For this study 1 cm^2 Hamamatsu 1723-06 PDs, which have fairly good green light sensitivity were coupled to 1 cm thick CsI(Tl) crystals (maximum emission at 540 nm). The output was amplified using an Ortec 142B preamp and 472 amplifier. With this setup and using a ^{22}Na source the results were very poor. The signal to noise ratio was 1.25:1. Wrapping the detector in Al foil greatly reduced the noise. It was found that a shaping time constant of 6 μsec gave the best resolution.

The results are very promising. The resolution of the 1.27 MeV line of ^{22}Na was 8.6%, similar to what one gets with a PMT. Tests with alpha sources in vacuum also gave good results. The resolution of the 5.49 MeV alpha from ^{241}Am was 5.3%. The resolution of the 7.68 MeV alpha from ^{214}Po was 4.7%.

Future investigations will center on using different scintillators such as $CdWO_4$ which is non-hygroscopic and has a density 1.8 times greater than CsI(Tl).

GERMANIUM DETECTOR DEVELOPMENT

D.L. Friesel, K. Komisarcik, R.H. Pehl, and Jingxu Xing

The NASA funded IUCF-LBL collaboration to study the charged-particle radiation damage rate effects in high-purity germanium detectors has continued into its third year. During the first 6 months of 1987, the development of the low intensity beam facility continued with good results. The large area, low intensity beams previously achieved with the primary beam from the cyclotrons and described in last year's report were reproduced using beams split from another user. A re-location of the 1000 mg/cm^2 lead diffuser foil and a four jaw slit assembly in beam line 4 to the Gamma cave was required to permit precise adjustment of the particle flux at the target area. With this change, particle flux adjustments between 50 and 10^5 protons/cm^2/sec were demonstrated on target using both the primary and split beams from the cyclotrons. The beam area at the target was 25 cm^2 with a measured density variation over this area of about 12%. When operating with split beam, this flux variation could be achieved by adjusting the slit width in beam line 4 while maintaining a constant 50 nA of beam on the target of the primary user. The more recent installation of the Buncher Phase Modulator system, explained in the Accelerator Performance section of this report, also made independent adjustment of the beam intensity ratio on the two targets of split beam users adjustable by a factor of ten. This new device, coupled with the system described above, has made the delivery of these low intensity beams with the beam splitter system quite routine. This capability has been used by several other experimenters for detector testing in addition to the use for our germanium detector radiation damage studies.

The two production runs for experiment E267, which were planned to study the radiation damage rate effects on high-purity germanium detectors, were conducted in February and in May of 1987. During the February run, 10 shifts of primary beam were used to irradiate 8 planar germanium detectors in 3 variable temperature cryostats, which were specifically designed and constructed at LBL for this study, with a 160 MeV proton beam at fluxes of 1×10^4 and 5×10^4 protons/cm^2/sec. Four detectors, two at nominal LN_2 temperature and two at room temperature, were simultaneously irradiated to 1.4×10^9 protons/cm^2 at a flux of 1×10^4 protons /cm^2/sec. A second set of four detectors, again two at LN_2 and two at room temperature, were similarly irradiated to 1.6×10^9 protons/cm^2 at a 5 times higher flux. All the detectors maintained at LN_2 temperature were monitored periodically during the irradiation to observe the change in ^{60}Co resolution with particle fluence. One immediate result from this run was that the resolution of the detectors irradiated at room temperature were significantly worse than those irradiated at LN_2 temperature, as expected from previous experiments. Also, there was no change in the observed rate of deterioration of detector performance with particle flux during this run. However, the detectors in the new variable temperature cryostats #1, #2, and #3, were able to maintain their good resolution for a particle fluence nearly 10 times higher than detector #280-1.0 in the older style LBL cryostat #102, which was observed in a test run here in December of 1986, and reported in last year's annual report. Furthermore, the data obtained then agreed well with other radiation damage studies made with this same detector/cryostat combination at the University of Maryland cyclotron in 1980 using a 100 MeV proton beam. This agreement is illustrated in the upper curve of Fig. 1, which is a plot of the resolution of detector #280-1.0 as a function of particle fluence for these two runs. The

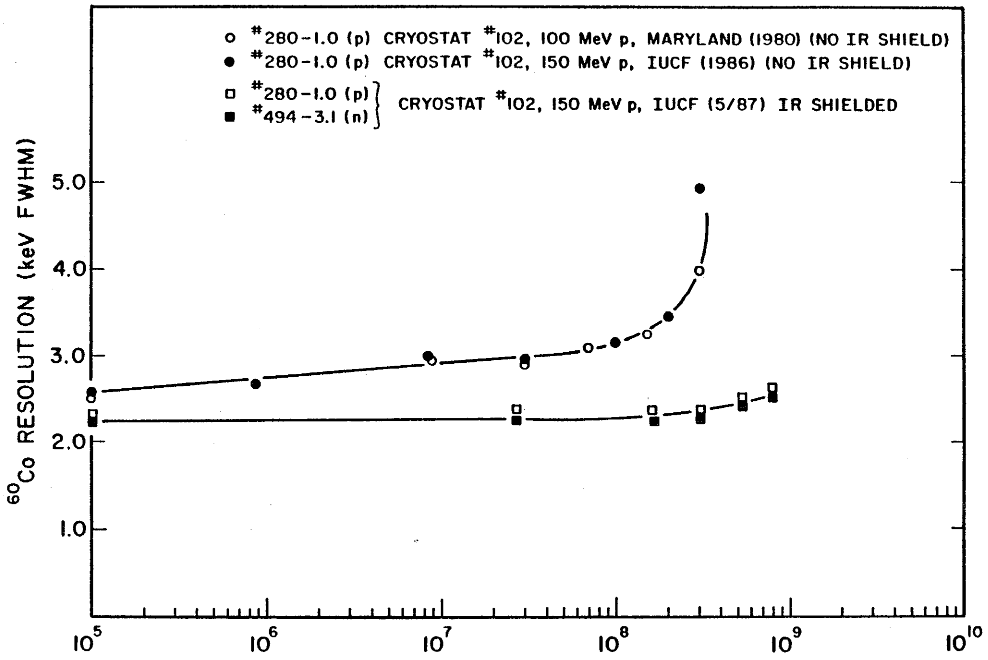

Figure 1. Radiation damage, as measured by the fwhm of a ^{60}Co source peak, shown as a function of particle fluence. The data has been separated into groups, measured with (squares) and without (circles) an IR shield.

temperature calibration of the two cryostat types was subsequently checked carefully, and the detectors in all cryostats were irradiated at nearly identical temperatures of 84 °K. The only difference between the new cryostats and the older style cryostat #102 was that cryostat #102 did not have an IR shield surrounding the detector. As will be seen later in this report, this was the surprising cause of the performance difference observed.

The second production run for this experiment occurred on May 21. The three new IUCF-LBL cryostats and 8 detectors used in the first run were returned to LBL for radiation damage repair, refurbishment, and rearrangement for optimal information gain during this run. Each variable temperature cryostat was fitted with an n-type and a p-type germanium detector to determine any behavioral differences during irradiation and annealing. The fabrication of a fourth IUCF-LBL variable temperature cryostat was completed in time for this run as well, and it too was fitted with an n- and a p-type detector. Also, an IR shield was fitted around detector #280-1.0 in cryostat #102 in an attempt to resolve the fluence/resolution differences observed between the detectors mounted in the two cryostat types. Hence, 5 cryostats housing a total of 9 detectors were on hand for irradiation during this run.

The primary goal of this run was to continue measuring the effect of increasing proton flux on the rate of deterioration of detector resolution as a function of particle fluence. To this end, the detectors in cryostat #1 were irradiated with a 150 MeV proton beam at a flux of 5×10^5 protons/cm^2/sec to a fluence of 1.3×10^9 particles/cm^2. This is the highest particle flux at which one might reasonably expect to operate a germanium detector telescope in an intermediate energy nuclear physics experiment, and a much higher flux than that produced by solar flares in space. The rate of detector resolution degradation with particle fluence for this run was identical to those measured at lower fluences in the February run. There was no measurable difference in the performance of the n- and p-type detectors as well. Hence, we have demonstrated that the resolution degradation of high purity germanium detectors is dependent only on the total fluence of the incident particle, and not on the flux, at least up to the a flux of 5×10^5 particles/cm^2/sec. The ^{60}Co resolution data for the 6 detectors irradiated at the 3 different particle fluences are shown in Fig. 2, and for all particle purposes, are identical.

The second priority of this run was to resolve the discrepancy observed during the February run between the resolution performance of the detectors in the older style LBL cryostat #102, and those in the new IUCF-LBL cryostats, discussed above. To accomplish this, cryostat #102, which had been modified by the addition of an IR shield, and which also had a second detector, #494-3.1, added for redundancy, was irradiated at a flux of 1.2×10^5 protons/cm^2/sec to a fluence of 1.1×10^9 protons/cm^2. The resolution performance of these detectors in this run as a function of fluence are also plotted in Fig. 1 for comparison with the data taken previously without the IR shield, and are in excellent agreement with the data shown in Fig. 2 for the new IUCF-LBL variable temperature cryostats. Hence, we are convinced that the discrepancy has been resolved, and that the use of an IR shield has a pronounced beneficial effect on the longevity of germanium gamma ray detectors in a particle radiation environment. This comes as somewhat of a surprise to us, and we cannot immediately explain why the IR shield has such a major effect. This result has a significant impact upon the conclusions drawn from previous measurements

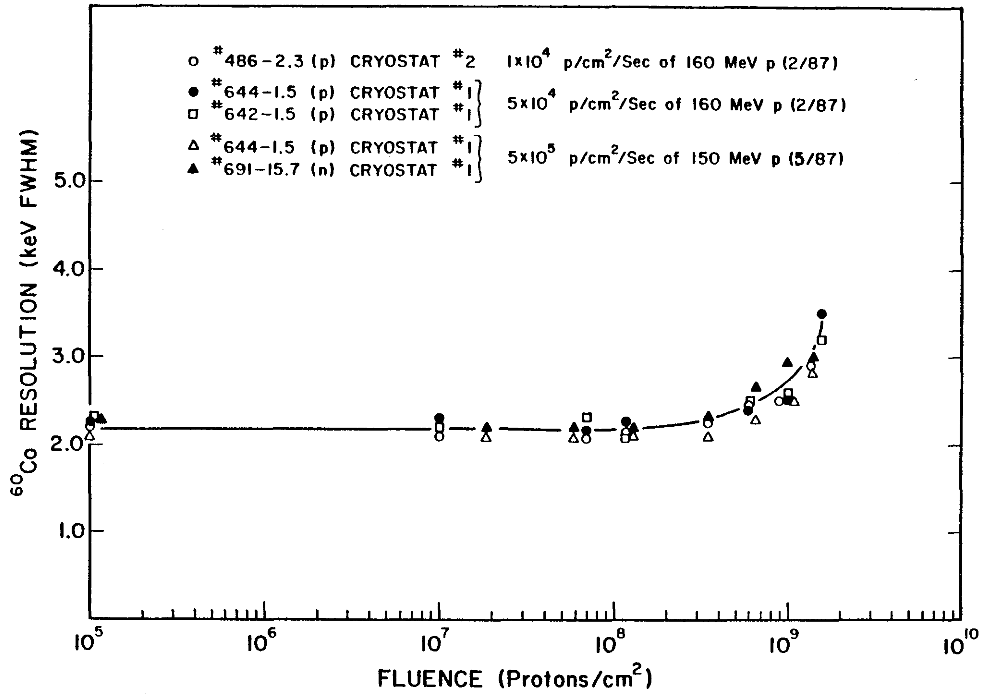

Figure 2. Radiation damage, as measured by the fwhm of a ^{60}Co source peak, shown as a function of particle fluence.

of the comparison between the damaging effects of protons and neutrons. The earlier proton damage studies were all made with cryostats similar to #102, with no IR shield, while all the cryostats used for studying the effects of neutron damage on the properties of germanium detectors were fitted with IR shields. The studies showed that germanium detectors could withstand about a 60 times larger fluence of neutrons than charged particles for a comparable detector performance deterioration. Hence part of this observed neutron/proton difference was caused by the presence of the IR shield on the cryostats used in the neutron damage studies. Also, the neutron damage studies were conducted using a neutron source, and the energies of these particles were considerably lower than the 150 MeV protons used for our study. The energy dependence of the damaging effects of radiation of the performance of germanium detectors is not well known. It would now be interesting to compare these proton radiation damage results with similar measurements using high energy neutron beams, such as those available at the beam swinger or PNF facilities here.

Another test made during the May run was to measure the effect of lower operating temperature on the longevity of germanium detectors in a charged particle environment. To achieve the lower temperature, the LN_2 dewar on one of the variable temperature cryostats was pumped to below atmospheric pressure with a mechanical roughing pump. This caused the temperature of the detectors in the cryostat to drop to 77 °K. The cryostat was maintained at this temperature while being irradiated to a fluence of

3.1×10^9 protons/cm^2. The resolution performance of the p-type detector in this cryostat is compared with our previous data taken at 84 °K in Fig. 3. While there appears to be a measurable improvement in the radiation damage resistance of the detector operating at cooler temperatures, the improvement may be too small to warrant the increased complexity.

Radiation damage annealing studies have been continuing at IUCF with the detectors irradiated in the May run, but have yielded some interesting preliminary results as well. First, there has been no observed difference in the time required to anneal n-type compared to p-type detectors to their pre-irradiation resolution and depletion bias levels. This was unexpected based on the data we reported in the 1982 annual report.[1] Also, for detectors which have been irradiated to proton fluences of 10^9 protons/cm^2 or more, an anneal temperature of 100 °C or higher is required to completely repair the radiation damage effects. Also, the rate of repair increases significantly as the annealing temperature is raised to 150 °C.

The use of high-purity germanium detectors for experiments continued at IUCF this year at about the same pace experienced in previous years. There are 14 high-purity planar detectors with thicknesses ranging from 5 to 20 mm and 4 detector cryostats available here for experiment. These detectors and their properties are listed in Table I.

1. 1982 IUCF Scientific and Technical Report, p. 215.

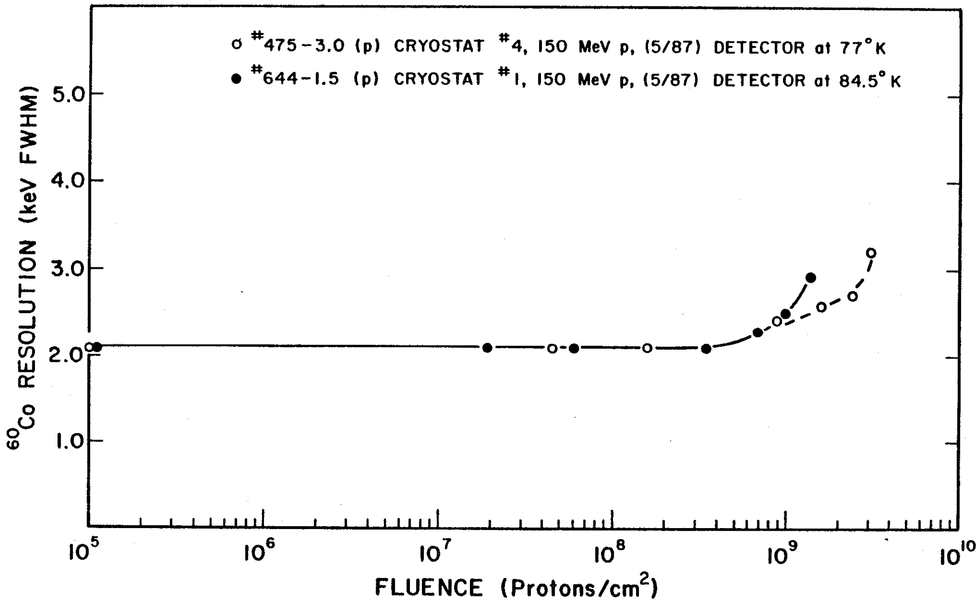

Figure 3. Radiation damage, as measured by the fwhm of a ^{60}Co source peak, shown as a function of particle fluence. The cryostat temperature was 77 °K (open circles) or 84.5 °K (dots).

Table I. IUCF Germanium Detector List

Detector No.	Ge Type	Thickness (mm)	Impurity Concent. ($\times 10^{10}$cm^{-3})	Depl. Bias (–V)	Total Hrs Beam Time	Li Layer Depth mm
TRANSMISSION DETECTORS						
501 - 9.3	n	~ 2.0	4.4	100	352	NA
501 - 9.6	n	~ 2.0	4.4	100	352	NA
551 - 11.8	n	5.18	7.5	1100	200	NA
475 - 10.7	n	9.07	3.3	1700	1404	NA
477 - 6.1	n	9.52	2.0	1000	928	NA
501 - 6.7	n	10.77	2.7	1800	2155	NA
474 - 5.8	n	~ 12.0	1.6	1600	469	NA
550 - 10.0	n	~ 13.0	2.4	2200	1210	NA
517 - 9.7	n	~ 15.0	1.2	1500	2120	NA
STOPPING DETECTORS						
172 - 3.1	p	10.6	0.98	350	721	1.23
514 - 7.0	p	~15.21	1.86	1600	2482	2.90
514 - 8.6	p	14.94	1.10	1200	2549	3.60
525 - 8.6	p	~12.0	1.10	1000	56	1.06
602 - 6.1	n	~20.0	0.75	1700	289	2.80