placement of **p** by $(-\mathbf{q})$ in $\not{p}$ corresponds to the neglect of Fourier momentum components of order m, or, equivalently, to the neglect of residues due to the poles of $(\not{p}-m)^{-1}$. (A pole occurs on the real axis only if the real photon has an energy $q \geq 2m$, for if energy is to be conserved in the intermediate state the electron must jump into a negative energy state.) The error involved in the replacement of **p** by $(-\mathbf{q})$ in $\not{p}$ is of order αZ, and the approximation is therefore consistent with previous ones.

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Average Neutron Total Cross Sections in the 3- to 12-Mev Region*

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Measurements of the average neutron total cross sections of N, F, Mg, P, Cl, Ti, Mn, Co, Ni, Zn, Se, Br, Mo, Ag, Cd, Sn, Sb, Te, La, Ta, W, Au, Hg, and Tl have been made over the 3- to 12-Mev energy range. The average energy spread of the measurements is approximately 10 percent and the over-all accuracy of the results is ±10 percent or better. The above data, together with those of a previous experiment, provide information on average cross-section behavior as a function of energy and atomic weight over most of the periodic table.

AVERAGE total cross sections for neutrons have been measured for a set of 24 elements over the 3- to 12-Mev energy region. The present measurements are an extension of a set of previous measurements made for 13 elements.[1] These earlier measurements showed that neighboring elements exhibit similar patterns in their average cross-section behavior. The aim of the present experiment was to supplement the previous data and to establish cross-section trends over the entire periodic table. Therefore, most of the elements were selected with the above objective in view; however, certain elements were chosen as a result of specific requests for total cross-section information.

The experimental arrangement for the present measurements was the same as that used in the previous measurements except for an improvement in the sample and detector geometry. In the present case, the distance from the sample to the detector was increased to 18 inches as compared to 11 inches in the earlier arrangement. All of the scattering samples were 1 inch in diameter and their length was chosen so as to give a neutron transmission of approximately 0.5. During the course of the work, the neutron source for the experiment was changed from one reactor to another reactor. The data from 6 to 13 Mev were obtained by using the Los Alamos fast reactor as previously described, while the 3- to 6-Mev data were acquired by using a U^{235} converter[2] placed in a hole which goes through the center of the Los Alamos water boiler. The neutron spectrum obtained from these two sources is the same over the energy region utilized for this experiment, i.e., above 3 Mev.

The results presented here retain the same characteristics as the previous measurements, i.e., the average energy spread is about 10 percent of the measured energy, and the over-all accuracy is at least ±10 percent over the 3- to 12-Mev energy range. Above 12 Mev the present data are subject to considerable error and the more accurate 14.1-Mev point obtained by Coon and others[3] has been weighted accordingly in determining the curve over the 12- to 14-Mev region. As previously, a smooth curve has been drawn through the data points and small fluctuations which are not well resolved by the experiment have been averaged over the curve. A curve has not been drawn where better-resolved data already exist. No corrections have been made on the measured cross sections for the effect of neutrons scattered into the detector by the sample. The geometry is such that this correction is probably less than 1.5 percent at 12 Mev.

The results obtained are shown in Figs. 1, 2, and 3 where the average neutron total cross section, σ_t, is plotted as a function of the neutron energy, E_n. In Fig. 1 the two sets of nitrogen data do not agree well over certain energy regions. The measurement employing melamine and polyethylene is probably

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[1] N. Nereson and S. Darden, Phys. Rev. **89**, 775 (1953).

[2] This converter was made by L. D. P. King of this laboratory and consisted of an assembly of 120 U^{235} disks each having a thickness of 0.01 inch and a diameter slightly less than 1 inch. This series of disks were sealed in an aluminum tube 3 feet long and 1 inch diameter and placed at the center of the reactor where the average thermal neutron flux is about 10^{12}. At a neutron energy of 3 Mev, this converter produced a collimated neutron flux at the wall of the reactor (77 inches distant from the converter) of 9×10^6 neutrons cm^{-2} sec^{-1} Mev^{-1}. The above figures are for a water boiler power of 25 kilowatts.

[3] Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952).

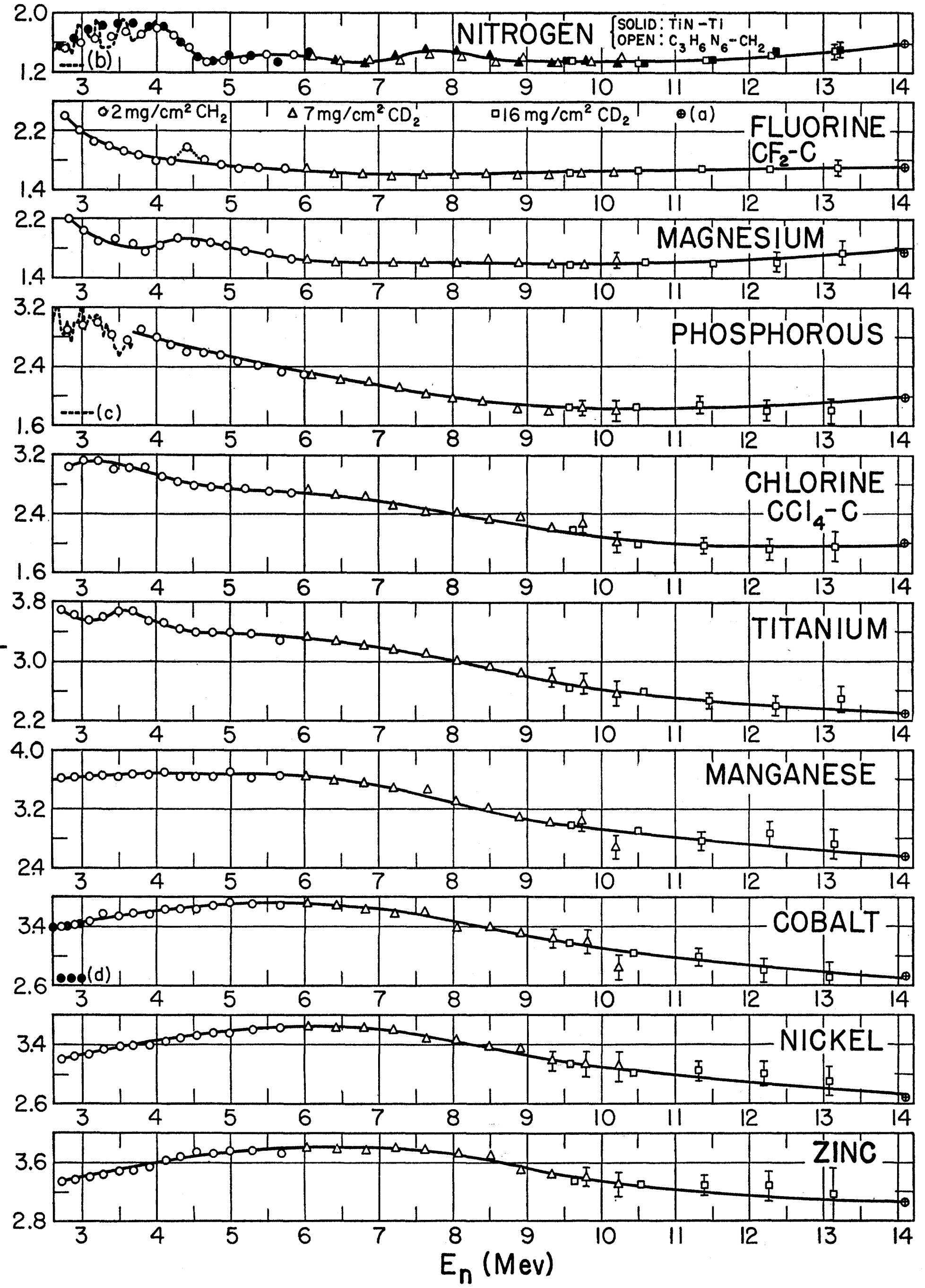

FIG. 1. Average neutron total cross sections of N, F, Mg, P, Cl, Ti, Mn, Co, Ni, and Zn. References to other experimental data shown in the figure are (a) Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952); (b) H. B. Willard, Oak Ridge National Laboratory, 1952 (unpublished data); (c) R. Ricamo, Nuovo cimento **8**, 383 (1951); (d) Walt, Becker, Okazaki, and Fields, Phys. Rev. **89**, 1271 (1953).

more subject to error on account of the carbon resonances in the 3 to 4 and 7 to 8 Mev regions. The data using titanium nitride and titanium are considered the more reliable since the titanium cross-section curve is smoother than the carbon curve. The latter data also agree better with the well-resolved data of Willard. The fluorine measurement (using Teflon and carbon) consistently showed a high point at 4.4 Mev; probably a resonance occurs in this vicinity. The fluctuations in the data points occurring over the low-energy sections of the Mg, P, Cl, and Ti curves are also indicative of resonance structure in this region. A

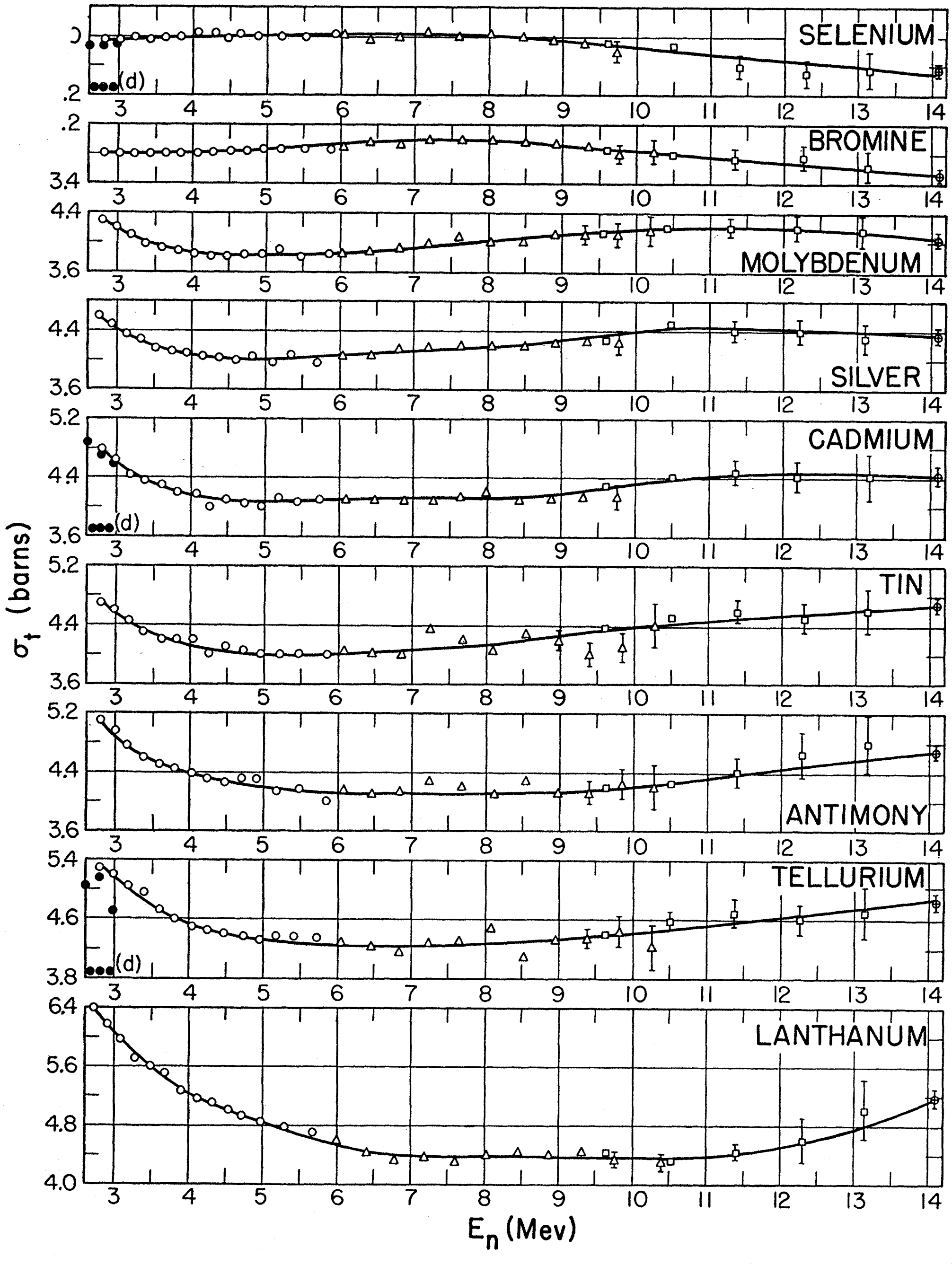

FIG. 2. Average neutron total cross sections of Se, Br, Mo, Ag, Cd, Sn, Sb, Te, and La.

comparison of the present data with the better resolved data of Ricamo in the case of P illustrates the type of average cross-section values obtained from the present experiment.

For neutron energies near 3 Mev, the present total cross-section values for some elements are about 10 percent higher than those measured by Miller *et al.*[4] As was pointed out by Miller, his results may be too low by as much as 10 percent in some cases because of forward scattering into the detector. That the observed discrepancies are probably due to this effect is borne out by the agreement between the present results and recent measurements made at Wisconsin (reference *d* in Figs. 1, 2, and 3). With the exception of Te, the results around 3 Mev for Co, Se, Cd, Au, and Hg all agree within 4 percent with the Wisconsin data for these

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[4] Miller, Adair, Bockelman, and Darden, Phys. Rev. **88**, 83 (1952).

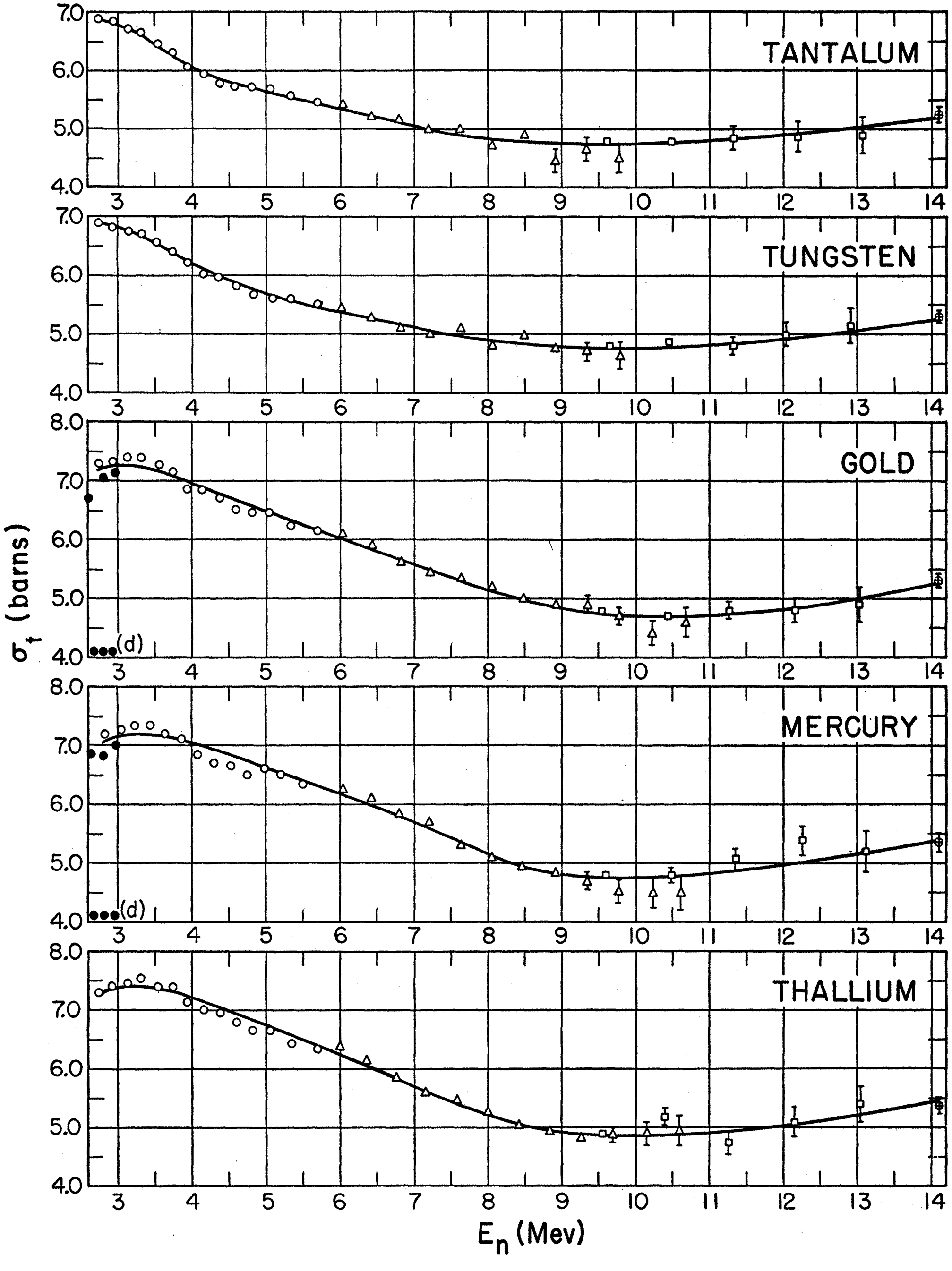

FIG. 3. Average neutron total cross sections of Ta, W, Au, Hg, and Tl.

elements; the latter average cross-section measurements were carried out in good geometry. Over the 12- to 13-Mev region, the present results join satisfactorily with the 14.1 Mev point[3] obtained with better geometry and higher statistical accuracy than the present experiment. The above correlations are considered important as verifications of the validity of the present cross-section measurements.

Average total cross-section trends for neutrons as a function of energy and atomic weight have been previously illustrated by Barschall[5] for the 0.1- to 3-Mev region. A similar presentation for the 3- to 14-Mev region can be made using the data of Figs. 1, 2, and 3, and those of the previous measurements.[1] Figure 4 shows such an illustration. In this figure, the measured cross sections divided by the nuclear geo-

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[5] H. Barschall, Phys. Rev. **86**, 431 (1952).

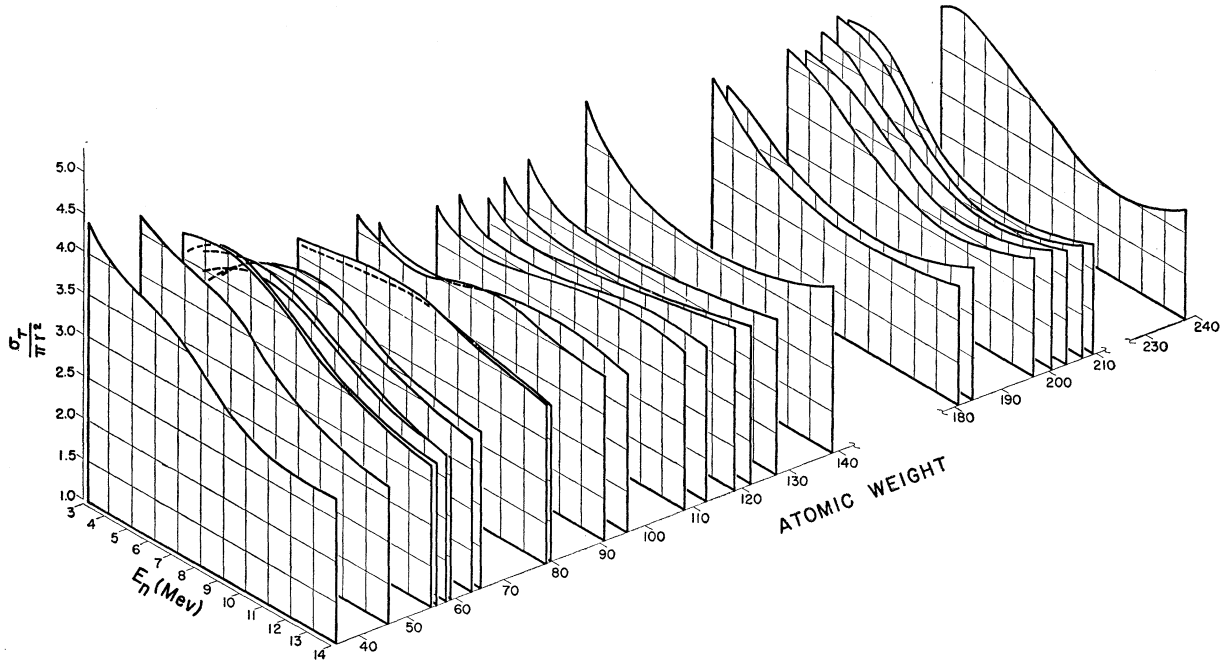

FIG. 4. Average neutron total cross sections as a function of energy and atomic weight for elements heavier than Cl.

metrical area[6] are shown in an isometric view as a function of atomic weight and energy. Breaks occur in the atomic weight axis at 140–180 and 210–230 on account of the absence of data in these regions. No data is plotted for elements of atomic weight less than 35 since for light elements fluctuations due to resonance structure become comparable in size to fluctuations in the average cross sections. The fluctuations appearing in the 3- to 4-Mev region for the Cl and Ti curves have been averaged over for this diagram.

Definite trends in cross-section behavior can be observed in the cross-section surface of Fig. 4. An outstanding feature is the movement of the valley or minimum which is most clearly evident in the case of elements of high atomic weight. For the energy range used here this minimum is first observed in the vicinity of Zr around 5 Mev; it shifts toward higher energies with increasing atomic weight until at La it is centered around 9 Mev. Above La, it continues to move slowly upwards until it reaches 11 Mev at U. It is evident from Figs. 2 and 3 that the movement of this minimum is considerably more rapid over the Zr to La region than over the Ta to U region. The above minimum seems to be a continuation of the same minimum which is centered around 2 Mev at Cu and Zn.[7]

The theoretical work of Feshbach, Porter, and Weisskopf[8] on average neutron cross sections has been compared with the experimental results above 3 Mev. For heavy elements ($A \gtrsim 100$), the calculated curves agree well with the experimental shapes as far as the calculations extend (approximately 4 Mev). However, in the case of light elements ($A \lesssim 50$), the theoretical predictions differ considerably from the experimental results. The present data, together with other total cross-section results, indicate that changing the well depth from 19 Mev to 40 Mev or higher in the calculations may provide better agreement with experiment.[9]

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[6] The nuclear geometrical area was computed using a nuclear radius of $1.45 \times A^{\frac{1}{3}} \times 10^{-13}$ cm.

[7] See data of Miller, Adair, Bockelman, and Darden, Phys. Rev. **88**, 83 (1952).

[8] Feshbach, Porter, and Weisskopf, Technical Report No. 62, Laboratory for Nuclear Science, Massachusetts Institute of Technology, 1953 (unpublished).

[9] R. K. Adair, Phys. Rev. **94**, 737 (1954).