At the time of this report, the four segments with their light guides and phototubes have been polished, glued and wrapped in the IUCF scintillator shop. Hardware for the support frame has also been machined at IUCF and is now being assembled, and the detector will be mounted in the A region of the Cooler during the next access period. One quadrant has already been tested with cosmic rays and with 430-MeV beam protons, and preliminary results show the expected performance.

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GAMMA-RAY ESCAPE-PEAK RESPONSE FROM A RADIATION-DAMAGED REVERSE-ELECTRODE COAXIAL GERMANIUM DETECTOR

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The effects of radiation-damage induced-hole trapping on the resolution of escape peaks compared to ordinary, multiple Compton and photoelectrically interacting, full-energy gamma-ray peaks from a reverse-electrode (n-type) germanium detector are studied. Coaxial detector geometry is the dominant factor, causing charge collection to be dramatically better near the outer periphery of the detector, as well as increasing the probability of escape events occurring in this region. It follows that the resolution of escape peaks is better than that of ordinary gamma-ray peaks. This is experimentally verified. A nearly identical, but undamaged, detector shows the effect of Doppler broadening in single-escape peaks.

Radiation damage has long been known to cause energy-resolution degradation in germanium detectors. This damage creates disordered regions in the germanium lattice that predominantly trap holes, resulting in a low-energy tail on gamma-ray peaks.[1] When gamma rays having sufficient energy to produce e^+-e^- pairs in germanium are incident on a radiation-damaged coaxial germanium detector, the energy resolution of the double and single escape peaks is consistently better than the resolution of the full-energy gamma-ray peaks. The amount of trapping caused by radiation damage is affected by factors such as electric field, ionization density, temperature, and geometry. By considering these and other factors independently we have gained a perspective on radiation damage in germanium detectors that enables us to explain this escape-peak phenomenon.

The IUCF/LBL experimental program to study the effects of radiation damage on high-purity germanium detectors and the subsequent annealing of these detectors has been

maintained since 1986. Highly controlled and monitored beams of protons and neutrons have been used to irradiate a number of germanium detectors to various levels of radiation damage.[2] Ten planar and four coaxial detectors were irradiated with 183-MeV neutrons in March 1993, the most recent irradiation. By the fall of 1994, one reverse-electrode (n-type) closed-end coaxial detector was still damaged from the irradiation so an investigation of escape-peak phenomena was possible. The detector is 68 mm in length, 67 mm in diameter with a 10 mm diameter hole that extends to 8 mm from the closed end. The detector had received a fluence of 3.2×10^8 n/cm^2 and was cycled in temperature from the nominal LN$_2$ temperature of 83 K to 125 K with the bias off for 3.5 days. This combination of events degraded the resolution of the 1332-keV gamma-ray peak from a ^{60}Co source placed above the closed end of the detector from a detector contribution of FWHM=1.81 keV/FWTM=3.7 keV to 4.1 keV/17.9 keV with 20,000 counts/s and 4.7 keV/22.2 keV with 3,800 counts/s between approximately 150 keV and 1400 keV, at an operating temperature of 83 K. The resolution improves with higher count rate because higher ionization density from the gamma-ray interactions produces more holes that fill the traps, thereby reducing the trapping cross section.[3,4]

To verify that the radiation damage caused by the 183-MeV neutrons was predominantly due to hole trapping, the detector was scanned radially with gamma rays. A 20-μCi ^{60}Co source was placed over a 4-mm diameter hole in a 10-cm thick Pb brick, the brick was held 5.2 cm from the closed end of the detector. This resulted in a line-of-sight 8-mm diameter beam spot on the detector, small enough to clearly establish a resolution-position correlation. During these scans the count rate was 550 counts/s. The Pb brick was held in place over the detector by an arm attached to a translation table that facilitated reproducible horizontal positioning to an accuracy better than 1 mm. Moving the collimator out from the center of the detector in 5-mm radial increments for 30 min measurements comprised a radial scan.

Figure 1 shows the spectra resulting from such a radial scan at an operating temperature of 83 K. The resolution improves immensely when the gamma rays interact nearer the periphery. The last two spectra (r=3.0, 3.5 cm) correspond to interactions in the outermost region of the detector; in the 3.5-cm spectrum, the rate has dropped off noticeably because some of the gamma rays are not impinging on the detector. These last two spectra give far better resolution than the high count-rate measurement quoted above, although the ionization density is far less. Most of the signal from interactions occurring near the outer radii is induced by electrons that migrate from the electron-hole creation site to the electrical contact in the center of the detector. Because holes from these interactions travel a small fraction of the total hole-electron collection distance to reach the outer contact, hole collection comprises a small fraction of the total signal, so hole trapping has a relatively small effect. Also, since the absolute amount of hole trapping is approximately proportional to the distance the holes travel before reaching the outer contact, there is less hole trapping for events occurring at larger radii. This scan clearly indicates predominant hole trapping. Spectra taken at radii less than about 2.0 cm show two peaks. The broad, lower energy peak comes from gamma rays interacting primarily within the purely coaxial section of the detector. This peak increases in energy with increasing interaction radius, which is consistent with hole trapping. The narrower, higher energy peak comes
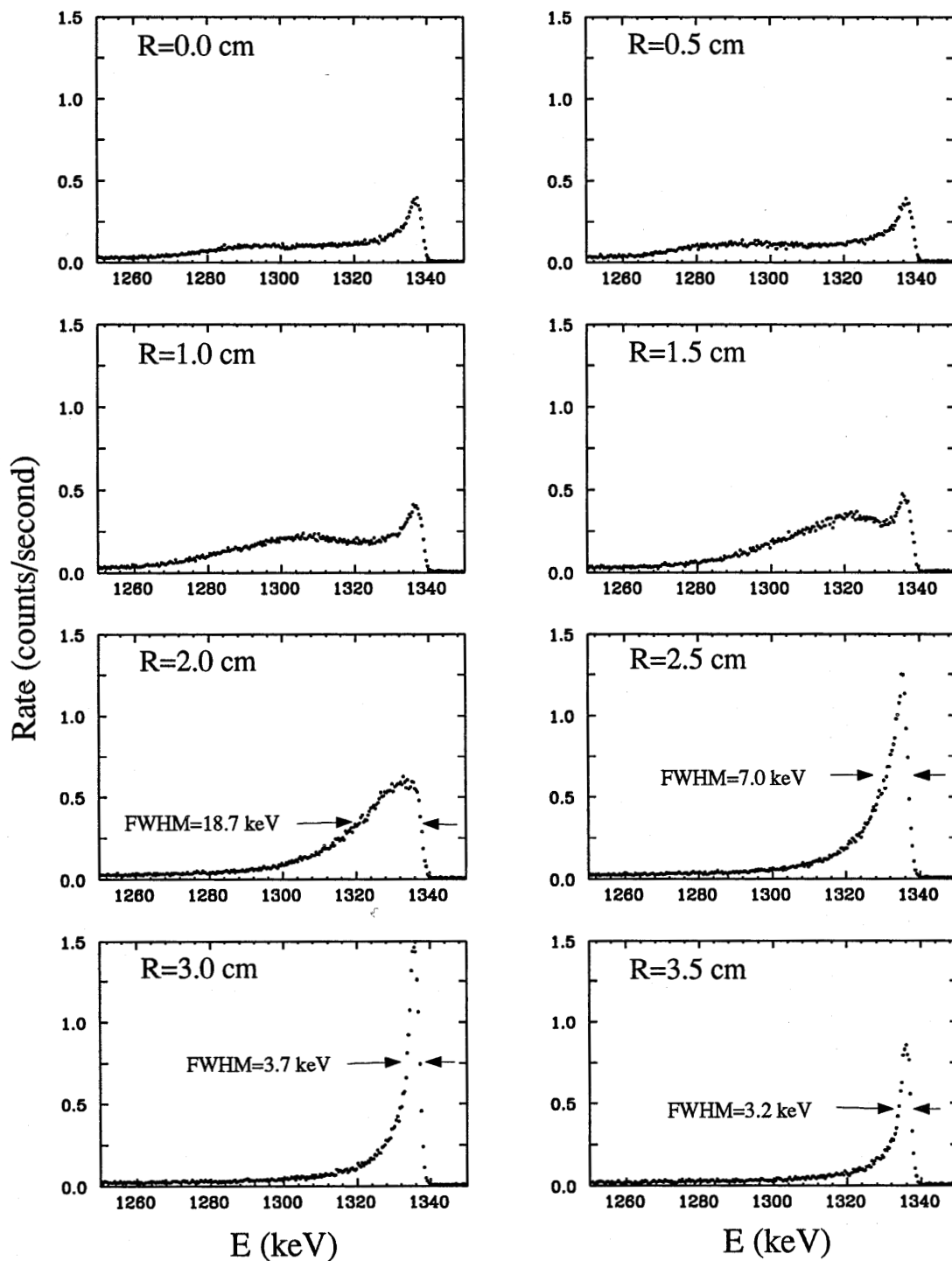
Figure 1. Gamma-ray spectra from a radial scan of a radiation-damaged coaxial germanium detector showing that hole trapping is responsible for the resolution degradation. Near the periphery of the detector the resolution is much better than measured when the detector is exposed to an uncollimated source in a configuration that gives higher ionization density but samples all radii at the same time.

from gamma rays interacting primarily within the central part of the closed end of the detector, where holes travel only a short distance to the electrical contact covering the closed end. This model was confirmed by scanning the length of the detector using the same apparatus. The resulting axial scan showed the closed end to have much better resolution, FWHM=4.6 keV/FWTM=14.6 keV, than the cylindrical section of the detector, 12.1 keV/42.4 keV. This huge difference is undoubtedly caused by the much longer average hole-drift distance in the cylindrical section, as well as by the range of hole-drift distances, giving a spread in the hole contribution to the signal. These observations and arguments are consistent with measurements where gamma rays are effectively radially collimated by electronic techniques.[5]

Gamma rays that produce e$^+$-e$^-$ pairs in the detector give escape peaks when one or both of the annihilation (511 keV) quanta exit the detector without undergoing any interaction. Electrons or positrons created by gamma rays having E~2000 keV deposit all their energy within a distance of about 1 mm. This is basically a point interaction when compared to gamma rays that deposit energy throughout the detector by multiple Compton scattering. The cylindrical cross section of a coaxial germanium detector greatly enhances the probability for a double-escape event to occur at a larger radius. The back-to-back annihilation quanta are both much more likely to escape the detector without interacting if the pair-production event occurs at a larger radius simply because the photons have less distance to travel through the germanium to escape, on average, than for an event occurring at a smaller radius. The same logic holds for single-escape events, but to a lesser degree.

The knowledge that the resolution improves dramatically with increasing radius, coupled with the logic saying more escape peaks come from pair-production events at outer radii, leads to the conclusion that escape peaks should have much better resolution than ordinary gamma-ray peaks. Shown in Fig. 2 is a portion of the gamma-ray spectrum obtained with a ^{228}Th source placed about 3 cm above the closed end of the detector at 83 K. Long measuring times were necessary because the source was rather weak, about 40 nCi. To accumulate this spectrum took 41 hours. The 2615-keV peak from the decay of ^{208}Tl is clearly visible along with the corresponding double and single escape peaks and various other peaks, some from background like the 1460-keV peak from ^{40}K and the 1173-keV and 1332-keV peaks from ^{60}Co. The double-escape peak is significantly narrower than the nearby gamma-ray peaks. The single-escape peak is also narrower. Since the statistical factors for charge-production and charge-trapping statistics, σ_F and σ_T, are proportional to the square root of the gamma-ray energy, a plot of FWHM vs. $\sqrt{E}$ is informative. Figure 3 shows such a plot for the resolvable gamma-ray peaks from the measurement taken to make Fig. 2. The full-energy gamma-ray resolution follows some power slightly greater than $\sqrt{E}$. As expected from geometry arguments, the double- and single-escape peaks clearly stand out as better resolution peaks than the normal gamma-ray energy dependence predicts.

Figure 4 is a plot of FWHM vs. $\sqrt{E}$ of the data obtained at 83 K when a 10 μCi ^{226}Ra source is placed 8 cm above the closed end of the detector such that the overall count rate was 15,000 counts/s. This source provides 2448-keV and 2204-keV gamma rays, both from the decay of ^{214}Bi, of sufficient intensity that the corresponding escape peaks are
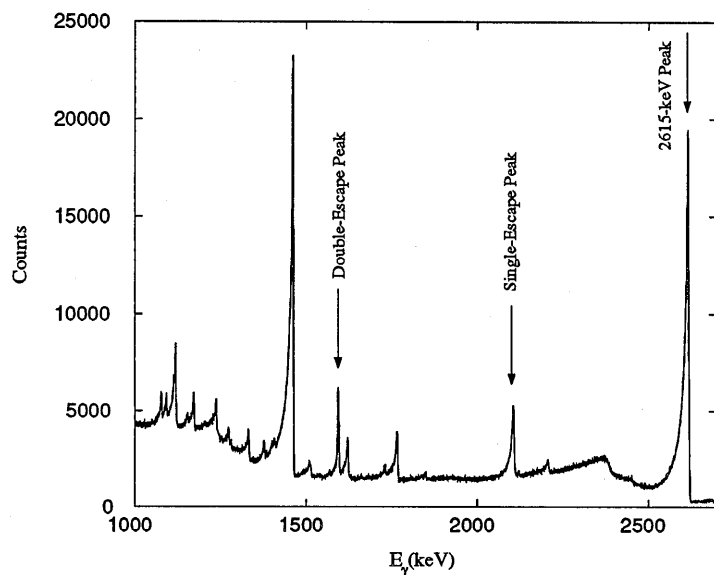
Figure 2. The single- and double-escape peaks from the 2615-keV gamma ray are clearly visible in the ^{228}Th decay chain spectrum. The double-escape peak has noticeably less tail than nearby gamma-ray peaks. This is because double-escape events come primarily from pair-producing events occurring near the outer periphery of the detector.
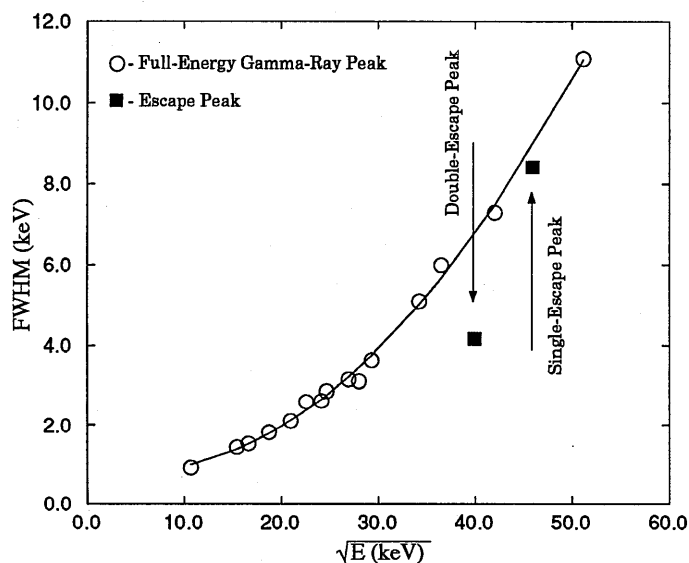

Figure 3. The detector resolution contribution, FWHM, of both full-energy gamma-ray peaks and the single- and double-escape peaks from the 2615-keV gamma ray from a ^{228}Th source is plotted against $\sqrt{E}$. The FWHM-$\sqrt{E}$ relationship of the full-energy gamma-ray peaks is not linear. The escape-peak resolutions are significantly better than the normal gamma-ray peak resolution.

resolvable. Again, the escape peaks clearly stand out as having better resolution than the gamma-ray peaks. The gamma-ray resolution is obviously proportional to a higher power of energy than the dependence shown in Fig. 3. Some improvement in the lower-energy gamma-ray resolution is observed because the increased ionization density improves the charge collection in the region of the detector where these gamma rays primarily interact. The resolution degrades with energy because of the nonuniform ionization density in the detector. The fraction of gamma rays from the decay chain of ^{226}Ra less than or equal to 609 keV is 78%. The 1/e attenuation length of 609-keV gamma rays in germanium is 2.5 cm, whereas the 2204-keV gamma rays have a 1/e attenuation length of 4.5 cm. Consequently, more of the higher-energy gamma rays interact in regions of lower average
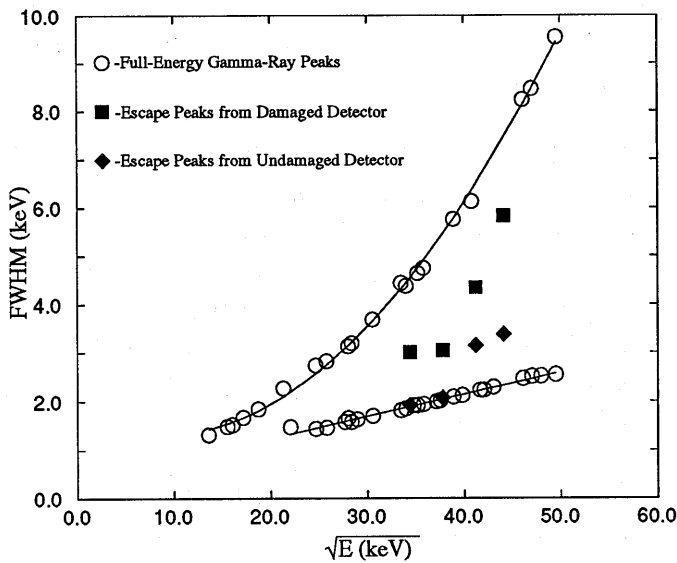
Figure 4. Comparison of the FWHM-$\sqrt{E}$ relationship for gamma rays from a ^{226}Ra source in radiation-damaged and nearly identical-sized undamaged coaxial detectors. The FWHM-$\sqrt{E}$ relationship of the undamaged detector is linear except for the single-escape peaks which reflect Doppler broadening. The relationship for the damaged detector has a higher power for the energy dependence and the escape-peak resolution is much better than the normal gamma-ray resolution.

ionization density. There will be high ionization density and therefore relatively good charge collection in the top 2-3 cm of the detector and extremely low ionization density and relatively poorer charge collection as one moves toward the open end of the detector, where a significant fraction of the higher-energy gamma rays interact. This ionization density difference causes more degradation of the resolution of the higher-energy gamma-ray peaks than of the lower-energy peaks. In Fig. 4 is the FWHM-$\sqrt{E}$ relationship for a nearly identical-sized but undamaged detector. Both the full-energy gamma-ray and double-escape peak resolutions are proportional to $\sqrt{E}$, however, the single-escape peak resolutions are noticeably worse. A Doppler shift of the annihilation-radiation energy is responsible for this broadening.[6] The positrons created in a pair-production interaction of a 2615-keV gamma ray initially have an average energy of about 920 keV but slow to thermal energies in a very short time compared to their lifetime in germanium.[7,8] The thermal positrons ($E \sim 7$ meV) annihilate with core or valence electrons having an energy of a few eV. If one considers the collision kinematics of $e^+e^- \rightarrow 2\gamma$ where the e^+ has $E=7$ meV and the e^- has $E=1$ eV, the annihilation radiation emitted parallel (antiparallel) to the direction of net momentum will be Doppler-shifted up (down) in energy by 0.5 keV. The magnitude of the shift goes to zero for annihilation radiation emitted perpendicular to the direction of net momentum. To an excellent approximation at these energies, the shifted energy of the isotropically emitted back-to-back annihilation quanta is given by $E=m_e c^2(1\pm\beta\cos\theta)$ where θ is the angle of the annihilation radiation direction relative to the direction of net momentum. This is the same process that broadens annihilation-radiation peaks from positron sources. In our measurements, this shift shows up as extra broadening of only the single-escape peak because only one of the annihilation quanta is fully absorbed. Pair-production interactions that result in events contributing to full-energy peaks include the complete energy deposition of both annihilation quanta, which always totals 1022 keV; thus there is no Doppler broadening. Likewise, since double-escape peaks include no energy deposition contribution from the annihilation quanta, they suffer

no Doppler broadening. This effect is visible only in detectors having sufficiently good resolution. The Doppler-broadening contribution to the resolution is negligible compared to the trapping contribution for badly damaged detectors.

The improvement of escape-peak resolution over that of gamma-ray peaks is attributed to the vast improvement in resolution with larger radii, as well as the fact that escape peaks are also much more likely to come from pair-producing interactions occurring at larger radii. The analysis of the charge collection in radiation-damaged coaxial detectors is very complex because charge trapping is greatly affected by the ionization density, the electric field, the temperature and the geometry of these detectors. In addition, we are currently debating whether a point interaction (a double escape event) gives an inherently different line shape than a multiple-point interaction (a gamma ray undergoing multiple Compton scattering). A different fundamental line shape from double escape events would be a valuable tool for the study of radiation damage in germanium detectors. The coaxial-geometry factor clouds this issue far too much to pursue this question based on the data presented here. This has motivated our study of escape-peak phenomena in greater detail in both radiation-damaged and fully-annealed planar-germanium detectors. This work is in progress.

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