Effect of Fission Spectrum Neutrons on *n*-Type Germanium

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The electron removal rate for *n*-type germanium irradiated with fission spectrum neutrons is 8±1 per neutron at room temperature. This value is compared with the results of monoenergetic neutron irradiations from 2 to 5 Mev. The fact that the removal rate is roughly constant is explained by the constancy of the energy dissipated in elastic collisions.

INTRODUCTION

MONOENERGETIC neutron irradiations of *n*-type germanium by Ruby, Schupp, and Wolley[1] have shown that the number of charge carriers removed per incident neutron is either constant or decreases with increasing neutron energy in the range 2 to 5 Mev. For 1.8, 3.2, and 4.8 Mev neutrons, the removal rates are 21, 12, and 13 per neutron, respectively, with estimated errors of 25%. It is of interest to compare these results with reactor irradiations as an indication of the variation with energy below 2 Mev. Results in a reactor hole with uranium converter will be described, where the irradiation effects were predominantly from fission spectrum neutrons. Previous results[2,3] on the basis of theoretical flux values gave removal rates at least twice as small as the monoenergetic irradiations. In this experiment, the neutron flux was measured with threshold detectors and the results were closer to the monoenergetic values.

EXPERIMENTAL MEASUREMENTS

Irradiations were carried out in hole 51N of the ORNL Graphite Reactor, which is a 4×4 in. hole cut transverse to the 8×8 in. lattice. The hole contains a hollow cylinder of enriched uranium. The uranium cylinder or "converter" absorbs half the thermal neutron flux to give a predominantly fission spectrum inside the converter.

The neutron flux was determined by measuring the fission yields in foils of Np^{237} and U^{238} by an extension of a method developed by Hurst *et al.*[4] The original method compared the fission product gamma rays from the fast fission of Np^{237} ($\gtrsim$0.7-Mev neutrons) and U^{238} ($\gtrsim$1.3-Mev neutrons) with the same gamma rays from the fission of Pu^{239} in a known thermal flux. It is necessary to eliminate gamma rays from thermal reactions in Np^{237} and U^{238}, and this was accomplished in the original method[4] by using large B^{10} shields during exposure, and counting only gamma rays >1.1 Mev after exposure.

The method was modified to permit the use of 30 mil cadmium covers. The dominant competitive reaction for Np^{237} is the (n,γ) reaction leading to 2-day Np^{238} gamma rays. These may be eliminated by a technique described elsewhere.[5] The competitive reaction in the U^{238} foils is the thermal fission of the U^{235} impurity. The U^{238} foils used for the measurements[6] were depleted to 10 ppm U^{235}, which made the thermal fission negligible. The new technique allowed the counting of gamma rays at integral biases of >0.4 Mev, >0.8 Mev, and >1.2 Mev.

The Np^{237} and U^{238} foils were irradiated in hole 51N for times either up to 30 min or greater than 60 hr. The fission-product yields were compared to that for Pu^{239} irradiated for the same times in a known thermal-neutron flux. The neutron flux values were determined by using cross sections for a fission spectrum, and the results are shown in Table I. The value of σ_f, the fission cross section, was obtained for Np^{237} by averaging the cross section vs energy curve of Schmitt and Murray[7] over a fission spectrum. The cross section for U^{238} was from a direct measurement in a fission spectrum.[8] The neutron flux was measured in the center of and outside the converter, and the difference between these values is in agreement with a fission spectrum.

The electron removal rate at room temperature for *n*-type germanium in the center of the converter had been previously quoted as 3.2 per neutron,[2,3] on the basis of a theoretical flux of 8×10^{11} fast neutrons/cm² sec⁻¹. The observed removal rate was then 26×10^{11}

TABLE I. Neutron flux values as determined by the Np^{237} and U^{238} fission reactions in hole 51N.

	Np^{237}	U^{238}
σ_f (barns)	1.35	0.305
Neutron flux (cm^{-2} sec^{-1})		
Center of converter	3.44×10^{11}	3.15×10^{11}
Outside of converter	1.16×10^{11}	0.92×10^{11}
Difference	2.28×10^{11}	2.23×10^{11}

[1] S. L. Ruby, F. D. Schupp, and E. D. Wolley, Phys. Rev. **111**, 1493 (1958).
[2] J. W. Cleland, J. H. Crawford Jr., K. Lark-Horovitz, J. C. Pigg, and F. W. Young, Phys. Rev. **83**, 312 (1951).
[3] J. W. Cleland, J. H. Crawford Jr. and J. C. Pigg, Phys. Rev. **98**, 1742 (1955).
[4] G. S. Hurst, J. A. Harter, P. N. Hensley, W. A. Mills, M. Slater, and P. W. Reinhardt, Rev. Sci. Instr. **27**, 153 (1956).
[5] D. Binder, Rev. Sci. Instr. **31**, 902 (1960).
[6] The U^{238} was kindly supplied by J. A. Martin of Oak Ridge National Laboratory.
[7] H. W. Schmitt and R. B. Murray, Phys. Rev. **116**, 1575 (1959).
[8] W. D. Allen and R. L. Henkel, *Progress in Nuclear Energy* (Pergamon Press, New York, 1958), Ser. 1, Vol. 2.

TABLE II. Fission fluxes and removal rates for hole 51N.

	Fission flux (cm^{-2} sec^{-1})	Removal rate (cm^{-3} sec^{-1})	Removal rate per neutron (cm^{-1})
Center	3.44×10^{11}	$(26\pm3)\times10^{11}$	8 ± 1
Outside	1.16×10^{11}	$(9\pm1)\times10^{11}$	8 ± 1
Difference	2.28×10^{11}	$(17\pm3)\times10^{11}$	8 ± 1

electrons/cm^3 sec^{-1}. This value was checked by Hall measurements[9] during the period of the neutron measurements and confirmed within 10%. The writer found by conductivity measurements that the center of the converter was 2.9 times as effective as the position outside. The results are summarized in Table II along with the fission fluxes determined from Np^{237}. The removal rate per neutron is insensitive to the change in spectrum and is constant at 8 ± 1 neutron.

DISCUSSION

To compare with the monoenergetic results of Ruby, Schupp, and Wolley, we must multiply the observed removal rate by 1.5, the factor between liquid nitrogen and room temperature irradiations in the reactor.[3] The result, 12 ± 2 per fission neutron, is close to the values of 21 ± 5, 12 ± 3, and 13 ± 3 for 1.8, 3.2, and 4.8 Mev neutrons. The removal rate, within error, is approximately independent of neutron energy.

An approximate constancy in defect production with neutron energy is predicted by a calculation of the average energy dissipated in elastic collisions. Two effects are important: (1) the increase in forward scattering as the neutron energy increases, and (2) the decrease in the elastic cross section. The energy dissipated in elastic collisions is proportional to $E_n\sigma_e(\bar{e}/e_{\max})$, where E_n is the neutron energy, σ_e is the elastic scattering cross section, and $(\bar{e}/e_{\max})$ is the ratio of the average to the maximum recoil energy. The ratio $(\bar{e}/e_{\max})$ decreases from the value of 0.5 for isotropic scattering as the neutron energy increases. Although angular distributions are not available for germanium, approximate values of $(\bar{e}/e_{\max})$ may be calculated from the neighboring elements, copper and zinc.[10] The results are shown in Fig. 1. Only the total cross section is known for germanium, but an approximate elastic scattering cross section is obtained by subtracting the inelastic cross section for zinc from the total cross section.[11]

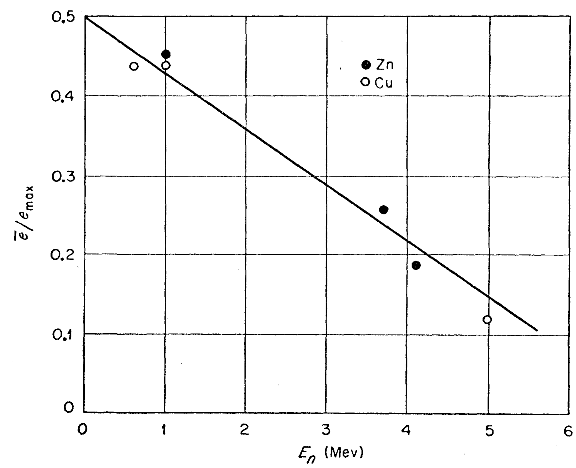

FIG. 1. Average recoil energy divided by maximum recoil energy, $\bar{e}/e_{\max}$, as a function of neutron energy E_n.

TABLE III. Removal rates compared with $E_n\sigma_e(\bar{e}/e_{\max})$.

E_n (Mev)	$E_n\sigma_e(\bar{e}/e_{\max})$ (Mev barn)	Removal rate (cm^{-1})
1.8 ± 0.1	1.7	21 ± 5
3.2 ± 0.6	1.6	12 ± 3
4.8 ± 0.1	1.6	13 ± 3
Fission spectrum	1.5	12 ± 2

The results are summarized in Table III, where the value for fission neutrons is obtained by averaging over a fission spectrum. The variation, within error, of the removal rates is in agreement with the energy dissipated in elastic collisions.

[9] J. W. Cleland (private communication).

[10] D. Binder (to be published).

[11] D. J. Hughes and R. B. Schwartz, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.