Nuclear Spectroscopy

Equipment scintillation counter and stand, detector output stage, high voltage power supply, sensor-CASSY, MCA box, lead bricks, radioactive sources (Co-60, Cs-137, Sr-90, Am-241), windows computer with Leybold software

Reading

1. Your textbooks. Look under nucleus, radioactivity, and x-rays.
2. "The Atomic Nucleus," Robley D. Evans (McGraw-Hill 1955)

Precautions

1. When the high voltage is on, do not touch the high voltage leads or connectors. They are insulated, but insulation can fail.
2. The radioactive sources are quite weak (they do not need a license). Nevertheless, treat them with respect. Do not hold the sources in your hands longer than necessary, and when not handling the sources, keep them as far from you as practical .
3. The scintillator tube is mechanically fragile. Please handle it with care.
4. When handling the heavy lead bricks used for shielding, take care not to drop them, particularly on your feet.
5. Please do not exceed a photomultiplier voltage of 600 V (0.600 kV).

1 Overview

Radioactive nuclei emit a variety of particles with various energy distributions. In this experiment you will measure and interpret these energy distributions, and investigate how the various kinds of radiation interact with matter.

The nuclear radiation will also eject atomic electrons, resulting in x-ray fluorescence. In some cases this fluorescence can be observed.

2 Introduction

Before 1910 the structure of the atom was unknown. During 1910-1911 the scattering experiments of Rutherford and his colleagues (Geiger and Marsden) determined that the positive charge of an atom was confined to a region smaller than 10^{-14} m. Rutherford termed this region the nucleus. Today we know that a given nucleus or nuclide consists of both protons whose number is the atomic number Z and neutrons whose number is the neutron number N. Both protons and neutrons are termed nucleons. The number A of nucleons in a nuclide, where A=Z+N, is called the nucleon or mass number. The radius of a nuclide is about $R_0 A^{1/3}$, where $R_0 \cong 1.2 \times 10^{-15}$ m. This implies that all nuclides have about the same density, since the volume, which is proportional to the radius cubed, is proportional to the mass number A.

X-rays, produced when energetic electrons smash into a metal target, were discovered by Röntgen in 1895. X-rays with a continuous energy distribution are produced by the electrons being accelerated in the electric fields of nuclei. This radiation is sometimes termed bremsstrahlung (braking radiation) after the German. X-rays with "line" distributions in energy are produced when an incident electron knocks out an inner shell electron and an outer shell electron loses energy and takes its place, emitting an X-ray photon in the process. X-ray line spectra can also be produced by two additional processes that remove an inner shell electron from its orbit. In electron capture (EC) the nucleus captures an electron that has an orbit that penetrates the nucleus. In Internal conversion (IC) an excited nucleus transfers its energy to an atomic electron which is ejected from the atom.

Nuclear radioactivity from uranium was discovered by Becquerel in 1896. He was shortly able to show that the radiation he was looking at was energetic electrons (from the decay chain of uranium). Following research showed that nuclides could also emit alpha particles (He nuclei) and gamma particles (energetic photons). Electrons emitted by a radioactive nucleus are often called beta particles. These three types of radiation are frequently called by the Greek letters α (He Nuclei), $\beta^{\pm}$ (positive and negative electrons), and γ (photons).

There are about 300 stable nuclides. Like the electrons in an atom, the stable nuclides have excited energy levels and can decay back down to a lower energy state or the ground state by emitting radiation in the form of γ particles. Due to the strength of the nuclear force, this radiation is of the order of MeV, while electronic radiation of atoms is of the order of eV to keV, depending on whether inner or outer shell electrons are involved.

There are about 2,500 known nuclides and about 90% of them are unstable. These unstable nuclides can decay into another nuclide by emitting an an α particle or a β particle. A collection of the same unstable nuclides in the same state decays in a time characterized by the half-life. Unstable nuclides will decay into stable ones by one decay or a series of decays. If the nuclide is unstable because it has too many protons it can emit α or β^+ particles, where β^+ particles are positrons, the antiparticle of the electron. It can also capture an atomic electron (EC). If the nuclide is unstable because it has too many neutrons it can emit β^- particles which are ordinary negative electrons. Fission products, nuclei resulting from the splitting of heavy nuclei, are neutron rich, and may decay by the emission of neutrons. This is of great interest in nuclear reactors and weaponry.

3 Radiation Characteristics

When a nuclide decays, energy and momentum must be conserved and selection rules obeyed. The emitted particles have energies of the order of an MeV.

3.1 Alpha Radiation

For a given decay, alpha particles are emitted with one energy. Alpha emitters are heavy nuclei.

3.2 Beta Radiation

β^+ radiation is the result of the following reaction taking place inside the nucleus:

$$p \rightarrow n + \beta^+ + \nu_e. \tag{1}$$

This reaction cannot take place outside a nucleus as it is endothermic. p stands for a proton. n stands for a neutron, which remains in the nucleus. ν_e is the electron neutrino, a spin 1/2 particle with very little mass (maybe a few eV, compared to 0.511 MeV for the electron and 0.938 GeV for the proton), and which interacts with other matter only by the weak force. The neutrino was proposed by Pauli in 1931 in order to conserve momentum and energy in beta decay, but was not a directly observed until 1953 by Reines and Cowan. The decay energy is shared mostly between the positron and the neutrino, so that there is a continuous spectrum of positron or neutrino energies going from zero up to essentially the energy available in the decay. Fig. 1 shows the beta energy spectrum for Radium E ($^{210}_{83}Bi$). The exact shape of the energy spectrum depends on the nuclide, but there is a definite high energy cut-off.

β^- radiation is the result of the following reaction taking place inside the nucleus:

$$n \rightarrow p + \beta^- + \bar{\nu_e}. \tag{2}$$

The proton stays in the nucleus.This equation is exothermic, and a free neutron (outside a nucleus) can decay by this reaction with a half-life of about 12 min. The $\bar{\nu_e}$ particle is an anti-electron neutrino. The decay energy is shared between the electron and anti-neutrino, and the emitted electrons and anti-neutrinos have a continuous energy distribution that goes from zero up to the maximum energy available for the decay.

3.3 Gamma Radiation

Gamma radiation consists of high energy photons. As other particles are not emitted simultaneously, for a given transition they are emitted with a single energy, within the constraint that energy and momentum must be conserved with the emitting nucleus. If the emitting nuclei are locked into a crystal, the recoil energy of the crystal is negligible, and the energy spread of the gamma rays is extremely narrow. This is called the Mossbauer effect. It is not unusual for an alpha or beta decay to produce a nuclide that is in an excited state which decays by the emission of a gamma ray.

4 Interaction of Radiation with Matter

To detect radiation the radiation has to interact with the matter of a detector. In general, interactions of radiation with matter are very important. Examples are the biological effects of radiation, medical uses of radiation, the effects of radiation on the components of nuclear reactors, and the shielding provided by our atmosphere from cosmic rays (we would not exist without that shielding!). The subject is quite complicated, and what follows is a very simplified version suitable as an introduction and hopefully sufficient for the purposes of this experiment and the radiation energies of this experiment.

Broadly, radiation can be divided into two categories, charged particles and gamma rays (photons). First we discuss charged particles. When energetic charged particles enter matter (solid, liquid, or gas) they lose energy by ionizing the matter or by exciting it, and by emitting electromagnetic radiation as x-rays. For the decay energies of this experiment the energy loss by radiation is small, but becomes larger at higher energies. For a given type of charged particle radiation at a given energy, let the energy loss per unit path length, or *stopping*

power, be $-dE/dx$. Taking into account only energy loss by ionization and excitation, theory gives approximately that

$$dE/dx \propto \frac{z^2 e^2 NZ}{mV^2}, \tag{3}$$

where ze is the charge of the radiation particle, N is number density of the absorber, Z is the atomic number of the absorber, m is the mass of the electron, and V is the speed of the radiation. (A factor logarithmic in V as not been included.) This expression does not depend on the mass M of the radiation particle. For alpha and beta particles of about the same energy, this equation predicts that the alpha particles will slow down much faster than the beta particles. Beta radiation is much more penetrating than alpha radiation. In fact, alpha radiation is absorbed so much in air that to do an experiment with them a vacuum is necessary. Gamma radiation, which is not described by Eq.(3), is more penetrating than beta radiation.

4.1 Alpha Radiation

When alpha particles stop in matter, they travel pretty much in straight lines until their speed is quite low. Many electron-ion pairs as well as electronic excitations are produced. The fastest electrons produced, called delta (δ) rays, produce secondary ionization and excitations. Due to the statistical nature of the collisions, all alpha particles of a given energy do not have the same "range," (distance until stopped), a phenomena called range straggling. Range straggling for alpha particles is small compared to range straggling for beta particles. The harmful biological effects of alpha radiation is about 10-20 times that of beta radiation. A significant source of biological alpha radiation is radon gas that has been inhaled.

4.2 Beta Radiation

Due to the small mass of the electron and the statistical nature of the collisions, beta particles do not travel in a straight line until stopped. There is significant range straggling. Delta electrons are produced which create secondary ionization and excitation.

4.3 Gamma Radiation

High energy photons can interact with matter in many ways. The principle ones are the photoelectric effect, Compton scattering, and pair production (electron plus a positron). Very roughly for lower energies the photoelectric effect dominates, around 1 MeV Compton scattering dominates, and for higher energies pair production is the most important mechanism. See Fig. 3, which shows, as a function of Z and photon energy, when the photoelectric effect and the Compton effect are equal, and when the Compton effect and pair production are equal. For the energies in this experiment, pair production is not important.

4.3.1 Photoelectric Effect

In the photoelectric effect the photon is completely absorbed by an atom, and the atom ejects an electron which has most of the energy of the incident photon minus its binding energy. Usually an inner shell electron is ejected. Recoil of the atom conserves energy and

momentum. The ejected electron loses its energy in the ways already described for charged particles. Letting the cross for photoelectric absorption be σ_{pe}, a useful approximation is

$$\sigma_{pe} \approx constant \frac{Z^4}{(h\nu)^3}, \tag{4}$$

where h is Planck's constant and ν is the frequency of the radiation. In reality, both exponents depend somewhat on the energy of the photon. Eq.(4) shows that the photoelectric cross section drops sharply as the energy increases, and increases as the nuclear charge increases. When having X-rays, there is a reason lead aprons are used (Z=82). In addition to the general trend given by Eq.(4), as the energy of the photon increases, there are also also abrupt increases in the σ_{pe} cross section when the photon energies reach the electron shell energies (K shell, L shell, etc.).

4.3.2 Compton Effect

The Compton effect is the elastic scattering of a photon off a stationary or loosely bound electron. The photon loses the energy that it gives to the electron. Assuming that the struck electron is initially stationary, the energy $E_\gamma^{'}$ of the scattered photon is given in terms of the energy E_γ of the incident photon by

$$E_\gamma^{'} = \frac{E_\gamma}{1 + (E_\gamma/mc^2)(1 - \cos\phi)}, \tag{5}$$

where ϕ is the angle through which the photon has been scattered. The scattered electrons have energies that lie between zero when $\phi = 0$ and $E_C = [E_\gamma - E_\gamma/(1 + 2E_\gamma/mc^2)]$ when $\phi = 180\ deg$. E_C has been defined as the maximum energy the scattered electrons can have and is referred to as the "Compton edge." Fig. 2 is a highly simplified energy spectrum of the electrons in the detector or scintillator that might be obtained when mono-energetic γ rays are incident on the scintillator. The total absorption peak b at energy E_γ is due to the photoelectric effect. Curve a is due to Compton scattering. Energy E_C is the Compton edge and is the maximum energy that the electrons can have and is due to photons that have been scattered by 180 deg. Curve "a" for energies below E_C is due to electrons that have scattered photons less than 180 deg and is a very approximate energy spectrum for those electrons.

The total Compton cross section σ_c monotonically decreases as the energy increases, but not as fast as the photoelectric cross section, which dominates at lower energies. Very roughly $\sigma_c = constant \cdot (h\nu)^{-1}$. It is interesting to note how this result and the predictions of Eq.(4) fit in with the left hand curve of Fig. 3.

4.3.3 Pair Production

A γ ray or photon whose energy is greater than $2mc^2$ can, when in the field of a nucleus, produce a positron-electron pair, with the excess energy going into the kinetic energy of these particles. Charge is conserved in this process. The nucleus is necessary to conserve energy and momentum. The cross section for pair production is zero at a gamma ray energy of $2mc^2$ and then monotonically increases. At high enough energies, pair production will dominate the interaction of gamma rays with matter.

4.4 Total Interaction of Gamma Rays

If one puts together the three processes that have been discussed, photoelectric, Compton, and pair production, for a given piece of matter or shielding the attenuation will be largest at lower gamma ray energies, will reach a minimum, perhaps at about 1-3 MeV, and then slowly rise. Fig. 3, from Evans book, show the relative importance of the three processes as a function of photon energy and nuclear charge of the absorber. The left curve shows the parameters for which the photoelectric and Compton effects are equal, and the right curve shows the parameters for which the Compton and pair production effects are equal.

5 Apparatus

The CASSY equipment for this experiment is built by Leybold. CASSY is an acronym for Computer Assisted Science SYstem, and is analogous to Pasco's SWS. The software, Cassy Lab, is installed on a PC, and supports the hardware. The hardware components are shown in Fig. 4 and are labeled. A description of these components follows.

1. The Detector The detector is the "thermos bottle" like structure shown in Fig. 4. The "cap" of the bottle contains the scintillator, and the radiation enters through the top of the cap. The body of the thermos contains the photomultiplier tube. The thermos bottle sits on top of a cylinder called the detector output stage.

   In this experiment the "thermos bottle" is mounted upside-down. The cap of the bottle or scintillator is attached to a wooden frame that has slots in it for sliding in a plastic sample tray. A plastic tray should be used for the small disk-like Co and Sr sources. The Cs source is a larger cylinder with a projection and should be used without a tray. The radiation travels upward into the scintillator.

2. The Scintillator See Fig. 5 for its location in the detector. When an energetic electron appears in the scintillator, either by entering the scintillator as a beta ray or being produced in the scintillator by a gamma ray, a number of 3 eV photons are produced. The number of these 3 eV photons is proportional to the initial energy of the electron. The NaI(Tl) scintillator is a crystal of sodium iodide that has been doped with Thalium (Tl). This crystal is transparent to 3 eV photons. An energetic β^- particle that has entered the crystal is slowed down by creating electron-hole pairs in the crystal. Each electron-hole pair requires the same energy to be created, and the number of electron-hole pairs is proportional to the energy of the incident electron. The Thalium atoms integrated into the crystal are ionized by the electron-hole pairs and produce photons of about 3 eV. If the incident particle is a gamma particle, it produces electrons by either the photoelectric effect or Compton scattering. These electrons interact with the scintillator the same way that the beta particles do. After all, beta particles are electrons.

3. Photomultiplier A schematic cross section of this device is shown in Fig. 5. On the left is the scintillator. A Radiation particle entering the scintillator is turned into photons each with an energy of about 3 eV. The number of photons is approximately proportional to the energy of the incident particle. Most of the photons strike a photocathode and liberate electrons, with the number of electrons being proportional to the number of

photons. These electrons are drawn to the first dynode of a photomultiplier tube which, along with the following dynodes, amplifies this pulse of electrons. The collector, or last dynode of the photomultiplier, delivers the pulse of electrons to the detector output stage. The height of this pulse is proportional to the energy of the electron(s) produced in the scintillator, but some kind of calibration of the energy scale is necessary.

4. Detector Ouput Stage Supplies a low impedance output for the electron pulses and also delivers high voltage to the photomultiplier. The low impedance output is necessary in order to negate capacitance effects of the output cable on the short pulses. The detector output stage is connected to a high voltage power supply and the multichannel analyzer (MCA) box.

5. High Voltage Power Supply Generates high voltage which goes to the detector output stage and then to the electron multiplier. Output voltage is determined by a multi-turn potentiometer and there is a digital readout of the voltage in kV. When turning this power supply on and off be sure that the potentiometer is fully CCW.

6. Multi Channel Analyzer or MCA Box This can also be called a pulse height analyzer. In the computer there are a number of memory registers or channels each with an address. The addresses and number of channels range from 1 to 256, 512 or 1024. When a pulse enters the MCA box an *analog to digital converter* (ADC) converts pulse height to a number or address that is proportional to the pulse height. The greater the pulse height the higher the address. The channel (memory register) at that address is incremented by one. A plot of register contents vs address is an energy distribution of the electrons in the scintillator. The electrons in the scintillator are either from beta decay of your radioactive sample, or have been produced in the scintillator by the interaction of decay gamma particles with the scintillator.

7. Sensor-CASSY Interfaces the sensors or transducers with the computer. There are two inputs, A and B. Input A can be used for voltage or current and input B for voltage. The MCA box should be plugged into input A.

8. Lead Bricks There is background radiation from cosmic rays and radioactive material that impinges on the scintillator. To reduce this unwanted signal, lead bricks are provided for shielding. To change radioactive sources it is necessary to move some of these lead bricks. They are heavy. TAKE CARE NOT TO DROP THEM, PARTICULARLY ON YOUR FEET!

6 Decay Spectrum versus Measured Spectrum

By decay spectrum we mean the actual energy spectrum of the decay products as they are emitted by nuclides. The measured spectrum is the output of the multichannel analyzer. In the case of β^- decay these two spectra, within the energy resolution of the apparatus and neglecting absorption in air and the source container, are the same. In the case of gamma rays they are not, mainly due to Compton scattering. In analyzing gamma ray spectrum remember that the part of the spectrum due to Compton scattering is not part of the original energy spectrum of the emitted gamma particles. The photoelectrons produced in the scintillator by the γ rays photons do have the same energy as the γ ray photons.

7 Energy Resolution

The energy resolution of this apparatus is limited by a number of statistical processes and electronics. Some examples follow. Two particles of the same type and energy will not produce exactly the same number of photons in the scintillator. Two photons of the same energy will not produce exactly the same number of electrons at the collector dynode. The specifications for the scintillator tube state that the energy resolution at 662 keV is <7.5%. The ADC has finite charge resolution. For these reasons it is not necessary to use too many channels when taking data. Use enough channels to make use of the energy resolution you have, but not more. Too many channels will decrease your signal to noise ratio for the same counting time (fewer counts per channel).

Surface barrier detectors are another detector type that have higher energy resolution, but are too expensive to buy and maintain for any but a well funded research lab. They must be kept at liquid nitrogen temperatures at all times.

8 Using CASSY with Cesium-137 Radiation

To introduce the CASSY software and hardware, the energy spectrum of the radiation emitted by the $^{137}_{55}Cs$ nucleus will be examined. ^{137}Cs has a half life of 30.2 y. The most probable decay is by the emission of a β^- particle [total energy (electron + neutrino) = 514 keV] followed by the emission of a 662 keV photon. The total absorption peak of the 662 keV photon will be used as one calibration point for the energy spectrum. The other calibration point will be provided by americium-241 ($^{241}_{95}Am$) which decays by emitting a 60 keV photon. The ^{241}Am source was obtained from a smoke detector which is why it looks quite different from the other sources. It should be used with the side having numbers facing up.

The software (CASSY LAB) is typical of PC software. A window can be clicked to activate it and dragged to get it out of the way, and a right mouse click in the right spot usually brings up a relevant menu. For this first energy spectrum somewhat detailed instruction will be given in the use of the software, but the student, who is probably much more computer literate than the person writing these instructions, will quickly find his/her way around.

Plug in the power for the interface (Sensor CASSY). This is a small black box that needs a special adaptor. On the main desk top double click the CASSY LAB icon. A CASSY LAB window will briefly appear and then the SETTINGS window, which has a number of tabs. (The settings window will not appear if you have not plugged in the power supply.) On top will be the CASSY tab, with an icon of the interface (Sensor CASSY, LD 524 010) on the left. Input A of the interface will be covered by an icon of the MCA Box. Click the MCA box icon and the main (experimental) window will appear. To get the SETTINGS window out of the way, drag the window title to the bottom of the main window. A description of the main window follows. Most of this window is taken up by a graph of counts per channel (N) vs either channel number (n) or energy. To change the parameters of the vertical axis right click just to the left of this axis to get a menu. To change the parameters of the horizontal axis right click just below this axis to get the menu. Right clicking the main part of the graph pulls up the *main menu* which you should examine. One item, energy calibration, will be of particular importance. To the left of the graph is a table which, when one or more energy spectra have been recorded, gives the counts for each channel for each set of data or run. At the top of the table the columns of channel numbers are given by n_r and the counts

per channel are given by N_r where r is the run number (1, 2, 3, ...). Above this table are two buttons, one marked STANDARD and the other marked OVERVIEW. If STANDARD is chosen all the runs are presented on a single graph. If OVERVIEW is chosen, each run is presented on a separate graph, but all the graphs appear in one window. In the STANDARD view (the default) the symbols N_r for all the runs are at the top of the vertical axis and also on the top of the graph. Clicking these N_r buttons produces the possibly different vertical scales for the various runs. The buttons at the very top and left of the standard window allow you to start and stop taking data, delete data, print, etc. You can find the function of these buttons either by vetting the icon or moving the arrow onto the button. The two most important buttons have the following icons.

1. Clock. Clicking this icon starts data taking. Clicking it again stops data taking, although this is usually done by a timer.
2. Page with corner folded. This is at far left and allows you to delete data. Clicking this icon once brings up a "save changes?" window. Clicking YES or NO in this window deletes a given run. Clicking this icon again deletes all runs (very useful).

A smaller window, somewhat akin to the SWS Experimental Set-Up window, is also present. This is labeled MEASURING PARAMETERS, and lets you choose such things as measurement time, number of channels, and amplifier gain. A good place for this window is toward the top and right. To begin, leave all items in this window at their default values except Measuring Time which you can begin by setting at 20 s. This will allow you to experiment without taking up too much time. For your final data, use a longer time so as to have better a signal to noise ratio. The High Voltage window will read zero, but this will automatically change when you apply the high voltage. Familiarize yourself with the remaining parameters in this window, and check that the choices and parameters are as follows.

- Multichannel Measurement
- Number of Channels = 512
- Measuring Time = 20 s. This measuring time is suggested for efficiency in setting up the apparatus. You will probably want to use longer measuring times in taking your final data so as to have adequate signal-to-noise ratios.
- $\surd$ in Negative Pulses box
- Gain Slider = X1 (Gain Box A1 may show -0.98). Gain can also be changed by writing in Gain Box.

When beginning to take data, if you want to be assured of starting with a completely new data set, click NEW SPECTRUM. You will see an appropriate N_r appear at the top of the screen. Otherwise, you may find that you just add to an existing data set.

Most of the lead shielding bricks can and should be left in place, but to access the radioactive sample area it is necessary to remove a lead brick at the front. Put in the ^{137}Cs source (Cs/Ba isotope generator) at the bottom. Replace the brick. Check that the high voltage pot is fully CCW on the high voltage supply and turn the supply on. The voltage readout on the power supply should be zero. Set the voltage at 0.600 kV. (About this value

will also appear in the High Voltage window of MEASURING PARAMETERS.) Take a 20 s run and note the spectrum. The 662 keV total absorption peak should be clearly visible to the right. If not, something is wrong. Note that this peak is not near the right end of the graph. Take a number of runs, increasing the gain by using the slider below the gain box or by writing in the gain box, until the peak is at the right end of the graph, but not off the graph. Note the value of the gain and leave it at this value. If you had set the gain too high to begin with, the peak would have been off the edge of the graph and would not have been observed. If the gain is set too low and the energy spectrum not spread out enough, you lose energy resolution.

If you left click in the main part of the standard window a blue-green doughnut will appear. This will mark a particular channel and the number of counts in that channel. In the table of n and N to the left of the graph the number of counts will be marked by a dotted line.

Now reduce the voltage on the electron multiplier to 0.550 keV and take another run. Comment on the difference from the previous run. Return the electron multiplier voltage to 0.600 kV.

It is evident from the preceding data that the horizontal axis has an arbitrary energy scale that is affected by both the photomultiplier voltage and by the amplifier gain. An energy calibration is necessary. The total absorption peaks of gamma rays are well suited for this as they are relative narrow. It might be thought that a single calibration point would suffice, but it turns out that the zero of the ADC is not precisely known so that two calibration points are necessary, and it is advantageous to have these two points fairly far apart in energy. Calibration to the ^{137}Cs peak and a peak of americium-241 is described. ^{241}Am emits a 60 kev gamma ray and is an appropriate calibration point at the lower end of the energy scale. At this point you may have a number of runs and may wish to delete them so as to not have the STANDARD graph look too messy. To do this click one of the N_r buttons at the very top of the main window and click the delete button. In the Save Changes? menu that apears click NO. Now click the delete button again to remove all the runs. This will bring you back to the SETTINGS window from you can return to the main window by left clicking the MCA box icon. Take a run of ^{137}Cs, using the appropriate gain that you have already determined. Remove the brick that gives you access to the sample area, and leaving the ^{137}Cs source in place, put the ^{241}Am source on a sample tray directly above the Cs source. Replace the brick and take another run. The Am peak should be clearly visible. Right click in the main graph and choose energy calibration from the menu. A vertical line appears which should be moved with the mouse to the Am peak and then left clicked. In the ENERGY CALIBRATION window the channel of the ^{241}Am peak will appear. Fill in the energy of the peak in the box to the right in keV, that is 60. Do not click accept, but right click in the graph region again and choose energy calibration. Move the vertical line that appears with the mouse to the ^{137}Cs peak and left click. Fill in the appropriate box with the energy of the Cs peak, 662 keV. Now click ACCEPT and the horizontal axis should be labeled and calibrated in keV. As long as you do not go back to the main desktop, the calibration should remain. If you delete all the data and go back to the SETTINGS window, you may find that the horizontal axis is now channel number, but you can go back to energy by right clicking below the axis.

Up to this point background radiation has been neglected. This results from cosmic rays and the fact that there is substantial natural radioactivity in all materials, including

yourself! Remove all sources and do not put the front-center shielding brick back. Take a run to determine the background. Now replace the brick and take another run. Are the bricks reducing the background? The software will subtract the background for you. Take a Cs run (same time as for the background run) with the shielding in place. Go to OVERVIEW and right click on the main part of the Cs graph to bring up an ADD SPECTRA window. Put in the run number that will subtract the background run (shielding in place) from your Cs run and obtain a new spectrum.

At this point keep the energy calibration but delete all your test data. Take a longer background and Cs run, and subtract the background. Print out your result. It should look something like Fig. 6, which is now discussed and has been annotated with $E_\gamma(Cs)$, E_C, and E_B. $E_\gamma(Cs) = 662\ keV$ is the total absorption peak for Cs. The Compton edge, $E_C = 477/kev$, is the maximum energy elastically scattered electrons can have and is due to the Compton effect. Compared to Fig. 2, this edge is smeared out due to the finite resolution of the scintillator and other effects. E_B, where the B stands for "backscatter," is the minimum amount of energy that a scattered photon can have in a Compton scattering event and is equal to $E_B = E_\gamma^{'}(\theta = 180\ deg) = 184\ keV$. These backscattered photons do not necessarily arise in the scintillator. They may well arise from material surrounding the scintillator, and in many experimental situations arise from γ ray scattering in the range of θ=120 to 150 deg. These scattered photons produce fast electrons in the scintillator by total absorption and are responsible for the peak to the right of E_B, the so called backscatter peak. Underlying these events initiated by gamma rays will be the continuous spectrum of the 515 keV beta decay.

You will also see peaks at about 25 keV and 72 keV. These peaks are due to X-rays produced in the Cs source and the lead shielding. The cesium $K_{\alpha 1}$ and $K_{\alpha 2}$ lines are at 30.3 and 30.6 keV and are produced when a K shell electron (n=1) is ejected from the atom and a L shell electron (n=2) replaces it. The corresponding energies for lead are 72.1 and 72.8 keV. The discrepancy between 25 keV and 30 keV for Cs might be due to the energy calibration not holding well at lower energies (below 60 keV).

9 Using CASSY with Cobalt-60 Radiation

$^{60}_{27}Co$, with a half-life of 5.271 y, decays into $^{60}_{26}Ni$ by β^- decay with total energy (electron + neutrino) of 0.316 MeV. The Ni goes to the ground state by successively emitting 2 gamma rays, the first with an energy of 1.17 MeV and the second with an energy of 1.33 MeV. The energy spectrum as observed with the scintillator will be characterized by the continuous spectrum of the beta decay, the total absorption peaks of the gamma decays, and the Compton distributions of the gamma decays. Investigate the Co spectrum. Place the Co disk cource on the plastic tray and insert the tray close to the scintillator in the source holder. Use a photomultiplier voltage of 600 V but adjust the variable gain appropriately. Calibrate the energy of the apparatus, perhaps proceeding similarly to what was done with Cs. When you have a energy spectrum you like, print it out, enter the various E_γ's, E_C's, and E_B's. Discuss your results.

10 Using CASSY with Strontium-90 Radiation

^{90}Sr has a half life of 29 y and β^- decays to the ground state of ^{90}Y with an energy of 546 keV. The ^{90}Y has a half life of 64 h and $\beta-$ decays to the ground state of ^{90}Zr with an energy of 2283 keV. Obtain a suitable calibrated spectrum of this decay and discuss the results. Note that your energy spectrum is the result of two decays with different energy end points.

11 Attentuation of Gamma Radiation

If a beam of mono-energetic gamma rays of intensity I_0 is incident normally on a plane parallel slab of material with thickness x the emerging intensity I of the beam will be

$$I = I_0 e^{-\mu x}, \tag{6}$$

where μ is the linear attentuation coeficient. We assume here that absorption (photo effect), angular scattering, or energy degradation (Compton scattering) removes a gamma ray from the beam. The absorption coefficient depends on

1. the energy of the gamma ray, and
2. the material of the absorber.

Use the gamma rays of Co (1.2 and 1.3 MeV), Cs (662 keV) and Am (60 keV) to investigate the energy dependence and absorbers of Al, Cu and Pb to investigate the material dependence. We illustrate the procedures with Co gamma rays and Al absorbers, but the techniques are similar for the other elements and absorbers.

1. Put the Co source into the apparatus near the bottom so as to leave plenty of room to insert absorbers, but do not add an absorber at this point.
2. Take a spectrum using an appropriate counting time.

Right click in the main part of the standard graph and in the menu produced left click on "calculate integral ▷ area to x-axis." In the lower left of screen will appear "click on start of range." Left click where the left peak starts to rise. Note the channel number. Now in the lower left of the screen will appear "click on end of range." Left click where the right peak has mostly fallen. Note the channel number. In the lower left of the screen appears $\Sigma = N$ where N is the number of counts in the integration range. Record N. Comments:

- The approximate integral of both peaks together is being calculated.
- The exact starting and stopping points of the integration range are not critical. What is important is that the same starting and stopping points are used for the measurements with absorbers in place.

Delete this data and put an Al absorber between the Co source and the detector. Use one of the thicker Al plates that is not part of the absorber set in the wooden box. Take another spectrum. You will want to measure the thickness of the Al plate and the number of counts N in the integration range. The integration range should stay in place, but if it

does not, you can use your recorded values of the range to reinstate the range. Repeat this procedure for different thicknesses of Al. Plot $\ln N$ vs x. Is the plot pretty much a straight line? Use your calculator to get the slope of the line by means of a least squares fit. The slope will be μ. Repeat for Cu and Pb absorbers.

Repeat the above for the total absorption of Cs and Am gamma rays.

Examine your data and answer the following questions.

1. How does the absorption coefficient depend on the mass density of the absorber?
2. How does the absorption coefficient depend on the energy of the gamma ray?

12 Exercise

Show that a photon cannot be completely absorbed by a stationary free electron. Use relativistic formulae.

13 Comment

In doing a critical experiment with limited signal, one would probably adjust the photo-multiplier voltage for maximum signal to noise. Our signals are not that low here, and to preserve the life of the scintillator counter, a maximum voltage of 600 V is used.

14 Vernacular

If you look up the electromagnetic spectrum in a text book, there is often an overlap between x-rays and gamma-rays. It is fairly customary to refer to photons that are emitted by nuclei as gamma-rays, and to photons that have been emitted by atoms which have had inner shell electron removed as x-rays. With this convention, some x-rays photons are more energetic than some gamma-ray photons.

Fluorescence is a general term that refers to the absorption of radiation and the immediate re-radiation of lower energy radiation. In this experiment the x-rays emitted by the Cs source and Pb shielding can be termed fluorescence. If the re-radiation is not immediate it is termed phosphorescence. Phosphors are used for oscilloscope displays.

The terms alpha radiation and beta radiation where assigned by Rutherford in 1899. He was studying the radiation from uranium and observed that there were two distinct types of radiation, one more penetrating than the other. The less penetrating radiation he called called alpha radiation and the more penetrating he called beta radiation.

15 Finishing Up

Please leave the bench as you found it. In particular,

1. on high voltage power supply turn potentiometer fully CCW and then turn supply off,
2. return to desktop, and
3. unplug interface power supply.

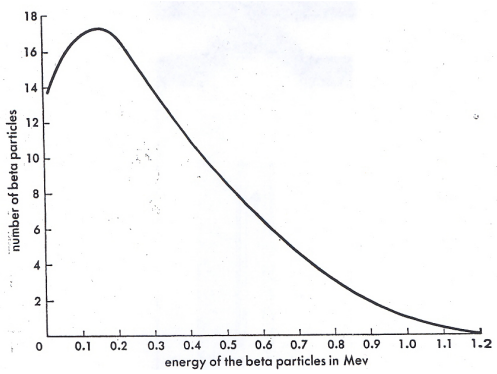

Figure 1: Distribution of energy among beta particles of radium E

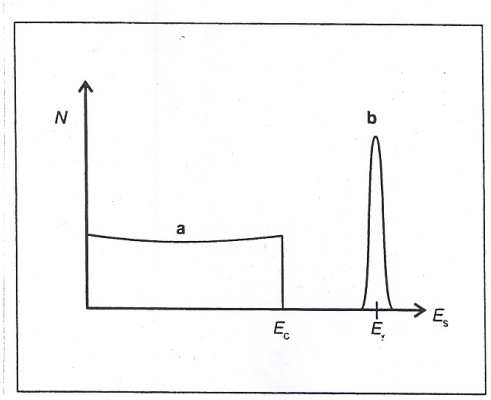

Figure 2: Histogram of a simplified pulse height distribution of a scintillation counter when monoenergetic γ radiation is absorbed. (a) Compton distribution (b) total absorption peak.

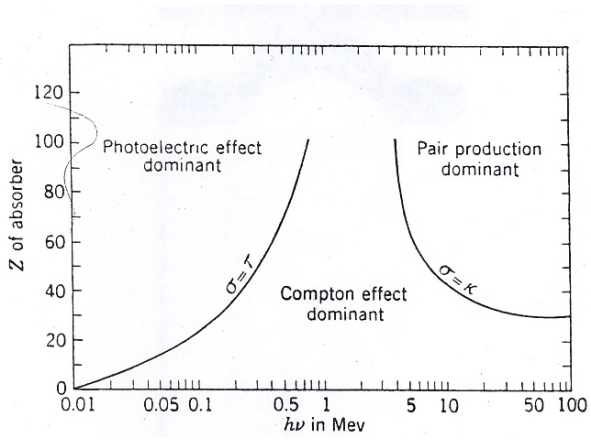

Figure 3: Relative importance of the three major types of γ-ray interaction. The lines show the values of Z and $h\nu$ for hich the two neighboring effects are just equal.

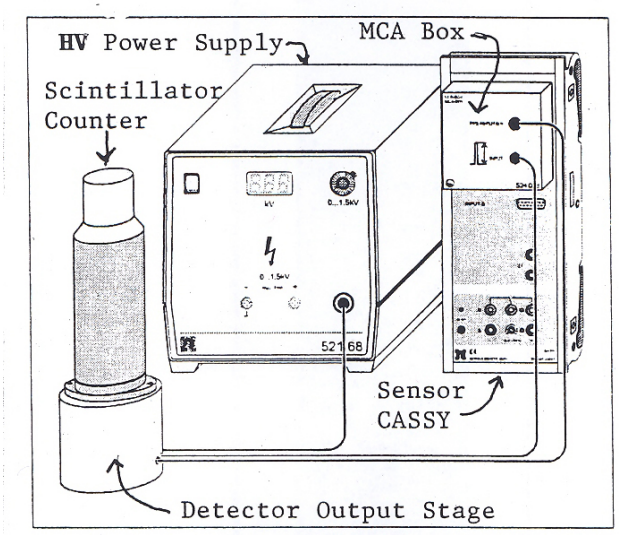

Figure 4:

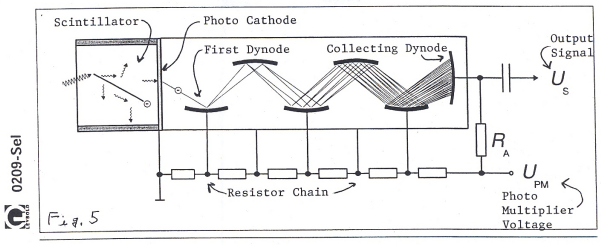

Figure 5:

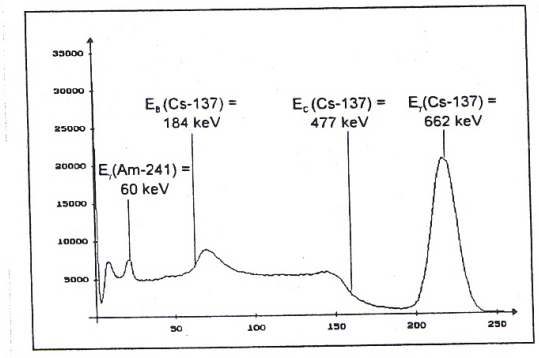

Figure 6: Graph of the pulse height spectrum of γ radiation of Cs-137.