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DETECTOR APPLICATIONS

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A. General Remarks

Semiconductor detectors are now applied to a very wide range of problems. The combination of relatively low cost, excellent energy resolution, and simultaneous broad energy-spectrum analysis is uniquely suited to many applications in both basic and applied physics. Alternative techniques, such as magnetic spectrometers for charged-particle spectroscopy, while offering better energy resolution, are bulky, expensive, and usually far more difficult to use. Furthermore, they do not directly provide the broad energy-spectrum measurements easily accomplished using semiconductor detectors. Scintillation detectors, which are approximately equivalent to semiconductor detectors in convenience and cost, exhibit 10 to 100 times worse energy resolution. However, their high efficiency and large potential size recommend their use in some measurements.

B. Charged-Particle Spectroscopy

Charged-particle spectroscopy is probably the simplest application of semiconductor detectors, and was the first area to feel their impact. Early work concentrated on the spectroscopy of low-energy natural α particles, electrons, and fission fragments because the range of these particles was within the stopping capabilities of surface barrier and diffused junction detectors. Development of the lithium-drifted process for thicker silicon detectors made high-resolution measurements on longer-range particles from accelerators possible.

Lithium-drifted silicon detectors up to 5 mm thick are routinely available, but the prospects of fabricating silicon detectors significantly thicker than this are very dim. Figure 1 presents the range-energy relationship for protons, deuterons, tritons, ^3He and α particles in silicon. We see that a 5 mm thick silicon detector will stop up to a 120-MeV α particle or a 30-MeV proton. For higher energies a stack of silicon detectors has often been employed. Figure 2 presents the range-energy relationship for protons, deuterons, tritons, ^3He and α particles in germanium. Germanium detectors up to 15 mm thick are reasonably available so we see that up to about 75-MeV protons, or 300-MeV α particles will be stopped in a single detector. At this point the possibility of employing side-entry detectors should be mentioned. With this geometry considerably longer ranged particles can be stopped. However, the elimination of dead layers on the side is difficult. Furthermore, multiple scattering of the long ranged particles can become a serious problem. Although germanium detectors were first demonstrated to provide excellent performance for charged particle detection in 1965,¹ their use has remained rather limited until recently. The biggest barrier to their use was the difficulty of cooling the

detector in the existing scattering chambers. Furthermore, the difficulty of handling lithium-drifted germanium detectors inhibited their use in scattering chambers.

The advent of high-purity germanium detectors has drastically diminished the handling difficulties, and germanium charged-particle detectors are now commercially available. Figure 3 shows the typical spectrum obtained with a high-purity germanium detector from a highly resolved 40-MeV proton beam at LBL. The energy spread in the beam itself was 10 keV.

With the operation of new high-intensity intermediate-energy accelerators (LAMPF, Indiana, SIN and TRIUMF) there is a need for particle spectrometers having a stopping power greater than available with a single germanium detector, thus the construction of multi-detector telescopes is required.

Since the detectors have to be stacked to achieve sufficient total stopping power, they must have thin windows on both the entrance and exit faces.** Unfortunately, the lithium-diffused n^+ surface layer that is typically used for the n^+ contact on high-purity germanium detectors results in a window thickness of at least 250 μ .

Lower diffusion temperatures have been successfully used to produce effective dead layers as thin as 10 μ -- acceptable for many spectrometer applications. However, the use of germanium spectrometers around accelerators will often result in radiation damage that will necessitate annealing the detectors at temperatures at least as high as 100° C for periods of several days. The lithium mobility at these annealing temperatures is sufficient to cause the effective dead layer to increase significantly to over 250 μ . Such an increase largely negates the great asset of being able to anneal high-purity germanium detectors without removing them from the cryostat, and consequently lithium-diffused n^+ contacts are not viable for multi-detector telescopes that are likely to be radiation damaged.

** Stacking detectors together has several significant benefits compared with one large detector of equivalent total thickness. A large fraction of high-energy charged particles undergo nuclear reactions prior to reaching the end of their range. For example, the low-energy tail from nuclear reactions will be about 9% for 100-MeV protons. If signals are available from each detector most of the events corresponding to a nuclear reaction in the germanium can be rejected by using appropriate electronic circuitry. The second major benefit arises because the electrons and holes do not have to travel as far to reach the electrodes when detectors are stacked together. Consequently, the detectors are less susceptible to charge trapping -- this is especially important in applications where radiation damage is likely.

Fortunately, phosphorus implanted n^+ contacts have recently been developed that satisfy the requirements for thin, stable n^+ contacts on high-purity germanium detectors.²

A photograph of an eight-detector telescope made at LBL is shown in Fig. 4. The first detector is 4 mm thick, the second 7 mm thick, and the remaining six detectors are each about 12 mm thick. This system has been successfully used at LAMPF by an experimental group from Carnegie-Mellon. Unfortunately, the detectors in this telescope have lithium-diffused n^+ contacts so when the detectors require annealing the lithium-diffused layer will have to be removed. Phosphorus implanted n^+ contacts will then be used.

If the energy region of interest is sufficiently low that a two-detector telescope will suffice, the lithium-diffused layer can often be acceptable. This was exploited in the LBL fabricated two-detector telescope shown in Fig. 5 that has been used very successfully at LAMPF by the experimental group from Carnegie-Mellon.³ Each detector is 15 mm thick so up to about 110-MeV protons can be stopped. By placing the thin-window p^+ contacts face-to-face, no gap in the energy scale is encountered; the resolution degradation caused by the relatively thick entrance window is negligible in many cases compared to the beam spread.

C. Photon Spectroscopy

A comprehensive review of the applications of semiconductor photon detectors is far beyond the scope of this paper. Instead, a few applications that illustrate the present and future potential of these detectors will be presented.

Although the use of semiconductor detectors has revolutionized, and to a large extent created, the field of X-ray fluorescence analysis in recent years, this paper will not dwell on it at any length. These X-ray spectrometers normally employ lithium-drifted silicon detectors. Germanium detectors provide slightly better energy resolution than silicon detectors because ϵ , the average energy required to produce a hole-electron pair, is about 26% larger in silicon, and the measured Fano factor is typically smaller in germanium. However, the fairly intense germanium X-ray escape peaks severely limit the usefulness of germanium spectrometers as analytical tools if photons in the energy region from 11.1 to about 30 keV are present. Furthermore, the entrance windows on germanium detectors severely degrade the performance of germanium spectrometers at X-ray energies under about 3 keV.⁴

Since silicon detectors are too inefficient at photon energies above about 30 keV, higher energy X-ray spectroscopy and almost all γ -ray spectroscopy requires the use of germanium detectors.

For my first example, I choose Exotic atom X-rays. Germanium spectrometers have made a great contribution to this field by providing the energy resolution necessary to observe the X-ray spectra generated. Figure 6 shows a spectrum from the first significant physics experiment to use a high-purity germanium detector. It is also the first spectrum to show a kaonic induced nuclear γ -ray; in addition, X-ray transitions from three different types of exotic atoms can be seen. The data were accumulated during three consecutive days of continuous running of the Bevatron.

Exotic atoms are expensive to make, especially those other than muonic and pionic atoms. Consequently there is considerable benefit in obtaining a high detection efficiency for the emitted X-rays. We have provided two arrays of high-purity germanium detectors to be used for these studies; one array consists of three, the other of four, planar detectors. Multiple-detector arrays in the same cryostat allow more detectors near the target than would be possible with each detector in a separate cryostat.

D. Multiple-Detector Arrays

The availability of high-purity germanium has opened up the possibility of employing arrays of detectors to provide large-area coverage and increased detection efficiency as we have done for exotic atom X-ray spectroscopy. The effort to mount arrays of lithium-drifted germanium detectors in the same cryostat is vastly greater than that required for high-purity germanium detectors. In fact, arrays of lithium-drifted germanium detectors could never be considered a standard instrument. Fabrication and application of these multiple-detector arrays is probably the major change in the germanium detector field recently, and is expected to play an ever increasing role in the years ahead. The increased detection efficiency afforded by arrays allows germanium detectors to be used for applications that were previously not practical.

For example, we fabricated an array of nine planar detectors, each 3.5 cm in diameter and 1.0 cm thick, to be used as a γ -ray scanner at the Vanderbilt University Medical Center.⁵ Although there has been considerable discussion concerning the merit of germanium γ -ray detectors for use in nuclear medicine, little clinical application has occurred, largely because the detection efficiency of available systems was insufficient to provide a practical instrument. Our nine-detector array should provide a good clinical test.

Two large arrays of high-purity germanium coaxial detectors have been fabricated by Princeton Gamma Tech for use by a group at the Naval Research Laboratory.⁶ The first array consisted of twelve 7% efficient detectors and the second has fifteen 10% efficient detectors. Each detector is mounted in its own vacuum enclosure, although all the detectors in an array are connected to a common cold plate attached to a single dewar. The amplified signals from each detector are fed to a multiplexer. This kind of operation avoids summing the noise from the detectors and therefore preserves the energy resolution. Each of the twelve individual detectors in the first array has a resolution of better than 2.0 keV at 1332 keV, and when the signals are summed via the multiplexer the resolution is 2.07 keV at 1332 keV. The summed resolution is approximately 1.0 keV in the region 60-120 keV.

Two arrays of four planar detectors for monitoring plutonium in the lungs have been fabricated by ORTEC for use at Rocky Flats. Each of the eight individual detectors is 3.6 cm in diameter and 1.0 cm thick, and has a resolution of better than 650 eV at 60 keV. For measurement of plutonium via the 59.54 keV γ -ray of ²⁴¹Am, the detection capability of the germanium system is about a factor of three better than the detectability of the phoswich system at Rocky Flats. Although pessimism has been expressed concerning the feasibility of using this system for measuring plutonium via L X-rays in the presence of ²⁴¹Am, or for quantities of ²³⁹Pu less than one or two Maximum Permissible Lung Burdens

(16 or 32 n Ci),⁷ the overall results have been sufficiently promising that two additional four detector arrays have been ordered. To increase the detection sensitivity, each detector in the new arrays will have an area of 15 cm².

An array of ten planar detectors, each 3.6 cm in diameter and 1.0 cm thick, to be used for measuring plutonium contamination in environmental samples and to grade waste as permanently disposable or retrievable has been fabricated by ORTEC for use at Hanford. Since easy field serviceability of the system was considered to be more important than packing density, each detector is mounted in its own vacuum enclosure although all are connected to a common cold plate attached to a single dewar.

F. Activation Analysis

For many years, nuclear reactors have been used to "activate" materials. After capturing slow neutrons from the reactors, these materials can be analyzed by observing the γ -rays emitted upon decay of excited nuclear states. This analysis usually involves the evaluation of complex γ -ray spectra. Consequently, the excellent energy resolution of germanium detectors has proven very profitable to this field of applied γ -ray spectroscopy.

Among the potential applications of germanium γ -ray detectors in space is another activation analysis technique.⁸ The surface of an airless planetary object emits γ rays directly into space. These γ rays are generated in two ways. First, the naturally radioactive elements Th, K and U emit γ rays either directly or in the course of decay chains. The second cause of γ rays is the interaction of surface material with cosmic rays. These high-energy nuclear particles cause nuclear reactions which result in γ rays characteristic of the target nucleus. Detection of these characteristic γ rays by a germanium spectrometer in an orbiting spacecraft provides a measurement of the concentration of many elements in the planetary surface. Spectrometers which are being developed may be used in possible future missions, such as Lunar Polar Orbiter, a Mars orbiter, a Mercury orbiter, outer planet satellite missions, and rendezvous with asteroids and comet nuclei.

Often in space applications, and sometimes elsewhere, maintenance of germanium detectors near liquid nitrogen temperature is difficult. Consequently, the energy resolution at higher temperatures is of considerable interest. Figure 8 shows the energy resolution of ⁶⁰Co 1.17-MeV γ rays measured by several germanium detectors over a wide temperature range.⁹ A serious degradation of resolution is seen to occur at temperatures above 150° K due to the rapid rise of detector leakage current. This temperature represents a good estimate of the maximum operating temperature of germanium detectors, although a recent study indicates that slightly higher temperatures are possible.¹⁰ However, there is a great advantage in operating germanium spectrometers that will be exposed to significant radiation damage as cold as possible - at least down to liquid nitrogen temperature.

F. Radiation Damage

Energetic particles can produce interstitial-vacancy pairs (a Frenkel defect) in a crystal by knocking the atoms from their normal positions. Detectors are unique among semiconductor devices in depending on

very low concentrations of electrically active impurities, and also on efficient transport of holes and electrons over relatively large distances. Because the dense regions of damage produced by energetic particles may result in donors and/or acceptors, and also provide trapping sites for holes and electrons, detectors are very sensitive to radiation damage. Compared to fast neutrons and charged particles, the damage caused by electrons and γ -rays is negligible and will not be discussed here. In addition to these effects occurring within the detector, radiation may also change the characteristics of the exposed surfaces causing unpredictable effects on the detector leakage current. Fortunately, radiation induced surface degradation has rarely, if ever, been observed for germanium detectors.

G. Fast Neutrons

Although several studies of the radiation damage effects of fast neutrons on germanium detectors have developed considerable empirical information, little physical interpretation of the electronic effects can be given in terms of microscopic detail due to the limited knowledge of the dynamics of collision produced vacancies and their coagulation and recombination. The following discussion summarizes our picture.

Significant energy resolution degradation in 1 cm thick planar germanium detectors, both lithium-drifted and high-purity, occurs after irradiation by between 10⁹ and 10¹⁰ n/cm² of 5 MeV neutrons.¹¹ A wide range of damage sensitivities (factor of ~ 10) exists among high quality detectors made from different germanium crystals. Unfortunately, the crystal parameter(s) which is/are responsible for this wide range of damage sensitivities is not presently known.

Small changes in the energy resolution take place after irradiation while the detectors remain near liquid nitrogen temperature. This is not inconsistent with the fact that some vacancy mobility exists at this temperature. Therefore, spectral degradation resulting from irradiation may exhibit a dependence on neutron dose-rate as well as fluence, although in most situations this will not be an important factor.

Complete collapse of the energy resolution occurs when high-purity germanium detectors are annealed at 200° K, dry ice temperature. The acceptor concentration is greatly increased after the dry ice anneal and decreases with further higher temperature anneals. From a practical viewpoint, it is obvious that if a germanium detector has been exposed to a significant flux of fast neutrons, it would be imprudent to allow the unit to go through a room temperature thermal cycle, even though the detector had exhibited no resolution degradation while being maintained near liquid nitrogen temperature.

Annealing high-purity germanium at 100° C for periods of hours produces a very large portion of recovery. Thus in situ annealing of high-purity germanium spectrometers is possible. (To diminish the risk of contaminating the detector surface during in situ annealing the cryostat should be connected to a good, clean external vacuum system. Unfortunately, this step invalidates the warranty on commercial germanium spectrometers. Nevertheless, to take full advantage of the attributes of high-purity germanium detectors, properly equipped users must seriously consider the merit of occasionally "repairing" their own

detector). Although complete recovery may not be obtainable with 100° annealing the spectrometer performance should be acceptable for nearly all applications. Complete recovery can be achieved at somewhat higher temperatures, not more than 150° C is necessary.

Hole trapping predominates as the degrading effect on energy resolution. This fact leads to a consideration of the possibility of minimizing hole trapping in charge collection by the use of a high-purity germanium coaxial detector configured with the p⁺ contact on the coaxial periphery. The holes then make only a short traversal from the outer portions of the detector (where most interactions occur) to the contact of collection. To establish high fields at the periphery one would want to use n-type germanium. A recent experiment by L.S. Varnell, R.H. Parker, B.D. Wilkins, L.E. Finmin, M. Fong and myself with high-energy protons has provided a strong indication that such a coaxial configuration is very beneficial for detectors that will be radiation damaged. Unfortunately, standard lithium-drifted coaxial detectors and all commercial high-purity coaxial detectors* are configured with the n⁺ contact on the coaxial periphery. Consequently, they are extremely vulnerable to radiation damage.¹²

H. Charged Particles

Until recently, no radiation damage measurements of germanium detectors comparable to those made with fast neutrons had been made with charged particles. Motivated by the possible use of germanium γ -ray spectrometers for astronomical and planetological observations on extended space missions, we have undertaken a program to study the radiation damage effects of high-energy charged particles. This program has been initiated by the exposure of six high-purity germanium planar detectors and one high-purity germanium coaxial detector to a flux of 6 GeV/c protons.

These protons caused about 60 times more damage than did 16.4 MeV neutrons, i.e., the degradation observed at 3×10^9 n/cm² was equal to the degradation observed at 5×10^7 p/cm².¹³ This difference is roughly consistent with the calculated number of lattice defects expected.

Although the spectrometer performance of the detectors was considerably worse following the proton irradiations than it was following the neutron irradiations, the detectors annealed far more easily, (lower temperature and/or shorter time) indicating a different damage mechanism for at least a large part of the damage.

The energy resolution of the coaxial detector, configured with the p⁺ contact on the coaxial periphery, degraded considerably less than did the energy resolution of a planar detector fabricated from the same germanium crystal when the high-energy proton beam passed through both detectors. If the n⁺ contact had been on the coaxial periphery we would have anticipated the energy resolution of the coaxial detector degrading much more than the energy resolution of the planar detector. Although additional experiments must be done, it now appears that coaxial germanium detectors having the n⁺ contact on the coaxial periphery should not be used on extended space missions, or in any situation subject to radiation damage.

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*The availability of high-purity coaxial detectors with the p⁺ contact on the coaxial periphery was announced after this paper was written.

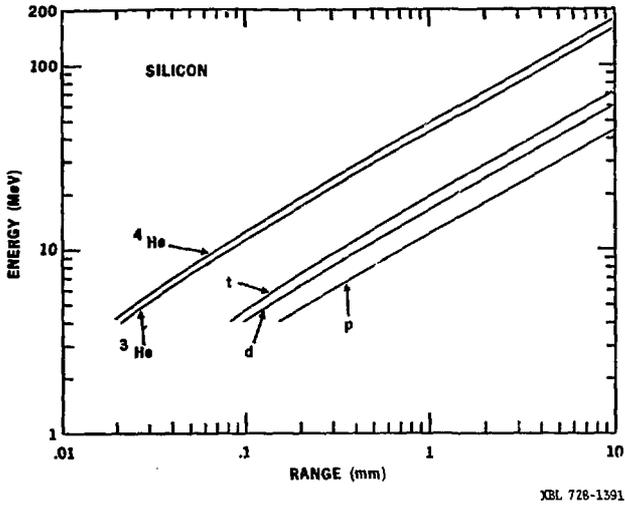


Fig. 1 Range-energy curves for protons, deuterons, tritons, ^3He and ^4He particles in silicon.

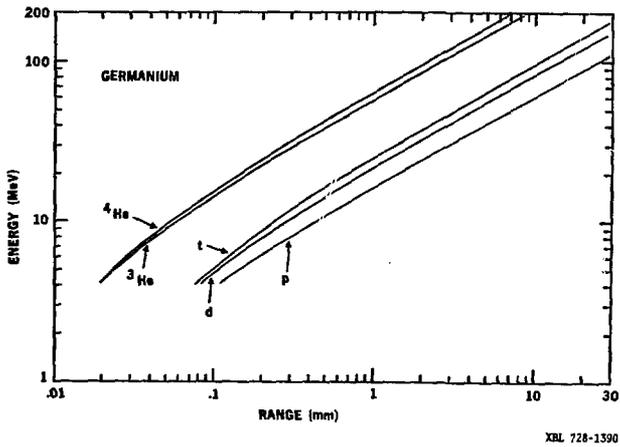


Fig. 2 Range-energy curves for protons, deuterons, tritons, ^3He and ^4He particles in germanium.

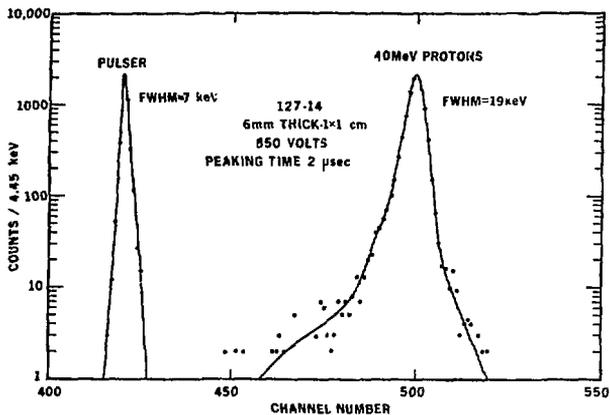


Fig. 3 Energy spectrum of 40-MeV protons.

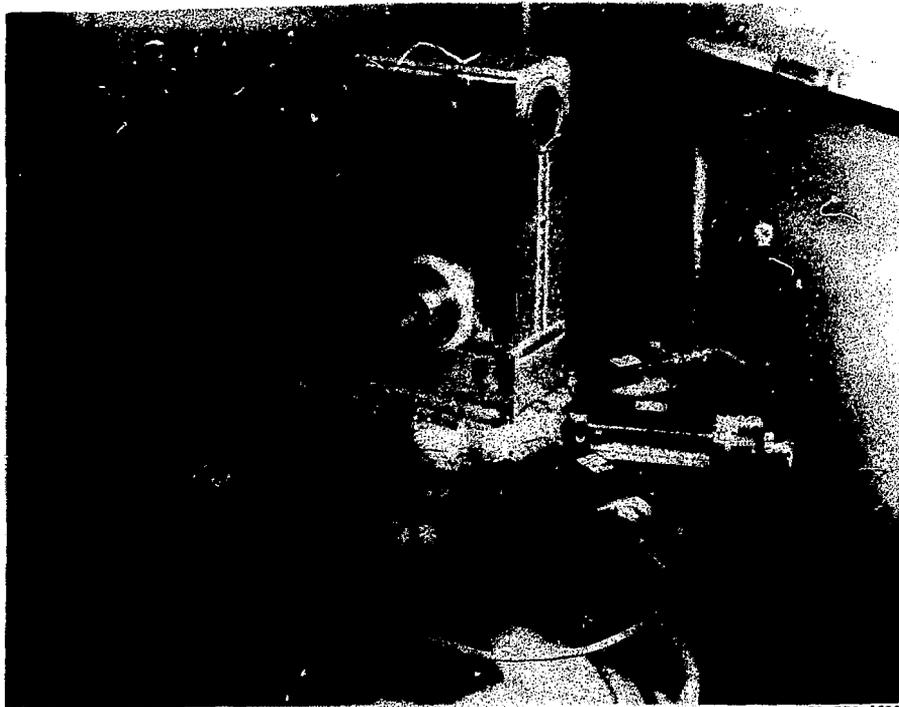
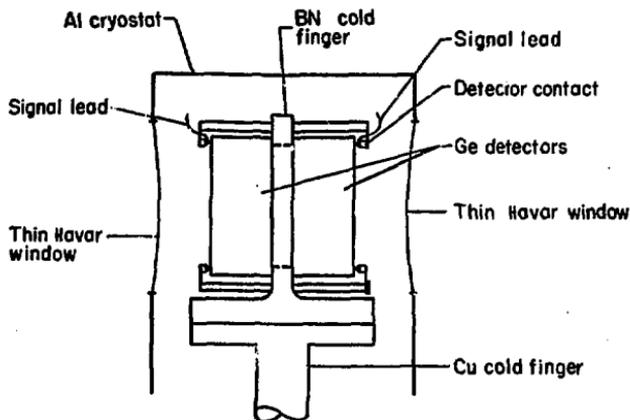


Fig. 4 Eight-germanium detector telescope for measuring long-range charged particles.



25 mm

XBL 7411-8021

Fig. 5 Schematic of a two-germanium detector telescope.

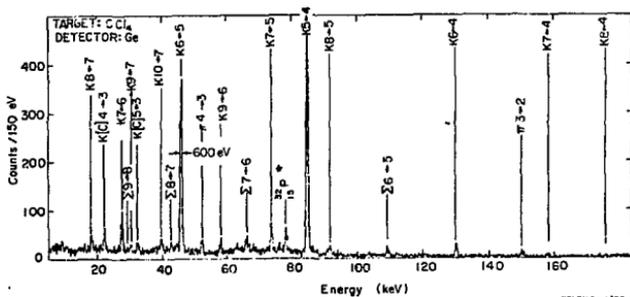
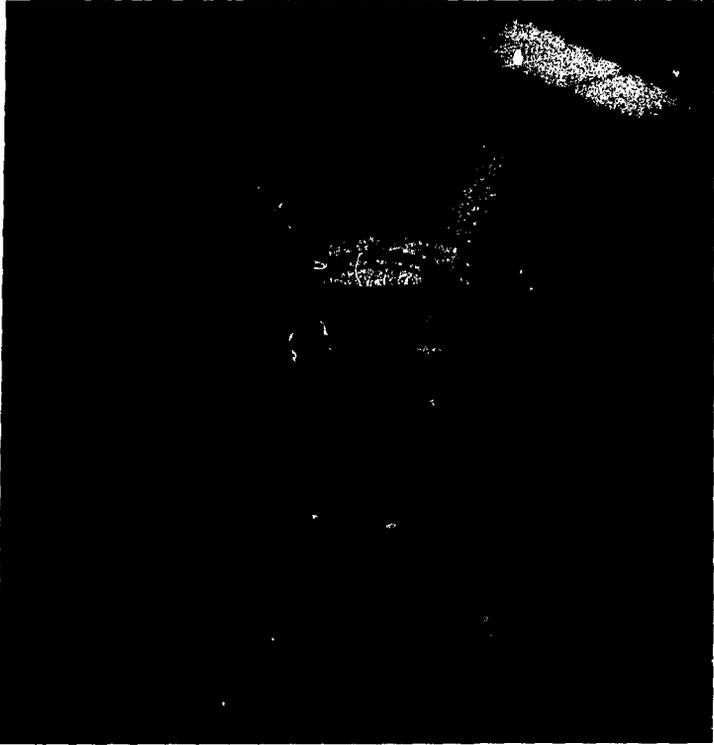
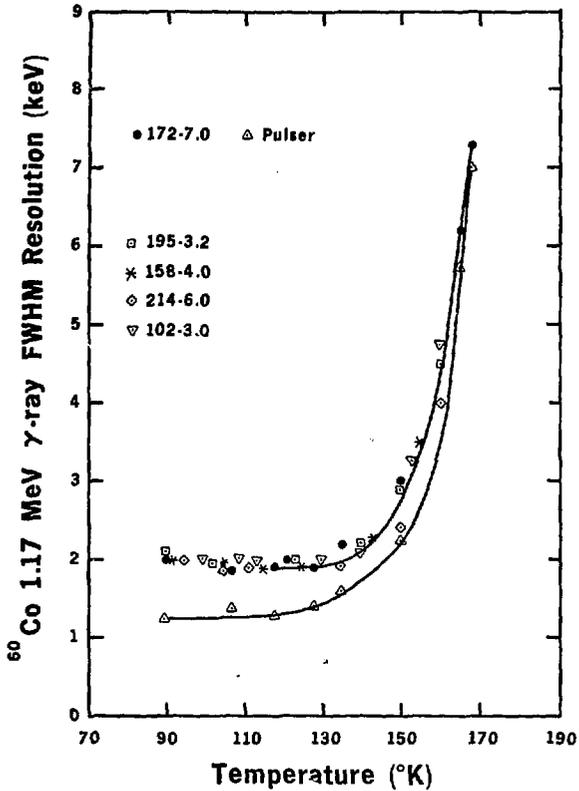


Fig. 6 Kaonic X-ray spectrum of Cl. X-rays from pionic and sigma-hyperonic atoms, and a kaonic induced nuclear γ -ray, were also detected.



CBB 760-11503

Fig. 7 Photograph of the cryostat containing nine planar detectors now being used as a gamma-ray scanner at the Vanderbilt University Medical Center.



XBL 7211-7460

Fig. 8 Resolution of the ^{60}Co 1.17-MeV gamma ray obtained with five germanium detectors as a function of temperature. The pulser resolution when detector 172-7.0 was used is also shown.