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DETECTOR TELESCOPES AND THEIR APPLICATIONS

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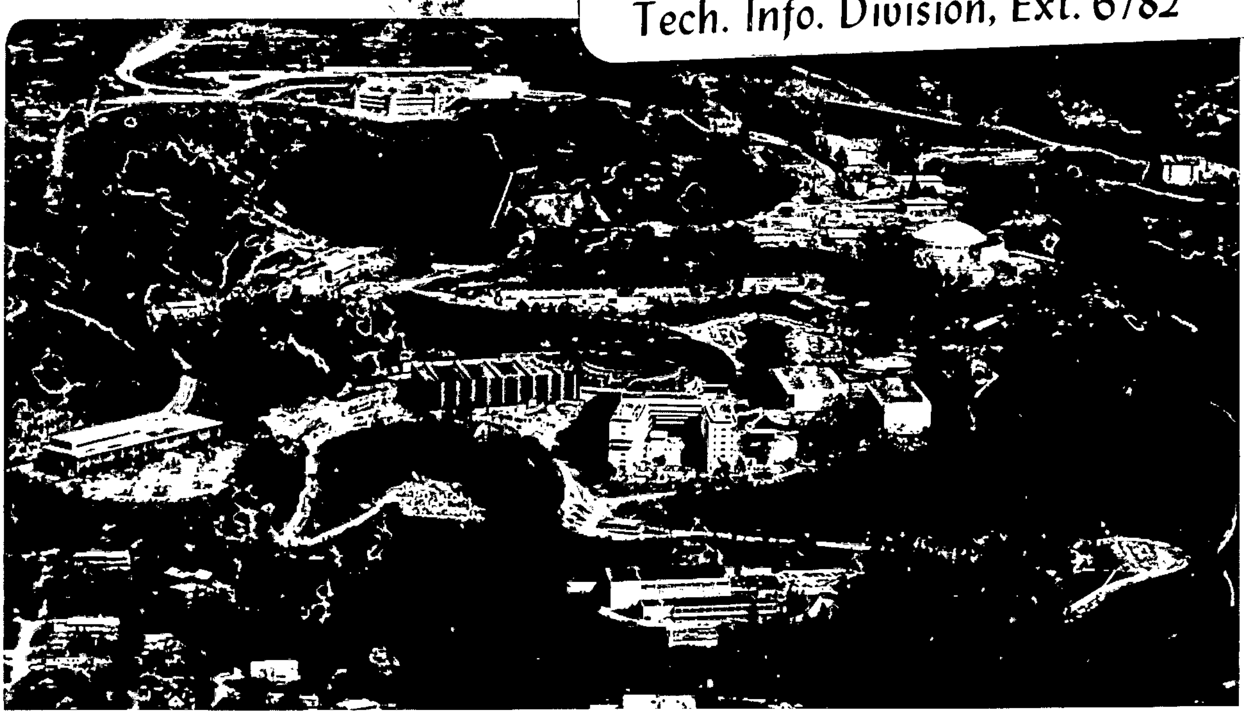

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DETECTOR TELESCOPES AND THEIR APPLICATIONS

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Introduction

This paper could also be entitled "silicon and germanium detector telescopes and their applications" because detectors made from other materials will not be discussed. An even more precise title would be "silicon and germanium charged-particle detector systems of which detector telescopes make up a major part." All of the examples to be discussed here have a direct, or indirect, connection to the semiconductor detector group at LBL--I make no claim that the topics have been impartially selected.

Historical Perspective

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 alpha particles, electrons, and fission fragments because the range of these particles was within the stopping capabilities of silicon surface barrier and diffused junction detectors. Development of the lithium-drifting 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 only a very few lithium-drifted silicon detectors thicker than this have been fabricated. Silicon surface barrier detectors up to 5 mm thick have also been made, but their availability and their area remains limited and their price rather high.

Figure 1 shows the range-energy relationship for pions, protons, deuterons, tritons, ^{3}He, ^{4}He, ^{6}Li and Li^7 particles in silicon and germanium. We see that a 5 mm thick silicon detector will stop up to a 120-MeV ^{4}He particle or a 30-MeV proton. For higher energies a stack of silicon detectors, called a detector telescope, has often been employed--as will be discussed in more detail below. The stopping power of germanium is about twice that of silicon. In addition, germanium detectors up to 15 mm thick are

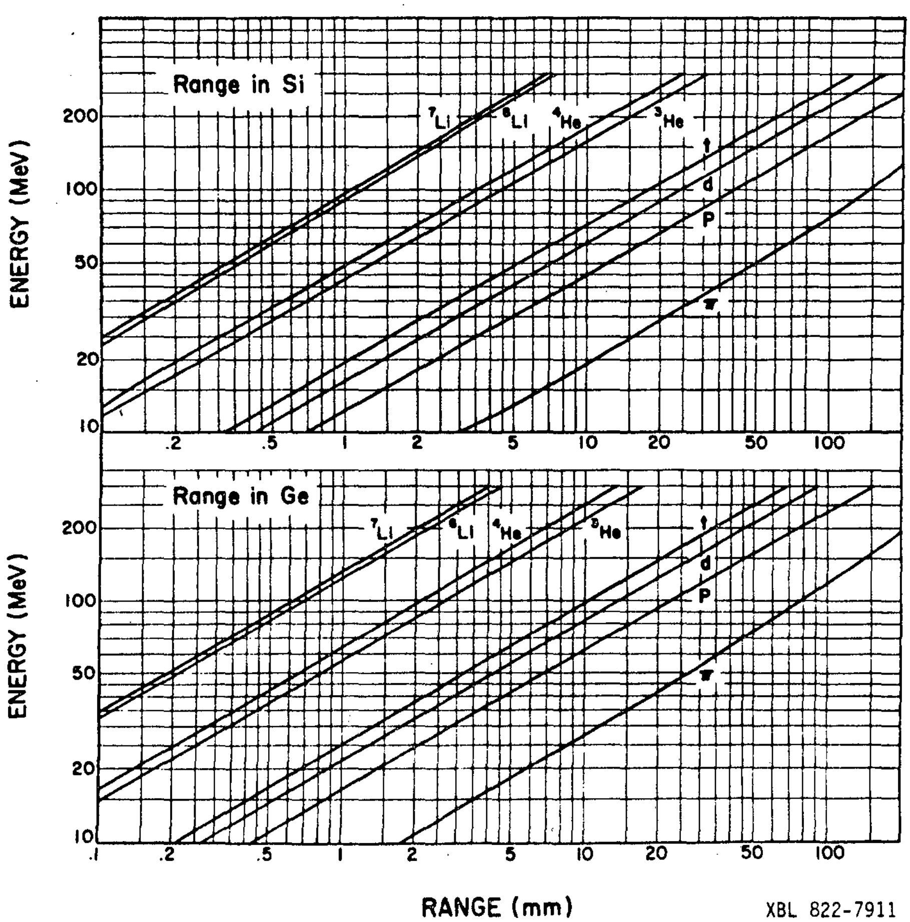

Figure 1. Range-energy curves for pions, protons, deuterons, tritons, ^{3}He, ^{4}He, ^{6}Li and ^{7}Li particles in silicon and germanium.

reasonably available. Up to about 300-MeV He^4 particles or 75-MeV protons can be stopped in a single germanium detector. At this point the possibility of employing side-entry germanium detectors should be mentioned. With this geometry, considerably longer-range particles can be stopped in a single detector because a much greater effective thickness can be obtained. Elimination of dead layers on the sides of germanium detectors has been a difficult problem, but application of a hydrogenated amorphous germanium (a-Ge:H) coating to adjust the electrical state and passivate the surface, recently developed at LBL,[1] has produced essentially windowless surfaces with very good charge collection at the surface. Consequently, side-entry germanium detectors will almost certainly prove to be useful in many situations. However, one must also recognize that multiple scattering of the long-range particles puts a severe limitation on the usefulness of a side-entry detector.

Stacking detectors together, i.e., a detector telescope, has several significant benefits compared with one large detector of equivalent total thickness. A detector telescope can provide signals that can be used to identify the type of incident particles. The field of particle identification is an extensive subject unto itself[2] and no attempt to provide a significant review will be made here. Suffice it to say the quantity MZ^2, where M is the mass and Z is the charge of the particle, can be obtained from a telescope that measures the energy loss of a particle passing through a relatively thin detector, called the ΔE detector, into a second detector, called the E detector, where its residual energy is deposited and measured. This particle identification is based on the nonrelativistic equation for the rate of energy loss of charged particles as they pass through matter:

$$\frac{dE}{dX} \propto \frac{MZ^2}{E}$$

which leads to

$$\left(\frac{\Delta E}{\Delta X}\right)\left(E\right) \propto MZ^2$$

E can be computed by summing the detector telescope signals, so the measurement of dE/dx provides a measurement of MZ^2. In a multiple-detector telescope the particle identifier circuitry can be applied to various detector combinations. The identifications obtained can be compared and events which fall outside set boundary conditions rejected.[3]

The second benefit from using a detector telescope arises because a large fraction of high-energy charged particles undergo nuclear reactions in the detector prior to reaching the end of their range. For example, as shown in Fig. 2, the low-energy tail from nuclear reactions will be about 9% for 100-MeV protons stopping in germanium. This means if 100 of these protons are incident on the detector, one will observe only 91 counts in the full-energy peak. Losing these 9 counts is usually not harmful to an experiment whose goal is solely to measure the full-energy peak. In practice, however, one often wants to measure relatively weak peaks that fall below the intense elastic peak but the tail from the elastic peak caused by nuclear reactions can easily obscure a weak peak. If signals are available from each detector in the stack most of the events corresponding to a nuclear reaction in the germanium can be rejected by using appropriate electronic circuitry. However, these nuclear reactions place a practical upper limit on the total thickness of germanium that is useful. About 25% of incident 200-MeV protons undergo a nuclear reaction before stopping in germanium—and the value of a detector telescope of greater thickness rapidly diminishes.

Another 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.

And, lastly, of course, faster timing signals are available from thinner detectors.

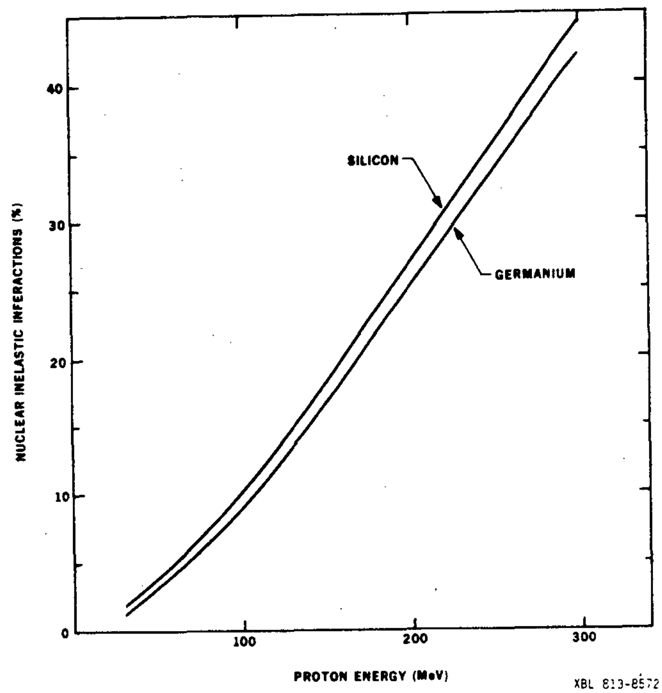

Figure 2. Calculated percentage of protons undergoing nuclear reactions in silicon and germanium as a function of the incident proton energy.(4)

The first use of a semiconductor detector in a telescope, that I am aware of, occurred in April 1960, when the group in which I was a graduate student replaced the CsI ΔE detector by a 400 μm thick silicon diffused-junction detector. A NaI E detector completed the telescope. The CsI detector was never used again. In January 1961, we replaced the NaI E detector with a lithium-drifted silicon detector to have, I believe, the first semiconductor detector telescope. These telescopes were used for studying (α,d) reactions on a series of light elements at the Crocker 60" cyclotron. Many improvements in semiconductor detector technology since then have allowed these telescopes to be used over a wide range of applications.

Germanium Detector Telescopes

Although lithium-drifted germanium detectors were first demonstrated to provide excellent performance for charged-particle detection in 1965,[5] their use was rather limited for many years. 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 such, in turn, has promoted the commercial availability of germanium charged-particle detectors. 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.

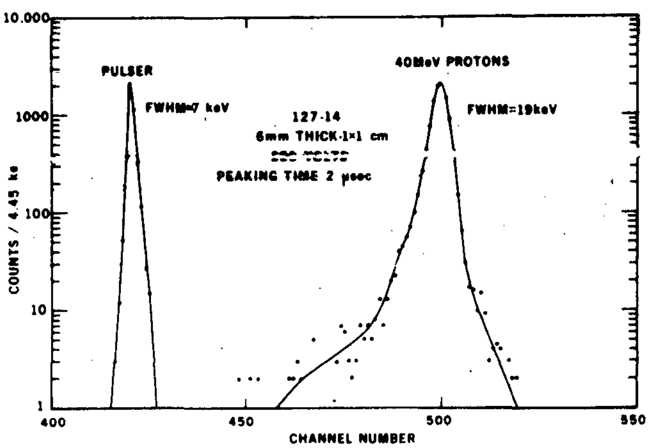

Figure 3. Energy spectrum of 40-MeV protons.

The construction of multi-detector telescopes was spurred by the operation of new high-intensity intermediate-energy accelerators (LAMPF, Indiana, SIN and TRIUMF) which require particle spectrometers having a stopping power greater than that available with a single germanium detector.

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 μm.

Lower diffusion temperatures have been successfully used to produce effective dead layers as thin as 10 μm--acceptable for nearly all spectrometer applications.[6] However, the use of germanium spectrometers at accelerators usually results in radiation damage that necessitates annealing the detectors at temperatures at least as high as 100°C for periods for several days. Lithium mobility at these annealing temperatures is sufficient to cause the effective dead layer to increase significantly to over 250 μm. 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. Even storage and handling at room temperature causes a significant increase of the effective dead layer so lithium-diffused n^+ contacts can lead to problems even when the detectors are not likely to be radiation damaged.

Fortunately, phosphorus ion implanted n^+ contacts have been developed at LBL[7] and Jülich[8] that satisfy the requirements for thin, stable n^+ contacts on high-purity germanium detectors--although at LBL we are still not completely satisfied with the state-of-the-art for these contacts.

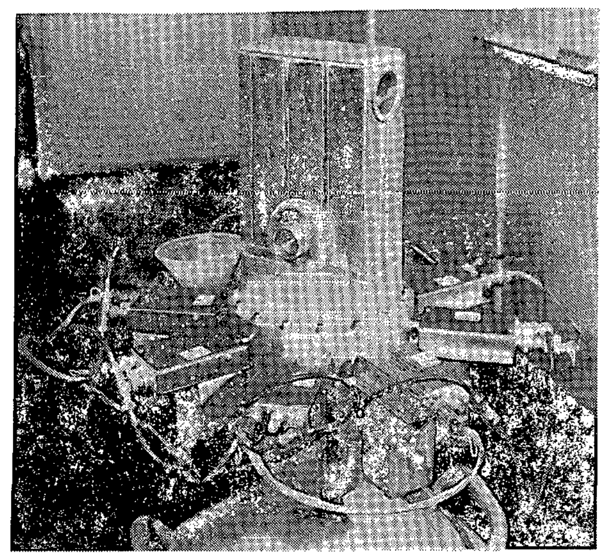

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Figure 4. Cryostat containing an eight-germanium detector telescope for measuring long-range charged particles.

A photograph of the cryostat containing 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 for a number of experiments by an experimental group from Carnegie-Mellon.

Figure 5 shows the detectors in another eight-detector telescope made at LBL for use at LAMPF and SIN by a group from the University of Virginia. The first detector is a 1 mm thick lithium-drifted silicon detector followed by seven germanium detectors, each about 12 mm thick.

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. 6 that has been used very successfully at LAMPF by the experimental group from Carnegie-Mellon.[9] 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.

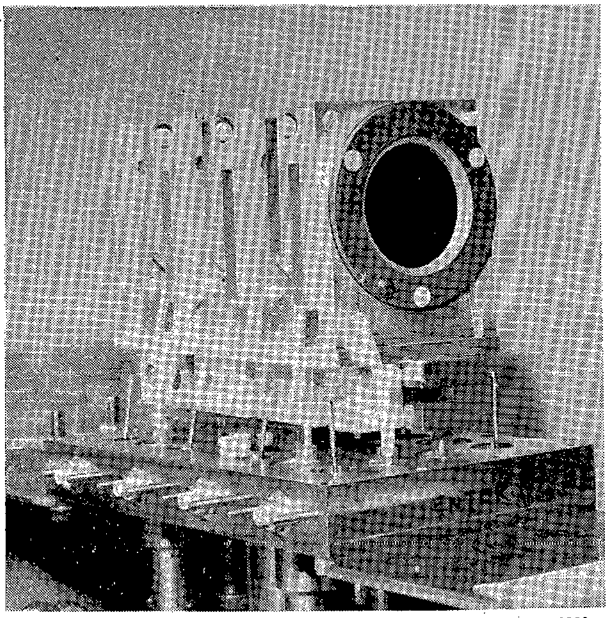

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Figure 5. Eight-detector telescope for measuring long-range charged particles.

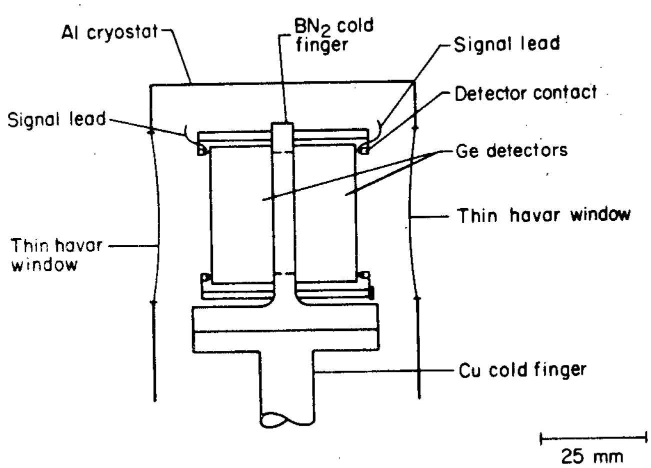

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Figure 6. Schematic of a two-germanium detector telescope.

Indiana University Cyclotron Results

The remainder of this paper will be devoted to the use of germanium detector systems at the Indiana University Cyclotron Facility.[10] This cyclotron produces a variety of light ion beams having an energy of 20 to 200 Q^2/A MeV. Because of this wide variety of intermediate-energy beams and because of the varying requirements of the experimenters using the facility, a fixed geometry closed system telescope was not considered sufficiently flexible.

Therefore, a collaborative program between Indiana and LBL to develop appropriate detector telescope systems was begun in 1976. The following features were sought:

a) high-purity germanium planar detectors of several thicknesses (from 1 to 15 mm), transmission mounted with negligible dead layers on both the entrance and exit surfaces, available to be stacked in any configuration required by the experimenter;
b) provision for the use of thin silicon surface barrier ΔE detectors in front of the germanium detector stack and for large area scintillation veto detectors behind;
c) a simple, fast, and convenient system for vacuum pumping, detector cooling, and in situ annealing at temperatures as high as 150°C to facilitate rapid reuse of radiation-damaged detectors either between or during experiments; and
d) a portable, self-contained system compatible with use in several experimental areas.

The basic components of the telescope/cryostat system design are shown in Fig. 7. The liquid nitrogen dewar is made of a 1.6 mm thick 31 cm diameter stainless steel cylinder and is surrounded by an aluminum vacuum chamber. Six turns of a metal sheathed, glass insulated, nichrome wire heater cable are soldered onto the outer surface of the dewar, which has an 18 liter capacity. A copper cold finger, located at the bottom center of the dewar, contains an iron-constantine thermocouple for monitoring temperature and has a copper detector mounting bracket attached. This assembly is mounted on top of an aluminum detector vacuum chamber which can be fitted with a variety of entrance and exit windows. The entire assembly is vacuum pumped through a 2.5 cm diameter Cajon "O" ring fitting located at the top of the liquid nitrogen dewar housing. The liquid nitrogen fill and vent lines are also attached here with metal seal 1.3 cm Cajon fittings. Stainless steel single braid flexible metal hoses are used to make the vacuum and liquid nitrogen fill line connections from the dewar to the pumping station. Access to the detector vacuum chamber is accomplished via removable side cover plates which permit the mounting of the germanium detectors. Both SHV and BNC hermetically sealed bulkhead feedthroughs are located just below the cover plate for detector signal and bias leads and for the thermocouple and heater cable electrical connections.

The entrance and exit windows of the detector chamber are constructed of 6 μm thick Type-C nickel foils. These windows also serve as a vacuum interface to the outside world allowing the cryostat/detector chamber assembly to operate as a stand-alone system used to perform all off-line detector testing. Provision for mounting the silicon surface barrier E detectors either internally or externally is made. The internal mount is shown in Fig. 7. Collimating aperatures of any type (active or passive) are mounted on the entrance flange, which also retains the thin nickel windows and the silicon detector mount. A plastic scintillator veto detector can be mounted in a reentrant aluminum cup behind the detector stack or an additional high-purity germanium detector can be mounted inside the cryostat for this purpose.

The entire cryostat and detector chamber assembly is designed to mount on radial arms inside a 1.6 m dia scattering chamber and to maintain a vacuum independent from the chamber vacuum. This allows for convenient change of target ladder or telescope collimators, preamps or cables wihout concern about the cryostat vacuum. The flexible metal vacuum and liquid nitrogen fill lines permit rotation of the telescopes

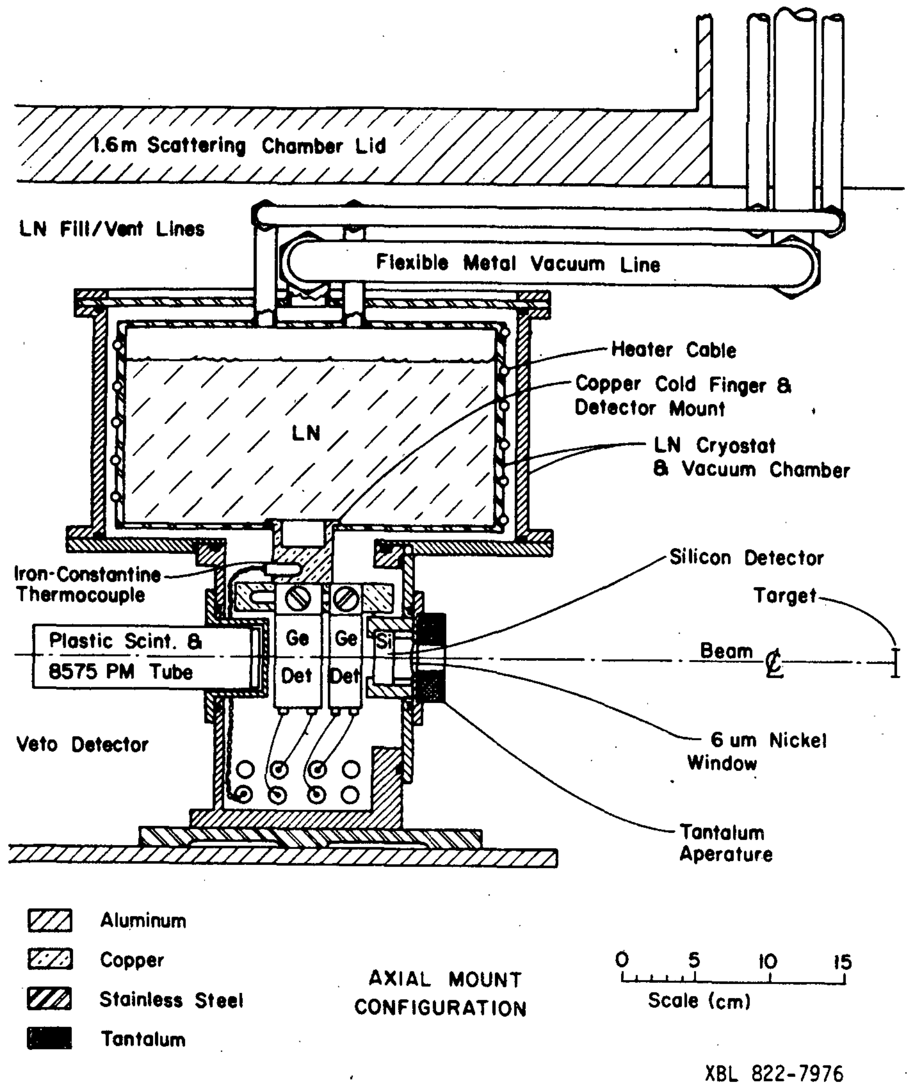

Figure 7. Standard axial mounting configuration of the Indiana germanium detector cryostat.

through 180° in the scattering chamber. The detector cryostats can be (and have been) used outside the 1.6 m scattering chamber and are adaptable to most experimental requirements without modification to much other than the entrance window flange. A dedicated oil-free vacuum pumping station consisting of a sorption roughing pump, a CTI Model 21 cryo-pump and a titanium sublimation ion pump is used to maintain a one μTorr vacuum in the detector chambers. A conventional pumping station using an oil-filled mechanical roughing pump and a Freon baffled diffusion pump has also been used with success.

An important consideration in the telescope system is the design of the germanium detector mount, which must be constructed of high quality vacuum materials, provide the electrical signal and bias connections, and withstand temperature changes from -196°C to +180°C over short time intervals while providing good thermal conduction to the germanium crystal. The mount should also be easily attached to the cryostat cold finger while providing good thermal conductivity. The design developed to meet these requirements is shown in Fig. 8. One of the major features of this mount is that it does not contain any indium, which has a melting point (156.6°C) dangerously close to the desired annealing temperature. Instead, the crystal is held in place by a compression springloaded back plate that allows for expansion and contraction of the crystal during required temperature cycles. Another feature of this design is that the germanium detectors may be easily removed from the mount for repair, if necessary.

The germanium detector cryostats were tested prior to their use to determine their vacuum and thermal properties when cycled over the required temperature range of -196°C to +150°C. The thermocouple in the copper cold finger is used to monitor and control the temperature of the cryostat over this range. A control unit is used to set and control the temperature from +15°C to +150°C to within ±5°C. The 18 liter capacity liquid nitrogen dewar has a holding time of 16 hours when the cryostats are used outside the scattering chamber, and up to 24 hours when mounted inside the scattering chamber. Inside the scattering chamber, the temperature readout of the thermocouple is generally accurate when the dewars are initially filled with liquid nitrogen. After several hours, however, the cryostat reaches thermal equilibrium with the detector chamber and silicon detector mount at approximately -5°C. Because the thermocouple output leads

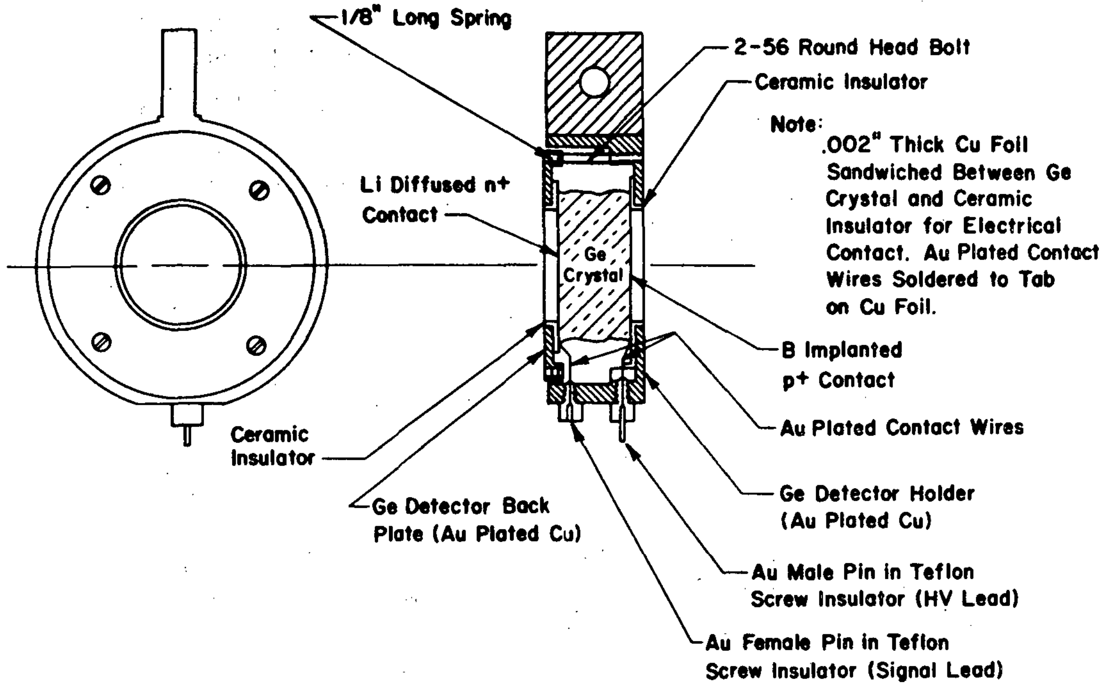

Figure 8. Assembly drawing of the Indiana germanium detector mount.

come through the detector chamber wall on a BNC bulkhead connector, the temperature monitor will be in error by the difference between room temperature and the detector chamber termperature, normally about -25°C. A side benefit of this cooling is that the silicon surface barrier detectors mounted on the entrance flange are also cooled to this temperature, enhancing their operation as well. If the liquid nitrogen is blown out of the dewar with compressed air, the time required to go from a completely filled liquid nitrogen dewar at -196°C to an annealing temperature of +150°C is nearly four hours. The time required to go from +150°C to liquid nitrogen temperature is, of course, much less--about one hour. These rapid temperature changes have produced no adverse effects on either the germanium detectors or the cryostat vacuum integrity. The usual procedure after annealing, however, is to blow room temperature compressed air into the dewar until the cryostats cool to about 50°C before they are filled with liquid nitrogen. This process takes about two hours. After the thermocouple reading has reached liquid nitrogen temperature, the germanium detectors require between 15 and 25 minutes of additional cooling before bias can be applied.

For several years we were troubled by what we thought were surface contamination problems that caused the leakage current on many detectors to increase drastically during the course of some experiments. Great effort was made to improve the vacuum but the problem continued.

In June of 1980 we finally realized what was happening. All our phosphorus ion implanted detectors are made from n-type germanium. Unfortunately, the maximum operating bias we can apply to these detectors is only about 200 V above their depletion voltage. The radiation damage that cannot be avoided during the experiments, and which will vary considerably from experiment to experiment because the beam intensity varies widely from experiment to experiment, creates p-type defects. Consequently, the net impurity concentration $|N_D - N_A|$ decreases during the course of an experiment when detectors made from n-type germanium are used. This, in turn, means the depletion voltage of the detectors must also be decreasing. If the permissible operating voltage above the depletion voltage remains constant (~ 200 V), we soon have a situation where we are attempting to operate the detectors at a voltage in excess of what the contact will allow. For the same reason, when detectors made from p-type germanium are used $|N_A - N_D|$ increases during an experiment causing the depletion voltage of these detectors to increase.

With this picture all of the so called surface problems we had been suffering from for so long could be explained. Furthermore, by appropriately decreasing the bias on transmission detectors during the course of an experiment we could greatly prolong the useful life of these detectors. This little step has made a quantum jump in the effectiveness of the phosphorus ion implanted detectors.

An example of this effect was recently observed in an experiment requiring a high particle flux in a two-element telescope consisting of a 10 mm thick transmission detector fabricated from n-type germanium (Detector #501-6.7) and a 15 mm thick stopping detector fabricated from p-type germanium (Detector #514-8.6). The p-type detector was expected to remain fully depleted during the experiment because this detector could be operated at -2800 V, nearly twice its depletion voltage. The n-type detector, however, had a depletion voltage of -1800 V and a maximum operating voltage of -2100 V, and was, therefore, closely monitored during the experiment.

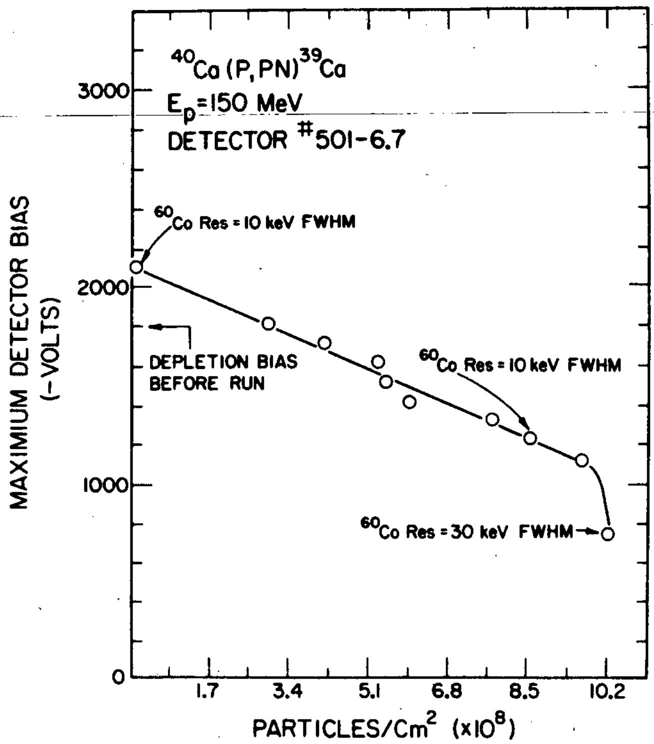

Figure 9. Effect of particle fluence on the maximum bias that could be applied to detector #501-6.7.

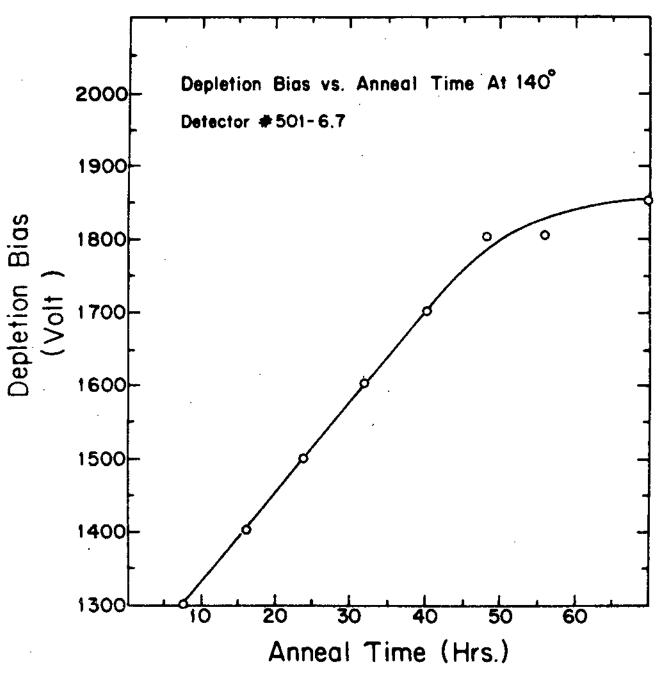

Figure 10. Effect of anneal time at 140°C on the depletion bias of detector #501-6.7.

Figure 9 illustrates the rate at which the bias of this detector had to be lowered as a function of particle fluence--the flux was nearly constant during the experiment. Within the errors of our estimates of the particle flux (about a factor of two), the change in depletion bias was linear with particle fluence. Decreasing the bias in this rather drastic manner did not cause any measurable degradation on the particle resolution. Undoubtedly the detector resolution did become worse during the experiment, but other resolution effects such as kinematic broadening and beam-energy spread were so dominant that the detector contribution remained negligible. This brings up a point that needs emphasizing: to my knowledge, an actual working experiment in which the resolution contribution of a germanium charged-particle detector was a significant part of the total measured resolution has yet to be done.

At the completion of an experiment such as this these detectors are annealed—usually at 140°C. The rate of improvement of the crystal properties, at least as measured by the depletion bias, is shown in Fig. 10. This is typical of many detectors after many different experiments.

The depletion bias of the p-type detector was also measured after the experiment, but, unfortunately, not prior to being warmed to room temperature, and was found to have risen to -2500 V. Fifty hours of annealing also restored this detector to its original depletion bias.

The conclusion from the experience gained at Indiana is that germanium detector telescopes can operate reliably for several days in most intermediate-energy nuclear research applications. Furthermore, these detectors, unlike their silicon counterparts, can be used and re-used indefinitely in spite of radiation damage sustained during each experiment because of the ability to anneal the crystals. This annealing process has not as yet had any adverse effects on the properties or usability of the detectors. A list of the detectors used at Indiana is given in Table I. Nine different germanium detectors have been used in various combinations in over thirty experiments since 1976. Today all these detectors have the same operating properties as when received from LBL.

Acknowledgment

The successful use of high-purity germanium detectors at the Indiana University Cyclotron Facility is largely due to Dennis Friesel. He has provided much of the information presented in the last section of this paper. Many members of the semiconductor group at LBL, both past and present, have provided the base for the charged-particle detector work reviewed here.

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TABLE I

Detector No.	Ge Type	Thickness (mm)	Depletion Bias (-V)	Delta (V)	Radiation Damage Anneal Cycles	Thermal Cycles	Total Anneal Time (hrs)	Li Layer Depth (mm)	Delivery Date
172-3.1	p	10.6	600	>2000	>15	>17	>200	1.13	~ 1976
514-7.0	p	15.21	1700	1300	13	50	752	1.59	3/21/77
514-8.6	p	14.94	1450	1500	26	62	1073	1.10	3/21/77
517-9.7	n	~15	1500	200	16	47	670	NA	8/15/77
550-8.6	n	13.5	700	200	6	14	227	NA	11/30/79
475-10.7	n	9.07	1700	300	4	22	216	NA	8/15/77
501-6.7	n	10.77	1800	300	15	52	768	NA	8/15/77
477-6.1	n	9.52	1750	150	0	2	3	NA	4/21/80
551-11.8	n	5.18	1100	200	1	2	20	NA	4/21/80

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