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Total Cross Section Measurements for Fast Neutrons

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The total cross sections of Zr, Ag, In, Sb, I, Ta, and Pb have been measured as a function of neutron energy in the energy range from 20 kev to 1600 kev. A spread in energy of 30 kev was used up to 200 kev, and a spread of 70 kev above this energy. Indications of structure were found in Zr and Pb. The results are compared with the predictions of the statistical theory.

INTRODUCTION

On the basis of statistical theory, Feshbach, Peaslee, and Weisskopf[1] have made calculations to find approximate expressions for the total neutron cross section as a function of neutron energy up to 1 Mev. When the results of the calculations were compared with the total cross sections for photo-neutrons measured by Fields *et al.*,[2] there appeared to be qualitative agreement. The comparison, however, was made difficult by the wide spacing in energy of the experimental results. Further, in order to permit a test of the theory, it is necessary that the experimental energy spread be much larger than the average distance between nuclear energy levels. It was not clear that this was the case for the photo-neutrons. An attempt was made previously at this laboratory to test the theory by measuring the total cross sections of Fe, Ni, and Bi with a resolution of about 150 kev.[3] Only in the case of Fe could agreement be obtained by appropriate choice of the parameters entering into the theory. The discrepancy in Ni was attributed to the presence of a strong resonance occurring at 15 kev, and in Bi the closed shell structure of the nucleus might make the theory inapplicable. In the present experiments, a survey of several medium-heavy and heavy nuclei was undertaken to investigate the validity of the statistical theory.

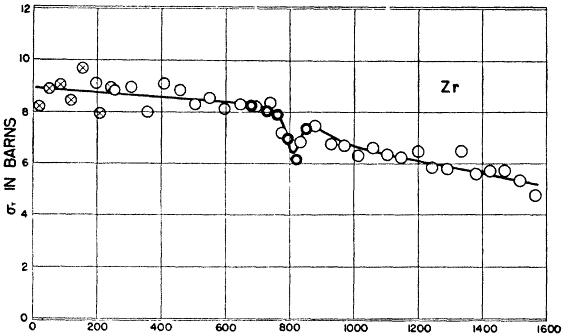

FIG. 1. The total cross section of zirconium as a function of neutron energy. Encircled crosses represent data taken at 115° with respect to the incident protons, the other symbols measurements in the forward direction. Single and double circles show two separate runs.

Since the previous work showed strong effects of resonances in Ni, only heavier elements were chosen for this study. The choice of the particular elements used was based on their availability and the desire to cover a wide range of atomic numbers.

PROCEDURE

Neutrons were produced by bombarding a Li film by protons accelerated by the electrostatic generator. A sufficient energy spread of the neutrons was obtained by using a Li target which had a stopping power of 60 kev for the protons. Up to neutron energies of 200 kev, observations were carried out in a direction making an angle of 115° with respect to the incident protons. For measurements at this angle, the spread in energy of the neutrons is about 30 kev. Above 200 kev, the observations were made in the forward direction with respect to the protons. In this case the resolution is about 70 kev.

The neutrons were detected in a proportional counter filled with $B^{10}F_3$[4] and covered by Cd sheet. Cross sections were determined by simple transmission experiments as described previously.[5]

The samples used were circular disks, 1.75 in. in diameter, machined or cast from pure metal, except in the cases of Sb and I where the powdered material was tightly packed into brass containers. Table I shows a list of the samples used.

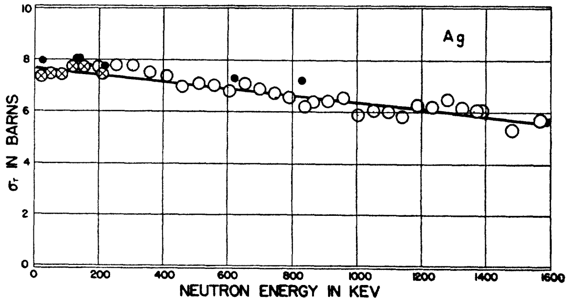

FIG. 2. The total cross section of silver as a function of neutron energy. The solid circles represent the data of Fields *et al.* (reference 2).

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[1] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).

[2] Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

[3] Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948).

[4] Furnished by the Isotopes Branch of the AEC.

[5] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949).

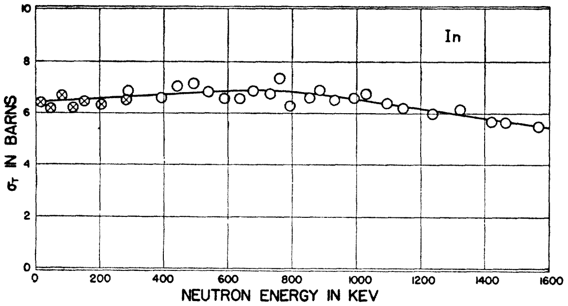

FIG. 3. The total cross section of indium. Encircled crosses represent data taken at 115° with the 1.25-cm thick sample, while the open circles show measurements taken in the forward direction with the 2.42-cm sample.

RESULTS

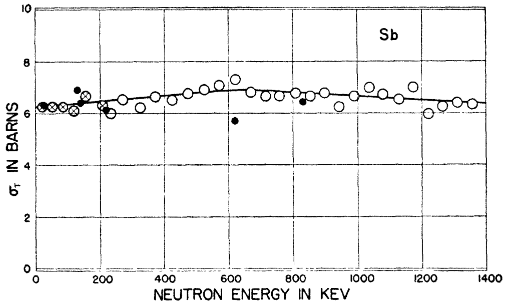

FIG. 4. Total cross section of antimony.

The results of the measurements are shown in Figs. 1–7 as plots of the total cross section in barns against neutron energy in kev. All cross sections were corrected for scattering into the detector and for background. As the neutron energies cover an appreciable energy interval, the median values of each energy interval are plotted. Encircled crosses indicate measurements taken at 115° with respect to the proton beam, while the open circles represent data taken in the forward direction. The height of the symbols is approximately equal to the statistical error of the measurements.

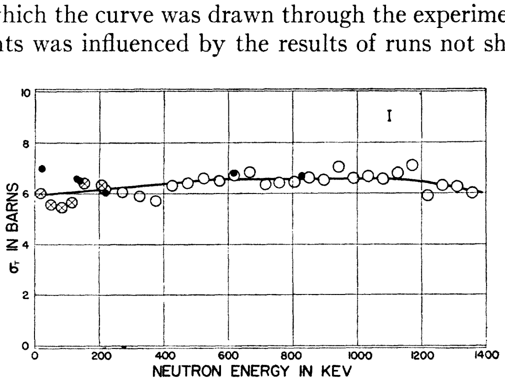

FIG. 5. Total cross section of iodine.

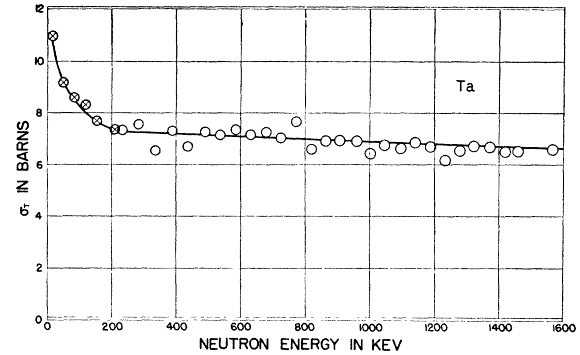

FIG. 6. Total cross section of tantalum.

For each element several runs were taken over the complete energy range. In some instances, the manner in which the curve was drawn through the experimental points was influenced by the results of runs not shown in the figures. Wherever available, the results of Fields *et al.*,[2] using photo-neutron sources, are indicated by solid circles.

DISCUSSION

According to the statistical theory, the total cross section should be a monotonic function of energy, increasing slowly as the energy decreases. The present measurements do not show this increase at low energies except in the case of Ta and Pb where the increase is more rapid than predicted by theory. A reason why the measurements might give too small a cross section at low energies was suggested by Feshbach and Weisskopf.[6] According to the theory, most of the rise at low energies is due to the effect of averaging over many resonances, the peaks of which reach higher values in this region. For medium-heavy nuclei, these resonances would be expected to be quite sharp and to have separations in energy of many times their widths. If this is the case, the experiment will not yield a cross section corresponding to the average over the resonances, since even a considerably thinner sample would be completely opaque to the neutrons which have energies close to the resonance energy. This argument does not help, however, to explain the behavior of Ta and Pb. There is other evidence

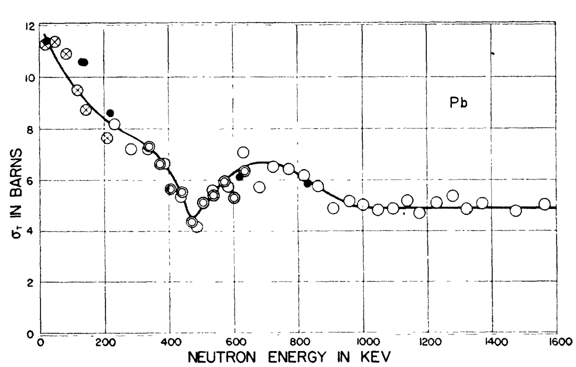

FIG. 7. Total cross section of lead. Up to a neutron energy of 1080 kev, measurements were made with the 1.90-cm thick scatterer. Above this energy the 3.18-cm sample was used. Double circles show a second run.

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[6] Private communication.

that Pb has relatively few levels so that the statistical theory might not be applicable, just as in the case of Bi.

Two of the elements investigated, Zr and Pb, show deviations from a smooth variation of the cross section with energy. These anomalies were quite reproducible and are shown in two typical runs in Figs. 1 and 7. It is somewhat surprising to find structure in heavy elements, considering the poor resolution used. Evidence for such a structure in Pb had previously been found by Bretscher and Murrell.[7] In view of the fact that the anomalies have the shape of dips rather than peaks, one might suspect that they could be caused by inelastic scattering. As the energy of the primary neutrons becomes just sufficient to produce the final nucleus in an excited state, low energy neutrons will be emitted from the scatterer, and the detector used will detect these neutrons with high efficiency. This effect would result in a decrease of the observed cross section. It does not appear likely, however, that this explanation could account for the observations. It is known[8] that at these energies the cross section for inelastic scattering, at least in the case of Pb, is very small (not more than 0.3 barn), and only three percent of the scattered neutrons will reach the detector in the geometry used. Furthermore, because of the wide spread in energy of the primary neutrons, only a very small fraction of the scattered neutrons will have energies in the range in which the sensitivity of the counter is very high.

TABLE I. Samples used in transmission experiments.

Element	Atomic weight	Thickness (cm)	Number of atoms/cm^2 $\times 10^{-24}$
Zr	91	1.27	0.0551
Ag	108	1.27	0.0746
In	115	1.25	0.0471
In	115	2.42	0.0923
Sb	122	3.18	0.0657
I	127	3.18	0.0723
Ta	181	1.27	0.0705
Pb	207	1.90	0.0630
Pb	207	3.18	0.1081

It is interesting to note that the most abundant isotopes of both Zr and Pb have closed neutron shells[9] (50 and 126 neutrons, respectively), and might, therefore, be expected to have broad and widely spaced levels. It is planned to investigate, with better resolving power, the energy regions in which the anomalies were observed.

The authors wish to thank Mr. R. L. Henkel for assistance in the experiments. This work was supported by the Wisconsin Alumni Research Foundation and by the AEC.

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[7] Bretscher and Murrell, quoted Goldsmith, Ibser, and Feld, Rev. Mod. Phys. **19**, 259 (1947).

[8] Barschall, Battat, Bright, Graves, Jorgensen, and Manley, Phys. Rev. **72**, 881 (1947).

[9] M. G. Mayer, Phys. Rev. **74**, 235 (1948).

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Measurements on Radioactive Krypton Isotopes from Fission after Mass-Spectrographic Separation

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Radioactive isotopes of krypton resulting from fission of uranium have been separated in a mass-spectrograph. The half-lives and the relative fission yields of the isotopes Kr^{85}, Kr^{87}, and Kr^{88} have been measured. The maximum energies of the β-particles from Kr^{85} and Kr^{87} have been checked by absorption. It has been shown that Kr^{88} emits soft β-particles and an intense γ-radiation. This result combined with other measurements indicates that the β-spectrum of Kr^{88} is complex.

INTRODUCTION

AMONG the radioactive nuclei formed in neutron-induced fission of uranium there are many krypton isotopes.[1,2] By using mixtures of these isotopes several radioactive periods have been isolated, either from the analysis of complex decay curves[3] or by the application of less direct methods.[4] The mass-numbers of the radioactive isotopes could be determined with considerable certainty from such experiments.

The present note describes experiments which were carried out with some long-lived krypton isotopes after they had been separated by means of the mass-spectrograph of this Institute.[5] This procedure is a crucial test of the assignment of activities to mass-numbers and,

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[1] Plutonium Project, Rev. Mod. Phys. **18**, 513 (1946).

[2] G. T. Seaborg and J. Perlman, Rev. Mod. Phys. **20**, 585 (1948).

[3] A. H. Snell, Phys. Rev. **52**, 1007 (1937). W. Seelmann-Eggebert and H. J. Born, Naturwiss. **31**, 59 (1943). E. P. Clancy, Phys. Rev. **60**, 87 (1941).

[4] G. N. Glasoe and J. Steigman, Phys. Rev. **58**, 1 (1940).

[5] J. Koch and B. Bendt-Nielsen, Kgl. Danske Vid. Sels. Math.-fys. Medd. **21**, No. 8 (1944). J. Koch, Phys. Rev. **69**, 238 (1946).