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MEASUREMENT OF FAST-NEUTRON FLUX
WITH A LITHIUM-DRIFTED GERMANIUM DETECTOR

by

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ABSTRACT

The use of lithium-drifted germanium detectors for measurement of fast-neutron flux has been investigated. The detection mechanism proposed is observation of a prominent spectral line attributed to deexcitation of ^{72}Ge nuclei (excited by neutron inelastic scattering within the active region of the detector) from the 0^+ first-excited state to the 0^+ ground state via emission of an internal-conversion electron. A 4.0-cm³ planar Ge(Li) detector has been calibrated for neutron-flux measurements over the energy range $E_N = 700\text{--}5000$ keV. The measured efficiency fluctuates considerably with energy for $E_N < 1400$ keV, but is relatively free of structure for higher energies. The absolute efficiency (ratio of neutrons detected to neutrons incident on the detector) has been determined to be $(8.2 \pm 0.5) \times 10^{-4}$ at $E_N = 1500$ keV, which is about 10% of the full-energy peak efficiency for 1332-keV ^{60}Co gamma rays. Insensitivity to thermal neutrons, gamma-ray discrimination capabilities, and stability are desirable features of this type of detector. Submicrosecond timing is not possible because the 0^+ first-excited state of ^{72}Ge has a 422-nsec half-life. Ge(Li) detectors suffer radiation damage from fast-neutron bombardment. However, the detector used in the present study continued to function effectively after receiving an integrated dose exceeding 10^{10} neutrons/cm².

1. INTRODUCTION

Lithium-drifted germanium detectors are used extensively for measuring gamma-ray energies and intensities and are also used occasionally for measuring charged particles.¹ Some consideration has been given to doping semiconductor junction devices with impurities such as lithium, boron, or uranium, which possess large neutron cross sections, and then detecting the charged-particle products of nuclear reactions that occur when these devices are exposed to neutrons.² Very little research appears to have been devoted to consideration of how the nuclear reactions

induced by neutron bombardment of the intrinsic material in semiconductor junctions might be exploited for neutron detection. The objectives of this report are (1) to point out a way in which Ge(Li) detectors can be used for detection of fast neutrons by means of interactions with germanium in the intrinsic region, (2) to report the results of experimental studies undertaken to test the concept, and (3) to discuss some of the advantages and disadvantages of the technique.

II. DETECTOR CONCEPT

The characteristic spectra produced by fast-neutron bombardment of Ge(Li) detectors have been investigated and the results published.^{3,4} The detailed features of the spectra depend upon the neutron energy. These spectra exhibit characteristic lines that can be attributed to $(n,n'\gamma)$ reactions with the germanium in the detector and with other materials found in the detector cryostat. When the incident neutron energy exceeds 700 keV, the most prominent line observed is at 691 keV and has been attributed to the deexcitation of the first-excited state of the isotope ^{72}Ge following excitation by inelastic neutron scattering. Both the ground and first-excited states of ^{72}Ge have spin and parity 0^+ .⁵ This means that electromagnetic deexcitation of the first-excited state of ^{72}Ge must proceed by emission of an internal-conversion electron. Events occurring within the active region of the Ge(Li) detector are observed with nearly 100% efficiency. Gamma-ray-producing transitions are detected less efficiently in full-energy peaks because the gamma rays can escape the active region more readily than electrons, or they may lose only part of their energy by Compton scattering and therefore not contribute pulses to full-energy peaks.

It is proposed that the measured yield of ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion transitions be used to calibrate a Ge(Li) detector for measuring neutron flux for beams of monoenergetic neutrons with energies $E_N > 700$ keV.

III. PHYSICAL CONSIDERATIONS

The level structure of $^{72}_{32}\text{Ge}_{40}$ has been the subject of extensive study because it is one of the few doubly even nuclei that has a 0^+ first-excited state. Other known members of this select group are $^{16}_8\text{O}_8$, $^{40}_{20}\text{Ca}_{20}$, $^{90}_{40}\text{Zr}_{50}$, and $^{98}_{42}\text{Mo}_{56}$. These nuclei are exceptions to the 2^+ spin and parity first-excited state observed for most medium-weight, doubly even nuclei.⁶⁻⁸

The isotope ^{72}Ge is stable and 27.43% abundant in natural germanium.⁹ Eichler *et al.* have found the half-life of the ^{72}Ge 0^+ first-excited state to be 422 ± 13 nsec.¹⁰ The relatively long lifetime of this state

prevents use of a Ge(Li) detector for neutron measurements when sub-microsecond timing conditions are required. Although this is a limitation for some type of experiments, there are other applications in which measurement of the average neutron flux is all that is required and the present approach could be used. The level structure of ^{72}Ge has been worked out largely from studies of the negaton decay of ^{72}Ge and the positon decay and negaton capture decay of ^{72}As .^{6-8,11-14} Measurements of gamma-ray transition energies have established the value 691.2 keV for the excitation energy of the 0^+ first-excited state of ^{72}Ge .¹⁴ Radioactivity studies have provided evidence that several of the higher excited states of ^{72}Ge deexcite with branches to the 0^+ first-excited state. Therefore, for neutron energies of several MeV, the yield of ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion transitions cannot be compared directly with the cross section for inelastic-neutron-scattering excitation of this state.

Chung has studied the $(n,n'\gamma)$ reactions for the stable germanium isotopes using a Ge(Li) detector and time-of-flight techniques.¹⁵ The ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion transition could not be observed in this work because an external germanium sample was exposed to fast neutrons while the Ge(Li) detector remained heavily shielded. The results of a study of inelastic neutron scattering for germanium by Lister and Smith¹⁶ are directly applicable to the present study. They have measured the cross section for inelastic-neutron-scattering excitation of the low-lying levels of the germanium isotopes by time-of-flight techniques as well as by direct neutron bombardment of a Ge(Li) detector. These measurements indicate that the cross section for excitation of the 0^+ first-excited state of ^{72}Ge by inelastic neutron scattering increases rapidly from threshold at 691 keV and approaches 500 mb for E_N in the range 1100-1400 keV.

IV. EXPERIMENTAL STUDIES

Figure 1 is a schematic diagram of the apparatus used for the measurements reported here. The closed (shielded) geometry was chosen in favor of an open (shadow-bar) geometry since preliminary measurements indicated that sizable corrections for air and room scattering would be required in an open configuration. Massive shielding ensured that most of the neutrons with energies exceeding the threshold of 691 keV that reached the Ge(Li) detector were primary neutrons which passed through the collimator hole. An epoxy resin was used to form the tapered collimator. The straight-wall collimator (not shown in Fig. 1) used for some of the measurements was made of aluminum. A brass plug was used for the measurements made with the collimator hole plugged. Boric acid powder was employed in the central part of the shielding near the collimator because of the large capture cross section of boron for thermal neutrons. The paraffin block, shown in Fig. 1 as part of the shielding, was doped with lithium in order to suppress radiative capture background. Finally, the

Ge(Li) detector itself was surrounded with approximately 5 cm of lead to further reduce background from gamma rays produced by neutron capture and neutron-induced reactions in the shielding.

Fig. 1. Schematic Diagram of the Apparatus Used in the Experimental Studies. ANL Neg. No. 116-682 Rev. 1.

The collimator hole was plugged for measurements at various energies within the range $E_N = 700\text{--}5000$ keV to determine corrections to the data for neutrons that scatter one or more times within the shielding before striking the detector. Measurements were made with both a tapered collimator and a cylindrical collimator to determine the effects of collimator-wall scattering.¹⁷ The apparatus was aligned so that no portion of the germanium crystal was shielded from the direct flux. Specifications for the Ge(Li) detector used in the present work appear in Table I.¹⁸ The end cap of the Ge(Li) detector was situated 261.6 ± 0.6 cm from the neutron source, as shown in Fig. 1.

TABLE I. Specifications of the Lithium-drifted Germanium Detector^a

Configuration:	Right-circular cylinder planar
Detector diameter:	2.2 cm
Thickness of intrinsic (active) region:	Approx 1.1 cm
Thickness of "p" layer:	Approx 0.05 cm (estimated from copper staining)
Volume of active region:	Approx 4.0 cm ³
Distance from front face of the detector to the end cap:	1.8 cm
End-cap thickness:	0.15 cm of aluminum

^aThe detector was fabricated at Argonne National Laboratory by H. Mann.

The neutron flux incident upon the Ge(Li) detector was measured with a methane-gas ionization chamber used as a fission counter.¹⁹ The chamber consisted of two 0.025-cm-thick stainless steel disks mounted on insulating standoffs inside a 10.2-cm-dia, 6.4-cm-high cylindrical steel can with 0.025-cm-thick walls. A thin, 2.54-cm-dia film of uranium, enriched in ²³⁵U, provided the necessary fissionable material for this chamber.

TABLE II. Specifications of the Uranium Deposit Used with the Fission Chamber

Mass of uranium in deposit	
$994 \pm 9 \mu\text{g}^a$	
Isotopic content of the uranium ^b	
²³⁴ U	0.856%
²³⁵ U	93.25 %
²³⁶ U	0.332%
²³⁸ U	5.56 %

^aDetermined by α -particle counting and chemical analysis.

^bDetermined by mass spectroscopy.

exposure so that deadtime corrections could be made. The deadtimes were quite small (less than 2%). Radioactive sources were used for energy calibration of the Ge(Li) detector.

Preliminary measurements were made using only a ¹³⁷Cs gamma-ray source to determine the dependence of the efficiency on the bias voltage applied to the Ge(Li) detector. For a detector in good condition, the efficiency is insensitive to the applied bias over a wide range.¹ Results from the present study support this conclusion. The stability of the detector during the neutron exposures was monitored by observing the full-energy peak yield from a ¹³⁷Cs gamma-ray source placed near the Ge(Li) detector in a fixed position.

Targets of natural lithium metal evaporated onto tantalum cups were bombarded with direct-current proton beams from the Argonne National Laboratory Fast Neutron Generator. Data were taken with

The isotopic content of the film was determined by spectrographic analysis, and the total mass of uranium in the deposit was measured by counting the emitted α particles.²⁰ The specifications of the uranium deposit appear in Table II. The uranium film was situated 6.65 ± 0.05 cm from the neutron source, as shown in Fig. 1.

Figure 2 shows block diagrams of the electronics used in the measurements. Fission-counter pulses exceeding the discrimination level were recorded in a scaler. The pulse-height spectra from the Ge(Li) detector were recorded in a pulse-height analyzer, and both the real time and livetime were recorded for each

Fig. 2. Block Diagrams of the Electronics for the Fission Chamber and the Lithium-drifted Germanium Detector. ANL Neg. No. 116-661 Rev. 2.

several target thicknesses. In regions where structure was evident in the efficiency function, measurements were made at the same energy with at least two target thicknesses to see whether this structure would average out with broader energy resolution.

V. DATA ANALYSIS

Figure 3 shows a typical pulse-height spectrum obtained from the fission counter when it was exposed to fast neutrons. Figure 4 is a typical energy spectrum observed when the Ge(Li) detector was bombarded by collimated neutron beams. (The ^{137}Cs source was not present for this measurement.) The Ge(Li) spectrum shown corresponds to bombardment with 1000-keV neutrons; few counts were obtained in the spectrum for pulse heights larger than an equivalent gamma-ray energy of 800 keV. Four spectral lines are identified. The 694-keV line is the $(0^+ \rightarrow 0^+)$ internal-conversion transition in ^{72}Ge . The 596-keV line is one of the strongest gamma-ray lines observed in Ge $(n,n'\gamma)$ measurements and arises from deexcitation of the 596-keV first-excited state of ^{74}Ge .¹⁵ The 427- and 478-keV lines arise from gamma rays produced in the lithium target.²¹ Additional lines appearing at lower energy in Fig. 4 have not been identified. Figure 5 shows part of a spectrum recorded with the ^{137}Cs source present.

A characteristic of some of the spectral lines generated by direct neutron bombardment of Ge(Li) detectors is that the lines broaden with

Fig. 3

Typical Pulse-height Spectrum Obtained with the Fission Chamber Exposed to Fast Neutrons. The α -particles (also present in the absence of neutrons) produce an intense peak in the low channels while the fission fragments are responsible for the broad distribution. The spectrum was plotted with a logarithmic ordinate so that the α -particle peak could be included. ANL Neg. No. 116-826.

Fig. 4

Pulse-height Spectrum Obtained with the Ge(Li) Detector When Bombarded with a Collimated Beam of 1000-keV Neutrons. Only the region of the spectrum corresponding to energies below about 800 keV is exhibited. Few pulses were observed at higher energies. ANL Neg. No. 116-825.

Fig. 5

A Portion of the Pulse-height Spectrum Observed When the Ge(Li) Detector Was Bombarded with 1200-keV Neutrons. A ^{137}Cs source was present so that both the 661.6-keV ^{137}Cs full-energy line and the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion line are observed. ANL Neg. No. 116-669.

increased neutron energy. The explanation for this phenomenon is that the recoil energy of the bombarded germanium atoms is added to the energy released by the electromagnetic deexcitation of the nuclei. The recoil energy depends upon the neutron scattering angle, so one observes a distribution that is broadened toward larger pulse heights up to a limit corresponding to 180° scattering of the incident neutrons. The peak-to-background ratio deteriorates with increased neutron energy. This limits the accuracy to which neutron-flux measurements can be made at higher neutron energies. Figure 6 exhibits the ^{72}Ge internal-conversion line for various neutron energies in the range 700-5000 keV.

The peak-area uncertainties were calculated by combining the statistical uncertainties and the uncertainties associated with the background subtraction procedure. The 661.6-keV ^{137}Cs full-energy peak yield per unit of exposure livetime for the analyzer was determined for each run. This ratio remained constant to within $\pm 3\%$ for the duration of the experiment. Fluctuations about the average value were random and could be attributed to uncertainties in determining the peak counts.

The Fast Neutron Generator has been calibrated by means of a series of threshold measurements. This calibration was checked by observing the threshold energy for the $^7\text{Li}(p,n)^7\text{Be}$ reaction with a long counter placed at 0° relative to the incident proton beam. The spread in neutron energy for each exposure was calculated from the thickness of the lithium targets, the variation with energy of the proton energy loss in lithium, and the solid angles subtended by the fission chamber and Ge(Li) detector.

The conversion of fission-chamber counts to neutron-flux values required considerable analysis and the application of various corrections. Values for the ^{234}U , ^{235}U , ^{236}U , and $^{238}\text{U}(n,f)$ cross sections were obtained from a compilation by Hart.²² Corrections were made for the second neutron group using recent unpublished data of Meadows.²⁰ The second-group

contribution is as large as 30% for proton energies in the range 6000-7000 keV. The ${}^7\text{Li}(p, {}^3\text{He}, n){}^4\text{He}$ reaction yields a broad neutron spectrum above a threshold of $E_p = 5.26$ MeV. There are indications that this reaction may be responsible for ~4% of all the neutrons produced at $E_p = 5.7$ MeV and as many as ~20% of the total yield at $E_p = 6.7$ MeV.²⁰ Insufficient data were available to make a correction for these additional neutrons. At higher energies, where they would be most likely to interfere, these neutrons add counts to both the fission-chamber spectrum and the Ge(Li) detector spectrum. Consequently, the error associated with neglect of the breakup neutrons is probably no more than a few percent for the relative measurements reported here. The tantalum backing is another source of neutron radiation for proton energies above 6000 keV. The magnitude of this correction was determined from the bare-cup measurements. It was found that a maximum correction of about 1% was required for the fission counter at the highest energy studied, while the correction for the Ge(Li) detector data was negligible. Geometric corrections were made for the finite solid angle subtended by the uranium film.

Fig. 6. The ${}^{72}\text{Ge}$ ($0^+ \rightarrow 0^+$) Internal-conversion Line, Exhibited for Various Neutron Energies. The decrease of the peak-to-background ratio with increased neutron energy and the recoil broadening of the line are evident. ANL Neg. No. 116-815.

Neutron scattering and attenuation by various portions of the fission counter was calculated using the neutron-scattering data for iron reported by Barnard *et al.*²³ Scattering and attenuation were responsible for a combined net addition to the observed fission counts of about 1%, and this correction was not very sensitive to neutron energy. An approximate correction for air scattering was made following the approach described by Langsdorf.¹⁷ This effect was estimated to contribute less than 1% to the observed fission-chamber counts. In the final analysis, the uncertainty in the flux as measured by the fission counter was dominated by the uncertainty in the $^{235}\text{U}(n,f)$ cross section. The values of this cross section that were used in the present work are listed in the appendix. It has been assumed that the $^{235}\text{U}(n,f)$ relative cross section is known to within $\pm 5\%$ in the region of interest.

Some of the fissions produce small pulses which are masked by the α -particle pulses. A correction was made to compensate for the fission events that are rejected by the discriminator (see Fig. 3). Extrapolation of an assumed flat fission spectrum from the discrimination level to zero pulse height yielded a correction of 2.3%. This correction is essentially the same for all the exposures and did not affect the relative efficiency.

An additional correction was made for counts in the $^{72}\text{Ge} (0^+ \rightarrow 0^+)$ internal-conversion line which arise from neutrons that have scattered in the shielding. This correction was measured at several neutron energies by observing the yield of $^{72}\text{Ge} (0^+ \rightarrow 0^+)$ counts when the collimator was plugged. The magnitude of the required correction versus neutron energy is given in Table III. This correction is a function of the specific shielding configuration for the detector.

TABLE III. Magnitude of the Shield-scattering Correction for the Shielding Configuration Shown in Fig. 1. The indicated percentages of counts were subtracted from the raw counts in the $^{72}\text{Ge} (0^+ \rightarrow 0^+)$ internal-conversion transition line of each Ge(Li) detector spectrum prior to computation of the detector efficiency.

E_n , keV	Shield-scattering Correction, ^a	E_n , keV	Shield-scattering Correction, ^a
	%		%
800	0.6	3600	5.0
1200	0.8	4000	6.0
1600	1.0	4400	10.0
2000	1.4	4600	12.0
2400	2.2	4800	14.0
2800	3.0	5000	18.0
3200	3.6		

^aThe uncertainty in these corrections is estimated to be about $\pm 20\%$.

VI. RESULTS

Figure 7 shows the results of a measurement of the variation in Ge(Li) detector efficiency with applied bias voltage over the region in which the greatest variation might be expected. The efficiency is nearly constant with applied voltage from 600 to 1500 V. The variation in the

Fig. 7. Variation of the Efficiency of the Ge(Li) Detector for the 661.6-keV ^{137}Cs Full-energy Line as a Function of Applied Bias Voltage over the Range 500-1500 V. ANL Neg. No. 116-660.

resolution was more pronounced, with considerable "tailing" of the 661.6-keV ^{137}Cs full-energy peak in evidence for the lower voltages.

The results of the efficiency measurements for the Ge(Li) detector appear in the appendix and in Fig. 8. The absolute efficiency for neutron detection via the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion line has been determined to be $(8.2 \pm 0.5) \times 10^{-4}$ for 1500-keV neutrons. This value corresponds to the value of unity for the normalized relative efficiencies of Table III.

The neutron-detection efficiency should exhibit the same energy dependence as the cross section for excitation of the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion transition by inelastic scattering. Therefore the results presented in Fig. 8 of this report can be compared with the data appearing in Fig. 7 of Lister and Smith.¹⁶ Resonance peaks in the vicinity of 900, 1080, 1200, and 1300 keV are observed for both data sets. Results of the present study indicate that most of this structure is washed out in broader-resolution measurements.

With the exception of a possible resonance in the vicinity of 1780 keV, the efficiency for the energy range 1400-2400 keV varies gradually with neutron energy. The data points for the energy range 2500-5000 keV are more scattered than those at lower energies. Figure 6 indicates that recoil broadening makes it increasingly difficult to determine the background under the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion line. This places an upper limit on the neutron energies for which the present detection scheme can be applied.

In the present experiment, shield scattering and complexities in the neutron spectrum produced by proton bombardment of ^7Li introduce additional uncertainty to the data.

The response of the Ge(Li) detector to recoiling germanium ions can be deduced from the widths of the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion peaks. The results of this analysis appear in Table IV. The pulse heights for the recoiling germanium ions appear to be quenched to ~30% of the pulse heights for equivalent-energy electrons.

Fig. 8. Measured Relative Neutron-detection Efficiency of a 4.0-cm³ Ge(Li) Detector. This is a graphical representation of data appearing in the Appendix. ANL Neg. No. 116-951.

TABLE IV. Relative Response of a Ge(Li) Detector to Recoiling Germanium Ions and Electrons

Energy, keV	Relative Response ^a	Energy, keV	Relative Response ^a	Energy, keV	Relative Response ^a
45	0.28	74	0.32	105	0.33
52	0.32	79	0.31	111	0.33
56	0.29	88	0.32	117	0.33
63	0.29	93	0.32	123	0.35
69	0.31	100	0.31	130	0.32

^aRelative response is the ratio of the magnitudes of the observed detector signals for germanium ions and electron ions of equal energy. This ratio was calculated by means of the formula

$$\text{Relative Response} = \frac{{}^{72}\text{Ge internal-conversion-line width (keV)}}{{}^{72}\text{Ge recoil energy (keV)}}$$

The estimated uncertainty in the calculated relative response values is estimated to be $\pm 10\%$.

VII. CONCLUSIONS

Considerably less fluctuation in the measured efficiency versus neutron energy is observed than was originally anticipated (see Fig. 8). It would appear worthwhile to investigate the region between $E_n = 1400$ and 2400 keV with increased neutron-energy resolution to determine whether there is fine structure in the $^{72}\text{Ge}(n,n')^{72}\text{Ge}_{691}^*$ (internal conversion) ^{72}Ge cross section. The presence of fluctuations in the efficiency from threshold to $E_n = 1400$ keV is confirmed by the results of the present study and those of Lister and Smith.¹⁶ Uncertainties in the data make it difficult to determine details of the structure in the efficiency calibration for the range $E_n = 2400$ - 5000 keV. In any event, the results of the present work indicate that for neutron-energy resolutions of 20 keV or broader, there is very little structure in the efficiency over a wide range of neutron energy and this is favorable for detector applications.

The threshold of 691 keV for excitation of the ^{72}Ge 0^+ first-excited state by neutron inelastic scattering is also a favorable consideration for fast-neutron detection because it ensures insensitivity of the detector to the low-energy scattered background, which always accompanies the primary fast-neutron beam. This property is especially important when one remembers that, because of the long half-life of the ^{72}Ge 0^+ first-excited state, no timing conditions can be imposed on the detector.

Discrimination of gamma-radiation in the detection of fast neutrons is a straightforward matter with a $\text{Ge}(\text{Li})$ detector. There appear to be no gamma-ray lines that interfere with the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion line in the data obtained during the present study. Compton scattering of gamma rays contributes to the structureless background that is subtracted from beneath the ^{72}Ge ($0^+ \rightarrow 0^+$) conversion line. A unique advantage of this type of detector is that a detailed study of the spectral lines provides information on the nature of the gamma radiation present (because the $\text{Ge}(\text{Li})$ detector can be calibrated for gamma-ray detection as well as for neutron detection). Knowledge of the gamma-ray field in turn gives a good indication of the manner in which the neutron radiation is being affected by the environment, since much of the gamma radiation is generated by inelastic scattering, capture, etc.

The neutron-detection efficiency of a $\text{Ge}(\text{Li})$ detector is not large, but appears to be adequate for many applications. The intrinsic full-energy peak efficiency (absolute efficiency divided by solid angle) of a 4-cm^3 $\text{Ge}(\text{Li})$ detector for the 1332-keV ^{60}Co gamma ray is $\sim 8 \times 10^{-3}$, which is an order-of-magnitude larger than the neutron efficiency measured in the present work.¹

A $\text{Ge}(\text{Li})$ detector cannot be used effectively to measure neutron flux when several neutron energies or a distribution of energies is present.

Such measurements would be possible in principle if one knew the neutron-energy distribution and lacked only the absolute normalization; however, in practice, this is rarely the case.

Extensive shielding of the Ge(Li) detector and attention to collimator design are essential for the proposed application as a neutron detector. This feature is shared by other types of neutron detectors such as scintillation counters and BF₃ counter assemblies if they are to be used for quantitative measurements. Ge(Li) detectors are subject to radiation damage from fast-neutron bombardment. Measurements by Kraner *et al.* indicate that Ge(Li) detectors suffer the effects of radiation damage after an integrated dose of fast neutrons of $\sim 10^{10}$ neutrons/cm².²⁴ The symptoms of incipient radiation damage include tailing of the spectral lines and general deterioration of resolution.

The mechanisms for neutron radiation damage are not well known. There is disagreement on the dose level for incipient damage, and estimates as low as 10^8 neutrons/cm² have been suggested.¹⁸ Kraner *et al.* have found that they could recover a neutron-damaged detector to pre-irradiation specifications by redrifting.²⁴

The Ge(Li) detector used in the present work had seen service in prior (n,n' γ) measurements and therefore had a history of neutron exposure. The resolution obtainable from this detector was not outstanding for a device of its size, and some indication of peak tailing was seen before the present set of measurements. During the present work, this detector received an additional dose of approximately 10^{10} neutrons/cm during somewhat over 100 hr of exposure time in the geometric configuration of Fig. 1. A slight deterioration in the performance of the detector was observed during this period, but this did not alter its performance as a neutron detector.

The conclusion from these observations is that one should not use choice Ge(Li) detectors (which are quite expensive) for measurements of this sort. Optimum resolution is not required for this application, and furthermore symptoms of radiation damage are unavoidable after extended service in a neutron environment. Although neutron damage is a consideration in the use of Ge(Li) detectors for neutron-flux measurements, it should not be a deterrent since considerable service can probably be obtained before a detector has to be redrifted and redrifting will probably restore the detector to preirradiation specifications. Until more is known about the nature of neutron-induced radiation damage of semiconductor devices, it will be difficult to treat the subject in a more quantitative manner.

The results of the present study indicate that the neutron-detection efficiency of a Ge(Li) detector is stable over a relatively long period of

time. No measureable change was observed during the experiment. This is a desirable feature of the detector. The insensitivity of the efficiency to changes in bias voltage and amplification has been discussed earlier in this report. Long-term variations in the efficiency of a detector as a result of accumulated neutron damage might be expected. However, this point was not investigated in the present work. Use of a ^{137}Cs monitor, as described earlier in this report, would appear to be a way of avoiding this potential problem.

APPENDIX

Fission Cross Sections σ_f and Measured Relative Neutron-detection
Efficiencies ϵ_n Versus Neutron Energy E_n

This appendix presents the measured values of the relative neutron-detection efficiency ϵ_n (with uncertainty $\Delta\epsilon_n$) versus the neutron energy E_n (with energy spread ΔE_n) for a 4.0-cm³ planar Ge(Li) detector. The calibration is based upon the ^{72}Ge ($0^+ \rightarrow 0^+$) internal-conversion transition. Normalization of this tabulation is based upon arbitrary assignment of the value unity to the average of several efficiency values for neutron energies in the vicinity of 1500 keV. Cross sections σ_f for the $^{235}\text{U}(n,f)$ reaction were extracted from the evaluated compilation of Hart.²²

E_n , keV	ΔE_n , keV	σ_f , barns	ϵ_n	$\Delta\epsilon_n$
695	11	1.13	6.52×10^{-3}	7.44×10^{-4}
719	11	1.14	1.42×10^{-1}	9.51×10^{-3}
744	11	1.14	1.92×10^{-1}	1.27×10^{-2}
770	11	1.15	3.48×10^{-1}	2.27×10^{-2}
790	41	1.15	3.42×10^{-1}	2.17×10^{-2}
795	10	1.16	5.21×10^{-1}	3.37×10^{-2}
822	10	1.16	5.13×10^{-1}	3.30×10^{-2}
846	10	1.16	5.50×10^{-1}	3.52×10^{-2}
871	10	1.17	6.05×10^{-1}	3.89×10^{-2}
874	42	1.17	5.87×10^{-1}	3.89×10^{-2}
895	10	1.18	7.96×10^{-1}	5.07×10^{-2}
922	10	1.18	7.26×10^{-1}	4.63×10^{-2}
928	42	1.19	6.68×10^{-1}	4.44×10^{-2}
946	10	1.19	7.18×10^{-1}	4.57×10^{-2}
964	42	1.19	6.84×10^{-1}	4.51×10^{-2}
970	10	1.19	7.63×10^{-1}	4.88×10^{-2}
977	65	1.20	7.11×10^{-1}	4.63×10^{-2}
995	10	1.20	7.07×10^{-1}	4.50×10^{-2}
1018	41	1.21	8.25×10^{-1}	5.34×10^{-2}
1021	10	1.21	7.70×10^{-1}	4.90×10^{-2}
1045	10	1.21	7.86×10^{-1}	5.00×10^{-2}
1070	38	1.21	7.33×10^{-1}	4.59×10^{-2}
1070	10	1.21	9.91×10^{-1}	6.29×10^{-2}
1073	41	1.22	8.23×10^{-1}	5.29×10^{-2}
1097	9	1.22	8.88×10^{-1}	5.60×10^{-2}
1122	9	1.22	8.11×10^{-1}	5.12×10^{-2}
1128	41	1.22	8.23×10^{-1}	5.30×10^{-2}
1146	9	1.22	8.13×10^{-1}	5.12×10^{-2}
1165	40	1.23	9.57×10^{-1}	6.15×10^{-2}
1165	40	1.23	9.17×10^{-1}	5.84×10^{-2}
1171	9	1.23	8.40×10^{-1}	5.30×10^{-2}
1195	36	1.23	8.32×10^{-1}	5.16×10^{-2}

E_n , keV	ΔE_n , keV	σ_f , barns	ϵ_n	$\Delta \epsilon_n$
1195	9	1.23	1.05	6.58×10^{-2}
1221	40	1.23	9.32×10^{-1}	5.98×10^{-2}
1221	9	1.23	9.19×10^{-1}	5.86×10^{-2}
1245	9	1.23	9.09×10^{-1}	5.85×10^{-2}
1273	9	1.24	1.14	7.33×10^{-2}
1277	40	1.24	1.00	6.56×10^{-2}
1298	9	1.24	1.00	6.47×10^{-2}
1321	9	1.24	1.01	6.54×10^{-2}
1333	40	1.24	9.06×10^{-1}	6.00×10^{-2}
1348	9	1.25	8.48×10^{-1}	5.57×10^{-2}
1371	39	1.25	8.76×10^{-1}	5.91×10^{-2}
1371	39	1.25	9.20×10^{-1}	6.37×10^{-2}
1373	9	1.25	9.20×10^{-1}	6.11×10^{-2}
1397	9	1.25	9.93×10^{-1}	6.52×10^{-2}
1398	34	1.25	9.51×10^{-1}	6.21×10^{-2}
1424	9	1.25	9.40×10^{-1}	6.22×10^{-2}
1428	39	1.25	9.71×10^{-1}	6.49×10^{-2}
1449	9	1.25	9.81×10^{-1}	6.47×10^{-2}
1466 ^a	39	1.26	9.90×10^{-1}	6.63×10^{-2}
1475 ^a	8	1.26	1.03	6.70×10^{-2}
1494 ^a	8	1.26	1.00	6.59×10^{-2}
1500 ^a	8	1.26	1.04	6.79×10^{-2}
1524 ^a	39	1.26	9.68×10^{-1}	6.56×10^{-2}
1526 ^a	8	1.26	1.06	6.96×10^{-2}
1551	8	1.26	1.01	6.66×10^{-2}
1575	8	1.27	9.80×10^{-1}	6.49×10^{-2}
1582	39	1.27	9.69×10^{-1}	6.60×10^{-2}
1582	38	1.27	9.32×10^{-1}	6.30×10^{-2}
1600	8	1.27	1.01	6.60×10^{-2}
1601	32	1.27	9.68×10^{-1}	6.34×10^{-2}
1621	39	1.27	9.34×10^{-1}	6.67×10^{-2}
1625	8	1.27	1.08	7.01×10^{-2}
1650	8	1.28	9.58×10^{-1}	6.31×10^{-2}
1676	8	1.28	9.98×10^{-1}	6.63×10^{-2}
1680	38	1.28	8.97×10^{-1}	6.14×10^{-2}
1701	8	1.28	9.34×10^{-1}	6.18×10^{-2}
1720	38	1.28	8.73×10^{-1}	6.08×10^{-2}
1727	8	1.28	9.30×10^{-1}	6.12×10^{-2}
1727	8	1.28	9.12×10^{-1}	6.03×10^{-2}
1753	8	1.29	8.09×10^{-1}	5.59×10^{-2}
1777	8	1.29	9.15×10^{-1}	6.14×10^{-2}
1779	38	1.29	9.59×10^{-1}	6.55×10^{-2}

^aData point included in calculation of an average neutron-detection efficiency for $E_n \approx 1500$ keV.

E_n , keV	ΔE_n , keV	σ_f , barns	ϵ_n	$\Delta \epsilon_n$
1779	38	1.29	1.01	6.92×10^{-2}
1802	8	1.29	8.50×10^{-1}	5.78×10^{-2}
1803	31	1.29	9.03×10^{-1}	5.96×10^{-2}
1819	38	1.29	8.23×10^{-1}	5.75×10^{-2}
1826	8	1.29	9.35×10^{-1}	6.17×10^{-2}
1852	8	1.29	7.97×10^{-1}	5.37×10^{-2}
1876	8	1.30	8.04×10^{-1}	5.45×10^{-2}
1880	38	1.30	7.39×10^{-1}	5.35×10^{-2}
1903	8	1.30	8.26×10^{-1}	5.55×10^{-2}
1920	38	1.30	8.28×10^{-1}	5.85×10^{-2}
1927	8	1.30	8.09×10^{-1}	5.47×10^{-2}
1951	8	1.30	8.64×10^{-1}	5.82×10^{-2}
1976	63	1.31	8.37×10^{-1}	6.01×10^{-2}
1977	8	1.31	8.79×10^{-1}	5.99×10^{-2}
2002	7	1.31	8.35×10^{-1}	5.69×10^{-2}
2002	38	1.31	7.57×10^{-1}	5.58×10^{-2}
2002	38	1.31	8.59×10^{-1}	6.38×10^{-2}
2005	30	1.31	7.52×10^{-1}	5.18×10^{-2}
2022	38	1.31	8.20×10^{-1}	6.39×10^{-2}
2027	7	1.31	8.68×10^{-1}	5.89×10^{-2}
2064	38	1.31	8.20×10^{-1}	6.21×10^{-2}
2070	15	1.31	8.37×10^{-1}	5.74×10^{-2}
2120	14	1.31	7.88×10^{-1}	5.40×10^{-2}
2126	38	1.31	8.42×10^{-1}	6.42×10^{-2}
2170	14	1.31	7.79×10^{-1}	5.35×10^{-2}
2188	38	1.31	8.20×10^{-1}	6.14×10^{-2}
2199	27	1.31	8.40×10^{-1}	6.57×10^{-2}
2220	14	1.31	7.98×10^{-1}	5.38×10^{-2}
2241	27	1.31	7.80×10^{-1}	6.15×10^{-2}
2262	27	1.31	7.81×10^{-1}	6.13×10^{-2}
2271	14	1.31	6.85×10^{-1}	4.73×10^{-2}
2283	27	1.31	7.73×10^{-1}	5.59×10^{-2}
2286	27	1.31	7.93×10^{-1}	6.02×10^{-2}
2294	37	1.31	7.42×10^{-1}	5.75×10^{-2}
2304	27	1.31	7.36×10^{-1}	5.99×10^{-2}
2321	14	1.31	6.75×10^{-1}	4.64×10^{-2}
2347	27	1.31	7.70×10^{-1}	5.95×10^{-2}
2368	27	1.30	7.34×10^{-1}	5.98×10^{-2}
2370	67	1.30	6.94×10^{-1}	5.31×10^{-2}
2373	14	1.30	7.72×10^{-1}	5.20×10^{-2}
2389	27	1.30	7.77×10^{-1}	6.22×10^{-2}
2389	27	1.30	7.23×10^{-1}	5.42×10^{-2}
2411	27	1.30	6.42×10^{-1}	5.59×10^{-2}
2422	14	1.30	6.69×10^{-1}	4.62×10^{-2}
2432	27	1.30	6.54×10^{-1}	5.52×10^{-2}

E_n , keV	ΔE_n , keV	σ_f , barns	ϵ_n	$\Delta \epsilon_n$
2454	27	1.29	6.08×10^{-1}	5.17×10^{-2}
2474	13	1.29	7.33×10^{-1}	4.99×10^{-2}
2475	27	1.29	5.77×10^{-1}	4.78×10^{-2}
2475	27	1.29	6.71×10^{-1}	5.40×10^{-2}
2519	27	1.28	6.30×10^{-1}	5.05×10^{-2}
2524	13	1.28	7.30×10^{-1}	4.94×10^{-2}
2524	13	1.28	7.09×10^{-1}	4.83×10^{-2}
2540	27	1.28	6.19×10^{-1}	5.21×10^{-2}
2562	27	1.27	6.80×10^{-1}	5.88×10^{-2}
2584	27	1.27	6.46×10^{-1}	5.04×10^{-2}
2617	44	1.27	5.95×10^{-1}	5.53×10^{-2}
2639	44	1.27	6.30×10^{-1}	4.89×10^{-2}
2682	44	1.26	6.66×10^{-1}	5.23×10^{-2}
2682	44	1.26	6.87×10^{-1}	5.27×10^{-2}
2742	44	1.26	6.28×10^{-1}	4.89×10^{-2}
2783	44	1.25	6.96×10^{-1}	5.29×10^{-2}
2783	44	1.25	6.72×10^{-1}	4.97×10^{-2}
2842	43	1.25	7.07×10^{-1}	5.23×10^{-2}
2883	43	1.24	5.96×10^{-1}	4.93×10^{-2}
2945	43	1.23	7.18×10^{-1}	5.79×10^{-2}
2981	70	1.23	6.24×10^{-1}	4.39×10^{-2}
2987	43	1.23	7.19×10^{-1}	5.67×10^{-2}
3045	43	1.22	6.29×10^{-1}	4.80×10^{-2}
3108	43	1.22	6.22×10^{-1}	5.26×10^{-2}
3108	43	1.22	6.88×10^{-1}	5.24×10^{-2}
3148	43	1.22	7.44×10^{-1}	5.55×10^{-2}
3186	43	1.21	7.77×10^{-1}	5.60×10^{-2}
3186	43	1.21	6.82×10^{-1}	5.29×10^{-2}
3228	43	1.21	6.65×10^{-1}	5.63×10^{-2}
3291	43	1.20	5.63×10^{-1}	4.85×10^{-2}
3348	43	1.20	6.80×10^{-1}	5.26×10^{-2}
3386	68	1.19	5.38×10^{-1}	4.35×10^{-2}
3390	43	1.19	5.64×10^{-1}	4.64×10^{-2}
3390	43	1.19	6.69×10^{-1}	4.86×10^{-2}
3453	43	1.18	6.14×10^{-1}	4.65×10^{-2}
3491	43	1.18	6.59×10^{-1}	5.20×10^{-2}
3553	43	1.18	6.51×10^{-1}	4.76×10^{-2}
3590	43	1.18	6.19×10^{-1}	4.82×10^{-2}
3590	43	1.18	5.75×10^{-1}	4.70×10^{-2}
3652	43	1.17	5.43×10^{-1}	4.63×10^{-2}
3695	43	1.17	5.81×10^{-1}	4.80×10^{-2}
3752	43	1.17	6.19×10^{-1}	4.94×10^{-2}
3788	67	1.16	5.30×10^{-1}	4.75×10^{-2}
3796	43	1.16	5.08×10^{-1}	4.50×10^{-2}
3796	43	1.16	5.54×10^{-1}	4.75×10^{-2}

E_n , keV	ΔE_n , keV	σ_f , barns	ϵ_n	$\Delta \epsilon_n$
3851	46	1.16	5.60×10^{-1}	4.80×10^{-2}
3894	46	1.15	5.02×10^{-1}	4.53×10^{-2}
3952	46	1.15	6.08×10^{-1}	5.37×10^{-2}
3994	46	1.15	6.28×10^{-1}	5.50×10^{-2}
3994	46	1.15	5.41×10^{-1}	4.55×10^{-2}
4132	46	1.14	5.32×10^{-1}	5.86×10^{-2}
4232	46	1.15	4.59×10^{-1}	4.90×10^{-2}
4311	71	1.13	4.32×10^{-1}	5.22×10^{-2}
4413	72	1.12	3.29×10^{-1}	5.24×10^{-2}
4513	70	1.12	4.31×10^{-1}	5.58×10^{-2}
4615	70	1.10	4.74×10^{-1}	6.15×10^{-2}
4718	70	1.10	4.51×10^{-1}	5.92×10^{-2}
4814	70	1.10	4.21×10^{-1}	6.11×10^{-2}
4916	70	1.09	4.68×10^{-1}	5.96×10^{-2}
4996	70	1.09	3.54×10^{-1}	5.82×10^{-2}
4996	70	1.09	3.15×10^{-1}	6.37×10^{-2}

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