GERMANIUM (Li)

GAMMA SPECTROMETER SYSTEMS

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Section 1
INTERACTION OF PHOTONS WITH MATTER

1.1 GENERAL

Since Ge(Li) detectors are primarily used in the detection and identification of gamma-rays, it will be useful to discuss the manner in which electromagnetic radiation interacts with matter.

The average specific ionization (production of ion pairs in dry air) of X-rays and gamma-rays is only about 1/10 to 1/100 of that caused by electrons of the same energy. Therefore, ionization observed with photons has to be almost secondary in nature. Study of the energy of the secondary electrons reveals at least three processes by which the photons lose their energy by passing through matter: photoelectric effect, Compton scattering, and pair production.

1.2 PHOTOELECTRIC EFFECT

At low energies the dominant process is the Photoelectric Effect. In this process the entire energy of the electromagnetic quantum appears as kinetic energy of an electron minus its binding energy.

Photoelectric absorption takes place primarily in the lower electron shells of atoms; if the photon energy is greater than the K-binding energy of the absorber, 80% of the photoelectrons originate from the K-shell. As might be expected, the photoelectric cross section, which is a measure of the amount of interaction, shows sharp discontinuities at energies equal to the binding energies of the K, L, . . . electrons.

Above 50 keV, photoelectric absorption first falls off rapidly with the gamma-energy approximately as E_γ^{-1} (Figure 1). The photoelectric effect is therefore useful for the determination of gamma-ray energies up to about 2 MeV, this determination being accomplished by measuring the total ionization due to photoelectrons. Since the photoelectric cross section is approximately proportional to Z^5, where Z is the atomic number of the absorber material, it is very desirable to use high-Z material for gamma-ray detectors.

1.3 COMPTON SCATTERING

In Compton Scattering the photon transfers only part of its energy to a bound or free electron when it is deflected from its original path. The scattered electron then loses its energy through the normal ionization process, while the scattered gamma-ray may either interact again or escape from the detector.

The incomplete energy deposition caused by this escape of a scattered gamma-ray has only nuisance value in gamma-spectroscopy; it results in a background continuum which obscures the detection of lower energy gamma-rays.

The cross section for the Compton effect (Figure 1) falls off much more slowly with energy than that for the photoelectric effect, as can be seen from the relation which was derived by Klein and Nishina:

$$\sigma_C \propto \left\{ NZE_\gamma^{-1} \left[\log(2E_\gamma/mc^2) + 0.5 \right]^{-1} \right\} \ (cm^{-1}) \qquad (1)$$

where N = number of absorber atoms/cm^3
Z = atomic number
E_γ = energy of the gamma-ray

It follows from this equation that the cross section for the Compton effect is proportional to the

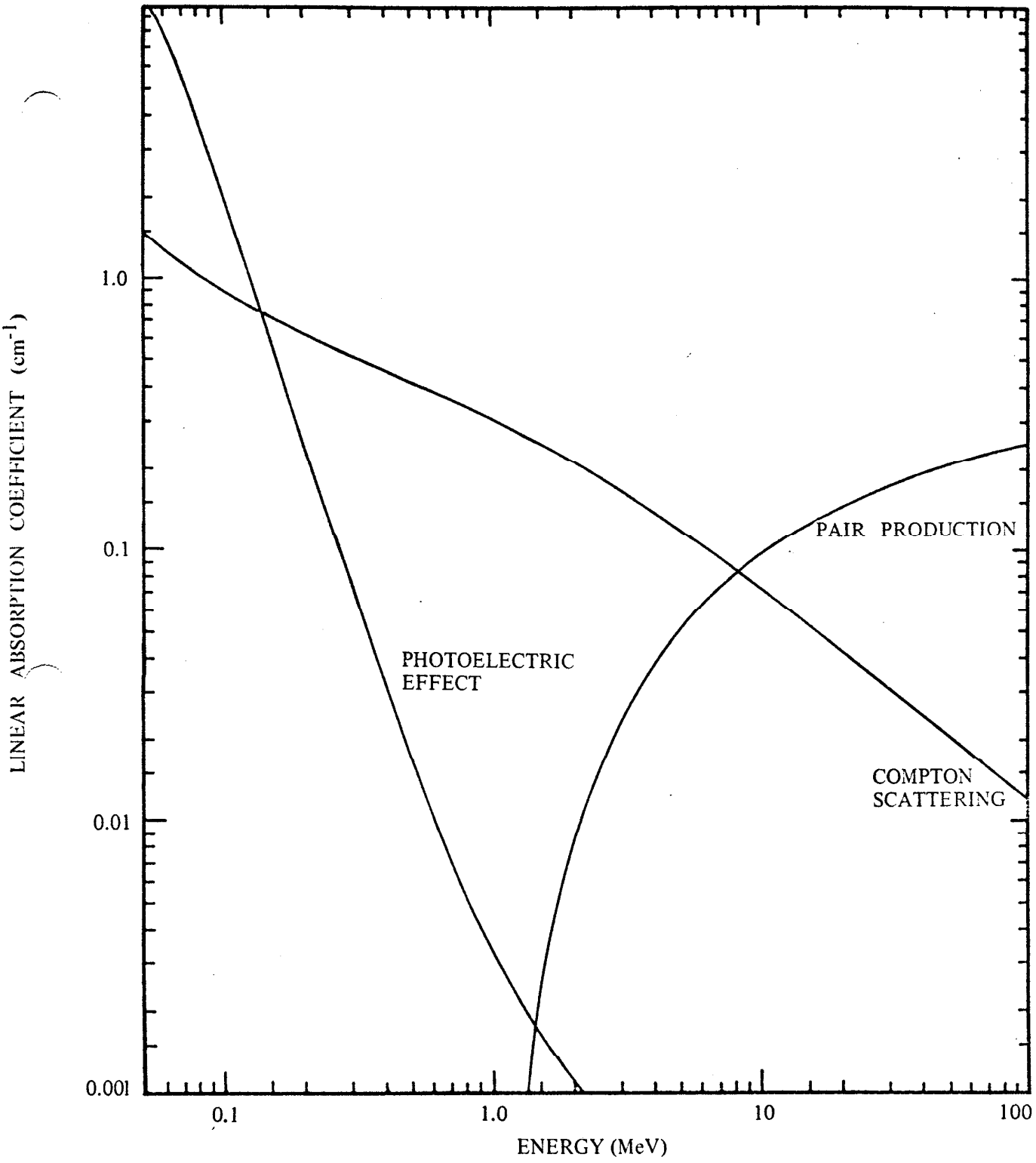


Figure 1. The linear absorption coefficients for Compton scattering, photoelectric effect, and pair production in germanium[1]. To obtain the absorption cross sections in barns/atom divide by 4.42×10^{-2}; to obtain the mass absorption coefficients in cm^2/gm multiply by 120.

atomic number of the absorber material. However, as the photoelectric cross section varies with Z^5, we see that it is desirable to use materials with high Z for detectors in order to emphasize the photoelectric effect relative to the Compton scattering process.

1.4 PAIR PRODUCTION

For gamma-rays with energies above 1.02 MeV, which is the threshold energy for the production of an electron-positron pair, another mechanism for full-energy absorption can occur. This phenomenon, called Pair Production, occurs if the gamma-ray interacts with the strong electric field in the vicinity of a nucleus. An electron and a positron are produced, with the original photon energy appearing now as the kinetic energy of the electron-positron pair plus their mass energy.

The kinetic energy of the electron-positron pair is nearly completely absorbed by ionization processes. The positron is unstable, however, and will annihilate with an electron producing two 0.511 MeV gamma-rays. The probability that the annihilation photons are absorbed is relatively small and depends strongly on the size and geometry of the detector. The resulting energy spectrum will usually have three peaks, corresponding to the escape of one, both, or neither of the two annihilation photons.

The cross section for pair production rises rapidly above the threshold energy and becomes nearly proportional to log E_γ above 4 MeV. (Figure 1). Therefore, this process is not only important for the absorption of high-energy gamma-rays but also is the principle means of their detection.

Since the cross section is proportional to Z^2, high Z materials show a better ratio for pair production to Compton scattering and are favorable as detector materials.

Section 2
GERMANIUM AS A SEMICONDUCTOR MATERIAL

2.1 INTRINSIC GERMANIUM

A semiconductor, by definition, is a crystal which is a perfect insulator at temperatures close to absolute zero. At higher temperatures, however, it shows a rapidly increasing electrical conductivity. Using the Hall effect, it can be shown that the electrical carriers in semiconductors are electrons and holes, not ions.

An explanation of this behavior is given by the energy-band model. At very low temperatures the valence electrons in a pure or so-called intrinsic semiconductor are all located on energy levels known as valence bands, whereas the next higher band of allowable energies, the conduction band, is unoccupied. However, with increasing temperature and thereby increasing vibration of the lattice, a few of the valence electrons are lifted from the valence band to the conduction band, thus leaving holes in the valence band.

This process is only possible if the energy difference between these two bands, the so-called band gap, is less than 2 eV. In germanium the band gap energy amounts to 0.6 eV. Typical insulators have values between 2 and 10 eV and no free electrons are available even at higher temperatures.

2.2 EXTRINSIC GERMANIUM

In practice, semiconductor materials of sufficient purity are not yet available, and one has to deal with materials in which conduction is dominated by electrical carriers introduced by electrically active impurities. Such materials are called impure or extrinsic. In most cases certain impurities are introduced purposely by a process called doping in order to enhance the electrical conduction by many orders of magnitude.

The effects of doping can be explained as follows: Germanium atoms have four valence electrons and the crystal structure formed by germanium atoms is known as the diamond lattice. If antimony, which is known to have five valence electrons, is introduced into a germanium crystal, four of its five can form covalent bonds with electrons from the four adjacent germanium atoms. However, one of the valence electrons of the antimony cannot take part in the formation of a chemical bond; it is very weakly bound and little energy is necessary to set it free.

In the energy-band model these impurity atoms (donors) occupy stationary energy levels which are located just below the conduction band. The energy gap between these donor levels and the conduction band is only 0.1 to 0.01 eV. Therefore, electrons can be lifted easily from the donor levels to the conduction band by thermal ionization. This kind of semiconductor material is called n-type because the carriers are exclusively negative electrons.

In contrast to n-type material, p-type semiconductors are characterized by a lack of valence electrons. This occurs if, for example, the tetravalent germanium is doped with trivalent boron, indium or gallium. Existing in the crystal lattice, therefore, is a so-called hole which can be filled by neighboring valence electrons at higher temperatures.

In the energy-band model, such acceptor atoms have to occupy stationary levels just above the usually completely filled valence band. By means of thermal energy the electrons can be lifted easily into the acceptor band, creating a certain number of holes in the valence band. In an electric field these holes behave like a positive electrical carrier since they move in a direction opposite to the negative electrons in n-type material. To understand Ge(Li) detectors, it is important to note that interstitial atoms can act as donors or acceptors. Lithium, for example, located interstitially in the lattice of silicon or germanium, introduces a donor level very close to the conduction band, whereas copper and nickel

introduce donor levels midway between the conduction and valence band. Another interesting impurity is gold which can act as donor or acceptor depending on its position in the lattice.

Crystal imperfections such as vacancies and/or dislocations, which may cause preferential trapping for electrons or holes, are also very important. These traps provide intermediate levels between the valence and conduction band through which recombination and generation processes can take place, leading to localized storage of electrical charge.

The number of free electrons or holes per cm^3, n_i, can be calculated as a function of the temperature by means of statistical mechanics. It is calculated for intrinsic semiconductors by:

$$n_i = \frac{2(2mkT)^{1.5}}{h^3} \quad \exp -(\Delta E/2kT) \tag{2}$$

and for extrinsic materials with n_o defects per cm^3 by:

$$n_i = \frac{(2mkT)^{0.75}}{h^{1.5}} \quad n_o^{0.5} \exp -(\Delta E/2kT) \tag{3}$$

where
- k = Boltzmann's Constant
- T = absolute temperature (^oK)
- m = electron mass
- ΔE = energy difference between energy bands
- h = Planck's Constant

Equation (2) is valid only if $n \gg n_o$, i.e,, as long as only a small percentage of the impurity atoms are ionized.

Both equations are simplified because the band gap energies are temperature dependent[2]. In intrinsic semiconductors, ΔE decreases with increasing temperature (approximately 4×10^{-4} eV/^oC for germanium). In extrinsic materials, ΔE also depends strongly on n_o, the number of impurity atoms per cm^3.

With increasing temperature, particularly at small ΔE, constant value of ΔE will be reached when all impurity atoms are ionized. Furthermore, if the energy difference between the valence and conduction band is small, as in germanium, the electrical conduction is dominated at increased temperatures by thermally excited electron-hole pairs rather than by electrons or holes produced by dopants. Therefore, at a high enough temperature any semiconductor can be considered as intrinsic.

2.3 RESISTIVITY

If the number (n) and mobility (μ) of electrical carriers in a semiconductor is known, the electrical conductivity, or its reciprocal, the resistivity, ρ can be calculated from the equation:

$$\rho = \frac{1}{\sigma} = (n\mu e)^{-1} \tag{4}$$

Since the mobility of electrons (μ_e) and holes (μ_h) are not equal, as can be seen from Figure 2, and since every electron excited into the conduction band also produces a hole, equation (3) can be re-written as:

$$\rho = \frac{1}{\sigma} = en(\mu_h + \mu_e)^{-1} \tag{5}$$

The restivity-impurity concentration for germanium at 300^oK is shown in Figure 3.

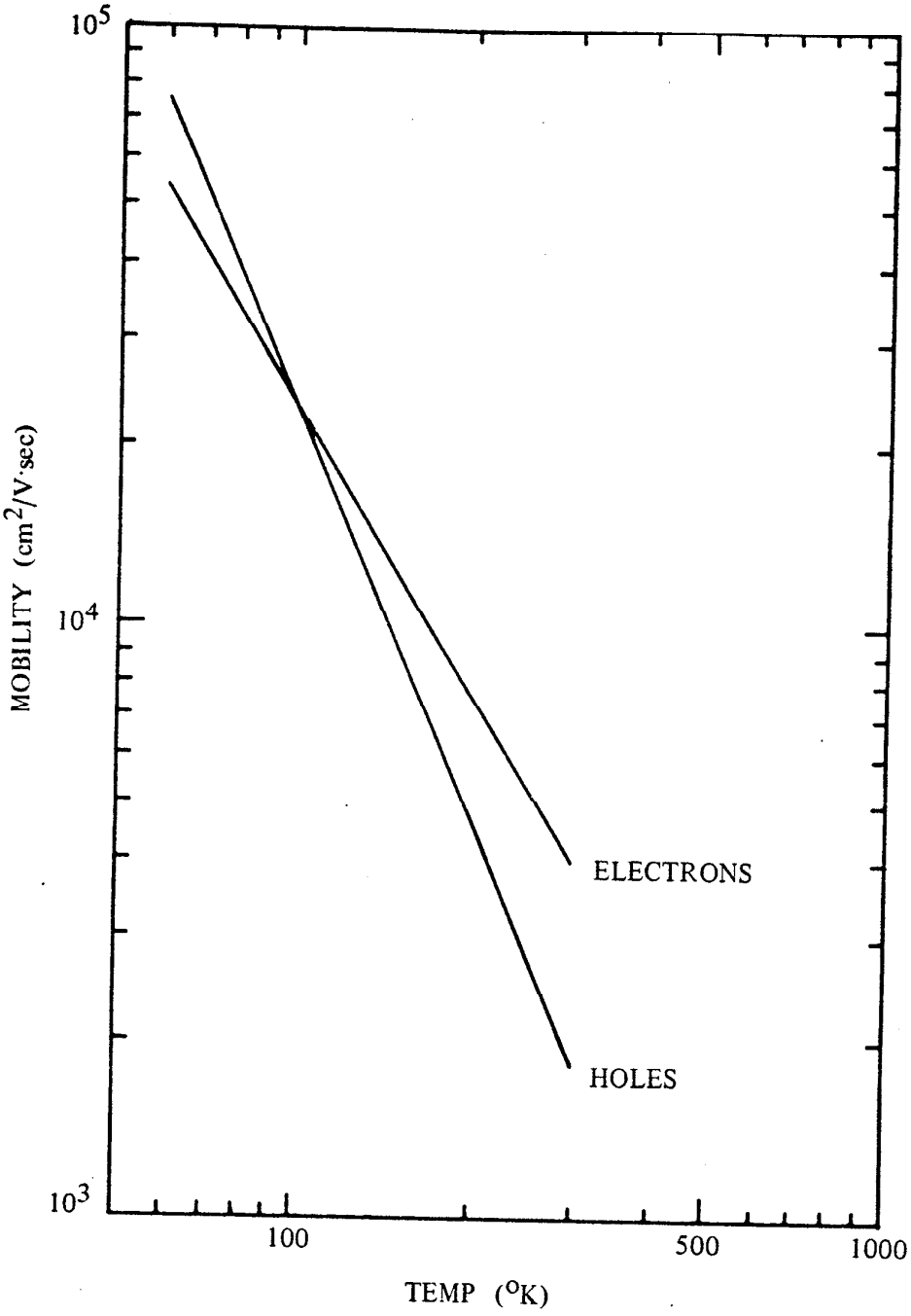


Figure 2. The mobility of electrons and holes in pure germanium as function of the temperature.

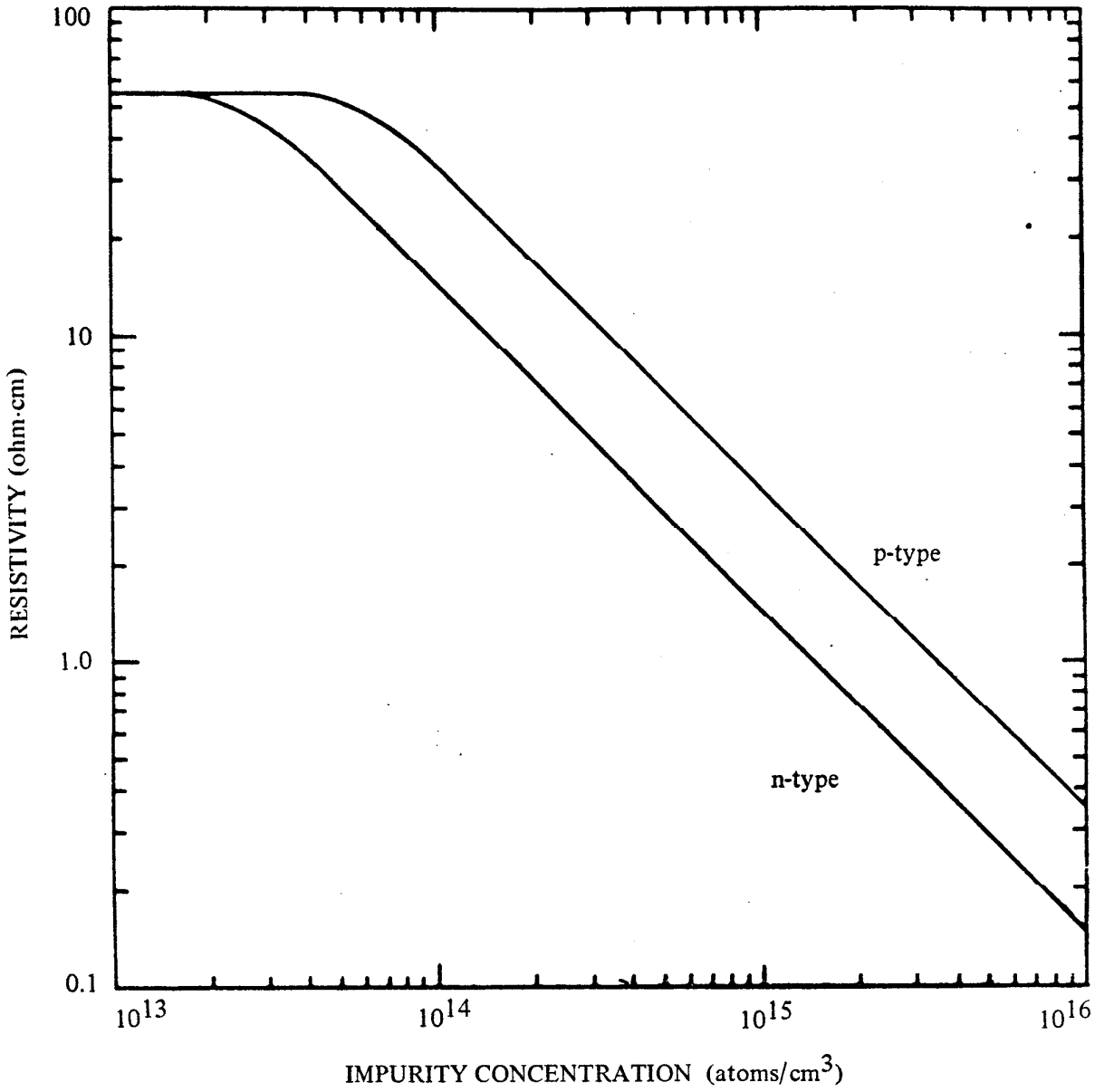


Figure 3. The variation of the resistivity of germanium with the concentration of added dopants.

2.4 JUNCTIONS

The usefulness of semiconductor devices would be practically insignificant were it not for junctions between regions of semiconductor material of opposite impurity type. Diodes and transistors, as well as radiation detectors, are dependent on junctions.

A p-n junction is formed if, as in the case of the Ge(Li) detector, a piece of p-type germanium is doped on one side with a donor such as lithium, resulting in that side changing to n-type. Under normal circumstances the acceptor and donor centers will not move in the lattice of the germanium crystal, but at temperatures above absolute zero the free holes and electrons will diffuse across the junction.

The diffusion of electrons into the p-region and of holes into the n-region produces a region about the junction which is essentially void of carriers and is thus called a depletion region. (Figure 4a). The net charge distribution about the junction is shown in Figure 4b. This charge distribution produces an electric field across the junction as shown in Figure 4c which acts to oppose the further diffusion of carriers across the junction. Thus, equilibrium conditions are established. It should be noted that if the concentrations of impurities are different on either side of the junction the depletion region will extend further into the region of lower impurity concentration.

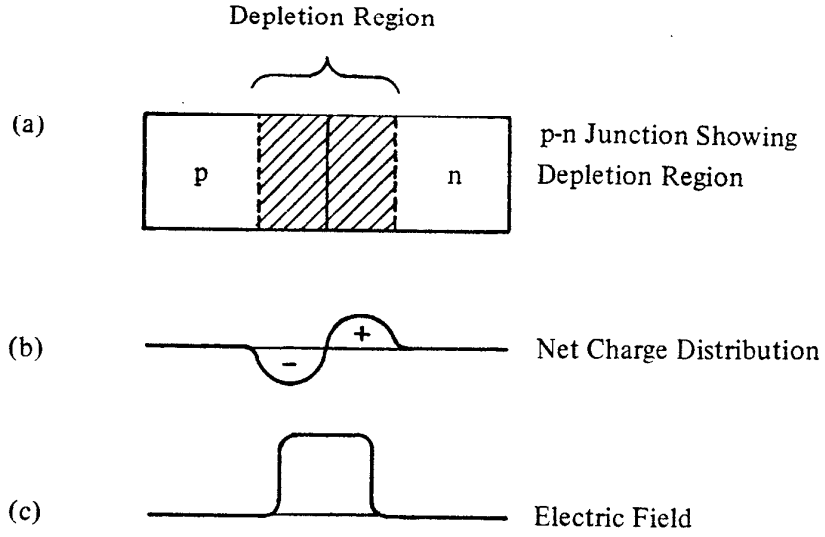


Figure 4. Depletion Region in a Semiconductor Material

If internal voltage is applied across the junction it will either enhance the built-in electric field or oppose it. A reverse bias (positive voltage to the n-type region) is of interest in detectors. In this case the built-in electric field is enhanced and minority carriers are swept across the junction, increasing the width of the depletion region.

Assuming that one side of the junction has a much higher concentration of impurities than the other, the depletion region will be almost entirely within the region of lower impurity concentration. The width (W) of the resulting depletion region is given by:

$$W = \frac{E\sqrt{V + V_o}}{2\pi N_a} \qquad (6)$$

where E = dielectric constant of the semiconductor material
V = applied voltage

V_o = the built-in voltage of the junction in equilibrium (approximately 0.3V for germanium)
N_a = net density of electrically active centers in lightly doped region
e = electrical charge

Such a device can operate as a radiation detector, since any electrical carriers formed in the depletion region by primary or secondary ionization are attracted to the electrodes, producing a current pulse.

2.5 LITHIUM DRIFTED GERMANIUM

As it is not yet feasible to grow germanium crystals with less than 10^{13} electrical impurities per cm^3, the thickness of the depletion layers obtainable is below 1 mm. It is therefore, not sufficient to use a simple p-n junction detector for gamma-ray spectrometry.

Fortunately, the high mobility of lithium in germanium and the fact that lithium acts as a singly-charged interstitial donor (with a low ionization energy of approximately 10^{-2} eV in germanium) make it possible to compensate the acceptors in p-type germanium; i.e., decrease N_a and hence form relatively thick depleted or intrinsic regions.

This compensation process is carried out at a temperature slightly above 20°C under the influence of a reverse bias. The process is called "drifting", and is described in more detail in the next chapter. The resulting p-i-n device acts exactly like a simple p-n detector under a reverse bias; free charge carriers produced in this region can move freely to the p or n side of the device and produce a current pulse.

The high mobility of lithium in germanium, although advantageous for the compensation process, makes the storage and operation of Ge(Li) detectors at very low temperatures compulsory.

Section 3
FABRICATION OF GE(LI) DETECTORS

3.1 MATERIAL SELECTION

The starting material for the fabrication of Ge(Li) detectors is a horizontally grown or pulled single crystal of germanium. As the crystals are being grown, they are doped with acceptor impurities such as indium, gallium or boron. The result is p-type material with a resistivity between 5 and 40 ohm-cm.

Horizontally grown crystals have sections that are usually trapezoidal with areas of up to 25 cm^2. Pulled crystals have irregular-round cross-sections with areas up to 35 cm^2. The dislocation density as revealed by etching is in the range from zero to a few thousand per cm^2. Minority carrier lifetime depends on the resistivity, but should be above 200 microseconds.

Unfortunately, it cannot be judged from these data whether or not certain crystals can be made into good detectors. In 1966, the supply of good germanium seemed to vanish, and research was initiated to find correlations between good detector material and its chemical or physical properties. At first it appeared that the oxygen concentration, even if very low, had a significant influence on the drift characterization.[3,4] However, later studies do not support these findings.[5] Although at present the availability of good germanium is no real problem, more luck than knowledge is necessary to select the right crystals.

Raw germanium crystals can be cut to length and shaped by a variety of means, including the use of diamond wheels, band saws, centerless grinders, and even drills. Great care must be taken in any of these mechanical operations not to fracture the brittle material.

3.2 APPLICATION OF IMPURITY

Before the germanium crystal can be drifted with the compensating impurity such as lithium, the impurity must be diffused into the surface of the crystal. Several methods which have been used are outlined below.

The simplest method involves painting a lithium-in-oil suspension on the surfaces from which drifting is to proceed and heating the crystal under an inert gas atmosphere to an elevated temperature. Unless special care is taken this procedure results in non-uniform lithium distribution on the surface. Since excess lithium in conjunction with germanium forms an intermetallic compound, the n-sides of such treated crystals have a pitted appearance.

Under vacuum conditions lithium can be deposited on the surfaces of the germanium crystals. The germanium is then heated in the presence of an inert gas until the lithium has diffused into the crystal.

A very simple and easily controllable method for producing uniform n-layers on germanium crystals is by electrodeposition of lithium from a molten lithium salt mixture [6]. A graphite crucible can be used for the molten salt and at the same time serves as the anode. The melt is kept at the optimum diffusion temperature (390°C to 410°C). The germanium crystal is used as the cathode and a D. C. voltage is applied between the crystal and the crucible.

The resistivity of the n-layer after diffusion is in the range of 0.1 ohm-cm; its thickness is less than one mm. The p-n junction is clearly and easily revealed by the electrodeposition of copper on the surface that is kept free of lithium.

3.3 DRIFTING

During the drifting process a reverse bias is applied to the p-n junction. Positively-charged lithium ions move into the p-region and there tend to compensate the acceptor atoms. The drift rate can be calculated by the formula given below. One obtains the drift depth, (W), as a function of time, (t):

$$W = \sqrt{2V\mu_{Li}\, t} \qquad (7)$$

where V = applied voltage
μ_{Li} = mobility of the lithium ions in germanium at the drift temperature

Drift rate can be increased by increasing the voltage across the junction and by increasing the temperature. However the voltage is limited by diode surface breakdown problems and the maximum temperature for germanium is about 50°C, for the material becomes intrinsic above this temperature and the p-n junction loses its diode characteristic.

Since the drift process generates heat, the device must be cooled. The temperature of small pieces can be controlled with a thermoelectric cooler or a cooled copper plate. Larger crystals are best immersed in an inert solvent with a boiling point close to the optimum drift temperature such as Freon, pentane or chloroform.

In practice, the above formula has only limited value since a number of secondary effects have a significant influence on lithium-germanium systems. One undesirable effect is the precipitation of lithium at vacancies [7,8,9]. This can occur if the amount of lithium necessary to compensate the acceptor atoms in germanium exceeds the maximum solubility of lithium in germanium (6.6×10^{13} atoms/cm^3 at 25°C). The excess lithium tends to precipitate at vacancies and loses its electrical activity.

Experience shows that, on the average, about four weeks are necessary to drift a distance of 12 mm. During this period the resistivity of the n-layer usually rises and has to be restored by one or more lithium re-diffusions.

After the desired drift depth is reached, a so-called clean-up drift at lower temperatures and higher voltages is recommended [10], particularly if the main drifting process was performed at high temperatures. The purpose of this procedure is to reduce the over-compensation caused by bulk leakage current during the high temperature drift.

3.4 FINAL PREPARATION

The final steps in the fabrication of the detector are: (1) setting of the surface states between the junctions and (2) mounting the detector in the cryostat. The surface has to be stabilized in such a way that the leakage current stays below 10^{-9} amperes.

This procedure is frequently considered as the most difficult and uncontrollable of the entire fabrication. Experiments show that various treatments can lead to the same I/V characteristic.

Section 4
THE VARIOUS TYPES OF GE(LI) DETECTORS

4.1 THE PLANAR DETECTOR

The simplest way to fabricate a Ge(Li) detector is to diffuse lithium into one surface of a round or square piece of p-type germanium and drift toward the opposite face. One obtains a planar device which, if carefully fabricated from good germanium, can be an excellent detector provided the depletion depth is at least five mm. Because the compensated region behaves very much like an insulator with a dielectric constant of approximately 1.44 pf/cm and the p and n regions act as electrodes, the capacitance of such a detector can easily be calculated by:

$$C = 1.44A/W \tag{8}$$

where A = area of the two junctions
W = depletion depth

Since the capacitance of a Ge(Li) detector strongly influences the energy resolution, as will be seen later, thick compensated regions are advantageous while large areas can be disadvantageous due to increased capacitance. As described previously, it is technically difficult to drift deeper than 12mm. Thus, large area planar detectors which have a desirable geometry cannot give the best energy resolution for a given active volume.

One way to increase the depletion depth is to drift from both sides towards the middle. Before the last p-material is compensated, one n-layer is replaced by a thin p-layer and drifting is completed [11, 12]. Unfortunately this technique has not been very successful. It is difficult to compensate completely the remaining p-material and build a perfect p-layer on compensated germanium. Moreover, the high potentials which are necessary for a complete charge collection can only rarely be applied without excessive leakage current.

A better method for obtaining large active areas with good resolution is to connect several good detectors in parallel [13, 14, 15]. The detectors in such a system must be adjusted carefully to obtain the best possible resolution. The efficiency is usually higher than the arithmetic sum of the efficiencies of the single detectors.

If gamma-rays or X-rays with low energies must be analyzed, the n-and p-layer of a simple planar detector is often too thick and most of the photons are absorbed in the dead region. Thin-window detectors have been fabricated which use a gold surface barrier as the p-contact and entrance window [17, 18]. Two designs have been studied; their geometries are shown in Figure 5.

4.2 THE U-TYPE DETECTOR

Another way to achieve large depletion depth has been suggested by Armantrout [19]. Lithium is diffused into three sides of a block of p-type germanium and drifted as shown in Figure 6. After the p-core is completely compensated the two n-layers on the side faces are removed, leaving behind a planar device with large depletion depth. Here difficulties have been encountered because of high leakage currents.

4.3 THE WRAP-AROUND CONFIGURATION

Since the active volumes attainable with planar detectors appear to be limited to about 15 cm^3 and larger detectors are necessary for the analysis of high-energy gamma-rays, another means of fabrication has been developed: the wrap-around configuration. Tavendale [20] and Fiedler [6] first fabricated such

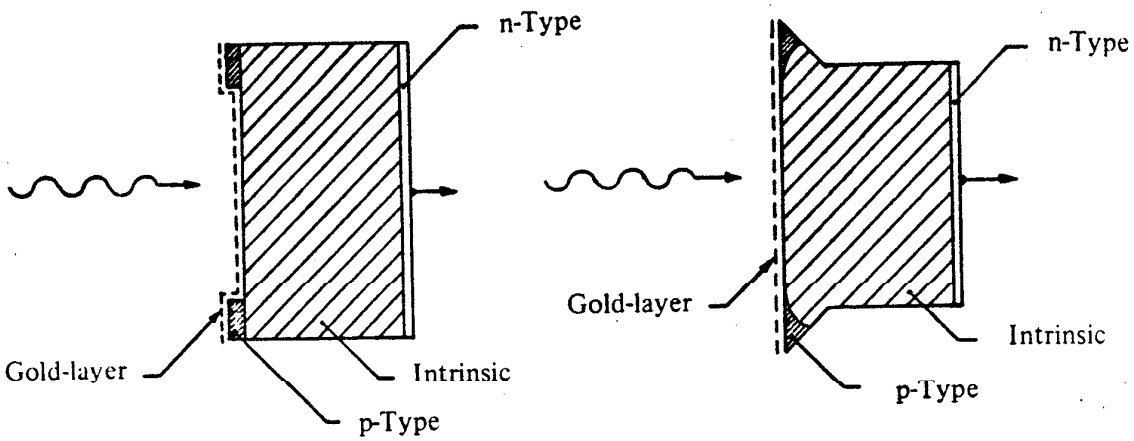


Figure 5. Two configurations of thin-window Ge(Li) detectors for X-ray spectroscopy [17,18]

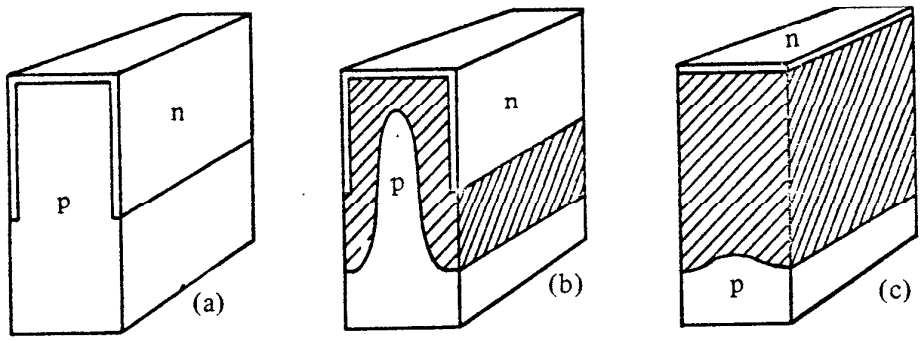


Figure 6. Junction configuration and drifting profile of a U-junction detector[19]. (a) after Li diffusion (b) after partial drift (c) completed detector with n-layers on the sides removed by lapping.

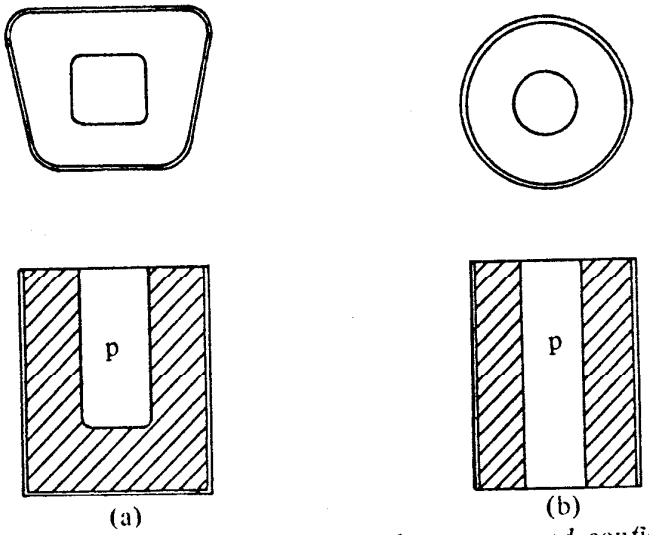


Figure 7. Ge(Li) detectors with wrap-around configuration (a) five-sided trapezoidal (b) true coaxial.

devices and proved the feasibility of this method. As shown in Figure 7, lithium is diffused into five sides of a germanium single crystal and drifted towards the center. With this method, detectors with active volumes up to 50 cm^3 can be produced successfully.

If one drifts more than nine mm deep the capacitance of such detectors compares favorably with that of planar detectors. Although higher potentials are necessary for complete charge collection, usually no difficulties arise due to excessive leakage current. However, the rise-time distribution of the output pulses is often unsatisfactory because of the variance in drift depth within the detector (distance between the n-layer and the p-core).

True coaxial detectors (Figure 6) show a definite improvement in timing characteristics. However, because of the limited circular cross sections currently available from germanium ingots, it is obvious that relatively long detectors must be produced in order to obtain the same active volume as with the five-sided geometry. The capacity of the true coaxial detector is given by:

$$C = 1.44 \frac{2\pi L}{\ln (r_2/r_1)} \tag{9}$$

where r_1 = inner radius in cm
r_2 = outer radius in cm
L = length of the cylinder in cm

Both wrap-around and true coaxial have become very popular as general-purpose detectors with good resolution and high efficiencies.

Section 5
THE CRYOSTAT

As mentioned earlier, Ge(Li) detectors have to be stored and operated at low temperatures, preferably at less than -200°C. To achieve this, the detector is permanently mounted in a cryostat.

Although the cryostat is in most cases an essential part of a Ge(Li) detector spectrometer system, attention to its design has frequently been neglected. Since the detector performance and life time can be strongly influenced by insufficient cooling, surface contamination, or vacuum leaks, it is important to understand the essential points which should be considered in selecting a cryostat.

5.1 GENERAL FEATURES AND REQUIREMENTS

The cryostat consists of a reservoir for the cooling medium, or dewar, and a vacuum chamber containing the detector (and in some cases the input stage of the preamplifier). Sometimes the dewar and the vacuum chamber are one integrated unit.

5.1.1 DEWAR

The dewar serves as a reservoir for the cooling medium, which is in most cases liquid nitrogen. Unless otherwise specified such dewars are designed for liquid nitrogen only. Liquid air or liquid oxygen cannot be stored in these containers as dangerous explosions might result.

In principle, the dewar is made of two or more concentric metal containers; the inner container serving as the reservoir. The holding time or evaporating rate of the liquified gas depends on how well these two containers are insulated from each other. Vacuum conditions are employed to minimize heat loss due to conduction and highly polished surfaces or superinsulation is used to reduce heat loss by radiation.

The design of the connection between the two containers is critical. This neck serves as the fill opening and in order to make refilling as fast and convenient as possible, a wide neck is desirable. However, this increases the amount of material directly connecting the two containers and leads to larger heat loss by conduction. Materials used for the neck are generally of low thermal conductivity such as laminated plastic or thin wall stainless steel tubing. As the neck is the only support for the inner container in the conventional dewar, mechanical strength is demanded.

Gravity feed dewars have two such openings, one for filling and the other for delivery of the liquified gas to the cooling finger. Since both openings are potential heat leaks, these dewar types cannot have the same holding time as the conventional dewar of equal capacity.

Frequently, the vacuum between the two containers is maintained by cryosorption pumping. Thus, a dewar stored for an extended period without liquified gas will first show a high evaporating rate until the activated charcoal or the molecular sieve is cooled down and absorbs the residual gases.

The lifetime of a dewar depends on its leak tightness. Loss of the vacuum means loss of heat by conduction and consequently excessive loss of the liquified gas. In some cases the dewar may be re-evacuated but usually the evacuating tube is pinched off and cannot be used again.

5.1.2 VACUUM CHAMBER

Many requirements must be taken into account in the design of a vacuum chamber for a Ge(Li) detector. First the detector must be kept at the lowest possible temperature. Using liquid nitrogen as the cooling medium, the detector should be maintained at below -190°C. Second, this must be achieved with a low evaporation rate of liquid nitrogen in order to maintain the holding time of the

cryostat. Third, a good and clean vacuum must be maintained at all times to prevent contamination on the detector surfaces due to condensation, to keep heat losses to a minimum and to prevent electrical discharge in the chamber when high voltage is applied to the detector.

All these requirements are satisfied with stainless steel as the material for the chamber walls. However, its low heat conductivity, advantageous in one respect, makes the use of this material as a heat sink impossible. And the relatively high atomic number of stainless steel makes it undesirable around the detector because of increased Compton scattering and greater absorption of photons.

Generally, copper or aluminum is used for the parts which conduct heat from the detector and for the cap surrounding the detector. OFHC copper is preferred because of its lower outgassing characteristics. Stainless steel/copper connections are usually made by brazing, which should be done without flux as the flux is difficult to remove and is a steady source of outgassing.

The detector compartment is outfitted with a vacuum feedthrough for the high voltage/signal connection to the detector. A ceramic insulator is preferred to glass as glass seals may be damaged when welded to the stainless steel body. Welding is absolutely necessary if long term reliability is desired. Feedthroughs should never be soft soldered or epoxied to the vacuum chamber.

Enveloping the detector and completing the vacuum chamber is a cap or "hat" which has a thin entrance window at its end for the passage of radiation. Beryllium windows, which are absolutely necessary for Ge(Li) photon spectrometers, are usually epoxied into the aluminum cap, although the use of a copper hat is preferrable in this case since beryllium can be brazed to copper.

The integrity of the seals that are made in a vacuum chamber has a direct effect on the performance of the detector system in the months and years that follow the final mounting of the detector. In general, all-metal seals are much preferred to the more simple, less costly Viton O-ring seals. Elastomeric seals will not guarantee a leak tight seal over several years, and do not permit high temperature bake-out of the vacuum chamber. They are also permeable to hydrogen, which will slowly increase the pressure in the vacuum chamber if it is not pumped by an appendage pump. For the same reasons a pinched-off evacuating tube is preferred to a high-vacuum valve with O-ring seals. Metal seal valves are very expensive and bulky.

Two methods are available to aid the maintenance of a vacuum within the chamber. The first involves the use of cooled molecular sieve or activated charcoal. These materials are located around the cold finger and pump most gases that may escape from the inside walls of the chamber after external pump down is complete.

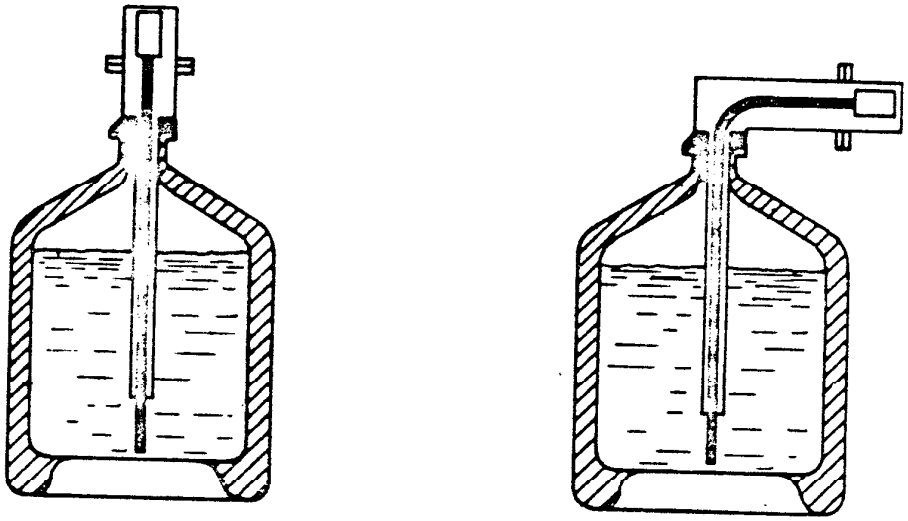
The second possibility is the addition of an appendage ion pump to the vacuum chamber. These pumps, although more expensive, have advantages in that they cannot contaminate the detector with dust as a molecular sieve might, and their pumping rate, which can be monitored, gives an indication of the vacuum existing within the chamber. And, ion pumps absorb hydrogen and helium which are not absorbed by cryosorb materials.

5.2 CRYOSTAT CONFIGURATIONS

Over the years several cryostat designs have been developed and manufactured. Those most frequently used will be discussed briefly.

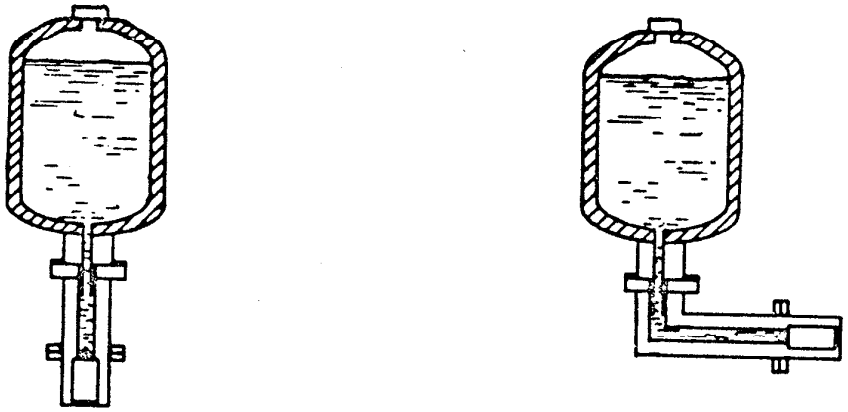
5.2.1 "DIP-STICK"

A cooling rod is immersed in liquid nitrogen stored in a large-volume dewar. The vacuum chamber surrounding this rod is either straight (Figure 8a) or bent 90^{o} (Figure 8b). In the first case the detector axis is vertical; in the second, horizontal. As discussed above, the cooling rod should be made of copper; all other parts except the cap around the detector should be type 304 stainless steel.



(a) (b)

Figure 8. Dipstick cryostats (a) vertical (b) horizontal



(a) (b)

Figure 9. "Chicken-feeder" cryostats (a) vertical (b) horizontal

The tube which is partially immersed in liquid nitrogen is the largest heat leak and should be of very thin-wall stainless steel tubing. It must be pointed out that the position of the detector, relative to the end window, changes slightly with the liquid nitrogen level in the dewar because of the thermal expansion of this stainless steel tube.

Dewars with wide necks can be supplied with a special fixture which allows them to be filled without removing the vacuum chamber.

5.2.2 "CHICKEN-FEEDER"

In the "chicken-feeder" cryostat the detector is mounted on the end of a hollow cold finger which is kept filled by gravity with liquid nitrogen from a reservoir above the vacuum chamber (Figure 9). Refilling the dewar is very convenient but the holding time with equal amounts of liquid nitrogen cannot be as good as that of the dipstick type because the dewar has two openings contributing to the heat leak.

A serious disadvantage of the chicken-feeder cryostat is that the bubbles formed by the evaporation of liquid nitrogen in the feed tube slowly rise to the surface, producing vibrations which can affect the detector resolution because of microphonics. Only careful design of the detector holder can minimize this effect. Good Baseline Restoration can effectually eliminate this low frequency noise.

A further disadvantage of the chicken-feeder cryostat is that the feeding tube of the dewar has a tendency to be clogged by ice, which forms at the filling neck and falls to the bottom. This can be prevented by closing the filling hole with a pressure valve which maintains a slight pressure over the liquid and keeps water vapor out of the dewar.

Regardless of their deficiencies, chicken-feeder cryostats are very popular, largely because they are handy and can be adopted more easily to special experimental setups than the dipstick types. Figures 9a and 9b show the two basic types.

Section 6
THE OPERATING CHARACTERISTICS OF GE(LI) DETECTORS

In the following chapter those characteristics of Ge(Li) detectors will be discussed which are pertinent to the operation of the detectors as part of a high-resolution gamma-ray spectrometer.

6.1 ENERGY RESOLUTION

The excellent energy resolution attainable with Ge(Li) detectors over a wide energy range is the principal reason these detectors have almost entirely replaced the gaseous and scintillation detectors in nuclear structure work. Ge(Li) detectors have opened completely new possibilities in the application of radioisotopes in chemistry and life science. However, to obtain the best possible results it is necessary to understand the various factors which contribute to the energy resolution. Some of these factors are discussed in the following section.

6.1.1 STATISTICAL FLUCTUATIONS IN CHARGE PRODUCTION

Statistical fluctuation in the number of electron-hole pairs produced for a given energy deposition in the active (compensated) region of a Ge(Li) detector is the truly fundamental limitation of the energy resolution. The reason for this fluctuation is that only part of the energy lost by gamma-rays is expended for ionization; a portion is dissipated in heating the lattice structure of the crystal. While no fluctuation should be observed in the energy required for ionization, normal statistical fluctuations can be expected in that portion of the total energy lost in heating the lattice structure.

The ratio of the observed mean square fluctuation (n_o^{-2}) in the number of ionizations events to the number of ionization events (n) is usually referred to as the Fano factor (F):

$$F = \frac{\bar{n}_0^{\,2}}{n} = \frac{\bar{n}_0^{\,2} \cdot \epsilon}{E} \qquad (10)$$

where E = energy deposited in the compensated region of the detector
ϵ = average number of electron volts necessary to form an electron-hole pair in Ge

The energy resolution of a Ge(Li) detector system is commonly expressed as the full width at half maximum (FWHM) of a peak in an energy spectrum. For spectral peaks with a Gaussian shape ΔE FWHM corresponds to 2.355 times the root mean square of the energy spread. To convert the fluctuation in the number of electron-hole pairs to energy spread, Equation (10) must be solved for the rms variance n_o^{-2} and multiplied by ϵ:

$$\epsilon n_o = \epsilon\sqrt{F \cdot n} = \sqrt{\epsilon \cdot E \cdot F} \qquad (11)$$

or

$$\Delta E(\text{FWHM}) = 2.355 \cdot \sqrt{\epsilon \cdot E \cdot F} = 4.06 \times \sqrt{E \cdot F} \qquad (12)$$

The factor ϵ is approximately 2.98 eV/ion pair [21, 22, 23] for germanium at 77°K, and varies slightly with temperature. This value is about one order of magnitude smaller than that for gaseous counters and nearly two orders of magnitude smaller than that for scintillation detectors. This is one reason for the better energy resolution of Ge(Li) detectors. The small value of ionization energy also means correspondingly larger charge flow for a given energy loss in the Ge(Li) detector and thus reduced statistical fluctuation for each photon detected.

Experience indicates that it is very difficult to determine experimentally an accurate value for the

Fano factor (which actually is a measure of the ultimately obtainable resolution).

The above analysis is for the detector alone. Since detector and electronics contributions to the resolution are uncorrelated sources of statistical fluctuations, the effects must be added in quadrature:

$$(\Delta E)^2 \text{ total} = (\Delta E)^2 \text{ detector} + (\Delta E)^2 \text{ electronics} \qquad (13)$$

From equation (12) it is obvious that at low energies the statistical spread is small and at present is generally less than the spread contributed by the electronics noise. At higher energies, detectors frequently show insufficient charge collection due to trapping or recombination, particularly if poor quality material or wrong techniques have been used for the fabrication of the detector. This results in a greater noise contribution from the detector than is predicted by equation (12). Therefore, experimental values will always give only an upper limit for the Fano factor.

Recently, Fano factor values of below 0.15 [24] have been reported. This is not at all in agreement with values calculated using various theories [25], [26], and further work is required to explain this discrepancy.

6.1.2 CHARGE COLLECTION, TRAPPING AND RECOMBINATION

Poor charge collection, excessive trapping, and recombination result in resolution loss and peak asymmetry (low-energy tailing). There are several reasons for these defects; unfortunately, detector performance cannot reliably be predicted in terms of material parameters [27], [28]. In any event, the basic prerequisite for fast and efficient collection of the electron-hole pairs is an adequate field strength. This can be obtained only if a high voltage can be applied across the junction with resulting leakage currents of less than one nanoampere.

For planar detectors, a good electric field strength is 100 volts per millimeter of drifted depth. To obtain an equal field strength throughout the compensated region of coaxially drifted detectors, much higher operating voltages are necessary. Only properly prepared surfaces and well compensated germanium allow such voltages without excessive leakage currents.

A very high bias voltage cannot guarantee complete charge collection. A large number of trapping centers within the compensated region due to poor material or poor compensation may exist, leading to poor charge collection and correspondingly poor resolution. Incomplete charge collection has a severe effect at higher energies; this defect may be uncovered in comparing the resolution of detector systems by examining the full width at 1/10 peak maximum (FW0.1M), as well as the FWHM figure.

6.1.3 DETECTOR NOISE

The Ge(Li) detector is a generator of several types of noise. The most important are shot noise, detector series resistance noise, and surface leakage current noise.

Shot noise arises due to thermal generation of electron-hole pairs in the compensated region. This is one reason for operating the detector at very low temperatures, which is only possible if the cryostat is designed for maximum heat conductivity and minimum heat loss due to radiation. Shot noise is usually of relatively high frequency.

Bad ohmic contacts of the p- and n-layer of the detector or high sheet resistivity can sometimes cause excessive noise, but proper handling and fabrication of Ge(Li) detectors should be effective in eliminating most of this noise.

6.1.4 DETECTOR CAPACITANCE

As mentioned earlier, a Ge(Li) detector can be considered a capacitor whose capacitance can easily be

calculated for simple detector geometries. However, this is true only if sufficient reverse bias voltage is applied. At zero or very low bias the capacitance is usually higher than the calculated value; this is particularly true for poorly compensated detectors or for detectors which have not undergone a clean-up drift.

Properly fabricated and treated Ge(Li) detectors have a fairly flat capacitance/voltage curve and approach their final (lowest) capacitance value after application of only about 30% of the normal operating voltage (Figure 10). If a charge sensitive preamplifier is used in connection with a Ge(Li) detector, the capacitance of the detector system has a great influence on the preamplifier resolution and thus the energy resolution of a Ge(Li) spectrometer system. Preamplifier input capacitance (including detector capacitance) acts as a feedback attenuator for output noise voltage, thus effectively increasing the closed loop gain for such signals. If high energy resolution is the goal, detectors with low capacitance should be selected.

Large volume detectors generally have higher capacitances. Such detectors demand preamplifiers with both low zero capacitance noise and low noise/capacitance slope. Charge sensitive room-temperature preamplifiers with zero input capacitance noise contribution of 0.8 Kev FWHM and a noise slope of 0.024KeV/pf are now commercially available.

6.2 DETECTOR EFFICIENCY

The response function or detection efficiency of a Ge(Li) detector for gamma-rays over a wide energy range is certainly next after energy resolution as the most important specification. But while there seems to be no doubt about the definition of the energy resolution in terms of full width at half maximum (FWHM) and full width at 1/10 maximum (FW0.1M), confusion exists about the proper definition of the efficiency of Ge(Li) detectors.

There are four basic types of efficiencies or response functions, each of which is a complicated function of the gamma-ray energy, the dimension of the detector, and the geometry of the experimental set up:

a) the total detection efficiency
b) the full-energy peak efficiency
c) the double-escape peak efficiency
d) the single-escape peak efficiency

All four efficiencies can be quoted as intrinsic, absolute or relative. The peak-to-total ratio further contributes to the confusion. Thus, care must be taken when comparing the efficiencies of various Ge(Li) detectors as specified by different manufacturers, although knowledge of the response function of a Ge(Li) detector is far more important for calibration for intensity measurements than for the comparison of Ge(Li) detectors.

6.2.1 TOTAL DETECTION EFFICIENCY

The *total* detection efficiency of a Ge(Li) detector is not particularly interesting for the researcher who uses it as a gamma-ray spectrometer. However, comparison of the calculated total efficiencies with those obtained by experiment can give information about the actual active volume of the detector which is not easily obtainable otherwise.

The *intrinsic* total detection efficiency is defined as the probability that a gamma-ray of a given energy which impinges on the detector is recorded. The calculation of this response function is relatively simple and accurate provided the total absorption coefficient for germanium in the given energy range is known [31].

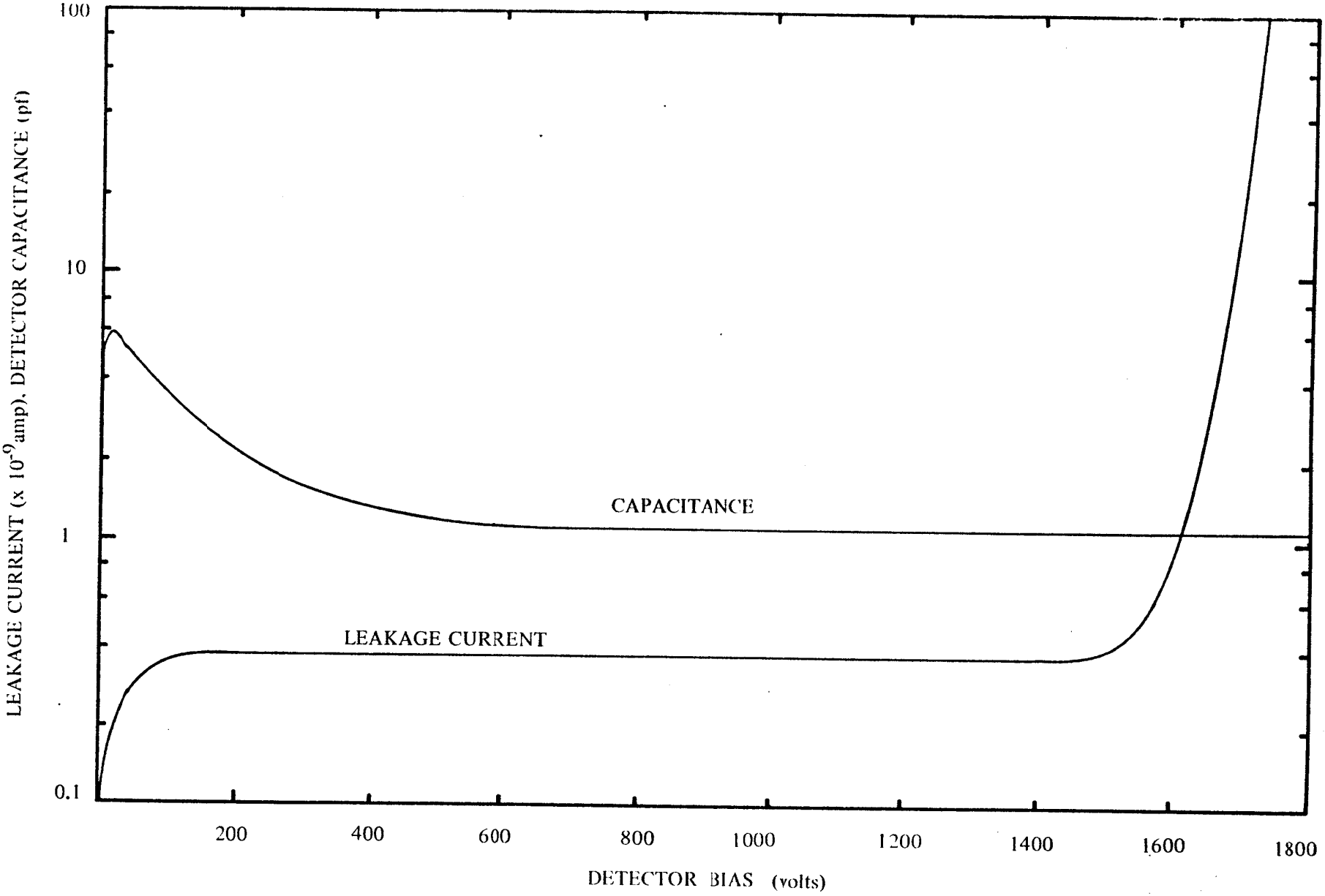


Figure 10. A typical I/V and C/V characteristic of Ge(Li) detectors

To obtain the intrinsic total detection efficiency of a specific detector, experimentally the number of gamma-rays impinging on the detector must be known, i.e., a parallel gamma-ray beam of known strength must be available and the active area perpendicular to this beam must be known. Both conditions are frequently not satisfied.

The *absolute* total detection efficiency is defined as the probablilty that a gamma-ray emitted from a specific source will be recorded in the detector. This response function is different for each detector and detector-source arrangement. The calculation of these response functions is more difficult than those for the intrinsic ones because of considerations of the solid angle subtended by the detector [29, 30]. For odd-shaped detectors, for example, those having trapezoidal five-sided geometries, the results will certainly be not very accurate. The experimental determination is easier; only gamma-ray sources of known strength and reproducible detector geometries are necessary.

6.2.2 FULL-ENERGY-PEAK EFFICIENCY

Ge(Li) detectors are mainly used as gamma-ray spectrometers for the medium energy region (40 KeV to 2MeV) where the photoelectric cross section is high in comparison to the cross section for pair production. Knowledge of the full-energy-peak efficiencies over this energy range must be known before information about the intensities of gamma-transitions can be obtained. Most of the work on response functions of Ge(Li) detectors has been done for the full-energy-peak efficiency, which is defined as the probability that a gamma-ray of a given energy will be recorded in the full-energy peak of the spectrum.

Contribution to this peak can come not only from photoelectric absorption but also from Compton scattering followed by photoelectric absorption of the scattered final gamma-ray and also, for energies above 1.1 MeV, from pair production plus total absorption of the annihilation radiation. Therefore, it is more accurate to call the peak in a spectrum the full-energy peak and not the photopeak.

Because of the multiple contributions to the full-energy peak, the Monte Carlo method is particularly well suited for the calculation of these response functions. Calculations of the intrinsic full-energy peak efficiency, which is defined as the probability that a gamma-ray striking the detector is recorded in the peak of the spectrum, have been carried out for various circular planar detectors[31, 32]. Determination of the intrinsic full-energy-peak efficiency by experiment is made difficult because parallel gamma-ray beams of known strength are necessary and the active area of the detector perpendicular to this beam must be known.

Monte Carlo calculations of the absolute full-energy-peak efficiency, which is defined as the probability that a gamma-ray emitted from a gamma-ray source of known activity is counted in the full-energy peak, have been done for circular and square planar detectors and for various detector-source geometries [31, 32]. For experimental determination, sources of accurately known activity and of regular shape (point sources are preferred) must be available. The source-detector arrangement must be kept unchanged for all runs.

In most nuclear structure work the relative rather than the absolute efficiency is required: that is, the full-energy peak efficiency of a gamma-ray of a given energy in comparison to a gamma-ray of another energy. These response functions can easily be determined empirically to an accuracy which depends only upon the reproducibility of the detector-source arrangement and the accuracy with which the relative intensities of the two or more gamma-ray transitions of the calibration sources have been determined [33, 34, 35]. Sources frequently used are tabulated below.

ISOTOPE	E_γ (KeV)	RELATIVE INTENSITY	REFERENCE
Ba^{133}	81	0.52	34
	356	1.00	
Hf^{180m}	93	0.20	34
	215	0.88 1.00	34 35
	332	1.15 1.16	34 35
	448	1.00 1.02	34 35
Na^{22}	511	1.00	34
	1274	0.55	
Tl^{208}	583	1.00	35
	2614	1.17	
Sc^{46}	889	1.00	34
	1120	1.00	
Y^{88}	898	0.94	34
	1836	1.00	
Co^{60}	1173	1.00	34
	1332	1.00	
Na^{24}	1368	1.00	34
	2753	1.00	
$N^{14}(n,\gamma)N^{15}$	1680	0.30	40
	1885	0.64	
	1997	0.15	
	2521	0.20	
	3532	0.32	
	3678	0.52	
	4509	0.54	
	5270	1.00	
	5298	0.70	
	5534	0.61	
	5562	0.33	
	6323	0.61	
	7299	0.33	
	8311	0.14	
	10830	0.43	

Table 1. Nuclides Used for the Empirical Determination of Relative Full-Energy Peak Efficiency Curves.

Naturally, if accurate intensity measurements are made available for long-lived nuclides with gamma-transitions that cover a very wide energy range, such as Ta^{182} only one or two sources need be measured to obtain a complete curve.

Sources of the four naturally radioactive decay chains with all their daughters in equilibrium appear to be ideal for this kind of determination but the accuracy and reproducibility is not very good since the

noble gas daughters might leave the system partially by diffusion and disturb the equilibrium.

The relative full-energy-peak response functions for three different detectors are shown in Figure 11. Since the same sources and source-detector arrangements were used in all three measurements, the three curves can be compared directly. It is obvious that the smaller detector has not only a much smaller efficiency overall but also that the efficiency for increasing gamma-energies decreases more rapidly than those of the large volume detectors.

The full-energy-peak efficiency relative to a 3" x 3" NaI(Tl) scintillation detector for 25cm source-to-detector distance is presently used for the comparison of commercial Ge(Li) detectors of various shapes. This specification is certainly much more reliable and useful than comparison by active volume. Not only is the true active volume difficult to determine but detectors of equal active volume can have very different full-energy peak efficiencies depending upon the shape and drift depth.

Care must be observed when comparing the number of counts in a given full-energy peak. The peaks are frequently not symmetric and the background due to Compton scattering events of gamma-rays with higher energies is not necessarily well defined. Thus best accuracy will result if one consistently uses the same method of comparison for all peaks.

6.2.3 DOUBLE AND SINGLE-ESCAPE PEAK EFFICIENCY

For gamma-rays with energies above 1.5 MeV the cross section for pair production becomes prominent and the cross section for the photoelectric effect decreases rapidly. Therefore, escape peaks, particularly double-escape peaks, become more important for isotope identification.

Basically the same considerations are valid for the escape-peak response functions as for those for the full-energy peaks. Calculations have been carried out [31, 32, 36] and some experimental data are available [10, 36, 40]. Since gamma-ray sources with energies above 2 MeV and practical half lives are rare, the (n, γ) reaction is used. This makes a reactor or accelerator a prerequisite.

Summarizing the results, it appears that the response function for the double escape peak reaches a maximum at approximately 4.5 MeV. Even though calculations [31, 36] show flat response functions for energies above 5 MeV, particularly for deeply drifted detectors, the empirical data clearly indicate a rapid decrease of the double-escape-peak efficiency with energy [10, 36].

6.3 TIMING CHARACTERISTICS

Although a great many publications deal with the energy resolution and detection efficiency of Ge(Li)-detectors, information on the timing characteristics of these detectors is still scarce.

H. G. STRAUSS *et al* [49] studied the pulse shape distribution of planar detectors as a function of the field intensity, gamma-ray energy, and drift depth. J. D. BALLAND *et al* [50] compared the timing resolution of one detector with that calculated by the Monte Carlo method. H. L. MALM [39] examined the time resolution of Ge(Li) detectors of various configurations, among them five-sided and double open-ended drifted detectors.

Their results, obtained in 1966, are not applicable to the large-volume detectors fabricated at the present time which offer lower capacitance, more uniform drift depth, and higher permissible field strength.

With sufficient information to detail the contribution of each, it can be stated that the timing distribution depends on the following factors:

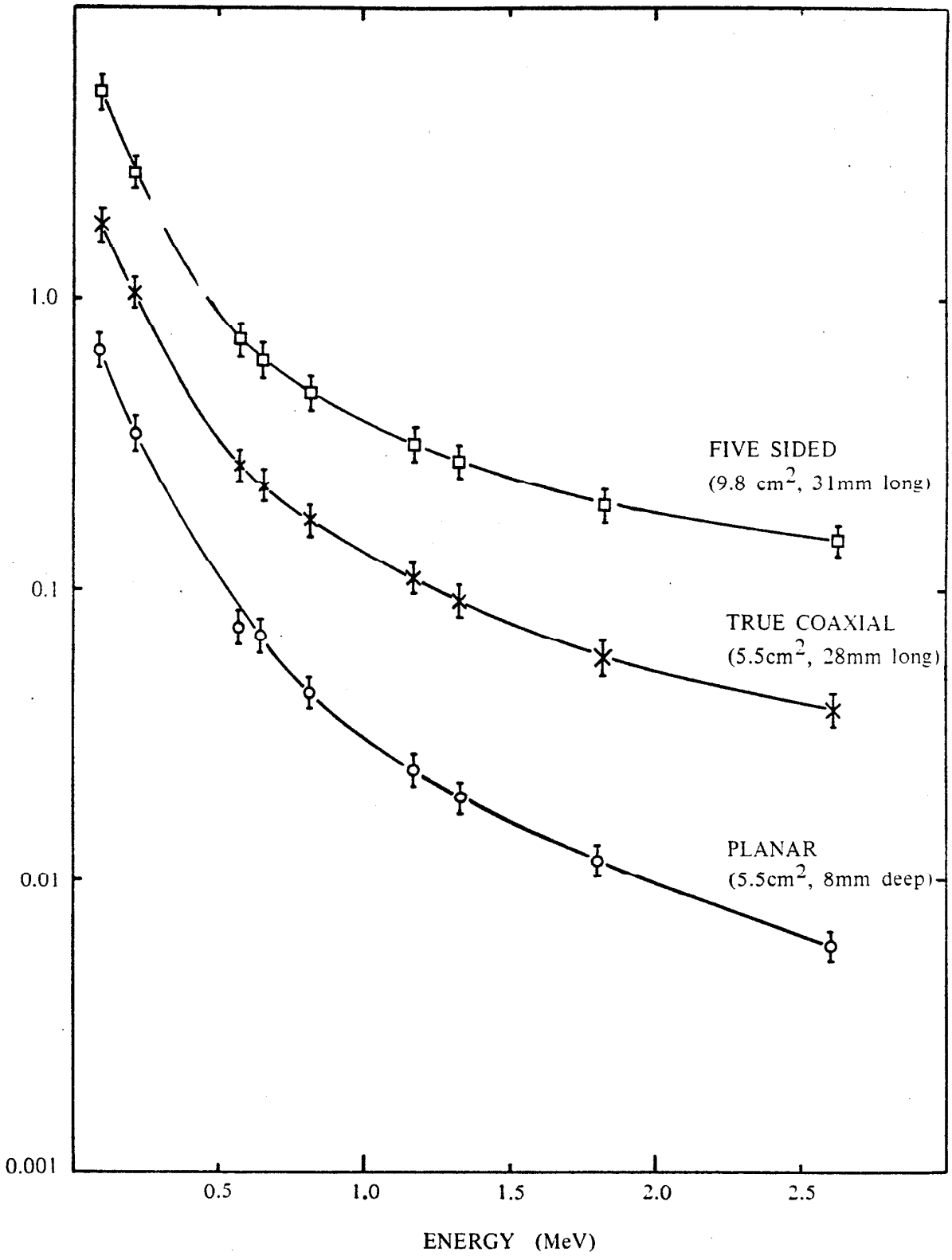


Figure 11. The relative full energy peak efficiency of three different Ge(Li) detectors.

a) drift depth

b) field strength distribution over the entire compensated region
c) detector capacitance
d) energy of the gamma-ray

The best timing performance can certainly be expected from small planar detectors operated at high bias voltages. The true coaxial detector is probably superior to a five-sided trapezoidal detector, but by what factor is questionable. It can be said, however, that Ge(Li) detectors of all configurations have been used successfully in many coincidence experiments.

Section 7
ELECTRONICS IN A GE(LI) SPECTROMETER SYSTEM

Presently, Ge(Li)detectors are almost exclusively used for gamma- or X-ray spectroscopy. Since these detectors with their necessary cryostats are only one part of a gamma-ray spectrometer system, it seems to be appropriate to discuss the performance and operation of the electronics system that is required for a complete Ge(Li) spectrometer.

In Figure 12 the block diagram of a Ge(Li) detector spectrometer is shown with the necessary and optional instruments. The right combination is frequently determined by the experiment and the available funds.

A high-performance Ge(Li) detector spectrometer is like a fine orchestra. It can show its best performance only if every instrument is of high quality and accurately tuned. The experimenter is like the conductor under whose proper guidance the best results can be obtained. The weakest member of the "orchestra" will determine the ultimate performance.

7.1 HIGH VOLTAGE POWER SUPPLY

As discussed earlier, every Ge(Li) detector requires high voltage for its operation. At present this operating bias will rarely exceed 3000 volts but, depending on the type of detector and its mounting, either positive or negative polarity may be required. The modern FET preamplifier is well protected against sudden voltage changes, so the voltage does not have to be continuously variable from zero to its maximum value.

Good voltage regulation is not essential for Ge(Li) detectors. Small voltage changes do not affect the amplitude of the output pulses to a large degree, as is the case with a scintillation detector. However, particular attention must be paid to the noise characteristics of the high-voltage source. The following factors have to be taken into account in selecting a high voltage power supply:

- very low noise level
- voltage adjustable to approximately 3000 volts
- both positive or negative polarity available
- maximum current requirements 1ma
- fairly good voltage regulation

A power supply that fulfills these requirements and is also inexpensive can be made using five to six photoflash batteries (Burgess Model U320 or Eveready Model 479). Each battery has taps at 200 and 500 volts. A stack of six batteries therefore allows 27 different values between 200 and 3000 volts in steps of 100 volts. Because of the extremely low current demand of the detector, the lifetime of these batteries is up to two years.

Since it is not necessary to change the optimum bias on the detector once it is established and since it is advantageous to keep bias on the detector all the time, the high-voltage battery pack can be wired for optimum detector bias voltage and rarely disconnected.

7.2 PREAMPLIFIER

The charge-sensitive preamplifier commonly used converts the charge (Q) created by the incident radiation in the detector to a voltage pulse according to the relationship:

$$E = \frac{Q}{C_f} \qquad (14)$$

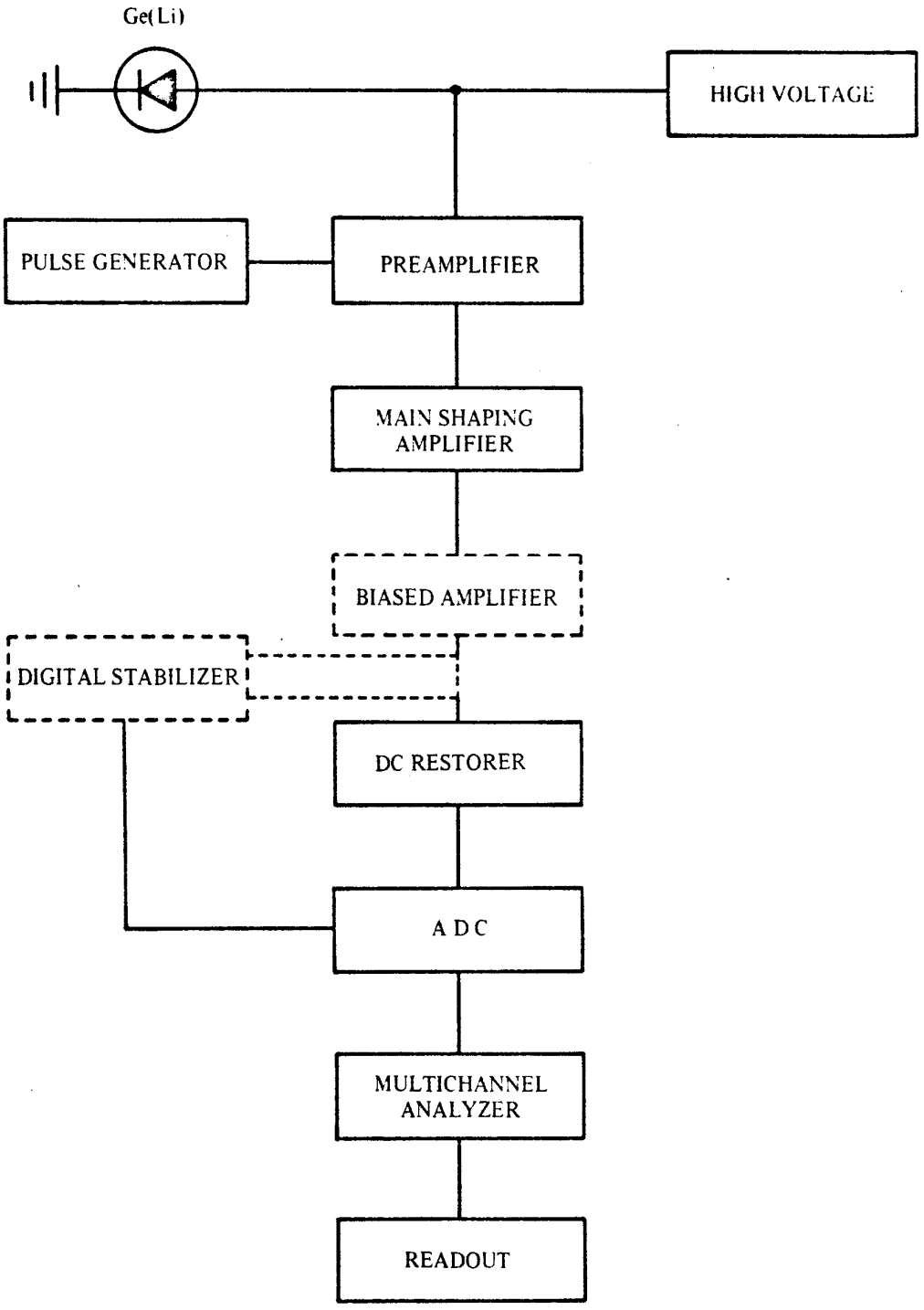


Figure 12. The electronic block diagram of a typical Ge(Li) Gamma Ray Spectrometer.

where E = output voltage
C_f = feedback capacitor

For example, with a feedback capacitor of 1 pf, a 122 keV gamma ray will produce a voltage pulse on the preamplifier output determined as follows:

$$\text{Number of Hole-Electron Pairs (n)} = \frac{122 \text{ keV}}{2.98 \text{ ev/pair}} = 4.1 \times 10^4$$

$$Q = ne = 4.1 \times 10^4 \ (1.6 \times 10^{-19}) = 6.5 \times 10^{-15} \text{ (coulombs)}$$

$$E = \frac{Q}{C_f} = \frac{6.5 \times 10^{-15}}{1 \times 10^{-12}} = 6.5 \times 10^{-3} \text{ (volts)}$$

The preamplifier, such as Canberra Industries' Model 1408C, consists of an operational amplifier with capacitive feedback and voltage amplifier-shaper. The operational amplifier makes use of the low noise and high input impedance of FET's in the input stage, which can be either AC or DC coupled to the detector (Figure 13).

The advantage of DC coupling is the elimination of the relatively large coupling capacitor C_c which tends to be a source of noise due to microphonics and leakage currents. In order to DC couple, however, the detector must be isolated from ground. This can be achieved by placing a small disc of a ceramic material such as sapphire, boron nitride, or beryllium oxide between the detector and the cold finger. The material must be a good electrical insulator with high thermal conductivity at low temperatures.

In general DC coupling is only advantageous for low-capacitance detectors; for large volume detectors AC coupling gives about the same results. Virtually all commercial detectors are AC coupled.

The transductance of FET's, unlike most other electronic amplifiers, can show an increase with decreasing temperatures. Since virtually all the sources of noise in the device increase with temperature, it follows that an improvement in resolution can result if the FET input stage of the preamplifier is cooled.

Several attempts have been made to locate the FET inside the vacuum chamber either on or near the cold finger itself. In addition to improvements in the device characteristics this technique offers other advantages as well. The parasitic capacitance of the preamplifier input can be minimized, and microphonics due to long flexible leads and movements of the crystal a top the cold finger with respect to the preamplifier are eliminated, reducing both high and low frequency noise. The optimum temperature of FET's may vary over a wide range. Thus some means of temperature control may be required if the detector vacuum chamber is to be used as the cooling vessel.

The difficulty of maintenance of the electronics and the rapid advances in preamplifier performance primarily through device improvements have made commercial detector manufacturers reluctant to offer integrated detector-cryostat-preamplifier assemblies. In light of the large cost of the detector and its susceptibility to damage this reluctance is fully justified, particularly considering that conventional preamplifiers offer noise contributions at room temperature of as low as 0.8 keV plus 0.024 keV/pf detector capacitance.

The feedback loop of the preamplifier determines not only the amplitude of the voltage pulse but also its fall time. To obtain high conversion gain, the feedback capacitor must be kept small, 1 pf is typical. Since resistors with low values are significant noise sources, special high-ohm resistors must be used. The combination of small feedback capacitance and large feedback resistance yields a fall time constant of approximately 1 millisec from the charge-sensitive stage. The rise time of the voltage pulse

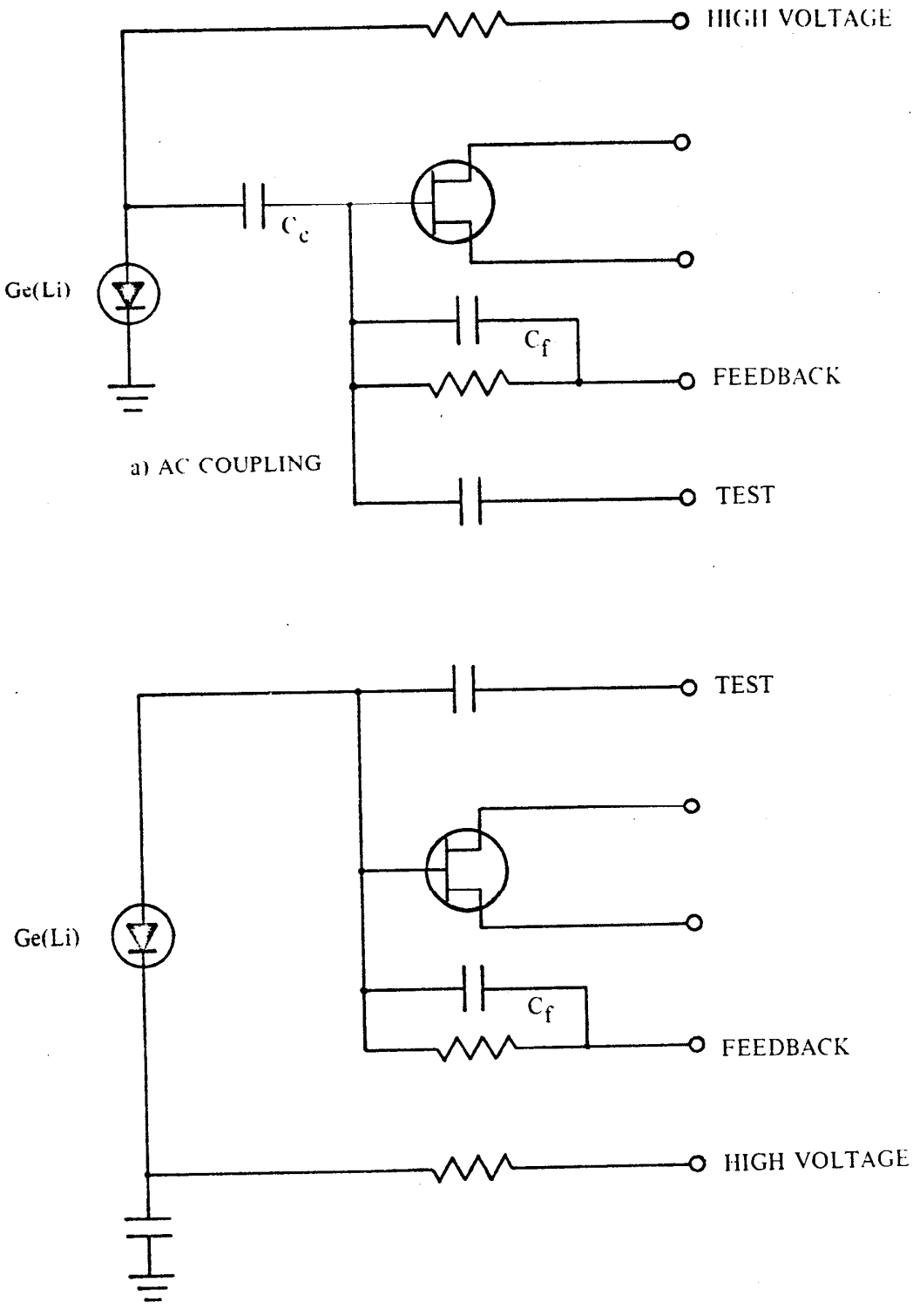


Figure 13. The two modes by which the input stage of a low-noise FET preamplifier can be coupled to the Ge(Li) detector.

depends on the charge collection in the detector, the detector capacitance, and the design of the input stage. In general, this time is approximately 30 nanoseconds.

The following voltage amplifier frequently has a variable gain. The pulse is differentiated between stages to result in a fall time constant of 50 microseconds. The second stage has pole-zero cancellation to compensate for the fall time of the first stage. The output is designed to drive long lengths of cable under conditions of matched impedance (typically 93 ohms).

7.3 MAIN SHAPING AMPLIFIER

The next link in the chain between the detector and the final readout is the main shaping amplifier. Its main functions are:

- to provide adjustable voltage gain
- to shape the pulses so that each is discrete and so that there is less tendency to pile up
- to insure that important timing and amplitude information is retained

7.3.1 AMPLIFIER SHAPING

Amplifier shaping is important because the preamplifier output not only consists of pulses which are proportional to the energy deposited in the detector by the incident radiation but also of pulses due to or affected by noise contributed by the detector and preamplifier. This noise covers a wide frequency range and can result in a very poor signal-to-noise ratio.

Specially designed pulse shaping networks, typically consisting of differentiators and integrators, can reduce this noise. Unfortunately, rise time variations of the preamplifier output, caused by variations of charge collection times in the detector, result in peak height fluctuations when treated by the various shaping networks. Therefore, a network which shows an excellent S/N ratio may be very sensitive to rise time variations.

Although other pulse shapes are theoretically capable of giving better signal-to-noise ratios, the accepted standard today in commercial spectroscopy amplifiers is Gaussian shaping. This shaping is obtained by a combination of passive RC differentiation and active RC integration techniques.

7.3.2 POLE/ZERO CANCELLATION

Because the preamplifier output pulse is not a step function but has a discrete fall time constant (typically 50 microseconds), a conventional RC differentiating circuit produces an undershoot following the pulse having a time constant equal to that of the preamplifier. The amplitude of the undershoot is approximately equal to that of the primary pulse times the ratio of the amplifier differentiating time constant to the preamplifier fall time constant:

$$A_u = A\,(t_a/t_p) \qquad (15)$$

where A_u = amplitude of the undershoot
A = amplitude of the primary pulse
t_a = amplifier differentiating time constant
t_p = preamplifier fall time constant

This undershoot causes two aggravating effects. If the count rate is sufficiently high, an appreciable number of pulses will fall into the trough caused by preceding pulses, decreasing their apparent pulse height and causing a broadening of the spectrum on the low-energy side.

Second, under overload conditions, although the primary lobe recovers with the amplifier time constant, the undershoot, if it saturates the amplifier, recovers at the much slower rate of the preamplifier fall time constant.

Pole/zero cancellation compensates for this effect, by artificially adding a laplace "zero" to cancel the laplace "pole" due to the preamplifier fall time constant, removing the undershoot caused by the preamplifier. The compensating circuit should be variable, to permit adjustment for a wide range of preamplifier fall time constants.Practically, this means the addition of a resistor across the differentiating capacitor.

Pole/zero cancellation, for all its virtues, has the disagreeable result of greatly increasing a main amplifier's response to low frequency hum, ripple and noise. An artificial second differentiation of long time constant (10 to 25 microseconds) can eliminate this effect, at the cost of introducing an undershoot which may lead to spectral line broadening.

In well-designed amplifiers this second differentiation can be switched in or out, leaving the user a choice between good high count rate performance at the expense of enhanced low-frequency noise response, or poor high-count rate performance with elimination of hum and ripple.

7.3.3 VARIABLE TIME CONSTANTS

Variable time constants for the pulse shaping network are desirable so that pulse widths can be changed to suit the count rate and to match the requirements of the pulse height analyzer that follows the amplifier.

The time constants of the differentiation and the integration need not necessarily be independently variable; unequal time constants usually result in poorer resolution. An improvement in resolution with unequal time constants can be expected only if the rise times of the detector pulses vary widely.

7.3.4 VARIABLE GAIN

One of the main functions of an amplifier is to provide voltage gain, in order to bring the pulse amplitudes into a range suitable for analysis. In general, the gain of main amplifiers is adjustable from 10 to 1000 and higher by means of both step and vernier controls. As performance can vary depending on the gain settings, consideration should be given to the gain of the main amplifier with respect to that of the preamplifier.

7.3.5 COMMON MODE NOISE REJECTION

A feature frequently found in good amplifiers is a differential input for common mode noise rejection. This input is useful if the amplifier is located far (50 feet or more) from its associated preamplifier, especially in environments high in low-frequency interference.

A terminated cable lying beside the preamplifier-to-amplifier cable will pick up the same noise as the cable which carries the true signal. If the output from the bogus cable is inverted and summed with the output from the true cable, the signals common to both will cancel, while the signals appearing on only one will be unaffected.

Using this technique, noise and pick-up may be reduced by more than 250:1.

7.4 DC RESTORER

Another important source of poor resolution at high count rates is the fluctuation of the baseline caused by random pulse bursts charging and discharging coupling capacitors in the system.

DC restoration clamps the baseline to the quiescent level whenever a true pulse is not detected.

Either active or passive DC restoration may be used. In the passive mode the DC restoration rate is limited by the AC impedance of restorer diodes [51] and it suffers from count rate limitations because of the slow recovery time.

In the active mode, [52] the restorer diodes are coupled to a feedback amplifier, lowering the effective AC impedance to a very low value for more precise and faster clamping of the baseline. The disadvantage of the active mode is increased noise on the output signal. The count rate at which active restoration begins to give better resolution that passive restoration for typical Ge(Li) systems is subject to many variables but is in the order of 15,000 cps.

A normal problem with DC restorers is the additional width introduced to spectral lines due to the addition of the partially correlated baseline noise to the peak height. As a consequence, resolution might be lost at low rates when compared to the system without the restorer. An additional stage of selectable integration at the output stage virtually eliminates this problem by attenuating the high frequency noise while maintaining true pulse amplitude.

Besides improving high count rate performance, the DC restorer also eliminates low frequency noise caused by oscillations, microphonics, and pick-up which are not effectively filtered in pole-zero cancelled amplifier systems.

A DC restorer should generally be connected as the last element in the system before pulse height analysis. If a linear gate or biased amplifier is used in the system it must be DC or DC restorer coupled. If DC coupled, the DC restorer should precede these modules. If DC restorer coupled, the DC restorer may be used after the gate or biased amplifier.

In the near future the DC restorer will probably be an integrated part of each high performance amplifier, thus eliminating the need for a separate instrument.

7.5 BIASED AMPLIFIER

A biased amplifier expands a region of interest in a spectrum to provide fuller utilization of the capabilities of a small multichannel pulse-height analyzer in high-resolution spectroscopy. The bias level determines the energy level of the linear input signal above which post amplification will occur.

The biased amplifier is a very useful instrument if a multichannel analyzer with only a small number of channels is available for use with a high resolution Ge(Li) detector. It should be kept in mind that a biased amplifier cannot replace a large multichannel analyzer, as a biased amplifier does not expand memory size.

Particular attention must be paid to the gain and bias level stability, because they ultimately determine the performance of the instrument. Antman *et al* [23] gave a relationship between the degradation of the resolution and these instabilities:

$$V/n\ \Delta C = KE_t\ T_{max} + KE_k\ T(1 - T_{min}/T) \qquad (16)$$

where V/n = voltage required for the saturation of an analyzer with n channels
ΔC = variation of the resolution expressed in number of channels
K = threshold gain
E_t = fractional bias level instability
E_k = fractional gain instability
T_{min} = minimum pulse amplitude
T_{max} = maximum pulse amplitude
T = any pulse amplitude between T_{min} and T_{max}

The instabilities E_t and E_k must be in the order of 10^{-4} if a resolution deterioration of less than 15% is to be reached. An improvement can be obtained if the bias level is stabilzed by a digital stabilizer in connection with a stable reference pulser.

7.6 MULTICHANNEL PULSE HEIGHT ANALYZER

The typical output device for Ge(Li) spectroscopy systems is a multichannel pulse height analyzer (MCA). The characteristics of the MCA in which we are primarily interested relate to the analog-to-digital converter (ADC), which is an integral part of the instrument. In some systems the ADC may be directly interfaced to a computer without the traditional memory and display of the MCA.

The Ge(Li) spectroscopist should recognize the importance of at least a few essential design aspects of the ADC. Among them are:

- input coupling (AC vs. DC)
- ADC resolution (number of channels)
- conversion time (ADC clock rate)
- linearity

7.6.1 ADC INPUT COUPLING

Many ADC's are AC coupled while others have additional inputs that are DC coupled. Some have AC coupled inputs that employ some means of DC restoration. At medium to high count rates it is unlikely that AC coupled ADC's, even those having DC restoration, will give results as good as are obtainable by using a DC restorer in the system between the amplifier and the ADC. The main reason for this is that MCA manufacturerss have not provided DC restorers that are as sophisticated and effective as modular units that are now commercially available.

In order to connect an external DC restorer, the ADC input must be DC coupled. To simplify this operation, DC restorer outputs have adjustable amplitude ranges and output offset to match the requirements of the modified ADC.

7.6.2 RESOLUTION

The number of channels of an MCA determines the best energy resolution obtainable by the instrument. If, for example, one wished to observe the 1.33 meV peak in the Co^{60} spectrum on a 100 channel analyzer he would find that the ADC resolution is 13.3 KeV/channel, which means that all the pulses produced by 1.33 MeV gamma-rays would store in one channel even with a relatively poor Ge(Li) detector.

The peak of interest must have a FWHM of at least 5 channels, otherwise the resolution measurement is questionable on a statistical basis alone. For good Ge(Li) spectroscopy systems, an ADC capacity of at least 4096 channels is recommended. The memory capacity may be significantly less, however, as the entire spectrum may not be checked all at once.

An ADC of less resolution (fewer channels) can be effectively augmented by a biased amplifier to increase its usefulness.

7.6.3 CONVERSION TIME

The conversion time of the MCA basically depends on the total time required to sense the peak of the input pulse and on the ADC clock rate.

Virtually all MCA's employ a ramp type Wilkinson ADC in which the clock rate divided into the number of channels gives the conversion time. The fastest ADC's have clock rates ranging up to 100 MHz which, for 4096 channels, gives a deadtime of about 40 microseconds. Thus, the MCA deadtime is significantly longer than the pulse-pair performance of most spectroscopy amplifiers.

If the MCA had only 400 channels, at the same clock rate the deadtime would be only 4 microseconds. A pulse which stores in a low channel, however, may have as much deadtime associated with it as one which stores in the highest channel, depending on the MCA being used.

7.6.4 LINEARITY

Both integral and differential non-linearities are specified by MCA manufacturers. Since the user assumes essentially perfect linearity in identifying peaks in a complex spectrum, it is important that the linearity be good. It seems to be normal among manufacturers to call the parameter linearity and give the specification for non-linearity; e.g., linearity - 2% integral.

The specifications for ADC's normally used in Ge(Li) detector systems, i.e., those having 1024 to 4096 channels, range from 0.1% to 0.5% integral nonlinearity and from 1% to 2% differential non-linearity. Sometimes the range over which these specifications apply is restricted to exclude the lower 2% to 5% of the channels indicating that linearity in this region may not be good. If a peculiar result is obtained, particularly at the lower end of the spectrum, the ADC should be checked with a sliding pulser to determine its contribution.

Section 8
THE COMPTON SUPPRESSION SPECTROMETER

The relatively poor ratio of complete conversions to the total number of events, even for deeply drifted, large-volume detectors, results in a large background continuum for high energy gamma rays. This background will obscure weak, low-energy gamma rays in the presence of intense high energy gamma rays, severely limiting the usefulness of the Ge(Li) detector.

A small fraction of this continuum is caused by pulses with a slow rise time component [49, 50]. This fraction of the low-energy background can successfully be eliminated by pulse shape discrimination [43, 53]. However, the large contribution of Compton interactions to the background can only be suppressed by multiple detector arrangements.

Various instruments have been designed to suppress this background which results from Compton interaction in the detector itself and in the surrounding material. Two types of these devices are frequently used and will be discussed separately: the Ge(Li) Scintillator Compton suppression spectrometer and the all-Ge(Li) Compton spectrometer.

8.1 THE GE(LI)-SCINTILLATOR COMPTON SUPPRESSION SPECTROMETER

The Ge(Li)-Scintillator Compton suppression spectrometer consists of a Ge(Li) detector which is virtually surrounded by a scintillator. Gamma rays which interact by Compton scattering and leave the detector before total absorption are detected in the scintillator. Events which occur simultaneously in the Ge(Li) detector and the scintillator are rejected by anticoincidence electronics The result is an effective suppression of the background continuum caused by Compton scattering. It is obvious that the effectiveness of this suppression depends very much on the capability of the scintillator to detect all gamma rays which are scattered from the Ge(Li) detector.

In order to achieve good suppression factors various designs have been developed. All of these systems feature the possibility of positioning the source inside the system close to the Ge(Li) detector or outside the anti-Compton shield frequently making use of a lead collimator. The latter arrangement decreases the efficiency of the system considerably and is advantageous only if strong sources are available. If the source is located inside the shield close to the Ge(Li) detector, almost complete utilization of the total efficiency of the Ge(Li) detector results. However, gamma ray cascades will be detected with drastically decreased efficiency, since the probability is small that all gamma rays of the cascade are detected in the Ge(Li) detector. The majority of these gamma rays will be detected in both the Ge(Li) detector and the scintillator and therefore will be rejected. In order to retain all available information it is possible to record both the anticoincidence spectra and the normal spectra simultaneously in separate parts of the multichannel analyzer memory [54].

8.1.1 SODIUM IODIDE SCINTILLATOR

The most frequently used anti-Compton shield is a NaI(Tl) annulus measuring up to 12" in diameter and length. The Ge(Li) detector is located in the center of the annulus; a lead collimator closes one end. Systems of this kind are described in the literature [41, 43, 56, 57, 58, 59, 60].

KANTELE AND SUOMINEN [61] replaced the lead collimator by a small NaI annulus to suppress the backscattered gamma-rays. The same results can be achieved if a well- type crystal is used and the source is positioned inside the shield [61]. The gamma-rays scattered in the direction of the Ge(Li) detector entrance are not detected in these devices, which limits the Compton suppression factor.

8.1.2 PLASTIC SCINTILLATOR

Although plastic scintillators have both a lower atomic number and a lower density than NaI, and thus have a very low photoelectric cross-section and a low absorption coefficient for gamma rays, they have been used very successfully as anti- Compton shields[54,62,63].

The small fraction of photoelectric interactions is of little disadvantage in the application of plastic scintillation as anti-Compton shields, since the output pulses are used for timing purposes only. The much larger size of the plastic anti-Compton shield in comparson to an equally effective NaI crystal is more than compensated for by: (1) the much lower cost of these materials, (2) the fact that plastic can be molded and machined into almost any desired shape, (3) their stability against humidity and laboratory environments which makes encapsulation unnecessary, and (4) their insensitivity to thermal shock.

The ease of machining makes it possible to arrange the position of the Ge(Li) detector/cryostat and the sample insert tube in a way such that all scattering angles are equally well detected in the anti–Compton shield, especially if the source is located close to the Ge(Li) detector. Since the plastic scintillator need not be encapsulated, the material between the Ge(Li) detector and the scintillator can be held to a minimum. This contributes to a better Compton suppression factor.

Also, the possiblity of a vacuum failure in the cryostat cannot be entirely disregarded. The result of such an accident could be a sudden decrease in temperature of the aluminum endcap surrounding the Ge(Li) detector. If this endcap is in direct contact with a NaI crystal a fracture is almost inevitable, whereas a plastic scintillator can withstand this thermal shock.

The best Compton suppression system reported in the literature [54, 55] makes use of a plastic anti-Compton mantle. This system shows a reduction of the Compton background by a factor of 10 for 662 keV gamma rays.

Successful Compton suppression in an anti-Compton spectrometer depends not only on the detector/shield arrangement but also on the electronics. It must keep in mind that the output pulses of the scintillators are much faster than those of the Ge(Li) detector. Furthermore, variations in the charge collection time in the Ge(Li) detector result in timing errors. It is preferable to use good leading edge timing rather than crossover timing in the Ge(Li) detector circuit. A pulse shape discriminator which rejects pulses with very slow rise times brings further improvement.

8.1.3 ANTI-COMPTON SYSTEM PERFORMANCE

The authors built and tested an anti-Compton system using an 8" x 12" NaI(Tl) crystal and a Ge(Li) detector with 5 sided video coaxial geometry having a peak-to-Compton ratio of 15:1. With an electronics setup similar to that shown in Figure 14 an improvement of 5:1 was obtained. The spectra of Co^{60} with and without anti-Compton rejection is shown in Figure 15.

One of the limitations of this system was in the relatively poor shielding used for the NaI(Tl) crystal. The background was not as low as it should be for optimum results and many chance coincidences resulted. With improved shielding, better timing in the Ge(Li) channel, and finer tuning of the entire system one might get a factor of 6-8 improvement in peak-to Compton ratio.

8.2 THE ALL-GERMANIUM COMPTON SPECTROMETERS

The all-germanium Compton spectrometer differs from the Ge(Li)-Compton suppression spectrometer with a scintillator anticoincidence shield not only in hardware but also in principle.Such a system

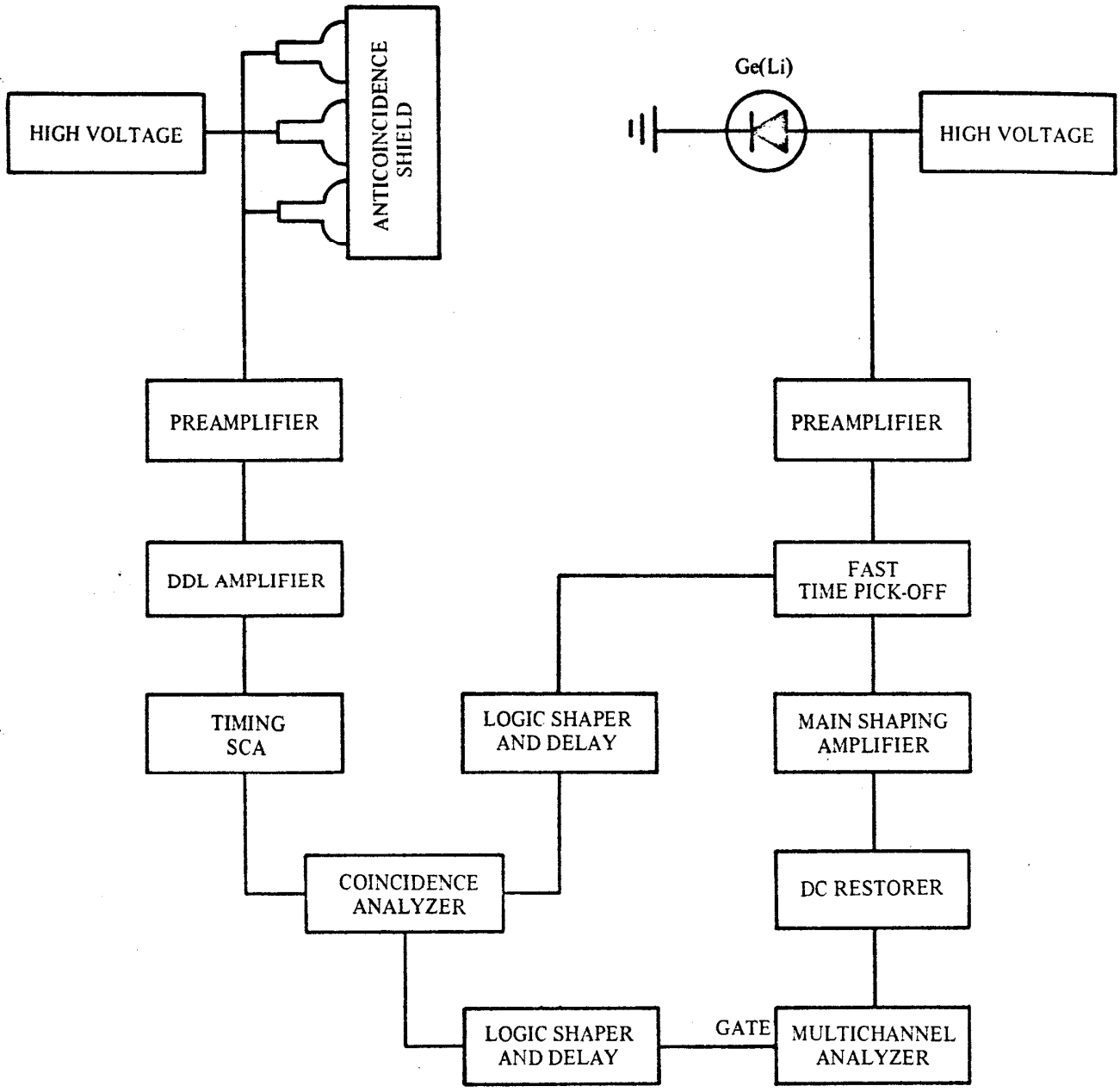


Figure 14. A typical electronic block diagram of a Ge(Li) Spectrometer System with Anticoincidence Shield.

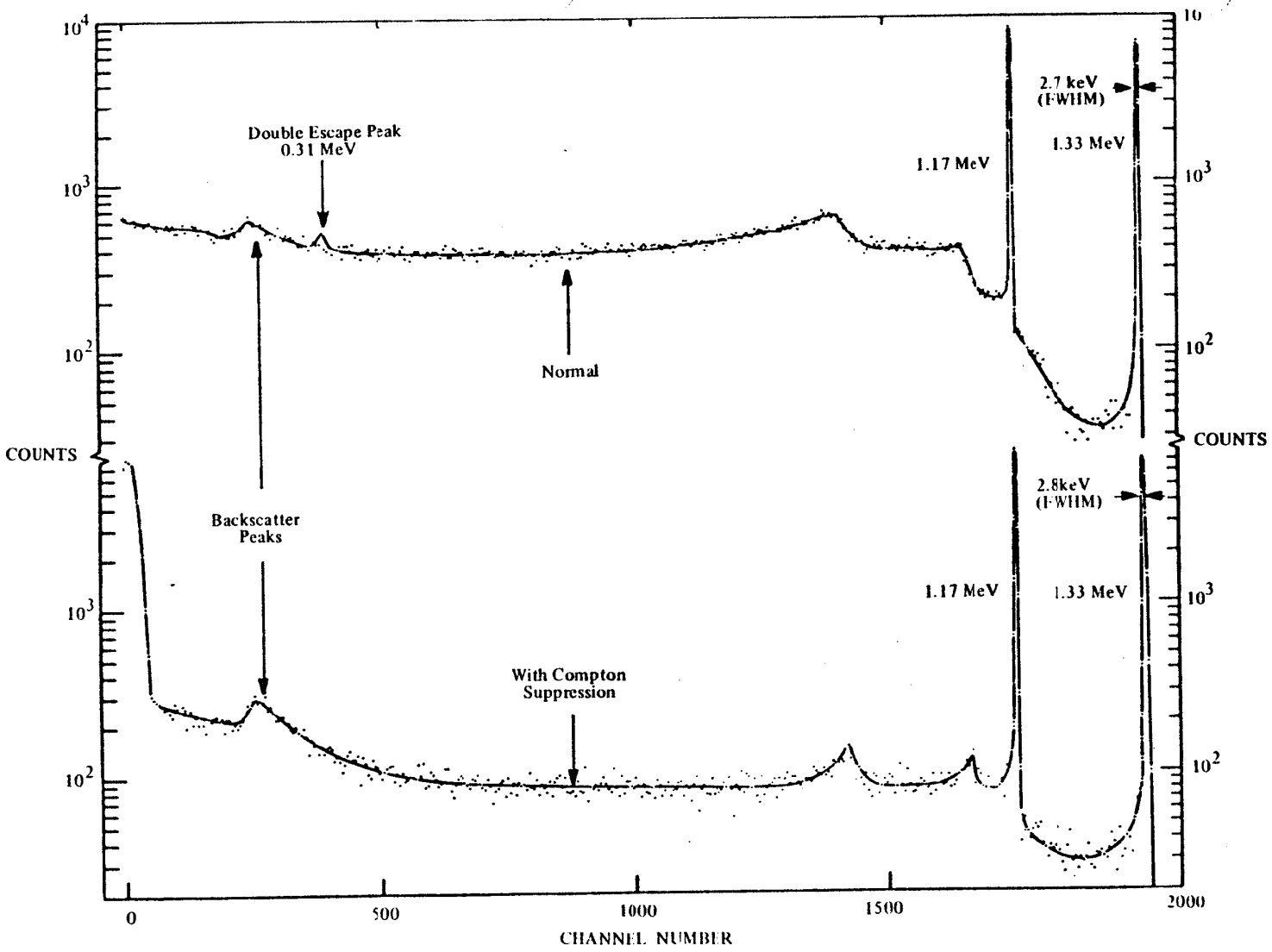


Figure 15. Co^{60} Spectra.

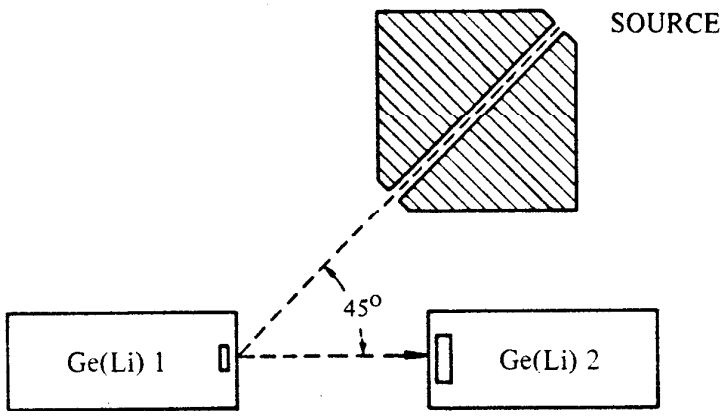


Figure 16. Simple Summing Compton Ge(Li) Spectrometer by KANTELE and SUOMINE [64].

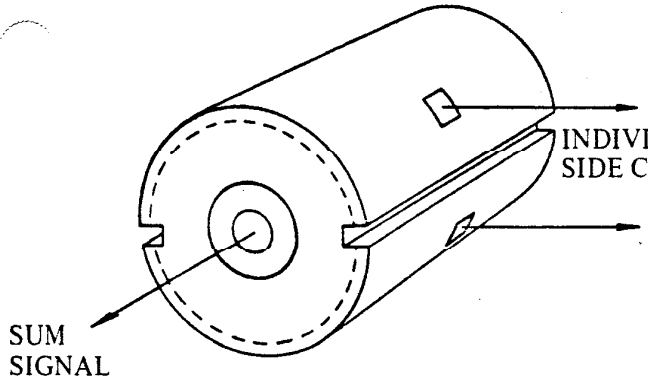


Figure 17. Total Absorption Ge(Li) Gamma Ray Spectrometer by KRANER[67].

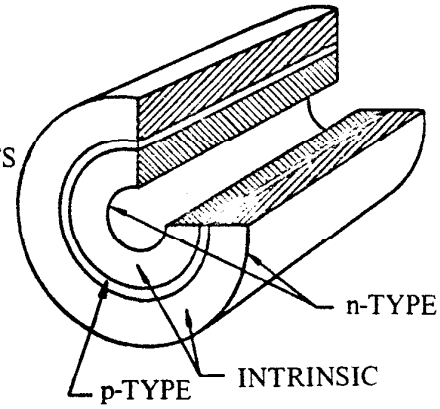


Figure 18. "Concentric Duode" by PALMS [68].

consists of two Ge(Li) detectors operated in the sum-coincidence mode. This means that only events which occur simultaneously in both detectors, such as a Compton interaction in one and a photoelectric effect in the other, and summed and recorded. A gamma ray which interacts only by photoelectric interaction is rejected. In the energy range between 250 keV and 2.5 MeV the fraction of the full energy peak due to photoelectric effect is relatively small. Understandably, the full energy efficiency of these systems is considerably less that that of the two detectors even in the energy region above 350 keV.

Various geometries have been suggested and fabricated. KANTELE and SUOMINEN[64] made use of two completely separated Ge(Li) detector systems facing each other as shown in Figure 16. A collimated gamma ray beam was directed in a 45^{O} angle to the smaller detector. The observed spectra cannot be called perfect although a significant background suppression was achieved.

SAYRES and BAICKER[65] used two planar detectors mounted in tandem in one cryostat. The spectra obtained with this arrangement are clean and show good background suppression. However the full energy peak deficiency is reduced to about 10% at 1.5 MeV and more at lower energies.

GRUHN *et al*,[66] and KRANER[67] built systems consisting of one Ge(Li) detector which has been divided by cutting the n- or p-layer as shown in Figure 17.

PALMS *et al*.[68] drifted a germanium annulus from the center and the outside producing two concentric ring detectors which are operated in the sum coincidence mode (Figure 18).

All these systems have only limited application because of their low full energy peak efficiencies and are, in most cases, inferior to a Compton suppression spectrometer with an anticoincidence shield.

Section 9
THE PAIR SPECTROMETER

For the identification measurement of gamma transitions above 2 MeV, a pair spectrometer is probably best suited. A pair spectrometer consists of at least three separate detectors and makes use of the pair production process.

A center detector is surrounded by two additional detectors. A high energy gamma ray which enters the center detector and interacts by pair production forms an electron-positron pair. The electron energy is usually totally absorbed in the detector while the positron, after losing most of its kinetic energy, is annihilated and produces two 511 keV photons traveling in opposite direction. These photons can undergo Compton scattering or photoelectric interaction in the detector or escape.

To record an event it is necessary that the annihilation radiation escape from the center detector and be completely absorbed in the two outer detectors in triple coincidence. The result is a spectrum which shows only double escape peaks provided 100% of the escaping annihilation radiation is detected.

Several geometries using Ge(Li) detectors as the center detector and NaI(Tl) scintillators as annihilation radiation detectors have been reported [41, 56]. The best system consists of a small, high resolution Ge(Li) detector and a large NaI annulus which is split into two or four optically separated segments. A small Ge(Li) detector is preferred in order to keep the number of multiple events low and to assure that the annihilation radiation escapes.

Figure 19 shows the electronics system. The signals from the two NaI detectors are routed to separate preamplifiers, amplifiers and timing single channel analyzers, the energy windows of which are adjusted to 511 keV. The output signals of the TSCA are fed into a coincidence analyzer. The signals from the Ge(Li) detector are processed by a normal high resolution amplifier-shaper system and fed into the multichannel analyzer. A timing pulse for the coincidence unit is supplied by a fast time pick-off. The logic signal out of the coincidence analyzer gates the ADC.

If four NaI quadrants are used, a more complicated coincidence unit is required since only coincident pulses of facing segments are considered and those of adjacent segments are rejected.

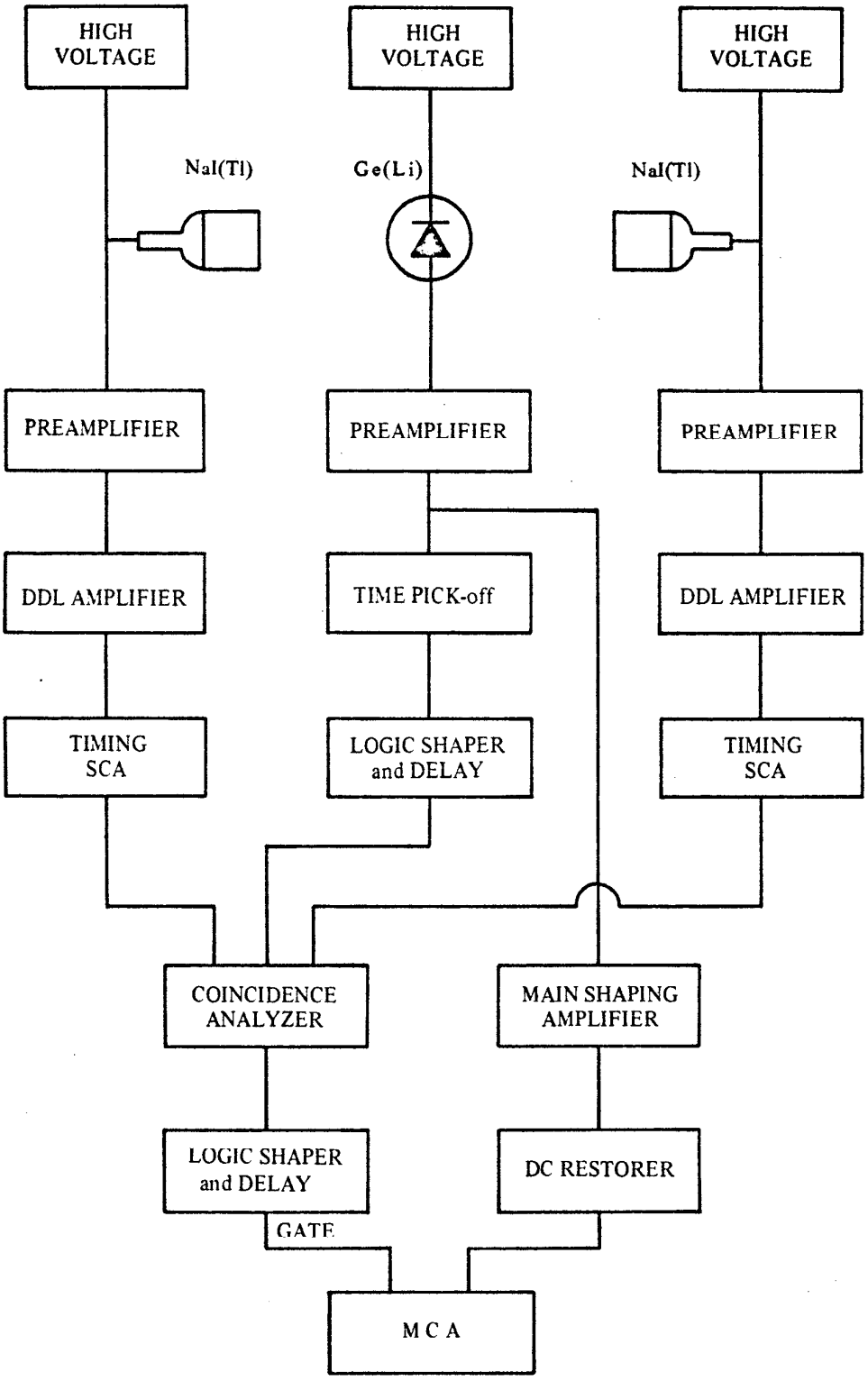


Figure 19. A typical electronic block diagram of a Ge(Li)/ NaI Pair Spectrometer.

Section 10
APPLICATION OF Ge(Li) DETECTORS

A comprehensive discussion of the application of Ge(Li) detectors would far exceed the scope of this work. Thus, only the fields where Ge(Li) detectors have been employed with great success are mentioned.

The first Ge(Li) gamma ray spectrometers were used in decay scheme studies. The excellent energy resolution gave accuracies which could previously be obtained only with bent crystal spectrometers. However, the much higher efficiency and the wider energy range of the Ge(Li) detector opened completely new possibilities, particularly in the study of short lived isotopes.

Gamma radiation emitted during nuclear reactions such as neutron capture has been examined very successfully with Ge(Li) detectors, particularly with Ge(Li)/NaI pair spectrometers.

Neutron activation analysis received, in the Ge(Li) detector spectrometer, a tool which saves time-consuming and expensive chemical separations and makes nondestructive analysis possible. Furthermore, shorter-lived isotopes can be used for the analysis, reducing the irradiating and counting times. Also, neutron capture gamma-rays have been used in neutron activation analysis. [69, 70]

The analysis of fall-out has been changed completely since the introduction of the Ge(Li) detector. Because fallout samples often have very low count rates, suppression of the background is very important. Cryostats manufactured of material with low natural radioactive background and systems involving anticoincidence shields are used extensively in this field.

Despite the necessity of cooling, Ge(Li) detectors have been sent into the outer atmosphere and into outer space in balloons and rockets and into holes drilled deep into the earth.

Because of their higher stopping power in comparison to silicon, Ge(Li) detectors are used as detectors for fast particles in accelerator work. [71, 72, 73]

The thin window Ge(Li) detector is recently becoming more important as the heart of X-ray emission spectrometers which provide for nondestructive analysis of materials using the characteristic X-ray emitted by elements when excited by monochromatic X-rays.

Because of their exceptional linearity, Ge(Li) detectors can be used as a calibration standard for the testing of the linearity of amplifiers and ADCs.

APPENDIX B

SOURCE	HALF-LIFE	E_λ(keV)	REFERENCE
Co^{57}	268 days	14.359 (37)	41
		121.969 (26)	41
		136.328 (27)	41
Am^{241}	458 years	26.350 (10)	42
		59.554 (11)	
Hg^{203}	47 days	70.830 (4)	43
		72.871 (4)	
		82.572 (4)	
		84.918 (4)	
		279.150 (20)	41
I^{131}	8.05 days	80.164 (9)	41
		284.307 (49)	
		364.493 (16)	
Ce^{141}	32.5 days	145.433 (18)	45
Ce^{139}	140 days	165.850 (8)	34
Cr^{51}	27.8 days	320.085 (6)	34
Be^{7}	53 days	477.556 (48)	41
Sr^{85}	64 days	513.95 (7)	47
Bi^{207}	30 years	569.62 (6)	41
		1063.578 (53)	41
Th^{228}	1.91 years	583.139 (23)	45
		2614.47 (10)	
Cs^{137}	30 years	661.632 (69)	46
Nb^{95}	35 days	765.83 (7)	47
Mn^{54}	314 days	834.861 (52)	41
Sc^{46}	84.2 days	899.25 (7)	47
		1120.50 (7)	
Y^{88}	108 days	898.01 (7)	34
		1836.111 (58)	41
Co^{60}	5.26 years	1173.226 (40)	34
		1332.483 (46)	
Na^{22}	2.58 years	1274.552 (55)	41
Na^{24}	15.0 hr.	1368.526 (44)	45
		2753.92 (12)	
K^{40}	1.3×10^{-9} years	1460.75 (6)	48
Sb^{124}	60.9 years	1691.24 (8)	46

Table 2. Commonly Used Gamma-Energy Standards.