EXPERIMENT 3

GAMMA RAY DETECTION WITH SCINTILLATION DETECTORS

PURPOSE

1. To demonstrate the use of a sodium iodide scintillation detector and its response to gamma rays.
2. To show the absorption of gamma rays in matter.

EQUIPMENT REQUIRED

Model 802–3 NaI(Tl) Scintillation Detector
Model 2007 Tube Base
Model 2005 Preamplifier
Model 2012 Amplifier
Model 2000 Bin and Power Supply
Model 3102 High Voltage Supply
Series 30 Multichannel Analyzer
Oscilloscope
Model A501 Absorber Set
Model 7443 Gamma Reference Source Set
Model 7445 Coincidence Source Set
Model C177–3 Coaxial Cable Set

A. RADIOACTIVE SOURCES AND SCINTILLATION DETECTORS

Radioactive nuclei decay by emitting beta or alpha particles. Often the decay is to an excited state of the daughter nucleus, which usually decays by emission of a gamma ray. The energy level sequence and therefore the gamma ray energy spectrum for every nucleus is unique and can be used to identify the nucleus. The energy levels and decay processes of ^{22}Na, ^{60}Co, and ^{137}Cs are given in Figure 3.1. The term beta decay means either $\beta-$ (electron) emission, $\beta+$ (positron) emission, or electron capture by the nucleus.

The thallium-activated sodium iodide detector, or NaI(Tl) detector, responds to the gamma ray by producing a small flash of light, a scintillation. The scintillation occurs when electrons, and in some cases positrons, are given energy by the incident gamma ray and are stopped by the crystal. The crystal is mounted on a photomultiplier tube that converts the scintillation to an electrical pulse. The first pulse from the photocathode is very small and is amplified in 10 stages in a series of dynodes to get a large enough pulse. This is taken from the anode of the photomultiplier, and is a negative pulse.

The NaI crystal is protected from collecting moisture in the air by encasing it in aluminum, which also serves as a convenient mounting for the entire crystal photomultiplier unit.

There are three dominant gamma ray interactions with matter:

1. The photoelectric effect
2. The Compton effect
3. Pair production

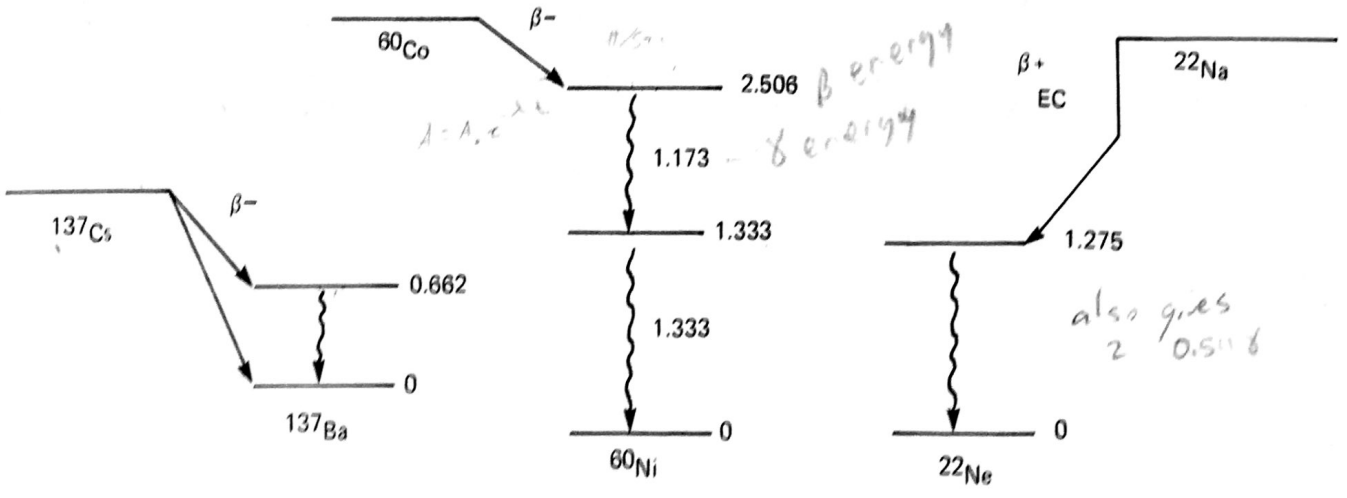

Figure 3.1 Decay Schemes.

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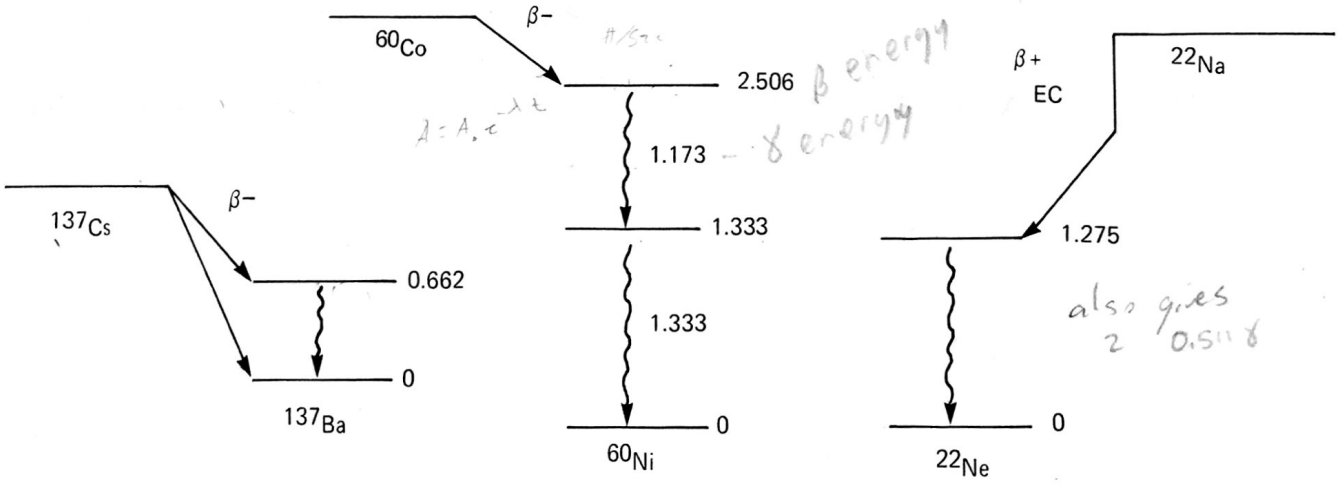

Figure 3.1 Decay Schemes.

Only the photoelectric effect produces an output pulse that is proportional to the gamma ray energy. In the photoelectric effect, all of the energy of the gamma ray is absorbed by an electron. In the Compton effect, the gamma ray scatters from an electron, giving the electron an amount of energy that depends upon the angle of scatter:

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

Where E' is the scattered gamma ray energy, E the incident gamma ray energy, and θ is the angle of scatter. The term mc^2 is the rest mass energy of the electron, equal to 0.511 MeV. The energy given the electron is just

$$E_e = E - E'$$

If the gamma ray escapes from the crystal, then the only energy deposited is the electron energy, and the output pulse is much less than that for the full energy. The spectrum is complicated by having many pulses not of the full gamma ray energy, as will be seen below.

If the gamma ray does not escape from the crystal, but either scatters again or gives up its remaining energy by the photoelectric process, then the full energy pulse is obtained. Since this is more likely in a larger crystal, the full energy efficiency increases by more than the increase in volume.

Pair production occurs when the gamma ray energy is greater than 1.022 MeV, but is not an important part of detection until energies of 2.5 MeV or higher. The positron and electron of the pair produced slow down and scintillate, just as for Compton scattered electrons. When the positron comes to rest it annihilates with an electron, producing two 0.511 MeV gamma rays. Both of these must be absorbed to get the full energy peaks. Pair production will be discussed further in Experiment 4.

The maximum energy given to an electron in Compton scattering occurs for gamma ray scattering of 180°, and the energy distribution is continuous up to that point. This energy, known as the Compton edge, can be calculated from the incident gamma ray energy.

B. GAMMA RAY SPECTRUM

1. Connect the apparatus as in Figure 3.2. Either the anode or dynode output from the tube base may be used. The anode signals are negative, while the dynode signals are positive. Place the ^{137}Cs source near the NaI detector and set the HV supply at +1000 volts. Set the amplifier gain and polarity so that the peak appears a little below the middle of the display.

2. Collect the data in half of memory (512 channels) and long enough so that the spectrum appears to vary smoothly from one point to the next. It should appear as in Figure 3.3A. Identify the photopeak. The mass of data to the left of the photopeak is the Compton distribution, which has a maximum value at the Compton edge. This is the response to a monoenergetic gamma ray of roughly medium energy. A very strong peak at low energy may be present if the discriminator is set low enough. This is the Ba x-ray at 37 keV, which follows internal conversion.

3. Read out the spectrum and make a graph of it.

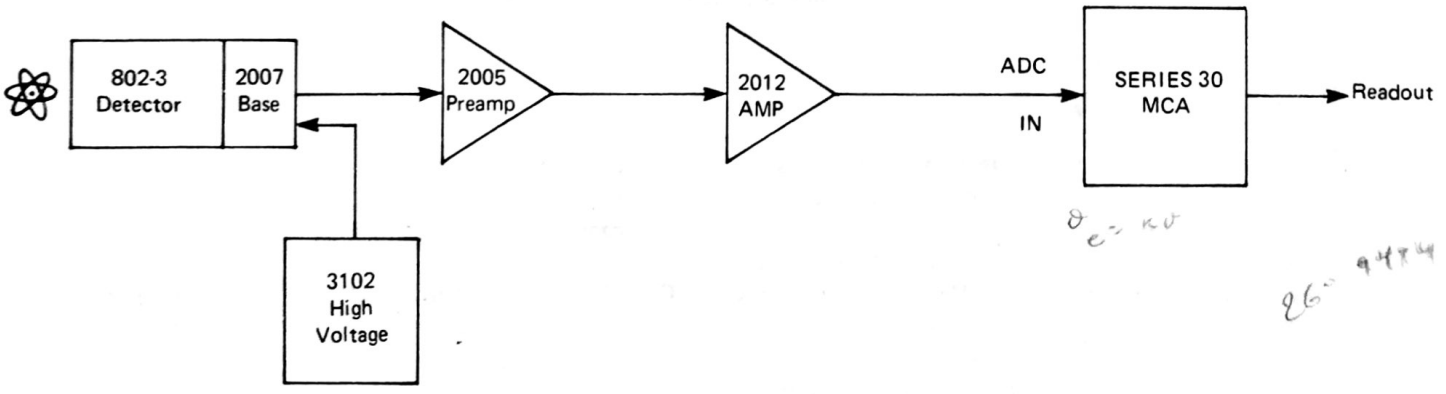

Figure 3.2 Electronics Setup.

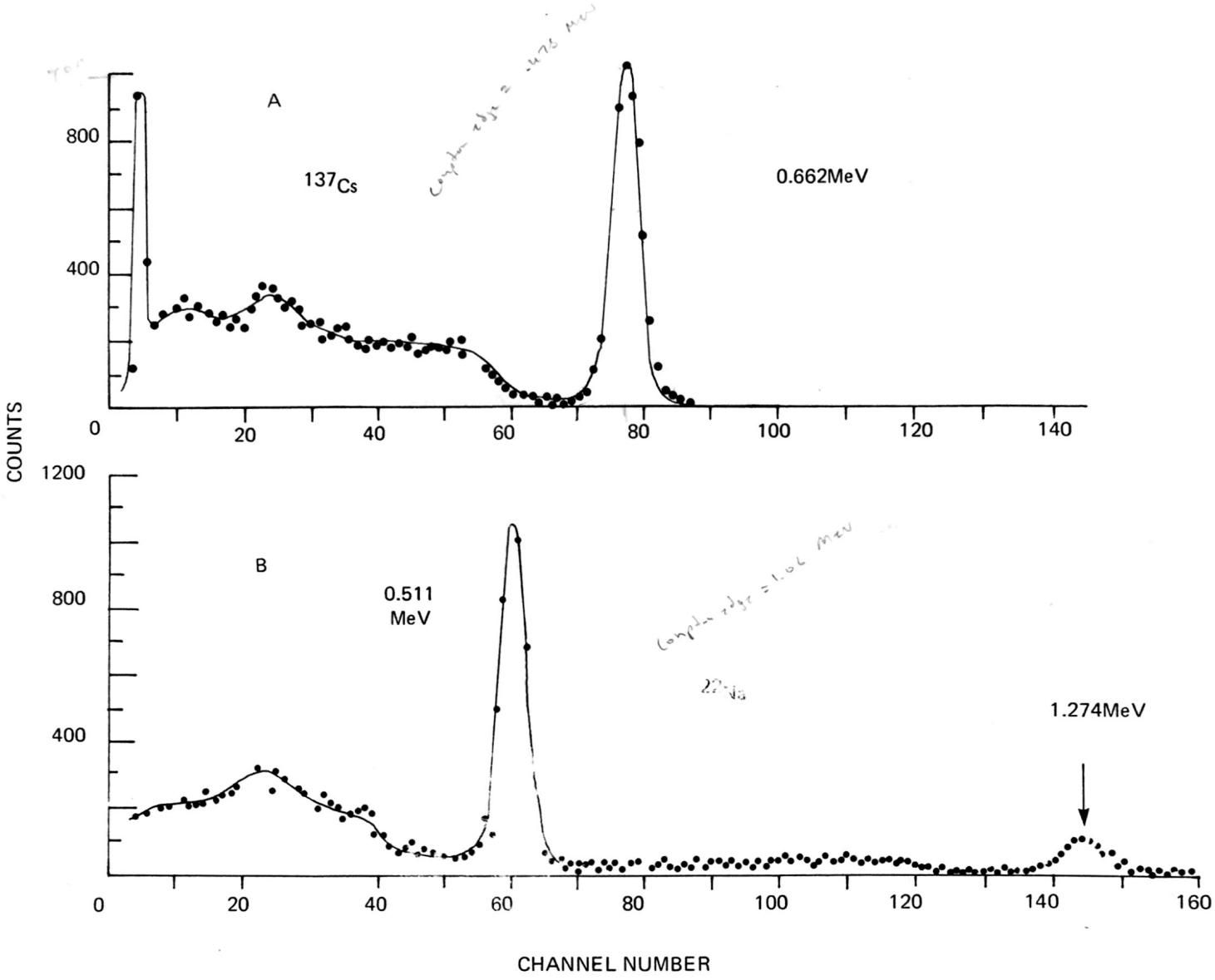

Figure 3.3 Gamma Ray Spectra.

4. Now place the ^{22} Na source near the detector instead of the ^{137}Cs source. Clear the memory and collect a spectrum. From the decay scheme (Figure 3.1) one could expect a similar spectrum to ^{137}Cs, but there are now two peaks. The higher one at 1.27 MeV is the gamma ray expected, while the lower one is at 0.511 MeV and is the radiation from positron annihilation. This "511" radiation will always be present when positrons are emitted by nuclei. Read out the spectrum and plot a graph of it. It should appear as in Figure 3.3B.

5. Place a large piece of lead (such as a lead brick) next to the source and take a fresh spectrum. There will be additional counts in the Compton region of the spectrum due to scattering from the lead. Any material near the source will cause scattering of gamma rays, so this effect cannot be entirely eliminated.

C. ENERGY CALIBRATION AND RESOLUTION

1. From the graphs of the ^{137}Cs and ^{22}Na spectra determine the central channel of each photopeak and plot the gamma ray energy of the peak vs. the corresponding channel. (Alternatively, move the cursors to the peak channel and read the cursor channel from the display.) Estimate the position to the nearest channel, and estimate the uncertainty in determining the peak position. Plot the uncertainty in position as error flags, as in Figure 3.4.

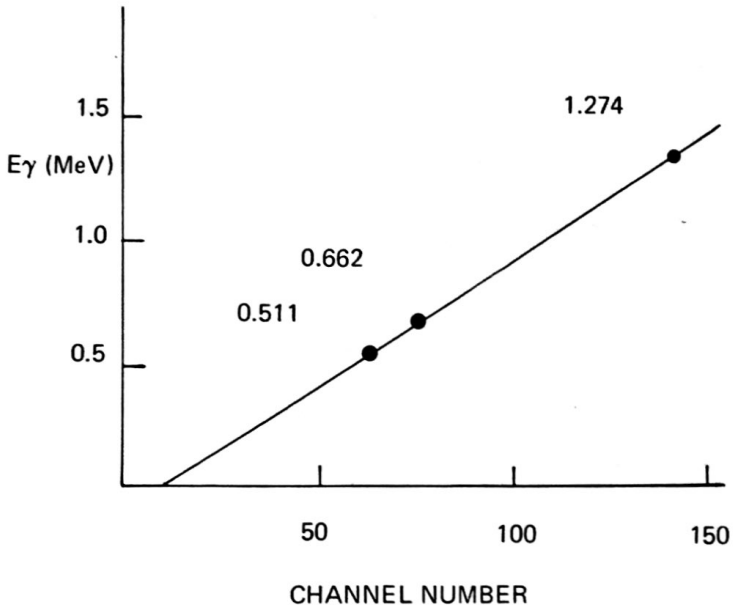

Figure 3.4 Energy Calibration.

A straight line through the data gives the energy corresponding to each channel of the MCA. The line may not go exactly through zero. This is due to the NaI detector not being exactly linear at low energies, but can also be due to variations in the adjustment of the zero setting of the ADC. Non-linearity may also occur if the amplifier gain is high enough to bring pulses into saturation, but this can be checked with an oscilloscope at the amplifier output.

2. The calibration curve can now be used to determine the energies of a different gamma ray source. Collect a spectrum for ^{60}Co and determine the energies of the two photopeaks that appear.

The uncertainty in the peak position is related to the width of the peak. The full width of the peak at half of its maximum value (FWHM) is used to determine the resolution by:

$$\text{RESOLUTION} = \frac{\text{FWHM} \times 100\%}{\text{Peak Position}}$$

where the FWHM and peak positions are given in channels. The performance of a scintillation counter is usually specified in terms of its resolution for the .662 MeV peak of ^{137}Cs since the resolution depends upon gamma ray energy.

3. Calculate the resolution for each of the three photopeaks in ^{137}Cs and ^{22}Na. This will be about 8 to 9% for a crystal-phototube combination that is working properly. If it is higher, there may have been some damage to the unit, resulting in poor optical coupling, or the high voltage is too low (it should be about +1000 volts), or the counting rate is too high.

4. Calculate the energy of the Compton Edge for the ^{137}Cs and ^{22}Na gamma rays and compare to the value obtained from the spectrum.

D. GAMMA RAY ABSORPTION IN MATTER

1. Remove all other sources and place the ^{137}Cs source at about 10 cm from the NaI detector and collect a spectrum. Move the cursor with INTENSIFY on to set a region of interest about the photopeak, as shown in Figure 3.5. Determine the number of counts in the region of interest by reading the integral value (labelled INT) from the CRT. (If the integrate feature is not available on the MCA being used, print the spectrum and add up the channels of the photopeak.)

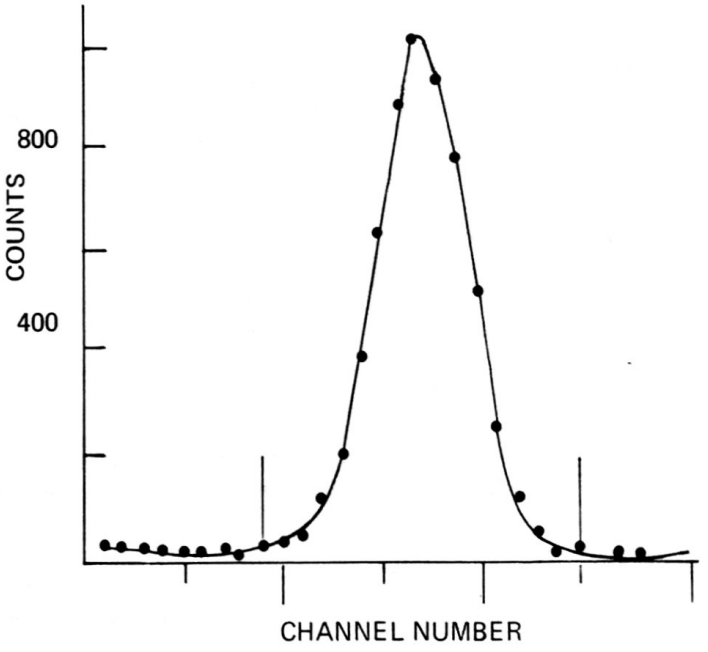

Figure 3.5 Peak Area.

2. Clear the MCA and Count these photopeak pulses for 100 seconds.

3. Place one sheet of lead between source and detector and count the number of pulses in 100 seconds. Repeat with an additional sheet of lead each time.

4. Remove the ^{137}Cs source and determine the background counts in the photopeak region in 100 seconds. Subtract the background from each of the data taken above. Calculate the error in the result from:

$$\sigma_{TOTAL} = \sqrt{\sigma^2_{data} + \sigma^2_{background}}$$

5. Plot the logarithm of the number of counts (and the error flags) vs. the absorber thickness of lead. Determine the absorption coefficient from the slope of the curve since:

$$\log\left(\frac{I}{I_0}\right) = -\mu\chi$$

where I is the intensity for the thickness x and I_0 is the intensity with no absorber. The absorption coefficient μ is usually expressed in units of cm^{-1}.

E. MULTICHANNEL ANALYZER DEAD TIME

The multichannel analyzer requires many microseconds longer than the input pulse width to convert the pulse to a memory location and increment that location. During that time the MCA is dead and will not accept any more pulses. A meter on the front of the MCA gives a measure of the percent of time that it is dead. The internal clock used in the preset time is corrected for the dead time, so that the preset time used is live time, and is always longer than clock time. Channel zero is incremented every second of live time in order to have a value of elapsed live time with the spectrum.

1. Set one or two sources near the NaI detector to produce a 30% or higher MCA dead time, as indicated on the dead time meter.

2. Set preset time at 100 seconds. Use a clock or timer and count the seconds clock time that correspond to the preset live time of the MCA. The clock time will be longer than the 100 seconds by the same percentage as the MCA dead time.

F. MULTICHANNEL ANALYZER INTERNAL PREAMP/AMP AND HIGH VOLTAGE

The Series 30 multichannel analyzer has an internal preamplifier and amplifier for use with scintillation detectors (the LOW input). The anode output should be used. Option 3100-01 of the MCA is an internal high voltage supply, allowing the scintillation detector and tube base to be the only units external to the MCA, as shown in Figure 3.6.

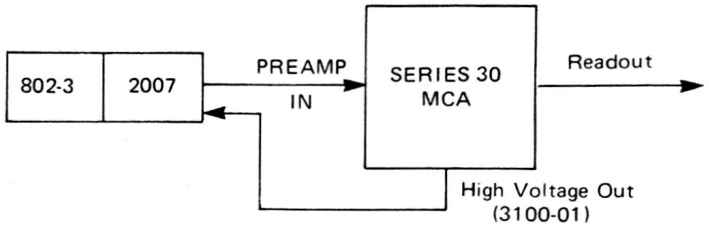

Figure 3.6 MCA with Internal Preamplifier and Amplifier.

References

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2. F. Ajzenberg-Selove, ed., Nuclear Spectroscopy, Academic Press, New York, (1960), pp. 211–334.
3. W.J. Price, Nuclear Radiation Detection, McGraw-Hill, New York, (1968).
4. J.B. Birks, The Theory and Practice of Scintillation Counting, MacMillan, New York (1964).