Gamma Rays

OBJECT:
To understand the various interactions of gamma rays with matter. To calibrate a gamma ray scintillation spectrometer, using gamma rays of known energy, and use it to measure the energy of an "unknown" gamma ray. To use positron annihilation radiation to determine the mass of the electron
and to observe correlated gamma rays.

READINGS: The lab manual (see supplementary reading)"Experiments in Nuclear Science" AN34, EG&G ORTEC provides an excellent hands-on discussion of the background and techniques for a number of undergraduate level nuclear experiments. The equipment described resembles, with some variation, the equipment available in the laboratory. Additional readings are given at the end of this write-up.

APPARATUS: NaI:Tl scintillator and photomultiplier tube detector with integrated preamplifier (2), high voltage power supply, Canberra model 2000 power supply, NIM bin, Canberra 2015A amplifier/single channel analyzer module (2), Rutgers P1075 scaler/timer, Canberra model 1446 coincidence module, Nucleus Personal Computer Analyzer (PCA-II) board in CompuAdd 286 personal computer, Analyzer software, monitor.

BACKGROUND: In this experiment you will study the radioactive decay of a nucleus by detecting gamma rays emitted consequent to the decay. Gamma ray detection is a multi-step process: the gamma ray enters a NaI:Tl scintillator crystal where it produces a rapidly moving free electron that, in turn, loses its energy by excitation of the ions in its path as it travels through the crystal. This excitation energy is given off in various ways, one being emission of visible light (fluorescence). Thus a single high energy gamma ray entering the scintillator produces a flash of low energy photons. These photons are directed to the photosensitive surface of a photomultiplier tube, where they eject electrons via the photoelectric effect. The electrons are collected in the photomultiplier and amplified to yield a current pulse, which is converted to a voltage pulse whose height is proportional to the number of photoelectrons and is thus proportional to the number of photons reaching the tube, which in turn is proportional to the initial energy of the fast electron.

When a radioactive source is placed near the scintillator, the photomultiplier produces a series of pulses, each corresponding to the decay of a single nucleus. The amplitude of each pulse is related to the energy of the electron freed by the gamma ray. These pulses are studied using either a single- or multi-channel analyzer. A single channel analyzer (SCA) counts the number of voltage pulses

whose height falls within a given (adjustable) window of values, while a multi-channel analyzer (MCA) sorts the pulses according to height and counts the number in each window to give a spectral (energy) distribution of the fast electrons. Figure 1 shows a typical MCA spectrum. In order to relate this spectrum to the nuclear decay, we need to understand how gamma rays interact with matter.

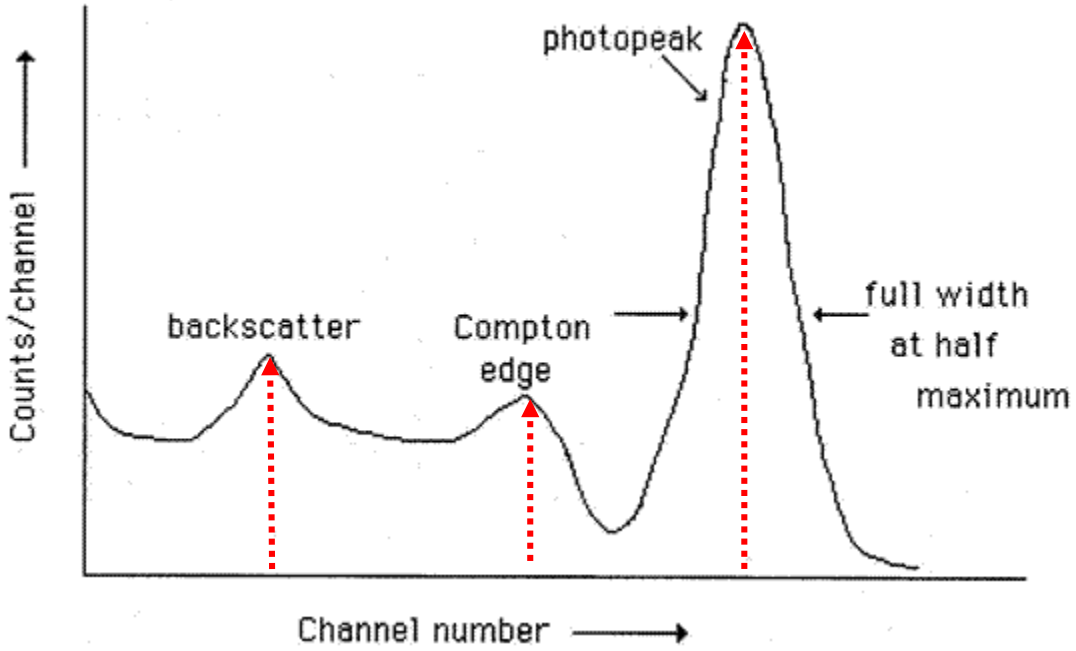

Figure 1. Na(Tl) Spectrum for Cs^{137}

DETECTION of gamma rays with NaI(Tl) detectors. Gamma rays are neutral, so that when entering the crystal they must first produce electrons in order to be detected. This conversion can occur by one of three processes: photoelectric effect, Compton effect and pair production. It is these fast electrons that give rise to scintillations. The observed spectral distribution will thus depend on the detailed interaction process of the gamma rays in the crystal. Below is a description of each of these processes.

Photoelectric effect. When a gamma ray strikes an ion in the crystal, it is absorbed and all of its energy is transferred to one of the bound electrons, which is freed and moves rapidly through the crystal. If for example an atomic K-electron is ejected as a result of the photoelectric process, its energy will equal the gamma ray energy less the electron binding energy in the K shell. Very shortly after, another bound atomic electron will "fall" into the K shell vacancy (or cascade down sequentially) with the subsequent emission of x-rays. These x-rays will have a large probability of producing light pulses in the scintillator by exciting other loosely bound electrons. These processes (initial photoelectron ejection and subsequent x-ray

production and interaction with the crystal) will usually happen within the resolution time of the counter, so that these successive light pulses add and cannot be distinguished from one another. Therefore in the end the photomultiplier output pulse will correspond to the full gamma ray energy, if the photoelectron stops in the crystal and if no light escapes the crystal. Thus the photoelectric effect results in a peak, called the **photopeak**, at an energy equal to that of the incoming gamma ray.

Compton scattering. In this case the gamma ray is not absorbed, but rather scattered through an angle θ by an electron, which recoils and carries away some of the gamma ray's energy E. The scattered electron energy is then detected in the photomultiplier. (The scattered gamma ray escapes from the scintillator; the probability that a gamma ray Compton scatters in a typical size scintillator is quite small (1% to 10%), which means you are unlikely to detect a gamma ray that has undergone two Compton scatterings.)
The energy of the Compton-scattered gamma ray $E_{\gamma'}$ as a function of the scattering angle, θ, and the initial energy E_γ is given by:

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

where m is the mass of the electron and c is the speed of light. Prove this using the kinematics of energy and momentum conservation illustrated in Fig. 2.

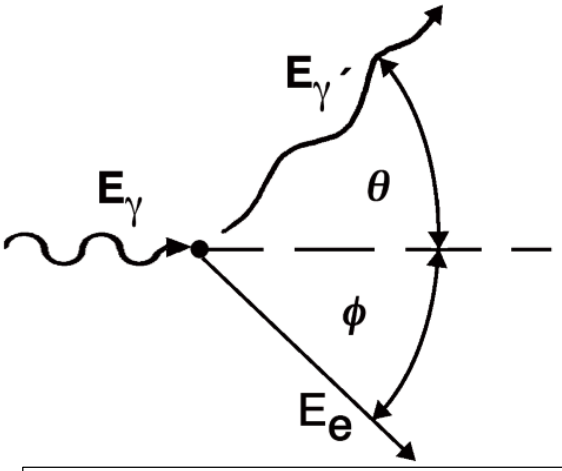

Figure 2. Angles and Energies Defined for the Compton

From this equation you can see that the energy of the scattered electron, which is the energy loss of the gamma ray, will vary from zero (when $\theta = 0^0$) to a maximum of $2E_\gamma^2/(mc^2 + 2E_\gamma)$ (when $\theta = 180^0$). This maximum energy is called the **Compton edge**. For comparing the predicted $E_{\gamma'}$ to the measured $E_{\gamma'}$ in this experiment, it is useful to rearrange equation (1) to the form:

$$\frac{1}{E_{\gamma'}} = \frac{1}{E_\gamma} + \frac{1 - \cos\theta}{mc^2}$$

The energy distribution of Compton scattered electrons is essentially a constant. So the Compton spectrum produced by a photomultiplier tube is an almost flat plateau from zero energy up to the Compton edge where it drops off sharply (at a rate limited by the energy resolution of the tube).

The discussion above refers to gamma rays that are Compton scattered by electrons within the scintillator. It is also possible for a gamma ray to be Compton scattered into the scintillator from an interaction outside the scintillator (Figure 3). In this case the observed signal is from the scattered gamma and not from the recoiling electron. The scattered gamma ray could then be detected through the photoelectric effect. However, because of the geometry of the detector, most of the gamma rays scattered into the scintillator will have been scattered through a large value of θ. But cos θ varies only slowly with θ for θ near 180^0, which means [see Eq. (1)] that these gamma rays will have energies close to $mc^2E_\gamma/(mc^2+2E_\gamma)$. The resulting energy peak is called the **backscatter peak**. It can be enhanced by placing a sheet of lead around the outside of the scintillator.

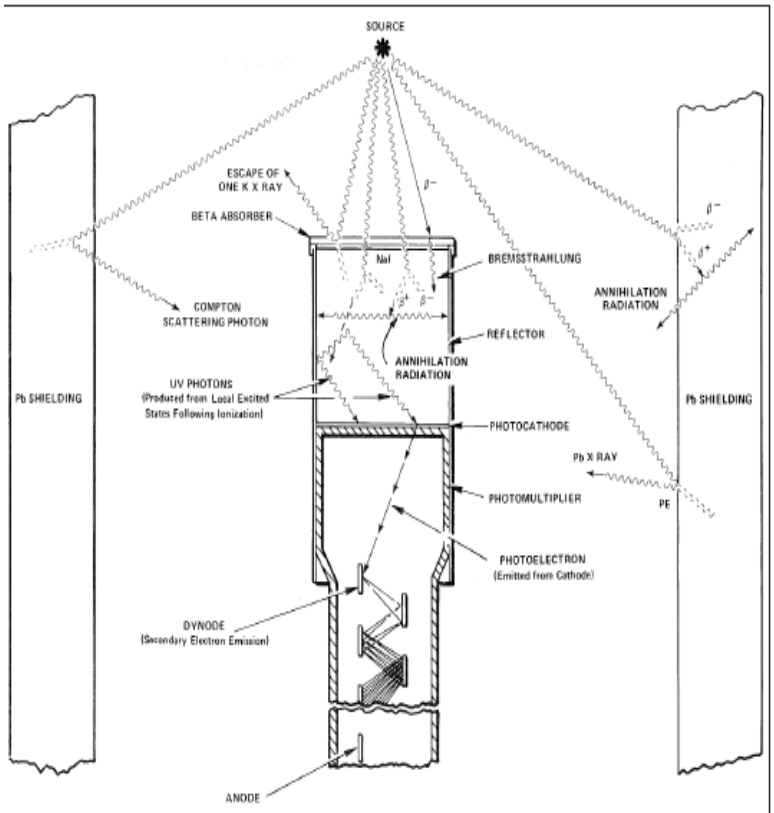

Fig. 3 The Structure of the NaI(Tl) Detector and Various Types of Gamma-Ray Interactions that Occur in the Typical Source-Detector-Shield Configuration.

Pair production. If the incoming gamma ray energy is above 1.02 MeV = $2mc^2$, the rest mass of an electron-positron pair, the gamma ray can spontaneously create an electron-positron pair and be totally absorbed. If both the electron and positron lose all of their kinetic energy while still in the scintillator, they would produce a photomultiplier pulse corresponding to an energy $2mc^2$ below the gamma ray energy ($E-2mc^2$). The short lived positron will eventually annihilate with an

electron, emitting two photons, each of energy mc^2. One of these may be absorbed in the crystal, and contribute a peak at energy mc^2 =0.511MeV. The annihilation may occur before the positron is completely stopped in which case the peak energy will be higher.
Additional peaks may appear if the positron annihilation occurs during the initial collection time of the photomultiplier. In this case the energy of the emitted photons will add to the signal produced by the slow-down of the electron-positron pair resulting in three peaks:

a. "Full energy" peak (E), when both annihilation photons are absorbed in the scintillator.
b. "One-escape peak" (E-mc^2) when only one annihilation photon is absorbed in the scintillator.
c. "Two escape peak" (E-$2mc^2$), if both annihilation photons escaped.

The final question to consider is that of the relative importance of the three interaction mechanisms, which depend in different ways upon the energy of the gamma ray. For low energy rays, the photoelectric effect predominates. Since the photopeak directly yields the energy of the gamma ray, most scintillators are designed to maximize the photopeak. In the NaI:Tl scintillator you will use, a small amount of the heavy metal thallium is added for this purpose when the crystal is grown. (The strength of the photoelectric effect depends strongly on the number of electrons bound to the ion.) As E increases, the photoelectric absorption deceases rapidly, while the Compton scattering decreases much more slowly and predominates above several hundred keV. The absorption coefficient for pair production rises rapidly above the threshold E = 1.02 MeV and exceeds the Compton scattering, while photoelectric absorption becomes negligible.

Energy resolution: The typical energy resolution that can be obtained with NaI(Tl) is ~7% for the 0.662 MeV ^{137}Cs gamma-ray line. For NaI(Tl) detectors, the resolution is a strong function of energy. The resolution is primarily controlled by the statistical fluctuation of the number of photoelectrons produced at the photocathode surface in the photomultiplier tube. The energy resolution (in percent) is defined as the ratio $R = 100(\delta E / E)$ where δE is the FWHM (full width at half maximum) of the peak at energy E. The resolution of NaI(Tl) detectors depends on energy: $R(E) \approx k\frac{100\%}{\sqrt{E}}$ where k is a proportionality constant characteristic of the particular detector. Thus you will note that the linewidth will become wider at higher energies.

Nuclear decay: You will study the decay of several light nuclei that proceed by beta decay -- the emission of an electron or positron (and the associated neutrino). These decays, Figure 4, leave the daughter nucleus in an excited state that then

returns to the ground state by the emission of one or more gamma rays. The range of the beta particles is so short that they cannot penetrate into the

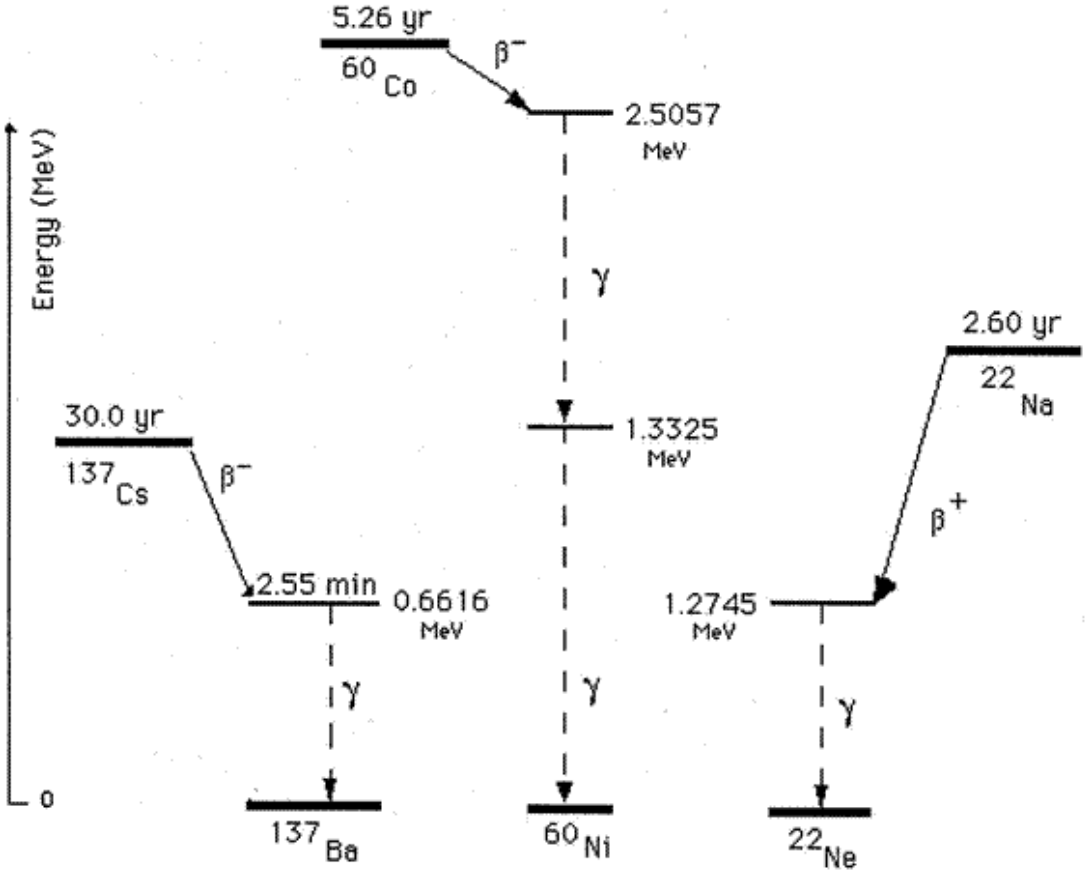

Figure 4. Principal Decay Modes of Cesium 137, Cobalt 60, and Sodium 22.

scintillator. So you will only be detecting the gamma rays. Table 1 gives the energies of the gamma rays emitted by the daughter nuclei for the three nuclei you will be studying. The Ba k X-ray occurs about 4% of the time when instead of emitting a gamma ray, the Ba nucleus de-excites by transferring its energy to one of the innermost electrons (K shell) that overlaps the nucleus. This gives the electron enough energy to escape from the atom. One of the outer electrons then drops into the hole left by the escaping electron and emits its excess energy as an X-ray. Although the escaping electron cannot penetrate into the scintillator, the K X-ray does and is efficiently detected.

Parent nucleus	Lifetime (years)	Decay mode	Daughter nucleus	Gamma energy (MeV)
Na^{22}	2.605	e^+	Ne^{22}	1.2746
Co^{60}	5.272	e^-	Ni^{60}	1.1732
				1.3325
Cs^{137}	30.17	e^-	Ba^{137}	0.6616
				0.0322*

*Ba K X-ray

Table 1. Nuclear Decay Data(from: Handbook of Chemistry and Physics)

γ–γ Angular Correlations: When the nuclei in a radioactive sample decay the individual decays are unrelated and the emitted particles (gamma rays) are emitted isotropically in all directions. We will study one case where the gamma rays from a sample are correlated -- the annihilation radiation of positrons. When a Na^{22} nucleus emits a positron, the positron rapidly slows and then annihilates, upon encountering an electron. Conservation of momentum requires that the two gamma rays that are emitted travel in exactly opposite directions. You will use two scintillation counters and a coincidence module to study this angular correlation.

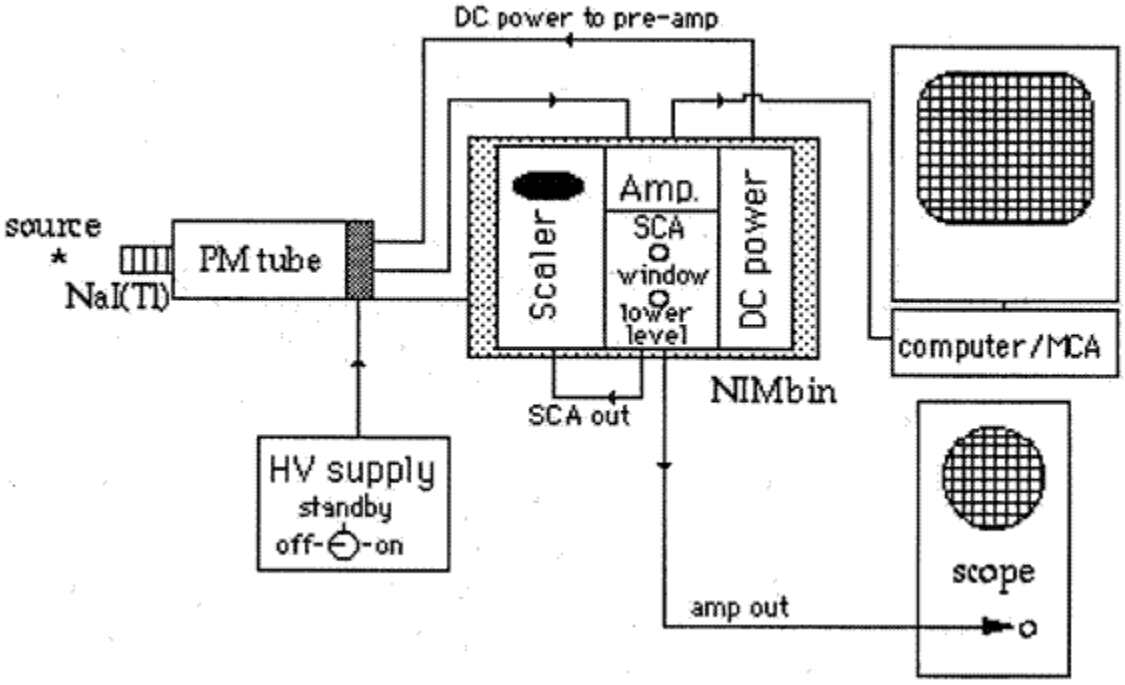

Figure 3: Block Diagram for Scintillation Counter Apparatus

PROCEDURE: Warning. *The experiment involves high voltages; do not turn on any switches or knobs until you have become familiar with the apparatus. The high voltage applied to the phototube should never exceed 1200 volts. Observe caution at all times with the scintillation detector since the crystal and photomultiplier are fragile and expensive.*

The apparatus is for the most part pre-wired and very simple to operate. The block diagram is shown in Fig. 3. The scintillation counter consists of a NaI:Tl crystal glued to a photomultiplier (PM) tube (Saint-Gobain, Bicron 2M2/2). The voltage output pulse of the PM detector is fed into a preamplifier attached to the PM tube (2007P Base/Preamplifier), then to an amplifier (CANBERRA 2015A) in a NIM bin. A Nuclear Instrument Module (NIM) bin is a rack with a number of slots for various instruments (amplifier, scaler, coincidence counter, etc) and a DC power supply for the modules. It allows great ease and flexibility in setting up an experiment. After amplification, the signal is divided and fed into two separate pulse height analyzers, which measure the gamma ray spectrum in different ways.

PM tube: The PM tube is powered by an adjustable high voltage supply. There are two parameters that ultimately determine the overall gain of the system: the high voltage furnished to the phototube and the gain of the spectroscopy amplifier (model 2015A mounted in the NIM rack). The gain of the photomultiplier tube depends sensitively on its high voltage. A rule of thumb for most phototubes is that, near the desired operating voltage, a 10% change in the high voltage will change the gain by a factor of 2. The desired high voltage value depends on the phototube being used. The operating voltage for our tube is in the range of +800 to +1200 Volts. The power supply is a vacuum tube model and should be set to "standby" for about 1 minute before turning to "on" to avoid damaging the vacuum tubes. If the voltage level was set by a previous group there is normally no need to adjust it. More information about this detector is available in the supplementary material (Scintillation detector manual).

Amplifier: The CANBERRA Model 2015A combines, in one single width module, a spectroscopy amplifier with gated baseline restoration and a timing single channel (SCA) pulse height analyzer. You will first use this unit as part of a multi-

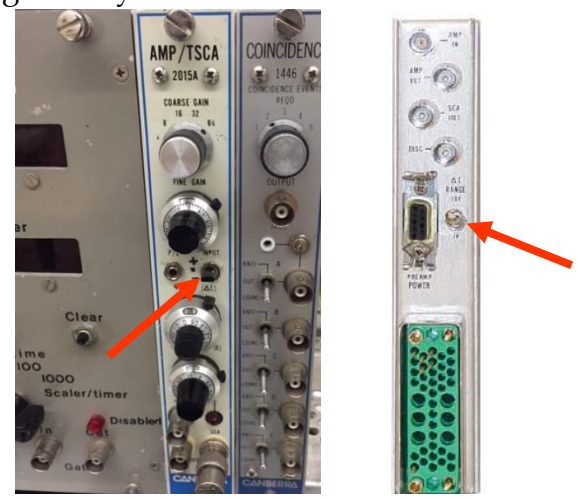

Figure 4. The Camberra 2015A amplifier. Left panel: Front view. Arrow points to the polarity switch, make sure it is set to +. Left panel: Rear view. Arrow points to ΔE RANGE toggle switch. The switch selects the front panel WINDOW (ΔE) range as 0 to 10 V or 0 to 1 V, full scale.

channel analyzer (MCA) and then as part of a single channel analyzer (SCA) and a coincidence circuit. To familiarize yourself with the unit read the manual Canberrra 2015A in the supplementary reading material. **Make sure that the polarity switch on the amplifier is in the + position (see arrow in figure).**

MCA function. In this part of the experiment the AMP output of the amplifier is fed into the MCA plug-in card and associated software on the computer. The MCA software sorts each PM pulse as it arrives from the amplifier according to pulse height and generates a fine-grained histogram of the number of voltage pulses from the detector versus pulse amplitude and, therefore, energy deposited in the scintillator. The amplifier output is proportional to the energy of the incoming signal with a maximum of 10V. The proportionality factor is controlled by the GAIN.

Note: If the gain is set too high the output corresponding to a signal of interest may be outside of the 10V range and the output will be saturated. The calibration procedure described below should prevent this.

SCA function. The SCA counts the number of events within a predetermined window of energies. In this mode the amplifier output is fed internally to the SCA, which has two knobs to adjust the range of pulse heights the SCA will pass. The first knob adjusts the lower level E and the second pulse the window width ΔE, so that pulses with heights between E and E+ ΔE will be passed to the output. The correspondence between energy and scale on the knobs is determined by the Gain,

which you will set during the calibration. The SCA output is attached to the scaler input. There is a switch on the back of the module for changing the full-scale range of ΔE from 1 V to 10V. When operating the SCA use the 1V range for best results. Careful – to change the position you have to pull on the switch.

Scaler. The scaler counts the number of pulses arriving during a set time interval. To obtain the same data with the SCA as you would get with the MCA, you will need to step E across the range of possible voltages keeping ΔE constant and counting for a fixed length of time.

1.**Calibration:**

Set up the system for the MCA function: turn the E pot to the minimum value and ΔE to the maximum value. Make sure that the toggle switch at the back of the amplifier is set to 10V.

a. Check that the apparatus is connected according to the diagram in Fig. 3 for detector 1. Turn on the NIM bin power supply and switch the high voltage PM supply to "standby". Turn on the computer. Log in as Student using the course password. The MCA program is called Maestro for Windows. Read the user manual (posted in the supplementary reading). Run the program. When opened the program will only show the buffer. Make sure to open MODPHYSLAB1 MCB in the top right drop down menu

b. Place the Na^{22} source on the Aluminum rod in front of detector. **Make sure you know which detector is hooked up to the MCA1.** Turn the PM power supply from "standby" to "on" and make sure that the setting is about 1000 V (this would have been set by previous groups). Make sure that the ΔE window is set to the maximum value and that the lower E setting is at 0.

c. Click on GO (in the top bar) to start accumulating the spectrum. It will take about five minutes to accumulate enough counts to resolve the spectrum. Note that the 1.2746 MeV photopeak is the highest energy feature in the spectrum, but not the strongest. Use the mouse left and right arrows and the page-up and page-down keys to move the cursor onto the photopeak to identify its channel number. Record the channel for the maximum of the photopeak.

d. Use the mouse to bring the cursor over the photopeak. The channel number and the number of counts will be listed at the bottom left of the screen. If the peak is not on channel 1500 adjust the gain accordingly and retake the spectrum. If necessary repeat a few times until the calibration the peak region falls in channel 1500 (plus/minus ~3). **Once you have set this gain do not change it**; otherwise you will change the calibration. Note: you should see the annihilation peak at a lower energy than the photopeak, but it'll be taller. Make sure you use the photopeak for this calibration.

e.With the mouse on the peak, channel 1500 calibrate the Maestro program so that channel 1500 corresponds to an energy of 1.2746 MeV. Use Calculate> Calibration in tool bar (see manual).

2. Saving the data. Save the data as an ASCII Maestro file then open in Origin

using Import ASCII.

a. Now take the spectrum of the Cs^{137} source. Note the channel number of the 0.6616 MeV photopeak. Is it consistent with your calibration?.

b. Remove all sources to distant storage, and measure the background spectrum with the MCA.

3. **MCA Decay Spectra.** Without changing the calibrated gain setting record the spectra of the other two isotopes Cs^{137}, Co^{60} and $Na^{22}$with the MCA. *When taking data, be sure that you have removed the other sources far away from the scintillator!* Also make sure to use the most recent samples for each isotope. Old samples may not give a response. When saving the data make sure that you include the collection time (you will need this later). For your report you will need to determine the (minimum) activity of each source in curies. To do this you have to measure the appropriate distances to calculate the solid angle subtended by the scintillator relative to the source.

4. **SCA Decay Spectra.** Now measure the gamma spectrum of the cesium source using the SCA. Set the SCA window width at 0.1 V, with the toggle switch on the back panel of the 2015A at 1V. Leave this setting fixed and step E from zero to a value beyond the Ba^{137} photopeak, recording at each step the scaler readings for a fixed count time (e.g. 100 s). In the region of the photopeak, where the counting rate changes rapidly with voltage, use 0.1 V steps in E. In the more slowly varying regions steps of 0.3 V should be adequate. Be sure to record all instrument settings, -- count time, PM voltage, etc. Plot the pulse height distribution spectrum [counting rate versus $E+(\Delta E/2)$].

4**. γ–γ correlation:** You will now study the correlation of the gamma rays emitted when the positron from the Na^{22} source annihilate. You will need two scintillation counters, two single channel analyzers (SCA), a coincidence module, and a scaler to observe this correlation. The first step will be to set the windows of the two SCAs to pass PM pulse heights corresponding to the ~511 keV annihilation gamma rays. The exact value should be set from the measured annihilation peak. When a pulse from the PM tube meets the window requirements, the SCA outputs a narrow pulse, which is fed into the coincidence module. The coincidence module outputs a pulse whenever it detects pulses from both SCAs at the same time. The scaler counts these coincidence pulses for a fixed length of time. The two scintillators are mounted on arms that pivot about the location of the Na^{22} sample. When the two arms are 180^0 apart, strong coincidences will be recorded, but when the angle is decreased the count rate will drop sharply. (There will still be a number of accidental coincidences for nuclei that just happen to decay at the same time.)

4A. The first step will be to set up the window for counter 1. With the sodium

source in place, observe the amplifier output with the MCA and with the oscilloscope (channel 1). [On the MCA spectrum of Na^{22} the ~511 keV gamma ray is the strongest feature. Note that the positron annihilation occurs in the sodium source not in the detectors.] Set the scope sweep speed at 5μs/cm and the gain to 1 V/cm with the trigger source channel 1 and the trigger level about 2 V. You will see a series of superimposed pulses of widely varying height, but with many falling in the same band, which results in the scope traces being brightest for that band. These pulses correspond to the 511 keV gamma rays. Adjust the amplifier gain so that this band corresponds to a pulse height of about 3 V.

Now connect the SCA output to channel 2, change the trigger source to channel 2, and set the scope to display both channels 1 and 2. [Note that the SCA pulses displayed in channel 2 are extremely narrow (~ 0.7 μs.) which places stringent limits on whether the coincidence module will consider two gamma rays to be in coincidence.] Observe how the channel 1 scope trace changes as you change E, the lower edge of the window, and ΔE, the window width. Set E to about 2.8 V and ΔE to about 0.4V. [Note that there is a switch on the back of the module that allows you changes full-scale for ΔE from 1 V to 10V.] These settings will limit the pulses accepted by the SCA to just those corresponding to the 511 keV peak.

4B. Repeat step A for the second counter. Be sure to shift the cable leading to the MCA from the first amplifier to the second one. **Note**: the two SCA's have different sensitivities. You will need to adjust the gain on the second SCA to roughly match the signal output of the first.

4C. Now connect the outputs of the two SCAs to channels 1 and 2 of the coincidence module, set the corresponding switches to "coincidence" and connect the output of the coincidence module to the scaler input. Set the scaler to count for 10 or 100 s. With the two counters set 180^0 apart, you should obtain a strong coincidence count rate, which should drop almost to zero when the angle is reduced.

4D. Record the number of coincidences (for a fixed counting interval) as a function of the angle of separation of the detectors. Make a plot for your report. Explain the width of this curve, i.e. why do you obtain coincidences even when the angle is not exactly 180^0?

4E. For your report you will need to measure the appropriate distances to calculate the solid angle subtended by both scintillators relative to the source.

5. Co^{60} γ–γ correlation (optional): Figure 2 shows that when Co^{60} decays it emits two gamma rays. The second gamma ray rapidly follows the first (the excited state

has a mean life of 0.7 x 10^{-12}s) and thus appears to be coincident. Its direction of emission is correlated with the direction in which the first is emitted. We will not go into the theory, which is complicated, but the prediction is that the angular correlation is given by

$$w(\theta) = 1 + \frac{\cos^2\theta}{8} + \frac{\cos^4\theta}{24}, \qquad (2)$$

where θ is the angle between the two gamma rays. This is a rather small effect. The correlation function is 1.00 at 90° and 1.17 at 180°. This is a more challenging measurement. To detect a 17% effect, you will need to measure the correlation rate to about 1%. The error in a measurement of N counts is sqrt(N). Thus to achieve 1% accuracy at a particular value of θ you will need to count until you have accumulated about 10^4 counts. For the source available in the lab this means you will need to count for 1000 s for each point.

5A. Mount the Co^{60} source at the center of the spectrometer and move the two detectors fairly close to the source (to get a large count rate).

5B. Set the windows for the two detectors to pass both of the gamma rays (1.1732 and 1.3325 MeV).

5C. Record the number of coincidences C(θ) as you vary θ in increments of 10° between 180° and 90°. Count for 1000 s for each point. Plot the ratio C(θ)/C(90°) and compare with the theoretical correlation, Eq. (2).

REPORT:

The report should contain:

1. The calibrated spectra (count number versus Energy) for the sodium, cobalt, and cesium sources with labels identifying each spectral feature. Indicate the k X-ray when present and explain how you determined that this is an X-ray rather than a spurious signal.
2. Make a table listing the gamma energies for each source. For each energy, list how much energy would be carried off by the electron and by the gamma for a Compton scattering angle of 180^0.

Parent nucleus	Emitted γ energy	Compton scattered electron energy	Compton scattered γ energy

3. Make a table listing for each source the expected and measured energies of

the different peaks

Source	Nature of peak	Predicted energy	Measured energy

4. Discuss all the spectral features you observe on the sodium spectrum. From the calibrated spectrum determine the rest mass of the electron with an estimate of your experimental error.
5. For the cobalt spectrum determine the energies of the two gamma rays and compare with the accepted value. Discuss how the overlap of the tails affects the energies you measure. Calculate the theoretical Compton edges for the two gamma rays and indicate where they fall on your measured spectrum.
6. Resolution: From your MCA spectra calculate the resolution (FWHM) of the counter for the various photopeaks. Present your results in a table; is the resolution dependent on the energy of the gamma ray?
7. Make a spectral plot (counts versus $E+\Delta E/2$) of your SCA data for cesium and compare with the MCA spectrum.
8. A plot of the number of coincidences (for a fixed counting interval) as a function of the angle of separation of the detectors. Explain the width of the curve.
9. Calculate the activity of each source in Curies. Discuss why this can only be an estimate of the minimum activity.
10. In the discussion section include answers to the following questions:

a. Why does the photoelectric peak not have zero width?

b. Why are there x-rays emitted after the "^{137}Cs " decays? To what atomic transition and to what atom do these x-rays correspond?

REFERENCES:

experimental details

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4. Beiser: Concepts of Modern Physics, pp 443, 471-473 (gamma decay)

5. Halliday: Introductory Nuclear Physics

6. Siegbahn: Alpha, Beta and Gamma Ray Spectroscopy