Total Cross Sections of Heavy Nuclei for Fast Neutrons*

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The total neutron cross sections of twenty-three heavy elements from iron to bismuth have been determined as a function of neutron energy from about 0.05 Mev to 3.2 Mev. Every element whose major isotope (>50 percent abundant) has a closed neutron shell of 50, 82, or 126 neutrons is included among the elements investigated. Below 1.4 Mev, neutrons having an energy spread of 20 kev were employed to take measurements at 20-kev intervals on strontium, yttrium, barium, lanthanum, cerium, and praseodymium. Niobium and molybdenum were also investigated in this region using energy intervals of 70 kev between measurements. These measurements and earlier low energy measurements on fifteen other heavy elements were extended to 3.2 Mev, using an energy spread of 20 kev and intervals between points of about 200 kev. The most unusual feature of the results is a very broad maximum which is clearly observed in the total cross sections of thirteen of the elements studied. This maximum appears to move to higher neutron energies with increasing mass number. The position and shape of the maximum seems to be independent of all other nuclear details, such as the nuclear spin or the binding energy of the added neutron. When averaged over resonances, the total cross sections of the closed-shell nuclei do not appear to be different from the total cross sections of other nuclei of about the same masses. There is some indication that the spacing of resonances in the total cross sections of the closed-shell nuclei is greater than observed in the cross sections of other nuclei.

I. INTRODUCTION

THE observed energy dependence of the total cross sections of nuclei for fast neutrons can be compared with theory most readily in the cases of very light or very heavy nuclei. Nuclear dispersion theory predicts the variations in the total cross section caused by the presence of excited states in the compound nucleus of the reaction. This theory has been successfully compared with experiment repeatedly in cases of light nuclei with widely spaced levels. For heavy nuclei, Feshbach, Peaslee, and Weisskopf[1,2] have developed a continuum theory which predicts the energy dependence of the total cross section averaged over resonances. Only two parameters are required in this theory, the nuclear radius and the wave number of the incident neutron within the nucleus. The most important result of this theory for the present study is that the predicted total cross section is a monotonically decreasing function of neutron energy, regardless of the choice of nuclear parameters. Before the present investigation was begun, the total cross sections of heavy elements then known indicated that the validity of the theory was uncertain. Although qualitative agreement was found in some cases, the total cross sections of the elements indium, tin, antimony, and iodine up to 1.4-Mev neutron energy did not show the predicted monotonic decrease.

To provide further results for comparison with the continuum theory, in the present work the energy dependence of the total cross section was determined for 23 heavy elements. In addition to an investigation of nine elements containing neutron closed shells, the measurements previously made at Wisconsin on 12 heavy elements[3] were extended to 3.2-Mev neutron energy. These twelve elements are iron, nickel, copper, zinc, silver, indium, tin, antimony, iodine, tantalum, wolfram, and radiogenic lead. The total cross sections of the elements niobium and molybdenum were also determined in the present experiment over the entire energy range from 0.12 to 3.2 Mev.

More than one-third of the heavy elements included in the study were chosen because they consist primarily of nuclei with closed shells in neutrons. This choice allows one to make a comparison between the total cross sections of closed-shell nuclei and nonmagic nuclei, in order to determine if any differences can be observed. Because the binding energy of a neutron added to a closed-shell nucleus is abnormally small, the closed-shell-plus-one compound nucleus is formed at a lower excitation energy than its neighbors. One therefore expects the total cross section of a closed-shell nucleus to exhibit fewer resonances than other nearby nuclei. Individual resonances in the cross sections of nuclei as heavy as those investigated here usually cannot be resolved in the fast-neutron energy region. This makes direct measurements of level densities impossible. However, if one is able to observe any structure at all in the cross sections of heavy closed-shell nuclei, it will indicate fewer resonances than have been observed for heavy nonclosed-shell nuclei.

At high excitation energies the closed-shell cores are expected to be broken up, so that highly excited states of closed-shell-plus-one nuclei are not expected to differ from the highly excited states of other nuclei. Since the smallest binding energy of a neutron added to any nucleus investigated in this work is 3.9 Mev, the compound nucleus is in all cases excited well above its ground state, and no closed-shell peculiarities other than reduced level densities were anticipated.

The elements investigated in this work included all

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

[2] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).

[3] See R. K. Adair, Revs. Modern Phys. **22**, 249 (1950) for references.

of the nine elements in which the major isotope (>50 percent abundant) has a closed shell of 50, 82, or 126 neutrons. These elements are strontium, yttrium, zirconium, barium, lanthanum, cerium, praseodymium, lead, and bismuth. Measurements of the total cross sections of some of these elements in the energy range covered by the present investigation have been published earlier.[3–5]

It was hoped that the present investigation would provide a test for the statistical theories, and at the same time determine if the total cross sections of closed-shell nuclei exhibit any special deviations.

II. EXPERIMENTAL PROCEDURE

All but six of the scattering samples used in the present experiment were metallic cylinders 1.75 inches in diameter. The niobium samples were in the form of 1.375-inch diameter cylinders. Antimony, iodine, yttrium oxide, strontium, and barium were enclosed in cylindrical brass containers of 1.688-inch outside diameter and 0.024-inch wall thickness. In all cases the samples were made from the element except for yttrium, which was available only in the form of yttrium oxide.

Samples of lanthanum and praseodymium, already machined to the proper dimensions, were provided by Dr. F. H. Spedding of the Ames Laboratory of the Atomic Energy Commission. Dr. Spedding's analysis stated that these samples were very pure, having a metal content greater than 99 percent. Rare earth and other metal impurities were present in such small amounts that they were not detectable by spectrographic means, or at most could be detected only in negligible amounts. Dr. Spedding also supplied the yttrium oxide, which was 99.7 percent pure and contained only traces of other rare earths. In order to drive off any water or carbon dioxide which might have been adsorbed, the yttrium-oxide powder was heated to red heat in a platinum dish immediately before being packed into the sample containers. A sample of zirconium, machined to the correct dimensions for the present experiment, was supplied by Argonne National Laboratory.

Cerium, barium, and strontium were obtained from commercial sources and machined to the proper dimensions. The analysis of the cerium metal was quoted by the supplier as 92.6 percent cerium, 1.1 percent iron, balance—other rare earth metals. For the barium the supplier gave the following analysis: 97.8 percent barium, 2.0 percent strontium and calcium. To prevent oxidation, the barium and strontium samples were sealed in brass containers immediately after machining. Samples of copper, zinc, and tin were machined from regular stocks of these metals. Antimony and iodine were pulverized and packed into brass containers. Samples of all of the remaining twelve elements were available from earlier experiments performed at Wisconsin.[6–10]

Since measurements in this experiment were taken on yttrium oxide (Y_2O_3), it was necessary to determine the oxygen cross section at each energy before the yttrium cross section could be calculated. If the oxygen cross section had been read from a curve, a small shift between the energy scales used in the earlier oxygen measurements[11] and the present measurements on yttrium oxide could have resulted in large errors in the yttrium cross section, because resonances produce rapid variations of the cross section of oxygen with energy. As a consequence, the oxygen cross section was redetermined at every energy immediately before or after the measurements on yttrium oxide. For this purpose, the transmission of neutrons through a brass can containing beryllium-oxide powder was compared with that through a brass can containing beryllium metal. The results obtained for the oxygen cross section were in excellent agreement with the earlier measurements.[11]

Cross sections were computed from the observed transmissions under the assumption that the neutron intensity decreases exponentially in the scatterer. The measurements at neutron energies above 1 Mev were carried out following the procedure described earlier,[11] using the $T(p,n)$ reaction as a neutron source. For neutron energies below 1 Mev, neutrons were obtained from the $Li(p,n)$ reaction. In most of the measurements, the neutrons were detected by observing proton-recoil pulses produced in a cylindrical ionization chamber.[11] For neutron energies above 1 Mev, the counter was filled with purified hydrogen at a pressure of 425 psi. In order to reduce the gamma-ray background, the hydrogen pressure was reduced as the neutron energy was decreased below 1 Mev. At low pressures the chamber was operated as a proportional counter in order to improve the signal-to-noise ratio.

Neutrons emitted from the target in the forward direction were used for all measurements above 0.12 Mev. Measurements were taken at an angle of 115 degrees with respect to the proton beam for neutron energies below 0.12 Mev, since $Li(p,n)$ neutrons emitted in the forward direction are not monoergic below this energy.

For measurements on lanthanum, niobium, and molybdenum below 1 Mev, and on cerium below 1.3 Mev, a BF_3 counter was used.[8] Measured backgrounds for the BF_3 counter varied from 8 percent of the direct neutron flux in the forward direction to 25 percent in the 115-degree direction. All data taken with the BF_3

[4] S. Kikuchi and H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 75 (1939); H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).
[5] Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).
[6] Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948).
[7] Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).
[8] Barschall, Bockelman, Peterson, and Adair, Phys. Rev. **76**, 1146 (1949).
[9] R. K. Adair, Phys. Rev. **77**, 748 (1950).
[10] Peterson, Adair, and Barschall, Phys. Rev. **79**, 935 (1950).
[11] Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951).

counter were corrected for background. No background corrections were applied to data taken with the recoil counter in the forward direction, because in this case the background was negligible. It was necessary, however, to make a correction to the measurements taken with the recoil counter in the 115-degree direction, where the background was of the order of 9 percent.

The scattering samples were placed midway between the target and the center of the active volume of the counter. For the recoil counter, the distance from the target to the center of the active counting volume was 14 inches, while for the BF_3 counter a distance of 10 inches was used. In addition to the background corrections, a correction was applied for the effects of neutrons scattered into the counter by the sample. The latter correction was made on the assumption that the neutrons were scattered isotropically from the sample. With this assumption, 1.5 percent of the scattered neutrons enter the counter in the 14-inch geometry and 3 percent in the 10-inch geometry.

For most of the low energy data taken in this investigation, lithium targets causing a 20-kev energy loss for protons of threshold energy were used. The only exceptions were niobium and molybdenum from 0.15 to 1.0 Mev (85-kev lithium target) and cerium from 0.006 to 0.110 Mev (8-kev lithium target). All of the high energy measurements employed a Zr—T target which caused an energy loss of 35 kev for 1-Mev protons.[11] Over most of the energy range investigated, however, the target thickness of the Zr—T target was about 20 kev.

For measurements above 1.4 Mev, widely-spaced points were taken in order to determine the energy dependence of the average cross section. In general, it is desirable to use a neutron energy spread which is equal to the spacing between measurements in order to obtain a smooth variation of the experimental cross section with a minimum number of measurements. Smaller neutron energy spreads are also wasteful of generator time, since the neutron yield and counting rate decrease with decreasing target thickness. In this investigation, however, the thickest Zr—T target available caused a neutron energy spread nearly ten times smaller than the energy intervals at which measurements were performed above 1.4 Mev. This disadvantage was partly offset by a small gain of information; namely, if the widely-spaced points indicated considerable variations in the cross section, one could conclude that the level spacing was comparable to or greater than the energy spread used. This statement should not be taken to imply that the level spacing was smaller than the neutron energy spread if the widely-spaced points exhibited no appreciable fluctuations, for narrow levels could easily have been missed.

III. RESULTS

The total cross sections of the elements studied are plotted as a function of neutron energy in Figs. 1 and 2. In those cases where experimental points are not indicated below 1 Mev, the solid curves reproduce the results of the earlier Wisconsin measurements.[6–11] Vertical bars indicate data obtained in the present investigation, the length of each vertical bar representing the standard statistical error in the measurement. The approximate neutron energy spread employed is represented by the length of the base of the large triangle in each energy region. It should be emphasized that the solid curve drawn above 1 Mev in each case represents an estimate of the cross section *averaged over resonances*. The best smooth curve was drawn through the experimental points obtained in the present work. Since the energy spread of the neutrons utilized in this region was usually less than the spacing between experimental points, fluctuations of the experimental points considerably beyond the statistical error from the solid curve indicate the presence of resonance structure.

Iron, the lightest element included in this study, is the only element investigated which shows appreciable structure at high neutron energies except for a few elements which consist principally of closed-shell nuclei. The experimental curve seems to indicate that the average cross section of iron reaches a minimum value at about 1.2 Mev, and then increases with increasing neutron energy to 3.2 Mev. This increase may not be significant because of the uncertainty in the average cross section introduced by the large number of resonances. The average cross section of nickel, the second element beyond iron in the periodic table, does not increase at high energies, but rather decreases with increasing neutron energy to about 1.5 Mev and is nearly constant from 1.5 to 3.2 Mev. With the neutron energy spread used, there is much less evidence at high neutron energies for structure in the nickel cross section than in the iron cross section. This may be caused partly by the presence of two isotopes in nickel.

The earlier Wisconsin results[9] for copper and zinc, indicated by the solid curves below 1 Mev, were obtained with thick lithium targets, which precluded the observation of individual resonances. It will be noted that the cross sections of nickel, copper, and zinc at high neutron energies are almost identical in shape and magnitude.

The principal isotope of each of the next three elements investigated, strontium, yttrium, and zirconium, contains 50 neutrons. Four peaks are observed in the strontium cross section below 0.7 Mev. It is not at all clear that these peaks are actually individual resonances; in fact, the shape of the peak at 0.33 Mev indicates the superposition of two or more resonances. The widths of the peaks at 0.12, 0.44, and 0.53 Mev are all about 40 kev, or twice the experimental energy spread. No attempt was made to study in detail the variations in the strontium cross section above 0.7 Mev. The solid curve drawn above this energy therefore represents the cross section averaged over resonances. Above 0.7 Mev, the large fluctuations in the experi-

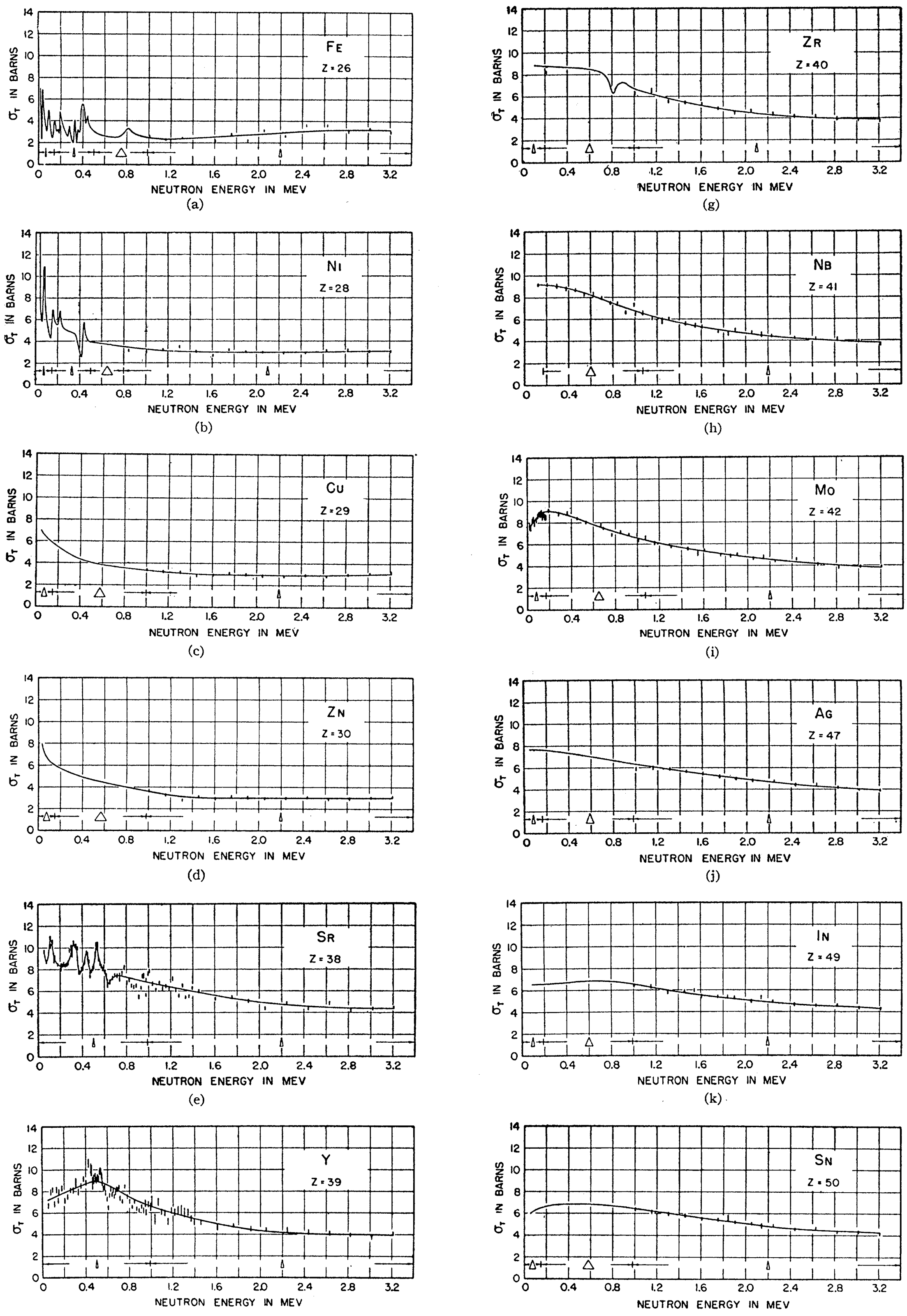
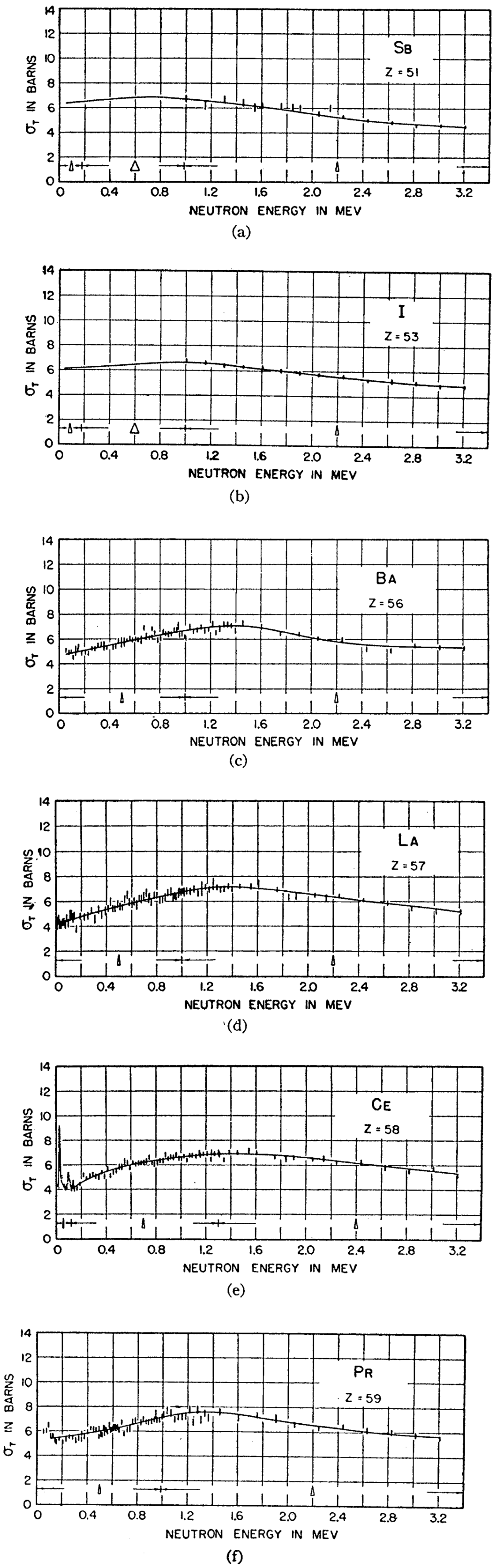


FIG. 1. Total cross sections for fast neutrons of iron, nickel, copper, zinc, strontium, yttrium, zirconium, niobium, molybdenum, silver, indium, and tin. See the first paragraph of Sec. III in the text for explanation of symbols and curves.



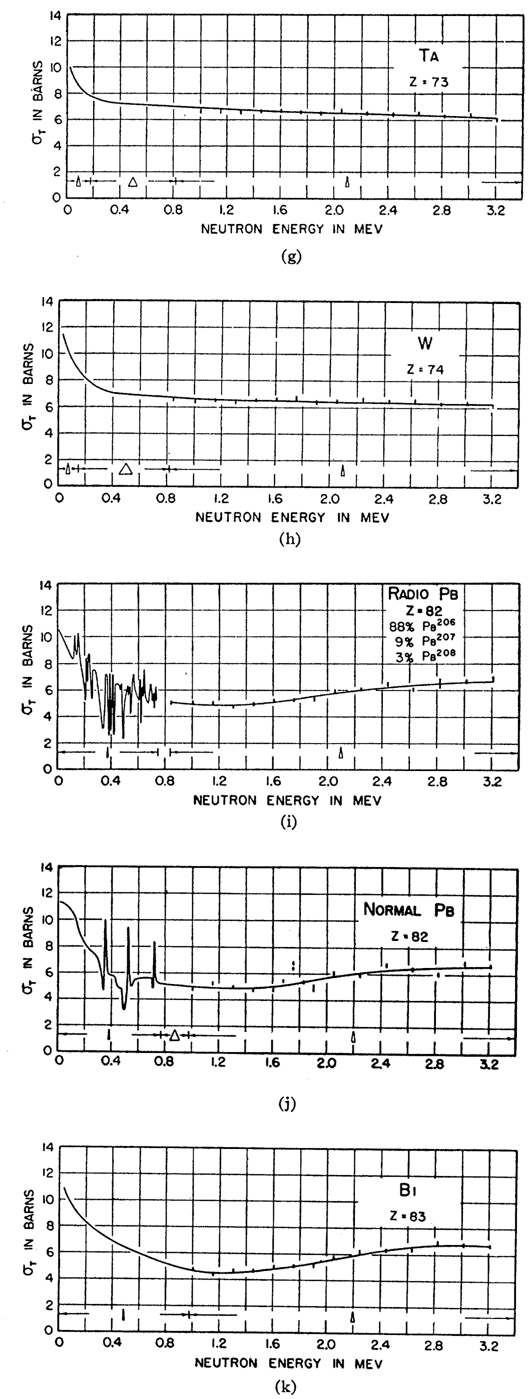


FIG. 2. Total cross sections for fast neutrons of antimony, iodine, barium, lanthanum, cerium, praseodymium, tantalum, wolfram, radiogenic lead, normal lead, and bismuth.

mental points indicate the presence of closely-spaced resonances, which are observable with the neutron energy spread employed to at least 1.5 Mev. The cross section of strontium averaged over this structure appears to decrease monotonically with energy from 0.05 to 3.2 Mev. For yttrium, considerable scattering of the experimental points about the curve representing the average cross section again indicates that a large amount of structure is observable with the neutron energy spread employed. The narrow energy region from 0.45 to 0.67 Mev was investigated with experimental points spaced somewhat closer together than the neutron energy spread. Strong evidence for the reality of the variations observed is provided by the smooth change of the cross section indicated by the experimental points in this narrow region. When averaged over resonances, the cross section of yttrium increases with neutron energy to a maximum at 0.5 Mev and then decreases as the neutron energy is increased to 3.2 Mev. The total cross section of zirconium, apart from the structure at 0.85 Mev, shows a monotonic decrease with increasing neutron energy from 0.1 to 3.2 Mev.

No measurements were taken on niobium in the 115° direction, so that the data extend from 0.12 to 3.2 Mev. Over this energy range the average cross section appears to decrease monotonically, although in the neighborhood of 0.2 Mev the cross section appears to be nearly constant. A similar behavior is indicated around 0.2 Mev by molybdenum, except that the molybdenum cross section shows a decrease below 0.12 Mev. That such a decrease might occur also for niobium is indicated by the fact that the cross section of niobium for thermal neutrons is 6.7 barns.[12] It should be mentioned that the niobium data below 1 Mev were thick target data, so that no structure could have been observed. As a consequence, no comparison should be made between the amount of resonance structure observed for strontium, yttrium, and zirconium, whose major isotopes contain closed neutron shells, and the amount of structure observed for niobium, which is nonmagic.

The total cross section of molybdenum was obtained in the present investigation over the entire energy range from about 0.02 Mev to 3.2 Mev. Below 0.16 Mev, the data were taken using a 30-kev lithium target, while the measurements from 0.16 to 0.98 Mev employed an 85-kev lithium target. No structure was observed in the low energy region with these targets. The average cross section of molybdenum increases to a maximum at 0.2 Mev, and then decreases smoothly from 0.2 to 3.2 Mev. Good agreement is obtained between the present results and those of Stubbins,[13] who measured the total cross section of molybdenum from 0.010 to 1.23 Mev.

The total cross section of silver does not appear to exhibit a maximum, although the slope of the curve is quite small below 0.2 Mev. The shapes of the cross section curves obtained for indium, tin (whose isotopes have closed shells in protons), antimony, and iodine are qualitatively the same. In each case the cross section increases slowly with energy to a maximum around 0.5–1.0 Mev, and then decreases again with increasing energy to 3.2 Mev.

The principal isotope of each of the next four elements investigated, barium, lanthanum, cerium, and praseodymium, contains 82 neutrons. Over the entire energy region investigated, the neutron energy spread employed was about 20 kev. In each case, the average cross section increases with energy to a maximum near 1.4 Mev and then decreases again to 3.2 Mev. Fluctuations in the experimental points may indicate the presence of closely-spaced resonances. In an attempt to determine whether individual levels could be separated, the energy ranges from 0.35 to 0.58 Mev for lanthanum and 0.40 to 0.61 Mev for cerium were reexamined at closely-spaced energies with a neutron energy spread of 10 kev, but no reproducible structure could be resolved. The results obtained with higher resolution are not plotted in the figures, but smooth curves representing the cross sections averaged over the resonance and statistical variations in the higher resolution results agreed quite well with the curves shown.

Definite structure may be observed below 0.1 Mev in the cross section of cerium with the neutron energy spread employed. The two peaks, which appear at neutron energies of 0.024 and 0.097 Mev, may be individual resonances. However, they are too narrow to be resolved completely in this experiment. It is probable that elastic scattering is the only important process in this region, and the minimum changes in cross section predicted by resonance theory for elastic scattering caused by individual levels at these energies are 98 barns and 24.2 barns, respectively. The changes in cross section actually observed are 5 barns at 0.024 Mev and 1.2 barns at 0.097 Mev. Since the experimental heights of these peaks are so much smaller than the theoretical values, the widths of the observed peaks represent the experimental neutron energy spread at these energies. The observed widths at half-maximum for these peaks are 5 kev at 0.024 Mev and 13 kev at 0.097 Mev. It will be noted that there is some evidence for a sharp increase in the cross section of praseodymium below 0.1 Mev, possibly caused by structure similar to that observed in cerium. However, measurements on praseodymium were not carried below 0.05 Mev.

The thick-target results obtained earlier[7] for the total cross sections of tantalum and wolfram are represented by the solid curves below 0.7 Mev. For these elements, the average cross sections are quite similar, both decreasing monotonically with increasing neutron energy from 0.02 to 3.2 Mev. Neither of them shows the maximum in the average cross section exhibited by

[12] Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).
[13] W. F. Stubbins, Phys. Rev. **84**, 902 (1951).

all elements heavier than silver which were investigated in this experiment.

Radiogenic lead and normal lead both contain closed shells in protons, but the isotope Pb^{208}, which also contains a closed shell in neutrons, is 52 percent abundant in normal lead and nearly absent in radio lead. When averaged over resonances, the cross sections of normal lead and radio lead exhibit very similar behavior. Both cross sections reach a minimum near 1.3 Mev, and then increase with increasing neutron energy to 3.2 Mev, where the curves appear to have zero slope. For normal lead some resonance structure, observable with the neutron energy spread employed, is indicated at high neutron energies by the scatter of experimental points. A reproducible high point at 1.75 Mev indicates the presence of one or more peaks in the lead cross section at about this energy. The solid line above 1 Mev represents the cross section averaged over this resonance structure.

Measurements on lead at the Massachusetts Institute of Technology[14] cover an energy region in common with the present experiment from 1.0 to 2.35 Mev. The M.I.T. data do not show the increase with energy indicated in the present measurements above 1.4 Mev. However, an investigation carried out by Stafford[15] shows an increase of the total cross section in this energy region similar to that obtained in the present measurements.

Bismuth is similar to normal lead in that its principal isotope contains a closed shell of 126 neutrons; however, bismuth does not contain a closed proton shell. The energy dependence of the average cross section of bismuth is qualitatively the same as found for radiogenic lead and normal lead, exhibiting a definite minimum around 1.2 Mev.

Aoki[4] and Zinn *et al.*,[5] obtained results for some of the elements included in this investigation using $D+D$ neutrons. In six comparisons made with the values obtained by Zinn *et al.*, agreement within the sum of the statistical errors quoted in the two experiments is found in five cases. The value obtained by Zinn *et al.*, for zinc is somewhat higher than that found in the present investigation. On the other hand, Aoki's measurements differ from the curves in Figs. 1 and 2 by more than the sum of the statistical errors in all of the thirteen cases compared. In twelve of the comparisons his results are lower than the present measurements, the only exception being barium.

The differences between the values obtained by Aoki and by Zinn *et al.*, can be explained in terms of the geometry and the inscattering corrections used in the two experiments.[16] In their experiments as well as in the present investigation, corrections for scattering into the detector were calculated on the assumption that the distribution of scattered neutrons was isotropic. This assumption is not expected to be correct at higher energies because of anisotropic diffraction scattering. As a result, the cross sections reported in all three experiments are expected to be low. If one is to retain the assumption of isotropic scattering, the error in the final result will be smaller if the geometry of the experiment can be improved; i.e., if the solid angle subtended by the scatterer at the detector can be reduced. In the three experiments under consideration, this solid angle was as follows: Zinn *et al.*, $d\Omega/4\pi=0.0025$; present investigation, $d\Omega/4\pi=0.0039$; Aoki, $d\Omega/4\pi=0.0055$. As a consequence, one expects the results of Zinn *et al.*, to be slightly higher and those of Aoki to be lower than the values obtained in the present measurement. This may explain the differences between the results of the three experiments.

The error in the cross section resulting from the failure of the inscattering correction to take diffraction scattering into account is expected to be largest for the heaviest elements and the highest energies. An investigation of this effect indicated that the maximum error introduced into the results by an isotropic inscattering correction amounts to about 10 percent in the worst cases.[17]

For the measurements on lanthanum, praseodymium, and zirconium, only thin samples were available for the present investigation. As a consequence, the high transmission caused a larger statistical error for these elements. Since the yttrium cross section was obtained from two separate measurements, the statistical error in the yttrium cross section was also high. The standard statistical error in nearly all of the measurements was between 2 and 4 percent.

IV. DISCUSSION

The outstanding features of the results of the present investigation concern the energy dependence of the total cross section averaged over resonances. In the energy region investigated, the total cross sections of neighboring elements show a striking similarity both in shape and in magnitude. Furthermore, a slow variation of the shape and magnitude of the cross section takes place with increasing nuclear mass or size.[18] The average cross section does not seem to depend strongly upon other characteristics of the nucleus, such as the nuclear spin, binding energy of the added neutron, or the closed-shell property. For example, the average total cross sections of niobium (single isotope) and molybdenum (seven isotopes) are almost identical. Again, the average cross section of lead, whose major isotope has a closed shell in neutrons, is nearly the same as that of radiogenic lead, whose major isotope is not neutron-magic. The binding energies of a neutron added to the

[14] Willard, Preston, and Goodman, unpublished Technical Report No. 45, Mass. Inst. Tech. (1950).
[15] G. H. Stafford, Proc. Phys. Soc. (London) **64A**, 388 (1951).
[16] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[17] M. Walt, private communication.
[18] This behavior is summarized by a three-dimensional representation of the cross section as a function of neutron energy and nuclear mass. See H. H. Barschall, Phys. Rev. **86**, 431 (1952).

principal isotopes of lead and radiogenic lead are also quite different; Harvey[19] lists them as about 3.9 and 6.8 Mev, respectively. A further illustration of the spin independence of the cross section when averaged over resonances is given by the similarity of the cross sections of lead, whose major isotope probably has spin zero, and bismuth, which has a spin of 9/2.

Another interesting feature of the experimental results is a very broad maximum which occurs in the cross sections of at least 13 of the 23 elements studied. In particular, such a maximum is observed for all elements heavier than silver which were included in the investigation, with the exceptions of tantalum and wolfram. In addition, this maximum appears to move to higher neutron energies with increasing mass number.

The rise in the cross sections of radiogenic lead, normal lead, and bismuth at high neutron energies is preceded by a minimum. It is interesting to note that the magnitude of the cross section at this minimum at 1.2 Mev is about $2\pi R^2$, which is much smaller than expected at this energy. This may result from some sort of interference effect, possibly similar to that observed between resonance and potential scattering of neutrons. It is not clear from the present results whether one should describe the cross-section curves for radio lead, normal lead, and bismuth as representing maxima at 3.2 Mev or minima at about 1.2 Mev. However, the results obtained by Stafford[15] for normal lead indicate that the cross section drops off again fairly rapidly at neutron energies higher than attained in the present investigation, the center of the resultant maximum occurring at 3.2 Mev, in agreement with the curve drawn in Fig. 2.

It may not be surprising that the average total cross section appears to be largely a function of the nuclear size at high energies where optical diffraction effects are prominent. However, one cannot readily explain the change in the position of the maximum in the average cross section using an optical model. If one assumes that the maximum represents evidence for some nuclear property, according to an optical model this property would be expected to depend only on $R/\lambda\!\!\!^{-}$. With this hypothesis, the maximum would be expected to shift to larger wavelengths or lower energies with increasing nuclear radius. Yet the results described above show the opposite behavior; the maximum appears to move to higher energies with increasing nuclear size.

It has been pointed out earlier that the continuum theory formulated by Feshbach, Peaslee, and Weisskopf[1,2] predicts a monotonic decrease in the total cross section as a function of neutron energy. At least thirteen of the twenty-three elements investigated in this work do not exhibit this behavior, but instead show a broad maximum in the total cross section. Results for cadmium obtained earlier by Fields *et al.*,[20] using photoneutrons, exhibit a similar behavior, making at least fourteen elements whose cross sections disagree with the theory in this respect. It would seem to be worthwhile, then, to attempt to find a modification of the theory which will account for the observed deviations. Such a modification has recently been proposed by Weisskopf.[21]

There is some evidence that the spacings between resonances exhibited by the total cross sections of the closed-shell nuclei are larger than shown by nonclosed-shell nuclei, in agreement with the considerations discussed earlier. Since the level densities of the compound nucleus near the energy of binding of the last neutron to the nucleus depend strongly upon the odd-even or even-even character of the target nucleus,[22] the effect of a closed shell will be superimposed upon this variation. The results of the present investigation show that the level densities indicated by the cross sections of strontium, primarily an even-even closed-shell nucleus, and yttrium, an even-odd closed-shell nucleus, are comparable to that shown by iron, a much lighter nonclosed-shell even-even nucleus. Again, cerium, an even-even closed-shell nucleus, exhibits some structure at low neutron energies, which indicates a level spacing much greater than one would expect for nuclei of this mass. The contrast between the level spacings indicated by the total cross sections of lead and radiogenic lead at low energies provides further evidence for reduced resonance densities in the cross sections of closed-shell nuclei.[10]

V. ACKNOWLEDGMENTS

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[19] J. A. Harvey, Phys. Rev. **81**, 353 (1951).

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

[21] V. F. Weisskopf, Phys. Rev. **86**, 582 (1952).

[22] H. Hurwitz and H. A. Bethe, Phys. Rev. **81**, 898 (1951).