Title

USE OF HIGH-PURITY GERMANIUM DETECTORS FOR INTERMEDIATE ENERGY PHYSICS EXPERIMENTS

Permalink

https://escholarship.org/uc/item/6qz4866n

Authors

Amann, J.F.
Barnes, P.D.
Dytman, S.A.
et al.

Publication Date

1975-03-01

Submitted to Nuclear Instruments and
Methods

USE OF HIGH-PURITY GERMANIUM DETECTORS FOR INTERMEDIATE ENERGY PHYSICS EXPERIMENTS

J. F. Amann, P. D. Barnes, S. A. Dytman,
J. A. Penkrot, A. C. Thompson, and R. H. Pehl

March 1975

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

Submitted to Nuclear
Instruments and Methods

LBL-3359

USE OF HIGH-PURITY GERMANIUM DETECTORS FOR INTERMEDIATE ENERGY PHYSICS EXPERIMENTS

by

J. F. Amann, P. D. Barnes, S. A. Dytman,
J. A. Penkrot and A. C. Thompson†

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

R. H. Pehl

Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

---

† Presently at the Lawrence Berkeley Laboratory

USE OF HIGH-PURITY GERMANIUM DETECTORS FOR INTERMEDIATE ENERGY PHYSICS EXPERIMENTS*

J. F. Amann, P. D. Barnes, S. A. Dytman,
J. A. Penkrot and A. C. Thompson†

Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

R. H. Pehl

Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

ABSTRACT

The applicability of high-purity germanium detectors for charged particle detection of intermediate energy particles was evaluated with a two detector system. The energy resolution for 100 MeV protons and 50 MeV positive pions was measured. The sensitivity of the detectors to radiation damage was estimated and the repair of the detectors was demonstrated.

---

* This work performed under the auspices of the U. S. Atomic Energy Commission.

† Presently at the Lawrence Berkeley Laboratory

1. Introduction

With the forthcoming operation of new high-intensity intermediate energy accelerators (LAMPF, SIN and TRIUMF), it is important to develop particle spectrometers to utilize the capabilities of these machines. Most high-resolution particle spectrometers use large magnets and complex arrays of proportional or spark chambers. These systems have the disadvantages that they are generally very expensive and only cover a limited energy range at one time. The recent development of large high-purity germanium detectors may make it possible to construct particle spectrometers which will be less expensive and cover a larger energy range at one time than present spectrometers. This type of spectrometer may be useful up to several hundred MeV and have an energy resolution better than 0.1%. These detectors may also be suitable for many experiments (i.e., two arm coincidence measurements) which are difficult to consider with other types of spectrometers.

Until recently, germanium detectors were made by drifting lithium through a germanium crystal to compensate for impurities. These detectors generally were unsuitable for particle detector telescopes because it was very difficult to make large detectors without having large inactive regions in the detector. With the advent of improved refining techniques, crystals can now be produced with less than 10^{10} impurities per cm^3. These crystals do not need to be lithium drifted and may be fabricated directly into detectors. Elimination of the lithium drifting procedure makes detectors easier to fabricate, store and repair since there is no longer any concern about the lithium moving if the detector is not kept cold. High-purity germanium detectors also have a great advantage for charged particle work in that large planar detectors (33 mm diameter by 15 mm thick) can be fabricated with very thin windows so that almost the complete volume is sensitive.

Very few charged particle experiments have been done using germanium detectors. Some work has been done with side entry of Ge(Li) detectors by Bertrand et al 1) at the Oak Ridge cyclotron, by Gruhn et al 2) with 40 MeV protons at the Michigan State cyclotron, by Horowitz and Sherman 3) at the McGill cyclotron and by Sundqvist et al 4) at the Uppsala synchro-cyclotron. There has also been some work with both thin window Ge(Li) and high-purity germanium detectors at the 88 inch cyclotron of the Lawrence Berkeley Laboratory to measure 42 MeV protons 5,6).

In order to evaluate the capabilities of high-purity germanium detectors for intermediate energy physics experiments, we have fabricated a two crystal spectrometer and tested it with beams of protons and positive pions at the Los Alamos Meson Physics Facility (LAMPF).

In the following sections the fabrication and construction of the spectrometer, its general properties, use of it with protons and positive pions and the effect and repair of radiation damage on the Ge detectors will be discussed.

2. Detector Fabrication and Construction

The high-purity germanium crystals used in this system were grown at the Lawrence Berkeley Laboratory 7). Two slices, each 33 mm in diameter and 15 mm thick, were obtained from good sections of two ingots. A palladium

(Pd) contact 0.1 micron thick was evaporated on one end and an n^+ contact was formed on the other by lithium evaporation followed by a low temperature diffusion (180°C). The lithium window thickness was estimated to be about 10 microns for one detector and about 40 microns for the other.

The crystals were mounted as shown in Fig. 1 with the Pd windows facing the cold finger (to minimize the dead layer between the detectors) and held by spring loaded contacts at the periphery of the crystals. The top of the cold finger was made of boron nitride and had a 29 mm center hole. The entrance and exit windows of the cryostat were 50 mm diameter and were made of 25 micron Havar.

High voltage leads were fed separately to the Pd sides of each crystal. The Li contacts were connected through low capacity feedthroughs to separate room temperature FET preamps. With this arrangement the first stage gain of the preamp could easily be changed to optimize the output range and electronic noise by changing the externally mounted RC feedback components. In our tests two RC networks were used--one for high-resolution gamma ray measurements up to 8 MeV and the other for particles depositing up to 300 MeV in each detector. The outputs of the preamps were fed to Tennelec TC205 linear amplifiers to produce slow linear signals and to Ortec 454 timing filter amplifiers followed by Ortec 463 constant fraction discriminators for fast timing signals. The fast timing signals were used in conjunction with scintillator signals to tag the event via a coincidence buffer and to strobe the ADCs. The slow linear signals went to separate Northern Scientific NS623 8192 channel ADCs which were interfaced to a PDP 11/45 computer. The computer read out the ADCs and the event tagging register, taped this data for later detailed analysis and also provided histogram displays of each individual spectrum and of the sum spectrum. A dot plot on a storage scope (Tektronix 4010) with the first detector signal as the absicca and the second detector signal as the ordinate to show particle identification was also available. Figure 2 shows an example of this dot plot where protons and deuterons which stopped in the second detector are clearly separated into two distinct bands.

3. Properties of the System

What are the general properties such as stopping ability, time jitter, energy resolution and solid angle of this spectrometer?

This system has an effective thickness of 30 mm of germanium which will stop 115 MeV protons, 155 MeV deuterons, 185 MeV tritons and 55 MeV pions.

The time jitter is an important property if this type of spectrometer is to be used in a two arm experiment or for measuring time of flight. The time resolution was measured using 300 MeV pions which do not stop in the spectrometer but leave about 11 MeV in each detector. A scintillator was placed just ahead of the cryostat and its signal output was used to start a time-to-amplitude converter which was stopped by the fast timing signal from one of the detectors. The time resolution between the scintillator and either of the detectors was about 600 ps (FWHM). This excellent timing resolution is much better than that measured for Ge detectors with gamma rays because the signal to noise is better. Furthermore, particles of the same energy and type have very similar pulse shapes since they all interact in almost the same fashion within the detectors. This is in contrast to gamma rays for which the pulse shape varies considerably since the event occurs randomly throughout the active volume.

An important contribution to the total spectrometer energy resolution is the energy uncertainty introduced by straggling in the various windows of the system. For 100 MeV protons the present windows (25 microns Havar, 10 microns Ge and 0.2 micron Pd) give a straggling width of 39 keV (FWHM). For special cases where very high resolution is critical, the cryostat window could be reduced to 5 microns Havar. Generally, however, the energy spread in the incident beam and the target thickness will make this unnecessary.

What is the ultimate energy resolution of this spectrometer? Using a Fano factor of 0.12 the detector resolution for 100 MeV protons would be 14 keV (FWHM). If the electronic noise is better than 5 keV, the possible resolution of the detector is 15 keV at 100 MeV. Straggling in the windows, as discussed above, of 39 keV broadens the possible energy resolution of our present spectrometer to about 42 keV (or 0.04%). It was not possible to measure this resolution because present beams at LAMPF do not have sufficient energy resolution. The resolution of the two detectors for ^{60}Co gamma rays was measured to be 2.1 and 2.5 keV at a bias of 2500 volts.

The solid angle of this system is determined by the diameter of the cold finger hole (29 mm). Particles which pass through the cold finger material have a lower energy loss in the second germanium detector than expected and therefore must be carefully removed to avoid spurious peaks in the energy spectrum. There are several ways in which this can be achieved. A thick metal collimator can be placed in front of the detector with a hole smaller than the cold finger hole. This method has the disadvantage that particles may scatter from the edges of the collimator into the detector. A second technique is to use a scintillator with a hole in it to replace the collimator and to electronically reject or tag those events which are associated with a scintillator pulse. Another method is to use multiwire proportional chambers to measure the particle position and trajectory. This technique allows the solid angle to be optimized since events can be sorted by the computer later to separate those events near the cold finger. We have successfully tested all three methods.

Not all particles observed actually stop in the detector. Therefore we have placed a 7.5 cm diameter scintillator just behind the exit window of the cryostat to veto or tag those events which traverse the detector but do not stop. A crude energy analysis and particle identification is possible on these events so normally these events are stored on magnetic tape along with the stopping events and studied later to estimate the high energy part of the particle spectra.

4. Detection of Protons

With the present LAMPF beam lines it is impossible to measure the intrinsic resolution of this spectrometer for charged particles. In order to study the general properties of this system, we used the P^3 channel at LAMPF and tuned it for 450 MeV/c positive particles (i.e., 102 MeV protons) from the pion production target. This channel has a design momentum resolution of 0.25% ($\Delta p/p$) which corresponds to an energy resolution of 486 keV for 102 MeV protons. Our spectrometer was placed directly in the highly collimated beam (about 5 k/sec instantaneous rate). A thick brass collimator with a 3/4 inch hole was placed in front of the detector to eliminate particles which might strike the cold finger. The resulting total energy spectrum with an energy resolution of 510 keV (FWHM) at 100 MeV is shown in Fig. 3. This resolution was limited primarily by the P^3 channel (in fact it served as confirmation of the channel resolution) and not by the germanium detectors.

The integrated number of events in the low energy tail from 40 MeV to 101 MeV was measured to be 9.2% ±0.3% of the number in the peak. This result agrees well with calculations by Measday and Richard-Serre^8) and by Makino et al^9) who estimate the low energy tail from nuclear interactions to be about 9% for 100 MeV protons. As well as being a rather small percentage, the distribution of events in the tail is smooth (since natural germanium has many isotopes with many excited states), which will make studies of inelastic scattering much easier than if the distribution contained peaks as have been seen with silicon detectors at lower energy^10).

5. Detection of Positive Pions

The use of this detector for positive pions presents special problems since the pion decays to a muon and neutrino with a lifetime of 26 ns and the muon then decays to a positron and two neutrinos with a lifetime of 2.2 μs. We have tested our detector with 50 MeV π^+ from the LEP channel at the LAMPF accelerator. The raw summed energy spectrum is shown in

Fig. 4. Since the detector collection time, about 100 ns, is much greater than the pion lifetime, the output pulse when a pion slows down and stops will almost always contain 4.12 MeV additional energy from the kinetic energy of the stopping muon as well as the original energy of the pion. When the muon decays, there will be a further pulse of varying energy (up to 50 MeV) from the energy loss of the positron in the detector. Some of the positrons will stop in the detector while some will escape.

The additional pulse from the pion to muon decay does not degrade the resolution since it almost always is there and is of fixed energy. The pulse from the muon to positron decay, on the other hand, produces a variable energy pulse which produces a high energy tail on the pion spectrum. This tail pulse can be reduced in several ways. One method is to reduce the amplifier integration time constant. By changing the time constant from 1 μs to 0.25 μs the ratio of counts in the pion peak to those in the high energy tail was improved from 1.7 to 3.6 without noticably degrading the energy resolution. As higher quality beams become available degradation of the peak resolution may become noticable at the short time constants due to incomplete charge collection. A second method to reduce the tail is to surround the sides and rear of the germanium detector with a scintillator to detect those positrons which escape. Events which have a scintillator pulse within 2 μs after the pion pulse are then vetoed electronically or tagged and separated later by computer. A third technique is to look for the second pulse (from the positron) in the germanium detector by connecting the output of the constant fraction discriminator to a pileup gate and vetoing those events which have a second pulse within 2 μs of the first. Changing the amplifier time constant moves events from the tail into the pion peak (increases the pion peak efficiency) but using a scintillator and/or a pileup gate only eliminates events in the spectrum tail from the final spectrum (no change in the pion peak efficiency). We have combined all three techniques and have obtained the improved spectrum shown in Fig. 5. The energy resolution of the pion peak is about 500 keV and is due primarily to the pion channel rather than the detector resolution.

6. Radiation Damage

An important consideration for the use of Ge detectors around intermediate energy accelerators is the sensitivity of these detectors to radiation damage (primarily from neutrons).[11)]

During the testing of this system the detectors were exposed to a total neutron dose of about 1 x 10^9 n/cm^2. The gamma ray resolution of both detectors was degraded from about 2.2 keV to 16 keV (FWHM) at 1.3 MeV. Due to the limited resolution of present beams at the LAMPF, we were unable to measure any effects of this radiation damage on the charged particle resolution. Since radiation damage produces trapping centers in the germanium crystals, the energy resolution is probably still proportional to the square root of the deposited energy. Therefore, in many experiments considerable degradation of the energy resolution will be acceptable because the experimental resolution will be limited by beam and target properties.

Once serious radiation damage has occurred, is it possible to easily repair the detectors? We have developed a procedure for repairing the germanium detectors without removing them from the cryostat. The system is first connected to a high vacuum pumping station; the cold finger is then removed from the liquid nitrogen dewar and placed in a flask of water that is gradually heated to boiling (91°C at Los Alamos Scientific Lab). After a number of hours the procedure is reversed and the detector resolution and capacitance as a function of voltage are measured. During the first cycle the detectors were warmed to only room temperature for 60 hours and then tested. The detectors were then recycled to 91°C for 60 hours, tested, and then cycled again until they had been at 91°C for a total of 300 hours. As can be seen in Fig. 6, the resolution was dramatically degraded after the first treatment but successive treatments gradually restored the detector resolution to 4 keV after 300 hours at 91°C.

However, following this treatment the thickness of the Li contact was measured with a ^{207}Bi source and found to have increased from about 40 microns to over 250 microns. With such long times at 91°C the Li ions were mobile enough to migrate considerably. This is a very serious problem for our spectrometer since the charged particles traverse the various Li and Pd windows and a thick window produces a large energy straggling. If a window contact other than Li can be developed, the prospect of using these detectors until they show serious radiation damage and then repairing them within the cryostat appears very promising.

7. Summary

From our experience with a two detector system, we are very optimistic about the use of high-purity germanium detectors for charged particle spectrometers. They will provide high energy resolution (better than 0.1%) and good particle identification for stable charged particles up to several hundred MeV. The high energy limit of these spectrometers will be determined by the large amount of germanium necessary to stop energetic particles and the rapid increase of the low-energy nuclear interaction tail with incident energy. They can also be used for positive pion detection where special electronic techniques are necessary to reduce the high energy tail from muon decay. The excellent timing resolution available with these detectors may make them very useful for time-of-flight or two-arm coincidence experiments.

Radiation damage may limit the application of these detectors. Total fluxes of about 10^9 n/cm^2 seriously degrade the gamma ray resolution but levels somewhat above this may be tolerable with charged particle spectrometers where the resolution may not be as crucial. If a different n^+ contact for germanium can be developed, repair of the damage can be done fairly easily without removing the detectors from the cryostat.

Acknowledgments

It is a pleasure to acknowledge the assistance of R. Cordi, F. Goulding, W. Hansen, E. Haller, D. Landis and D. Malone in the design and construction of the germanium spectrometer. We also wish to thank R. Eisenstein and R. Macek for assistance with the data taking and the LAMPF operations personnel for their care and efforts in providing us with beam. One of us (PDB) wishes to thank the Meson Physics Division for their hospitality during his leave of absence from Carnegie-Mellon University.

References

1) F. E. Bertrand, W. R. Burrus, N. W. Hill, T. A. Love and R. W. Peelle, Nucl. Instr. and Meth. 101 (1972) 475.

2) C. R. Gruhn, T. Kuo, C. Maggiore, B. Preedom, L. Sammelson and J. Chander, IEEE Trans. Nucl. Sci. NS-15, No. 3 (1968) 337.

3) Y. S. Horowitz and N. K. Sherman, Can. J. Phys. 45 (1967) 3265.

4) B. Sundquist, E. Hagberg and P. Grafstrom, Nucl. Instr. and Meth. 94 (1971) 343.

5) R. H. Pehl, D. A. Landis and F. S. Goulding, IEEE Trans. Nucl. Sci. NS-13, No. 3 (1966) 274.

6) A. D. Bacher, W. T. Sloan, D. G. Kovar and R. H. Pehl, Bull. Am. Phys. Soc. Series II, 19 (1974) 529.

7) W. L. Hansen and E. E. Haller, IEEE Trans. Nucl. Sci. NS-21, No. 1 (1973) 251.

8) D. F. Measday and C. Richard-Serre, Nucl. Instr. and Meth. 76 (1969) 45.

9) M. Q. Makino, C. N. Waddell and R. M. Eisberg, Nucl. Instr. and Meth. 60 (1968) 109.

10) M. Makino, R. Eisberg, K. Richie, R. Carlson and C. Waddell, Nucl. Instr. and Meth. 80 (1970) 299.

11) H. W. Kraner, R. H. Pehl and E. E. Haller, "Fast Neutron Radiation Damage of High-Purity Germanium Detectors" Report No. BNL-19488, to be published in IEEE Trans. on Nucl. Sci. NS-22 (1975).

Figure Captions

Fig. 1. Arrangement of germanium detectors in the cryostat.

Fig. 2. Example of particle identification dot plot generated with detectors at 90° to an 800 MeV proton beam on a Mg target. The events indicated by 1, 2 and 3 are protons, deuterons and tritons respectively which stopped in the second detector. Events labeled by 4 are particles which traversed the detector but did not stop. Those events near 5 are probably from pions which stopped in the second detector. The part of the figure below the diagonal line was collected for about 1/5 of the time of the rest of the figure to prevent dot saturation.

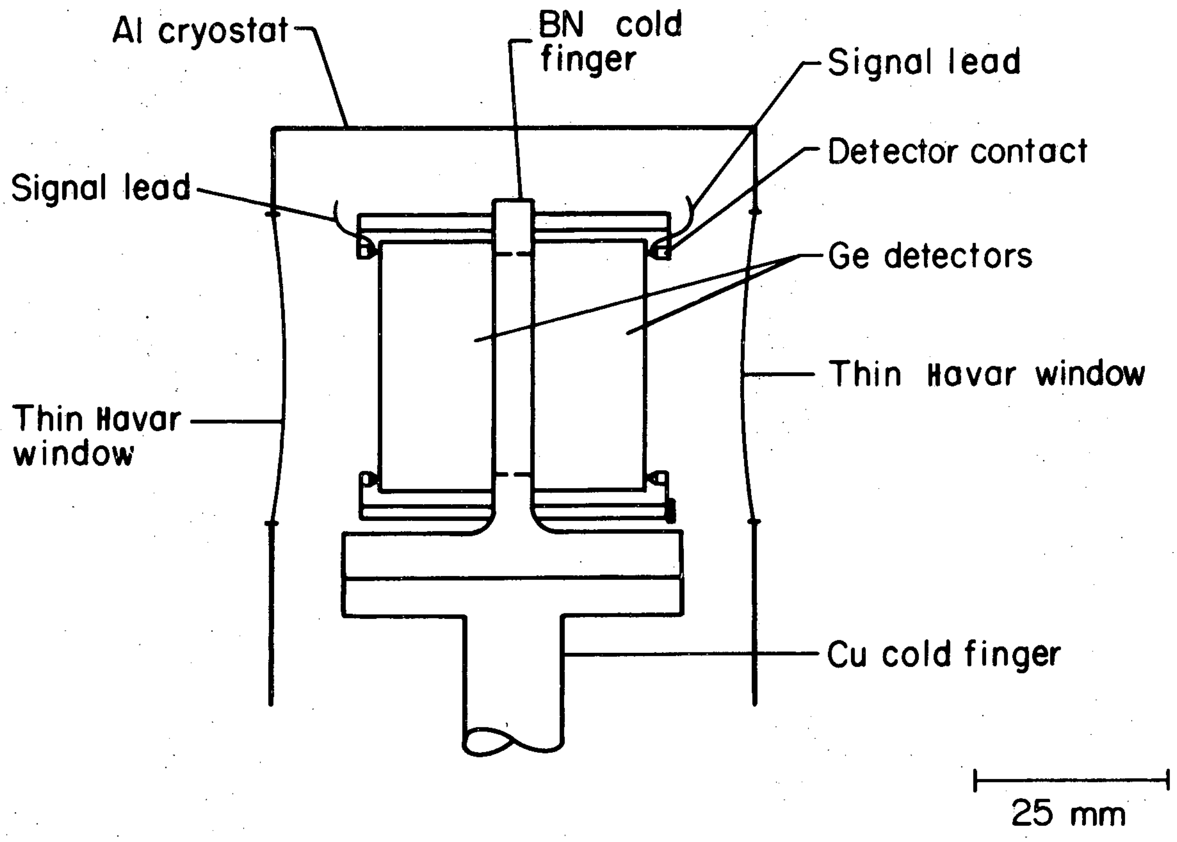
Fig. 3. Energy spectrum observed with the detector in a 102 MeV proton beam. The peak around 25 MeV is from minimum ionizing particles (pions, muons, etc.) also in the beam.

Fig. 4. Raw energy spectrum measured with the detector in a 50 MeV ($\Delta p/p$ = 2%) pion beam at LAMPF. The amplifier time constant was 1 μs. The broad peak around 35 MeV is from the background of muons of positrons which do not stop in the detector.

Fig. 5. Improved pion energy spectrum with a peak resolution of 500 keV (FWHM). The pion channel resolution was improved to $\Delta p/p$ = ± 0.10%. The muon decay tail and background events were reduced by using an amplifier time constant of 0.25 μs, veto scintillators and a pile-up gate.

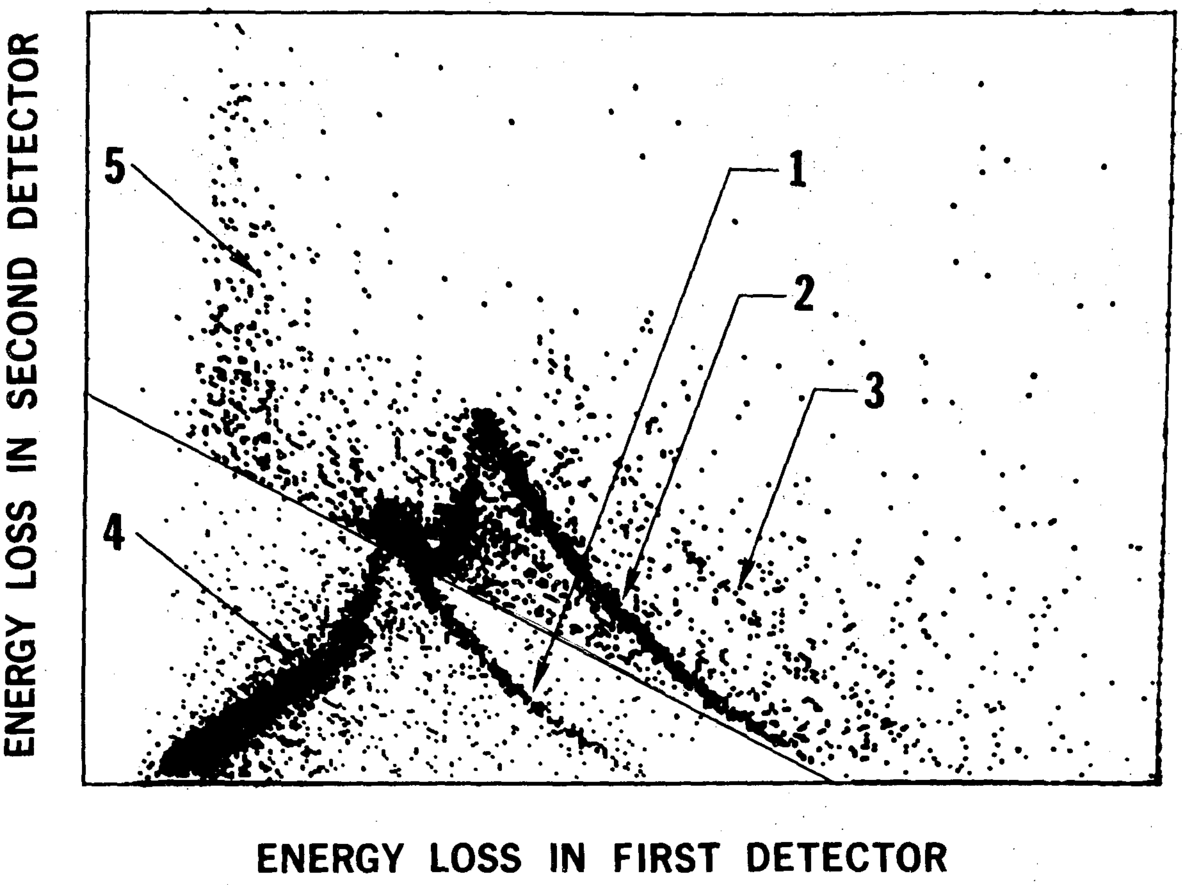
Figure Captions (Continued)

Fig. 6. Shape of the 1332 keV ^{60}Co peak from one of the germanium detectors before, during and after treatment for radiation damage.



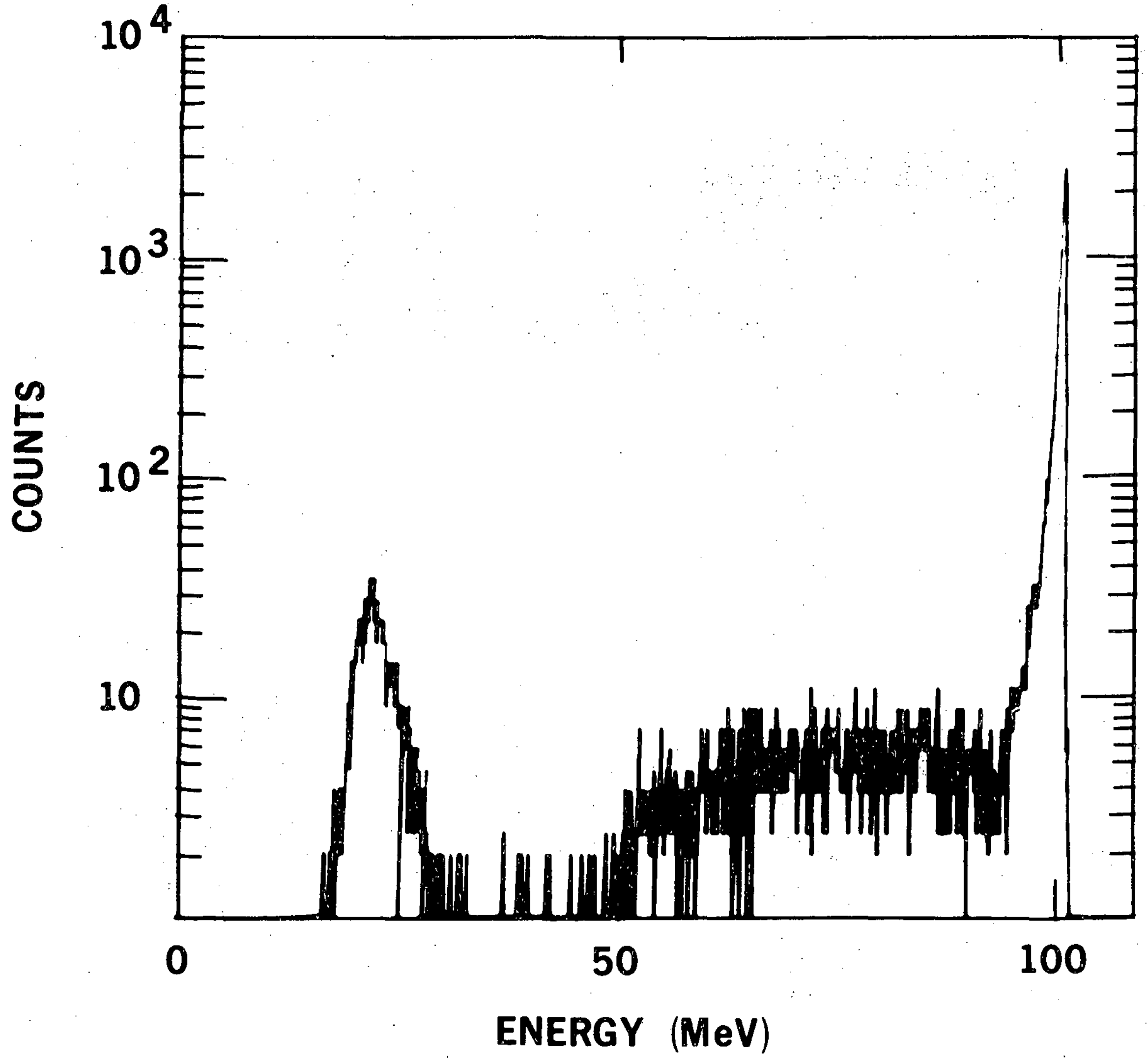
XBL 7411-8021

Fig. 1



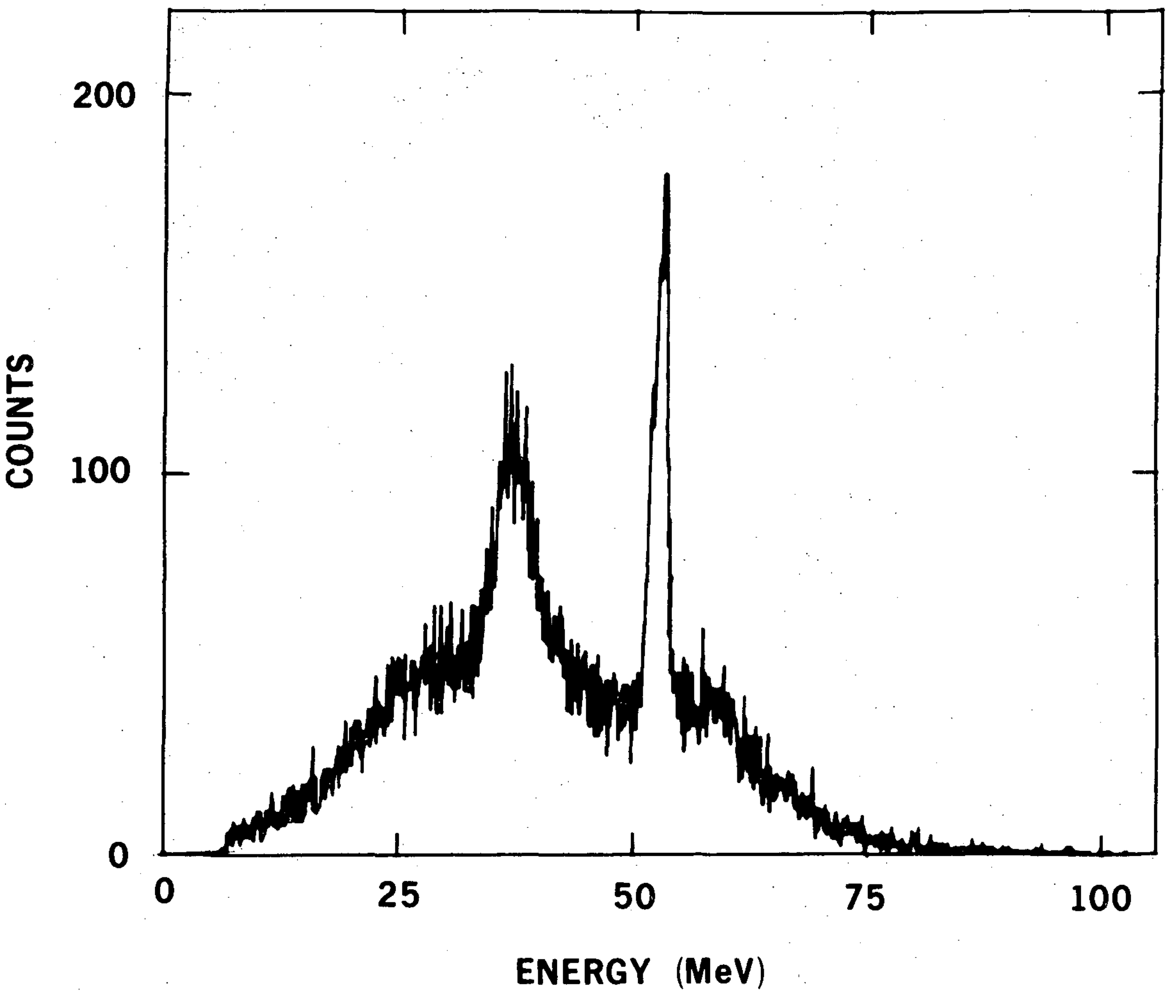
XBL 7411-8020

Fig. 2



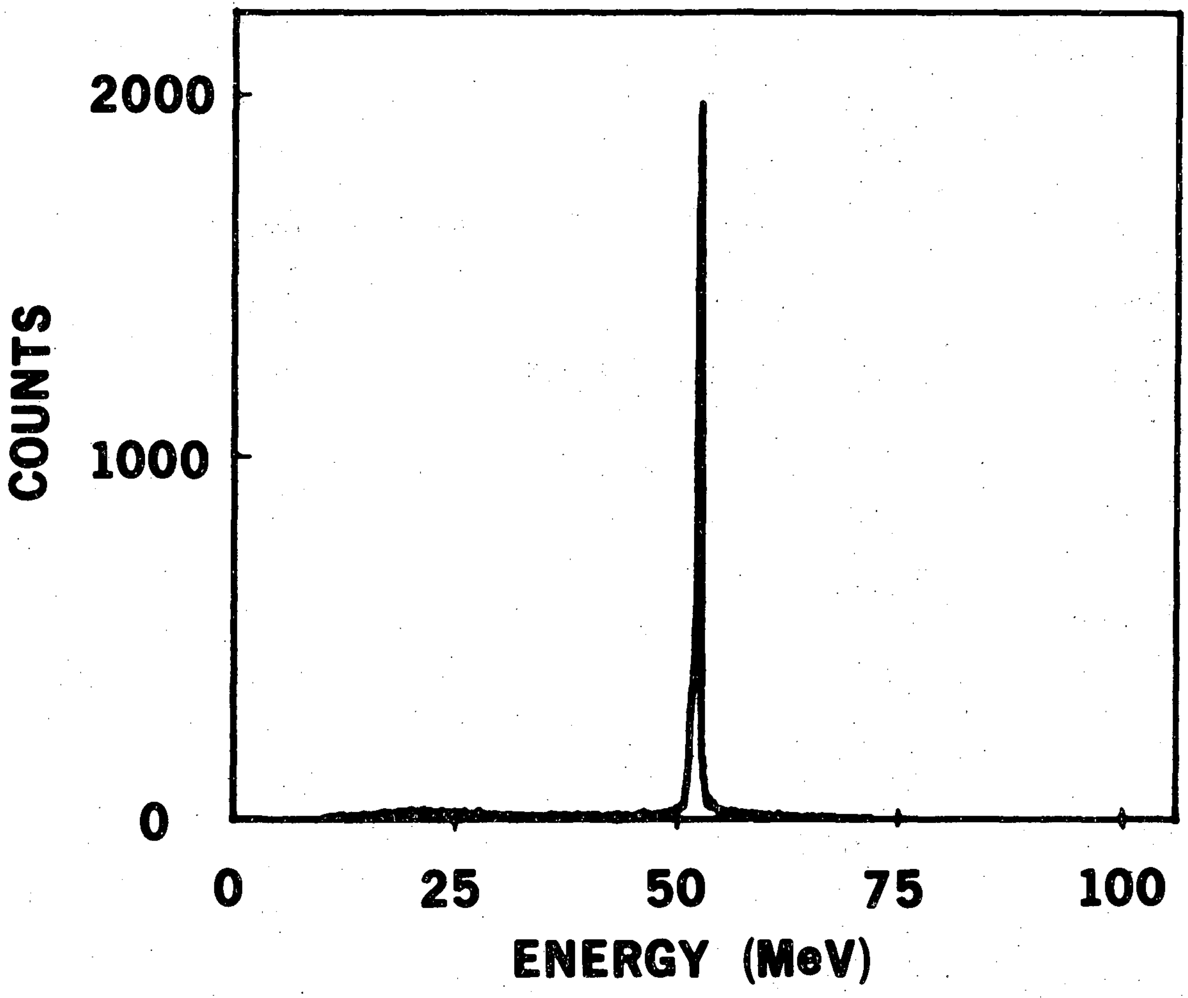
XBL 7411-8019

Fig. 3



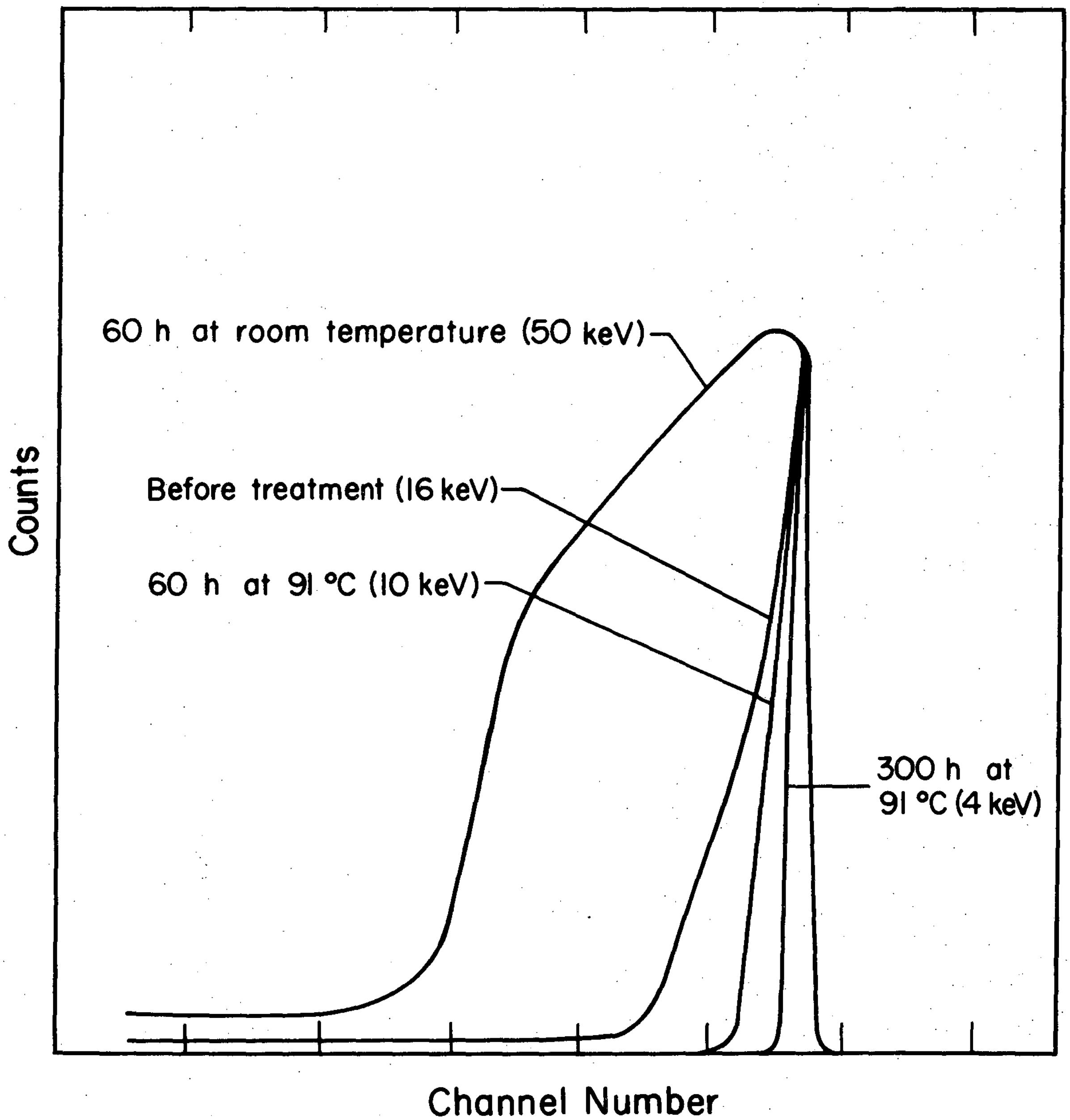
XBL 7411-8018

Fig. 4



XBL 752-316

Fig. 5



XBL 7411-8022

Fig. 6

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720