In view of Ilahovac's[7] positive results with liquid sources of Zu^{63}, we looked for resonance fluorescence effects from the germanium scatterer using liquid sources of As^{72} and of As^{74}. In both cases the result was negative, i.e., the observed effect, if any, was smaller than 3% of the effect measured with a gaseous source of the same strength.

ACKNOWLEDGMENTS

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Neutron Cross Sections for Zirconium

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The inelastic neutron cross section for the excitation of the 930-kev level in zirconium has been measured as a function of neutron energy between 0.9 and 2.2 Mev. The de-excitation gamma radiation has been observed with a single-crystal NaI(Tl) spectrometer. Isotopic assignment of the observed level is still uncertain. The total cross section for zirconium has been measured for neutrons with energies between 0.7 and 1.2 Mev, using a hydrogen recoil counter in a good-geometry transmission experiment. Some correlation between inelastic and total cross sections has been observed.

I. INTRODUCTION

THE inelastic scattering of neutrons by nuclei has been a subject for much experimentation during the last few years. Several different techniques for the determination of cross sections have been worked out, and are discussed in the literature.[1] Determinations of the inelastic cross section as a function of bombarding neutron energy have been made for a number of elements,[2,3] mainly those with first excited states of 800 kev or more. Resonance structure observed in the cross sections for Al, Cr, Ni, and Fe has been attributed to resonances in the formation of the compound nucleus. Griffith[4] has determined the inelastic cross section for Zr for 4.5-Mev neutrons. The purpose of the work reported here was to observe the inelastic cross section for zirconium as a function of incident neutron energy, and to endeavor to compare it with the total cross section, in both magnitude and resonance structure.

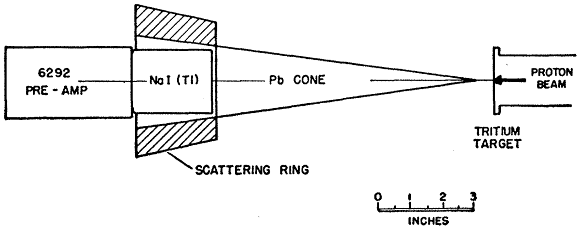

FIG. 1. Large-crystal experimental geometry. The single-crystal NaI(Tl) spectrometer is mounted inside, and coaxially with, the conical scatterer. The 8-inch lead cone effectively shields the crystal from neutrons and gamma rays coming from the tritium target. The resolution of neutrons striking the scattering cone is about 20 kev, the solid angle subtended by the scatterer at the crystal is close to 2π.

II. EXPERIMENTAL METHOD

Inelastic Cross Section

The method chosen for this investigation was the same as that described by Kiehn and Goodman.[2] A single-crystal NaI(Tl) spectrometer is used to observe the gamma-ray spectrum arising from the de-excitation of those levels in the scattering sample which have been excited by the inelastic scattering of the incident neutrons. The scatterer was made of natural zirconium, in the form of a hollow truncated cone (i.d.$=2\frac{1}{4}$ in., o.d.$=3\frac{3}{4}$ in., thickness$=2\frac{1}{2}$ in. at the face presented to the neutron beam). This was placed on the axis of symmetry of the incident neutron beam, as shown in Fig. 1. The detector was a 2 in.×2 in. Harshaw

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[1] Garrett, Hereford, and Sloope, Phys. Rev. **92**, 1507 (1953); Eliot, Hicks, Behegian, and Halban, Phys. Rev. **94**, 144 (1954); Taylor, Lonsjo, and Bonner, Phys. Rev. **94**, 807(A) (1954); R. E. Carter and J. R. Beyster, Phys. Rev. **90**, 389(A) (1953); M. Walt and H. H. Barschall, Phys. Rev. **93**, 197 (1954).

[2] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954).

[3] R. B. Day, Phys. Rev. **89**, 908(A) (1953).

[4] G. L. Griffith, Phys. Rev. **98**, 579 (1955).

"canned" NaI(Tl) crystal, placed inside the scattering ring, and shielded from the direct neutron beam by an 8-in. lead cone. A DuMont 6292 photomultiplier tube, bonded to the crystal with a thin film of nujol, served as a detector for the light pulses produced by the gamma rays from the scattering ring. The pulse height distribution was analyzed by a ten-channel pulse sorter, and energy and yield calibrations made using the photoelectric peak of the pulse-height distribution.

Figure 2 illustrates the method of calibration. A pulse-height spectrum of the gamma rays from zirconium was taken at a neutron energy high enough to give a good counting rate. The yield of gamma rays was determined by integration of the photopeak for a given number of bombarding neutrons. An iron cone of the same dimensions was substituted, bombarded with the same number of neutrons, and the pulse-height spectrum and gamma-ray yield determined. Comparison of the two yields allows the calculation of the absolute value of σ_{in} for Zr from the known value of σ_{in} for Fe, as given by Kiehn and Goodman.[2] The gamma-ray yields must of course be corrected for variation of neutron flux within the scatterer, gamma-ray attenuation within the scatterer, and efficiency of the crystal detector. Energy calibration was made by comparison with the known gamma rays from Co^{60} and Cs^{137}, as indicated in Fig. 2.

Neutrons were produced by the $H^3(p,n)He^3$ reaction, using protons from the Rockefeller electrostatic generator. The proton beam was monitored by a calibrated beam current integrator; its energy was determined by the proton-resonance controlled analyzing magnet of the generator. Neutron flux was monitored by an enriched BF_3 long counter, placed at 90° to the proton beam, and 2 meters from the target. The spread in neutron energy at the scatterer was about 20 kev at 1 Mev.

Total Cross Section

Total cross-section measurements were made using a good-geometry transmission method, with a pressurized (70 psi) hydrogen recoil counter as a detector of neutrons. The geometry was similar to that used previously in this laboratory.[5] The scattering samples were in the form of cylinders, one inch in diameter, and of a thickness sufficient to decrease the neutron flux by about a factor of 2. Thin lithium targets were used for this part of the work, to produce neutrons with an energy spread of about 5 kev. Monitors for both proton and neutron beams were the same as described above. The use of the hydrogen recoil counter, which is insensitive to neutrons of energies below about 400 kev, minimizes background effects due to room-scattered neutrons.

III. RESULTS

The only gamma ray observed was at 930 kev, corresponding to a level in Zr^{92} observed by Preiswerk and Stahelin.[6] No other gamma rays between 0.6 and 2 Mev were observed. Table I gives the stable isotopes of zirconium, with their abundance and energy levels, where known.

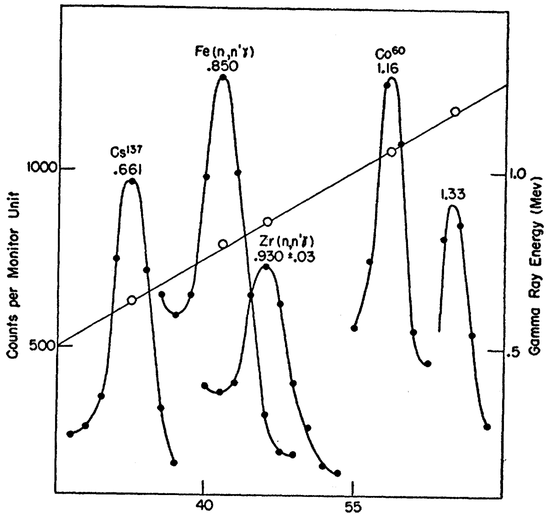

FIG. 2. Calibration of zirconium gamma ray: $E_n=1.3$ Mev. Energy calibration of the 930-kev gamma radiation from the de-excitation of zirconium was made using two standard sources and the gamma ray from the de-excitation of the first level in Fe. Yield calibration was made from the known inelastic cross section for Fe.

The yield of the 930-kev gamma ray from Zr as a function of neutron energy is shown in Fig. 3. It should be pointed out that the calculation of an absolute value for σ_{in} is dependent on how many isotopes of the element under investigation take part in the observed excitation. The ordinate in Fig. 3 is in barns per atom of the natural element. Thus if one were to attribute the 930-kev gamma radiation to the single isotope Zr^{92}, the inelastic cross section for the excitation of this particular isotope would be the value in barns given in the figure, divided by 0.171, to take into account the isotopic abundance. Since this would give an abnormally high cross section, it seems likely that more than one isotope is contributing to the observed radiation. Care should be taken in interpreting the results of experiments of this type, as cross sections are sometimes quoted as above, and sometimes as barns per atom of the particular isotope excited. The first method of designation is probably to

TABLE I. First excited states of stable Zr isotopes.

Mass number	Percent abundance	Lowest level (kev)
90	51.5	2030
91	11.2	
92	17.1	930
94	17.4	
96	2.9	

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[5] J. B. Guernsey and C. Goodman, Phys. Rev. 92, 323 (1953).

[6] P. Preiswerk and P. Stahelin, Helv. Phys. Acta 24, 300 (1951).

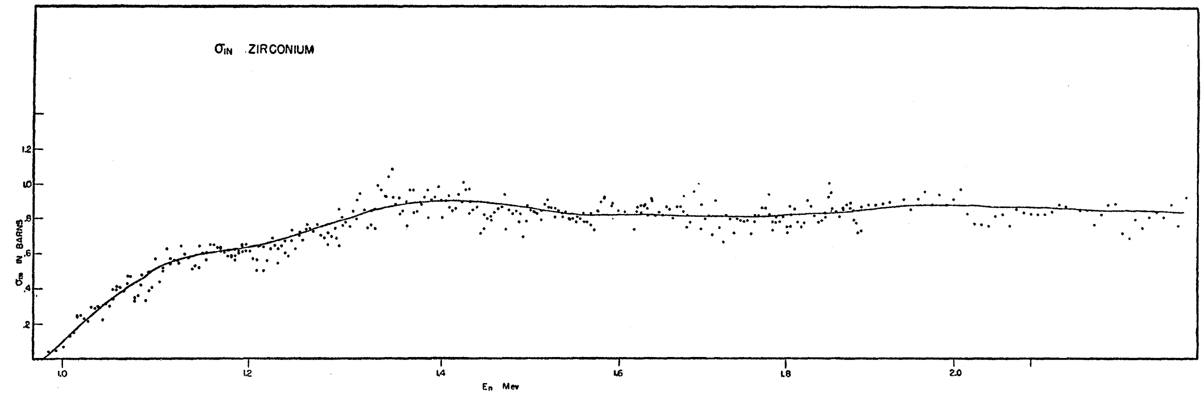

Fig. 3. Neutron inelastic cross section for zirconium. The inelastic cross section is for the natural element. There is repeatable evidence of closely spaced resonances throughout the energy region investigated. The neutron energy resolution is about 20 kev. No attempt has been made to assign energies to individual resonances.

be preferred from an engineering standpoint (i.e., reactor design) while the latter should be used for comparison with theoretical calculations, such as those of Hauser and Feshbach.[7]

Another difficulty in the evaluation of cross section is the calculation of neutron flux within the scatterer. For a thin scatterer one may well assume that essentially every neutron undergoing an elastic encounter will be scattered out of the sample. For a scatterer whose dimensions are of the order of a mean free path, however, the assumption of a single scattering encounter is of doubtful validity. Calculations made by Day[8] at

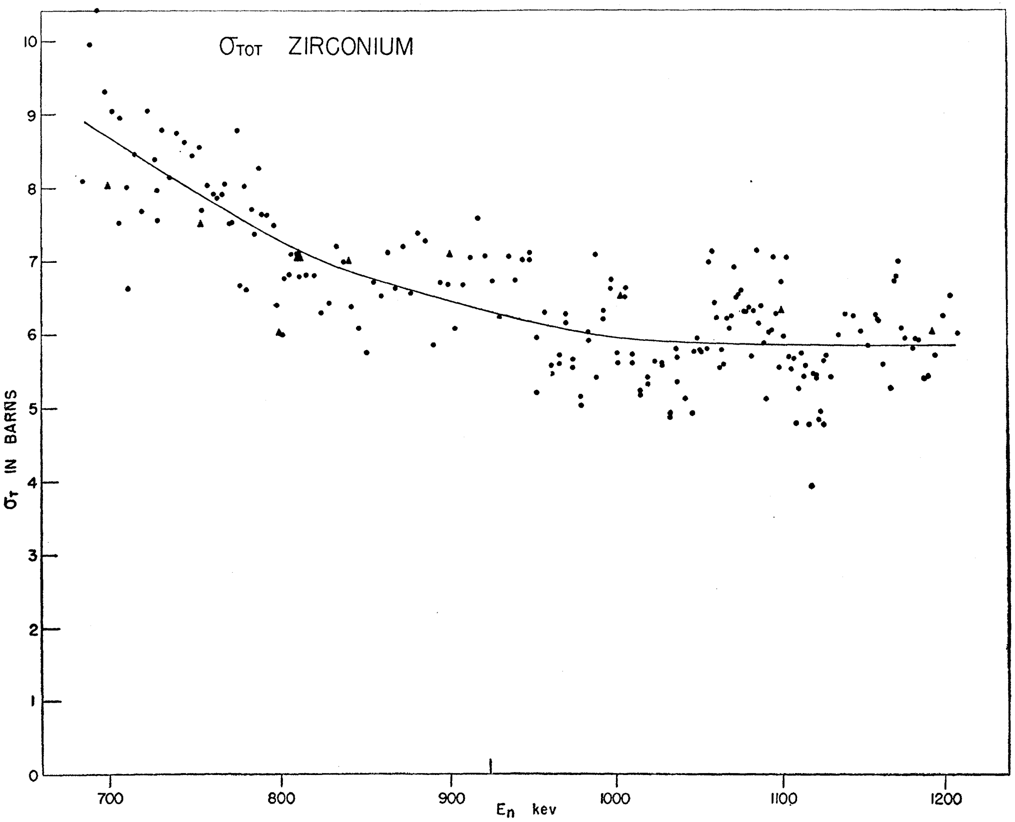

Fig. 4. Total neutron cross section for zirconium. This cross section, obtained by a transmission experiment, shows evidence of closely spaced resonances. The data are in good agreement with the latest published values, represented on the figure by solid triangular points. The neutron energy resolution is about 3 kev.

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[7] W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

[8] R. B. Day (private communication).

Los Alamos for a somewhat different geometry indicate that multiple scattering may put the cross sections in error by as much as 50% for a scattering sample of the dimensions used in this work. Calculations for the geometry used here are extremely tedious, if not impossible; accordingly, an experimental determination was attempted. The experiment was repeated with iron cones of different dimensions; the indication was that the multiple scattering effect was only of the order of 10%, but was not reliable enough to yield a value for the correction. Therefore the results given in Fig. 3 have not been corrected for multiple scattering.

In Fig. 3, the solid line represents an average cross section. The deviations of the experimental points about the curve are interpreted as unresolved resonance structure, since the variations in gamma-ray yield were repeatable experimentally over a period of two months.

The total cross section for zirconium is given in Fig. 4. Here again the solid curve is an average value, and the deviations of the experimental points are probably unresolved resonance structure. Since the calculation of σ_T is dependent only on a knowledge of relative neutron flux, absolute values of the cross section are accurate to within 2%. They compare favorably with those of other workers.[9] Figure 5 compares the resonance structure of the total and inelastic cross sections for a small portion of the energy region covered. The energy spread of the neutrons used in the total cross-section determination is smaller than that of the neutrons used in the inelastic cross section measurement by a factor of 4. Thus the structure is expected to be more pronounced in the former case. There appears to be some correlation between resonances in the two cases. It should be pointed out that σ_T appears as a factor in the calculation of σ_{in}; therefore calculations were made using both actual and average values of σ_T, and compared. The structure in the inelastic scattering was preserved in both cases. Figure 5 represents cross sections calculated using an average value of σ_T. The possibility should not be overlooked, however, that multiple scattering may contribute to the resonance structure observed in the inelastic cross section. Multiple scattering at a resonance in the elastic cross section would serve to increase the effective neutron flux within the scatterer, and thus also to increase the observed inelastic scattering. Recent results on inelastic scattering from manganese tend to support this conclusion. The total cross section for this element shows a strong resonance at a neutron energy of 300 kev.[10] The inelastic cross section for the excitation of the first level (at 128 kev) has been determined in this laboratory, using a technique which employs a scatterer only 0.7 cm thick.[11] No resonance structure is observed between 200 and 400 kev neutron energy. This indicates that multiple scattering in the large sample may account for the structure observed with this technique. Experimental work is in progress toward a clarification of this point.

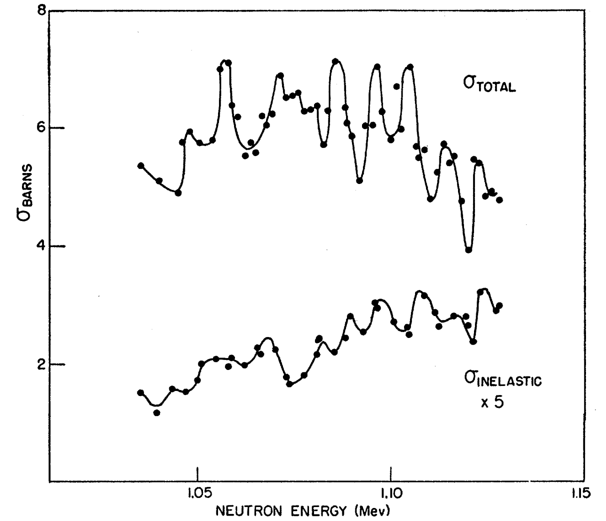

FIG. 5. Neutron cross sections for zirconium. A comparison between the total and inelastic cross sections for zirconium shows essentially the same density of nuclear levels. The level spacing is about 10 kev. The inelastic cross section is still rising from its threshold value. The neutron energy resolution is about 3 kev for the total cross-section measurement; about 20 kev for the inelastic cross-section measurement.

IV. ACKNOWLEDGMENTS

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[9] *Neutron Cross Sections,* Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1952), Supplement 3, 1954 (Wisconsin data).

[10] *Neutron Cross Sections,* Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1952) (Argonne-accelerator data).

[11] J. Guernsey and A. Wattenberg (to be published).