

γ - Ray and X - RAY SPECTROSCOPY with SCINTILLATION and SEMICONDUCTOR DETECTORS

This experiment examines the interactions of γ rays and X rays with matter, utilizing several detectors with contemporary electronic instruments and experimental techniques. Scintillation detectors contain a special material that emits light when ionizing radiation transfers energy to it. A Photomultiplier Tube (PMT) is used to convert that light to electrons and amplify them for further processing and analysis. Inorganic single crystals provide high detection efficiency (into the GeV range) with good energy resolution; organic materials provide fast response and large area. A semiconductor detector delivers detection efficiencies similar to inorganic crystals but with much higher energy resolution.

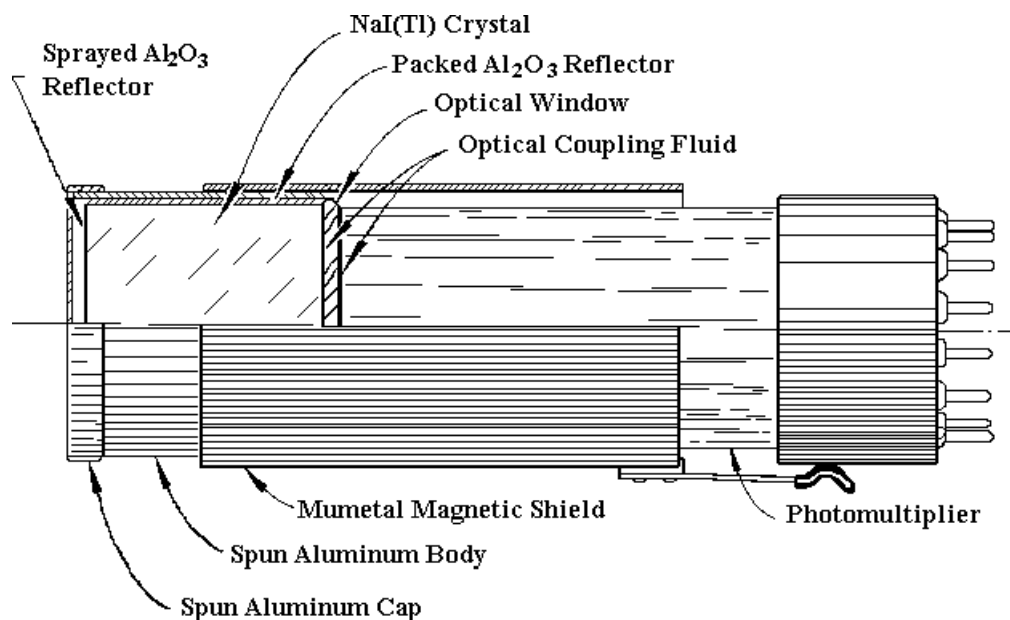


Figure 1. The components of a scintillation detector.

INTERACTIONS BETWEEN IONIZING RADIATION AND MATTER

The basic mechanism for the detection of ionizing radiation is the transfer of energy to material. The transfer depends upon the nature of the radiation and the amount of energy that it carries.

X RAYS AND γ RAYS:

The two types of *electromagnetic radiation* of interest here are X rays produced by the de-excitation of atomic bound states ($E_{\max} < 150 \text{ keV}$) and γ rays emitted by nuclei ($E_{\max} < 3 \text{ MeV}$). They can interact with matter by any, or all, of three processes; *Compton Scattering*, *Photoelectric Effect*, and *Pair Production*. (Two additional processes that produce Bremsstrahlung and Cerenkov radiation are possible, but will not be significant at the low energies available to this experiment.)

$E < 1.022 \text{ MeV}$: *Compton and Photoelectric* interactions are possible. If a *Compton* event occurs, the incident photon transfers part of its energy to a free electron, the direction and energy of the remanent photon being changed appropriately. The amount of energy lost by the photon, and the amount transferred to the electron, varies from a very small amount (small angle scattering) to a maximum when the photon scatters at 180° . In the *Photoelectric* interaction, all of the energy of the photon will be transferred to an electron, the incident photon disappearing. The electron carries away all of the energy minus the binding energy of the electron.

References: (1) Chap. 23 - 26; (2) Chap. 4; (3) p. 62-66.

$E > 1.022 \text{ MeV}$: *Compton and Photoelectric* interactions plus another process, ***Pair Production***. With *Pair Production*, a γ ray creates an electron-positron pair in the field of a nucleus, with 1.022 MeV of the γ ray energy producing the rest masses of the **electron-positron pair, and the remainder appearing as kinetic energy of the pair**. When the positron later comes to rest and annihilates with an electron, two 0.511-MeV photons are produced. The energy deposited in the detector can produce outputs proportional to E_γ , $E_\gamma - 1.022 \text{ MeV}$, $E_\gamma - 0.511 \text{ MeV}$, or 0.511 MeV.

References: (1) Chap. 23, (2) p. 147-149, 357-360, (3) p. 67.

ELECTRONS AND BETA (β) PARTICLES:

Charged particles (electrons) (generated by X or γ rays in this experiment) lose energy by interactions between the electric field of the moving charge and the atomic electrons (and to a lesser extent the nuclei) of the material they encounter. This causes deceleration of the original particle, while the electrons that they encounter gain sufficient energy to escape from their parent atoms. The two principal processes for the loss of energy are:

- **Collisions**, with energy transferred to the electrons of the material. (The primary mechanism for electrons and β rays.)

- **Bremsstrahlung**, the emission of electromagnetic radiation by the decelerating particle. (Main source of energy loss for $E \gg mc^2$.)

Electron: $E \approx \frac{800 \text{ MeV}}{Z}$ for radiation and ionization losses approximately equal.)

References: (1) Chap. 18-21; (2) Chap. 4; (3) p. 56-62.

γ - RAY SPECTRA

Theoretical spectra describing the interactions of γ rays with scintillation and solid - state detectors are relatively simple. Real spectra show additional structures produced by subsidiary processes with all features degraded by

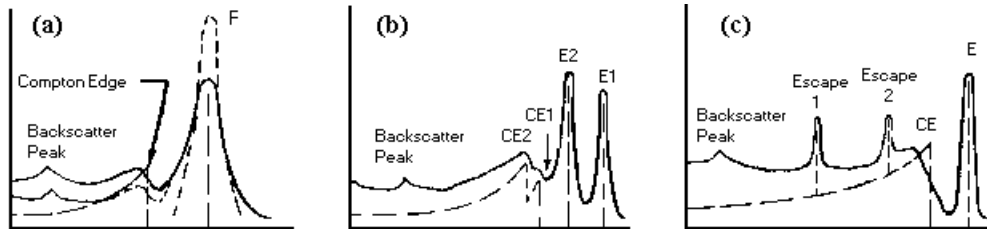


Figure 2. Theoretical and actual spectra of detected γ rays. (a) Single γ ray < 1 MeV, (b) Double γ ray < 1 MeV, (c) Single γ ray $> \sim 2$ MeV.

statistical fluctuations. A chain of Compton interactions that eventually accounts for the full energy of a γ ray, adds significantly to the **full - energy peak** (Fig. 2), especially with a large detector volume. The lowered level of the Compton continuum of Figure 2 is also a consequence of a larger detector volume. Additional complicating features are produced by scattering within the source mounting, with the environment, in the detector itself, plus photons that "escape", and the excitation of X - ray fluorescences.



Figure 3. Theoretical and actual spectra produced by a plastic scintillator from a single 1 - MeV γ ray.

Reference: (3) p. 306-326, (2) p. 353-368.

THE SCINTILLATION MECHANISM

When a charged particle (electron) transfers energy to matter, that energy either produces heat or raises other electrons into excited states. When the material is a scintillator, these excited states decay to lower energy states, some of the excess energy being carried away by the emission of photons. To be useful, the wavelength of these photons must lie in the blue and/or long UV regions of the spectrum where PMT photocathodes have usefully high conversion efficiencies. In all cases in which it is a charged particle that produces a scintillation, the energy of electromagnetic radiation must first be transferred to electrons before any scintillation photons can be produced.

SODIUM IODIDE - ACTIVATED ALKALI-HALIDE SCINTILLATORS:

Energy absorption and photon emission by activated alkali-halide scintillators are complex processes most conveniently described by means of the band theory of solids. A pure single crystal is represented in Fig. 4 by a **valence band**, which is normally filled with electrons, and the normally empty conduction band above it.

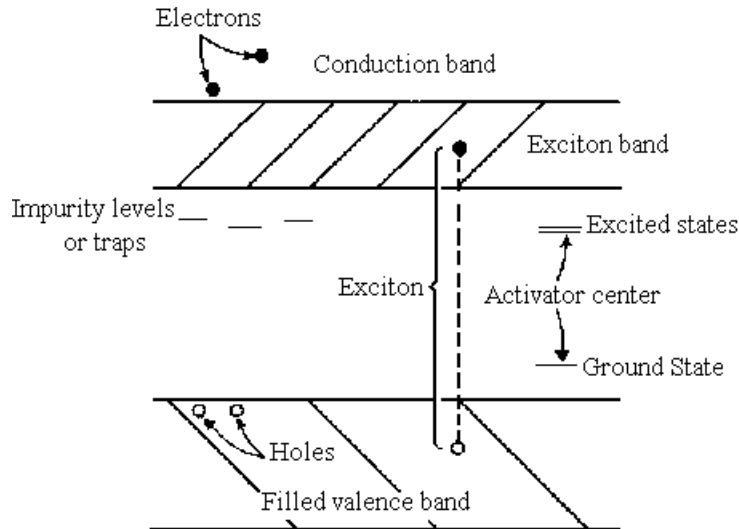


Figure 4. The band theory representation of an activated alkali-halide crystal scintillator.

Separating them is a forbidden band of energies (~ 8 eV), called the **band gap**, where free electrons cannot exist. A particle interacting with the crystal may cause an electron to move from the valence band up to the conduction band by an ionization process, producing a vacancy in the valence band that is called a hole. Conduction band electrons, and the valence band holes, are free to move independently throughout the crystal. When a conduction band electron decays to the ground state, the emitted photon has a short wavelength (UV) with a high probability of being re-absorbed, and eventually contributing to the excitation of activator sites (below). There is a finite probability that the quantity of energy that is deposited will be insufficient to produce ionization, but large enough to cause excitation, i.e., the elevation of an electronic state above the valence band. This electron will remain electrostatically bound to the hole it left in the valence band, to constitute an electron-hole pair called an **exciton**. The exciton states form a thin band (width ~ 1 eV) whose upper level will coincide with the lower edge of the conduction band.

Lattice imperfections such as **vacancies**, or **impurity atoms** that are supplied by an "**activator**", produce relatively low energy states in the band gap at isolated sites in the crystal lattice. The elevation of an activator atom to an excited state may result from the absorption of a photon produced by the decay of an excited state in the conduction band, the capture of a migrating electron and hole (in any order), or the capture of an exciton. The decay of an excited activator state (the predominant mode of scintillation) produces a photon in a decay time of the order of 100 ns, at a wavelength in the short blue or long UV region. Because the energy that is needed to produce an activator photon is always lower than what is required to excite a conduction band electron, very little re-absorption takes place, i.e., **the parent crystal is highly transparent to the scintillation photons**.

The most common alkali-halide scintillator is single - crystal Sodium Iodide with about 0.1% Thallium activator content [NaI(Tl)]. It provides relatively high Z and density, with the highest currently available luminescent efficiency. Principal deficiencies are extreme toxicity from the Thallium content, mechanical fragility, and the need for a hermetic sealed enclosure for protection from H₂O.

γ rays generate about 5×10^4 ion-pairs/MeV of energy deposited in NaI(Tl), giving a detection conversion efficiency of $\sim 12\%$, or about 4×10^4 photons/MeV, with each photon having an average energy of ~ 3 eV, or about 1 emitted photon/ion-pair generated.

References: (2) p. 195-200; (3) p. 254-261.

Relevant parameters for NaI(Tl) are:

- ** Density : 3.67 g/cm^3 .
- ** Z : Na=11, I=53, Tl=81.
- ** Luminescent efficiency : 12% of energy of incident radiation.
- ** Temperature coefficient of luminescence : 0.2 to 2%/°C.
- ** Wavelength of maximum emission : 420 nm.
- ** Index of refraction : 1.85 at 420 nm.
- ** Decay time : 230 ns @ 25 °C.
- ** Energy resolution : 6.5% @ 662 keV at best. (7.5% typical)

A photon attenuation coefficient plot will be found in Appendix A.

BISMUTH GERMANATE (BGO):

Another single crystal scintillator coming into wide use is $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (or "BGO"). This material is mechanically and chemically stable with a high density and high Z. Compared to NaI(Tl) it provides a total absorption cross section 2.5 times higher at 1 MeV, permitting a 16x reduction in linear dimensions for the same stopping power. Disadvantages are: high cost, difficulty in fabricating even modest sized single crystals with consistent characteristics, a low luminescent efficiency (no activator scheme has yet been developed), a high refractive index, and only moderate energy resolution.

Relevant parameters for $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ are:

- ** Density : 7.13 g/cm^3 .
- ** Z : Bi=83, Ge=32, O=8.
- ** Luminescent efficiency : 8% of NaI(Tl).
- ** Temperature coefficient of luminescence : -1.5%/°C
- ** Wavelength of maximum emission : 480 nm.
- ** Index of refraction: 2.15 at 480 nm.
- ** Decay time : 300 ns.
- ** Energy resolution : 16% @ 662 keV.

A photon attenuation coefficient plot will be found in Appendix A.

ORGANIC SCINTILLATORS:

Photons are produced by a molecular process most easily described by the energy diagram of Figure 5. The lower curve shows the potential energy when all electrons are in the ground state, the upper curve showing an excited state. The Franck-Condon principle requires the energy deposited by a charged particle, not dissipated as heat, must raise the molecule from A_0 to A_1 ($E_e = E_{A_1} - E_{A_0}$) in a time (~ 0.1 ps) short compared to the vibration time. Energy lost through lattice vibrations moves the molecule to B_1 . After a time (~ 10 ns) long compared to the vibrational time the excited state decays to ground level (B_1 to B_0), excess energy ($E_p = E_{B_1} - E_{B_0}$) being carried away by a photon. This fluorescent emission produces ~ 1 photon/100 eV of energy deposited. Energy required to excite a state (E_e), exceeds that carried by a photon (E_p), so there is negligible re-absorption; thus the scintillator is transparent to the photons.

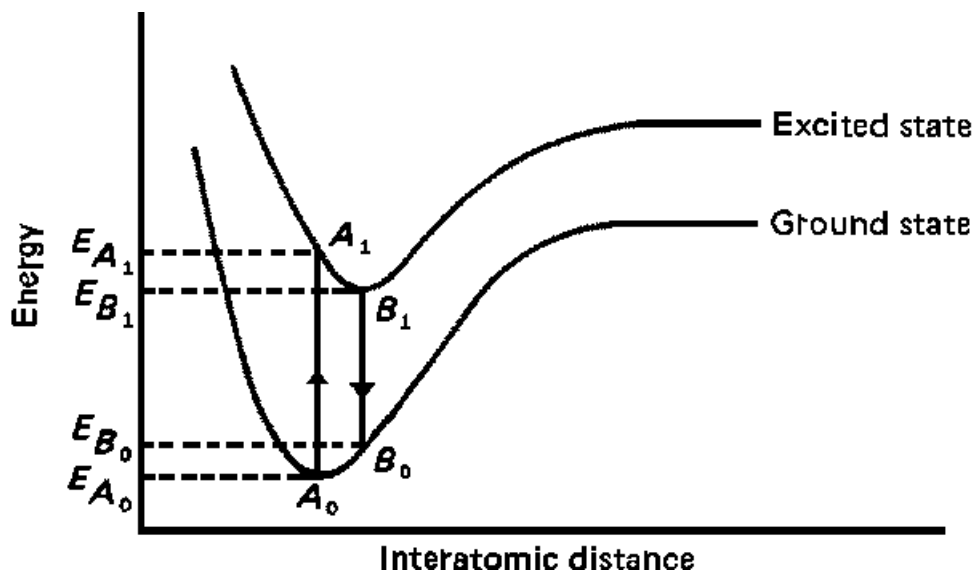


Figure 5. Energy diagram (simplified) of an organic scintillator.

Plastic scintillators usually consist of a carrier (commonly acrylic, styrene, or vinyltoluene polymer) with a small quantity of active solute (POPOP or p-terphenyl) added before polymerization. Secondary active solutes are often used to shift the wavelength of the primary photons to match the spectral response of a PMT. Energy resolution and efficiency are fair for β particles and monoenergetic electrons, but very poor for X and γ rays (very low Z and density). This is also true for organic crystals and liquid scintillators. The scintillator for this experiment, NE-102, has the following properties:

- ** Density : ca. 1.03 g/cm^3 .
- ** Electrons/cm³ : 3.39×10^{23} .
- ** H atoms/cm³ : 5.28×10^{22}
- ** C atoms/cm³ : 4.78×10^{22}
- ** Ratio of H to C : 1.104 .
- ** wavelength of emission : $\sim 4.23 \text{ nm}$.
- ** Decay time : $\sim 2.4 \text{ ns}$.
- ** Luminescent efficiency : typically 18% of NaI(Tl).

References:(2) p. 195-204, (3) p. 239-254, (4) p. 163-166.

INSTRUMENTATION

THE PHOTOMULTIPLIER TUBE (PMT):

Photomultipliers specifically designed for scintillation service utilize alloys of cesium-antimony (Cs-Sb), or potassium-cesium-antimony (K-Cs-Sb), evaporated as a semi-transparent film onto the spherical interior surface of the faceplate, to convert photons to electrons. The spectral response (S-11) is peaked at ~ 400 nm, with a conversion efficiency (Quantum Efficiency) of 10 to 30%. The cathode shape plus focusing electrodes insure that photoelectrons are efficiently accelerated to the input of the dynode chain. The low photoelectron energy at emission ($\sim eV$), requires careful magnetic shielding of the PMT since a field of only 1 Gauss can reduce sensitivity by 50%. The dynode chain (5 to 14 stages) utilizes the phenomena of secondary emission to multiply the number of primary photoelectrons by as much as 10^8 . Surface coatings on the dynodes produce 1.5 to 50 secondary electrons for every primary electron that strikes them. The number of secondary electrons depends on the coating material and the operating voltage. Values of 2 to 3 are more typical for the PMT's used for this experiment.

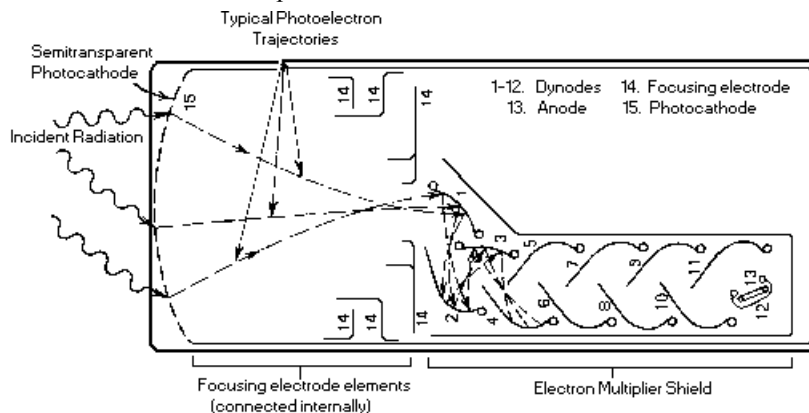


Figure 6. Electron multiplier (dynode chain/anode) system.

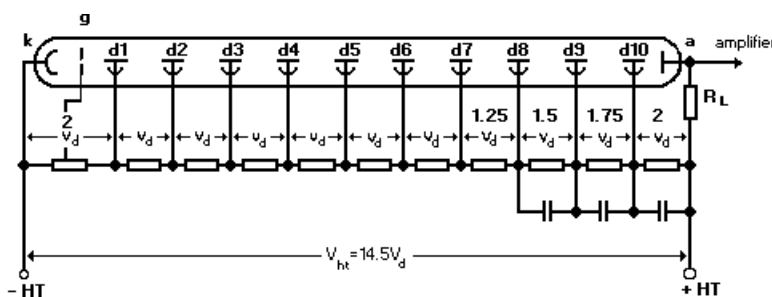


Figure 7. Photomultiplier resistive voltage divider components.

Operating potentials for the electrodes of the PMT are derived from a voltage divider, usually resistive. A positive high voltage supply, with the photocathode at ground potential, is always used with integrated PMT/Scintillators designed for high resolution spectroscopy. This insures zero leakage currents between the photocathode and the grounded outer case of the detector assembly, eliminating electrical "noise" and destructive sparks.

SCINTILLATION SPECTROSCOPY INSTRUMENTATION:

A charge - sensitive preamplifier converts the PMT output charge pulse to a relatively fast rise (~230 ns) long decay (50 μ sec) "tail pulse" suitable for input to the shaping amplifier that follows. A TEST input allows a pulse generator to simulate PMT pulses.

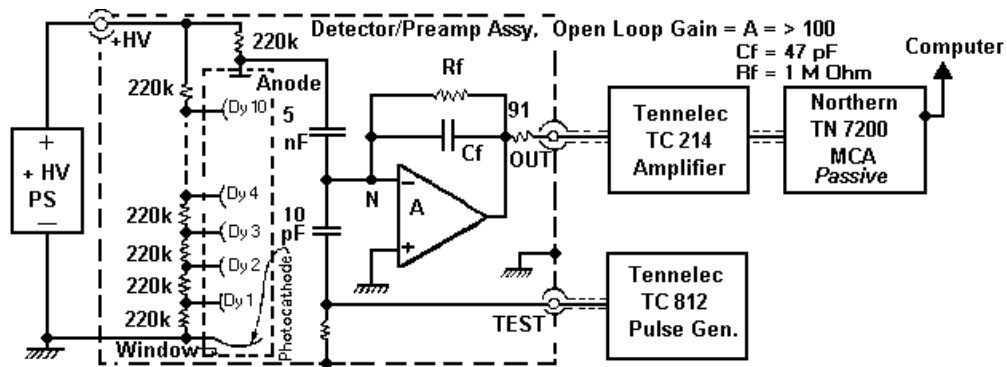


Figure 8. The scintillation detector electronic system.

A variable - gain main amplifier (Tennelec TC 214) modifies the preamp pulse by differentiation followed by integration, producing a short (0.8 μ s) Gaussian pulse shape that can be unipolar, or (with a second differentiation) bipolar. This amplifier is designed to tolerate heavy overloads, without damage or detriment to the linearity of smaller signals. Nonlinearity is < 0.1% for outputs of < 8 V.

SEMICONDUCTOR - DETECTOR SIGNAL - PROCESSING INSTRUMENTATION:

These components must perform to the highest standards to utilize the energy resolution of the detector. The preamplifier, integrated into the detector cryostat, provides high conversion gain (170 mV/MeV) with nonlinearity < 0.05%. Noise is minimized by cooling the input FET (Field Effect Transistor) to -150° C to reduce thermal noise. A minimum capacitance connection between the FET and detector is used.

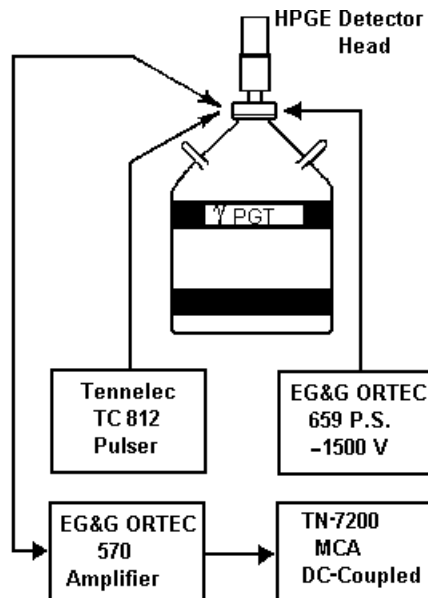


Figure 9. The cooled Germanium detector electronic system.

The main shaping amplifier, a multi-stage RC differentiator/integrator (EG&G ORTEC Model 570) also provides high gain (1500x) with low noise and a nonlinearity of < 0.05%. An ORTEC 571 or 575 amplifier may be used instead, with similar characteristics. Filtering both low - and high - frequency components of the input signal reduces the effects of noise, and optimally shapes the pulses for MCA analysis. If a pulse should start on the tail of a preceding pulse, rather than from true zero, energy resolution suffers. This is avoided by an automatic gated Base Line Restorer (BLR) that senses the peak of the input pulse and closes a transmission gate that rejects all following input pulses until the amplifier output can be clamped to true zero level. When the gate opens, the next pulse starts from zero. The improvement in energy resolution varies from a few percent to 5x.

A precision pulse generator produces constant - amplitude (monoenergetic) pulses that accurately simulate the detector output. If the amplifier chain were noiseless, the MCA would show a pulser peak only one channel wide, and detector peaks widths would accurately represent the energy resolution of the detector. Amplifiers are not noiseless, and the pulser peak has a width proportional to this noise. Detector peaks are broadened by this noise, which adds in quadrature.

Reference: (2) p. 316-320, (5), and the manufacturer's manuals.

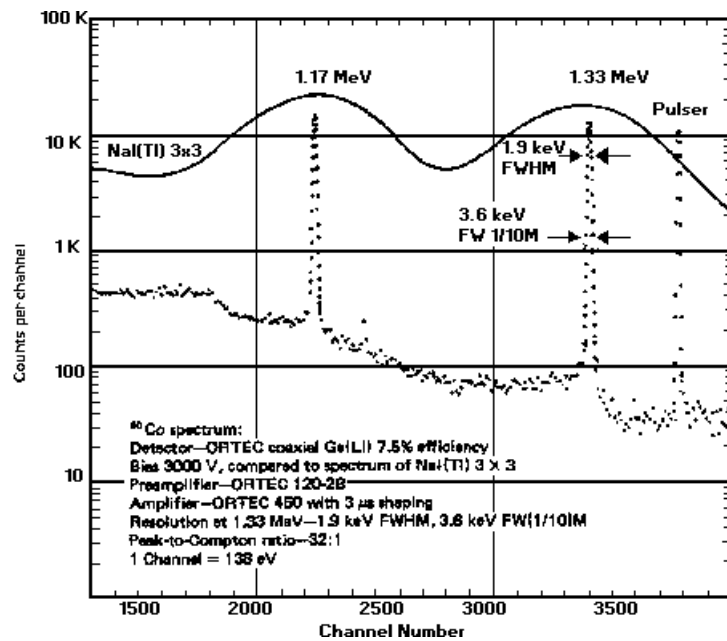


Figure 10. Energy resolution of NaI(Tl) and Germanium detectors. Note LOG scale.

DATA ANALYSIS:

Consider carefully what is appropriate for the task. The full-width-at-half-maximum of a NaI(Tl) full energy peak can be very quickly obtained manually with acceptable precision by use of the MCA cursor. The total number of counts in a peak can be quickly determined by setting a Region of Interest (ROI) on the MCA, and then reading the NET counts from the display. If you forget to do this while the data are still in the MCA, a print out of the numbers in the data file will allow the same information to be obtained quickly by simply adding numbers. The FFIT program on the PCs can be used for a variety of fitting and data - analysis functions. Of particular interest in this laboratory are the X - and γ - ray lookup tables. See the Appendix to the *Introduction to Physics 77* document for instructions.

EXPERIMENTAL TASKS

Before coming to the laboratory, become familiar with the decay schemes and energies of the sources you will use. *They are ^{57}Co , ^{137}Cs , ^{60}Co , and ^{24}Na .* If you are not yet familiar with Reference (4), *The Table of Isotopes* by Lederer and Shirley, obtain a copy of and refer to the "Guide to the Table of Isotopes" and take the time to find your way about in it. Notice the useful tables at the back of that book. *The Table of Isotopes*, 8th edition (1998 Update), is also available on CD-ROM.

The detectors available are: a demountable photomultiplier unit with NaI(Tl), $\text{Bi}_4\text{Ge}_3\text{O}_{12}$, and plastic scintillators, two integral NaI(Tl) units (1 3/4" dia. x 1 1/2" and 3" dia. x 3"), and an ultra-pure Intrinsic Germanium device with a thin entrance window designed for low - energy photons (2 to 150 keV) but usable to 1 MeV and slightly above.

Instruction manuals for the instrumentation are collected in a binder at each setup. Additional copies are available for overnight borrowing. Study the material for each instrument before attempting to operate it.

Set the MCA rear - panel Direct Input Coupling switch to DC (center) when a PMT is used. Check the MCA USER'S GUIDE and APPENDIX B of this write-up for the SETUP parameters to allow sending data to the computer. At least 256 Channels must be displayed on the MCA screen before a successful data transmission to the computer can be made. *Only those channels actually displayed will be sent.*

N.B.: CONNECT ONLY THE OUTPUT CONNECTOR OF THE PMT PREAMP TO THE TENNELEC 214 AMPLIFIER INPUT CONNECTOR. That input is biased to -24V and will destroy any other device connected to it.

1. MCA LINEARITY AND ZERO OFFSET TESTS:

It is necessary to know if the channel where a pulse is stored is precisely proportional to its amplitude (is the MCA ADC linear?), and if a hypothetical zero - amplitude pulse is stored in channel zero (is the zero offset?). The latter is the most critical parameter, the design of the ADC providing inherently excellent linearity.

Connect the TC 812 pulser Attenuated Output to the TEST input of the demountable PMT base unit. Be sure to select the correct polarity. Preset the amplifier Gain controls to mid - scale, and the TC 812 PULSE HEIGHT dial to 900. Adjust amplifier gain controls, TC 812 step attenuators, and the Pulser CALIB. control (Front Panel screwdriver adjust), to set the Pulser output exactly in channel 450 (or 900) of the smallest MCA memory group available (1024 Channels). Use the MCA Cursor and Horizontal Expansion. You can then set the Pulser output to specific values with the ten - turn PULSE HEIGHT dial (non-linearity $\ll 0.1\%$). Is the response of the preamp/amplifier/MCA chain linear? Is the zero offset? If it is, a correction must be applied to data. Is this test completely valid for the measurements that are required below? Consider exactly what components have been tested.

2. COMPARISON OF SCINTILLATOR TYPES:

The demountable NaI(Tl) and $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ detectors are fragile and must be handled gently. The NaI(Tl) crystals are hermetically sealed in a low Z, thin - Al case optically coupled to a UV - transmitting glass window. The inner walls of this case are coated with a layer of aluminum oxide to diffuse and redirect the generated light towards the window that must itself be optically coupled to the PMT faceplate with a thin layer of fluid. The integrated detectors are similarly assembled, but deliver much better energy resolution

and stability. They are even more fragile than the demountable crystal assemblies. (Refer to the Harshaw Scintillation Phosphors booklet, and the Bicon data sheets for information on the characteristics of these devices.) Use the 1 μ Ci calibration sources (in their plastic boxes) for all measurements.

- a.** Be certain that the HP 6515A High Voltage power supply is turned OFF. DISCONNECT THE HIGH VOLTAGE CABLE at the PMT base assembly. Remove the light shield from the photomultiplier tube base assembly by turning and lifting the shield. Attach the small NaI(Tl) crystal to the PMT faceplate using a modest quantity of fluid (Vaseline) for optical coupling. Avoid trapping any air bubbles. Replace the light shield, attach the High Voltage cable, and set the HP 6515A HV Power Supply to +600 V (the Variable control fully counterclockwise.). Place a ^{137}Cs source disk directly upon the entrance window of the light shield. Take a spectrum with at least 1000 counts in the highest full - energy peak channel. Always use the minimum number of channels consistent with spectral detail and the detector resolution. In another memory quadrant, determine the pulser setting that matches the photopeak channel. Transfer data to the computer and plot it. Identify all features. What is the energy resolution (FWHM @ 662 keV) and detection efficiency @ 662 keV for the ^{137}Cs full energy peak? TURN OFF THE HV AND DISCONNECT THE HV CABLE FROM THE PMT BASE ASSEMBLY.
- b.** Replace the NaI(Tl) crystal with the BGO scintillator. With the same HV setting and source-detector geometry used for **2(a)**, take a ^{137}Cs spectrum. Increase the amplifier gain to spread the spectrum over the PHA channels. Determine the pulser setting that matches the ^{137}Cs photopeak channel. Describe and explain the differences between the ^{137}Cs spectra taken with the NaI(Tl) and the BGO. Compare the energy resolution, detection efficiency, and luminescent efficiency of BGO to NaI(Tl).
- c.** Replace the BGO scintillator with the plastic unit. Take a ^{137}Cs spectrum. Once again use the amplifier gain to adjust the span of the spectrum, and the pulser to determine the pulse height of a relevant spectral feature. Compare this spectrum with the previous crystal spectra and explain the differences. Be sure you understand this spectrum, you will need it for later experiments.

3. SPECTRAL ANALYSIS WITH A NaI(Tl) DETECTOR:

Change over to the 1 3/4" diameter Bicon integrated NaI(Tl) detector/Hamner tube base, set the HV to +810 V (HV Variable control 1-turn CW from stop), and record the following spectra:

- a.** ^{137}Cs (Use the calibration disk directly on the detector faceplate, placing a lead plate on top of it). Set the MCA LLD as low as possible. What is the resolution (FWHM @ 662 keV) of this detector assembly? What is the detection efficiency @ 662 keV? Compare with the ^{137}Cs spectrum of **2(a)**. Do you see any additional artifacts? (Hint: look at low end.) What effect(s) do(es) the lead plate produce?
- b.** ^{137}Cs , as above, with a 10 V reduction in HV. Why is the shift in the photopeak position so large? Calculate the rate of change of PMT amplification with respect to changes in HV. (10-stage PMT.)

- c. Change to the 3" diam x 3" Bicron integrated NaI(Tl) detector. Take a composite $^{137}\text{Cs}/^{60}\text{Co}$ spectrum with FS at about 3 MeV, keeping the HV at 800V. Use plastic foam under the source buttons, if needed, to keep the MCA Dead Time below 10%. Count long enough to accumulate more than 10000 counts in the 1.33 MeV peak channel. Identify all peaks and features (HINT: examine both the low and the high energy regions with the LOG display mode). Use the previously measured MCA Zero offset data to determine the detector/electronics linearity. Discuss your results in detail. What influence does the detector entrance window have on your data at the lowest energies? Would the results be different, and perhaps better, if separate spectra were taken for each source? Explain.
- d. With full scale set about 4.5 MeV, take a spectrum with the ^{24}Na source, . Ask a T.A. about its location and fabrication. Check the "Guide to the Table of Isotopes". Use enough channels (2048 suggested) in order to clearly delineate all features. Identify contributions from environmental background. Explain the origins and relative heights of all peaks and features. Examine the mid and high energies.

4. X - RAY FLUORESCENCE ANALYSIS WITH A LOW ENERGY PHOTON (LEP) DETECTOR:

The detector is left continually under bias, at **-1500 V**. Never change or exceed this voltage. Be sure that you examine the disassembled GeLi detector found near the setup.

- a. Change the MCA input to the Germanium detector system. This will involve moving the MCA input cable from the Tennelec 214 amplifier to the unipolar output of the EG&G ORTEC 570 amplifier. Verify that the output signal from the Ge detector is connected to the input of the Ortec 570. Set the MCA Direct Input Coupling switch to DC. Connect the TC 812 Pulse Generator to the Preamp TEST input and measure the spectral broadening caused by electronic noise.
- b. Set full scale at about 150 keV (2048 channels suggested), with the ^{57}Co Calibration source. The ^{57}Co calibration source is mounted in a lead brick: CAUTION: The detector's 0.25 mm beryllium entrance window is FRAGILE. The slightest touch with a warm moist finger will cause it to shatter, totally destroying the (very expensive) detector. Ask the T.A. to setup the fluorescence source/sample geometry with the stronger ($\sim 8 \mu\text{Ci}$) ^{57}Co working source. This source is also mounted in a lead brick to shield both people and the detector from its emissions. The sample scatterers available are: U, Pb, Ta, Pt, Ag, Sn, Cd, etc. This is a non - destructive technique for investigating materials. You may also select, or supply, materials of your own choosing. Use the ^{57}Co source to establish an accurate energy/offset/linearity calibration. Determine the energy and resolution (corrected for electronic noise) for all peaks and their relative heights. What is the effect of the detector entrance window on energy determinations? What analytic techniques will be required to obtain best results for the energy and intensity values? What is the origin of the radiation that produces the various peaks? [Check, and consider QUESTION 5.]

References: (2) Chap. 11, (3) Chap. 11, 12, and 13.

QUESTIONS

1. What polarity of pulse is seen at the photomultiplier anode? At the last dynode? What are their relative amplitudes? How would this polarity change if the PMT base were rewired for the opposite polarity (Negative) HV supply voltage?
2. What is the theoretical % resolution (FWHM) of the full energy peak for a 1 - MeV γ ray detected by a 3" x 3" NaI(Tl) crystal? Consider the various interactions, conversions and amplification that produces the full - energy peak as seen on the MCA. Make a quantitative estimate of the contribution that each makes to the broadening of the full - energy peak.
3. What is the theoretical FWHM of the full - energy peak obtainable from a germanium detector when it is exposed to a 1 - MeV γ ray? An 80 - keV X ray? How does this compare with your measured values (corrected for the noise contributed by the electronic system)? Explain any difference.
4. How does the material of the "entrance window" of the Germanium X ray detector influence linearity and energy calibration at low energies? How would you correct for such an effect, if any?
5. What produces the counts found between the full energy peak and the Compton edge of a spectrum as seen on the MCA?
6. Describe the origins of the "backscatter peak". At what energy is it seen for a 0.5 - MeV γ ray? A 2 - MeV γ ray? Why? Where does "backscatter" occur, in the source, detector, nearby material?

REFERENCES

- (1) R. D. Evans, *The Atomic Nucleus*, (McGraw-Hill Book Company, 1955).
- (2) N. Tsoulfanidis, *Measurement And Detection Of Radiation*, (McGraw-Hill Book Company, 1983).
- (3) G. F. Knoll, *Radiation Detection And Measurement*, (John Wiley & Sons, Inc., 1979) and 2nd edition (1989).
- (4) C. M. Lederer and V. S. Shirley, *Table Of Isotopes*, 7th Edition, (Wiley-Interscience, 1978), and 8th edition with CD-ROM (1996).
- (5) *Harshaw Scintillation Phosphors*, Third Edition.
- (6) P. R. Bevington, *Data Reduction And Error Analysis For The Physical Sciences*, (McGraw-Hill Book Company, 1969, and 2nd edition with D. K. Robinson, 1993).
- (7) W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments: A How-to Approach*, 2nd. rev. ed., (Springer-Verlag, 1994).

All above are available in the laboratory. Additional reference material will be found in the bookshelf, in sign - out binders, and at the experiment setup.

Appendix A

Photon Attenuation in NaI(Tl)

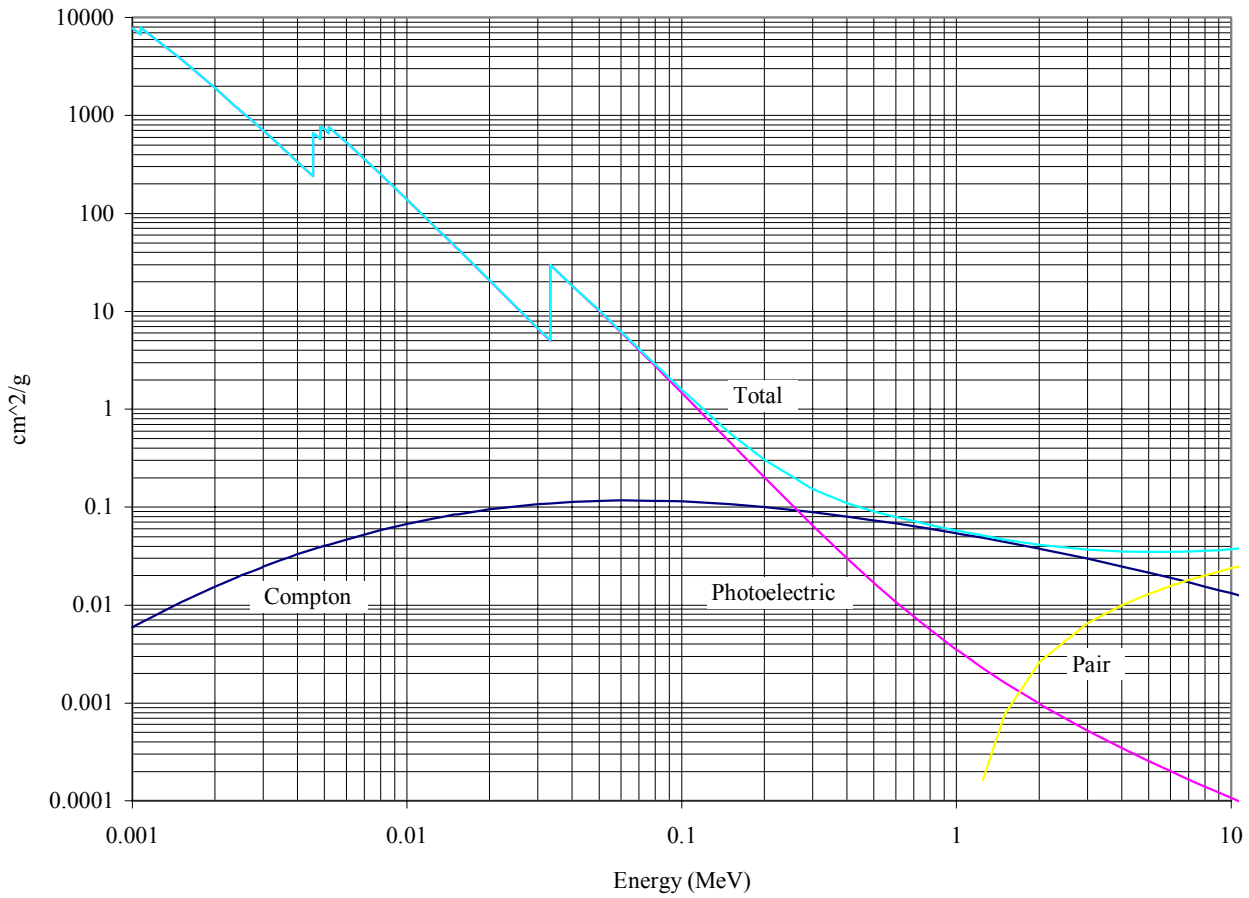


Figure A-1. Complete cross-sections of sodium iodide with 1.36% Tl by weight showing total absorption and fractional components due to Compton scattering, photoelectric absorption, and pair production. Data are from the NIST program XCOM. $\rho = 3.67 \text{ g/cm}^3$.

Photon Attenuation in Bismuth Germanate

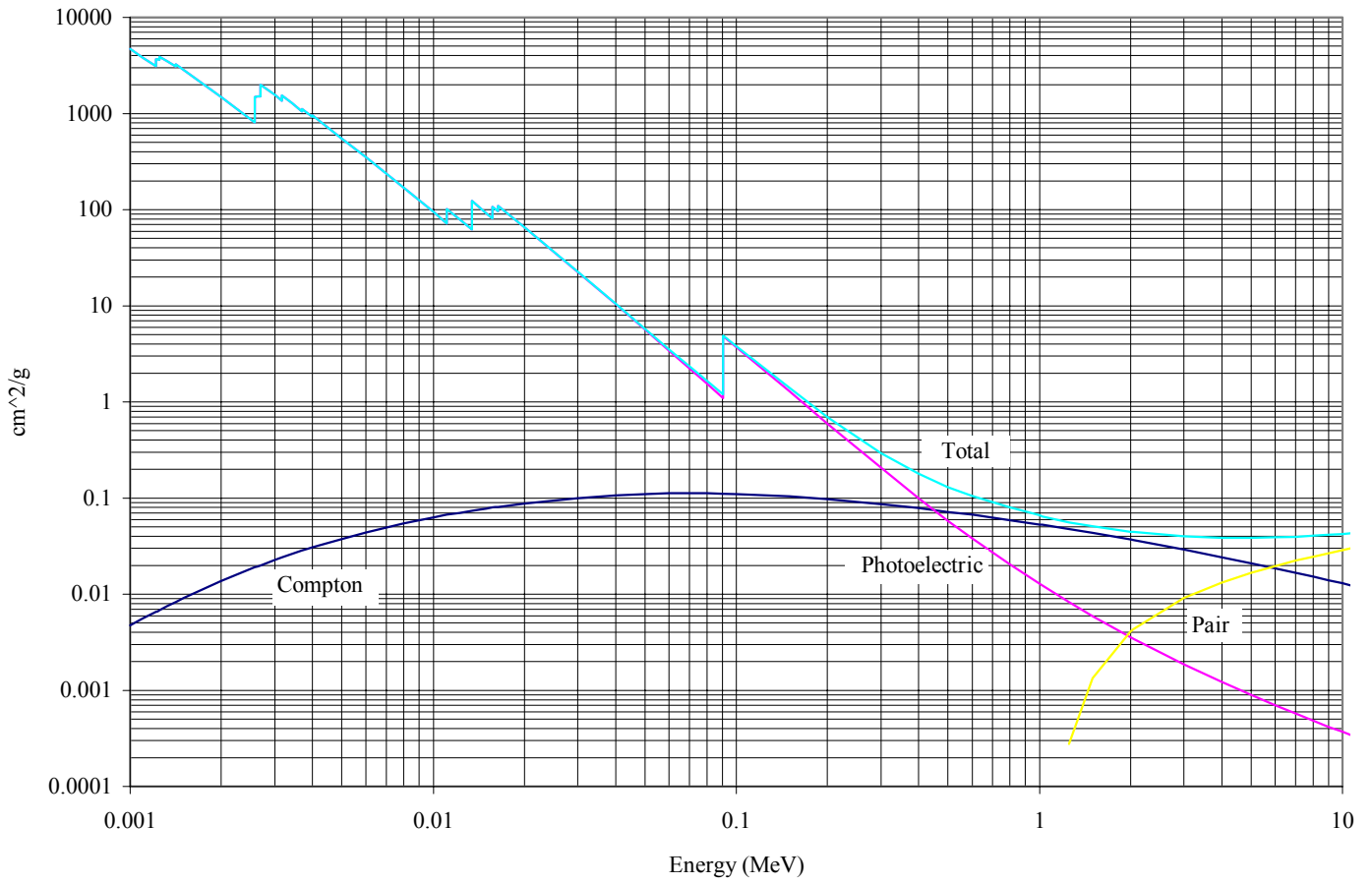


Figure A-2. Complete cross-sections of $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ showing total absorption and fractional components due to Compton scattering, photoelectric absorption, and pair production. Data are from the NIST program XCOM. $\rho = 7.13 \text{ g/cm}^3$.

Photon Attenuation in Germanium

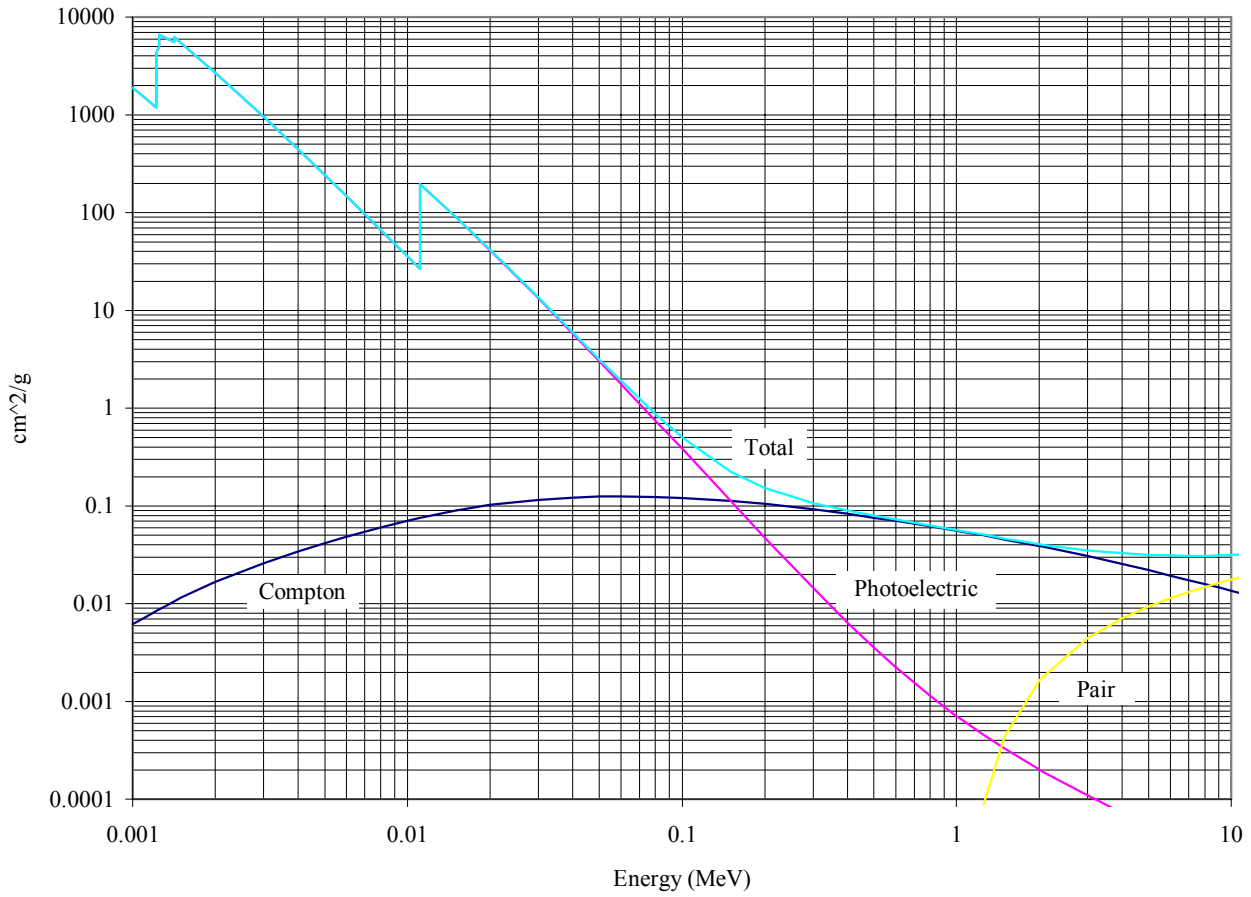


Figure A-3: Germanium absorption data from the NIST program XCOM. $\rho = 5.33 \text{ g/cm}^3$.

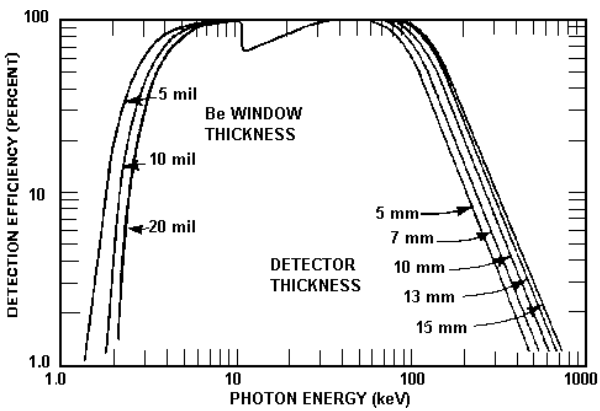


Figure A-4. Efficiency vs. energy for a planar X ray detector.

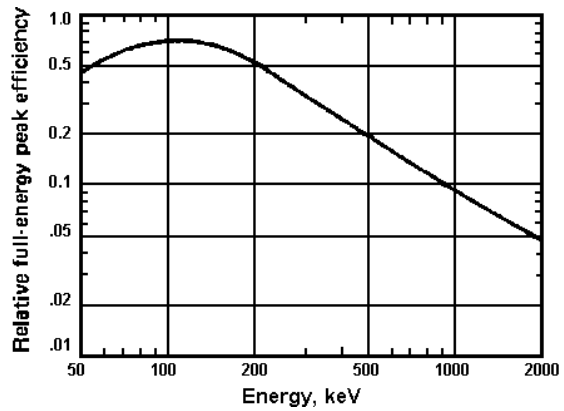


Figure A-5. Efficiency vs. energy for a coaxial germanium detector.

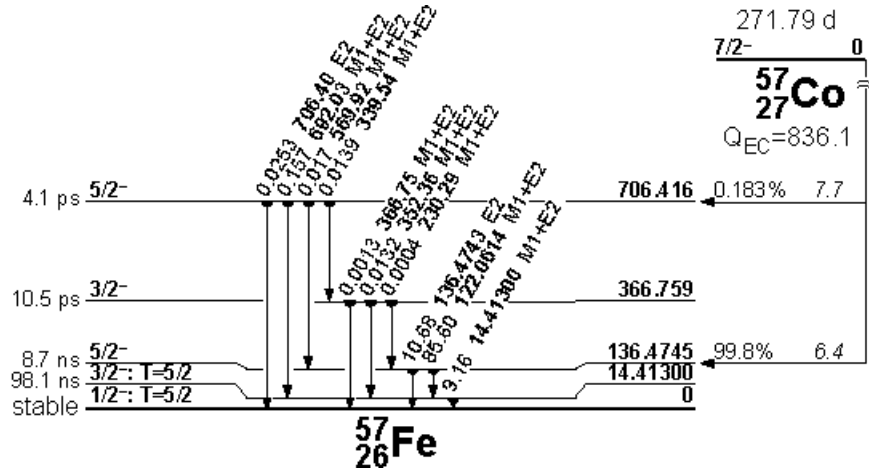


Figure A-6. Decay scheme of ^{57}Co .

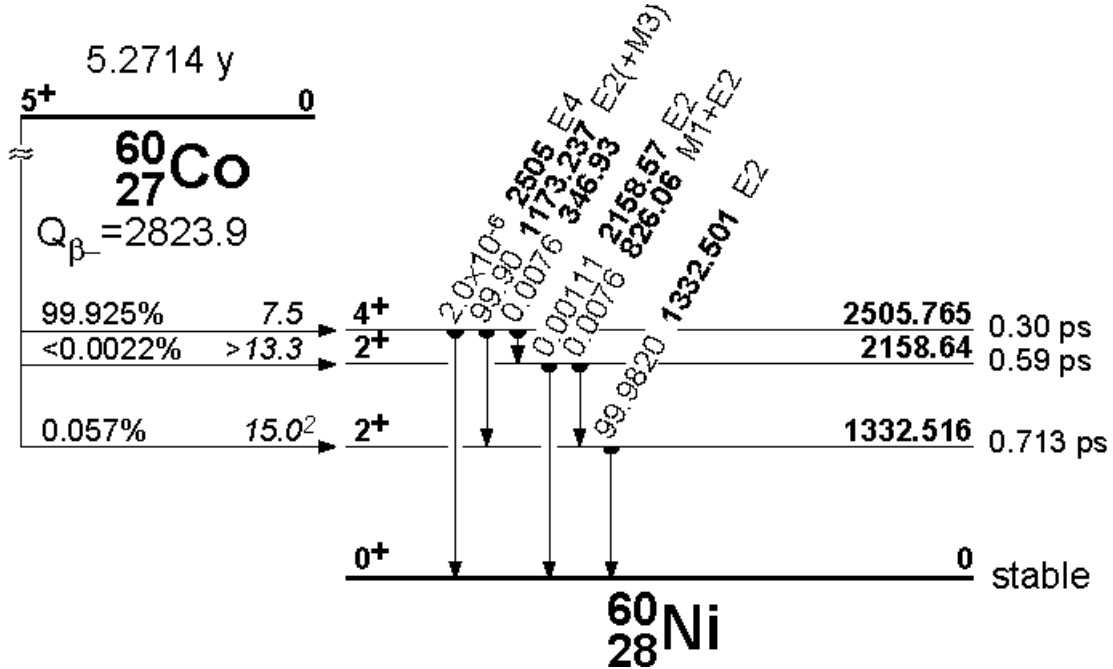


Figure A-7. Decay scheme of ^{60}Co .

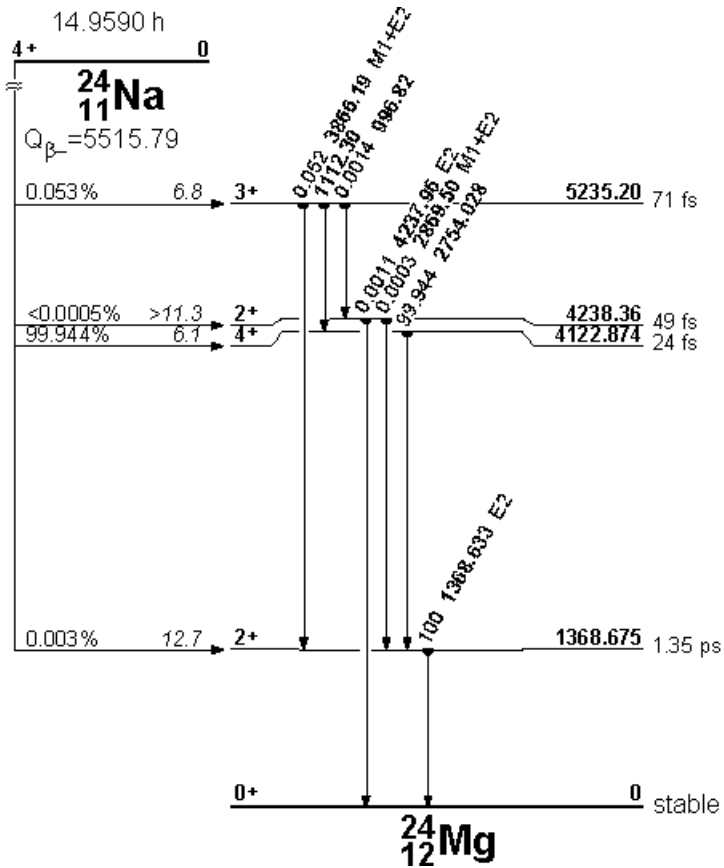


Figure A-8. Decay scheme of ^{24}Na .

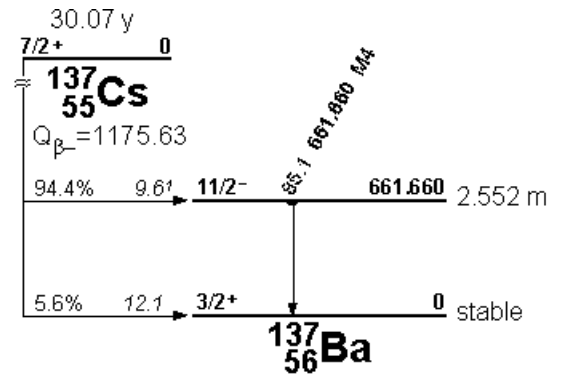


Figure A-9. Decay Scheme of ^{137}Cs .

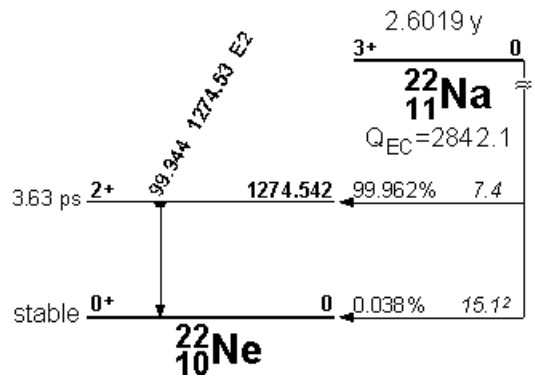


Figure A-10. Decay scheme of ^{22}Na .

Appendix B

Instructions for file transfer between TN-7200 and Lab Personal Computer systems via Kermit or NetTerm program

SET-UP: Four of the personal computers in Room 210 are connected to the 4 MCAs in Room 210 via 2 data switches using a null modem. On the **COMPUTER SELECT** switch, select which computer you will be using and on the **MCA SELECT** switch, which experimental station data will be transferred to/from. It is strongly suggested you create your own data directory (C:\users\yourname). The particulars depend on which program you intend to use for the transfer. The primary program now used (with the Pentium II systems) is called `NetTerm`. Instructions for the MS-DOS program `Kermit` follow these paragraphs. `NetTerm` can be run from the Windows 98 Start menu. Click **Start, Programs, NetTerm, NetTerm** to run the program. By default, the program should start with the **Tracor** configuration. If not, select **Tracor** from the directory menu. Then connect, either via the command menus or by clicking the **connect** icon on the toolbar. The red dot in the lower left of the application window should turn green.

TRANSFER TO COMPUTER: Next, click **Receive, ASCII** from the `NetTerm` program menu. You will be prompted for a file name. Give your data file a name and specify your data directory. On the MCA, press the **SETUP** key and then the **OUT** key; press **1** to select **BAUD RATE** and set it to **4800**. Press **OUT** again and press **0** to select **PRINT**. Select **SPECTRUM, STANDARD FORMAT**, and **8** columns. This will produce ASCII output which is easily read into `FFIT` and other programs. Remove the "header" which precedes the numerical data if you want to open the file with `Curvefit`. Press **SETUP** once more to return to the command mode and press the **OUT** key. If everything has been done correctly the file will transfer to the computer. If the MCA displays the message << **TERMINAL DISCONNECTED** >> then most likely one of the data switches has been set incorrectly or the wrong serial port on the computer has been selected. Some of the computers use COM2 for data transfer. After successfully transferring the spectrum, click **Receive, ASCII** to un-check ASCII. This closes the file. For some unknown reason, the file may not be read by another application until `NetTerm` is exited.

TRANSFER TO TN-7200: On the MCA, select a memory group to accept the incoming data, then press the **SETUP** key and then the **IN** key; press **1** to select **BAUD RATE** and set it to **4800**. Press **SETUP** twice, then press **IN** again and then **0** to select **READ**. Press **SETUP** once more to return to the command mode and press the **IN** key. Open the data file with a text editor, such as **Notepad**. Remove any leading blank lines (Not including the **TN-7200 ...** line), then **Select All** and **Copy** it to the clipboard. In the `NetTerm` window, **Connect to Tracor**, then **Paste** the data (which will not appear in the `NetTerm` window). If everything has been done correctly the file will transfer to the TN-7200 (you can watch its progress on the MCA screen). If the MCA displays the message << **TERMINAL DISCONNECTED** >> then most likely one of the data switches has been set incorrectly or the wrong serial port on the computer has been selected. Some of the computers use COM2 for data transfer.

KERMIT SETUP: After having selected MCA and computer via switches, get into the `Kermit` directory on the computer (using the `CD` name and `DIR` commands to change directory to "name" and to view the contents of the directory) and then type `KERMIT`. In Windows, double-click on the Kermit icon to start Kermit. You can then `CD \users\yourname` while Kermit is running. The

computer baud rate and COM port settings are specified in the Kermit initialization file. If incorrect, type the command SET BAUD 4800.

KERMIT TRANSFER TO COMPUTER: At the MS-Kermit> prompt change into your user directory then type LOG SESSION name where name is the filename of the file to be received. Then type C to connect to the TN-7200. Proceed with the MCA setup as above. If the transfer is successful, when it is done type <CTRL> -] C to get out of terminal mode on the computer and then type CLOSE SESSION to save the file. (<CTRL> -] is one keystroke, followed by C for "close"). You can quit Kermit by typing Q.

KERMIT TRANSFER TO TN-7200: Setup the MCA for input as above. At the MS-KERMIT> prompt type TRANSMIT name where "name" is the filename of the file to be sent. If the transfer is successful, when it is done type <CTRL> -] C to get out of terminal mode on the computer. You can quit Kermit by typing Q.