Introductory Laboratory -- Nucleons
P373

β–decay and γ –ray Spectroscopy with NaI Detectors

Reference Materials

OHIO
UNIVERSITY

Physics 373 – Introductory Laboratory – Nucleons

Beta Decay and γ-ray Spectroscopy in NaI

Purpose: The purpose of this experiment is to acquaint the student with some of the basic techniques used for measuring gamma rays, as well as the characteristics of a typical gamma ray spectrum. It is based on the use of two sodium iodide (NaI) detectors that are thallium-activated (Tl).

Gamma Emission: Most isotopes that are used for gamma ray measurements also have betas (electrons or positrons) in their decay schemes. The typical decay scheme for the isotope will include a beta decay to a particular level followed by gamma ray emission to the ground state of the final isotope. The beta particles will usually be absorbed in the surrounding material and not enter the detector at all. However, these betas will oftentimes interact with bound atomic electrons in the material and produce other gamma rays that can be clearly seen in the detector. Understanding the characteristics of the measured gamma ray spectra is an important goal in this experiment. Necessary background information for this laboratory is contained in the accompanying write-up *"Gamma Ray Spectroscopy in NaI"*. You may need to pursue other references as well for a complete introduction to the physics, terminology, techniques, and equipment relevant for a full understanding of this field.

List of Goals:

A). Understand the decay schemes of several different sources: ^{22}Na, ^{60}Co, and ^{137}Cs.

B). Understand the overall electronics layout, as well as the purpose of each module employed, and the set-up of the gates, timing, and gains.

C). Understand the detailed features of the energy spectra for each of the different sources.

D). Perform an energy calibration on the accumulated spectra using the photopeaks as reference.

E). Measure the energy resolution of the system.

F). Measure the relative efficiency of one NaI detector relative to the other for each of the gamma rays detected from ^{22}Na.

G). Keep a detailed logbook of all relevant details of this measurement.

H). Be able to access the available literature to understand the expected properties of each of the different isotopes.

I). Prepare a detailed formal lab report on all aspects of this investigation.

I. Pre-Experiment Approach and Details

◇ Before beginning the experiment, be sure to read *all* of the background material in the laboratory binder.

◇ Be sure that you have spent adequate time researching the general topic so that you can appreciate the basic ideas outlined above under the *"List of Goals"*.

◇ After performing the essential pre-lab preparations, begin to understand the experimental setup. This includes understanding the purpose of each part of the system. Get familiar with the use of the oscilloscope and how to use it to look at all of the linear and logic signals in the setup. With no source present, why can you still see signals in the detectors? Note that manuals for each of the electronics modules used in the setup are contained in a binder in the lab room. The basic layout of the gamma ray spectroscopy system is shown in Fig. 1.

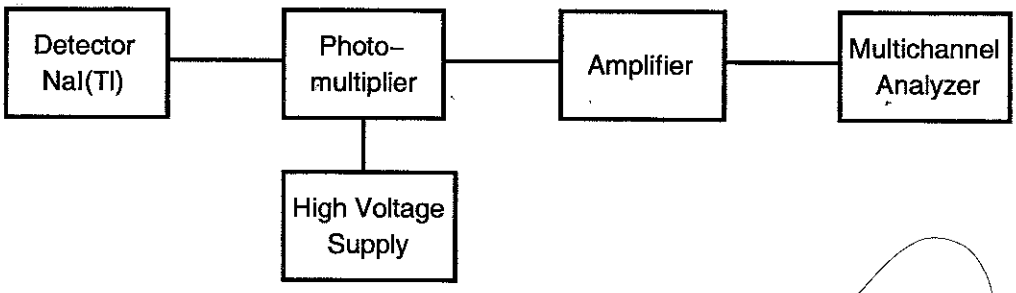
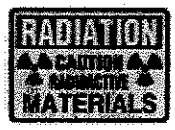


Figure 1: Major components of the gamma ray spectroscopy system set up for this laboratory.

◇ Be sure that you have full understanding of the concepts behind radiation safety and the risks inherent in using radioactive sources. Remember the adage *"time, distance, and shielding"* to minimize your exposure. Do not be afraid to ask questions. You should always strive to keep your risk of exposure as low as reasonably achievable!



◇ After putting a source in place, go through the set-up step by step to understand how all signals look, how they are timed in, and how all gates are setup. Be sure to provide clear and complete documentation in your logbook. Also begin to understand how to operate the data acquisition system and how to print out histograms.

II. Single Spectrum Analysis

a). Understand the qualitative features of the gamma ray spectra for the radioactive isotopes ^{22}Na and ^{137}Cs. Make sure that you can identify the relevant photopeaks, the Compton edge, and the back-scattering peak and understand how they arise.

b). Calibrate the energy response of each NaI detector using the radioactive isotopes ^{22}Na and ^{137}Cs. This will amount to analyzing your data to produce an equation to calculate the energy of the photopeaks from the channel location information. Perform a least-squares

fit to this data and list all experimental uncertainties (both statistical and systematic) that affect your measurement.

c). After your calibration has been determined, study the spectrum associated with the ^{60}Co source. Measure the energy of the photopeaks and compare to their known values.

d). Repeat all measurements with the amplifier coarse gain doubled.

e). Show a simple calculation of the energy resolution and suggest any $\Delta E/E$ energy dependence your data may show.

f). Quantitatively account for the positions of the Compton edge and the back-scatter peaks in the spectra for each of the different isotopes used above.

III. Coincidence Spectrum Analysis

a). Measure a coincidence spectrum for ^{22}Na in the large NaI detector with both a 0.511 MeV and a 1.275 MeV annihilation tag from the small NaI detector. Use digital gates to select each photopeak (selecting the photopeaks from the small detector spectrum). Verify that the simultaneous gamma ray decay is a separate source event, i.e. the 0.511 MeV γ ray is not from a nuclear decay.

b). Since the detection of one 0.511 MeV gamma ray in the small NaI detector signals a decay has taken place, can you calculate the intrinsic efficiency of the large NaI detector from detection of the other 0.511 MeV gamma ray? How? What geometry is required? How many 1.275 MeV photons are expected in coincidence with the 0.511 MeV photon?

> Use these data to calculate the efficiency of the large NaI for E_γ=0.511 MeV and 1.275 MeV. Be sure to save a singles spectrum (total events spectrum) for the large NaI to compare the ratio of 0.511 MeV gamma rays to 1.275 MeV gamma rays. This latter data will help you to find the efficiency at 1.275 MeV by comparison to that at 0.511 MeV.

c). Describe the coincidence spectrum you expected to measure in the large NaI detector for each digital gate set on the small detector spectrum. Can you describe the expected accidental coincidence rate? Can you detect the accidental coincidences by observing the spectra? Perform this measurement.

d). Diagram a decay event and indicate the numbers of each photon expected per event.

e). Can you devise a technique to measure the absolute efficiency of a gamma ray detector?

IV. Gamma Ray Absorption in Matter

a). Compare the energy spectrum from the ^{137}Cs source in the NaI detectors with and without different thicknesses of lead and copper sheet present. With proper accounting of the background, determine the absorption coefficient and compare to the value in the literature.

TECHNICAL REPORT PREPARATION

The following sections should be included in the Technical Report.

a). **Abstract** - The abstract should be a very short and concise description of what is in the report. Its purpose is to help others who may be looking up the literature on a particular subject. The researcher should be able to read the abstract in a matter of seconds and discern the salient details and results of the report.

b). **Theory** - This section should contain a complete exposition of the theory discussing the physical phenomena and the equations behind the experiment. A proper derivation of the formulas used in the experiment must be included. The theory should be relevant and complete. Any relevant figures should be included.

c). **Experimental Details** - This section should include a complete description of the experiment and all equipment used. A schematic drawing of the equipment and/or any critical components must be included.

d). **Data** - The data from the experiment must be included, organized into tables with the quantity and its units given. Be consistent and correct with significant figures. This section must also include a complete detail of all statistical and systematic uncertainties in the data along with a complete description of how they were determined or assigned.

e). **Results** - Detailed analysis of the measured data should be included here. The various calculated values should be included here in tabular form. All data should be plotted on graphs with both axes clearly labeled. Any relevant fits to the data should be included here and the results discussed in full.

f). **Conclusions** - The conclusions should contain a summary of the outcome of the experiment (e.g. what was learned), calculated values, mathematical statement of errors, and an interpretation of graphs and tables. The conclusions reached as to verification of theory and a detailed discussion of the causes and the elimination of errors should also be included. Suggestions about improvements, further research, and other remarks should also be made. The conclusion is important and should show considerable thought about the experiment.

g). **Bibliography** - Any and all references that have been used in the preparation of the report should be listed here. An example of a bibliography item is:

P.A. Tipler, *"Physics for Scientists and Engineers"*, (Freeman-Worth, New York, 1999), pp. 1284.

Note: It is good for the student to look at textbooks to see how equations, graphs, figures, and tables are handled and displayed. These are good models to use.

Gamma Ray Spectroscopy in NaI

1 Introduction

Gamma rays are high energy photons created in the decay transitions of radioactive nuclei. The gamma ray energy spectrum measures the energy levels of the nuclear states in the same way that visible line spectra measure atomic structure. In many experiments (e.g. in nuclear astrophysics) the measured gamma ray energies are used to analyze the composition of unknown systems.

In this experiment, you will measure the spectra of several well known gamma emitters using NaI scintillation counters, modular electronics, and some histogramming software that is part of a data acquisition (DAQ) system. Observation of a gamma ray starts with an interaction that transfers energy to an electron, which then ionizes a trail of atoms. The *scintillator* is a material that converts the energy of such an ionization trail into visible or near-visible light. The small pulse of scintillation light is directed to a *photomultiplier* (PMT), which converts it into an amplified electrical signal. The voltages from the PMT are amplified and digitized by the electronics so that they can be further analyzed. At every step of this processing, the devices maintain linearity between the amplitude of the signal and the original energy deposited, allowing you to study the energy spectra in great detail. Figure 1 shows what can occur in the vicinity of a typical source, scintillation detector, and shielding configuration.

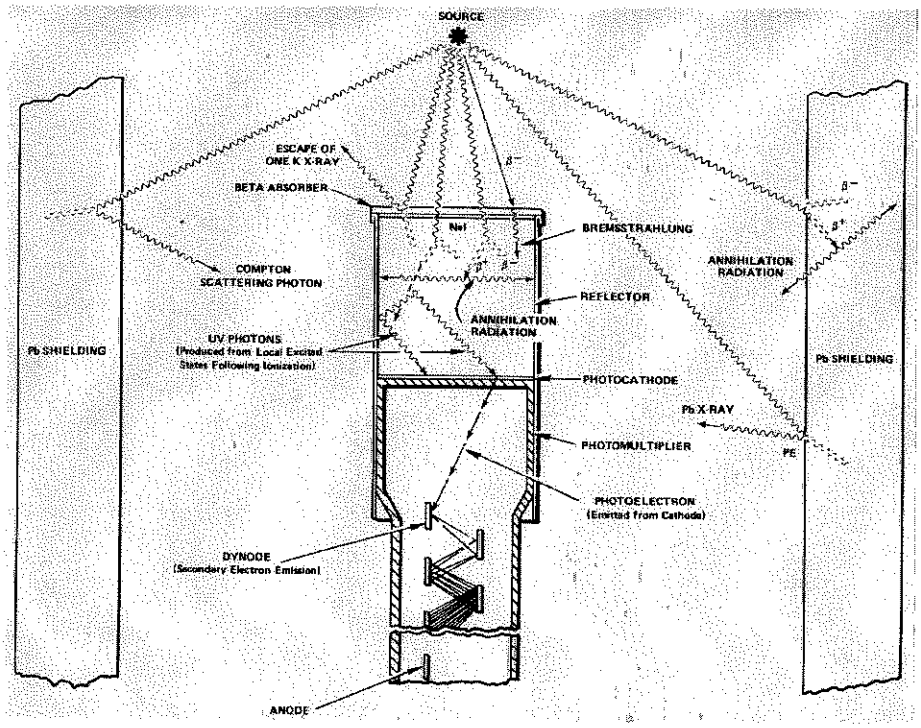


Figure 1: Various events in the vicinity of a typical source, scintillation detector, and shield configuration. Taken from Ortec Application Note AN-34.

2 Origin of Gamma Rays and Some Nuclear Physics

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

$$E_f - E_i = \Delta E = h\nu. \tag{1}$$

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 entire atom. The nucleus and its collection of electrons finds 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 (together called *nucleons*) held together by the "strong" nuclear interaction, whirling about themselves in bound configurations with stationary wavefunctions and quantized energies. There is no fixed attractive center (the nucleus itself does not have a nucleus!), but the net effect of all the nucleons is to create an average nuclear potential (called the mean field) 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 (called a gamma ray).

Several features of the nuclear environment make nuclear emission spectra far more complicated than the atomic case. See Eisberg and Resnick Chapters 15 and 16 for more details.

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 Pauli Exclusion Principle allows four particles in each state, and changes of state can therefore include changes in particle identity.

b). The **strong nuclear interaction** is independent of charge, i.e. 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 protons provides 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 of the nucleus, and gaining an additional binding energy contribution from the fact that helium is a very tightly bound nucleus. These changes of nuclear state are called radioactive α decays, and the emitted helium nuclei are called α particles.

c). The **weak nuclear interaction** can change a proton into a neutron and vice versa, moving the excess charge and energy into a positron/electron and neutrino/anti-neutrino. A free neutron is unstable and decays into a proton in 887 s as $n \rightarrow p + e^- + \bar{\nu}_e$. 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 Pauli Exclusion Principle. Alternatively, in some particular states, the inverse process $p \rightarrow n + e^+ + \nu_e$ 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 called β particles.

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 gamma decays, and the photons are called gamma rays. The spectrum of nuclear gamma rays shows a rich line structure, and the situation is very reminiscent of atomic transitions, with the salient difference that nuclear states are separated by MeV scale energies as opposed to the eV scale in atomic physics. In many cases, gamma decays occur right after α or β decays, a kind of final electromagnetic cleanup rearrangement after the gross changes in atomic number and weight.

3 Interaction of Gamma Rays and Charged Particles with Nuclear Matter

Henri 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 the techniques for sensing the ionization in the next section.

3.1 The Quantum Interactions of Light with Matter

We describe here the three main mechanisms by which a photon transfers energy to an electron. 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 the effective size of the target as seen by the projectile. In some cases the cross section is actually related to the size of the target, in other cases it measures the range of the interaction between the scatterers. In all cases, just like throwing a ball at a barn, the bigger the cross section, the greater the likelihood of hitting the target.

3.1.1 The Photoelectric Effect

In the photoelectric 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 the atom of the target. Since inner shell electron ionization potentials, typically keV, are $\mathcal{O}(10^{-3})$ of the gamma ray energy, we may consider that the electron energy measures the gamma ray energy. The cross section for the ejection of one electron from the K-shell of an atom with nuclear charge Z is:

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

where σ_T is the classical Thomson (after J.J. Thomson) cross section for an electromagnetic 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 ray 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.

3.1.2 Compton Scattering

In Compton scattering (named after Arthur Compton), the photon is not absorbed, but instead scatters elastically with the electron, like a collision between two 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 pieces of convincing evidence 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:

$$E' = \frac{E}{1 + E_o(1 - \cos\theta)}, \tag{3}$$

where $E_o = E/m_e c^2$. In our case, the scintillator records the energy of the recoiling *electron*, which obviously acquires the energy lost by the photon, $E_e = E - E'$. Since there is a continuum of scattering angles, there is therefore a continuum of scattered electron energies, up to a maximum angle at $\theta = \pi$, when the photon bounces straight backwards, and the electron recoils in the original direction of the photon.

The cross section of Compton scattering is given by the so-called Klein-Nishina formula. It peaks in the forward direction, and is proportional to the atomic number Z of the target nucleus (which should be obvious as the cross section must depend on the density of target electrons). The cross section for Compton scattering is shown in Fig. 2 as a function of the recoil electron energy. The result shows that the spectrum of scattered electrons is flat at low energies, and then rises to a peak at the maximum energy transfer at $\theta = \pi$. This feature is called the *Compton edge.*

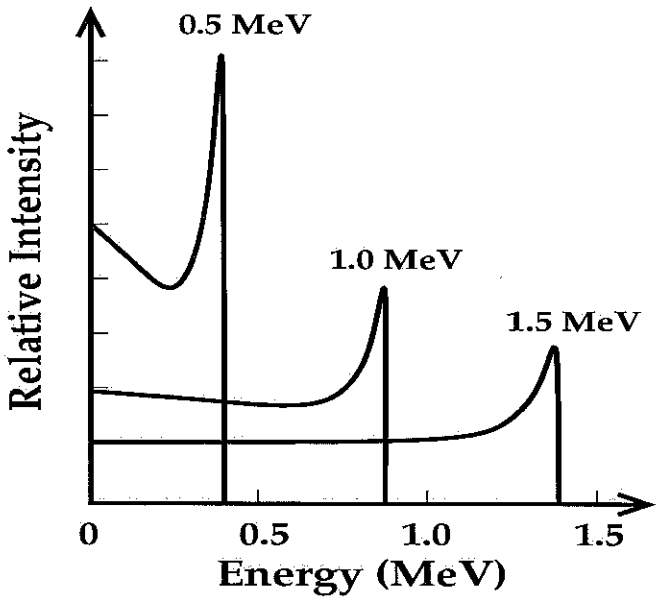


Figure 2: The relative cross section vs. energy for Compton recoil electrons for three characteristic gamma ray energies.

3.1.3 Pair Production

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 would violate 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.

3.2 The Interaction of Charged Particles with Matter

Every gamma ray ultimately interacts with matter in a way that transfers energy to electrons, and the detection of gamma rays then becomes the problem of detecting MeV-type 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 these phenomena, and it all follows the treatment of Neils Bohr, who wrote down the rate of energy loss as a function of distance, dE/dx, for charged particles.

4 Experimental Detection of Gamma Rays

The detection of gamma rays relies on transfer of energy to the electrons of the scintillator material and the measurement of the ionization created as the high energy electrons move through matter. We review here how this is done with a scintillator, photomultiplier, and associated electronics.

4.1 Scintillators

One method for the detection of ionizing radiation is based on materials (known as *scintillators*) that convert the ionization energy into visible light. Scintillators are as common as the video display, where the image is a result of an electron beam striking "phosphors" on the inside face of the CRT. For particle detection, and particularly detection with energy measurement, the scintillators of choice are certain inorganic crystals doped with small amounts of "activators" in a strategy vaguely reminiscent of the use of dopants in semiconductors. In this laboratory, we use NaI(Tl), sodium-iodide doped with thallium.

In the pure crystal, electron-hole pairs are created as the ionization promotes electrons from the valence to the conduction band. Decay of the electrons back to the valence band is inefficient. The role of the activator is to create sites in the crystal energy levels in the forbidden region, close to the conduction band. Electron holes in the valence band drift to the activators and ionize them. The free electrons find the ionized sites and drop in, creating excited activator states. If these decay quickly to visible photons ($t < 500$ ns) the result is called *fluorescence*; this is the most useful component of the scintillation. Other metastable states require additional perturbations, say via thermal energy to de-excite, and lead to a slower release of light, called *phosphorescence.* In other cases, the excited activator states decay without radiation, and the energy of the ionization is said to be *quenched.* The number of electron-hole pairs that result in a scintillation photon is called the efficiency of the scintillator. The frequency of the scintillation light should be in a regime where the scintillator is transparent and the photomultipliers are sensitive.

NaI(Tl) is commonly used because the large Z's give a good cross section, it has a large light yield, and is inexpensive to grow into large ingots, enabling large arrays for e.g. medical x-ray detection. It is hydroscopic (being a salt), so the crystals have to be contained in hermetically sealed containers. The benchmark performance specifications for NaI(Tl) are 5×10^4 ion pairs per MeV of incident particle energy, and a scintillation efficiency of approximately 12%, yielding 4×10^4 photons per MeV incident.

The large light yield leads to a good energy resolution, but the time constant for the signal in inorganic scintillators is rather long, $\mathcal{O}(200$ ns). In high rate or timing applications, an alternative family of plastic scintillators is used to reduce pile-up effects and to achieve good timing resolution, respectively. In these materials, excitation and decay of molecular states happens with atomic time scales, uncomplicated by transport effects, and the scintillation pulse widths are of order nanoseconds, with fractional nanosecond resolution on the rise time. However, the light output is lower and the energy resolution is poor compared to the inorganics.

4.2 Photomultipliers

The photomultiplier (PMT) is a tube device that functions as a one channel image intensifier. Light falls onto the photo-cathode, and electrons are emitted via the photoelectric effect. Some simple electromagnetic optics accelerates these electrons and directs them onto the first of a series of surfaces called *dynodes*, chosen from materials with good secondary electron

emission. The dynodes are arranged mechanically so that adjacent dynodes are within millimeters of each other, and a single high voltage power input is directed down a resistor chain that maintains a potential difference of 50-100 V between each pair of dynodes (see Fig. 3).

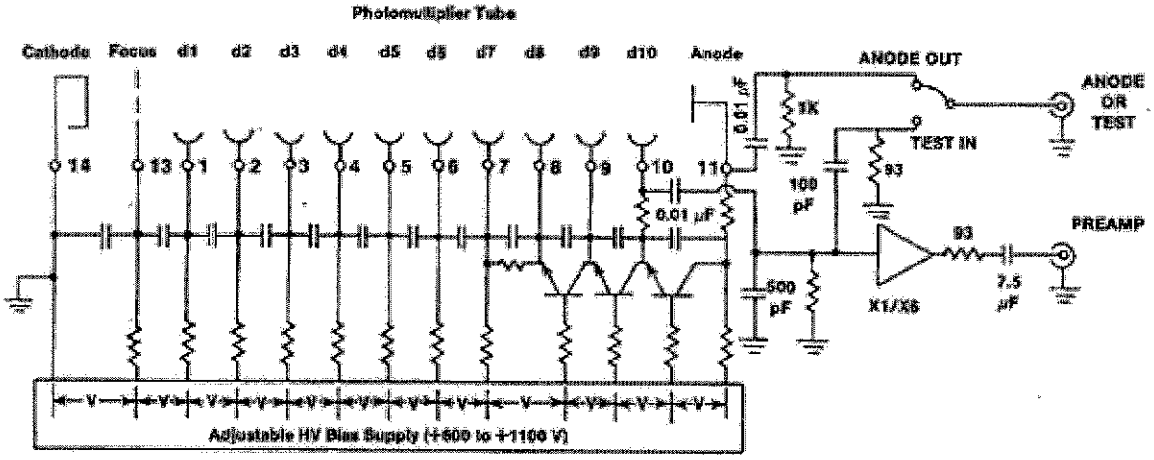


Figure 3: Typical PMT resistor chain in a grounded cathode system.

In this arrangement, the photo-electronics create a larger shower of electrons off the first dynode, and then a chain-reaction of electron emission flows down the tube, amplifying the size of the electron bunch at the dynode. Finally collected at an anode, amplifications of $\mathcal{O}(10^6)$ are typical, so if 1000 electrons leave the cathode, the final charge pulse is $\mathcal{O}(0.1$ nC), well within the input compliance of decent charge integrating amplifiers.

PMT's come in a variety of sizes and designs tuned to different applications. Recent developments include large light-collecting inputs, for use in detecting the Cherenkov radiation of solar and astrophysical neutrinos in huge underground water tanks, multi-channel tubes for processing position-sensitive signals from bundles of scintillating fibers, and tubes that can operate in large magnetic field environments. The main PMT that we use in our experiment is designed to provide appropriate amplification for the signals from the NaI scintillator. In these tubes the cathode is grounded and the anode is at positive high voltage.

The PMT gain is fixed by the dynode design and the applied high voltage (HV). Small changes in HV lead to significant effects in gain, so good HV regulation is important. With the fixed gain, the tube output depends entirely on the number of electrons at the first step, and one of the key performance issues for PMTs is the number of electrons produced per unit photon, this ratio is called the *quantum efficiency.*

Fig. 4 shows the quantum efficiency for several typical photocathode materials. Notice that the quantum efficiency varies with frequency. The NaI(Tl) scintillation peaks at 415 nm, so the PMT's employed in this experiment (with bi-alkali photocathodes) are chosen to match this response. One expects good cathode materials to have quantum efficiencies greater than 20% at the frequencies of interest.

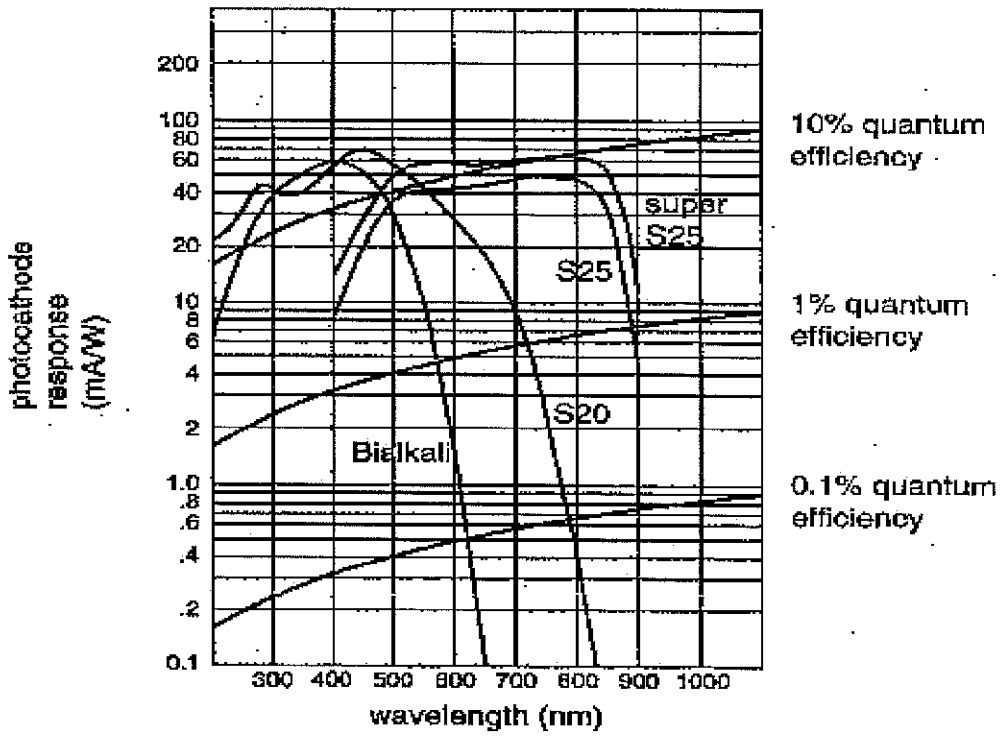


Figure 4: Quantum efficiency of typical photocathodes.

4.3 Electronics

At this point in the signal chain, for a given gamma ray interaction, we have at the PMT anode output a small charge pulse proportional to the energy deposited in the scintillator. If there is more than a single mono-chromatic energy to measure, then we want to convert the charge signal to a voltage signal, digitize the voltage pulse heights, one by one, and plot a histogram of the number of occurrences of each pulse height. Knowing the conversion from pulse height into energy will then turn this histogram into a plot of the *energy spectrum* produced by a given source of gamma rays.

The conversion of the PMT anode charge signal to a voltage signal is done with a charge-integrating preamplifier. This signal is then sent to a linear amplifier. The signal is differentiated to remove baseline shifts, and then integrated to remove high frequency noise. Finally, the amplifier output is sent to an analog-to-digital converter (ADC), whose output is sent over a serial bus to the computer. The computer runs the data acquisition (DAQ) system that is used to plot the results.

5 Spectral Analysis

The gamma ray spectrum obtained for a given isotope is a direct reflection of its decay scheme. As an example, the decay scheme of ^{137}Cs is shown in Fig. 5. The corresponding gamma ray spectrum that is typical for this isotope, obtained using a NaI(Tl) detector,

is shown in Fig. 6. The spectrum shows a number of features characteristic of a gamma ray spectrum. Here we see the photopeak at 0.662 MeV, as well as the Compton edge at 0.478 MeV. Another feature that is typical is the so-called *backscatter* peak. Backscatter occurs when gamma rays make Compton interactions in the material that surrounds the detector. Backscattered gamma rays from these interactions make photoelectric interactions in the NaI(Tl) detector when they enter the crystal. The energy of the backscattered peak can be found by solving Eq.(3).

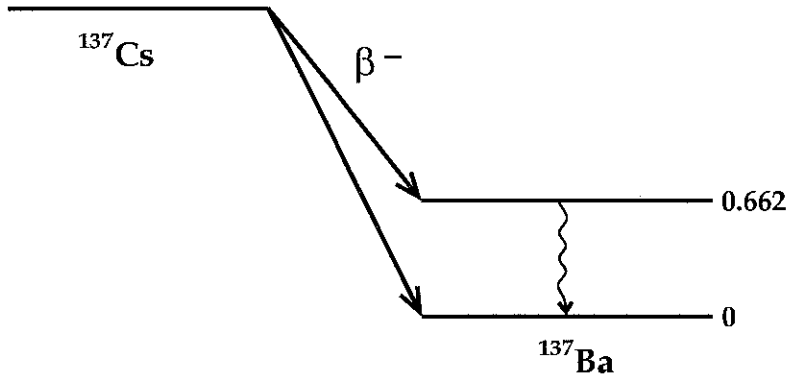


Figure 5: The decay scheme for ^{137}Cs to ^{137}Ba. Energies are given in MeV.

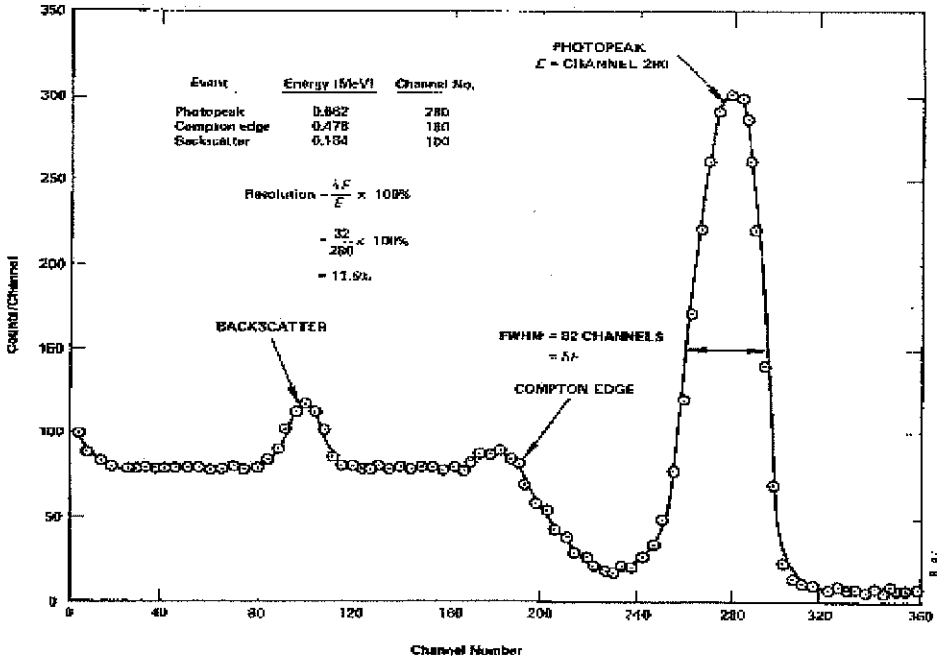


Figure 6: NaI(Tl) spectrum for ^{137}Cs identifying the different features.

Another source that will be used extensively in the laboratory is ^{22}Na, which is excellent for a simple gamma-gamma coincidence experiment. The decay scheme for this isotope is shown in Fig. 7. From this decay scheme it can be seen that 99.95% of the time the decay of

^{22}Na occurs by positron emission and electron capture through the 1.275 MeV state of ^{22}Ne. Ninety percent of these decay events occur with positron emission, which then annihilate and produce a pair of 0.511 MeV gamma rays that can be seen in the gamma spectrum. Fig. 8 shows a typical gamma ray spectrum for ^{22}Na that was obtained with a NaI(Tl) detector. The 0.511 MeV peak will usually be quite a bit more intense than the 1.275 MeV peak, primarily because of detector efficiency differences at the two energy levels and the annihilation process.

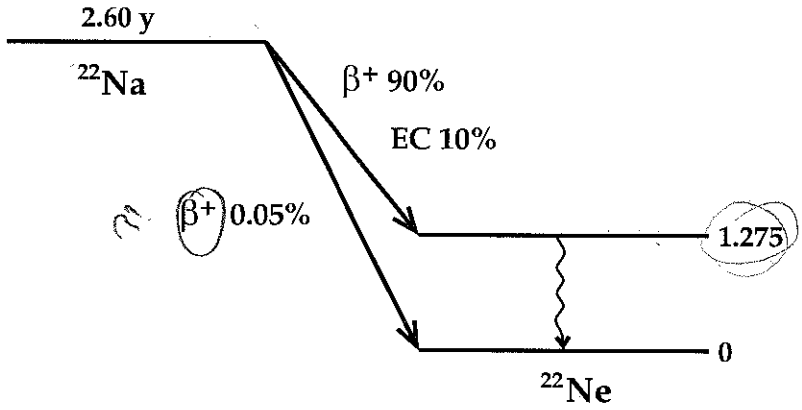


Figure 7: The decay scheme for ^{22}Na to ^{22}Ne. Energies are given in MeV.

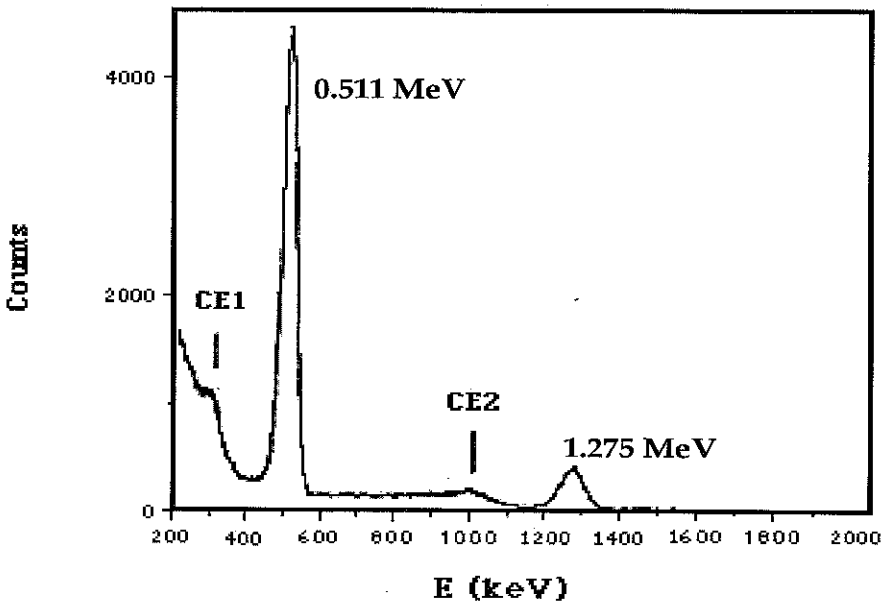


Figure 8: NaI(Tl) spectrum for ^{22}Na identifying the different features.

6 Gamma Ray Absorption in Matter

The measured intensity of gamma rays from the source depends on the materials between the source and the detector. If the volume is filled with a given material characterized by an absorption coefficient μ, then the intensity of the detected radiation I is related to the emitted intensity I_0 by the exponential relation:

$$I = I_0 e^{-\mu x}. \tag{4}$$

Here x is the thickness of the material. The absorption coefficient is usually expressed in units of cm^{-1}.

7 Acknowledgements

Many of the details in this write-up were extracted from notes for the Advanced Physics Laboratory at the University of Michigan.

Relevant References

1). *"Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles"*, R. Eisberg and R. Resnick, published by J. Wiley.

2). *"Nuclear and Particle Physics"*, W.S.C. Williams, published by Oxford Science Publications.

3). *"Introductory Nuclear Physics"*, K. Krane, published by J. Wiley.

4). *"Particle Detectors"*, C. Grupen, published by Cambridge University Press.

5). *"Techniques for Nuclear and Particle Physics Experiments"*, W.R. Leo, published by Springer-Verlag.

6). *"Physics for Scientists and Engineers"*, P.A. Tipler, published by Freeman-Worth.

Note: You may well find other references besides these that will be relevant and useful. This is just a suggested starting point for your research.

Detector Definitions

1). **Total Source Efficiency** – The ratio of the number of events detected to the total source strength.

2). **Intrinsic Efficiency** – The ratio of the events detected in a detector to the source events incident on the detector.

3). **Singles Spectrum** – A spectrum containing all the events in the detector.

4). **Coincidence Spectrum** – A spectrum of the events in a detector that are simultaneous with events in another detector.

5). **Accidental Coincidence** – The simultaneous detection of two events in a pair of detectors or a single detector that are the result of chance and are not correlated with the same source event.

6). **Tag Event** – An event identified in a detector that is simultaneous with a known source event.

7). **Simultaneous Events** – Two source events that cannot be distinguished in time as separate, i.e. events occurring within the resolution time of the detector or detectors.

Detector Resolution

The energy resolution of a scintillation detector is a measure of its ability to distinguish the presence of two gamma rays closely spaced in energy. Since the essential information is contained in the "photopeak", the practical measure of resolution is the width of the photopeak or "instrumental line width". The convention adopted is to define the resolution as the relative full width of the photopeak measured at half the maximum height of the peak (FWHM). Thus, the resolution will be FWHM divided by the mean photopeak position on the pulse-height scale. As a matter of convenience, the resolution of a NaI scintillation detector is usually reported for the 0.662-MeV gamma ray emitted by ^{137}Cs.

The photoline width is primarily a result of statistical fluctuations in each step following the initial event that produces ionization in the detector. Among these are the following:

[1] Conversion of the kinetic energy of the primary electrons to light.

[2] Efficiency of light collection and transfer of photons to the photocathode.

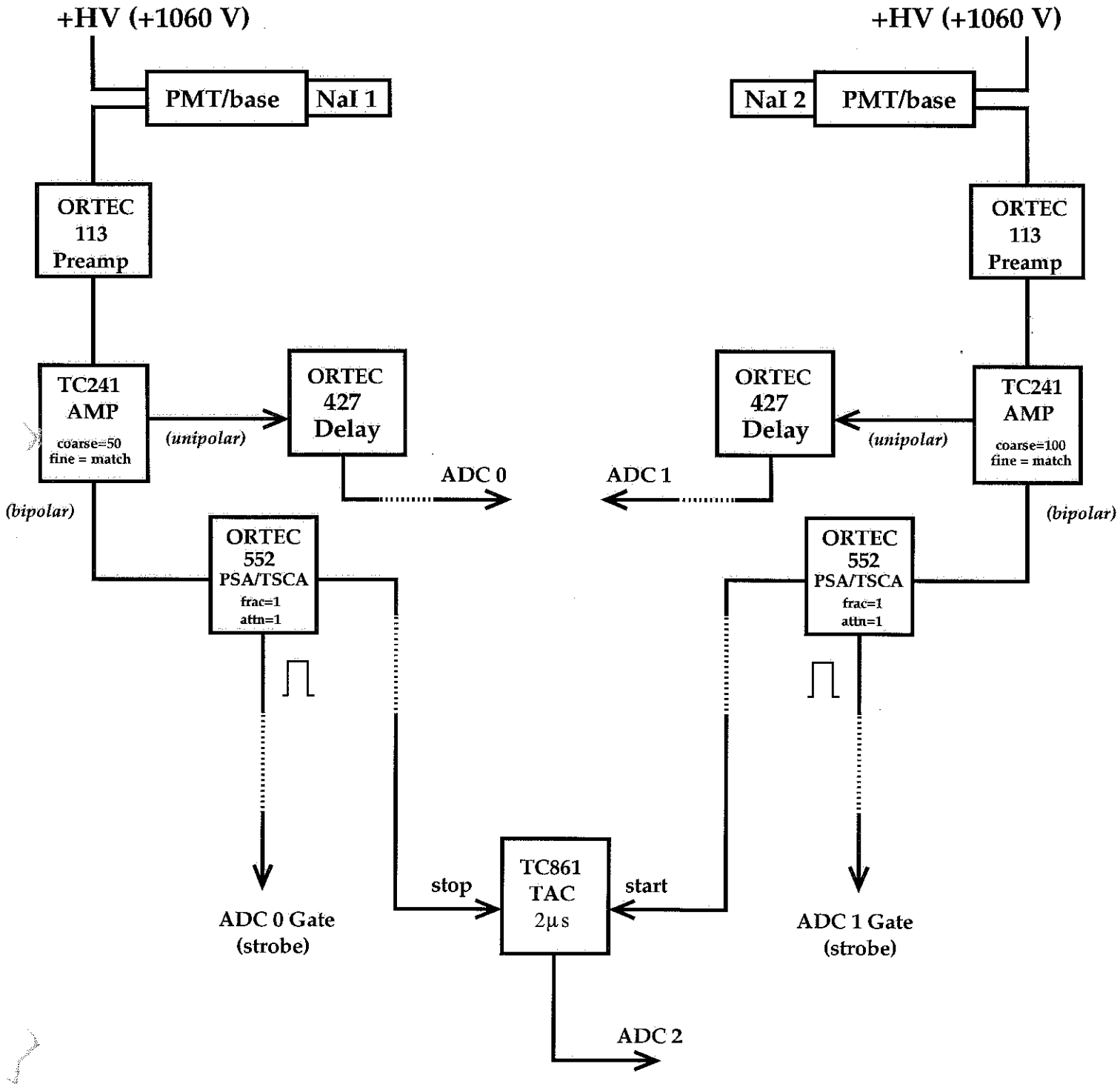
[3] Efficiency of the photocathode in the conversion of photons to photoelectrons.

[4] Efficiency of electron optics in phototube for focussing of electrons on the first secondary-emitting dynode.

[5] Electron multiplication in the dynode structure.

Each of these steps in the scintillation process will ultimately affect the statistical variance in the pulse amplitude appearing at the anode of the electron multiplier.

Electronics Set–up



Electronics Modules List

- **Ortec 113 Preamplifier** : This preamplifier is designed for use with dynode or anode signals from photomultiplier tubes. The charge in the photomultiplier output pulse is integrated on the input capacitance of the preamplifier to produce a voltage pulse.
- **Tennelec TC 241 Amplifier** : This high performance spectroscopy amplifier is designed for low noise and high count rate operations that are ideally suited for scintillation detectors.
- **Ortec 427a Delay Amplifier** : This module is designed for general purpose variable delay of linear or logic signals. The amplifier ensures the output amplitude matches the input amplitude.
- **Ortec 552 PSA/T-SCA** : This Pulse-Shape Analyzer and Timing Single Channel Analyzer is designed for performing pulse height analysis, timing signal derivation, and determination of pulse shapes.
- **Tennelec TC 861 TAC** : This Time-to-Amplitude converter is designed to produce an analog output pulse proportional to the time interval between the START and STOP inputs.

Pre-Defined Histograms

vector	histogram name	type	comment
0	gam1	1D	energy of NaI 1
1	gam2	1D	energy of NaI 2
2	gtac	1D	time between NaI 1 and NaI 2
3	g1_t	2D	time vs. gam1
4	g2_t	2D	time vs. gam2
5	g1_g2	2D	gam2 vs. gam1
10	g11	1D	gam1 cond. $\equiv$ gate 0 $\cdot$ gate 1
11	g21	1D	gam2 cond. $\equiv$ gate 0 $\cdot$ gate 1
12	g12	1D	gam1 cond. $\equiv$ gate 0 $\cdot$ gate 2
13	g22	1D	gam2 cond. $\equiv$ gate 0 $\cdot$ gate 2
14	g13	1D	gam1 cond. $\equiv$ gate 0 $\cdot$ gate 3
15	g23	1D	gam2 cond. $\equiv$ gate 0 $\cdot$ gate 3

TO SET GATES:

Use the command *"gate i limlo limhi"*

Here i is the gate number (0,1,2) and the lower and upper limits are given by *limlo* and *limhi*, respectively.

TO RUN FOR A FIXED TIME DURATION

Use the command *"time"* to set the time duration in seconds.

Use the command *"run"* to run the DAQ system for this duration.

Four-Input Multi-Channel Analyzer

The "home-made" multi-channel analyzer consists of 4 "sample-and-hold" units that can measure the amplitude of an input signal and hold this amplitude (0 to 10 volts) until it is digitized by a single fast-successive approximation analog-to-digital converter (ADC). The digitized data are stored in a first-in-first-out (FIFO) buffer after averaging out the differential non-linearity of the ADC's, providing a very linear response (this is referred to as channel width averaging). The unique feature of the buffered data is its sequenced storage as input 0 to input 3, which allows the four input channels to be analyzed separately within the time resolution of the analyzer. The data can then be saved for later analysis or plotted for on-line observation.

The computer interrupt routine (the controlling program of the Data Acquisition system, or DAQ) also allows the user to set gates. In the $\gamma - \gamma$ coincidence interrupt, the gates sort the data on-line, i.e. as it is being acquired. The gates are pre-defined (in the `ugl1` interrupt) as follows:

Gate 0 : The coincidence time overlap of the two NaI signals from the output of the time-to-amplitude converter (TAC). This spectrum is called `gtac`.

Gate 1: Set on the `gam2` spectrum to identify the 0.511 MeV gamma ray peak of ^{22}Na.

Gate 2: Set on the `gam2` spectrum to identify the 1.275 MeV gamma ray peak of ^{22}Na.

Differential non-linearity: Ideally any two adjacent digital codes correspond to output analog voltages that are exactly one LSB apart. Differential non-linearity is a measure of the worst case deviation from the ideal 1 LSB step. Ideally one should expect that if the detector is irradiated by a sufficiently homogeneous source, then the number of counts in each ADC pixel is linearly proportional to the size of the pixel. To put it differently, the relative deviation from the average size of the pixels is a measure for the differential non-linearity.

TO SAVE DATA

1). At the *DAQ* prompt enter the subdirectory where you want the data to be stored. The subdirectories are created on /home/ugl1/data. You carry out this process by defining a "disk number" via the command: *disk #*. This will create the subdirectory */home/ugl1/data/disk#* where all of the histograms will be saved. You should choose a number that does not yet exist.

2). At the *DAQ* prompt enter the starting label (called a "tag") for the histogram set. Use the command: *tag #*.

3). At the *DAQ* prompt type *sav* to save all histograms.

TO RECOVER THE DATA FOR PLOTTING

1). Clear out all histograms already in memory with the command: *clear **.

2). At the *DAQ* prompt use the script command *review*. This will load all histograms in the defined *disk* area starting with the defined *tag* number.

3). Note that individual histograms can be printed using the on-screen "print" button.

File: IPL.daq (also called setup.daq)

```
define gam1 1024
define gam2 1024
define gtac 1024
define g1_t 4096 type 1
define g2_t 4096 type 1
define g1_g2 4096 type 1
define g11 1024
define g21 1024
define g12 1024
define g22 1024
define g13 1024
define g23 1024
vector 0 gam1 1024
vector 1 gam2 1024
vector 2 gtac 1024
vector 3 g1_t 4096
vector 4 g2_t 4096
vector 5 g1_g2 4096
vector 10 g11 1024
vector 11 g21 1024
vector 12 g12 1024
vector 13 g22 1024
vector 14 g13 1024
vector 15 g23 1024
loadint ugl1
t0 10
gate 0 280 330
gate 1 145 180
gate 2 285 335
gate 3 380 455
```

Note: ugl1 is one of the many interrupt routines in `int8.c` (so it acts like a subroutine).

Interrupt Routine: ugl1

```
#include <dos.h>
#include <bios.h>
#include <stdio.h>
#include <oual.h>
#include <signal.h>
#include <conio.h>
#include <stdlib.h>
#include <time.h>
#include <string.h>

char oual_system_name[] = "UGL Gamma-Gamma_Coinc 27 March 1996\n"; */
/* gamma1 energy signal applied to adc0
 * gamma2 energy signal applied to adc1
 * coincidence tac signal applied to adc2
 * vector 0 = gam1
 * vector 1 = gam2
 * vector 2 = g1-g2 tac
 * vector 3 = gam1_coinc 2d
 * vector 4 = gam2_coinc 2d
 * vector 5 = gam1_gam2  2d
 * vector 10 = gam1 gated
 * vector 11 = gam2 gated/

extern int oual_event_flag;
void ugl_int(void)

{
unsigned g1,g2,g12t,flag;
unsigned g1_g2,g1_t,g2_t;

databufferptr = (struct databuffer *) shmptr;
databufferptr->dav = 1;
if(databufferptr->nevents <= 0) goto ret;  //return;

if(oual_anal == 0) goto ret;

oual_lastadc=-1;
ouindex=0;

while(databufferptr->nevents-- > 0)
  {if(((oual_rawdata=databufferptr->data[ouindex++]) & 0x8000) == 0) /* is data present */
     {if (oual_anal == 0) goto ret;
     oual_adcdata=oual_rawdata & 0xfff;
     oual_adcnumber=(oual_rawdata & 0x3000) >> 12;
     if (oual_adcnumber == 0)
                {g1 = oual_adcdata;
                oual_lastadc = 0;
                histogram(0,g1);}
     if ((oual_adcnumber == 1) && (oual_lastadc == 0))
                {g2 = oual_adcdata;
                oual_lastadc = 1;
                histogram(1,g2);
                g1_g2=((((g2 & 0xfc0) << 6) | g1) >> 6);
```

```
            histogram(5, g1_g2);}
    else if (oual_adcnumber == 1)
            {histogram(1,oual_adcdata);
            oual_lastadc = -1;}
    if ((oual_adcnumber == 2) && (oual_lastadc == 1))
            {g12t = oual_adcdata;
            histogram(2,g12t);
            g1_t=((((g12t & 0xfc0) << 6) | g1) >> 6);
            histogram(3, g1_t);
            g2_t=((((g12t & 0xfc0) << 6) | g2) >> 6);
            histogram(4, g2_t);
            if((checkgate(1,1,g2) == 1) && (checkgate(0,2,g12t) == 1))
               {histogram(10,g1);
                histogram(11,g2);}
            if((checkgate(2,1,g2) == 1) && (checkgate(0,2,g12t) == 1))
               {histogram(12,g1);
                histogram(13,g2);}
            if((checkgate(3,1,g2) == 1) && (checkgate(0,2,g12t) == 1))
               {histogram(14,g1);
                histogram(15,g2);}
            oual_lastadc = -1;}
     else if (oual_adcnumber == 2)
            {histogram(2,oual_adcdata);
             oual_lastadc = -1;}
    }
  }

ret:
databufferptr->nevents = 0;
databufferptr->dav = 0; /* set no data available */
return;}
```

Nuclear Data (NuDat) Retrieval

Decay Radiations

Mass Number: 22 **Radiation:**
Element: NA **Radiation Energy (keV):**
$T_{1/2}$: **Radiation Intensity:**
Decay Mode:
Sort order: Mass number, Proton number, Half-Life, and Radiation

A	ELEMENT	Z	Decay Mode	Half-Life	Rad. Type		Radiation Energy (keV)	Radiation Intensity (%)	Dos (G-E /UCI
22	NA	11	EC	2.6019 Y 0.0004	B+		215.54 0.21	90.498 0.003	0.41
22	NA	11	EC	2.6019 Y 0.0004	B+	TOT	215.92 0.21	90.554 0.015	0.41
22	NA	11	EC	2.6019 Y 0.0004	B+		835.00 0.23	0.056 0.014	0.00
22	NA	11	EC	2.6019 Y 0.0004	E	AU K	0.8200	9.20 0.03	0.00
22	NA	11	EC	2.6019 Y 0.0004	G	X K	0.84	0.1253 0.0005	0
22	NA	11	EC	2.6019 Y 0.0004	G	AN	511.	<=181.11	
22	NA	11	EC	2.6019 Y 0.0004	G		1274.530(20)	99.944 0.014	2.71

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Nuclear Data (NuDat) Retrieval

Decay Radiations

Mass Number: 60 **Radiation:**
Element: CO **Radiation Energy (keV):**
$T_{1/2}$: **Radiation Intensity:**
Decay Mode:
Sort order: Mass number, Proton number, Half-Life, and Radiation

A	ELEMENT	Z	Decay Mode	Half-Life	Rad. Type		Radiation Energy (keV)	Radiation Intensity (%)	Dos (G-F /UCI
60	CO	27	B-	1925.3 D 0.3	B-		95.77 0.15	99.88 0.03	0.20
60	CO	27	B-	1925.3 D 0.3	B-	TOT	96.41 0.15	100.00 0.05	0.20
60	CO	27	B-	1925.3 D 0.3	B-		625.87 0.21	0.12 0.03	0.00
60	CO	27	B-	1925.3 D 0.3	E	AU L	0.8400	0.0366 0.0020	0
60	CO	27	B-	1925.3 D 0.3	E	AU K	6.540	0.0156 0.0006	0
60	CO	27	B-	1925.3 D 0.3	E	CE K	338.81 0.07	0.000038(3)	0
60	CO	27	B-	1925.3 D 0.3	E	CE L	346.13 0.07	0.0000038(3)	0
60	CO	27	B-	1925.3 D 0.3	E	CE K	817.77 0.03	0.0000024(4)	0
60	CO	27	B-	1925.3 D 0.3	E	CE L	825.09 0.03	0.0000002	0
60	CO	27	B-	1925.3 D 0.3	E	CE K	1164.895(3)	0.0151 0.0009	0.00
60	CO	27	B-	1925.3 D 0.3	E	CE K	1324.159(4)	0.0115 0.0006	0.00
60	CO	27	B-	1925.3 D 0.3	E	CE K	2150.24 0.03	0.00000005	0
60	CO	27	B-	1925.3 D 0.3	E	CE L	2157.56 0.03	0	0
60	CO	27	B-	1925.3 D 0.3	E	CE K	2497.359(5)	0	0
60	CO	27	B-	1925.3 D 0.3	E	CE L	2504.684(5)	0	0
60	CO	27	B-	1925.3 D 0.3	G	X L	0.8500	0.000140(8)	0
60	CO	27	B-	1925.3 D 0.3	G	X KA2	7.46089(4)	0.00327(13)	0
60	CO	27	B-	1925.3 D 0.3	G	X KA1	7.47815(4)	0.0064 0.0003	0
60	CO	27	B-	1925.3 D 0.3	G	X KB	8.260	0.00131(6)	0
60	CO	27	B-	1925.3 D 0.3	G		347.14 0.07	0.0075 0.0004	0
60	CO	27	B-	1925.3 D 0.3	G		826.10 0.03	0.0076 0.0008	0.00
60	CO	27	B-	1925.3 D 0.3	G		1173.228(3)	99.85 0.03	2.50
60	CO	27	B-	1925.3 D 0.3	G		1332.492(4)	99.9826(6)	2.84
60	CO	27	B-	1925.3 D 0.3	G		2158.57 0.03	0.00120(20)	0
60	CO	27	B-	1925.3 D 0.3	G		2505.692(5)	0.0000020(4)	0
60	CO	27	B-	1925.3 D 0.3	G		248.80 0.06	0.0084 0.0008	0
60	CO	27	B-	10.467 M 0.006	B-	TOT	593.77 0.06	0.238 0.005	0.00
60	CO	27	B-	10.467 M 0.006	B-		606.37 0.05	0.230 0.004	0.00
60	CO	27	B-	10.467 M 0.006	B-		0.7500	125. 4.	0.00
60	CO	27	IT	10.467 M 0.006	E	AU L	6.070	48.93 0.06	0.00
60	CO	27	IT	10.467 M 0.006	E	AU K	50.894 0.007	79.080 0.024	0.08
60	CO	27	IT	10.467 M 0.006	E	CE K	57.677 0.007	14.036 0.005	0.01
60	CO	27	IT	10.467 M 0.006	E	CE L	0.7800	0.441 0.015	0
60	CO	27	IT	10.467 M 0.006	G	X L	6.91530(4)	8.94 0.03	0.00
60	CO	27	IT	10.467 M 0.006	G	X KA2	6.93032(4)	17.62 0.06	0.00
60	CO	27	IT	10.467 M 0.006	G	X KA1	7.650	3.59 0.07	0.00
60	CO	27	IT	10.467 M 0.006	G	X KB	58.603 0.007	2.0359 0.0007	0.00
60	CO	27	IT	10.467 M 0.006	G		826.28 0.09	0.008 0.004	0.00
60	CO	27	B-	10.467 M 0.006	G		1332.501(5)	0.24 0.03	0.00
60	CO	27	B-	10.467 M 0.006	G				

```
 60 CO  27    B- 10.467 M 0.006  G              2158.77 0.09 0.0007 0.0004  0
```


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Nuclear Data (NuDat) Retrieval

Decay Radiations

Mass Number: 137 **Radiation:**
Element: CS **Radiation Energy (keV):**
$T_{1/2}$: **Radiation Intensity:**
Decay Mode:
Sort order: Mass number, Proton number, Half-Life, and Radiation

A	ELEMENT	Z	Decay Mode	Half-Life	Rad. Type		Radiation Energy (keV)	Radiation Intensity (%)	Dos (G-F /UCI
137	CS	55	B-	30.07 Y 0.03	B-		174.32 0.07	94.40 0.20	0.35
137	CS	55	B-	30.07 Y 0.03	B-	TOT	187.87 0.07	100.0 0.3	0.40
137	CS	55	B-	30.07 Y 0.03	B-		300.57 0.07	0.00058(8)	0
137	CS	55	B-	30.07 Y 0.03	B-		416.26 0.08	5.60 0.20	0.04
137	CS	55	B-	30.07 Y 0.03	E	AU L	3.670	7.2 0.5	0.00
137	CS	55	B-	30.07 Y 0.03	E	AU K	26.40	0.757 0.024	0.00
137	CS	55	B-	30.07 Y 0.03	E	CE K	624.216 0.003	7.66 0.23	0.10
137	CS	55	B-	30.07 Y 0.03	E	CE L	655.668 0.003	1.39 0.05	0.01
137	CS	55	B-	30.07 Y 0.03	G	X L	4.470	1.0 0.3	0
137	CS	55	B-	30.07 Y 0.03	G	X KA2	31.8171(3)	1.96 0.06	0.00
137	CS	55	B-	30.07 Y 0.03	G	X KA1	32.1936(3)	3.62 0.11	0.00
137	CS	55	B-	30.07 Y 0.03	G	X KB	36.40	1.32 0.05	0.00
137	CS	55	B-	30.07 Y 0.03	G		283.50 0.10	0.00058(8)	0
137	CS	55	B-	30.07 Y 0.03	G		661.657 0.003	85.10 0.20	1.20

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EXPERIMENT 3

Gamma-Ray Spectroscopy Using NaI(Tl)

EQUIPMENT NEEDED FROM EG&G ORTEC FOR EXPERIMENTS 3.1 THROUGH 3.7, 3.9, and 3.10

Bin and Power Supply
905-3 NaI(Tl) Crystal and Phototube Assembly
266 Photomultiplier Tube Base
556 High Voltage Power Supply
113 Scintillation Preamplifier
575A Amplifier
^{137}Cs gamma source, 5 μCi ±5%
SK-1G Source Kit (see Appendix)
Absorber Kit Model 3-Z2
Absorber Kit PbAl-23
M-NaI-3 Stand for Sodium Iodide Detector
ACE-2K MCA System including suitable IBM PC (other EG&G ORTEC MCAs may be used)
Oscilloscope

ADDITIONAL EQUIPMENT NEEDED FROM EG&G ORTEC FOR EXPERIMENT 3.8

427A Delay Amplifier
551 Timing Single-Channel Analyzer
426 Linear Gate
875 Counter

Purpose

The purpose of this experiment is to acquaint the student with some of the basic techniques used for measuring gamma rays. It is based on the use of a sodium iodide (NaI) detector that is thallium (Tl) activated.

Gamma Emission

Most isotopes that are used for gamma measurements also have betas in their decay schemes. The typical decay scheme for the isotope will include a beta decay to a particular level followed by gamma emission to the ground state of the final isotope. The beta particles will usually be absorbed in the surrounding material and not enter the scintillator at all. This absorption is normally assured with aluminum absorbers (ref. 10). For this experiment the betas offer no real problem, and so absorbers are not specified. There will be some beta absorption by the light shield over the phototube. The gammas, however, are quite penetrating and will pass easily through the aluminum light shield.

Generally there are two unknowns that we would like to investigate about a gamma source. One is the energies of the gammas from the source; the other is the number of gammas that leave the source per unit of time. In this experiment the student will become familiar with some of the basic NaI(Tl) measurements associated with gamma-emitting unknowns.

A total time of ~6 h is required to complete all the parts of Experiment 3 (3.1 through 3.10). The complete series can be done in two 3-h lab periods, since each is written to be fairly independent of the others.

EXPERIMENT 3.1

Energy Calibration

Setup of Equipment

Set up the electronics in the arrangement shown in Fig. 3.1. There are two parameters that ultimately determine the overall gain of the system: the high voltage that is furnished to the phototube and the gain of the linear amplifier. The gain of the photomultiplier tube is quite dependent upon its high voltage. A rule of thumb for most phototubes is that a 10% change of the high voltage will change the gain by a factor of 2. The high-voltage value depends on the phototube being

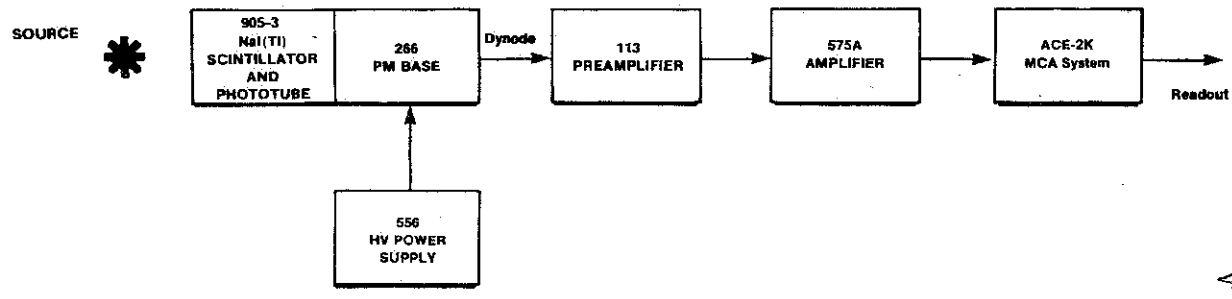


Fig. 3.1. Electronic Block Diagram for Gamma-Ray Spectroscopy System with NaI(Tl) Detector.

MCA = Multi Channel analyzer

used; consult your instruction manual for the phototube and select a value in the middle of its normal operating range. (The instructor may wish to recommend a value.)

Set the indicated modules as follows:

556 High Voltage: See phototube instructions and set the level at about the middle of the acceptable operating range (normally about +1000 V).

113 Scintillation Preamplifier: Set the Input Capacity switch at 200 pF. The output pulses will be positive.

575A Amplifier: Positive input and Bipolar output. Shaping time set to 0.5 μsec. The gain will be adjusted during the experiment.

Multichannel Analyzer: PHA Analysis mode; 1000 channels are adequate for this experiment.

Procedure

1. Place the ^{137}Cs source from SK-1G (E_γ = 0.662 MeV) ~2 cm in front of the NaI(Tl) crystal.

2. Adjust the coarse and fine gain controls of the linear amplifier so that the 0.662-MeV photopeak for ^{137}Cs falls at approximately channel 280. For the illustrations shown in Figs. 3.2 and 3.3, the gain of the system has been set so that 1 MeV falls at about channel 420 to 425. Since the system is linear, 2 MeV would therefore fall at approximately channel 840 to 850.

3. Accumulate the ^{137}Cs spectrum for a time period long enough to determine the peak position. Figure 3.2 shows a typical ^{137}Cs spectrum that has been plotted. Although these spectra are usually plotted on semilog graph paper, the figures shown in this experiment are plotted on linear paper to point out some of the features of the spectra.

4. After the ^{137}Cs spectrum has been read out of the MCA, erase it and replace the ^{137}Cs source with a ^{60}Co source from SK-1G.

5. Accumulate the spectrum for a period of time long enough for the spectrum to be similar to that in Fig. 3.3.

6. Read out the MCA.

EXERCISES

a. Plot both the ^{137}Cs and ^{60}Co spectra and fill in items 1, 2, and 3 in Table 3.1.

b. From items 1, 2, and 3 in Table 3.1 make a plot of energy of the photopeaks vs channel number. Figure 3.4 shows this calibration for the data taken from Figs. 3.2 and 3.3. If other calibration sources are available, additional data points can be added to Fig. 3.4. The other entries in Table 3.1 will be filled out in Experiment 3.3.

c. Use the energy calibration feature of the MCA and compare the results with those found in Exercise **b**.

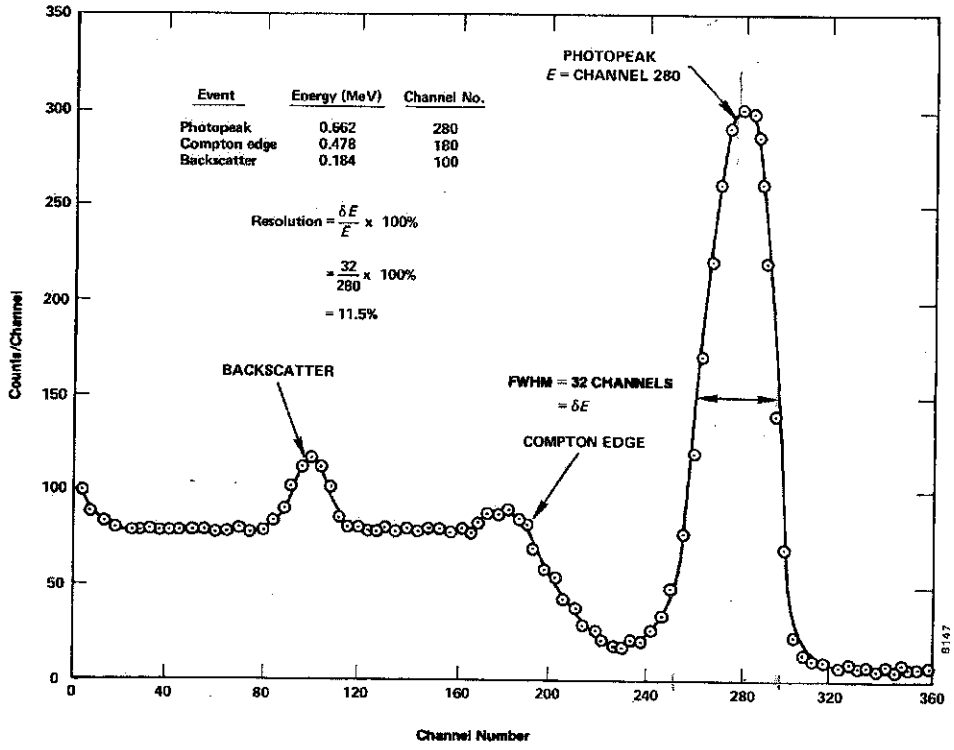


Fig. 3.2. NaI(Tl) Spectrum for ^{137}Cs.

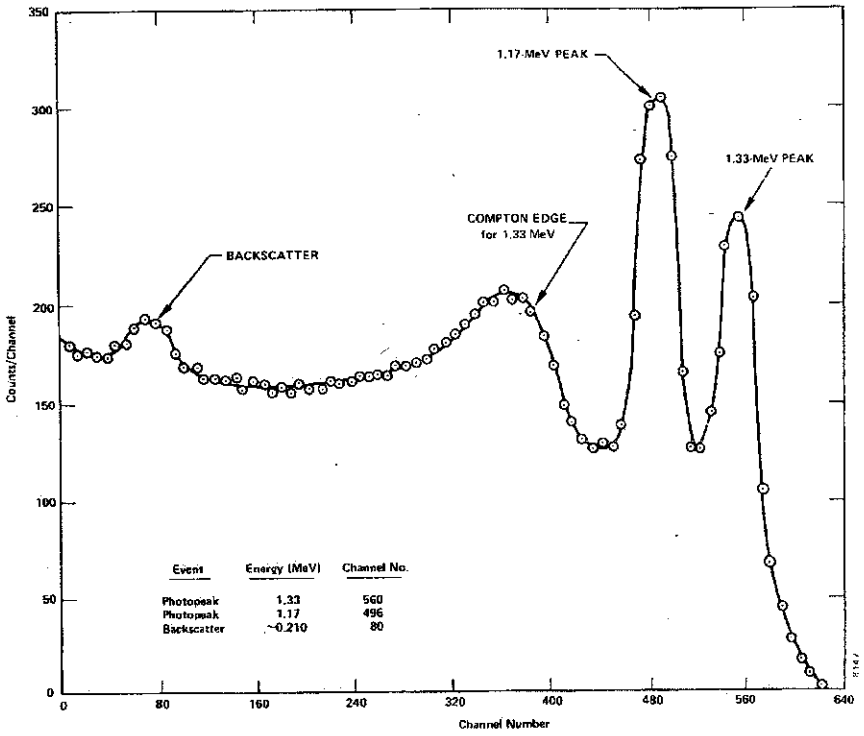


Fig. 3.3. NaI(Tl) Spectrum for ^{60}Co.

Table 3.1

	Event	Energy (MeV)	Channel Number
1.	0.662-MeV photopeak	0.662	
2.	1.17-MeV photopeak	1.17	
3.	1.33-MeV photopeak	1.33	
4.	Compton edge ^{137}Cs		
5.	Backscatter ^{137}Cs		
6.	Backscatter ^{60}Co		

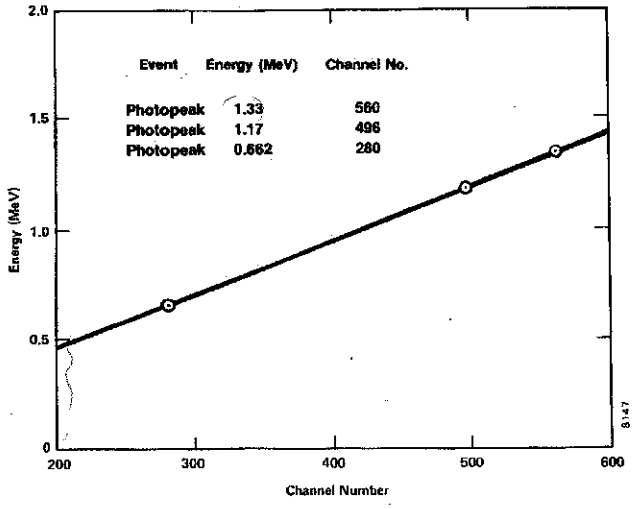


Fig. 3.4. Energy Calibration Curve for NaI(Tl) Detector.

EXPERIMENT 3.2

Energy Analysis of an Unknown Gamma Source

Purpose

The purpose here is to use the calibrated system of Experiment 3.1 to measure the photopeak energies of an unknown gamma emitter and to identify the unknown isotope.

Procedure

1. Erase the ^{60}Co spectrum from the MCA, but do not change any of the gain calibration settings of the system.

2. Obtain an unknown gamma source from the instructor. Accumulate a spectrum for the unknown source for a period of time long enough to clearly identify the photopeak(s) of the source. From the calibration curve, determine the energy for each photopeak.

EXERCISE

Use refs. 7 and 8 to identify the unknown isotope.

EXPERIMENT 3.3 (just calculations)

Spectrum Analysis of ^{60}Co and ^{137}Cs

Purpose

The purpose of this experiment is to explain some of the features, other than the photopeaks, that are usually present in a pulse-height spectrum. These are the Compton edge and the backscatter peak.

The Compton interaction is a pure kinematic collision between a gamma photon and what might be termed a free electron in the NaI(Tl) crystal. By this process the incident gamma gives up only part of its energy to the electron. The amount given to the recoil electron (and the intensity of the light flash) depends on whether the collision is head-on or glancing. For a head-on collision the gamma imparts the maximum allowable energy for the Compton interaction. The energy of the scattered gamma can be determined by solving the energy and momentum equations for this billiard ball collision. The solution for these equations in terms of the scattered gamma can be written approximately as

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 2E_\gamma\,(1 - \cos\theta)}\ , \qquad (1)$$

where

$E_{\gamma'}$ = energy of the scattered gamma in MeV,
θ = the scattering angle for γ',
E_γ = the incident gamma-ray energy in MeV.

If $\theta = 180°$ due to a head-on collision in which γ' is scattered directly back, Eq. (1) becomes

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma}\ . \qquad (2)$$

As an example, we will calculate $E_{\gamma'}$ for an incident gamma energy of 1 MeV:

$$E_{\gamma'} = \frac{1\ \text{MeV}}{1 + 4} = 0.20\ \text{MeV}. \qquad (3)$$

The energy of the recoil electron, E_e, for this collision would be 0.80 MeV. This is true since

$$E_e = E_\gamma - E_{\gamma'}\ . \qquad (4)$$

Then the position of the Compton edge, which is the maximum energy that can be imparted to an electron by the Compton interaction, can be calculated by Eq. (4).

EXERCISES

a. Calculate the energy of the Compton edge for the 0.662-MeV gammas from ^{137}Cs. Enter this value in Table 3.1. From your plot and calibration curve, does this calculation agree with your measured value?

b. Backscatter occurs when gammas make Compton interactions in the material that surrounds the detector. Figure 3.5 was taken from ref. 10 and is a good illustration of the various events that can take place in a typical source–NaI(Tl) detector–lead shield arrangement. Backscattered gammas from these interactions ($E_{\gamma'}$) make photoelectric interactions in the NaI(Tl) when they enter the crystal. The energy of the backscattered peak can be found by solving Eq. (2).

Solve Eq. (2) for the background gammas from ^{137}Cs and for the 1.33-MeV gammas from ^{60}Co. Fill in the rest of Table 3.1. How do your measured energies compare with the theoretical energies from Eq. (2)? If the backscatter peak is not very pronounced in your spectrum, it can be improved by accumulating a spectrum with a sheet of lead absorber placed slightly to the left of the source in Fig. 3.1.

EXPERIMENT 3.4

Energy Resolution (just calculations)

Purpose

The resolution of a spectrometer is a measure of its ability to resolve two peaks that are fairly close together in energy. Figure 3.2 shows the gamma spectrum that was plotted for the ^{137}Cs source. The resolution of the photopeak is found by solving the following equation:

$$R = \frac{\delta E}{E} \times 100, \quad = \frac{32}{280} \times 100 \qquad (5)$$

where

R = the resolution in percent,
δE = the full width of the peak at half of the maximum count level (FWHM) measured in number of channels,
E = the channel number at the centroid of the photopeak.

In Fig. 3.2 the photopeak is in channel 280 and its FWHM = 32 channels. From Eq. (5) the resolution is calculated to be 11.5%.

EXERCISE

Calculate the resolution of the system from your ^{137}Cs spectrum. Record this value for later reference.

EXPERIMENT 3.5

Activity of a Gamma Emitter (Relative Method)

Purpose

In Experiments 3.1 and 3.3, procedures were given for determining the energy of an unknown gamma source. Another

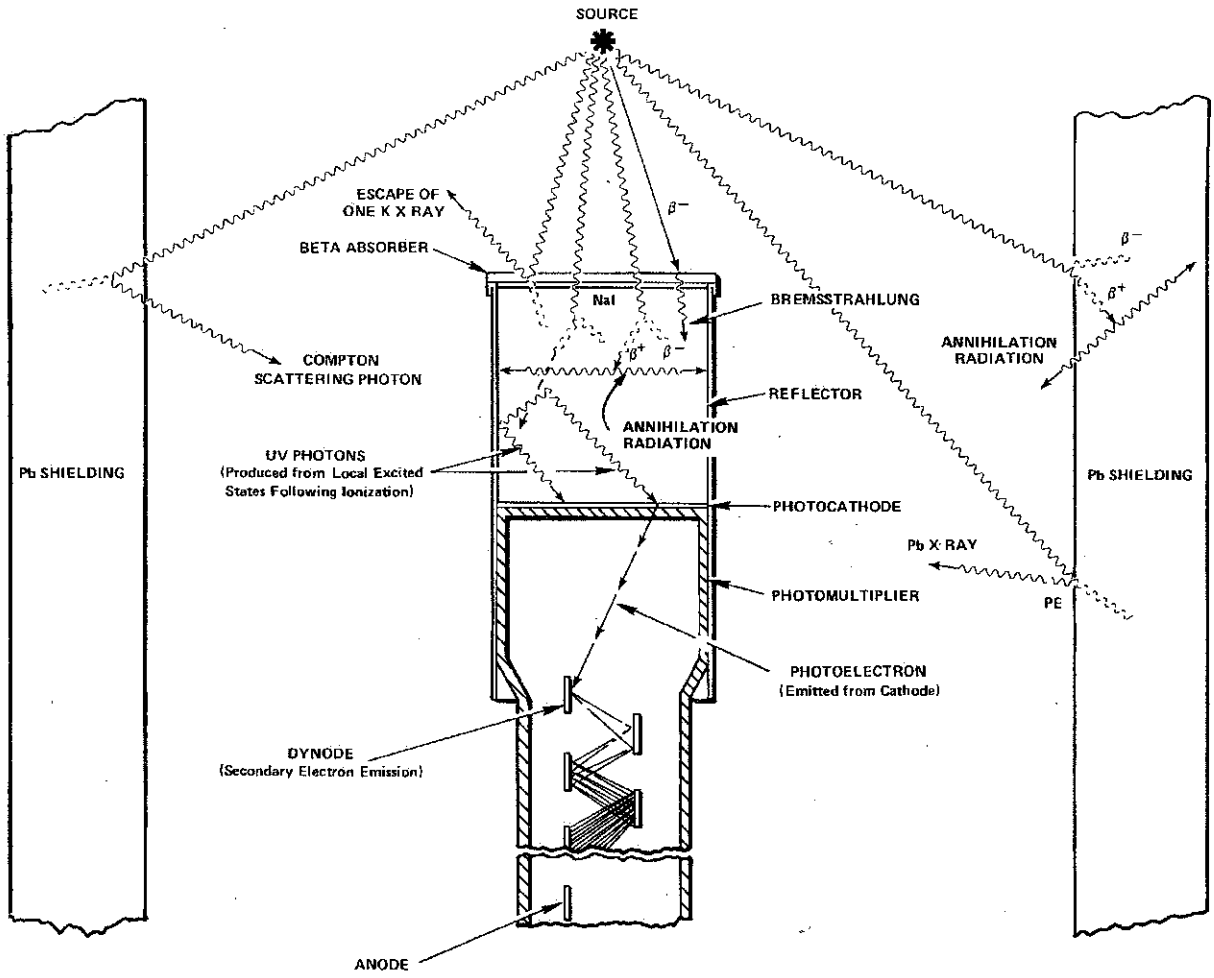


Fig. 3.5. Various Events in the Vicinity of a Typical Source–Crystal Detector–Shield Configuration.

unknown associated with the gamma source is the activity of the source, which is usually measured in curies (Ci); 1 Ci = 3.7×10^{10} disintegrations/s. Most of the sources that are used in nuclear laboratory experiments have activities of the order of microcuries (μCi). The purpose of this experiment is to outline one procedure by which the activity of a source can be determined, called the relative method.

In using the relative method, it is assumed that the unknown source has already been identified from its gamma energies. For this example, assume that the source has been found to be ^{137}Cs. Then all that is necessary is to compare the activity of the unknown source to the activity of a standard ^{137}Cs source that will be supplied by the laboratory instructor. For convenience, call the standard source S1 and the unknown source U1.

Procedure

1. Place the S1 source about 4 cm from the face of the detector (or closer if necessary to get reasonable statistics) and accumulate a spectrum for a period of live time, selectable on the analyzer, long enough to produce a spectrum similar to Fig. 3.2.

2. Use the cursor to determine the sum under the photopeak. In the example shown in Fig. 3.2, this would correspond to adding up all counts in channels 240 through 320. Define this sum to be Σ_{S1}.

3. Erase the MCA spectrum. Remove source S1 and replace it with source U1, positioned **exactly** the same distance from the crystal as the S1 source was. Accumulate a spectrum for the same period of live time that was used in step **1**. Sum the peak as in step **2**. Σ_{U1}

4. Erase the spectrum from the MCA. Remove the U1 source and accumulate background counts for the same period of live time that was used in steps **1** and **3** above.

5. Sum the background counts in the same channels that were used for the photopeaks in steps **2** and **3** above. Call this sum Σ_b

EXERCISE

Solve for the activity of the U1 by using the following ratio:

$$\frac{\text{activity of U1}}{\text{activity of S1}} = \frac{\Sigma_{U1} - \Sigma_b}{\Sigma_{S1} - \Sigma_b} \qquad (6)$$

Since the efficiency of the detector is only energy dependent, the standard and unknown sources do not have to be the same isotope. It is only necessary that their gamma energies be approximately the same (±10%) in order to get a fairly good estimate of the absolute gamma activity of the unknown.

EXPERIMENT 3.6

Activity of a Gamma Emitter (Absolute Method)

Purpose

The activity of the standard used in Experiment 3.5 can be determined by the absolute method. The purpose of this experiment is to outline the procedure for this method. Here the source that is to be measured will be called U1.

Procedure

1. Place the U1 source 9.3 cm away from the face of the detector.

2. Accumulate a spectrum and note the live time that is used.

3. Use the cursor to determine the sum under the photopeak, Σ_{U1}. Then erase the spectrum, remove the source, and accumulate background for the same live time and calculate Σ_b.

4. Use the following formula to calculate the activity of U1:

$$\text{activity of U1} = \left(\frac{\Sigma_{U1} - \Sigma_b}{t}\right) \frac{1}{G\epsilon_p f}, \qquad (7)$$

where

t = live time in seconds,

ϵ_p = intrinsic peak efficiency for the gamma energy and detector size used (Fig. 3.6 and ref. 10),

f = the decay fraction of the unknown activity which is the fraction of the total disintegrations in which the measured gamma is emitted (refs. 7 and 8 and Table 3.2),

G = area of detector (cm^2)/$4\pi s^2$,

s = source-to-detector distance in cm.

Table 3.2. Gamma Decay Fraction, (f), for Some Common Isotopes.

Isotope	Gamma Energy (MeV)	f
^{137}Cs	0.662	0.92
^{51}Cr	0.323	0.09
^{60}Co	1.17	0.99
^{60}Co	1.33	0.99
^{22}Na	1.276	0.99
^{22}Na	0.511	0.99
^{54}Mn	0.842	1.00
^{65}Zn	1.14	0.44

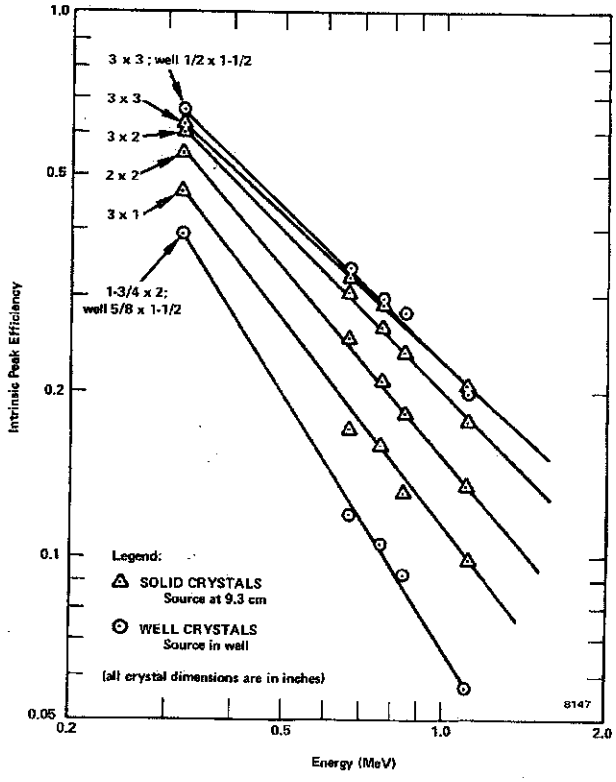


Fig. 3.6. Intrinsic Peak Efficiency of Various NaI(Tl) Crystals vs Gamma Energy.

EXPERIMENT 3.7

Mass Absorption Coefficient

Purpose

The purpose of the experiment is to measure experimentally the mass absorption coefficient in lead for 662-keV gamma rays.

References 2, 3, and 5 point out that gammas interact in matter primarily by photoelectric, Compton, or pair-production interactions. The total-mass absorption coefficient can be measured easily with a gamma-ray spectrometer. In this experiment we will measure the number of gammas that are removed from the photopeak by photoelectric or Compton

interactions that occur in a lead absorber placed between the source and the phototube.

From Lambert's law (ref. 1) the decrease of intensity of radiation as it passes through an absorber is given by

$$I = I_0 e^{-\mu x}, \quad (8)$$

where

I = intensity after the absorber,
I_0 = intensity before the absorber,
μ = total-mass absorption coefficient in cm^2/g,
x = density thickness in g/cm^2.

The density thickness is the product of the density in g/cm^3 times the thickness in cm.

The half-value layer (HVL) is defined as the density thickness of the absorbing material that will reduce the original intensity by one-half. From Eq. (8):

$$\ln I/I_0 = -\mu x. \quad (9)$$

If $I/I_0 = 0.5$ and x = HVL, $\ln 0.5 = -\mu(\text{HVL})$ and hence

$$\text{HVL} = \frac{0.693}{\mu} \quad (10)$$

In this experiment we will measure μ in lead for the 0.662-MeV gammas from ^{137}Cs. The accepted value is 0.105 cm^2/g. Values for other materials can be found in ref. 8.

Procedure

1. Place the ^{137}Cs source about 5.0 cm from the NaI(Tl) detector and accumulate the spectrum long enough for the sum under the 0.662-MeV peak ($\Sigma_{Cs} - \Sigma_b$) to be at least 6000 counts. Determine ($\Sigma_{Cs} - \Sigma_b$).

2. Erase the MCA and insert a piece of lead from the absorber kit between the source and the detector. Accumulate the spectrum for the same period of live time as in step **1** above. Determine ($\Sigma_{Cs} - \Sigma_b$).

3. Erase the MCA and insert another piece of lead. Determine ($\Sigma_{Cs} - \Sigma_b$). Repeat with additional thicknesses of lead until the count-sum is >1000. Fill in the data in Table 3.3.

Table 3.3. Data for Mass Absorption Coefficient.

Absorber	Absorber Thickness (mg/cm^2)	$\Sigma_{Cs} - \Sigma_b$
1	0	
2		
3		
4		
5		
6		
7		

EXERCISES

a. Using semilog graph paper, plot I vs absorber thickness in mg/cm^2, where $I = (\Sigma_{Cs} - \Sigma_b)$/live time. Determine the HVL from this curve and calculate μ from Eq. (10). How does your value compare with the accepted value of 0.105 cm^2/g?

b. Repeat the above experiment for the aluminum absorbers in the Absorber Kit. The μ for aluminum is 0.074 cm^2/g.

EXPERIMENT 3.8

The Linear Gate in Gamma-Ray Spectroscopy

Purpose

The purpose of this experiment is to show how a linear gate can be used with an MCA in gamma-ray spectroscopy. The linear gate will limit the analysis of input pulse amplitudes to those that will be included within the photopeak.

The measurement of the mass absorption coefficient in Experiment 3.7 required the accumulation of several complete spectra, although the data of interest were included within only a fraction of the total number of channels that were used. The normal time for completing Experiment 3.7 is approximately 45 min. By using a linear gate, the same information can be obtained in about 1/3 of the time. An equivalent saving of time can also be made in Experiments 3.5 and 3.6 (Source Activity Determinations). Since the procedures are about the same as for Experiment 3.7, the student should repeat these experiments with the linear gate to see how much time will be saved.

See equipment list at beginning of Experiment 3 for additional equipment required for Experiment 3.8.

Connect the system components as shown in Fig. 3.7. Connect the bipolar output of the 575A Amplifier to both the 427A Delay and the 551 Timing Single-Channel Analyzer. Connect the Delay output to the linear Input of the 426 Linear Gate and connect the gate output to the analyzer input. Connect the SCA output to both the 875 Counter input and the Enable input of the Linear Gate.

The Linear Gate is a module that permits linear pulses to be passed only during the time interval that follows each Enable input. In normal operation the adjusted time interval will allow only one linear pulse to be furnished into the MCA.

The Timing Single-Channel Analyzer determines whether each input pulse amplitude is within the window and generates a logic output pulse for each input pulse that satisfies the criteria. By adjusting the lower and upper levels of its window, the 551 then can determine what portion of the spectrum is gated through for analysis in the MCA. This is true since it delivers the enable logic pulse to open the linear gate.

From the standpoint of timing, one would like to have the logic pulse arrive at the enable input of the linear gate just prior to the arrival of the corresponding linear pulse that is to be gated. Since the amplifier provides a bipolar output to the SCA, and since the SCA generates an output at 50% of full amplitude on the trailing edge of the positive lobe, the SCA output will occur at about 2 μs after the onset of the pulse. Thus, if the 427A Delay is set for 3 μs and the 426 Linear Gate width is adjusted to maximum, 4 μs, the gate passes the input pulse for a period from 1 μs before the delayed pulse reaches the 426 until 3 μs of elapsed pulse time. This passes the positive portion of the bipolar pulse, which is all that affects the MCA measurement; the negative portion of the bipolar pulse is not used.

The inclusion of a counter in Fig. 3.7 permits a direct total of the counts to be observed, and the adjustment of the window width will limit these to the peak area. This simplifies the summing of counts for peak area integrations.

Figure 3.8 shows how Fig. 3.2 might look if the window of the SCA were set properly to just span the ^{137}Cs photopeak. Since the MCA has a live display while it is accumulating, it is quite simple to adjust the window of the SCA properly.

The single-channel principle and the control of the linear gate are examined here with individual modules. Both functions are also included in the MCA, so the separate modules are not required for other experimental applications.

Module Settings:

Use the same settings for the high-voltage power supply, preamplifier, and amplifier that were used for Experiment 3.1. Set the 426 Linear Gate for Normal with its Gate Width control fully clockwise for 4 μs. Set the 875 Counter for count and use the Positive input from one of the Pos Out connectors on the 551 Timing SCA; reset the 875 Counter to zero. Set the 551 Timing SCA for Normal operation, the Lower-Level control at 030, the Upper-Level control fully clockwise

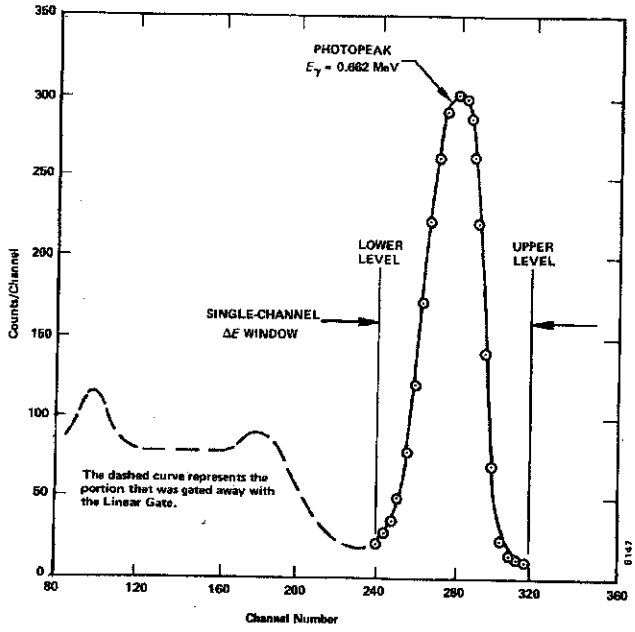


Fig. 3.8. ^{137}Cs Spectrum with the Linear Gate.

at 1000 divisions, and Delay at minimum for 0.1 μs. Set the 427A Delay Amplifier for a 3-μs delay.

Procedure

1. Place the ^{137}Cs source from SK-1G about 4 or 5 cm from the crystal face. Accumulate a spectrum in the MCA while adjusting the E and the ΔE window on the 551 Timing SCA. Set the window so that it just brackets the photopeak as in Fig. 3.8. You are now ready to make the first measurements.

2. Clear the MCA and reset the counter to zero. Start both at the same time and accumulate for a period of time long enough to obtain about 6000 counts in the counter. Record

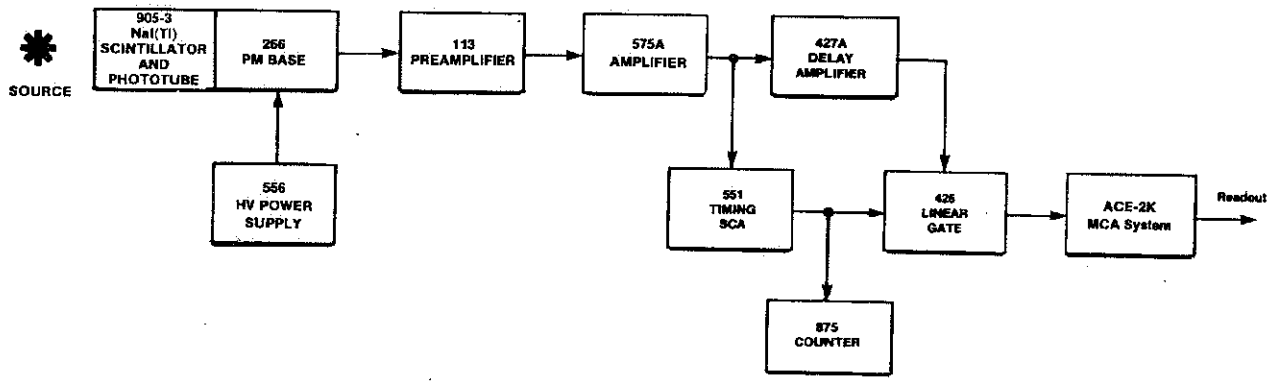


Fig. 3.7. Block Diagram of Electronics for Gamma-Ray Spectrometry System with a Linear Gate.

the total elapsed time for the measurement, the average dead time from the MCA, and the count in the counter. Read out the analyzer and then clear both the MCA and the counter.

3. Place the first lead absorber between the source and the detector as in Experiment 3.7 and accumulate for the same period of time that was used in step **2** above. Record only the counter counts and the total elapsed time. It is not necessary to read out the MCA for each spectrum since the counter is summing the counts under the photopeak. You should observe the MCA for each spectrum to make sure that the proper spectrum is being stored.

4. Repeat step **3** for each added absorber thickness that was used in Experiment 3.7. Make a background run with the source removed, and fill in Table 3.4 as in Experiment 3.7.

Table 3.4

Absorber	Absorber Thickness (mg/cm^2)	$\Sigma_{Cs} - \Sigma_b$
1	0	
2		
3		
4		
5		
6		
7		

5. Calculate the same data as in Experiment 3.7, Exercises **a** and **b**.

6. In step **2** the output of the MCA was read. Sum this output spectrum and compare it with the counter sum that was taken from the same run. The counter sum should be slightly larger since it does not suffer from dead-time corrections at these counting rates. The MCA does suffer, because it requires some amount of time to measure and store each pulse and thus does not actually analyze as many pulses as have been furnished to it. The MCA sum should be equal to the counter count times the percent of live time, which is equal to the live time of the MCA divided by the clock time for the spectrum accumulation.

EXPERIMENT 3.9

Sum Peak Analysis

Figure 3.3 shows the two pronounced peaks in ^{60}Co. Figure 3.9 shows the decay scheme of ^{60}Co.

Most of the time the decay occurs by β emission to the 2.507-MeV excited state of ^{60}Ni. Subsequent decay to the ground state always occurs by gamma emission to the 1.3325-MeV level (a 1.174-MeV gamma) followed almost simultaneously by the 1.3325-MeV gamma to the ground state. In Experiment 19 we will show that these two events are in coincidence and have an angular correlation that deviates from an isotropic distribution by only 16%. For the purposes of this experiment we can assume that each of these gammas are isotropically distributed. In other words, if γ_1 goes in a particular direction, γ_2 can go in any of the 4π steradians that it wishes. There is a certain probability that it will go in the same direction as γ_1. If this occurs within the resolving time of the detector, γ_1 and γ_2 will be summed and hence a sum peak will show up in the spectrum. From the definitions in Experiment 3.6, the number of counts, Σ_1, under the γ_1 peak is given by:

$$\Sigma_1 = \epsilon_1 G f_1 t A, \tag{11}$$

where A is the activity of the sample and t is the time. In a similar calculation, the sum Σ_2 for γ_2 is given by:

$$\Sigma_2 = \epsilon_1 G f_2 t A. \tag{12}$$

From Eqs. (11) and (12) the number of counts in the sum peak, Σ_s, is given by:

$$\Sigma_s = \epsilon_1 \epsilon_2 f_1 f_2 G^2 A t \, [W(0°)], \tag{13}$$

where W(0°) is a term that accounts for the angular correlation function. For the case of ^{60}Co, Eq. (13) is quite simple. Σ_s becomes:

$$(\Sigma_s)_{^{60}Co} \cong \epsilon_1 \epsilon_2 G^2 A t, \tag{14}$$

since $W(0°) \cong 1.0$.

In this experiment we will show that the sum peak for ^{60}Co has an energy of 2.507 MeV and that its sum is given by Eq. (14).

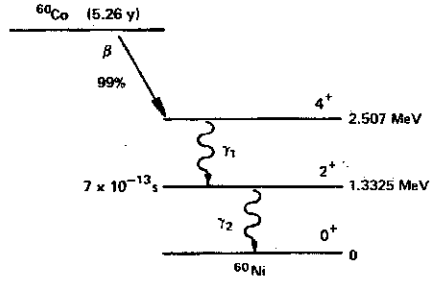


Fig. 3.9. The Decay Scheme of ^{60}Co.

Procedure

1. Set up the electronics as shown in Fig. 3.1.

2. Use the gammas from the source kit to calibrate the MCA so that full scale is ~3.0 MeV. For 1024 channels this would put the ^{137}Cs (0.662 MeV) peak at approximately channel 225.

3. Construct a calibration curve as in Experiment 3.1.

4. Place the ^{60}Co source from the source kit at exactly 9.3 cm from the face of the detector. Count for a period of time long enough so that the area under the sum peak is ~1000 counts. This procedure was outlined in Experiment 3.6.

EXERCISES

a. Verify that the energy of the sum peak is 2.507 MeV. Subtract the background from the sum peak and verify its sum from Eq. (14).

b. Repeat this sum peak analysis for the ^{22}Na source. Figure 3.10 shows the decay scheme for ^{22}Na and a typical spectrum with the sum peak.

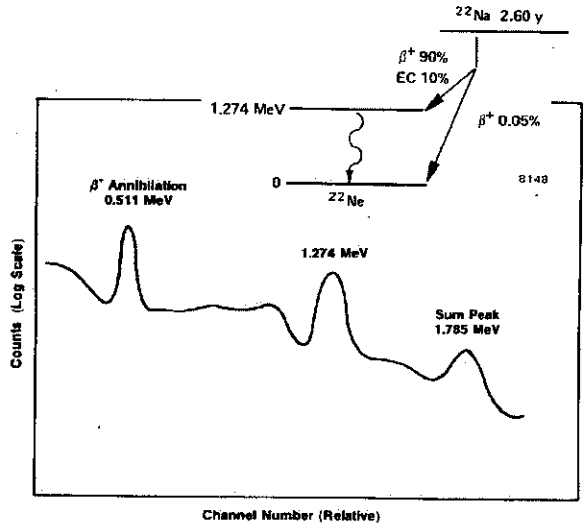


Fig. 3.10. Sum Peak for the ^{22}Na Source from Source Kit SK-1G.

EXPERIMENT 3.10

Photoelectric Absorption

Purpose

The purpose of this experiment is to study the photoelectric absorption of photons and verify the strong dependence of this process on the atomic number of the absorbing material.

When a gamma of energy <150 keV interacts with matter, the interaction has a high probability of being photoelectric. In the photoelectric interaction, the photon interacts with one of the tightly bound electrons in the material. The electron, in general, is knocked out of the atom with an energy given by:

$$E_e = hf - E_b,$$

where f is the frequency of the photon and E_b is the binding energy of the electron that is involved in the interaction. The probability of photoelectric interaction is dependent on the atomic number of the absorbing material and the energy of the gamma or x-ray photon. Although it is difficult to write out an exact analytic expression for this probability, it can be shown that for low energy photons

$$\mu = \frac{K \cdot Z^n}{E_\gamma^3}, \qquad (15)$$

where K is a constant, Z is the atomic number, and n is usually between 4 and 5.

Procedure

The set up for this experiment is the same as for Experiment 3.7.

1. Place the ^{57}CO source ~3.8 cm from the NaI detector. Accumulate for a time period long enough to get reasonable statistics in the 122-keV line. As in Experiment 3.7, $\Sigma - \Sigma_b$ should be at least 6000 counts.

2. Clear the MCA and place the thinnest aluminum absorber between the source and the detector. Count for the same period of time as in step **1**. Repeat for the other two aluminum absorbers.

3. Repeat steps **1** and **2** for the other thin absorbers, Fe, Cu, Mo, Sn, Ta, and Pb, in the Model 3-Z2 source kit. Note: The counting time might have to be increased as the atomic number of the absorber is increased.

EXERCISES

a. For the three measurements made with the thin aluminum foils, calculate and average μ, Eq. (9). Repeat for the other absorbers.

b. Make a plot of μ vs $Z^{4.5}/E_\gamma^3$ from your experimental data. How do your results compare to the theory?

References

1. G. F. Knoll, *Radiation Detection and Measurement*, John Wiley and Sons, New York (1979).

2. J. B. Birks, *The Theory and Practice of Scintillation Counting*, Pergammon Press, Oxford (1964).

3. S. M. Shafroth, Ed., *Scintillation Spectroscopy of Gamma Radiation*, Gordon and Breach, London (1967).

4. K. Siegbahn, Ed., *Alpha, Beta and Gamma Spectroscopy*, North Holland Publishing Co., Amsterdam (1968).

5. P. Quittner, *Gamma Ray Spectroscopy*, Halsted Press, New York (1972).

6. W. Mann and S. Garfinkel, *Radioactivity and its Measurement*, Van Nostrand-Reinhold, New York (1966).

7. C. M. Lederer and V. S. Shirley, Eds., Table of Isotopes, 7th Edition, John Wiley and Sons, Inc., New York (1978).

8. *Radiological Health Handbook*, U.S. Dept. of Health, Education, and Welfare, PHS Publ. 2016. Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia.

9. 14th Scintillation and Semiconductor Counter Symposium, *IEEE Trans. Nucl. Sci.* **NS-22**(1) (1975).

10. R. L. Heath, *Scintillation Spectrometry, Gamma-Ray Spectrum Catalog*, **1** and **2**, Report No. IDO-16880. Available from the National Technical Information Center, U.S. Dept. of Commerce, Springfield, Virginia.

Gamma-Gamma Coincidence

EQUIPMENT NEEDED FROM EG&G ORTEC

Two 113 Scintillation Preamplifiers
Two 266 Photomultiplier Tube Bases
Two Bins and Power Supplies
Two 551 Timing Single-Channel Analyzers
426 Linear Gate
567 Time-to-Amplitude Converter and SCA
Two 556 High Voltage Power Supplies
480 Pulser
418A Universal Coincidence
875 Counter
Two 575A Amplifiers
427A Delay Amplifier
719 Timer
Two 905-3 NaI(Tl) 2- x 2-in. Scintillation Detectors and PM Tubes
ACE-2K MCA System including suitable IBM PC (other EG&G ORTEC MCAs may be used)
Oscilloscope
10-μCi ^{22}Na source
Source Kit SK-1G
306 Gamma-Gamma Angular Correlation Table with rotating detector and shields
ORC-13 Cable Set

Purpose

Two annihilation quanta are radiated from a ^{22}Na source in coincidence with each other for each radiation event that will be measured in this experiment. The purpose of the experiment is to verify that these quanta emanate from the source with an angular separation of 180°.

Introduction

Sodium-22 is an excellent source for a simple gamma-gamma coincidence experiment. The decay scheme for this isotope is shown in Fig. 13.1. From the decay scheme it can be seen that 99.95% of the time the decay occurs by positron emission and electron capture through the 1.274-MeV state of ^{22}Ne. Ninety percent of these decay events occur with positron emission, which then annihilate and produce a pair of 0.511-MeV gamma rays that can be seen in the gamma spectrum.

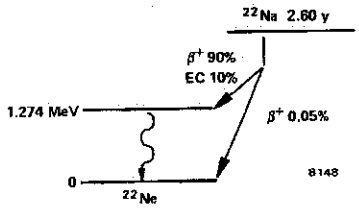


Fig. 13.1. Decay Scheme for ^{22}Na.

Figure 13.2 shows a typical gamma spectrum for ^{22}Na that was obtained with an NaI(Tl) detector. The 0.511-MeV peak will usually be quite a bit more intense than the 1.274-MeV peak, primarily because of the detector efficiency differences at the two energy levels (see Experiment 3) and the annihilation process.

Figure 13.3 shows a typical instrument configuration for measuring a gamma-gamma coincidence. The ^{22}Na source is usually covered with a thin absorber such as a thin piece of metal or plastic. Positrons from the source will lose energy in the absorber by dE/dx and will be annihilated in the absorber. The NaI(Tl) detectors will see an approximate point source of radiation. When the positrons are annihilated, two 0.511-MeV gammas will leave the source with an angular separation of 180°.

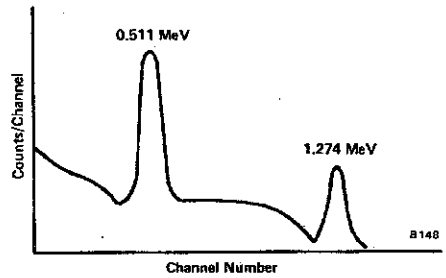


Fig. 13.2. NaI(Tl) Spectrum of ^{22}Na.

Experimentally this pair of gamma rays is detected and measured with one detector that is fixed and another detector that can rotate about the source. Figure 13.4 shows some of the details of a rotating assembly that is used for the experiment.

The ^{22}Na coincidence experiment will use three different electronic system configurations. In the first, the events that enter the two detectors will have to produce pulses that overlap each other to indicate that a coincidence exists, and the counter will then count the number of coincidences that are sensed during its timed counting interval. In the second, a pulse from the movable detector will enable the gate of the 426 Linear Gate, and any corresponding pulse from the fixed detector that arrives within the adjusted gate width interval will be considered coincident and will be counted in the counter. In the third setup, the 567 Time-to-Amplitude Converter, (TAC), and SCA will be used to measure the variations in time at which the coincident events are sensed by the two detectors; a counter can count all of the coincidences that occur within about a 500-ns range, and then an MCA can be used to obtain a spectrum of the precise timing variations.

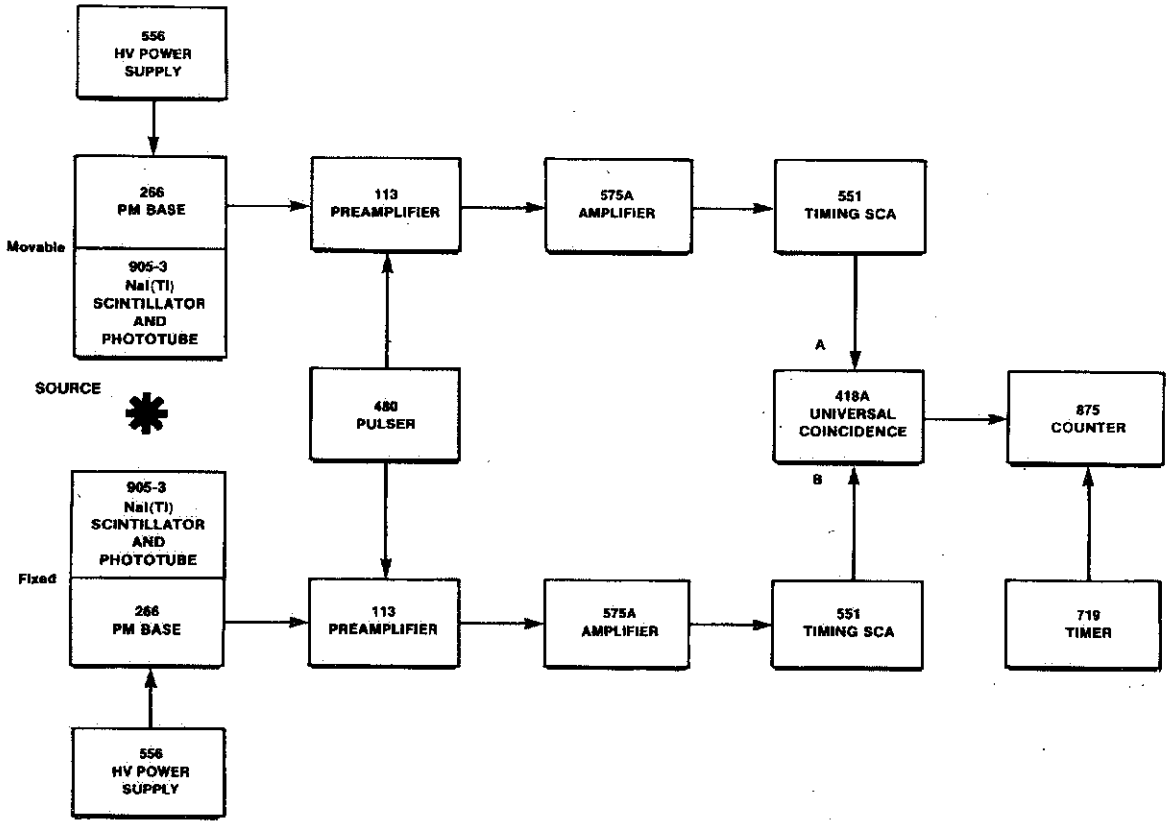


Fig. 13.3. Electronics for Experiment 13.1.

The student should complete Experiment 9 before starting this experiment and should be somewhat familiar with the principles of coincidence measurements.

EXPERIMENT 13.1

Overlap Coincidence Method for Measuring Gamma-Gamma Coincidence of ^{22}Na

Procedure

1. Set up the electronics as shown in Fig. 13.3. Use Fig. 13.4 as a guide to arranging the two detectors.

2. Set the 575A Amplifiers for negative input and unipolar output. Adjust the gain of both amplifiers so that the 1.274-MeV line of ^{22}Na results in ~6 V pulses at the outputs.

3. Set the 551 Timing SCAs for Integral mode. Set the Delay controls at minimum and the Lower-Level dials at 40/1000. Use the SCA outputs.

4. Connect the SCA Out from one of the 551 Timing SCAs to the A input of the 418A and connect the output from the other 551 to the B input of the 418A. Set the 418A Coincidence Requirements switch at 2 and the Resolving Time at maximum (2 μs). Set the A and B toggle switches at Coinc and set the C, D, and E toggle switches at Off. With the source removed and the 480 Pulser turned on, the 418A output will indicate coincidence for the two signal paths. Turn off the 480 and return the source.

5. Set the 719 Timer for a long timing period, such as 8 min, and permit the 875 Counter to operate while the movable detector is rotated slowly to both sides of 0°. The counting rate should be maximum at $\theta = 0°$.

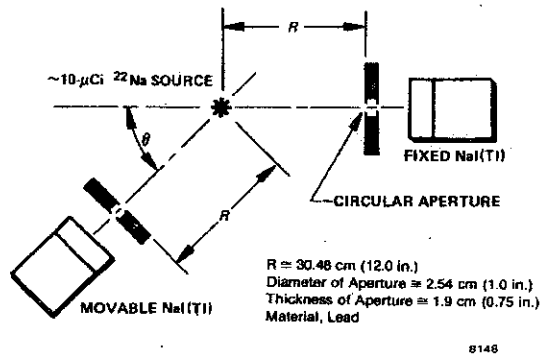


Fig. 13.4. Mechanical Arrangement of Detectors on EG&G ORTEC 306 Angular Correlation Table.

6. Set the timer for a long enough accumulation period to provide reasonable statistics at the points of interest and fill in the values in Table 13.1.

EXERCISE

Plot the data in Table 13.1 on linear graph paper. For each counting rate, (N), the statistical variation $\pm\sqrt{N}$ should be included on the graph. Figure 13.5 shows a typical set of data for this experiment.

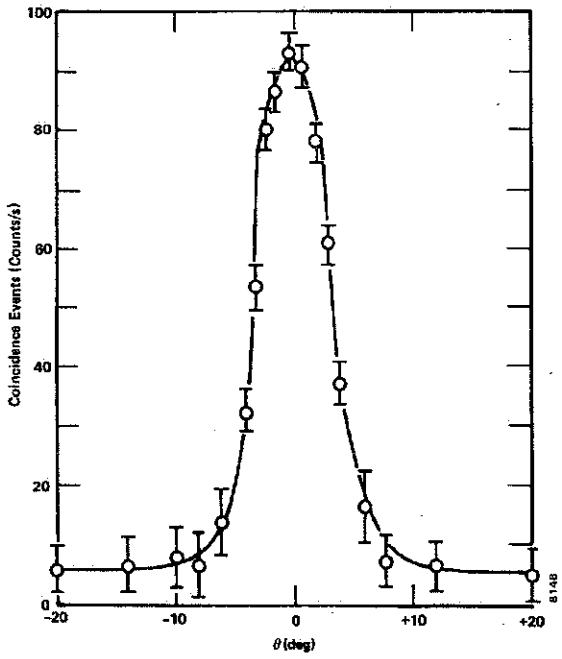


Fig. 13.5. Coincidence Data.

Table 13.1

θ (deg) Positive	Counts/s	θ (deg) Negative	Counts/s
0		0	
1		1	
2		2	
3		3	
4		4	
5		5	
6		6	
7		7	
8		8	
10		10	
14		14	
20		20	
25		25	

EXPERIMENT 13.2

Linear Gate Method for Measuring Gamma-Gamma Coincidence of ^{22}Na

Procedure

1. Set up the electronics as shown in Fig. 13.6. Use the same mechanical detector placement as in Experiment 13.1.

2. Using the ^{22}Na source, adjust the gain of each 575A Amplifier for an output of ~6 V for the 1.274-MeV gamma line.

3. Remove the source. Turn on the pulse generator and adjust the Pulse-Height dial, the Cal control, and the attenuators so that the amplifier output pulses are the same as in step **2.**

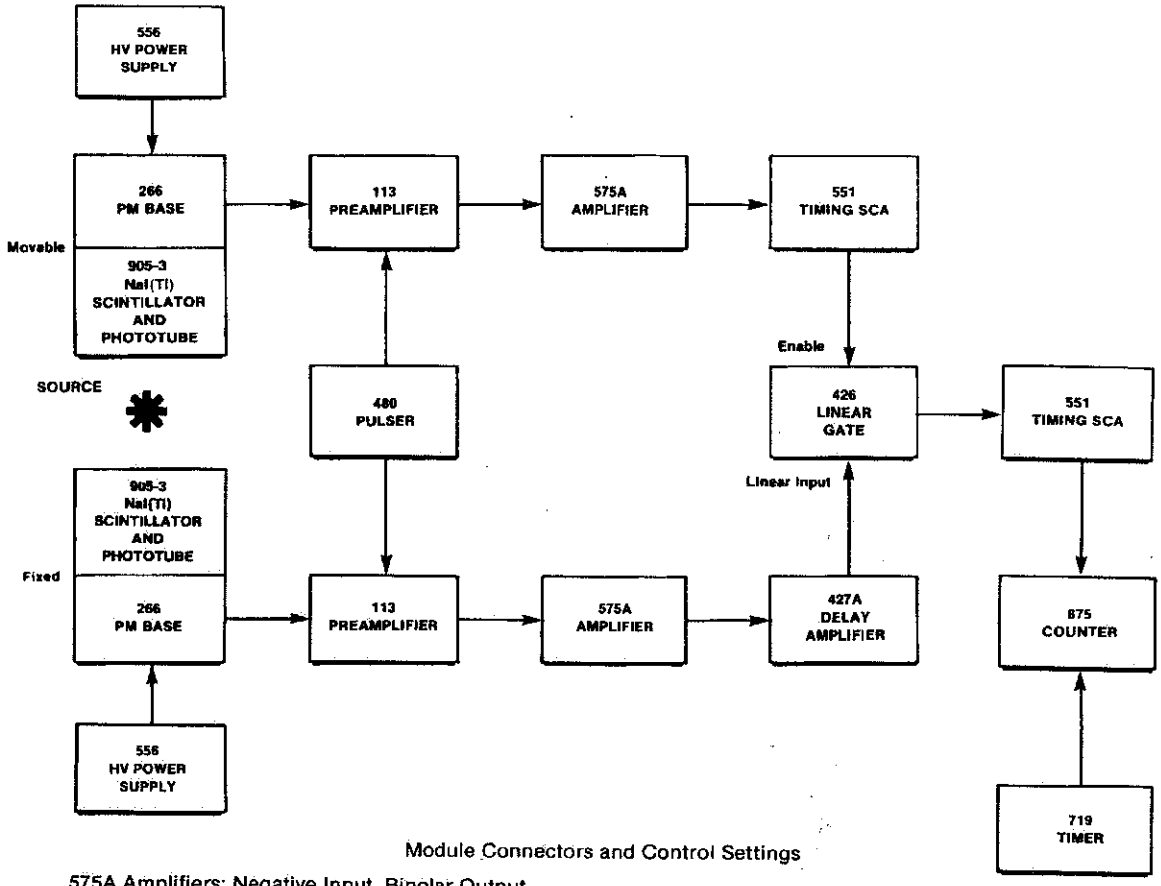
4. Look at the output of the 426 Linear Gate with the oscilloscope. If the timing is correct, a unipolar pulse should be observed whose amplitude is proportional to the pulse-height dial setting on the 480. Vary the pulse height and see that there is a linear response. If no output pulses are seen from the 426, adjust the Delay time of the 551 on the movable detector side and recheck the Gate Width control on the 426 until output pulses are seen normally.

5. Turn off the pulser and return the ^{22}Na source to its proper position as shown in Fig. 13.4. Measure the angular distribution of pulse rates from the system as in Experiment 13.1, using the angles in Table 13.1.

6. (Alternate) The output of the Linear Gate can be fed into an MCA. The spectrum should resemble Fig. 13.2 except that the 1.274-MeV peak will not be present. The coincidence requirement has virtually eliminated this peak from the spectrum.

EXERCISE

Plot the data on linear graph paper as in Experiment 13.1. Compare the count rates at $\theta = 0°$.



Module Connectors and Control Settings

575A Amplifiers: Negative Input, Bipolar Output.
551 Timing Single-Channel Analyzer on movable detector side: Lower Level = 40/1000, Integral mode, SCA Output, Delay minimum.
551 Timing Single-Channel Analyzer following the Linear Gate: same settings.
426 Linear Gate: Normal mode, Gate Width maximum (4 μs).
480 Pulser: Attenuated output, negative polarity, power switch Off.
875 Counter: Input from the 551, Gate from the 719 Interval Out.

Fig. 13.6. Arrangement of Electronics for Experiment 13.2.

EXPERIMENT 13.3

Time-to-Amplitude Converter Method for Measuring Gamma-Gamma Coincidence of ^{22}Na

Procedure

1. Set up the electronics as shown in Fig. 13.7. Use the same mechanical detector placement as in Experiment 13.1.

2. Using the ^{22}Na source, adjust the gain of each 575A Amplifier for an output of ~6 V for the 1.274-MeV gamma line.

3. Remove the source. Turn on the pulser and adjust the Pulse-Height dial, the Cal control, and the attenuators so that the amplifier output pulses are the same as in step **2.**

4. Observe the output pulses of the 567 with the oscilloscope. They should be ~6 V in amplitude. Change the delay on either 551 SCA while observing these output pulses (they can also be observed with the MCA).

5. Determine a delay vs pulse-height curve for the 567 TAC. This procedure is outlined in Experiment 9.2.

EXERCISE

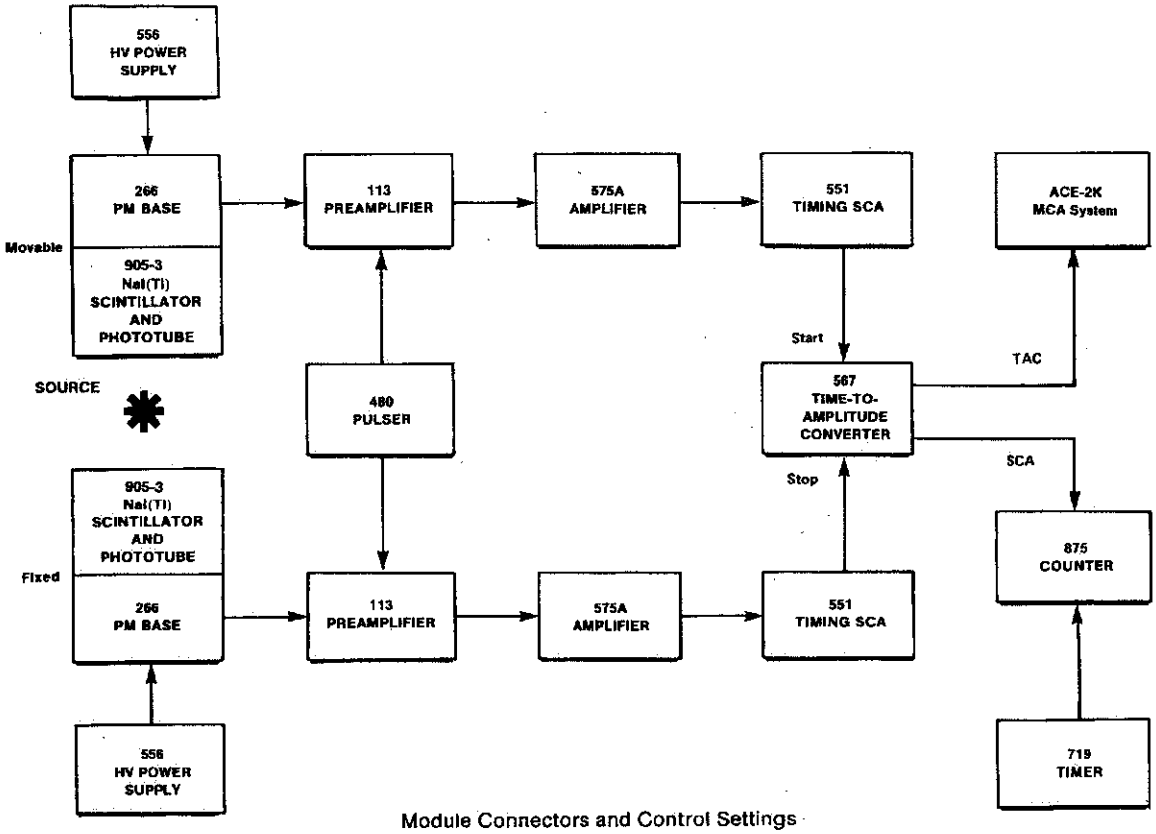
a. Determine the time resolution of the pulses from the 480 Pulser.

6. Turn off the pulser when the delays of the 551 SCAs are set for a 5- to 6-V output from the 567. Return the ^{22}Na source to its proper position as shown in Fig. 13.4. Measure the angular distribution of pulse rates from the system using the FWTM levels of the time spectrum and integrating the counts in the channels between these levels.

EXERCISES

b. Plot your data on linear graph paper as in Experiment 13.1. Compare the count rates at $\theta = 0°$.

c. Determine the time resolution for the coincidence measurements from the MCA readout.



Module Connectors and Control Settings

575A Amplifiers: Negative Input, Bipolar Output.
551 Timing Single-Channel Analyzer on movable detector side: Integral mode, Lower Level = 40/1000, Delay = 0.1 μs, Neg Out to Start Input on 567.
551 Timing Single-Channel Analyzer on fixed detector side: Integral mode; Lower Level = 40/1000, Delay = 5 μs, Neg Out to Stop Input on 567.
567 TAC and SCA: Range 400 ns, TAC Out to MCA, SCA Out to 875.
480 Pulser: Attenuated output, negative polarity, power switch Off.

Fig. 13.7. Arrangement of Electronics for Experiment 13.3.

References

1. A. C. Melissinos, *Experiments in Modern Physics*, Academic Press, New York (1966).

2. H. A. Enge, *Introduction to Nuclear Physics*, Addison-Wesley (1966).

3. K. Seigbahn, *Alpha, Beta, and Gamma Spectroscopy*, North Holland Publishing Co., Amsterdam.

4. L. C. Biedenharn and M. E. Rose, *Rev. Mod. Phys.* **25**, 729 (1953).

5. R. D. Evans, *The Atomic Nucleus*, McGraw-Hill, New York (1955).

6. B. L. Cohen, *Concepts of Nuclear Physics*, McGraw-Hill, New York (1971).

7. C. E. Crouthamel, *Applied Gamma-Ray Spectrometry*, Pergammon, New York (1960).

8. C. M. Lederer and V. S. Shirley, Eds., Table of Isotopes, 7th Edition, John Wiley and Sons, Inc., New York (1978).

9. P. Quittner, *Gamma Ray Spectroscopy*, Halsted Press, New York (1972).

10. W. Mann and S. Garfinkel, *Radioactivity and Its Measurement*, Van Nostrand-Reinhold, New York (1966).