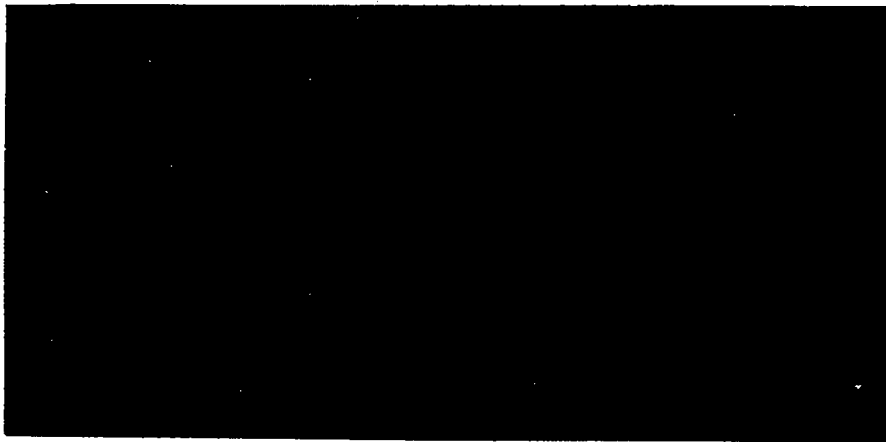


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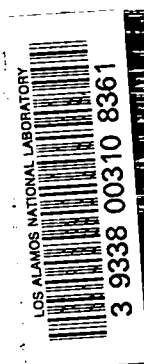
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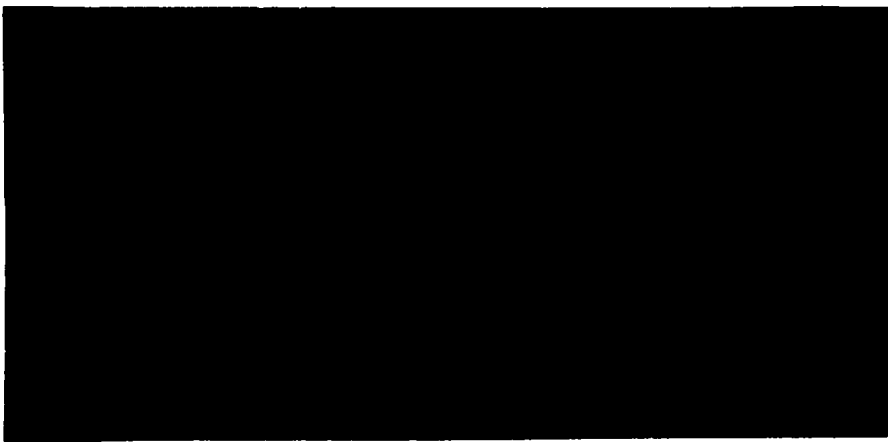
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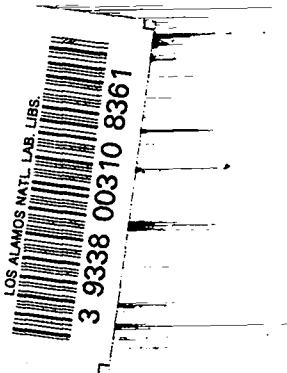
SURVEY OF AVERAGE NEUTRON TOTAL CROSS
SECTIONS FROM 3 TO 13 MEV

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PHYSICS

ABSTRACT

Neutron total cross sections of 41 elements have been measured over the 3 to 13 Mev energy region. The data are averaged over an energy interval of 10 per cent of the neutron energy and the overall accuracy of the measurements is about ± 10 per cent. In addition to showing cross sections as a function of energy, the combined results illustrate cross section trends as a function of atomic weight over most of the periodic table.

1. Report Objective

The purpose of this report is to present the results of a survey program of measuring total neutron cross sections over the 3 to 13 Mev energy range. The experimental method and the results of a preliminary survey have already been published while the results of an additional more comprehensive survey are in the process of publication. Therefore, in order to avoid repetition of material which is available in public literature, the present report will not give many details of the experimental method and procedure but will confine itself to presenting the general features of the measurements and the results of the investigation. This report combines the cross section data from both surveys as well as data on a few light elements not included in the open literature reports.

2. Experimental Objectives

At the time that this experiment was started (early 1952), a considerable amount of total cross section data was available at energies below 3 Mev.¹ Most of these data were contributed by the Wisconsin group who made a survey of average total cross sections over the 0.1 to 3.2 Mev energy region for heavy elements ($A > 55$). The aims of the Wisconsin survey were mainly to provide experimental results for comparison with theoretical work and to observe if the cross sections of closed-shell nuclei were different from those of adjacent nuclei. The present survey was undertaken primarily to furnish cross section information at energies above 3 Mev; such data were especially needed for reactor design and shielding calculations. A second objective was to extend the information on cross section trends as a function of atomic weight.² Finally, during the course of the experiment, a considerable amount of new theoretical work on total cross sections has been performed; this work has involved revision of older theories and extension of the numerical calculations toward higher energies. The present survey has been useful in providing results to check the above calculations.³

1. Miller, Adair, Bockelman, and Darden, Phys. Rev. 88, 83 (1952). Later similar measurements were also made by Walt, Becker, Okazaki and Fields, Phys. Rev. 89, 1271 (1953).
2. The Wisconsin survey showed that the cross sections of neighboring elements were very similar in both shape and magnitude; furthermore, the cross section behavior of the elements was observed to change slowly with nuclear mass.
3. Feshbach, Porter, and Weisskopf, NYO 3076, April 1953, and ONR 62 August 1953.

3. General Experimental Information

This section gives a brief description of the general features and major components used in this experiment. For more detail the reader is referred to previous publications on this subject.⁴

The neutron source for these experiments was a collimated fast neutron beam (0.75 in. diameter) obtained from the Los Alamos reactors at Omega Site. Most of the data was acquired using the east port (No. 5E) of the fast reactor. When the fast reactor was disassembled in early 1953, the experiment was moved to the water boiler where a fast neutron beam was obtained by inserting a U^{235} disk source into the center of the glory hole. Above an energy of 3 Mev, both of these sources produced a spectrum similar to that of the fission neutron spectrum.⁵ For the same reactor power, the neutron flux derived from these two sources was practically identical above 3 Mev.

The experiment was carried out in good geometry. The experimental geometry on the source side of the sample was excellent since the neutron beam was collimated over a distance of about 40 in. The distance from sample to detector was 11 in. at the fast reactor and 18 in. at the water boiler. The samples used were 1 in. in diameter and their length was such that the neutron transmission was approximately 0.5. With the above geometry, the correction for neutrons scattered into the detector by the sample is less than 2 per cent of the cross section at an energy of 13 Mev.

The detector for this experiment was a parallel plate ionization chamber which operated as a neutron spectrometer. The chamber operated directly in the neutron beam, converted the neutrons into protons (or deuterons) by a radiator, then collimated these charged particles into the main chamber volume where their energy was recorded. A perspective cut-away view of the chamber is shown in Fig. 1. In order to reduce background effects in the main chamber, the following auxiliary counters were made an integral part of the chamber: (1) a small proportional counter preceding the main chamber was used in coincidence with the chamber pulse, and (2) an ionization chamber electrode in the form of an extension of the main chamber collecting electrode was used in anticoincidence with the main chamber signal. The proportional counter served to detect the incoming protons while the end chamber electrode cancelled the signals of protons leaving the main chamber volume.

4. See references 6 and 7.

5. D. Hill, Phys. Rev. 87, 1034 (1952); B. Watt, Phys. Rev. 87, 1037 (1952); N. Nereson, Phys. Rev. 85, 600 (1952) and LA-1234 (1951).

By employing different radiators, a factor of about 3 in energy could be covered by this chamber at a particular gas filling. A check of the chamber with 5, 6 and 7 Mev monoergic neutrons gave pulse height distributions having a total width at half maximum height equal to about 10 per cent of the neutron energy. The minimum energy spread that could be obtained by using a very thin radiator amounted to 8 per cent of the neutron energy. It should be mentioned that this chamber is not especially suitable as a general neutron spectrometer device; it works considerably better with fission-type neutron spectra on account of background effects being diminished with the latter type of spectra.

The standard method of making a neutron transmission measurement was employed to determine the total cross sections of the elements. In practice, this merely consisted of recording the chamber pulse heights on a multi-channel analyzer with and without a sample in the neutron beam. Each channel responded to a certain range of pulse heights which in turn corresponded to a certain neutron energy interval. The energy spread employed in the cross section measurements averaged about 10 per cent of the neutron energy. This energy resolution is rather poor; however, none of the objectives of the survey demanded good energy resolution, and effort was therefore placed on obtaining data with fair resolution for a large number of elements rather than well-resolved data on a few elements. The statistical accuracy of the measurements varied from around ± 3 per cent at 3 Mev to about ± 8 per cent at 13 Mev. The small correction for inscattering at the higher energies has been deleted since it is quite small compared to the statistical error. When all nonstatistical errors are taken into account the over-all accuracy is approximately ± 10 per cent; the above figure is quite conservative for the lower energy regions. The background effect, as obtained with the radiator removed from the chamber, was a maximum of 8 per cent at energies around 3 Mev and a minimum of 2 per cent at energies around 13 Mev.

A photograph of the experimental arrangement used at the water boiler is shown in Fig. 2. This picture shows the chamber pulled back from its customary position at the west wall of the water boiler. When in position at the reactor wall, a shield enclosure approximately 1 ft. thick composed of borax and paraffin completely enclosed the chamber and scattering sample. This shield did not influence the cross section results or raise the chamber background but reduced the room background well below the neutron weekly tolerance level. A sample changer, which could be manually controlled from the exterior of the shield enclosure, is shown attached to the reactor wall; this permitted samples to be changed without shutting down the reactor. The glory hole port is No. 3 in the figure. A photograph showing the front of the chamber is shown in Fig. 3. The upright cylinder immediately to the right of the chamber is the gas purifier.

All of the samples used in the experiment were at least 98 per cent pure and were checked for uniform density by X-ray photographs. The cross sections of the gases were obtained by employing solid compounds and elements; as a check, the gaseous elements were measured by using two different sets of samples.

During the past two years over which this survey program has been in progress, the total cross sections of about 40 elements were determined over the 3 to 13 Mev energy region. The first set of 13 elements investigated⁶ contained many elements for which some previous data was available above 3 Mev. This provided a check on the data obtained by the present method with that obtained from accelerator measurements. In general, the agreement was well within the ± 10 per cent accuracy claimed for the present results. Measurements on an additional group of 28 elements⁷ were next undertaken in order to provide more complete information on cross section trends over the periodic table. The majority of elements in this latter group were chosen with the objective of securing cross section behavior as a function of atomic weight for $A > 35$; a few light elements were included in this group as a result of specific requests for cross section information.

4. Results

The combined cross section data obtained from the two surveys are shown in Figs. 4, 5, 6, 7, 8, and 9. Data obtained with various radiator thicknesses are identified by separate symbols. A solid line representing the average cross section has been drawn through the present experimental points only in energy regions where better resolved data do not already exist. Where more accurate cross-section information is available, the points from the present experiment are plotted merely for comparison purposes. In conformity with the objective of the experiment, a smooth curve has been drawn through the data points rather than an irregular curve following small fluctuations. This procedure has been especially followed in regions where cross section variations are less in energy width than the resolution of the measurements and where the statistical errors are large, as over the 12 to 14 Mev range.

The averaging effect of the present measurements is clearly shown by comparing the present data with better resolved data. Examples of the fine structure that exists in the total cross sections of the elements are shown in the cases of N, P and S around the 3 Mev energy region (Figs. 4 and 5). In general, the present results agree satisfactorily with the average of the fine structure data within the ± 10 per cent accuracy of the data.

6. N. Nereson and S. Darden, Phys. Rev. 89, 775 (1953).

7. N. Nereson and S. Darden, Phys. Rev. 94, June 15, 1954.

The energy resolution limits of the present measurements can be determined by observing various resonance widths in the light elements. For example, the broad peaks such as the Be resonance at 2.75 Mev and the C and O resonances at 3.5 Mev are satisfactorily resolved; however, the narrow peaks such as the C resonances at 2.9 and 6.3 Mev, and the oxygen resonance at 4.4 Mev, appear only as slight rises in the present data. The above examples indicate that the resolution of the chamber behaves as previously mentioned, i. e., only resonances having an energy spread at half maximum height greater than about 10 per cent of the neutron energy will be resolved.

The results of the Wisconsin survey¹ for energies below 3.2 Mev show lower total cross sections by about 10 per cent than the present results.⁸ This discrepancy is accounted for by the fact that the Wisconsin measurements were not carried out in as good a geometry as the present experiment; also, corrections for in-scattering were made on the assumption of isotropic scattering which is now known to be incorrect.⁹ Later Wisconsin cross section measurements carried out in better geometry by Walt et al.¹ agree well with the present results.¹⁰

The discrepancies between the two different sets of data taken for O and N are probably representative of the effect of systematic errors present in the measurements, i. e., sample purity, sample measurement and weighing, amplifier drift, the analyzer instability. Except for three points, the two sets of O data agree within ± 10 per cent. The two sets of N data are in good agreement except over certain energy regions. The measurement employing melamine and polyethelene is probably more subject to error on account of the carbon resonances in the 3 to 4 and 7 to 8 Mev regions. The TiN and Ti data are considered more reliable since the Ti cross section curve is smoother than the C curve; also, the TiN and Ti data agree better with the well-resolved data of Willard.

The results of the light elements in Figs. 4 and 5 show no marked resemblances in cross section characteristics of adjacent elements. However, the heavy elements in Figs. 6, 7, 8, and 9 demonstrate definite similarities in the cross section patterns of neighboring elements. For example, Fig. 6 shows a maximum beginning in the vicinity of Mn at 4 to 5 Mev and a shifting towards higher energies with increasing atomic weight. This maximum continues in Fig. 7 where it is evident in Zr at 9 Mev; finally, it shifts beyond 14 Mev in the curve for Sn. Coincident with the movement of the above maximum is the development of a minimum

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8. The Wisconsin data were compared with the present data in the preliminary survey (see Ref. 6). This comparison is shown in the curves for Fe, Cu, Zr, Pb, and Bi.
 9. See angular distribution data of E. Journey, LA-1339 (1952).
 10. It is possible to compare the present data on Co, Se, Cd, Te, Au, and Hg with the measurements of Walt et al.; with the exception of Te, the two sets of data agree within 4 per cent (see Figs. 6, 7, 8, and 9).

which, for the present energy range, is first observed in Zr around 5 Mev.¹¹ This minimum steadily moves toward higher energies over the remaining elements until it reaches 11 Mev at U. The movement of the above minimum is considerably more rapid over the Zr to La region than over the Ta to U region.

The results of this experiment for elements of $A > 35$ are summarized in Fig. 10. In this figure the measured cross sections divided by their nuclear geometrical area¹² are shown in an isometric view as a function of energy and atomic weight. The maximum and minimum features discussed in the previous paragraph are clearly evident in the surface pattern of this presentation. The light element results were not plotted in this figure as an irregular surface is produced due to the fact that resonance structure for these elements is comparable in magnitude to their average cross section variations. A similar figure for the 0.1 to 3 Mev energy range has been presented by Barschall.¹³ Figure 11 is a photograph of a cardboard model which was constructed to show total cross section behavior over the 2 to 14 Mev energy range as a function of atomic weight for the entire periodic table. This figure shows the same general features as Fig. 10 but, in addition, illustrates the resonances present in the light elements ($A < 35$) over the low energy regions.

At energies below 3 Mev, theoretical calculations on average total cross sections agree well with the experimental results for the heavy elements.¹⁴ In the case of the light elements, the calculations do not predict the results well on account of resonance structure influencing the cross section properties. However, over energy regions which exhibit no resonances the calculations should be on a comparable basis with the heavy elements. At the present time a restudy of the theoretical work is being made for elements of atomic weight < 55 .¹⁵ Recent work indicates that the value of the potential well entering into the calculations should be changed from 19 Mev to about 40 Mev.

The work extending these calculations to higher energies for the heavy elements is just being carried out at the present time. Therefore, it is not yet possible to compare the heavy element results of the present experiment with theoretical predictions. However, the calculations on the medium and light elements extend into the energy region covered by the present data

11. At lower energies, the minimum is probably the same one which is centered around 2 Mev in the region of Cu and Zn.¹
12. A smoother surface results from using the quantity $\sigma_t/\pi r^2$ rather than σ_t . A nuclear radius of $1.45 \times A^{1/3} \times 10^{-13}$ cm was used.
13. H. Barschall, Phys. Rev. 86, 431 (1952).
14. Feshbach, Porter and Weisskopf, NYO 3076, p. 24, April 1953.
15. Various private communications with C. E. Porter, Jr. and R. K. Adair (Feb. - April 1954).

and a comparison of the calculated and experimental results is shown in Fig. 12. Owing to the transitory nature of the theoretical work at this time, this comparison is not very appropriate but it does serve to present the status of the calculations at energies above 3 Mev. It is evident from this figure that the calculations are close to the experimental results above 3 Mev only for $A > 80$. However, the following facts in regard to this figure should be emphasized: (1) the comparisons have been made chiefly for light and medium weight elements whereas the theory holds best for heavy elements, and (2) Porter has mentioned that certain constants entering into these calculations are at present uncertain and may change over various energy regions as well as vary with atomic weight. In view of the latter uncertainties, an absolute comparison between theory and experiment is difficult at the present stage of computing.

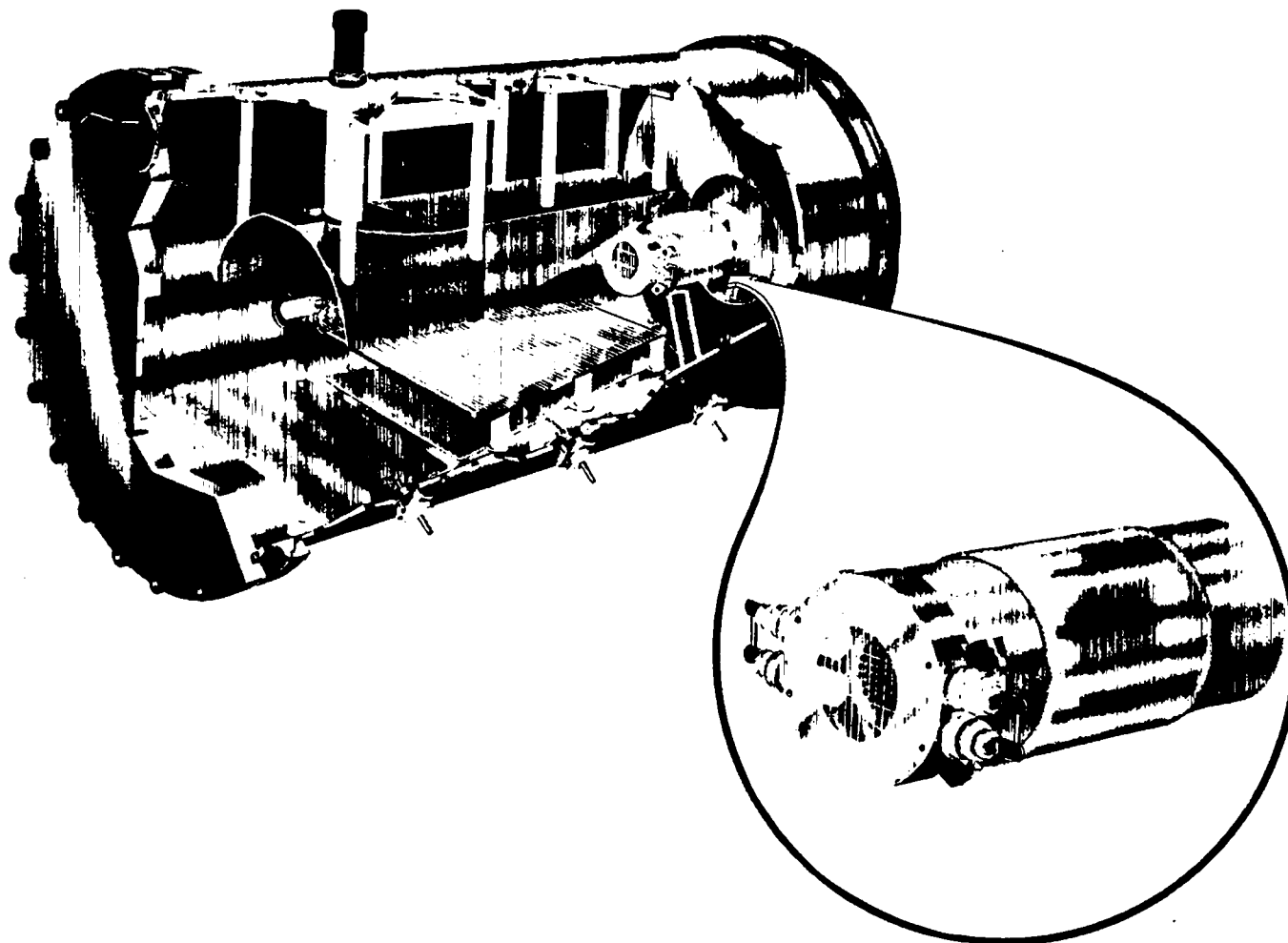
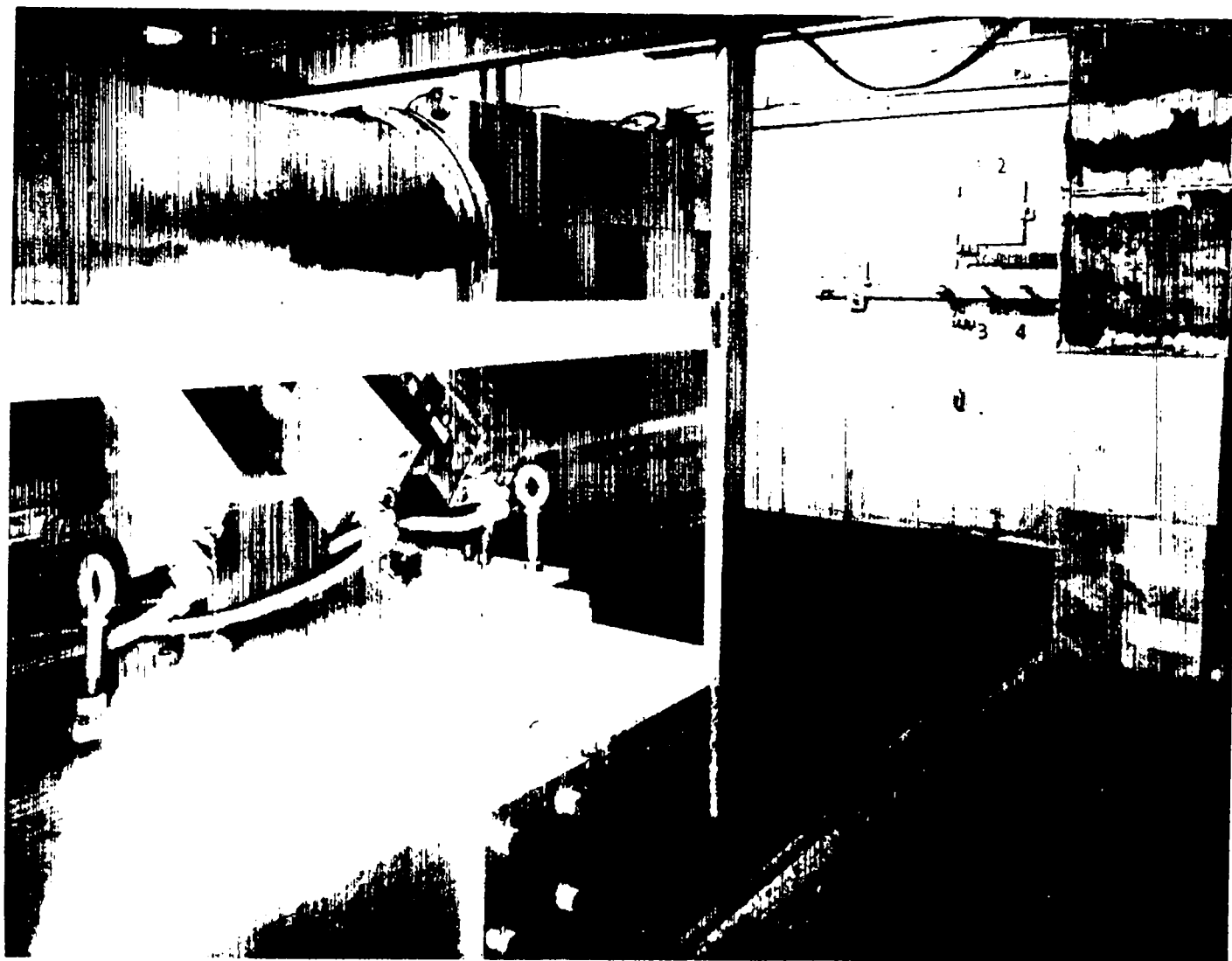


Fig. 1 Cut-away view of ionization chamber



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Fig. 2 Experimental arrangement at water boiler

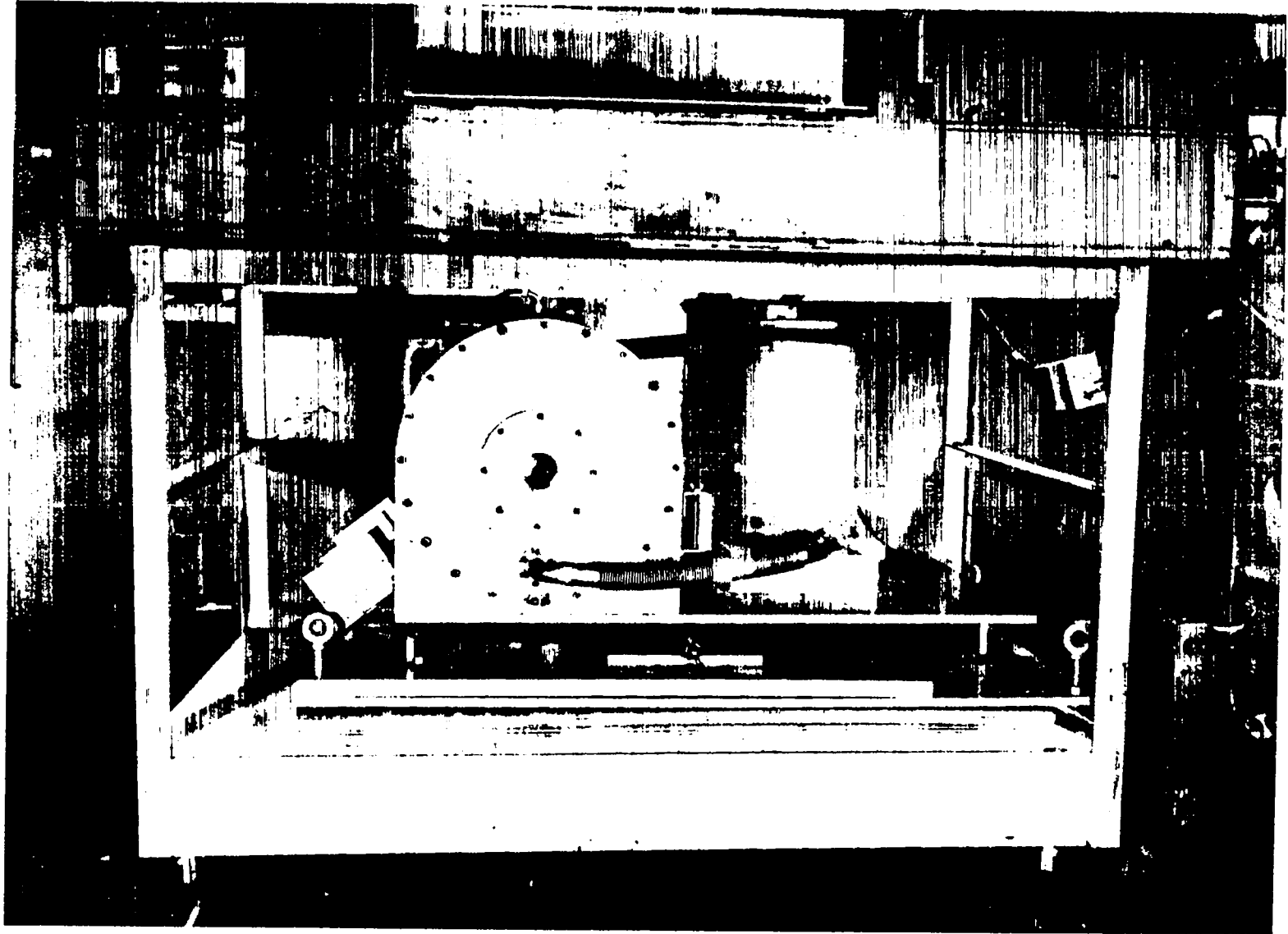


Fig. 3 Front view of ionization chamber

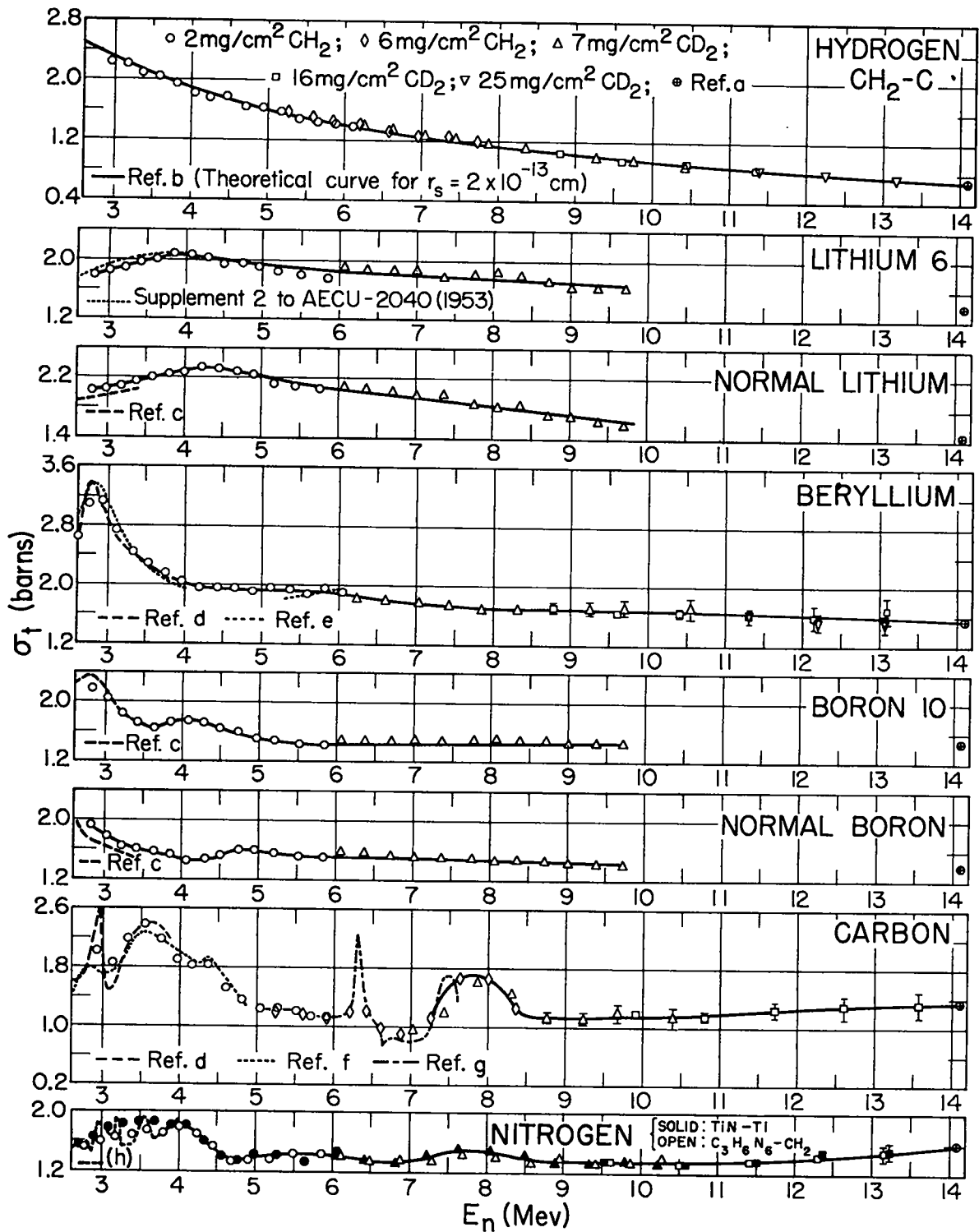


Fig. 4 Average total neutron cross sections of H, Li⁶, Li, Be, B¹⁰, B, C, and N

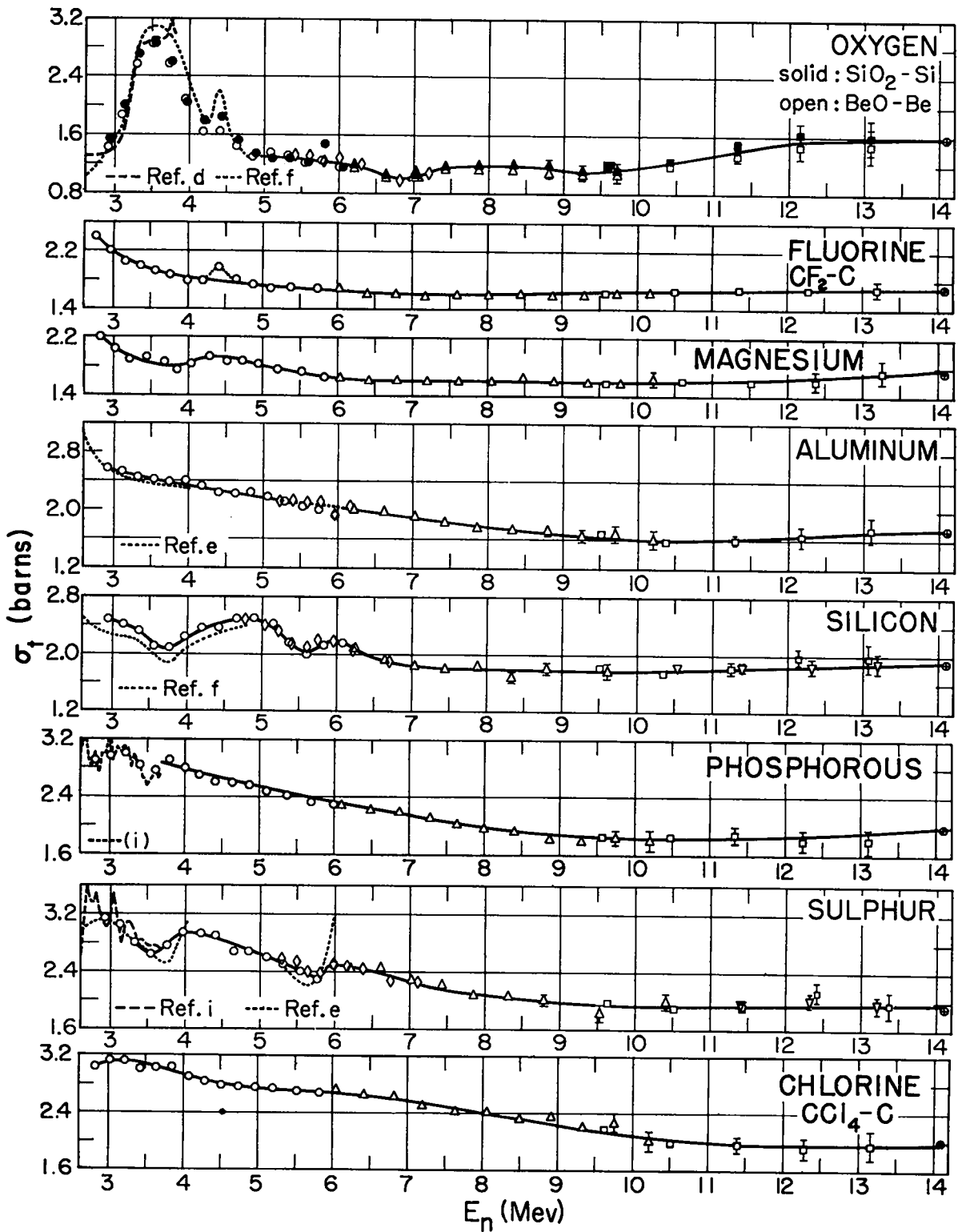


Fig. 5 Average total neutron cross sections of O, F, Al, Si, P, S, and Cl

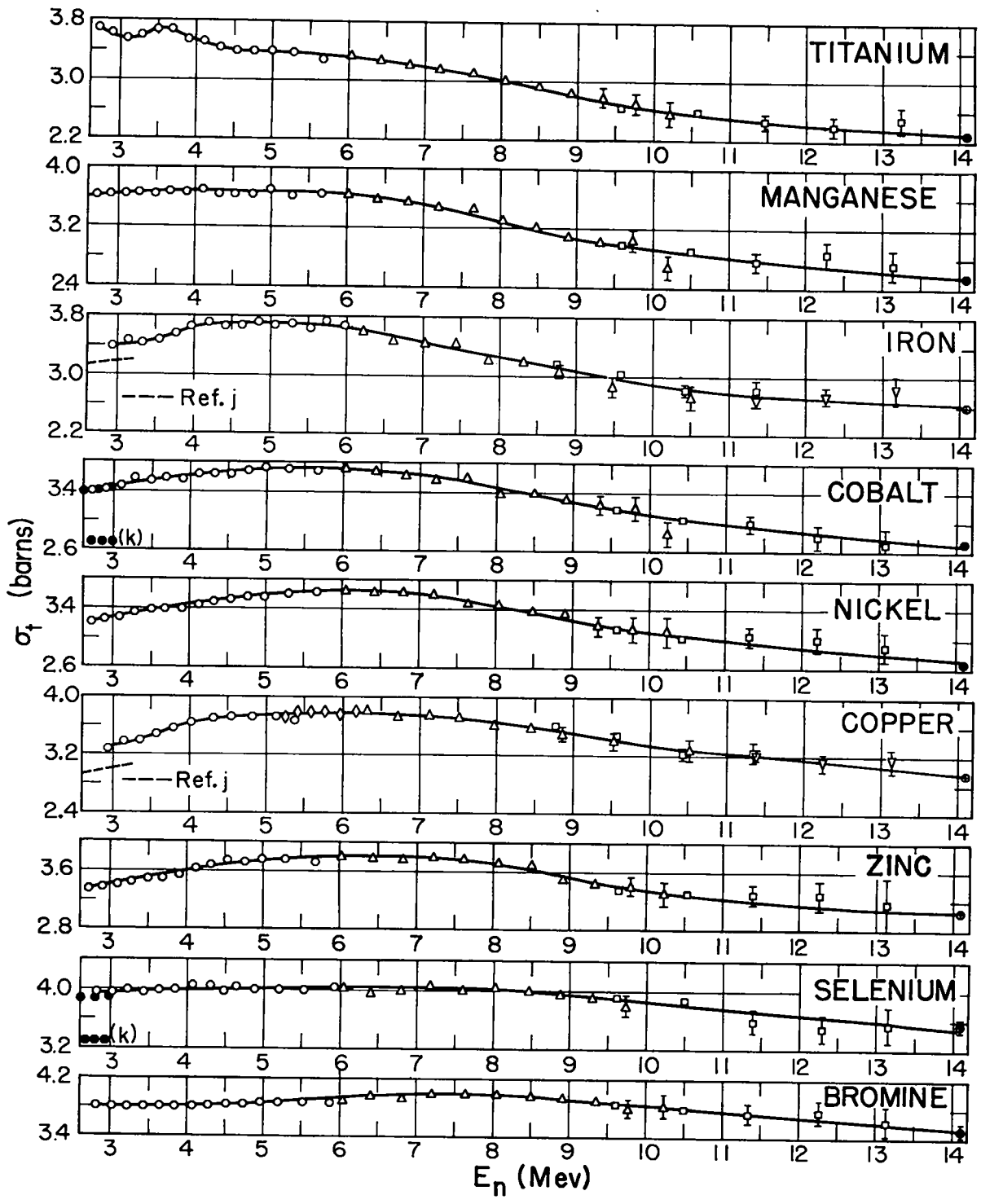


Fig. 6 Average total neutron cross sections of Ti, Mn, Fe, Co, Ni, Cu, Zn, Se, and Br

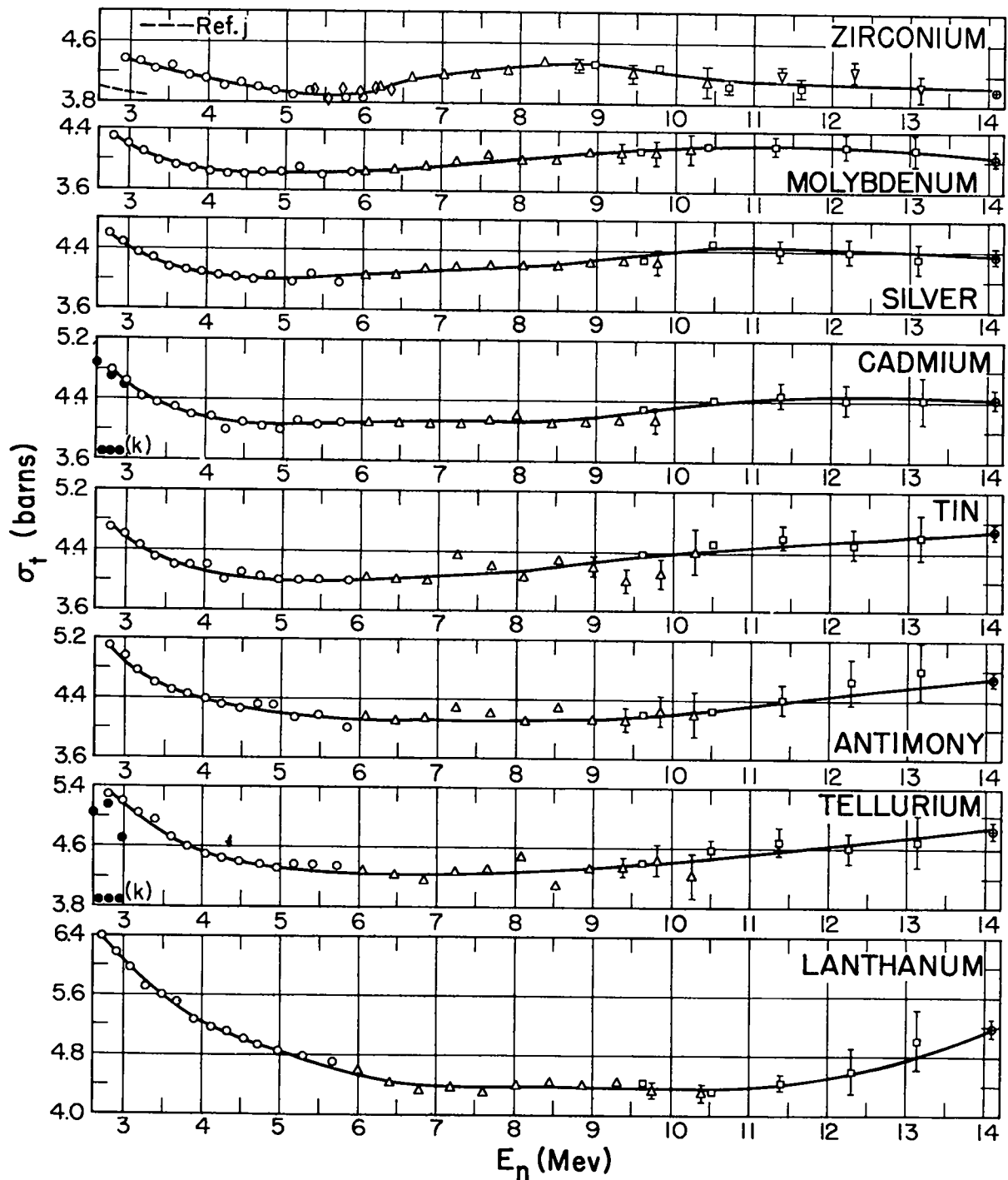


Fig. 7 Average total neutron cross sections of Zr, Mo, Ag, Cd, Sn, Sb, Te, and La

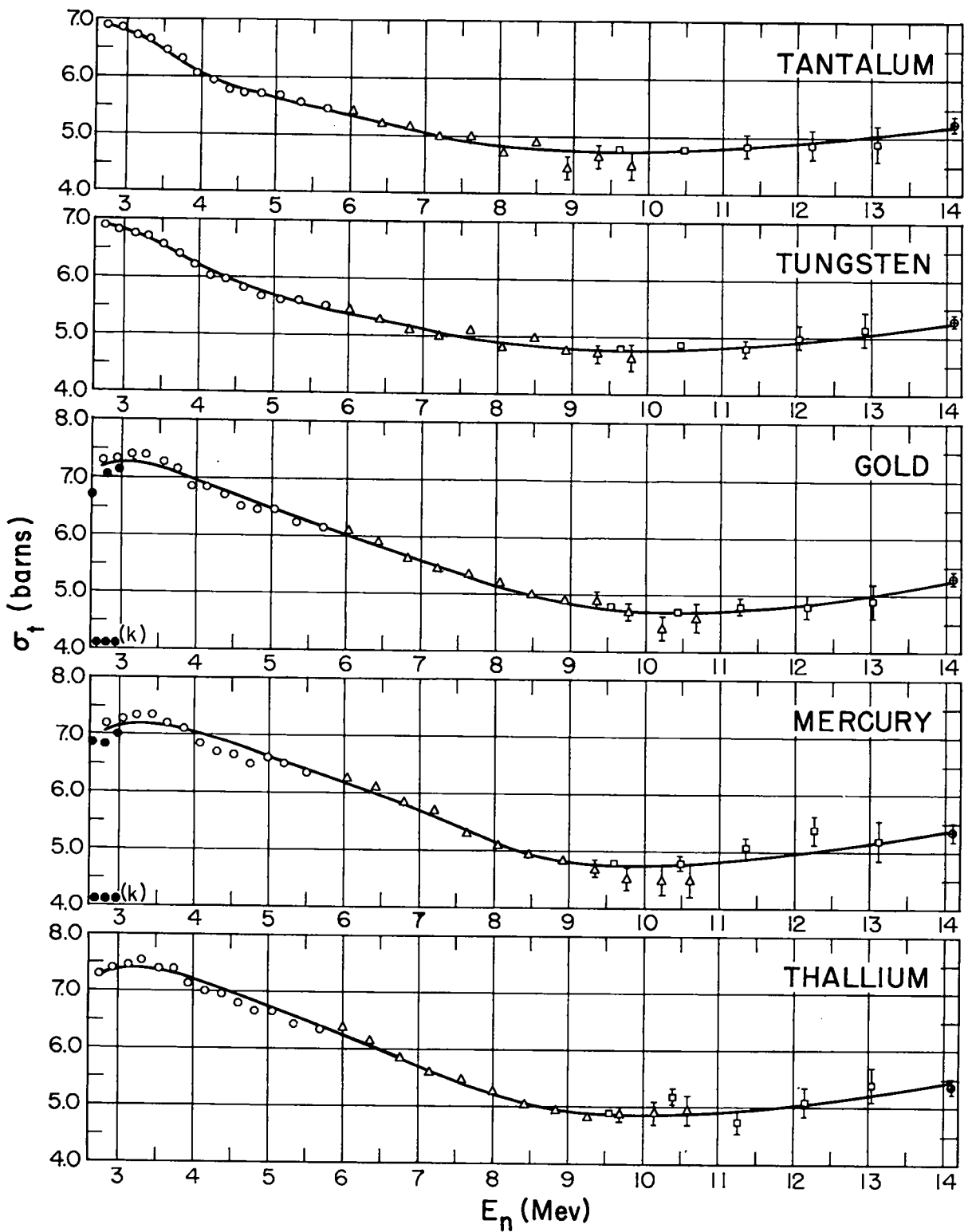


Fig. 8 Average total neutron cross sections of Ta, W, Au, Hg, and Tl

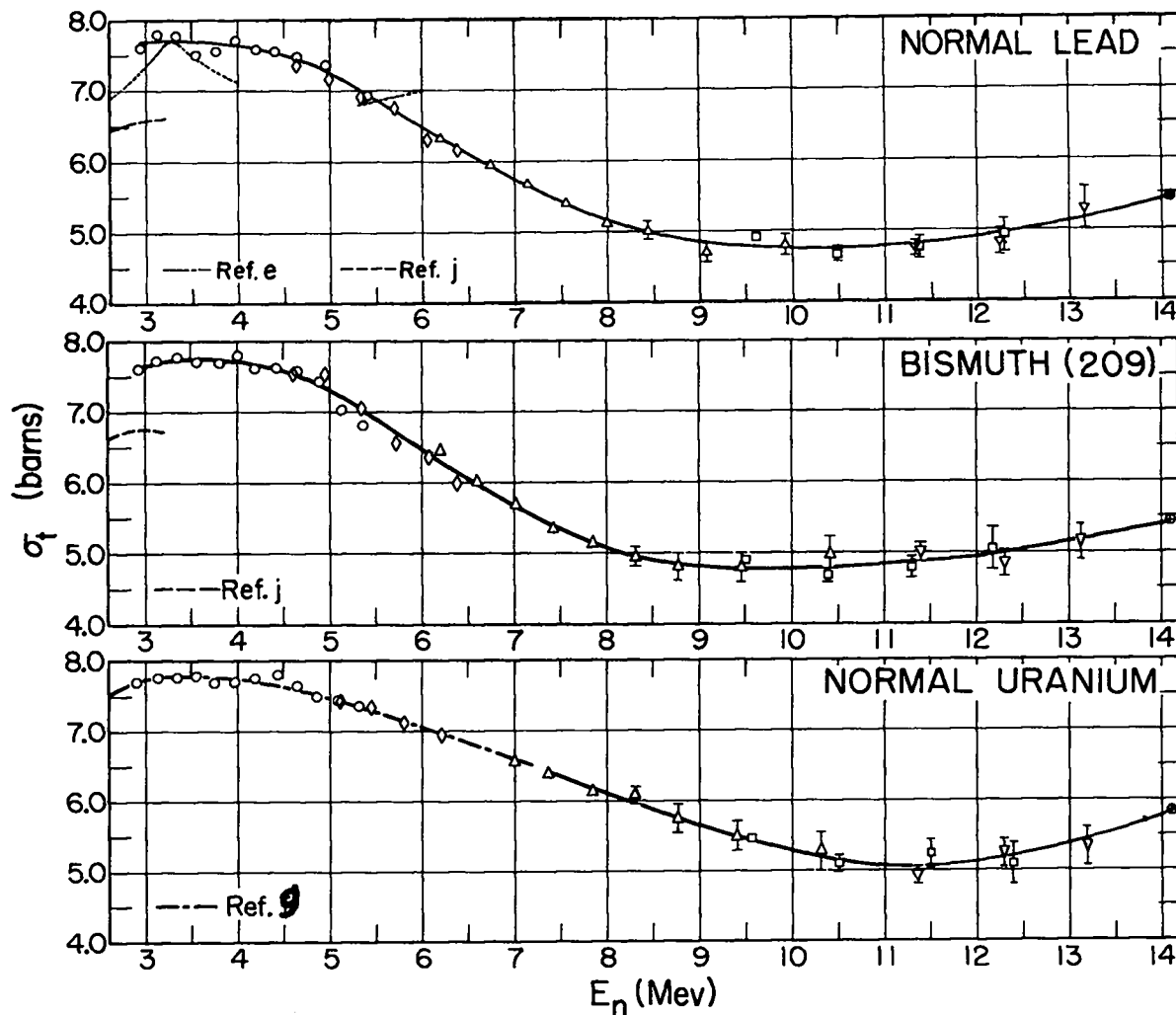


Fig. 9 Average total neutron cross sections of Pb, Bi, and U

References for Figs. 4 - 9 are as follows:

- (a) Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952)
- (b) J. M. Blatt and J. D. Jackson, Phys. Rev. **76**, 18 (1949)
- (c) Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951)
- (d) R. Ricamo and W. Zunti, Helv. Phys. Acta **8**, 419 (1951)
- (e) G. H. Stafford, Proc. Phys. Soc. (London) **A64**, 388 (1951)
- (f) Frier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950)
- (g) Los Alamos Electrostatic Accelerator Group, unpublished data (1952)
- (h) H. B. Willard, Oak Ridge National Laboratory, unpublished data (1952)
- (i) R. Ricamo, Nuovo Cimento **8**, 383 (1951)
- (j) Miller, Adair, Bockelman, and Darden, Phys. Rev. **88**, 83 (1952)
- (k) Walt, Becker, Okazaki, and Fields, Phys. Rev. **89**, 1271 (1953)

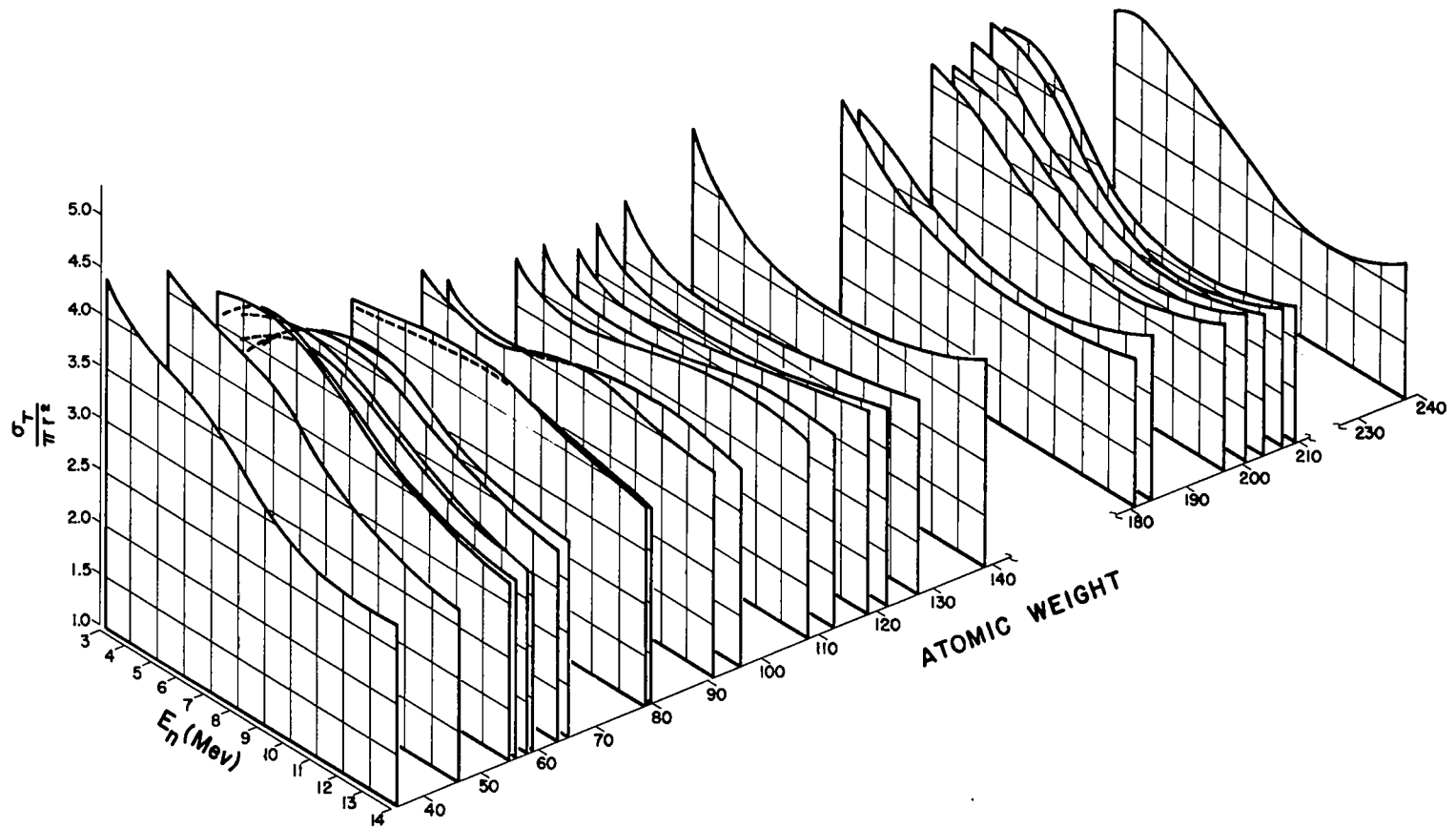


Fig. 10 Neutron cross sections for elements heavier than Cl as a function of energy and atomic weight

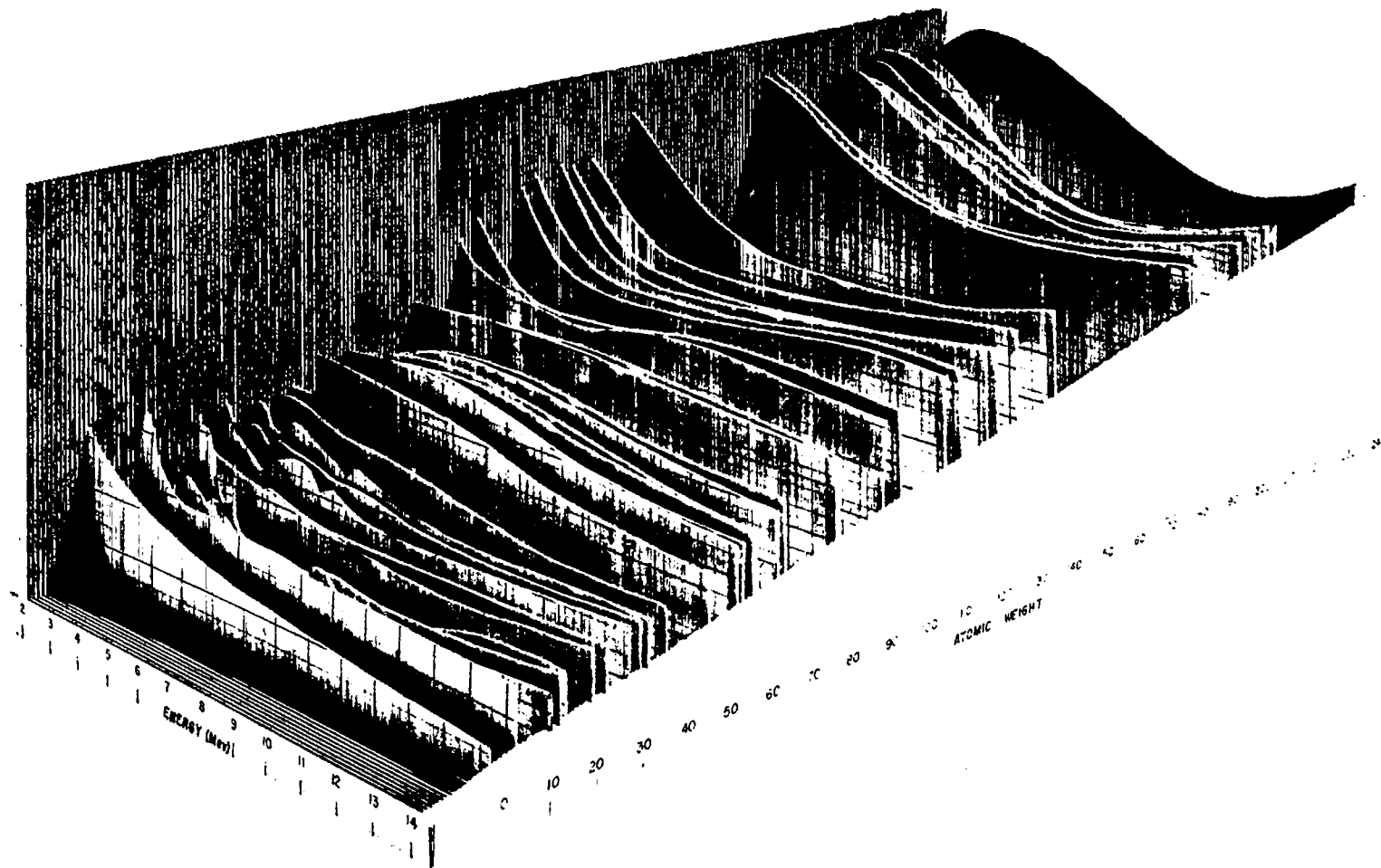


Fig. 11 Model showing variation of average total neutron cross section with energy and atomic weight. Each large unit on the vertical scale represents one barn

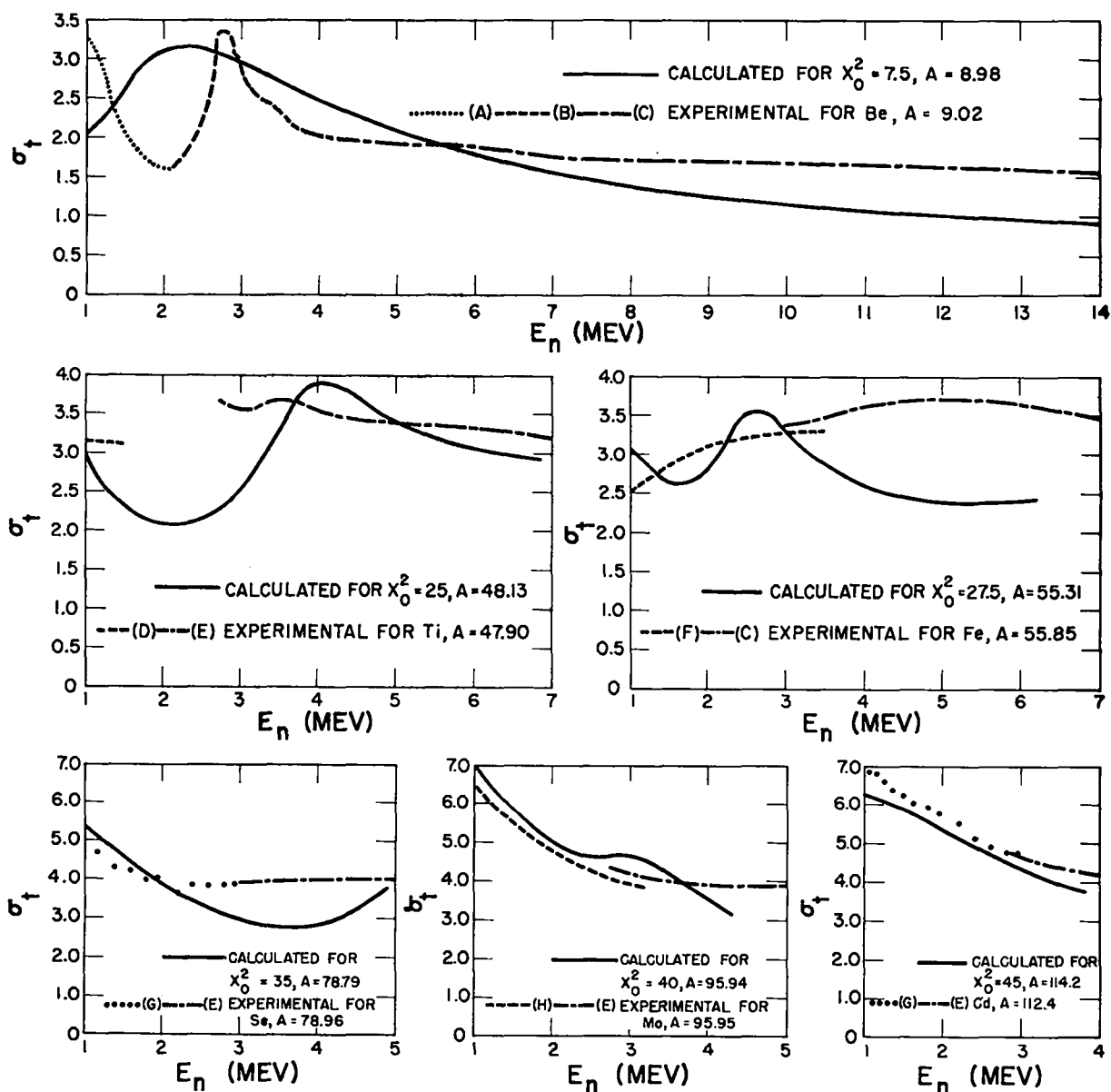


Fig. 12 Comparison of experimental results and theoretical calculations (using a potential well of 19 Mev). Experimental references are:

- (a) Bockelman, Miller, Adair, and Barschall, Phys. Rev. 84, 69 (1951)
- (b) Ricamo and Zunti, Helv. Phys. Acta 8, 419 (1951)
- (c) Nereson and Darden, Phys. Rev. 89, 775 (1953)
- (d) R. K. Adair, Rev. Mod. Phys. 22, 249 (1950)
- (e) Data from present report
- (f) H. Willard, Oak Ridge National Laboratory, unpublished data (1952)
- (g) Walt, Becker, Okazaki, and Fields, Phys. Rev. 89, 1271 (1953)
- (h) Miller, Adair, Bockelman and Darden, Phys. Rev. 88, 83 (1952)

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