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Total Cross Section of Fe, Ni, and Bi for Fast Neutrons

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The total cross sections of Fe, Ni, and Bi have been measured for neutrons of from 10-kev to 500-kev energy with a resolving power of approximately 20 kev, and from 200 kev to 1400 kev with a resolving power of about 150 kev. With the higher resolving power marked fluctuations in cross section, indicating the presence of resonances, were observed in Fe and Ni, but not in Bi.

I. INTRODUCTION

IN a previous paper[1] measurements of the total cross section of aluminum as a function of neutron energy were reported. The results indicated that in aluminum the energy levels are sufficiently far separated to be observable with a resolving power of approximately 20 kev. Measurements of the radiative capture of protons by aluminum[2] give for the level spacing of Si^{28} at low proton energies about 50 kev. This result is compatible with the upper limit of the level density in Al^{28} which one would deduce from the variation of the neutron cross section of aluminum.

In the present work the level spacing in heavier nuclei was investigated. From theoretical considerations and from the results of experiments on the capture of slow neutrons one would expect the level density in medium-heavy and heavy nuclei to be small compared to 20 kev. On the other hand, measurements of the total neutron cross section of some heavy elements using photo-neutron sources show fluctuations in cross section which might be attributed to energy levels of considerable separation. Goloborodko,[3] using neutrons of many kev energy spread found strong fluctuations in the total cross section of nuclei as heavy as Tl and Pb. Fields *et al.*,[4] showed the presence of fluctuations in fast neutron cross sections in elements as heavy as Sb and I.

The choice of elements for the present investigation was based primarily on the results of Fields *et al.*[4] These authors observed an anomalous behavior in the cross section of Fe and Ni for the 24-kev neutrons from an Sb−Be source. While the cross section of Fe (2.2 barns) is lower at that energy than at both higher and lower energies, the cross section of Ni (23 barns) has a higher value than at both higher and lower energies. It appeared interesting, therefore, to follow the cross sections of Fe and Ni as a function of neutron energy.

In addition, the investigation of a heavy

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[1] L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947).

[2] G. P. Plain, R. G. Herb, C. M. Hudson, and R. E. Warren, Phys. Rev. **57**, 187 (1940); K. J. Boström, T. Huus, and R. Tangen, Phys. Rev. **71**, 661 (1947).

[3] T. Goloborodko, J. Phys. U.S.S.R. **8**, 106 (1944), and **11**, 44 (1947).

[4] R. Fields, B. Russel, D. Sachs, and A. Wattenberg, Phys. Rev. **71**, 508 (1947).

element seemed desirable. Bi was chosen for this experiment. Of the heavy elements it was most likely to show a wide spacing of levels for the following reasons: it consists of only one stable isotope, it has an unusually small capture cross section for slow neutrons,[5] and a relatively small cross section for inelastic scattering of fast neutrons.[6]

II. PROCEDURE

The experiments were carried out in the same manner as the measurements of the scattering cross section of aluminum.[1] Neutrons were produced by bombarding lithium with protons accelerated by the electrostatic generator.[7] In most of the experiments the lithium target was about 10 kev thick, except in the experiments described as "thick target" measurements in which the lithium target was about 150 kev thick. The neutrons were detected by means of a BF_3 proportional counter.

In order to make the alignment less critical, scatterers of slightly larger diameter, i.e., 1.75 in., were used in the present experiments. Consequently, the geometry was such as to measure scattering through angles greater than 25°. In this geometry the correction for scattering into the detector was approximately five percent.**

III. RESULTS

In Figs. 1–3, the corrected total cross section is plotted against the neutron energy. The data shown in the upper and lower parts of the figures are measurements for the same energies taken some time part. Open circles indicate measurements taken at an angle of 115° with respect to the proton beam; all other open symbols represent data taken in the forward direction. A

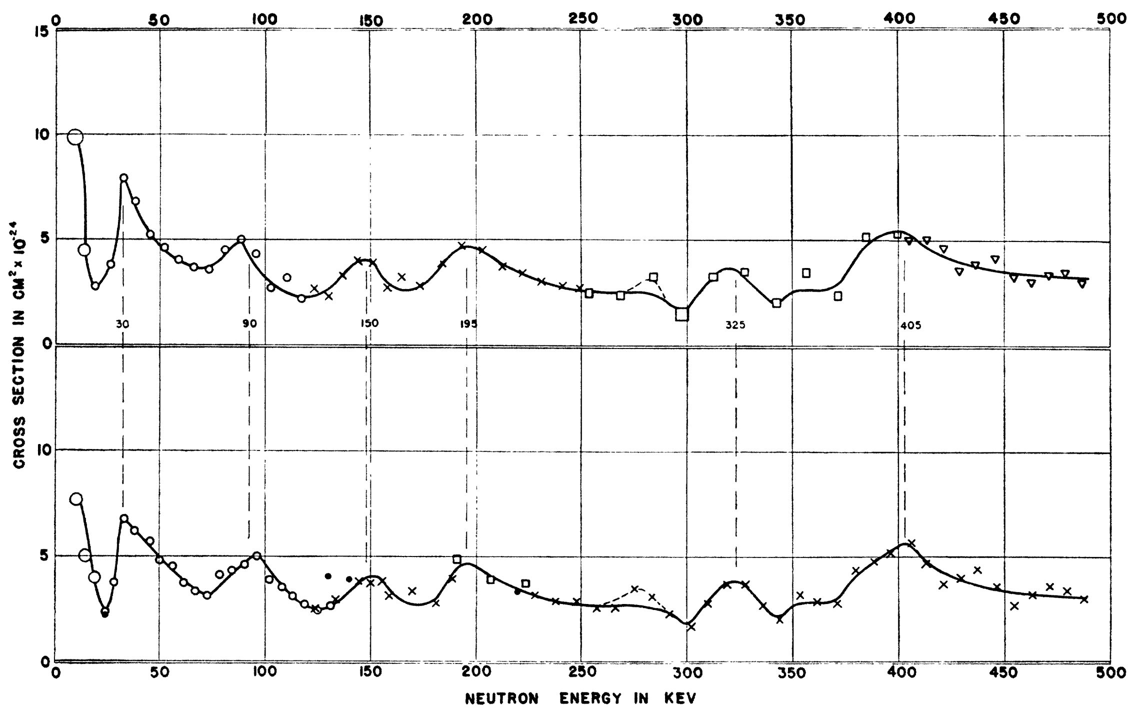

FIG. 1. The total cross section of iron as a function of neutron energy. The neutron energy spread was about 20 kev. Open circles indicate measurements taken at 115° with respect to the proton beam; other symbols represent measurements taken in the forward direction. The height of the symbols used is equal to the standard statistical errors. Solid circles give the results of Wattenberg.[4]

[5] R. D. O'Neal and M. Goldhaber, Phys. Rev. **59**, 102 (1941).
[6] H. Aoki, Proc. Phys. Math. Soc. Japan **19**, 369 (1937).
[7] Herb, Turner, Hudson, and Warren, Phys. Rev. **58**, 579 (1940).
** At the lowest energies this correction may be somewhat too large, if absorption is appreciable, while at high energies the correction may be too small because of the effect of diffraction scattering.

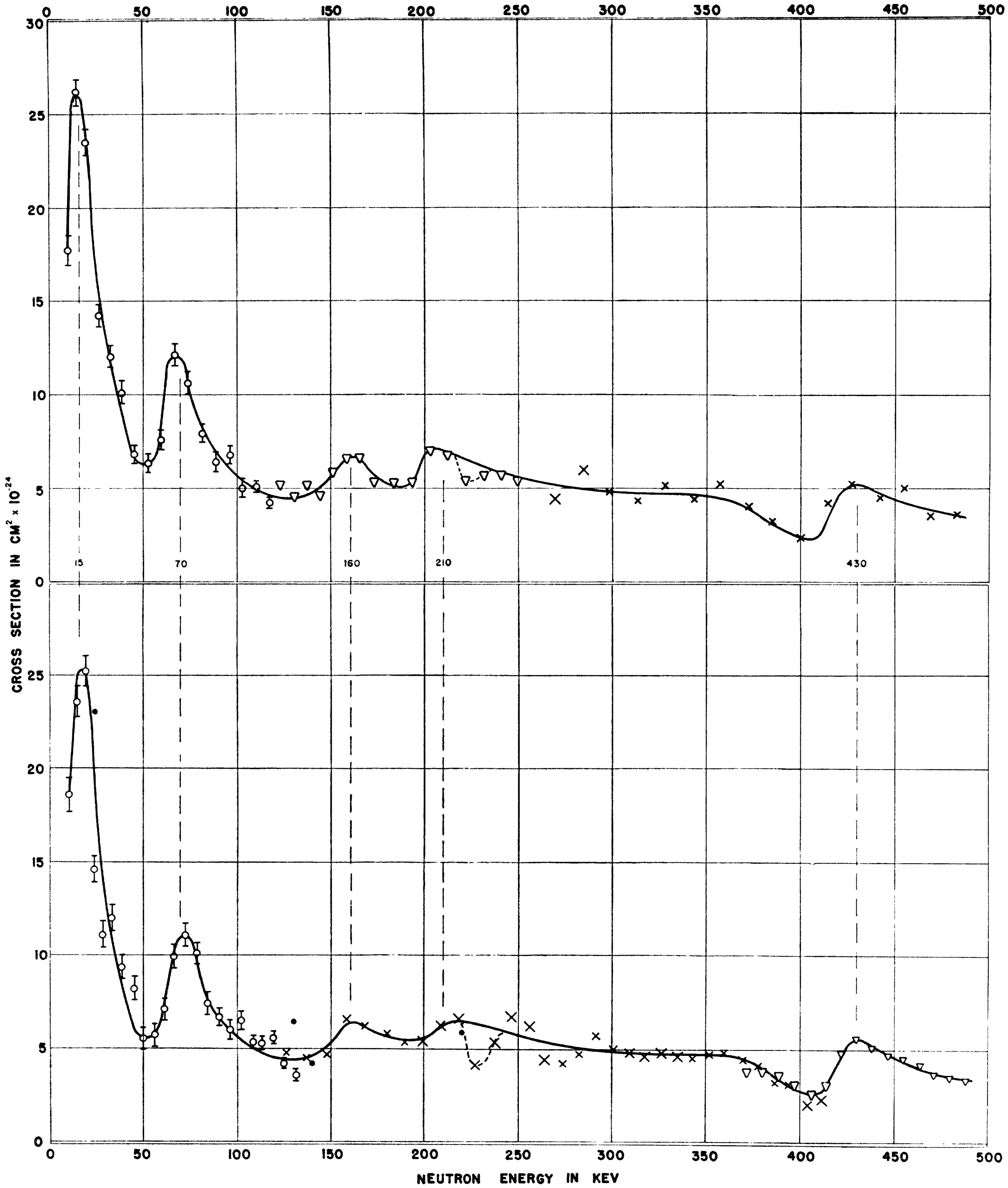

FIG. 2. The total cross section of nickel as a function of neutron energy.

change in symbol indicates a lapse of time between measurements. The size of the symbols is chosen so that their heights are equal to the standard statistical errors except in those cases in which the errors are given by vertical lines through the symbols.

In addition to statistical errors the measurement of the cross sections may have systematic errors for low neutron energies. Because of the strong forward maximum of the neutron intensity at low energies, the correction for room background becomes very appreciable for mea-

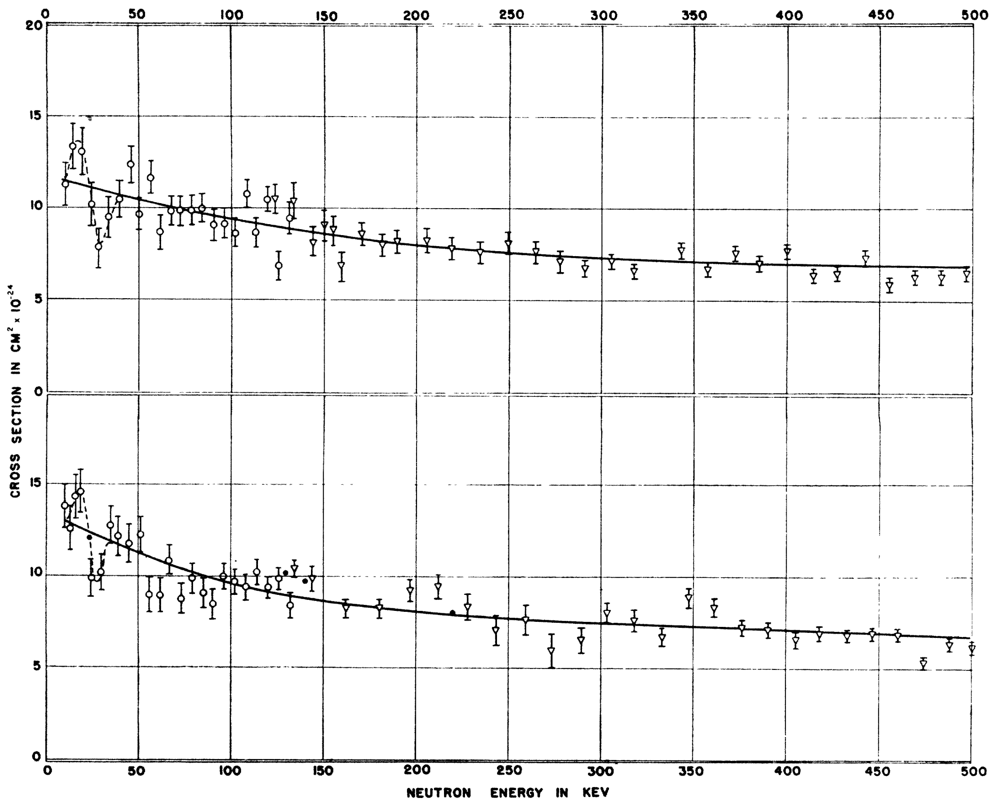

FIG. 3. The total cross section of bismuth as a function of neutron energy.

surements at 115°. The measurement of the background may be inaccurate, since the shadow cone used will also shield the counter from some of the neutrons reflected by the floor. For this reason, measurements taken below 10 kev were not included.

In the lower sections of Figs. 1–3, the solid circles at 24, 130, 140, and 220 kev represent the results of Wattenberg.[4] An exact agreement of the results should not be expected, since the distribution in energy of the photo-neutrons[8] differs considerably from that of the Li+p neutrons. In addition, there is an uncertainty in the absolute value of the neutron energies both for the Li+p neutrons and for the photo-neutrons. In the present measurements, the neutron energies were calculated by using the threshold of the Li(p,n) reaction as a reference energy, taken as 1.860 Mev.

[8] D. J. Hughes and C. Eggler, Phys. Rev. **72**, 902 (1947).

1. Iron

The iron scatterer was 1 in. thick, and contained 0.215×10^{24} atoms/cm^2. It was made out of Armco iron which contains more than 99.9 percent Fe.

The results for iron are shown in Fig. 1. Most of the energy range was covered more than twice with results in substantial agreement with those shown. The variations of the measured cross section with energy are so much larger than the statistical error that it does not seem possible to draw a smooth curve through the experimental points. Clear indications of maxima are found at 30-, 90-, 150-, 195-, 325-, and 405-kev neutron energy. There are some other regions (280, 445, and 475 kev) in which the best fit of the data would be given by small maxima, but the latter points are not sufficiently far from a smooth curve to make the existence of maxima convincing.

2. Nickel

Two nickel scatterers were used in the experiments, one $\frac{1}{4}$ in. thick, containing 0.0578×10^{24} atoms/cm^2, the other $\frac{1}{2}$ in. thick, containing 0.1156×10^{24} atoms/cm^2. The thinner scatterer was used in all measurements below 105-kev neutron energy, the thicker one above 105-kev energy.

Figure 2 shows the measurements of the total cross section of nickel. Definite maxima are shown at 15, 70, 160, 210, and 430 kev, and there is a slight indication of a maximum at 245 kev.

3. Bismuth

For measurements below 300-kev neutron energy a bismuth scatterer $\frac{1}{2}$ in. thick containing 0.0358×10^{24} atoms/cm^2 was used, while above 300 kev a scatterer 1 in. thick containing 0.0713×10^{24} atoms/cm^2 was employed.

In Fig. 3 the results of the measurements on bismuth are shown. None of the points shown in Fig. 3 give any clear indication of deviations from a smooth variation of the total neutron cross section of bismuth with energy. There may be some evidence for a minimum at 30 kev, as indicated by the dashed line in Fig. 3, but the reality of this dip appears doubtful.

IV. THICK TARGET MEASUREMENTS

In order to compare the measurements of total cross section with the predictions of Feshbach, Peaslee, and Weisskopf,[9] experiments were carried out with lower resolving power so as to smooth out the effect of fluctuations in level density. For this purpose a Li target, 150 kev thick, was used. The measurements were extended to a neutron energy of 1400 kev. For iron and bismuth the 1-in. thick scatterers were employed in these investigations while the experiments on nickel were carried out with the $\frac{1}{2}$-in. thick specimen.

The results are shown in Fig. 4. A smooth monotonically decreasing curve could be drawn through all the points for a given element with the possible exception of the cross section for iron at 800 kev. This latter point was outside the statistical error from a smooth curve in two separate measurements.

To facilitate the comparison with the theoretical predictions the smooth curves of Fig. 4 are replotted in Figs. 5 and 6 on a different scale. The cross sections are given in units of πa^2, where a is the nuclear radius calculated according to $a=1.5\times10^{-13}A^{\frac{1}{3}}$ cm. Instead of energy, ka is plotted, where k is the wave number of the incident neutron. The solid lines in Figs. 5 and 6

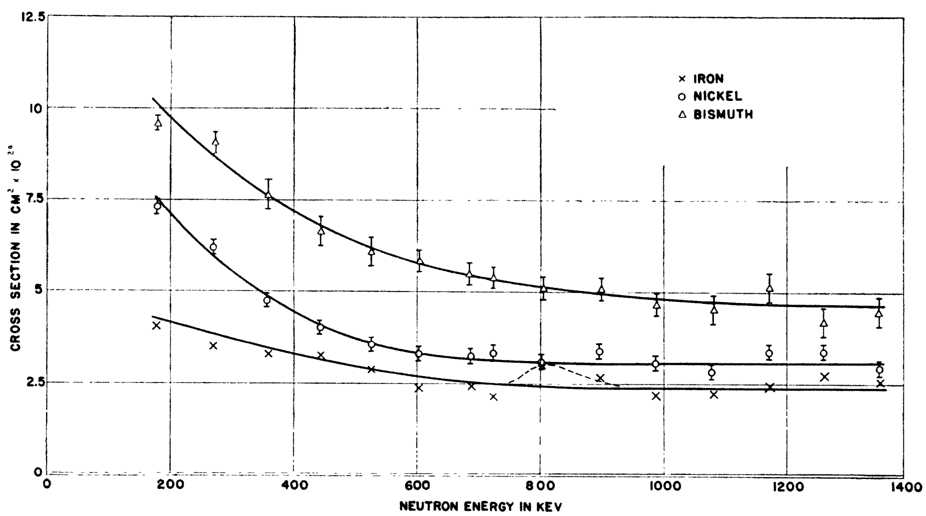

FIG. 4. The total cross section of iron, nickel, and bismuth as a function of neutron energy. The neutron energy spread in these experiments was about 150 kev. The points are plotted for the average neutron energy used.

[9] H. Feshbach, D. C. Peaslee, and V. F. Weisskopf, Phys. Rev. 71, 145 (1947).

are the theoretical predictions obtained from Fig. 5 of reference 9 according to the method described on p. 157 of reference 9. In order to extend the comparison to higher neutron energies than were covered in the present experiments, the results of Aoki[10] for neutron energies between 2 and 3 Mev are also included in Figs. 5 and 6.

V. DISCUSSION

The fluctuations in the total cross section of Fe and Ni observed with a resolving power of 20 kev could be explained as the effect of either individual levels or fluctuations in level density.

In the case of iron, only the effects produced by the most abundant isotope (abundance of Fe^{56} is 92 percent) are likely to be observed with the accuracy of the present experiments. In the range of energies investigated there is evidence that elastic scattering is the predominant interaction between neutrons and iron.[11]

If a maximum is due to a single level of the compound nucleus, and if the angular momentum of the incident neutron is zero, one would expect the total cross section at the maximum of a resonance to be $4\pi k^{-2}$ (neglecting potential scattering, which would tend to increase it). At 90 kev, $4\pi k^{-2}$ is approximately 30 barns, while the peak observed at that energy for iron reaches only 5 barns. Similar considerations can be applied to the other observed peaks. The discrepancy between the observed and calculated heights indicates that the resolving power of the apparatus is considerably too small to obtain the true shape of the resonances. This conclusion is reinforced by experimental evidence in the previous work on Al, in which it was found that use of a higher resolving power over the energy range of one of the resonances resulted in a sharpening of the peak.

It is, therefore, not possible to decide whether the observed maxima are due to single levels. The fact that the maxima do not have the shape expected for scattering resonances[9] might lead one to believe that the peaks are due to fluctuations in level density.

In Bi no good evidence for the presence of

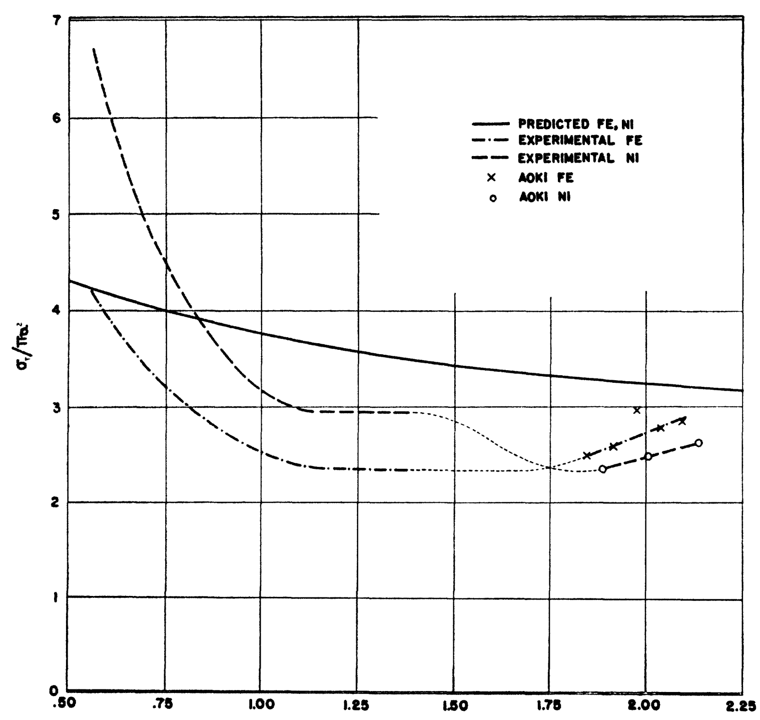

FIG. 5. Comparison of thick target data for iron and nickel with theory.[9]

[10] H. Aoki, Proc. Phys. Math. Soc. Japan 21, 232 (1939).

[11] H. H. Barschall, M. E. Battat, W. C. Bright, E. R. Graves, T. Jorgensen, and J. H. Manley, Phys. Rev. 72, 881 (1947).

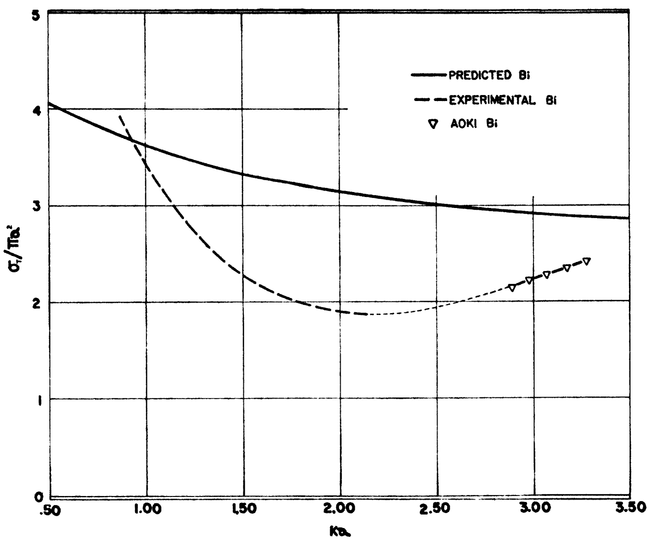

FIG. 6. Comparison of thick target data for bismuth with theory.[9]

fluctuations in total cross section were obtained. From nuclear theory[12] one would conclude from this fact that the levels are so closely spaced that their effect is not noticeable. On the other hand, the small capture cross section of Bi combined with the lack of resonances in the low energy region as shown by the slow modulation experiments of Rainwater and Havens, make the assumption of a very much closer level spacing in Bi than in Fe and Ni doubtful. It does not appear certain, therefore, that the observed smooth variation of cross section with energy is due to very many levels rather than an absence of levels.

According to Weisskopf and Feshbach[13] the difference between the observed thick target data (Figs. 5 and 6) and the theoretical predictions[9] is probably due to an uncertainty in the knowledge of the constants on which the calculations are based. For the purposes of the theory the nuclear radius is uncertain by $\pm 10^{-13}$ cm. In addition, the cross sections were calculated under the assumption that the levels are distributed at random ($D^*/D=\frac{1}{2}$, Eq. (25) of reference 9). This assumption may not be valid, and D^*/D may have values from 0.3 to 1. The observed values of cross section lie approximately within the limits of the mentioned uncertainties. For iron the best fit with the experimental data is obtained by using a nuclear radius of 4.6×10^{-13} cm and a value of D^*/D of 0.8. The cross sections of nickel and bismuth rise more rapidly at low neutron energies than one would expect from the theory. This fact may be due to the effect of a wide level or of a group of levels at those energies.

[12] For example, H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, New York, 1947), p. 116.

[13] Private communication.

VI. ACKNOWLEDGMENTS

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