate up to about 2 MeV γ -rays. The electrons released in these processes travel a short distance in the crystal and lose their kinetic energy by excitation and ionization. A fraction of this energy then appears in the form of visible light quanta emitted when the atoms return to the ground state. Since the number of excitations is proportional to the energy deposited in the scintillator, a measurement of the total light emitted serves to determine that energy. The light emission occurs in a short interval (0.23 μ sec decay time) following the interaction of the initial high energy photon with an electron within the scintillator. The light is reflected into the photocathode of the photomultiplier tube where the visible photons produce photoelectrons that cascade through the photomultiplier, increasing in number at each diode (Fig. VII-3). The total charge reaching the anode produces a voltage pulse across the anode resistor.

The number of electrons which are collected at the anode is many orders of magnitude greater than the initial number of photoelectrons because of this multiplication process. Suppose that every electron produced at a given dynode produces, on average, *m* secondary electrons upon impact with the next dynode in the chain. The total gain in electron number in a tube with *N*-dynode stages is m^N . The average multiplication *m*, depends upon the potential difference between two dynodes. For typical operating voltages, the multiplication per dynode is about 3 to 4. We use an RCA 6655A photomultiplier in this experiment. This is an N = 10 PMT whose current gain is 1.6×10^6 at 1000 volts. This corresponds to a multiplication $m \cong 4.2$. In this experiment you will study the response of such a detector to 0.662 MeV γ -rays. Due to light collection efficiency and the conversion efficiency of the photocathode, one obtains approximately 1 photoelectron per keV of energy loss by the γ ray. Assuming all of the photons reach the photocathode within 1/2 µsec, the expected average output current at an operating potential of 1000 volts is

$$(0.622 \,\text{MeV}) \left(10^3 \,\frac{\text{photoelectrons}}{\text{MeV}}\right) \left(1.6 \,\text{x} \,10^6\right) \left(\frac{10^{-6}}{2} \,\text{sec}\right)^{-1} = 2.1 \,\text{x} \,10^{15} \,\text{electrons/sec}$$

The PMT is connected to an ORTEC Model 276 PMT base whose anode output has an internal impedance of 1 k Ω . The average potential of the output pulse is therefore

$$\left(2.1 \times 10^{15} \frac{\text{e}}{\text{sec}}\right) \left(-1.6 \times 10^{-19} \frac{\text{C}}{\text{e}}\right) \left(10^{3} \Omega\right) = -0.34 \text{ volts}$$



Figure VII-3

In addition to the signals produced in this fashion, there will also be a substantial rate of PMT noise pulses. These noise pulses are generated when electrons are emitted from the photocathode because of thermal effects. This thermal emission occurs whenever an electron acquires sufficient thermal energy to overcome the potential barrier which binds electrons in the material of the photocathode. Evidently the rate for such emission increases as the temperature increases. It also depends upon the PMT potential which gives rise to an electric field at the photocathode. It is generally desirable, therefore, to operate the PMT at the lowest possible potential in order to reduce the noise rate.

The noise pulses are typically of much lower pulse height than the signal for single photoelectrons which is estimated at 1000 volts as

$$\left(-1.6 \,\mathrm{x} \, 10^{-19} \,\frac{\mathrm{C}}{\mathrm{e}}\right) \left(1.6 \,\mathrm{x} \, 10^{6}\right) \left(0.1 \,\mu \,\mathrm{sec}\right)^{-1} \left(10^{3} \,\Omega\right) = -3 \,\mathrm{x} \, 10^{-3} \,\mathrm{volts}$$

Fig. VII-4 shows the energy loss in the crystal due to the photoelectric and Compton interactions. The data shown in this figure are obtained from the irradiation of the detector by γ -rays of a unique energy. The resulting distribution of pulse heights exhibits three distinct features:

The photopeak corresponds to events in which the entire energy of the incident γ -ray is absorbed in the NaI crystal. These events are mainly due to photoelectric capture of the γ ray. In this case the resulting electron stops in the crystal and yields all of its kinetic energy to atomic excitation. Alternatively, the incident γ -ray undergoes an initial Compton scattering followed by the photoelectric capture of the scattered γ -ray. Here again the entire initial energy appears as kinetic energy of electrons and this energy is converted as atomic excitation in the crystal.



The **Compton scattering structure** is due to Compton scattering events in which the scattered γ -ray **escapes** from the crystal. In such cases only a fraction of the initial energy is converted in the crystal. Note that the upper edge corresponds to 180° scattering, the maximum energy which can be transferred to the electron.

The **backscatter peak** corresponds to γ -rays which undergo Compton scattering inside of the radioactive source, or other nearby objects, and then enter the crystal. At $\theta \sim 180^{\circ}$ for such events, the energy, E', of these back scattered γ -rays is given by

$$E'_{\gamma} = \frac{E_{\gamma}}{1 + \frac{2E_{\gamma}}{mc^2}}$$
 VII-4

For $E_{\gamma} = 0.662$ MeV, $E'_{\gamma} = (0.278)E_{\gamma} = 0.184$ MeV. Since there are fluctuations in the light output of the crystal and because of the statistical nature of the processes occurring in the photocathode, the voltage spectrum is smoothed or "smeared out". This "smearing" is most clearly seen in the photoelectric peak which results from monoenergetic recoil electrons but is spread into a spectrum of signal amplitudes that appears Gaussian in shape.

For γ -rays above a threshold of 1.02 MeV pair production is possible, although it is not too important below about 2 MeV. The γ -ray creates a positron-electron pair with total kinetic energy of $E - 2m_ec^2$. The positron is unstable and, after coming to rest, annihilates on an electron producing two photons each of energy 0.511 MeV. If both of these annihilation quanta escape from the detector, the energy absorbed by the scintillator will be 1.02 MeV or $2 m_ec^2$ less than that of the incident γ -ray. With the additional possibility that one or both of the annihilation quanta will suffer photoelectric capture within the scintillator, energies of $E_{\gamma} - 2 m_ec^2$, $E_{\gamma} - m_ec^2$, or E_{γ} may be released in the material. Peaks in the response of the crystal may be noted at each of the three energies. The first occurs if both 0.511 MeV γ -rays totally escape from the crystal, the second if one escapes and the other is captured by a photoelectric event, and the third if both undergo photoelectric capture. An example of such is presented in Fig. VII-5.



Figure VII-5

The 0.511 MeV γ -rays may, instead, undergo Compton scatterings in the crystal resulting in a distributed energy loss. These effects are described in greater length in the references listed at the beginning of the write-up to Experiment VIII.

V. Experiment

A. Electronic Set-Up

The various components of the apparatus should be connected as shown in Fig. VII-6. The connections are made using 50 Ω coaxial cables (RG58) fitted with BNC connectors, with the exceptions of the H.V. cable and the preamplifier power cable that is permanently connected. The function of each component is as follows:

1. **The PMT Base and Preamplifier:** The photomultiplier tube is RCA 6655A connected to ORTEC Model 276 base. The base supplies the dynode potentials in uniform steps from 0 at the cathode, to the full +H.V. at the anode. These dynode potentials are tapped off of a resistor voltage dividing chain and are distributed to the PMT through the appropriate pins on the bottom of the tube. The base has an output for the charge collected at the anode. This ANODE output produces a negative pulse whose width is about 0.5 μsec. The base also contains a preamplifier which amplifies the charge collected on the 10th dynode. The arrangement is shown in Fig. VII-7:





Figure VII-7

The charge-sensitive preamplifier is designed to provide a modest gain while maintaining a high signal-to-noise ratio. This requires a large feedback resistor, R_f , which in turn causes a long decay time for the output pulse (~30 µsec). The preamplifier appears to the source as a large capacitor, C_f , and must in fact be much larger than the source capacitance. The gain, A, is typically greater than 10^{4} .

2. The Amplifier and SCA: The ORTEC Model 490B includes both a low-noise shaping amplifier and a single channel analyzer (SCA). The amplifier accepts positive pulses up to 12 volts. The pulse is shaped into an approximately Gaussian shape and amplified by a continuously adjustable gain from ×12 to ×1280. The AMP output is the output of the

amplifier stage and is used when making the proper gain adjustment. This output is linear in the range 0 to 10 volts. The amplifier contains a "pole zero" adjustment. This adjustment allows one to minimize the time it takes the pulse to return to zero, thereby minimizing pile up. It should be adjusted before taking data. Expand the vertical scale of the oscilloscope so that one can observe the tails of the pulses during the adjustment.

The SCA produces a fixed-shape output pulse whenever the amplifier output falls in the range V (lower) to (lower)+ Δ V (window). Both V (lower) and Δ V (window) are selectable from 0 to 10 volts using the potentiometers on the front panel of the unit. The SCA output is a +5 volts square pulse that will drive the gate input of the multichannel analyzer.

3. **The TEKTRONIX Oscilloscope:** Either of the two input channels (1 or 2) can be used to display the NaI pulses. Connect the signals to the appropriate channel and choose the display via the buttons in the section labeled MODE. The vertical gain can be adjusted independently for each channel. Turn up the READOUT intensity to see the vertical and horizontal scales across the lower portion of the screen.

The horizontal sweep can be triggered externally or by the pulse itself. Set the trigger select to A, the mode to NORM, the channel to either 1 or 2 (depending on which input you've chosen) and the coupling to DC. Choose the trigger slope to be positive or negative depending on the type of signal you're looking at, and adjust the trigger level until a trace appears; the 'TRIG'D indicator will light whenever a pulse has triggered the display. The signal height and width can be measured using the MEASUREMENTS buttons and the TIME/POSITION cursors.

4. **Multichannel Analyzer (MCA) and its Use:** Measuring the spectrum of a source with a single channel analyzer set at a certain window width is obviously slow and tedious. Furthermore, one would not obtain a true spectrum for a rapidly decaying sample.

A multichannel analyzer accepts a wide range of pulse sizes. The pulses are sorted by size and stored in separate channels or bins of a memory chip. The sorting is accomplished by an analog-to-digital converter (ADC). In the operation of a typical ADC the pulse height of a particular signal charges a capacitor up to the peak voltage of the pulse. The input signal drops quickly to its zero level but the capacitor is forced to discharge at a constant current. The length of time for the voltage on the capacitor to discharge to zero is therefore proportional to the magnitude of the input pulse. The length (time) of the discharge is digitized by counting pulses from a fixed frequency oscillator (100 MHz) during this period. The number of counts recorded determines which of the many channels are to be incremented. Typically, each channel has a capacity of approximately 10⁶ counts. A multichannel analyzer is therefore somewhat analogous to many single channel analyzers and scalars, each with the same window width, but successively greater baseline settings.

A multichannel analyzer can only evaluate one pulse at a time. The time that is spent doing this is considerably longer than the length of the input pulse. For typical operation of an MCA an average of approximately 10 μ s per event is required for analysis. The multichannel analyzer is therefore "busy" after receiving a pulse and succeeding pulses during the "busy time" are lost. For high counting rates this can be an appreciable portion of the time. For example, with a random count rate of 10⁴ per second, approximately 10% of the events would be lost. Analyzers have clocks which can be preset to certain "live" times rather than actual times so that the true counting rates can be determined. Always specify collection time as livetime, not clock time.

The multichannel analyzer (MCA) used for this experiment is a PC plug-in board (ORTEC MCB or multichannel buffer) coupled with MAESTRO software provided by ORTEC. This device is also used for Experiment IX. For a more detailed description of the MCA program and its use consult the manual or the on-line help files. Because of the sophistication of the MCA, we suggest that you start the experiment when one of the instructors is present.

B. The Pulse-Height Spectrum for ¹³⁷Cs

¹³⁷Cs is an isotope which undergoes decay with a half-life of 27 years. It decays 92% of the time to the first excited state of its daughter nucleus ¹³⁷Ba which, in turn, decays to the ground state by emitting a γ -ray of 0.662 MeV. There is, therefore, one single γ -ray energy, which greatly simplifies the spectrum and its interpretation (see Fig. VII-8).



Figure VII-8

NOTE: While the radioactive sources used in this lab are fairly weak and not dangerous to handle, some basic training on the safe use and handling of radioactive material is a University requirement before you can carry out this experiment. Hopefully this will have been accomplished during a class period at the beginning of the semester. If not, contact your instructor or the laboratory technical staff to arrange. A Geiger counter must be operating in the vicinity of the experiments so that its audio signals will be a reminder that there is radiation in the area. As the counter is battery powered, make sure both batteries are off when the counter is not being used.

Fix the standard source at a distance of roughly 10 cm from the face of the detector on the axis of the detector. In determining the source-to-detector distance and the time interval to be used note the following:

- 1. If the source is too close to the detector, the high counting rate increases the possibility of two or more pulses "piling up" and being counted as a single pulse with an amplitude greater than either individual pulse;
- 2. If the source is too far from the detector, the counting rate due to the source will be comparable to the background rate. The true source spectrum will not be easily determined, therefore;
- 3. If the total number of counts recorded for a given time and channel is N, the percentage error in N will be 100 ($\sqrt{N/N}$) (Poisson statistics). The time interval should thus be sufficient to make the average percentage error less than 5%.

Before starting to take data it is instructive to examine the anode pulses. Set H.V. = +900 volts and use the oscilloscope to examine the time structure and pulse height of the traces. Sketch the pulse shape in your notebook. Indicate the amplitude and duration. Notice a bright band near the maximum. This corresponds to the pulses in the photopeak. The lesser pulses correspond to the Compton scattered events and to the backscatter peak. Remove the source and notice the tube noise pulses. Compare the pulse height with the approximate estimates given above and comment in your notebook.

Return the source to its previous place and examine the pulses from the preamplifier. Finally examine the AMP output signals from the 490B. Set the H.V. to a modest +700 volts and adjust the amplifier gain until the photopeak band is somewhat less than 5 volts. This will allow the highest energy gamma-ray from ⁶⁰Co (see Table 1) to be displayed with the same gain settings. If necessary, adjust the pole-zero compensation on the amplifier. Sketch the pulses from both the preamplifier and the shaping amplifier.

Measure the ¹³⁷Cs pulse height spectrum with the MCA. Save the spectrum on disk. Take another measurement over the same time-period with the source removed. Save this background spectrum on disk.

A useful measure of the relative number of γ -rays being detected via the photoelectric interaction is the peak-to-total ratio, P, defined as (the number of counts in the photopeak)/(the total number of counts in the spectrum). Use the ROI feature of the MCA software. Calculate this quantity for your measured spectrum, and compare to figure VII-9. You should subtract background before computing the ratio. Use the MCA software (or Mathematica). Other features not part of the response of the NaI crystal to a monochromatic gamma-ray should also be removed. These include the backscatter peak from Compton scattering in the source, any noise tail at low MCA channels, and any peaks from other sources. Peaks around 10 keV and 60 keV are frequently observed and may be due to scattering from the lead shielding, impurities in the source, or contamination from other sources.

Next you should calibrate the multichannel analyzer (determine a channel number to energy conversion) using at least two other sources with known gamma-ray energies as listed in Table 1. The sources should supply gamma rays with at least three widely spaced energies. An example is ²²Na, which supplies two energies. ⁵⁷Co is a good choice for low-energy gammas. One caution with ⁵⁷Co; although all the sources in our Reference Set are produced with similar levels of activity (~10 μ Ci), the ones with shorter half lives decay significantly within a few years. Calculate the current activity of a short-lived source before using it. Don't use a "dead" source. Record spectra from the sources and identify the photopeaks. Use the MCA software to determine the channel numbers and uncertainties of each peak. Produce a linear linear least-squares fit calibration curve with channel number on the x-axis and the peak energy in keV or MeV on the y-axis.

Use your calibration to determine the energies of the photopeak and backscatter peak in the Cs spectrum. It is not difficult to find the photopeak. The backscattered peak can be easily found by using the expression for E'_{γ} in Eq. VII-4. Identify the Compton "peak". Also identify any additional peaks. Compare the results using your calibration to those expected for a ¹³⁷Cs source.

The peak-to-total ratio will clearly be a function of energy, since the photoelectric, Compton, and pair-production interaction processes depend on energy. It will also be a function of the size and placement of the detector, since gammas and electrons lost through the sides of the detector or scattered into the detector from the surroundings will not produce counts in the photopeak. Thus, the peak-to-total ratio will be, in a certain sense, a measurement of the quality and efficiency of detection versus energy. Compare your measured value of P with a value for a similar size NaI crystal (3" x 3") as shown in Fig. VII-9.



Figure VII-9

Standard Sources		
Isotope	Energy of emitted γ	Half-life
¹³³ Ba	356 keV	10.51 yr
(3 most intense lines are listed)	81.0 keV	
	303 keV	
¹⁰⁹ Cd	88.0 keV	463 day
⁵⁷ Co	122 keV	272 day
	136 keV (10%)	
⁶⁰ Co	1173 keV	5.27 yr
	1333 keV	
¹³⁷ Cs	662 keV	30.07 yr
⁵⁴ Mn	835 keV	312 day
²² Na	511 keV	2.60 yr
	1275 keV	

Table 1



Figure VII-10

VI. Detector Efficiency

The NaI(Tl) detector will obviously not detect all gamma-rays emitted by the source. Only those emitted within the solid angle cone subtended by the face of the detector have any possibility of being detected (see Fig. VII-10). Even these have some probability of passing through the detector without any interaction taking place. A useful quantity that quantifies this process is the total detection efficiency, ε_T , which is defined as the fraction of gammarays emitted from the source which interact with the detector. This will not only depend on the source-detector geometry, but also the probability that the γ -ray will lose some of its energy once it enters the detector.

Problem (to be done as a pre-lab question).

Calculate the total efficiency of the detector. This will involve determining the probability that a given gamma ray impinges on the detector times the probability that it then loses some of its energy in the NaI crystal.

The first part, the probability that a given gamma ray hits the detector, is determined by the geometric solid angle subtended by the face of the NaI crystal, Ω , is divided by 4π . Actually the NaI crystal is a right cylinder and presents varying distances from the source (see Fig. VII-10). For large distances (h_0) relative to the dimensions of the detector one can obtain the solid angle by computing it at the back face of the detector. The sodium iodide crystal used in this experiment is 3 inches long. In our case h_0 is not so large, so it makes sense to calculate upper and lower limits, so one approach is to calculate the solid angle subtended by the closer and farther ends of the NaI crystal.

Once the geometric solid angle is know, one then has to multiply this by the probability that a gamma ray will interact inside the detector.

Let N(x) be the number of photons per cm² at x traveling along the x axis. The number dN of photons which interact, and hence lose energy in a distance dx between x and x+dx is proportional to N(x) and the distance dx.

$$dN(x) = -\mu N(x)dx \qquad \text{VII-5}$$

The factor of proportionality (μ) is called the total linear attenuation coefficient. Solving the differential equation subject to the boundary condition that $N(x) = N_0$ at x = 0 (corresponding to the front face of the detector) we get

$$N(x) = N_0 e^{-\mu x} \,. VII-6$$

The fraction of photons which interact in traversing a distance x' is then

$$\frac{N_0 - N(x')}{N_0} = 1 - e^{-\mu x'}$$
 VII-7

The total linear attenuation coefficient includes contributions from pair production, photoelectric and Compton interactions. The linear attenuation coefficients for sodium iodide are shown in Fig. VII-11.



If the detector thickness were d for all incident gamma-rays the total efficiency is given by $(\Omega/4\pi)(1-e^{-\mu d'})$ where Ω is the solid angle at the source subtended by the face of the NaI detector. Again, a strategy for this experiment is to just compute the detector efficiency at the front face and at the back face of the detector and take the average. This works reasonably well as long as h_0 is greater than about 5 cm.

Calculate its efficiency as a function of the energy of the incident gamma-ray (0.1 MeV to 10 MeV) and bring a graph of the points with you to the laboratory.

The photopeak efficiency can be defined as

$$\varepsilon_P = \frac{\text{gammas in the photopeak}}{\text{gammas from the source}} = \varepsilon_T P$$
 VII-8

Calculate a value for this quantity using your calculated value for ε_T at the ¹³⁷Cs gamma-ray energy of 0.662 MeV and the peak-to-total ratio *P* determined in Section V.

The emission rate of a source can be experimentally determined using the expression.

$$N_0 = \frac{N_P}{\mathcal{E}_P}$$
 VII-9



where N_P is the number of counts in the photopeak. Divide counts by accumulation livetime to get counts/s. For the ¹³⁷Cs source calculate this quantity and compare it with the source activity printed on the source, corrected for its age and decay. Explain any discrepancies. What are the advantages (if any) of using N_P and ε_P rather than the total number of counts and ε_T ? (Suppose the source were not monoenergetic.) Compare your value of ε_T for the 0.662 MeV gamma-ray energy and your source-to-detector distance with that shown in Fig. VII-12. Explain the differences.