

Gamma Ray Scintillation Spectroscopy

'86, rev'94 (THK)

Object

To understand the various interactions of gamma rays with matter.

To calibrate a gamma ray scintillation spectrometer, using gamma ray sources of known gamma energy.

To use the calibrated spectrometer to measure the energy of:

Gamma rays from a particular radioactive nucleus,

Positron annihilation radiation, thus obtaining a measurement of the mass of the electron via conservation of mass-energy.

References

1. Serway, Moses and Moyer: Modern Physics, pp 431-432 (scintillator-photomultiplier), 389-392 (beta and gamma decay)
2. AN34: Experiments in Nuclear Science, 3rd Ed., EG & G Ortec. Experiment 1, Basic identifications in Electronic Measurement Systems, pp 1-7; Experiment 3, Gamma Spectroscopy Using NaI, pp 15-24; Linear and Logic Signals in EG & G Ortec NIM Instruments, pp159-160
3. D.W. Preston & E.R. Dietz: The Art of Experimental Physics, Appendix B Counting and Sorting Particles: The Scintillation Counter, pp376-385
4. Beiser: Concepts of Modern Physics, pp 443, 471-473 (gamma decay)
5. A. Melissinos, Experiments in Modern Physics: Chapter 5 - scintillation counter
6. Halliday: Introductory Nuclear Physics
7. Siegbahn: Alpha, Beta and Gamma Ray Spectroscopy
8. R. D. Evans, The Atomic Nucleus, McGraw-Hill (1955)
9. J.G. Bradley, J.S. Schweitzer, J.A. Truax, Alan Rice and T.A. Tombrello: A Neutron Activation Gamma Ray Spectrometer for Planetary Surface Analysis, Brown Bag Preprint BB-127 (Cal Tech), June 1994 (IAA-L-0202P, to be published in Proceedings of the IAA Workshop)
10. R.C. Hertzog: Laboratory and Field Evaluation of an Inelastic Neutron Scattering and Capture Gamma Ray Spectroscopy Tool, Soc. Petr. Eng. Journ., v20, 327-340, 1980

11. J.S. Schweitzer: Nuclear Techniques in the Oil Industry, Nucl. Geophysics, v5, No. 1/2, 65-90, 1991
12. J. A. Grau, J. S. Schweitzer and R. C. Hertzog: Statistical Uncertainties of Elemental Concentrations Extracted from Neutron Induced Gamma-Ray Measurements, IEEE Trans. Nucl. Sci., v37, No. 6, 2175-2178, 1990
13. C. L. Melcher and J. S. Schweitzer: A Promising New Scintillator: Cerium-Doped Lutetium Oxyorthosilicate, Nucl. Instr.& Meth. in Phys. Research, vA314, 212-214, 1992
14. Light Emission Mechanism of Lu₂(SiO₄)O:Ce, BB-115
15. C. L. Melcher, J. S. Schweitzer, R. A. Manente and C. A. Peterson: Applicability of GSO Scintillators for Well Logging, IEEE Trans. Nucl. Sci., v38, No. 2, 506-509, 1991
16. Energy Transfer from Gd to Ce in Gd₂(SiO₄)O:Ce, BB-123
17. Energy Transfer Mechanisms in Gd₂(SiO₄)O:Ce Scintillators, BB-124
18. The Role of Gadolinium in the Scintillation Process of Cerium-Doped Gadolinium Oxyorthosilicate, BB-126

I. Gamma ray interaction mechanisms and scintillator-photomultiplier detection

When a charged particle enters the phosphor of a scintillation counter, it is slowed down, losing energy in the usual way by excitation and ionization of the crystal electrons. The energy can be given off in various ways, one of them being emission of light (fluorescence). A group of light pulses from a single primary event may strike the photosensitive surface of a photomultiplier tube and thus be transformed into a current signal which, when sent into the phototube anode load resistance, results in a voltage pulse. If the crystal is large enough so that the charged particle is completely stopped, and no excitation energy escapes in the form of light, the size of the phototube voltage pulse will be proportional to the particle energy. The pulse height distribution will therefore be similar to the initial primary energy distribution, and an instrument which measures this distribution can be used as a spectrometer.

Gamma rays are neutral and, when entering the crystal, must first produce fast charged electrons by one of three processes: photoelectric effect, Compton effect and pair production. It is these fast electrons which give rise to scintillations; not the gamma ray. (The same holds true for semiconducting crystal detectors.) The observed spectral distribution will thus depend on the detailed interaction process of the gamma rays in the crystal (full or partial energy loss). (See the Compton effect experiment.)

Consider a beam of mono-energetic gamma rays. The Compton electrons produced by these gammas will have a continuous energy distribution from zero to a maximum energy (less than the initial photon energy, since the recoiling electron carries energy). This distribution can be used to determine the gamma ray energy, especially in the case where the crystal used is anthracene or stilbene (organic), or a plastic scintillator, where the probability of the photoelectric effect is very small. However, this is usually not the most accurate or the most convenient method, because the Compton spectral features are not as sharp as a photoelectron peak (the spectrum of photoelectron interaction by the gamma ray where the energy loss is always total.)

At low gamma energies, and also if the scintillation crystal contains elements of higher atomic number, such as NaI doped with small quantities of thallium (Tl), the cross section for the photoelectric effect is greatly enhanced relative to the Compton cross-section. The energy of photoelectrons bears a definite relationship to the gamma ray energy, in contrast to the Compton electron situation. If 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. The photomultiplier output pulse will correspond approximately to the full gamma ray energy, if the photoelectron stops in the crystal

and if no light escapes the crystal.

Other multiple processes may occur. For example, if a Compton scattered gamma ray produces a photoelectron, the output pulse will be the result of the summing of energies lost in the crystal by the first scattered Compton recoil electron and, possibly (particularly if the crystal is large), by a second photoelectron resulting from interaction of the Compton gamma of the first interaction. This pulse will therefore contribute to the peak caused by direct primary photoelectric processes. For another summing process, see [AN34](#), Fig. 3.10, page 24.

If the gamma-ray energy is above the pair production threshold (1.02 MeV, the rest mass of an electron-positron pair), the kinetic energy loss of a pair produced in the crystal will produce pulses corresponding to an energy $2m_0c^2$ below the gamma-ray energy. (Of course, either the positron or electron may escape the crystal after partial loss of kinetic energy).

Pair production is not really dependent on atomic electrons. The interaction picture for the uncharged gamma is with "virtual" (e^+e^-) pairs, concentrated in the high field region close to the nucleus. The pair interaction cross section, with threshold at $2m_0c^2$ (1.02 MeV) increases with energy. Starting at low energies the total cross section is successively dominated by the photoelectric, Compton and pair-production effects, the details depending on the nuclear charge Z .

If the positron has been slowed down and stopped in the crystal (a very rapid process) it will annihilate, mainly with the emission of two photons, each of energy m_0c^2 . One, or both, of these may produce secondary electrons (and then light) in the crystal, and thus contribute to the height of the photomultiplier output pulse. Pair production therefore produces a "full energy" peak, a "one-escape peak" and "two-escape peak", with relative probabilities depending on the crystal size. The same gamma rays might also have interacted by the Compton or photoelectron processes. Study the dependence on gamma energy of these three processes.

Peaks in the pulse height distribution will have widths depending primarily on the efficiencies of the various energy conversion processes. Since all the gamma energy is converted in a photoelectron ejection, the corresponding "photopeak" is frequently the best defined feature of a gamma ray pulse height spectrum. The fractional full width of a peak at half its maximum height (**FWHM**) is a convenient measure of the resolution of the instrument. It is limited by escape of secondary quanta (electrons, X-rays or gammas) from the crystal (a size dependent matter), by statistical fluctuations in the number of visible and UV photons which are produced by the charged particles and which travel successfully thru the transparent crystal to the photocathode, as well as by statistical fluctuations in the number of initial photo electrons ejected from the multiplier photocathode and in subsequent multiplication processes at the dynodes.

Signal/noise considerations

Contact potentials between cathode and anode in a multistage multiplier tube are

probably small (eV) relative to applied voltage (keV); therefore they probably don't play a significant role for a multi-stage multiplier tube. Within a certain range, voltage probably does not matter much. The important considerations for energy resolution are "noise" and where it is introduced - statistical (crystal, tube), preamp, cables, amplifier etc. The rule of thumb is to boost signal early with a low-noise pre-amplifier, before additional noise is introduced. Statistical fluctuations in the crystal can't be controlled; once these dominate, the location of subsequent gain does not matter. Multiplication fluctuations in the tube may be proportional to signal gain over some range of voltage; eventually, sufficiently high voltage may introduce excess noise in the voltage divider resistor string, or micro breakdown in the tube.

For fast coincidence work, different considerations may apply. Rise time may be more important than signal resolution. One way of handling signals for both fast timing and good energy resolution is to take the anode signal (maximum amplitude, possibly saturated and non-linear) for timing while taking a smaller, non-saturated, linear signal from an earlier dynode for pulse height analysis. In this case, the two signals will have opposite polarities, since electrons arrive at the anode without any departing, while more electrons leave a dynode than arrive (multiplication).

II. Beta emission as gamma ray precursor

In beta decay, the energy available for the decay must provide for the rest mass of the emitted electron (β^+ or β^-), for the rest mass (if any) of the emitted $\bar{\nu}$ (for β^-) or ν (for β^+). The remainder of the available decay energy is partitioned mainly between kinetic energy of the light β and ν particles, with a tiny amount of recoil energy for the massive final nucleus. All energy comes from the nuclear mass difference from the initial and final states.

Nevertheless, many nuclear decay diagrams, such as that below for ^{22}Na , show the difference in atomic mass (energy) between the initial and final ground states. This requires explanation.

Conventional nuclear mass spectrometry (with magnetic and/or electric spectrometers) accelerates to known voltage (energy), and then bends an ion, not a bare nucleus. Usually the ion is singly charged, differing from the atom by one electron mass. A +1 ion is a lot closer to an atom than it is to a bare nucleus-i.e., it is much easier to add one electron mass to the measured +1 ion mass to obtain atomic mass (with subtraction of a small and fairly reliable additional binding energy for the one valence electron), than to subtract many electron masses to obtain the mass of the bare nucleus (with large and quite poorly known electron binding energies).

It may seem that we will have to do this difficult atomic structure calculation anyhow for our case, since it is nuclear mass that we are interested in. However, for decays we are really concerned only with nuclear mass differences between isobars ($\Delta A = 0$), with $\Delta Z = \pm 1$ and $\Delta N = \mp 1$ (for β^-/β^+) so, once again, the main difference is only electron mass, plus a small electron binding energy, which we will not discuss further.

In the case of positron decay, as shown for $^{22}\text{Na} \rightarrow ^{22}\text{Ne}$ below, the initial (upper) nuclear state has higher Z by 1e than the final, and therefore one extra atomic electron mass which must be subtracted from the atomic mass to give the nuclear mass differences. In addition, the available nuclear mass difference must, first and foremost, supply m_0c^2 to the rest mass of the electron (assuming zero neutrino rest mass). Only any excess is available as total kinetic energy release (known as Q) to the three final state particles (β , ν and recoiling final nucleus). These two effects are additive for β^+ decay, so no positron decay (no kinetic energy release) can happen unless the initial and final state atomic mass differences exceed $2m_0c^2$; any excess is partitioned as kinetic energy to the final particles. If all the kinetic energy goes to the observable electron (neutrino produced at rest), it then has its "end point" energy. In the case where the atomic mass difference $< 2m_0c^2$, positron decay is energetically impossible but there is still a weak interaction decay mode with $\Delta Z = -1$ --- the initial nucleus captures a pre-existing atomic electron, most probably from the atomic K shell. Where the atomic mass difference $> 2m_0c^2$ and positron emission is energetically allowed, this "electron capture" is still a competitor to β^+ decay, as

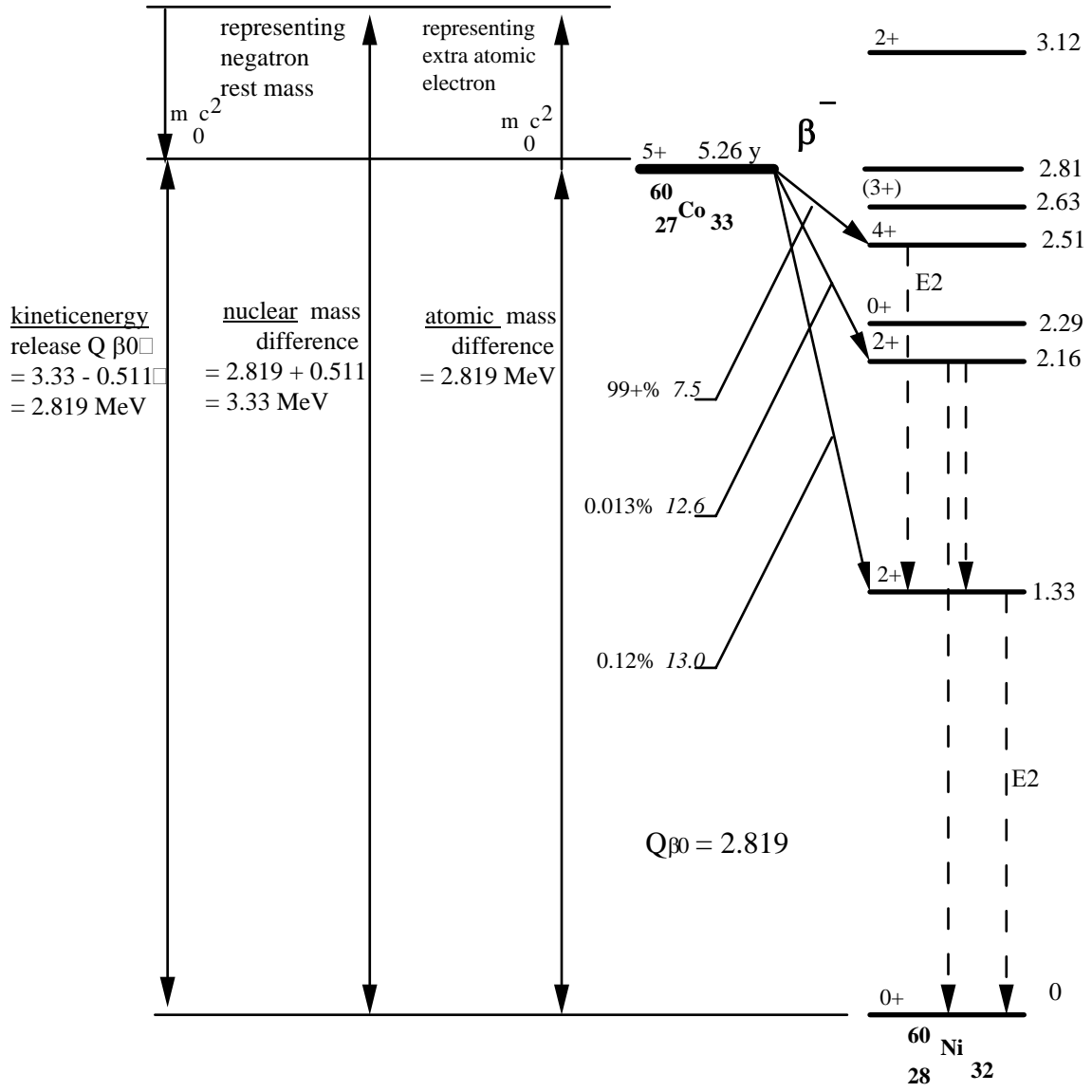
seen in the ^{22}Na diagram.

In the case of negatron (β^-) decay, the available nuclear mass difference must again first be able to provide m_0c^2 of energy to the newly created (non pre-existing) beta electron; any excess again goes to kinetic energy Q . But now the atomic mass of the initial system is one electron mass smaller than that of the final ($\Delta Z = +1$), so the atomic mass difference is less than the nuclear (in contrast to β^+ decay). Therefore, as illustrated for the ^{60}Co and ^{137}Cs β^- decays below, the initial nuclear mass difference energy given to β^- rest mass is already incorporated in the atomic mass difference (ignoring small electron binding energies), and there is no offset from the upper atomic mass to find the available kinetic energy release to various nuclear final states, in comparison with the $2m_0c^2$ offset in the positron decay diagrams.

Finally, note that the 1.27 MeV gamma ray in " ^{22}Na decay" really results from an electromagnetic interaction entirely within the various quantum states of ^{22}Ne . As far as the 1.27 MeV γ is concerned, the ^{22}Na weak interaction β^+ decay merely serves to provide slow production of the ^{22}Ne excited state. (Of course, the ^{22}Na positron decay provides annihilation quanta, which are of interest in their own right.)

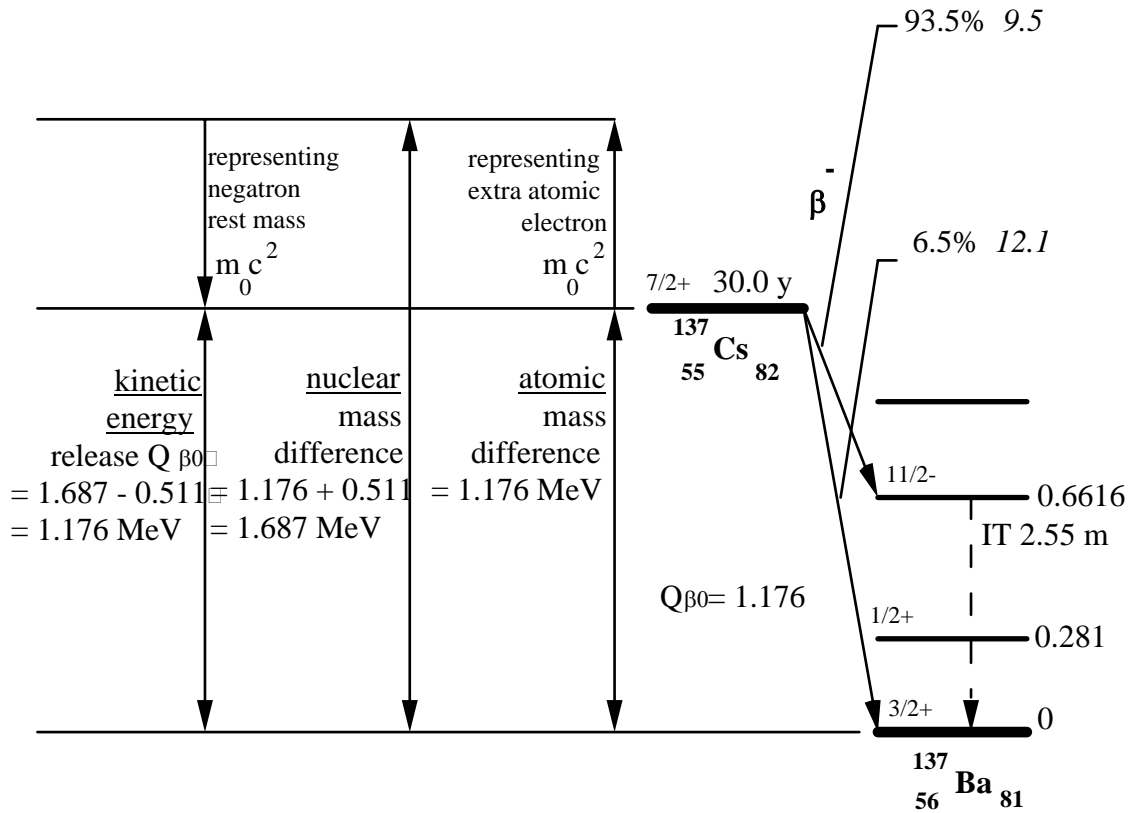
Similarly, the 662 keV gamma ray sometimes referred to as a parent ^{137}Cs gamma is, in reality, entirely concerned with the energy levels of daughter ^{137}Ba , the ^{137}Cs beta decay again serving merely as a slow-release precursor. Likewise, the " ^{60}Co gamma rays" actually involve transitions between two states of daughter ^{60}Ni .

The level and decay schemes of your radioactive sources are shown below. Study them until you understand completely the meaning of all quantities.



Energy relations and decay scheme of ^{60}Co and ^{60}Ni

Table of Isotopes Lederer, Hollander and Perlman



Energy relations and decay scheme of ^{137}Cs and ^{137}Ba

Table of Isotopes Lederer, Hollander and Perlman

III. Apparatus

The scintillation counter consists of a NaI(Tl) crystal (an inorganic sodium iodide crystal activated with a very small amount of thallium) glued to a photomultiplier tube by means of a very clear but highly viscous ($\sim 2,000,000$ centistokes) silicone oil. The voltage output pulse of the detector is fed through a preamplifier to an amplifier, then to a "pulse height analyzer" either a single channel (SCA) or a multichannel (MCA) instrument. The MCA sorts all pulse heights into a fine-grained histogram of the number of voltage pulses from the detector, as a function of pulse amplitude and, therefore, of energy loss in the crystal. The SCA operates sequentially on limited portions of the pulse height spectrum, and hence is much less efficient than a MCA .

An integral pulse height analyzer is equivalent to a discrimination circuit in which the level of discrimination ("base line") can be varied between 0 volts and the maximum voltage put out by the amplifier. In a differential pulse height analyzer (SCA) adjustable lower ("baseline" \underline{E}) and upper ($\underline{E} + \underline{\Delta E}$ "window") discriminator levels are provided, such that only pulses whose height lie between the two discriminator levels \underline{E} (lower level) and $\underline{E} + \underline{\Delta E}$ (upper level) will trigger the following circuits, while all other pulses will produce no effect. A differential pulse height analyzer thus selects

pulses falling in a chosen voltage interval, called the "window." For each pulse falling within the window a standard output pulse is provided, suitable to feed into a scaler. In a multichannel analyzer, pulses of any amplitude are sorted and stored in a memory location proportional to the pulse height, available for display. See [Using a Multichannel Analyzer \(MCA\)](#) for further discussion.

Warning

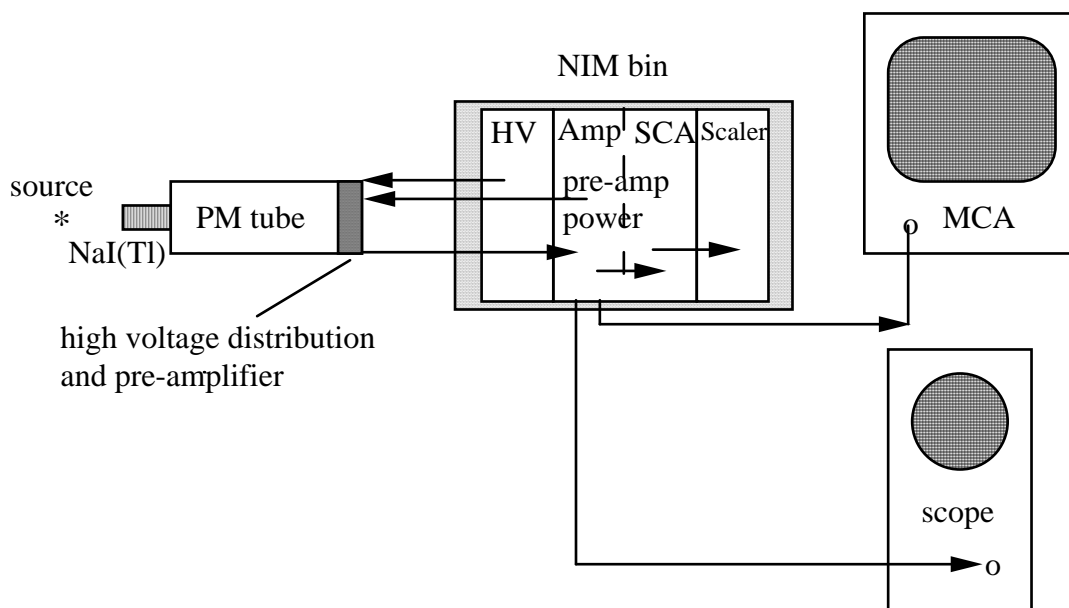
Do not turn on any switches or knobs until you have become familiar with the apparatus. The experiment involves high voltages which can be harmful to both the experimenter and the scintillation counter.

Observe caution at all times with regard to the scintillation detector since the crystal and photomultiplier are fragile and expensive.

The high voltage applied to the phototube should never exceed 1200 volts.

IV. Procedure for measurement of ^{22}Na , ^{137}Cs and ^{60}Co spectra.

For illustrations of the expected gamma ray spectra, see the level schemes above; also [AN34](#), Fig. 3.2 page 16 (^{137}Cs); Fig. 3.3, page 17 (^{60}Co); and Fig. 3.10, page 24 (^{22}Na , log scale). Using 50 ohm coaxial cable, connect the electronics as shown below.



1. Set the high voltage on the photomultiplier to approximately 1000 volts (record setting). Using a ^{137}Cs gamma source, adjust the amplifier gain until the pulses corresponding to the photopeak (maximum pulse height and maximum intensity on oscilloscope screen) correspond to about 3.0 volts. Set an SCA window width at 0.1 volt. Record the scaler readings, and plot the pulse height distribution spectra (counting rates (record counting times) vs. $(E + \Delta E/2)$ of ^{137}Cs , ^{22}Na ,

and ^{60}Co . Use the same photomultiplier accelerating voltage and amplifier gain for all measurements (record all settings) to make intercomparison possible. Take readings in 0.3 volts steps except in the regions of the photopeaks, where the counting rate changes rapidly with voltage (use 0.1 volt steps). Sketch in your report the spectral distribution of the following ^{22}Na pulses as seen on the oscilloscope face, with proper relative scales and polarity: Amplifier output and single-channel pulse height analyzer output.

If you cannot do all parts of this experiment in one laboratory period, start with the same settings and recheck the calibration of the system. This does not necessitate your taking complete pulse height distributions. A number of points judiciously chosen in the neighborhood of one of the standard peaks should be sufficient. Adjust amplifier gain, if necessary, to reproduce the previous peak position.

2. Observe the spectra of the three isotopes with the multichannel analyzer. Use the same amplifier gain, phototube high voltage and MCA conversion gain for all spectral measurements. Set regions of interest (ROI's) on the photopeaks and record (background-corrected) ROI net peak counts and corresponding statistical uncertainties, live times, centroid channels and widths (FWHM (full width-half maximum) and FWTM (full width-tenth maximum)). Plot the spectra if possible; otherwise sketch. Indicate on each photopeaks and the Compton regions (see AN34).
3. Remove all sources to distant storage, and measure the background spectrum with the MCA.

V. Analysis

1. Photopeak spectra

From your SCA data make a plot of counting rate vs. $(\underline{E} + \underline{\Delta E})$ for the " ^{137}Cs " (actually ^{137}Ba , as discussed previously) gamma pulse height spectrum.

Using your MCA spectral data plot the photopeak channels vs energies (662 keV and 1270 keV) for the ^{137}Ba (^{137}Cs source) and ^{22}Ne (^{22}Na source) nuclear gammas. Determine an energy-channel calibration from a least square linear fit and use the calibration and the MCA photopeak channel locations to determine the energies of the ^{60}Ni gamma decays (^{60}Co source) and of the ^{22}Na positron annihilation quanta.

(The two " ^{60}Co " gamma rays are sufficiently close, relative to the crystal resolution, that the apparent peak channel of each is shifted by the tail of the other. Therefore, we do not use these for energy calibration.

In which direction will they shift - toward or away from each other? Consider the effects of the "tails" of the photopeaks, and of the continuous Compton spectra. "Spectrum stripping", using known shapes of "pure" gamma spectra, could help

to disentangle these.)

2. Electron rest mass

^{22}Na exhibits two photopeaks. Explain the origin of these gamma radiations. How can one obtain the mass of the electron from the observation of a calibrated ^{22}Na gamma ray spectrum? Calculate m_0c^2 (in keV) from your MCA data, using your calibration, and compare with the accepted value of 511 keV.

3. Compton spectrum

From the expression in AN34, Eq. 10.4, page 65, calculate (for the case of a primary " ^{137}Cs " 662 keV gamma ray), the energy of that secondary gamma ray resulting from a Compton collision which gives the Compton recoil electron the maximum possible energy (channel). (Maximum Compton-electron energy loss in the scintillator (maximum Compton pulse height) corresponds to the minimum Compton scattered gamma energy, i.e., to the electron recoiling forward at 0° with the Compton gamma scattered backward at 180° . The electron energy will be the total primary gamma energy (the energy difference of initial and final nuclear states), less the energy of the secondary Compton gamma.

Use your MCA calibration to convert your result (maximum Compton pulse height) to the corresponding MCA channel; indicate by a labeled arrow on the corresponding ^{137}Cs spectral plots. See AN34, Fig. 3.2, page 16 for an example of the expected " ^{137}Cs " pulse height spectrum.

4. Crystal resolution

Calculate and tabulate, from MCA spectra, the resolution (FWHM) of the counter for various observed photopeaks. (See AN34, page 18). Is the resolution energy dependent? What is your expectation, and why?

VI. Discussion

Chapter 25 of Evans' "The Atomic Nucleus" (Attenuation and Absorption of Electromagnetic Radiation) may be helpful.

1. Explain the origin of each feature (bumps, plateau, and valleys) of the " ^{22}Na " pulse height distribution (see AN34).
2. Why does the photoelectric peak not have zero width?
3. What would be the effect on the shape of the MCA spectral curves if the gain of the amplifier were increased by a factor of two?
4. Why are there any x-rays emitted after the " ^{137}Cs " decays? (Study the level and decay scheme above.) To what atomic transition and to what atom do these x-rays correspond?

5. Which of the gamma rays you have observed are capable of producing positron-electron pairs in the electric field of the nucleus? For that (those?) gammas, what are the (approximate) relative interaction probabilities for Compton: photoelectric: pair production? Does the answer depend on the Z of the detector? Which is preferable for pair production - a detector with high or low Z ?
6. Assume the ^{137}Cs sources whose spectrum you have measured has $5\ \mu\text{Ci}$ (microcurie) activity. (Look up the definition of the Curie.) Make an estimate of the solid angle subtended by the crystal and, for the $662\ \text{keV}$ ^{137}Cs gamma, calculate (from the MCA ROI (background corrected) peak counts/counting time) the total photopeak efficiency ε_{γ} of the crystal (# of photopeak counts/unit time \div total # gammas/unit time into 4π solid angle).

(Remember that the activity (Curies) of a source refers to all decays. If there are modes other than gamma, you will have to reduce the activity (number of decays/second) by the known gamma branching ratio, in order to calculate correctly the photopeak efficiency. Again, study the decay scheme.)