Neutron Cross Sections of the Elements

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INTRODUCTION

DURING the past three years a considerable volume of work was completed on the determination of the neutron cross sections of the elements. The utility of such measurements in reactor design, and the value of the information they provide on the theories of nuclear resonance processes and nuclear structure, made desirable this revision of a previous compilation of cross sections.[1]

The available data on neutron cross sections covers an energy range from nearly 0.001 ev to almost 300 Mev. Values of the cross sections also cover a wide range of values. This makes evident the difficulties inherent in a graphical representation of this kind.

In the low energy region, most measurements are made by using neutrons whose energies are determined by measuring their time of flight over an interval,[2,3] or by using the monochromatic neutrons produced with a crystal interference spectrometer.[4] The neutron energy resolution obtained by either method is very strongly energy dependent; the energy spread is very much smaller at the lower energies. The energy separating the experimental points is, in most experiments, of the same magnitude as the neutron energy spread. Therefore, the points are spaced much closer together at the lowest energies. This consideration together with the wide proportionate range covered with these techniques led to the use of a logarithmic energy scale to best illustrate the data.

The medium energy data, from 15 kev to a few Mev, are in general plotted on a separate graph. Most of the work in this range utilizes monoenergetic neutrons from charged particle reactions.[5,6] The neutron energy spread, and hence spacing of experimental points, is nearly independent of energy in most of this work, so the data seemed to be best presented on a linear energy scale.

The high energy work, extending from one or two Mev to 300 Mev, consists to a large degree of a collection of sets of measurements made at a particular energy with a particular technique. It was most convenient to plot these values on a logarithmic energy scale.

The neutron cross sections will in general include elastic and inelastic scattering, the radiative capture (n, γ) process, which is designated on the charts as σ_r, and the various particle reactions (n, α), (n, p), $(n, 2n)$, etc., and fission. These are labeled σ_α, σ_p, $\sigma_{n,2n}$, and σ_f, respectively. The sum of the cross sections for events of all types is the total cross section, σ_t, which is measured by determining the transmission of neutrons through a sample of the material in question. Because of the simplicity of transmission measurements, the bulk of the data deals with total cross sections. Therefore, ordinate scales were selected which best portrayed this information.

Where it was inconvenient to follow this general pattern, as in some of the reaction cross-section work, curves have been introduced in a more arbitrary fashion. It is hoped that increased legibility of the data will compensate for the somewhat inconsistent representations.

While we hope that the most useful data are included in this report, there has been no attempt to include all neutron cross-section measurements. In particular, certain types of data have been excluded deliberately. Measurements of inelastic scattering were not considered as they are not amenable to graphical representation. The large field of thermal neutron activation studies has been omitted, as it is difficult to estimate an effective energy for graphical portrayal. These values have been compiled by Ross and Story.[7] Most of the studies of crystal structure effects have been arbitrarily excluded as beyond the intended scope of this work. The early fast neutron cross-section determinations made with a radium beryllium source[8] have been left out. Such neutrons have a very broad distribution of energies, and an assignment of an effective energy is necessarily arbitrary. Certain absorption cross sections have not been included because of the difficulty of including these results on the graphs. Values obtained with unmoderated fission neutrons have been obtained by Hughes *et al.*,[9] whose paper presents a critical

* AEC Predoctoral Fellow.
[1] Goldsmith, Ibser, and Feld, Rev. Mod. Phys. **19**, 259 (1947).
[2] L. J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946).
[3] T. Brill and H. V. Lichtenberger, Phys. Rev. **72**, 585 (1947).
[4] Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).
[5] L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947).
[6] Hanson, Taschek, and Williams, Rev. Mod. Phys. **21**, 635 (1949).
[7] M. J. Ross and J. S. Story, Progress in Physics **12**, 291 (1949).
[8] Dunning, Pegram, Fisk, and Mitchell, Phys. Rev. **48**, 265 (1935).
[9] Hughes, Spotz, and Goldstein, Phys. Rev. **75**, 1781 (1949).

discussion of other high energy absorption measurements.

SLOW NEUTRON CROSS SECTIONS

The interaction of neutrons with nuclei can be explained in terms of the formation of a compound nucleus.[10,11] The compound nucleus will have an excitation energy equal to the binding energy of the added neutron plus its kinetic energy. This state may decay through many channels. The compound nucleus may emit radiation and pass to its ground state, or particles may be emitted under various conditions of energy and angular momentum. These processes will be competitive and will occur in proportion to their respective transition probabilities.

When the sum of the binding energy of the extra neutron and its kinetic energy falls within the width of an energy level of the compound nucleus, the probability of formation of the compound state is greatly increased, resulting in an increase in cross section or resonance in the processes associated with its decay. The cross section for a process p near an isolated level can then be expressed by the Breit-Wigner single level formula.[11–14] At low energies only the interaction of neutrons with zero units of orbital angular momentum will be important and the cross section takes the form:

$$\sigma_p = g\pi\lambda\!\!\!^{-2}\frac{G_nG_p}{(E-E_r)^2+G^2/4}, \tag{1}$$

where G_n is the neutron width, equal to $\hbar\omega_n$, where ω_n is the transition probability for the emission of a neutron by the compound state. Similarly, G_p is the width for the process p, and G is the sum of the widths for all possible processes. In this $\lambda\!\!\!^{-}$ is the neutron wave-length divided by 2π, and g is a statistical weight factor depending on the spins† of the states involved. All dynamical quantities are referred to the center-of-mass coordinate system.

All possible processes p can conveniently be divided into two classes, elastic scattering and absorption. Absorption includes radiative capture, and the emission of particles as (n, p) and (n, α) reactions. The widths for these events are dependent upon the energy of the particle or quanta emitted. For the absorption-type process this energy is of the order of a Mev. These widths will then vary only slightly over the few volt range of the slow neutron experiments and G_a may be replaced by Γ_a, the width at exact resonance. The neutron width, however, is proportional to the neutron velocity and may change appreciably through the experimental range. We can then replace G_n by $\Gamma_n\lambda\!\!\!^{-}_r/\lambda\!\!\!^{-}$ where Γ_n is the width and $\lambda\!\!\!^{-}_r$ the wave-length divided by 2π, at resonance. The term G will be predominant in the denominator only near resonance, so it can be replaced by Γ at resonance with little error. The absorption cross section then takes the form

$$\sigma_a = g\pi\lambda\!\!\!^{-}\lambda\!\!\!^{-}_r\Gamma_n\Gamma_a/[(E-E_r)^2+\Gamma^2/4] \tag{2}$$

which is the product of a resonance term and a $1/v$ term as $\lambda\!\!\!^{-}$ is inversely proportional to the neutron velocity v. If $\Gamma \ll E_r$ the ratio $g\lambda\!\!\!^{-}_r\Gamma_n\Gamma_a/E_r^2$ can be determined by measuring the slope of the cross section near zero neutron energy. The peak height, $4\pi\lambda\!\!\!^{-}_r{}^2g\Gamma_n/(\Gamma_n+\Gamma_a)$, can be determined by self-absorption measurements. These values, together with E_r, the position of the resonance, can then be used to find $g\Gamma_n$ and Γ_a. In some cases[15] the ratio of the scattering cross section and the absorption cross section has been measured and used to find g, which for slow neutrons, where $l=0$, is equal to $\frac{1}{2}(2J+1)/(2I+1)$. If the spin I of the target nucleus is known this determines J, the spin of the compound state.

Values of Γ_n, besides being proportional to the neutron velocity are also related to the average distance between levels. Feshbach *et al.*[14] show that $\Gamma_n \simeq 2\lambda\!\!\!^{-}{}'D/\pi\lambda\!\!\!^{-}$ where D is the average distance between levels of the same spin and parity, and $\lambda\!\!\!^{-}{}'$ is the wave-length/2π of a neutron in the nucleus, which corresponds to an energy of the order of 30 Mev. The level density is presumed to increase very rapidly with E, the excitation energy, and A, the mass number of the nucleus. It may also be different in even A and odd A nuclei, and in closed shell nuclei.‡ For heavy elements such as I, Ta, Ag, etc. $\Gamma_n\lambda\!\!\!^{-}$ is of the order or 10^{-13} kev cm, while for light elements as aluminum, sulfur, and oxygen, this reduced width may be several hundred or a thousand times as large.[16]

For all but the lightest nuclei, the Coulomb field precludes the emission of charged particles, and the absorption widths are radiation widths. Values of Γ_r range from 10 or 15 ev in very light nuclei to about 0.1 ev in heavy nuclei. Below a few volts $\Gamma_r \gg \Gamma_n$ and absorption is the dominating process while the resonances at energies as high as 100 volts are mainly scattering resonances with $\Gamma_n \gg \Gamma_r$.

[10] N. Bohr, Nature **137**, 344 (1936).
[11] G. Breit and E. P. Wigner, Phys. Rev. **49**, 519 (1936).
[12] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).
[13] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).
[14] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).

† If the spin of the target nucleus is I, and the spin and angular momentum of the neutron are s and l, respectively, there will be $(2l+1)(2I+1)(2s+1)$ different ways in which a compound nucleus may be formed. These will differ in the magnitude of J, the spin of the compound state; in the coupling, or relative orientation of the vectors I, s, and l; and in the final spatial orientation of J. The distribution of levels of different J will be independent, and it is expected that there will be sufficient spin orbit coupling in the nucleus to remove the degeneracy in coupling. Since there is no preferred azimuth direction, a $2J+1$-fold spatial degeneracy will occur and the fraction

$$g=(2J+1)/[(2I+1)(2s+1)(2l+1)]$$

of the l neutrons will be affected by a level of spin J.

[15] W. Selove, Phys. Rev. **77**, 557 (1950).
‡ Nuclei containing 50, 82, or 126 neutrons, or 50 or 82 protons.
[16] E. P. Wigner, Am. J. Phys. **17**, 99 (1949).

Besides resonance scattering, a non-resonance or potential scattering is observed which is not closely associated with the formation of a compound state. These processes are coherent and interfere. Writing the potential scattering phase shift as δ, and noting the velocity dependence of the neutron widths, we can for slow neutrons write:

$$\sigma_n = g4\pi\left|\lambda_r\frac{\Gamma_n/2}{E-E_r+i\Gamma/2}-\lambda e^{-i\delta}\sin\delta\right|^2+4\pi(1-g)\lambda^2\sin^2\delta.$$

The cross product of the resonance term and the potential term represents an interference effect which results in a diminished value of the cross section at energies just below resonance. The potential term is divided into two parts, as interference in total cross section only occurs between states of the same l and J. Far from resonance, the cross section should equal $4\pi\lambda^2\sin^2\delta$. δ is expected to be equal to $-R/\lambda$ where R is the nuclear radius. At low energies, where $R/\lambda \ll 1$, $\sigma_n = 4\pi R^2$ which is equivalent to the scattering from a rigid sphere of radius R. Experimentally the value of the low energy non-resonant cross section does not agree very well with this picture. Some of the anomalous effects may be due to the tails of far-off levels. The contributions of high lying levels will tend to lower the cross-section values, while levels below zero neutron energy would raise the cross section.

Sometimes levels are found whose separation is not much greater than their widths. These levels will then interfere and distort the simple picture of cross section behavior. The effect of interference between scattering resonances can be calculated explicitly, as the phase shifts are uniquely determined by the resonance parameters. The interference behavior of absorption resonances is dependent upon the relative phase of the final states of the two or more resonances involved. This depends upon details of the transitions which are not known.[17] Heavy nuclei can pass to a large number of states upon emission of the first quantum. Phase correlations between the many final states resulting from radiation of adjacent resonance levels may then average to zero, and the cross sections would be nearly additive.

The relation of the experimental data to the cross section near a resonance is determined by the effective energy spread of the detected neutrons. An estimate of the resolution of the various spectrometers is listed in Table I.[18] This spread is large enough so that not many of the slow neutron peaks are resolved. The quantity measured in these experiments is the neutron transmission of the sample, averaged over the neutron energy distribution. The cross section measured in this way will be smaller than an average of the cross section with neutron energy, and its value will depend upon the sample thickness or transmission. This hardening effect results in a smaller area under the experimental curve than under the true curve. Some workers plot values of transmission as ordinates, avoiding misinterpretation of the data. Cross-section values were plotted in this compilation, so that results at different energies with different samples could be easily compared. It must be realized, however, that the absolute values have meaning only in terms of the experimental conditions.

TABLE I. Characteristics of neutron spectrometers.

Type	Useful range (ev)	Resolution *vs.* energy (ev) 0.025	1	10	100
Mechanical spectrometer	0.001–1000	∼0.001	∼0.1	∼ 6	∼30
Crystal spectrometer	0.01–100	∼0.001	∼0.5	∼10	···
Modulated cyclotron	0.001–10,000	∼0.001	∼0.1	∼ 1	∼20

MEDIUM FAST NEUTRONS

The light elements, $A \lesssim 50$, and the heavy closed shell nuclei‡ such as Bi and the Pb and Sn isotopes, show few resonances in the low energy region. The spacing between levels in these elements is presumably large compared to the range covered by low energy methods, so there is but a small chance that a resonance will occur in this region. The low level density is attributed to the small number of particles in the light elements, and to the low excitation energy of the compound nucleus which is formed by the addition of a neutron to the closed shell nuclei.[19,20] The nuclear spectra of these elements are then better investigated by cross-section measurements at higher neutron energies, covering a broader energy range.

At neutron energies above a few kev, the absorption widths are negligible compared to the neutron widths, and the only process which contributes appreciably to the total cross section is elastic scattering. This condition obtains up to energies where a neutron can be re-emitted inelastically, leaving the product nucleus in an excited state. Such inelastic scattering is not expected to be important at energies below 0.5 Mev in these elements.

At energies greater than a few hundred kev, λ is not very much larger than R and the effect of neutrons with orbital angular momentum becomes important. The scattering cross section which is very nearly equal to the total cross section takes the form, for an isolated resonance of spin J produced by interaction of neutrons

[17] S. Flugge, Zeits. f. Naturforschung **3a**, 97 (1948).
[18] T. I. Taylor and W. W. Havens, Jr., Nucleonics **5**, 1 (December, 1949).
[19] Hanson, Duffield, Knight, Divens, and Palevsky, Phys. Rev. **76**, 578 (1949).
[20] J. A. Harvey, Phys. Rev. **78**, 345 (1950).

with angular momentum l':

$$\sigma=(2l'+1)g_{Jl'}4\pi\lambda^2\left|\frac{\Gamma_n/2}{E-E_r+i\Gamma_n/2}-\exp(-i\delta_{l'})\sin\delta_{l'}\right|^2+(2l'+1)(1-g_{Jl'})4\pi\lambda^2\sin^2\delta_{l'}+\sum_{l\neq l'}(2l+1)4\pi\lambda^2\sin^2\delta_l$$

for

$$\Gamma_n\cong\Gamma\ll E_r. \tag{5}$$

This consists of the partial cross section, for l' neutrons forming a state of spin J, which is affected by the resonance, plus a constant potential scattering background. The part affected by the resonance can be written simply as:

$$\sigma=(2l'+1)g_{Jl'}4\pi\lambda^2\sin^2\varphi,$$

where $\varphi=\tan^{-1}\Gamma_n/2(E_r-E)+\delta_{l'}$. The cross section will then be at a maximum when $\varphi=90°$ and at a minimum where $\varphi=0°$. The difference between the cross-section maximum and minimum will be equal to $4\pi\lambda^2(2J+1)/2(2I+1)$ determining J the spin of the compound state. The depth of the dip will equal $(2l'+1)4\pi\lambda^2 g_{Jl'}\sin^2\delta_{l'}$ giving a measure of $\delta_{l'}$. This can sometimes be used to obtain l' the orbital angular momentum of the interacting neutron, which in turn determines the relative parities of the target nucleus and the compound state. To a first approximation the δ_l will be equivalent to the phase shifts caused by the scattering[14] from a rigid sphere of radius R: where $x=R/\lambda$

$$\begin{aligned}\delta_0&\simeq -x\\ \delta_1&\simeq -x+\tfrac{1}{2}\pi-\cot^{-1}x\\ \delta_2&\simeq -x+\pi-\cot^{-1}(x^2-3)/3x.\end{aligned} \tag{7}$$

At low energies, $x\ll 1$, only δ_0 will be important. A dip before a peak is then evidence that the resonance is excited by S neutrons. At higher energies such identification seems to be less certain.

It is also possible to obtain information as to the angular momentum of the interacting neutrons by considering the widths of the levels. The transition probability and hence width for the emission of a neutron is dependent upon the magnitude of the centrifugal potential barrier. These widths can be separated into three parts:

$$\Gamma_{nl}=2(1/\lambda)\gamma_n^2 T_l \tag{8}$$

where γ_n^2, the reduced width,[16] is proportional to the square of the matrix element for the transition, and depends upon the configuration of the states involved. This quantity is not dependent on l and should not vary much from resonance to resonance. In particular it cannot be larger than $3\hbar^2/2mR$, where m is the mass of the neutron.[16] The term $1/\lambda$ is proportional to the volume of phase space available to the emitted neutron, and T_l is a centrifugal barrier penetration factor analogous to the usual Coulomb barrier penetration factors. The T_l can be calculated explicitly:[14]

$$\begin{aligned}T_0&=1\\ T_1&=x^2/(1+x^2)\qquad x=R/\lambda.\\ T_2&=x^4/(9+3x^2+x^4)\end{aligned} \tag{9}$$

These quantities are very much different for small x. Therefore the magnitude of Γ_n is an indication of the angular momentum of the neutrons which excited the level.

The characteristics of the experimental cross-section curves are dependent upon the neutron energy resolution used. In many of the curves triangles are introduced to represent the spread in energy of the incident neutrons. Most of the resonance work was conducted with energy spreads greater than 10 kev. This is sufficient to resolve resonances in only the lightest elements. Recently work has been done with neutron energy spreads as small as one kev,[21] extending the region of detailed analysis.

There has been some total cross-section work with very broad energy spreads, of the order of 100 kev. The results of these measurements relate to the cross section averaged over a large number of resonances. Such measurements are useful in the fast neutron diffusion calculations of reactor design, and as a test for statistical theories of nuclear interactions.

Absorption cross sections have also been measured as a function of neutron energy. The cross section for such processes near an isolated resonance of spin J formed by l neutrons is:

$$\sigma_a=(2l+1)g_{Jl}\pi\lambda^2\Gamma_n\Gamma_a/[(E-E_r)^2+\Gamma^2/4]. \tag{10}$$

A peak in the absorption cross section will then occur at E_r. The scattering peak will be displaced from E_r by the interference with the potential scattering; $E_{\max}-E_r=-\Gamma_n/2\tan\delta$. This displacement is often small compared to the distance between resonances and the peaks for the two processes nearly coincide.

The level spacing in heavier elements is only a few volts and measurements determine average contributions over resonances. For this average absorption cross section, Wigner presents:[16]

$$\sigma_a=4\pi^2\lambda\frac{\gamma_n^2}{D}\Gamma_a\frac{(1+R/\lambda)^2}{(\Gamma_a+2\gamma_n^2/\lambda)}, \tag{11}$$

where γ_n^2 is the reduced width [Eq. (8)] and D is the average distance between levels of a determined spin and parity. The terms γ_n^2/λ will generally be very much larger than Γ_a, and the cross section will be nearly proportional to Γ_a/D and relatively independent of γ_n^2. When D is known, as from total cross-section measurements, a value for Γ_a can be found. This

[21] R. E. Peterson and H. H. Barschall (unpublished).

relation (11) should be valid up to energies where inelastic scattering takes place. The competition of this process will lower the absorption cross section for heavy nuclei at energies over a few hundred kev.

FAST NEUTRON CROSS SECTIONS

Interaction of high energy neutrons with nuclei will produce a highly excited compound nucleus. This compound state can emit neutrons and charged particles leaving the residual nucleus in various excited levels. The number of states available for the emission of neutrons will be equal to the number of levels of the target nucleus which have an excitation energy less than E_n, the kinetic energy of the incident neutron. The states available for the emission of charged particles will consist of levels in the residual nucleus whose energy is smaller than E_n+Q above the ground state, where Q is the reaction energy. Different processes will occur in proportion to their widths. A width $\Gamma_{\rho s}$ for a transition from a level ρ of the compound nucleus to a level s of the residual nucleus will be equal to $2\gamma_{\rho s}^2(1/\lambda\!\!\!^-_{\rho s})T_l$, where $\gamma_{\rho s}^2$ is the reduced width. Here $\lambda\!\!\!^-_{\rho s}$ is the wave-length/2π of the emitted particle, and T_l is the barrier penetration coefficient, equal to the Gamow factor for charged particles and to Eqs. (9) for neutrons. We expect $\gamma_{\rho s}^2$ to be the same magnitude for all transitions. The Coulomb barrier will suppress the emission of charged particles and the widths for radiative capture will remain small, so that the re-emission of neutrons will be the dominant process connected with the formation and decay of a compound nucleus. Widths for transitions to excited levels s may be of the same order of magnitude as the width for the elastic scattering transition to the ground state. Therefore, when many states s are energetically available, the total of all of the widths Γ will be very much larger than Γ_n. From Eq. (3), Γ_n at high neutrons energies is not much smaller than D, the spacing between levels. Then Γ will be much larger than D, resonance effects will not be observable, and the cross sections will be smooth functions of energy. This condition will obtain at neutron energies of one or two Mev for heavy nuclei.

As $\Gamma \gg D$, a classical evaporation model[22] can be used to explain the decay processes. The emitted neutrons will be expected to have a nearly Maxwellian distribution about a temperature T, related to the kinetic energy of the particles in the residual nucleus. Charged particle distributions will be further affected by the Coulomb field. At very high energies the energy available may be sufficient to "boil off" several particles and $(n, 2n)$, (n, np) type reactions are observed.

Since $\Gamma_n \ll \Gamma$, elastic re-emission of the incident neutron will be an improbable process and nearly all neutrons which strike the nucleus will be absorbed (in the sense that they are removed from coherency with the incident beam). The cross section for this absorption will be equal to πR^2. There will still occur an elastic scattering analogous to optical Fraunhofer diffraction. These diffracted neutrons will be scattered through small angles of the order of $R/\lambda\!\!\!^-$. The cross section for this effect is also πR^2, therefore, the total cross section will equal $2\pi R^2$. This is strictly valid only for $\lambda\!\!\!^- \ll R$. Feshbach and Weisskopf[23] show that $\sigma_r = 2\pi(R+\lambda\!\!\!^-)^2$ is a more generally valid approximation.

At very high energies, of the order of 100 Mev, the nucleon-nucleon cross section is small, and the mean free path of the neutron in the nucleus is comparable to the dimensions of the nucleus. The neutron will then have a finite chance to pass through the nucleus undeflected and the resulting transparency will reduce the total cross section[24] to values less than $2\pi R^2$.

Total cross sections are measured by determining the transmission of neutrons through the material in question. Under conditions of good geometry the sample will subtend a very small angle at the detector and any particle which is at all deflected will not reach the detector. In practice this is not strictly true, and a correction must be made for neutrons scattered into the counter. If the sample is placed midway between the source and the detector, the correction will be positive and equal to $f\sigma_t(d\Omega/\pi)$, where $d\Omega$ is the solid angle subtended by the sample at the detector and f is the gain in the forward direction, equal to the number of neutrons emitted, per unit solid angle, in the forward direction, divided by $\sigma_t/4\pi$, the number which would be expected if the distribution were symmetric. This expression is valid only at high transmissions.

When most of the neutrons which strike the nucleus are re-emitted inelastically, f will be approximately equal to $\frac{1}{2}+\frac{1}{2}(R/\lambda\!\!\!^-)^2$, $R > \lambda\!\!\!^-$. The $\frac{1}{2}$ is the contribution of the inelastically scattered neutrons and will be modified by the energy dependency of the detector sensitivity. The other term is due to the diffracted neutrons.[25] The terms f will be larger if elastic scattering from the face of the nucleus is appreciable. Most of the total cross-section work from one to three Mev was corrected for in-scattering under the assumption that $f \simeq 1$. Because of this error, these values are almost always low. In particular, this effect explains the difference between values obtained by Aoki[26] and those measured by Zinn *et al.*[27] $d\Omega/\pi = 0.006$ in Zinn's work and 0.026 for Aoki's measurements. This difference is sufficient to account for the large discrepancies in their results. Proper allowance for this effect was made in the high energy determinations.

[22] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).

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

[24] Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).

[25] G. Placzek and H. A. Bethe, Phys. Rev. **57**, 1075 (1940).

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

[27] Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).

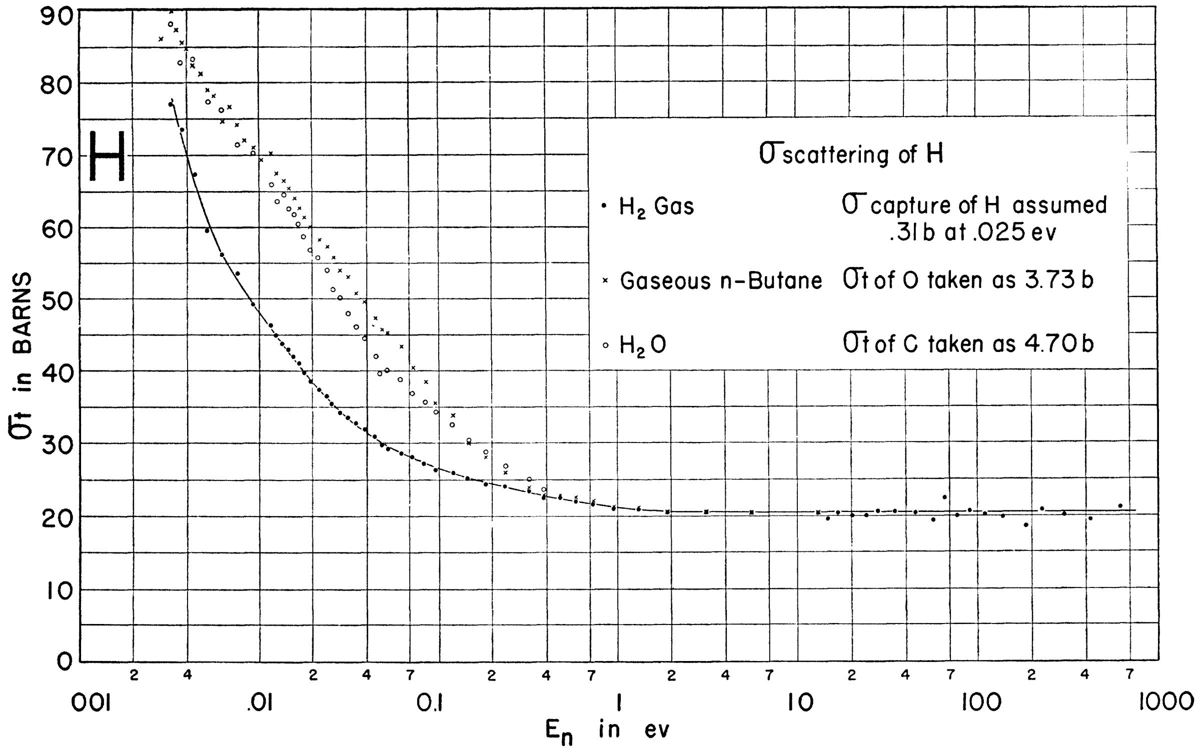


FIG. 1. Edward Melkonian,. Phys. Rev. **76**, 1750 (1949). Also see W. B. Jones, Jr., Phys. Rev. **74**, 364 (1948).

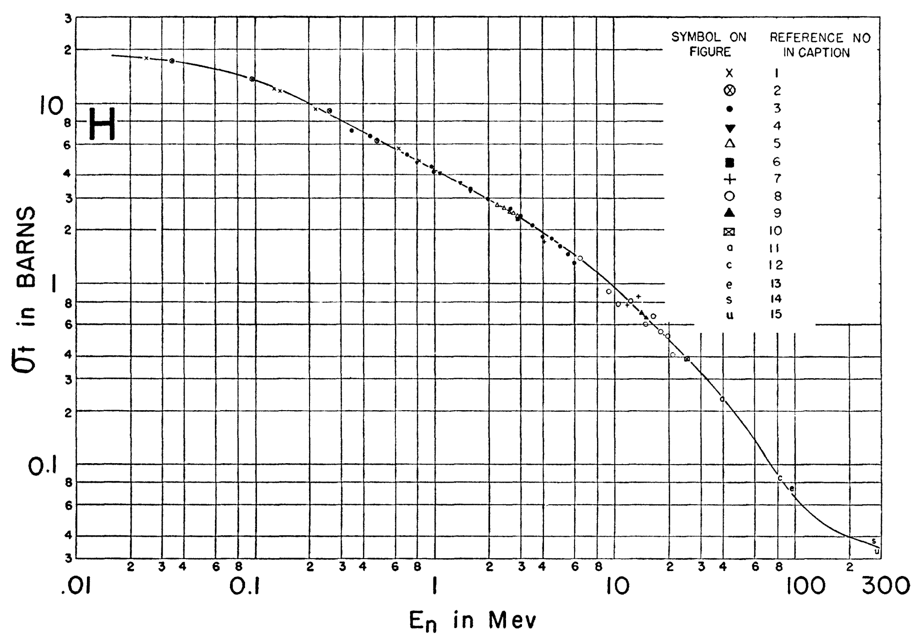


FIG. 2. (1) A. Wattenberg, Phys. Rev. **71**, 497 (1947). (2) D. H. Frisch, Phys. Rev. **70**, 589 (1946). (3) Bailey, Bennett, Bergstralh, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946). (4) Lampi, Freier, and Williams, Phys. Rev. **76**, 188 (1949). (5) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (6) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (7) Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947). (8) W. Sleator, Jr., Phys. Rev. **72**, 207 (1947). (9) E. O. Salant and N. F. Ramsey, Phys. Rev. **57**, 1075 (1940). (10) R. Sherr, Phys. Rev. **68**, 240 (1945). (11) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (12) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (13) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (14) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (15) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

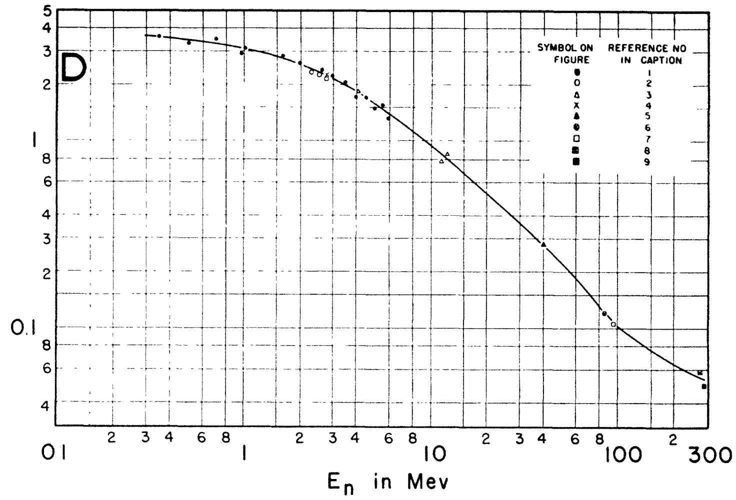


FIG. 3. (1) Nuckolls, Bailey, Bennett, Bergstralh, Richards, and Williams, Phys. Rev. **70**, 805 (1946). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947). (4) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (7) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (8) DeJuren, Knable, and Moyer, Phys. Rev. 589 (1949). (9) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

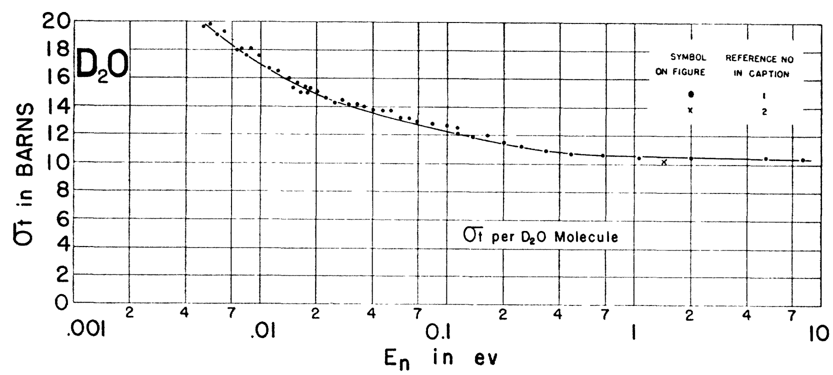


FIG. 4. (1) Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948). (2) J. Marshall, Phys. Rev. **70**, 107 (1946).

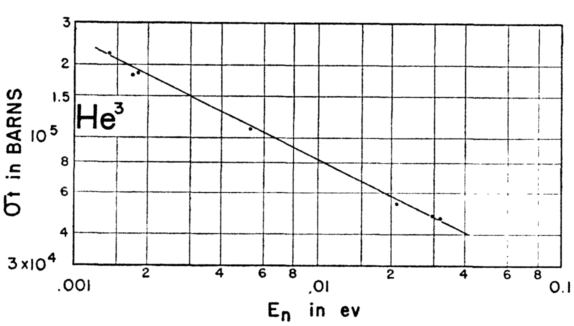


FIG. 5. L. D. P. King and L. Goldstein, Phys. Rev. **75**, 1366 (1949).

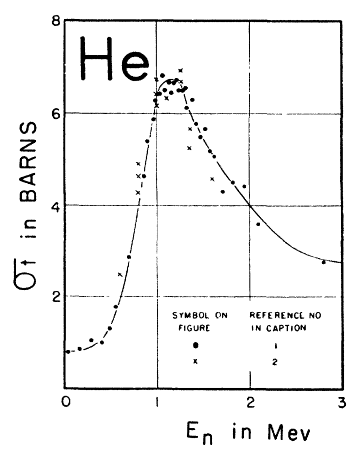


FIG. 6. (1) Bashkin, Petree, Mooring, and Peterson, Phys. Rev. **77**, 748 (1950). (2) T. A. Hall and P. G. Koontz, Phys. Rev. **72**, 196 (1947).

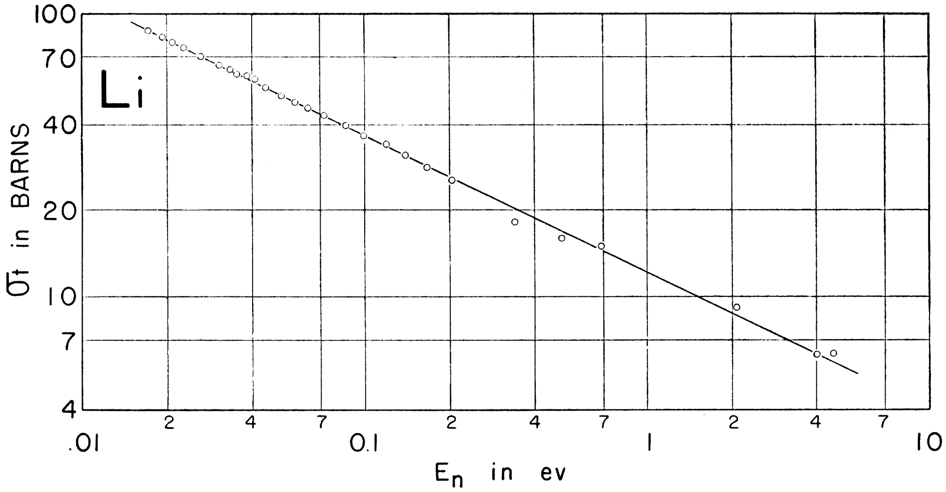


FIG. 7. W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **70**, 154 (1946).

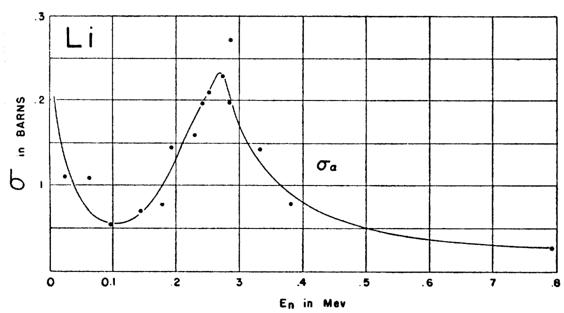


FIG. 8. J. M. Blair *et al.* (unpublished).

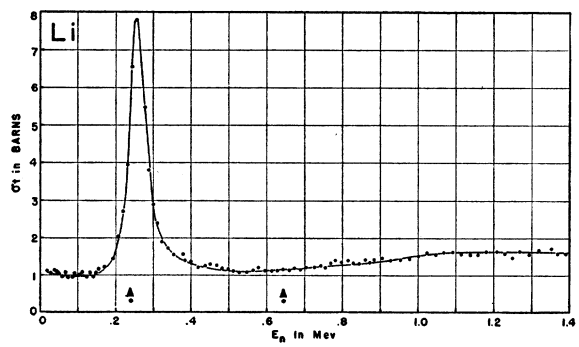


FIG. 9. R. K. Adair, Phys. Rev. (to be published).

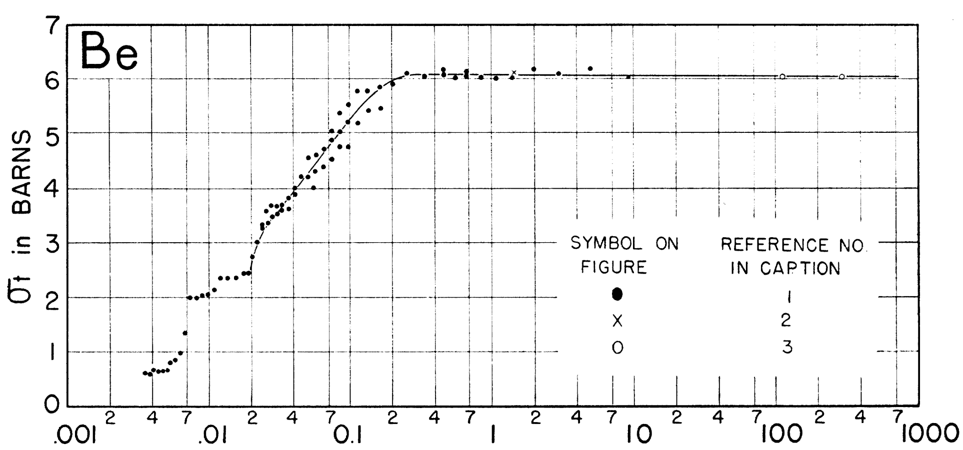


FIG. 10. (1) Columbia Velocity Selector (unpublished). (2) J. Marshall, Phys. Rev. **70**, 107 (1946). (3) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

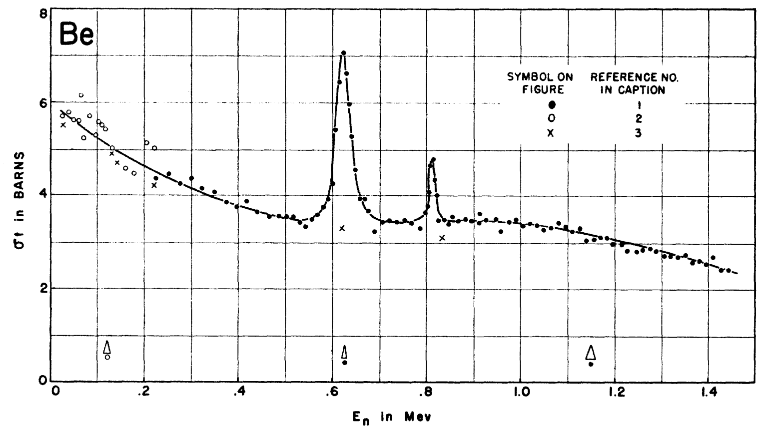


FIG. 11. (1) C. K. Bockelman (unpublished). (2) Adair, Barschall, Bockelman, and Sala, Phys. Rev. **76**, 1124 (1949). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

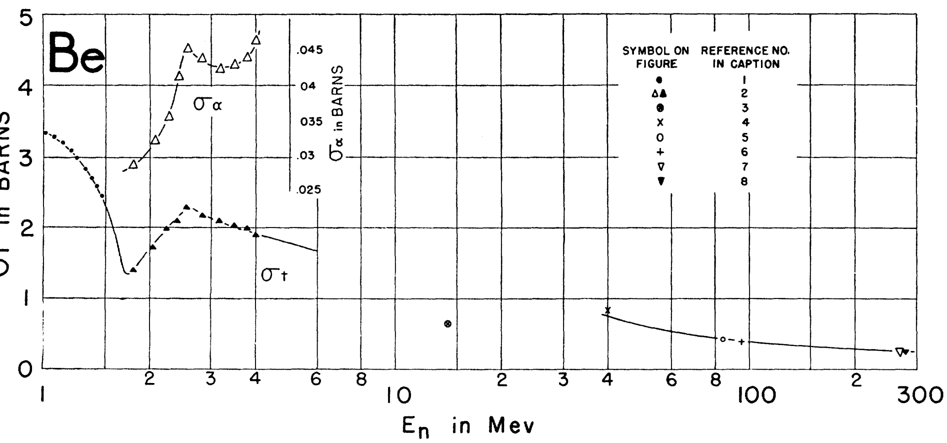


FIG. 12. (1) C. K. Bockelman (unpublished). (2) Allen, Burcham, and Wilkinson, Nature **159**, 473 (1947). (3) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (4) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (5) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (6) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (7) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (8) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

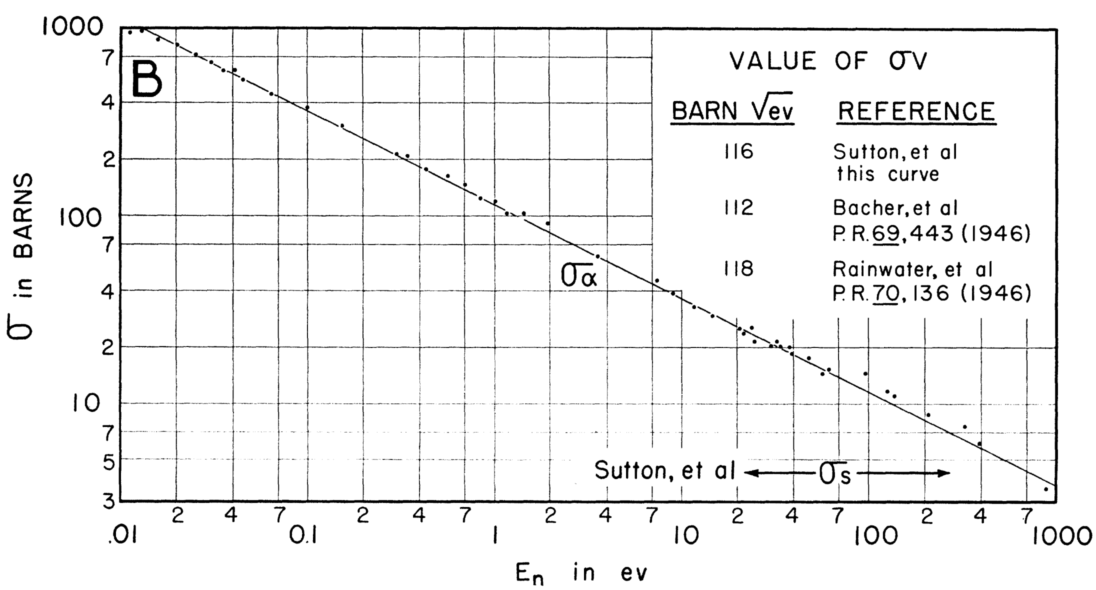


FIG. 13. Sutton, McDaniel, Anderson, and Lavatelli, Phys. Rev. **71**, 272 (1947).

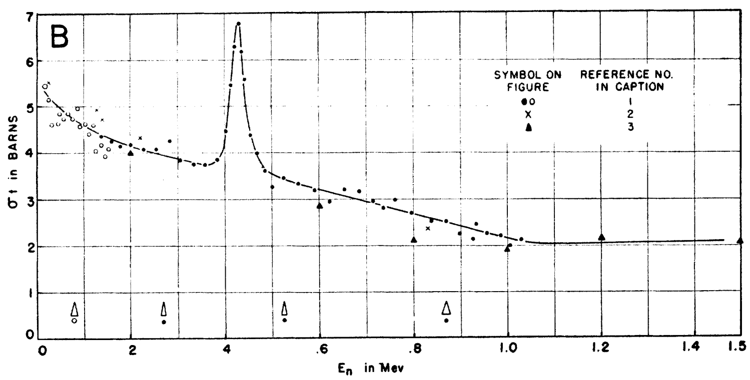


FIG. 14. (1) C. K. Bockelman (unpublished). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). (3) Barschall, Battat, and Bright, Phys. Rev. **70**, 458 (1946).

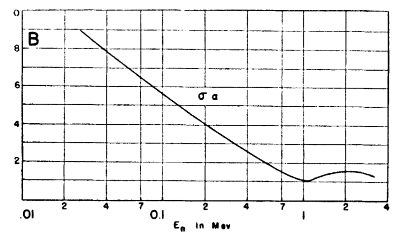


FIG. 15. C. L. Bailey *et al.* (unpublished).

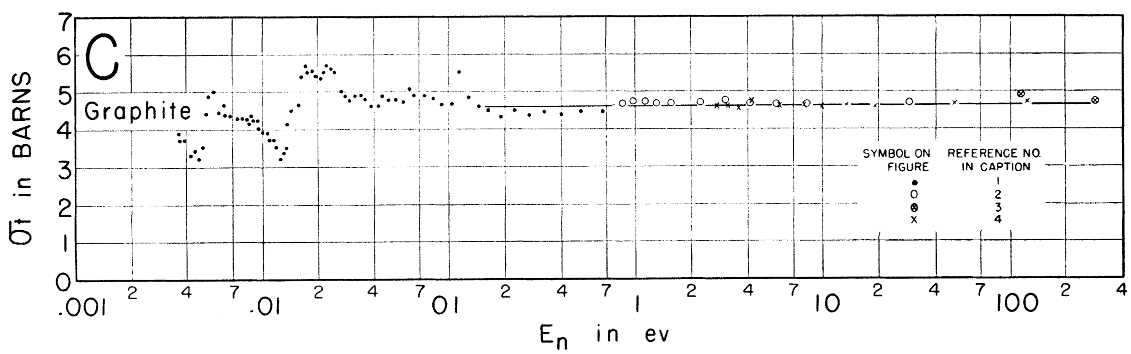


FIG. 16. (1) Columbia Velocity Selector (unpublished). (2) W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949). (3) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (4) W. B. Jones, Jr., Phys, Rev. **74**, 364 (1948).

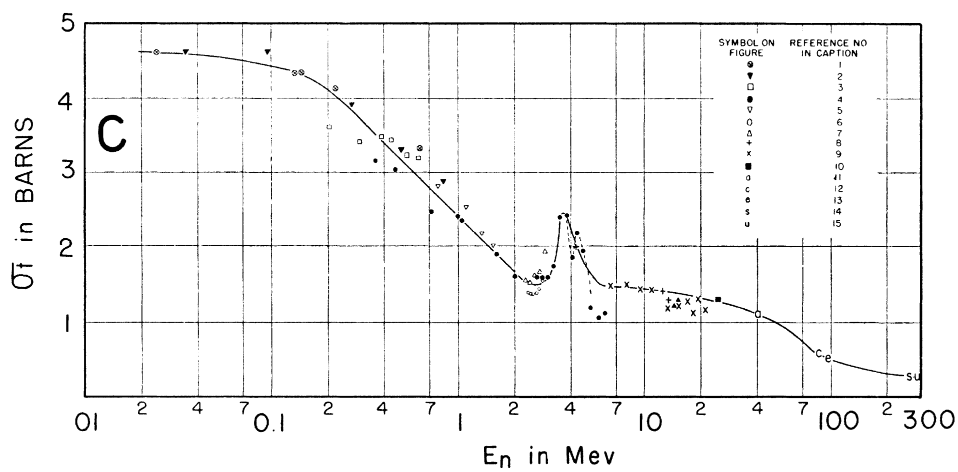


FIG. 17. (1) A. Wattenberg, Phys. Rev. **71**, 497 (1947). (2) D. H. Frisch, Phys. Rev. **70**, 589 (1946). (3) E. Bretscher and E. B. Martin, Helv. Phys. Acta **23**, 15 (1950). (4) Bailey, Bennett, Bergstralh, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946). (5) Lampi, Freier, and Williams, Phys. Rev. **76**, 188 (1949). (6) M. R. MacPhail, Phys. Rev. **57**, 669 (1940). (7) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (8) Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947). (9) W. Sleator, Jr., Phys. Rev. **72**, 207 (1947). (10) R. Sherr, Phys. Rev. **68**, 240 (1945). (11) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (12) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (13) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (14) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (15) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949). Also see Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950); L. L. Green and W. M. Gibson, Proc. Phys. Soc. **62**, 296 (1949) (disintegration cross section); D. W. Miller, Phys. Rev. **78**, 806 (1950).

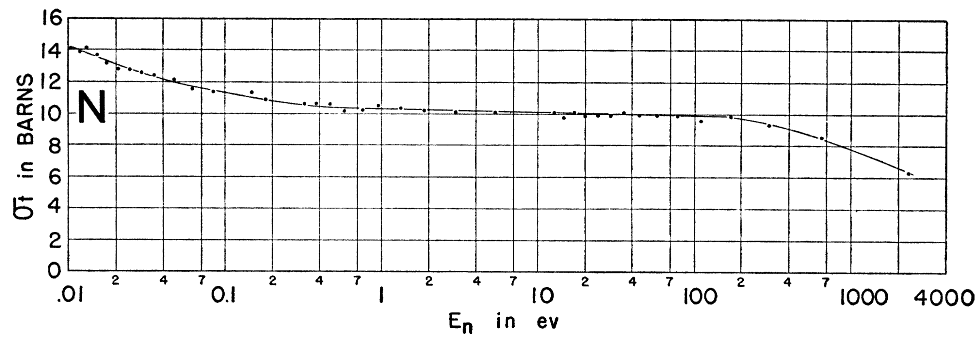


FIG. 18. Melkonian, Rainwater, Havens, and Dunning, Phys. Rev. **73**, 1399 (1948); Edward Melkonian, Phys. Rev. **76**, 1750 (1949).

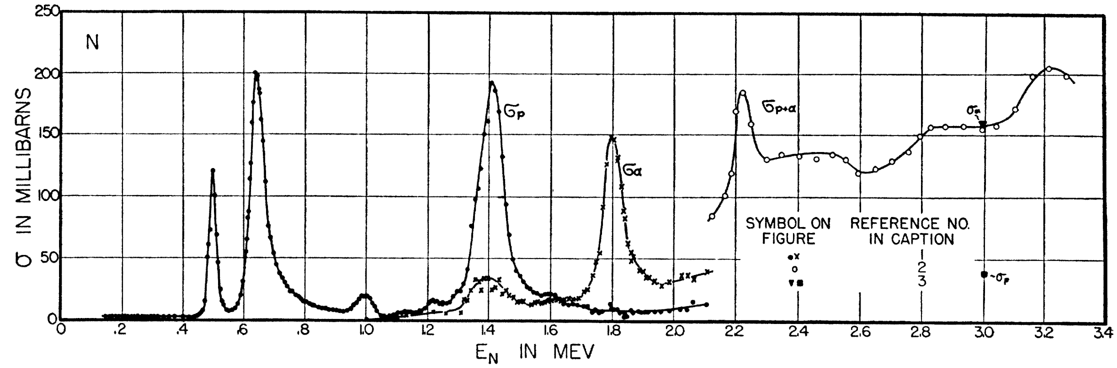


FIG. 19. (1) C. H. Johnson and H. H. Barschall (unpublished). (2) C. P. Sikkema, Nature **162**, 698 (1948). (3) E. Baldinger and P. Huber, Helv. Phys. Acta **12**, 330 (1939).

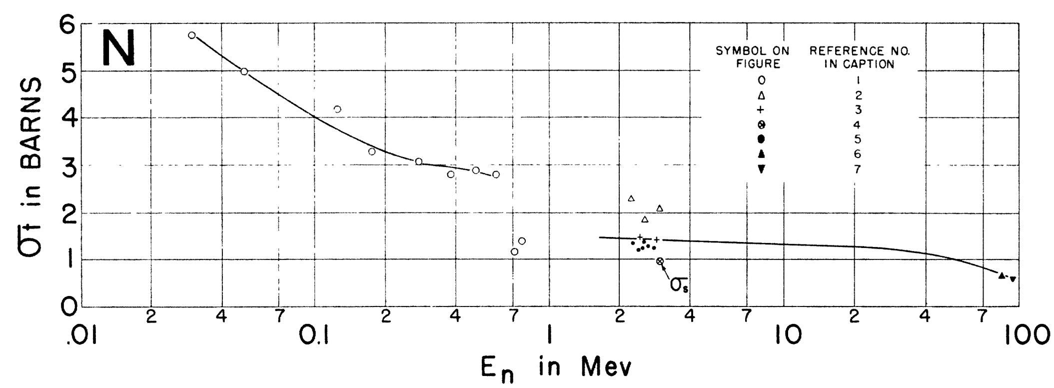


FIG. 20. (1) D. H. Frisch (unpublished). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Huber, Huber, and Sherrer, Helv. Phys. Acta **13**, 209 (1940). (5) M. R. MacPhail, Phys. Rev. **57**, 669 (1940). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (7) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950).

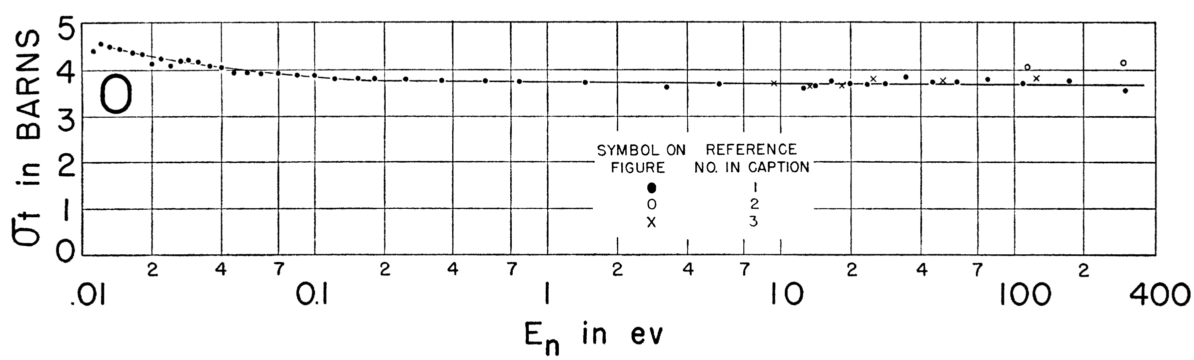


FIG. 21. (1) Edward Melkonian, Phys. Rev. **76**, 1750 (1949); Melkonian, Rainwater, Havens, and Dunning, Phys. Rev. **73**, 1399 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) W. B. Jones, Jr., Phys. Rev. **74**, 364 (1948).

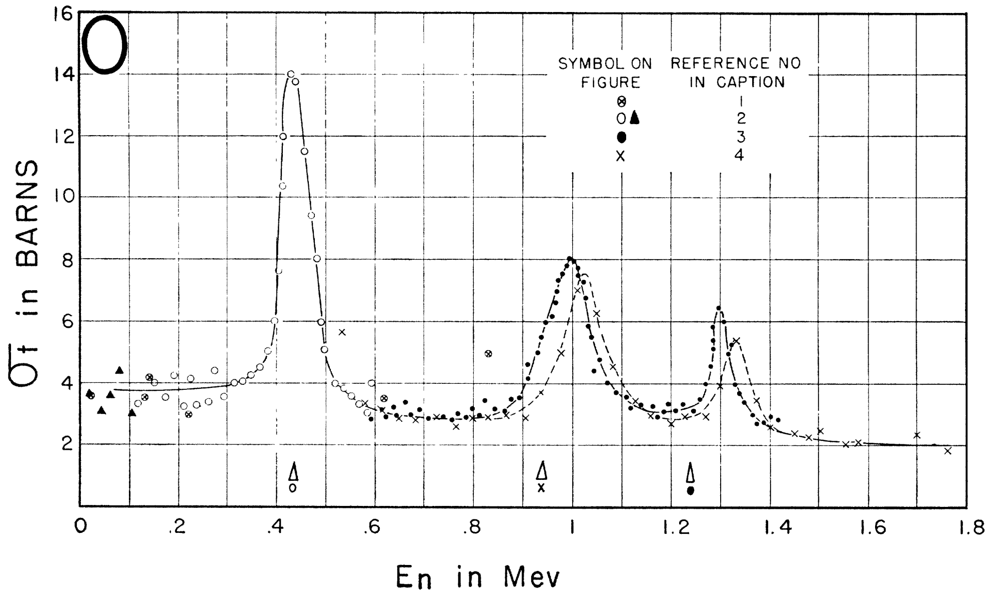


FIG. 22. (1) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). (2) Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949). (3) C. K. Bockelman (unpublished). (4) Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950).

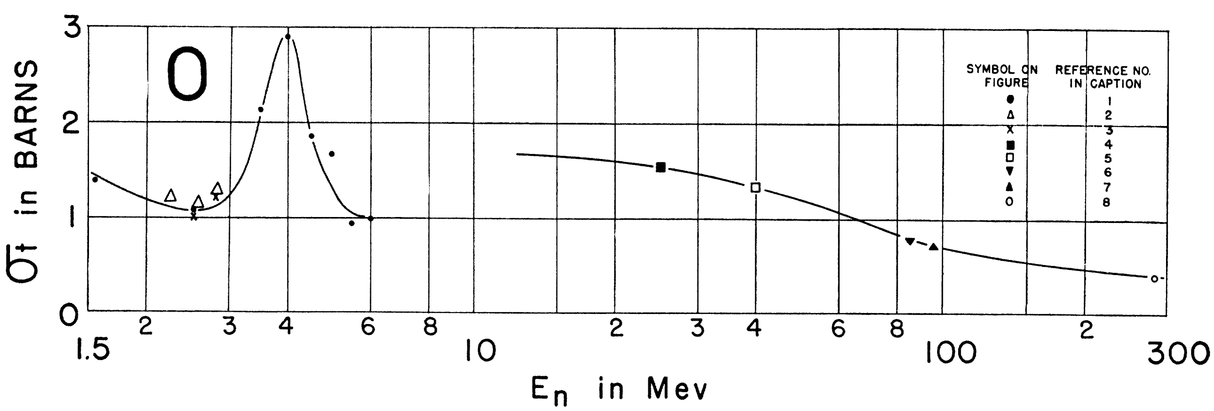


FIG. 23. (1) Nuckolls, Bailey, Bennett, Bergstralh, Richards, and Williams, Phys. Rev. **70**, 805 (1946). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) R. Sherr, Phys. Rev. **68**, 240 (1945). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (7) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (8) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949). Also see Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950).

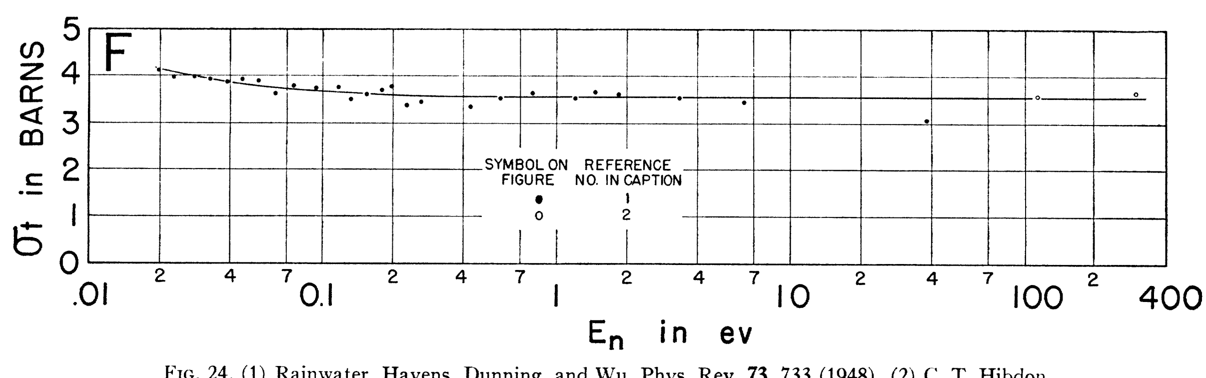


FIG. 24. (1) Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

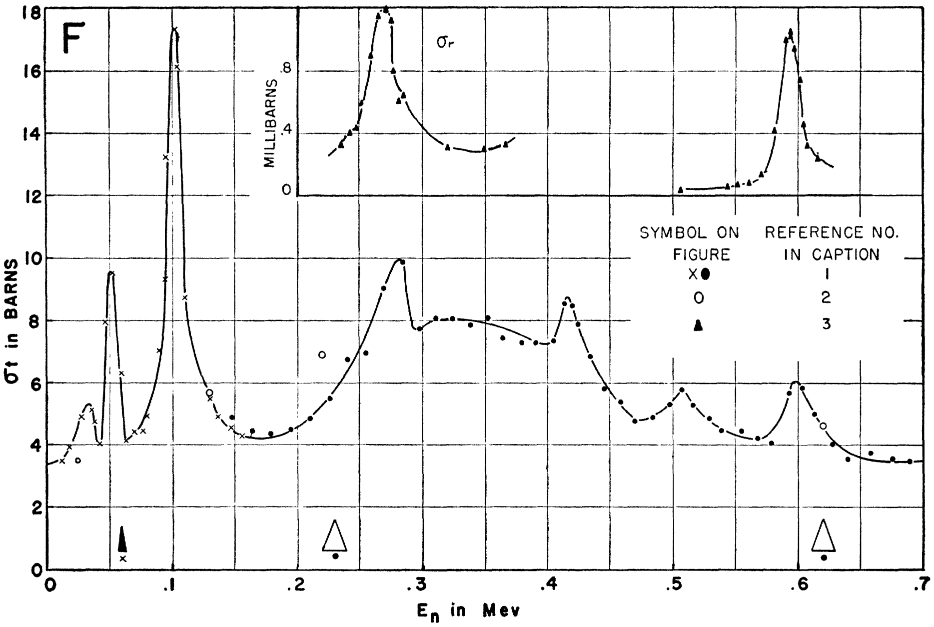


FIG. 25. (1) C. K. Bockelman, Phys. Rev. (to be published). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). (3) R. L. Henkel and H. H. Barschall (unpublished). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).

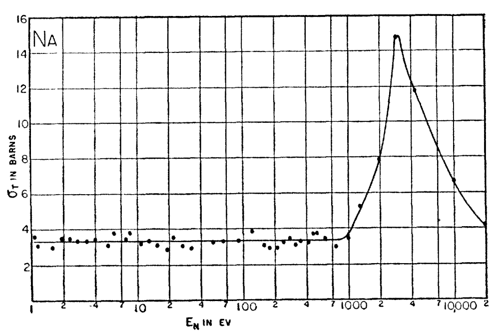


FIG. 26. Hibdon, Muehlhause, Selove, and Woolf, Phys. Rev. **77**, 730 (1950).

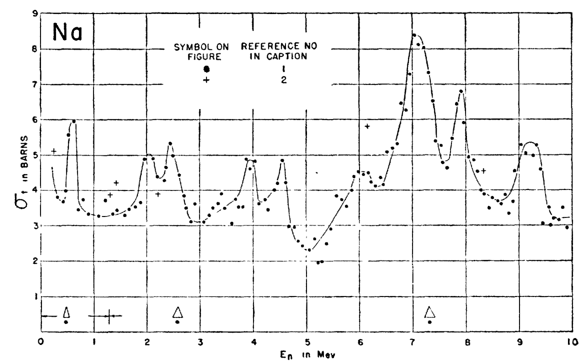


FIG. 27. (1) Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1947); Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).

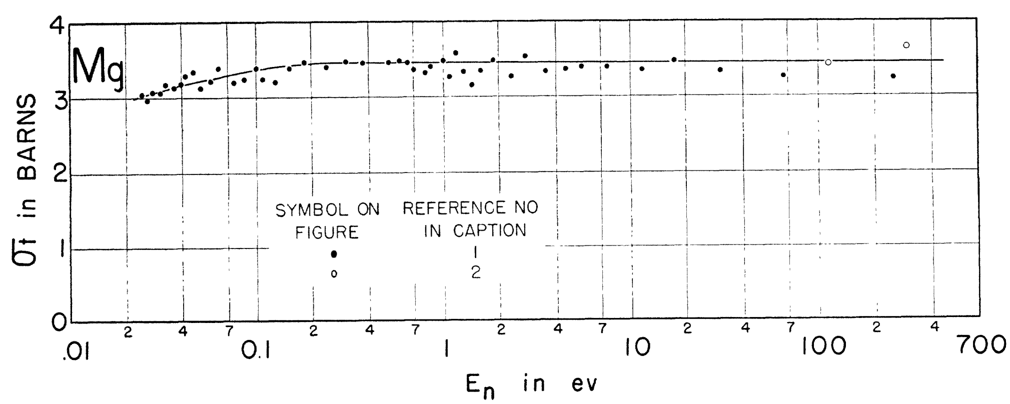


FIG. 28. (1) Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

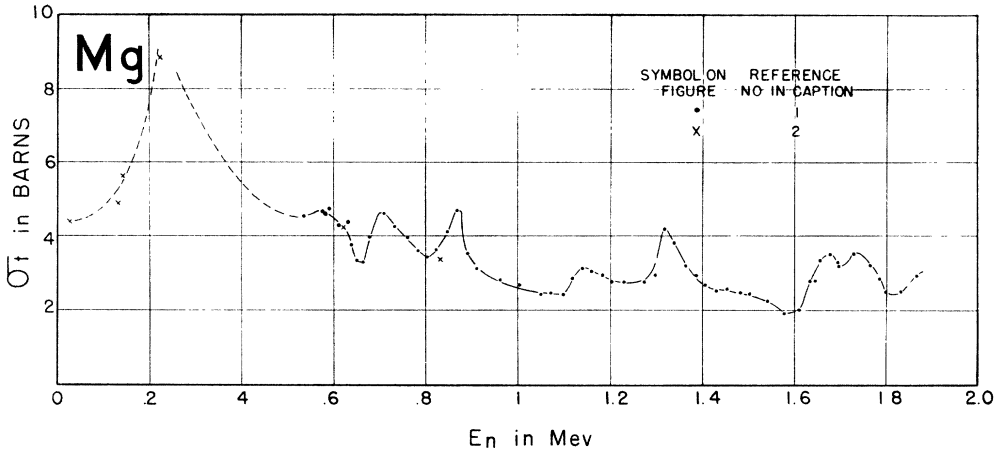


FIG. 29. (1) Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

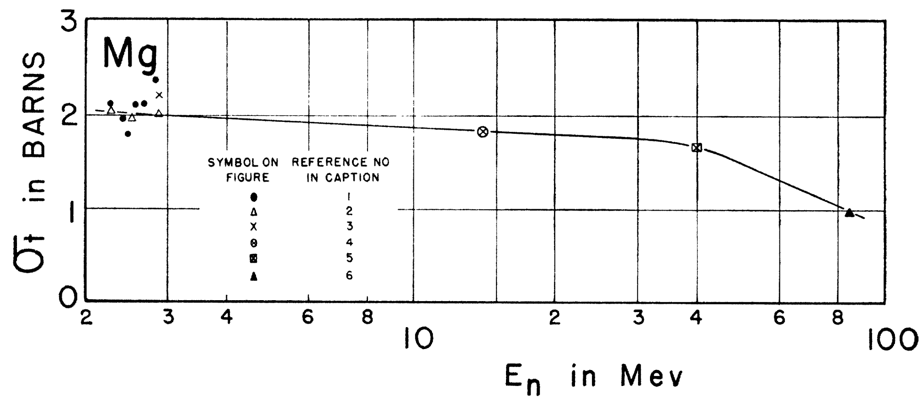


FIG. 30. (1) M. R. MacPhail, Phys. Rev. **57**, 669 (1940). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).

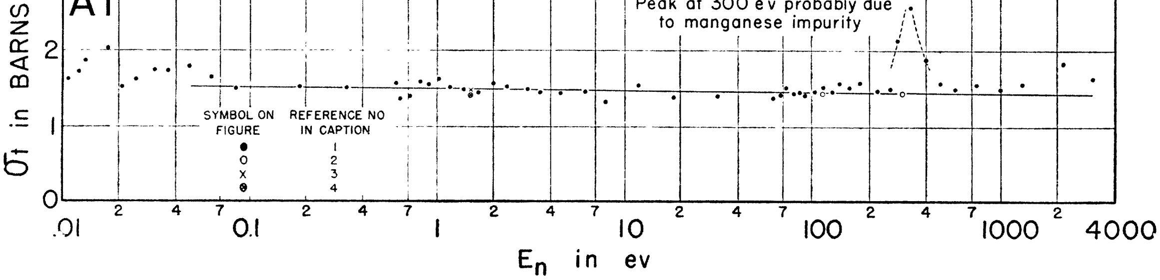


FIG. 31. (1) Columbia Velocity Selector (unpublished); W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **75**, 1399 (1949). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) H. B. Hanstein, Phys. Rev. **59**, 489 (1941). (4) J. Marshall, Phys. Rev. **70**, 107 (1946).

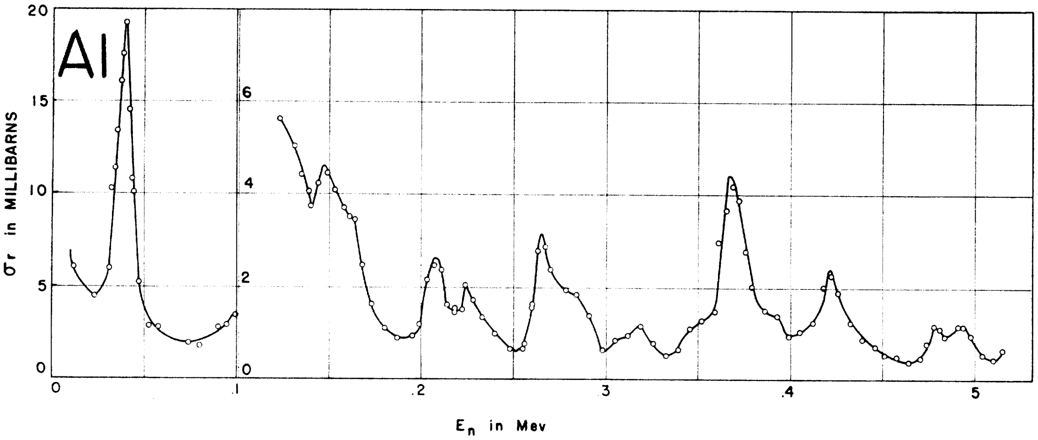


FIG. 32. R. L. Henkel and H. H. Barschall (unpublished). Also see E. Bretscher and D. H. Wilkinson, Proc. Camb. Phil. Soc. **45**, 141 (1949) (σ_p).

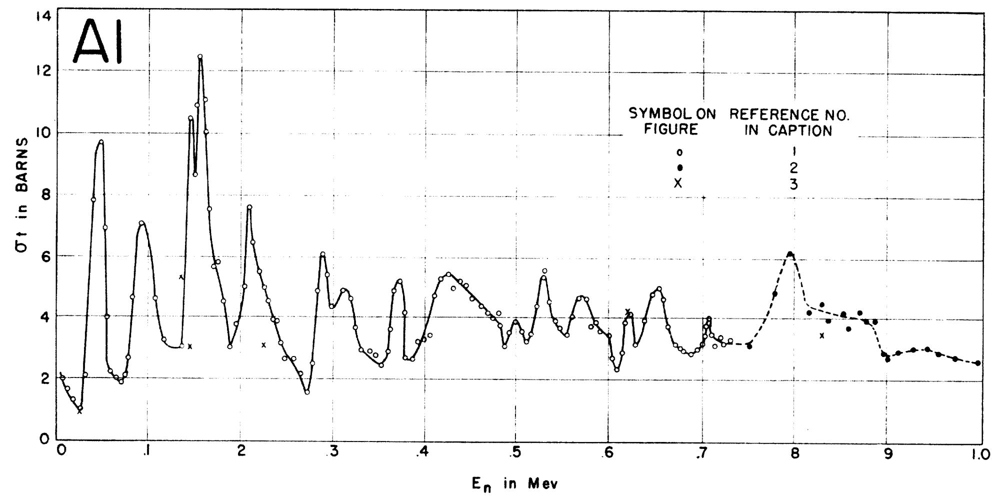


FIG. 33. (1) R. L. Henkel and H. H. Barschall (unpublished). (2) L. W. Seagondollar and H. H. Barschall, Phys. Rev. **72**, 439 (1947). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

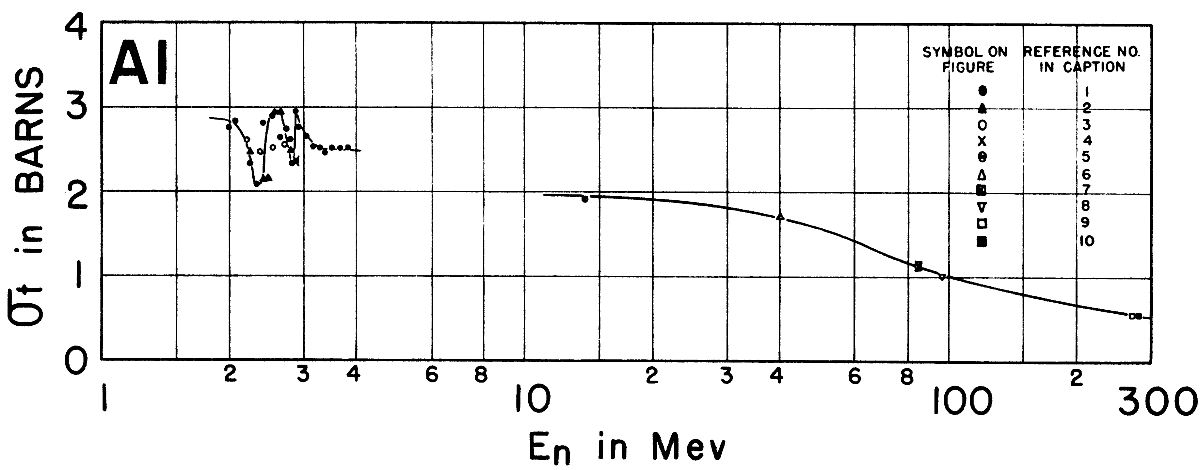


FIG. 34. (1) Allen, Burcham, and Wilkinson, Proc. Roy. Soc. **192**, 114 (1947). (2) M. R. MacPhail, Phys. Rev. **57**, 669 (1940). (3) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (4) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (5) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (6) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (7) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (8) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (9) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (10) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

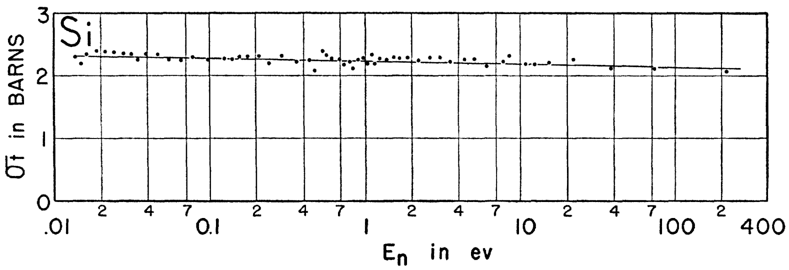


FIG. 35. Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948).

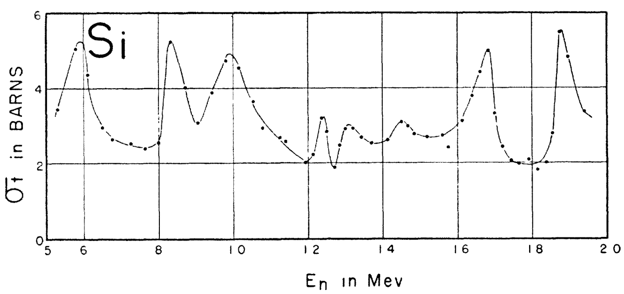


FIG. 36. Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939); Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).

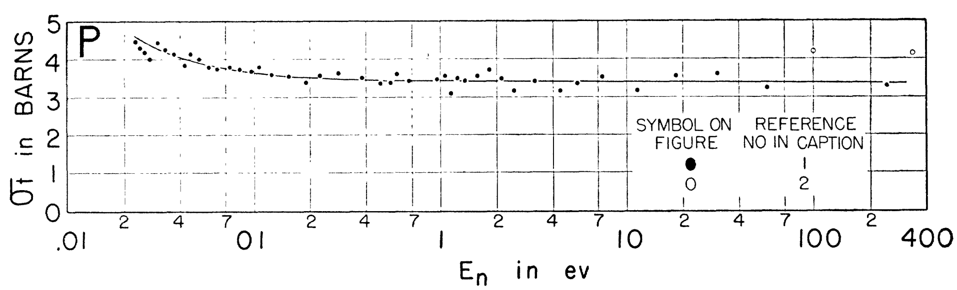


FIG. 37. (1) Columbia Velocity Selector (unpublished). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

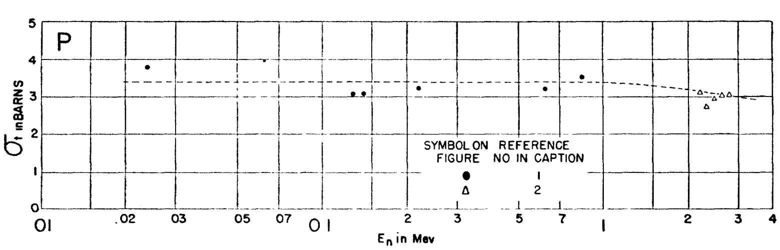


FIG. 38. (1) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). Also see E. Bretscher and D. H. Wilkinson, Proc. Camb. Phil. Soc. **45**, 141 (1949) (σ_p).

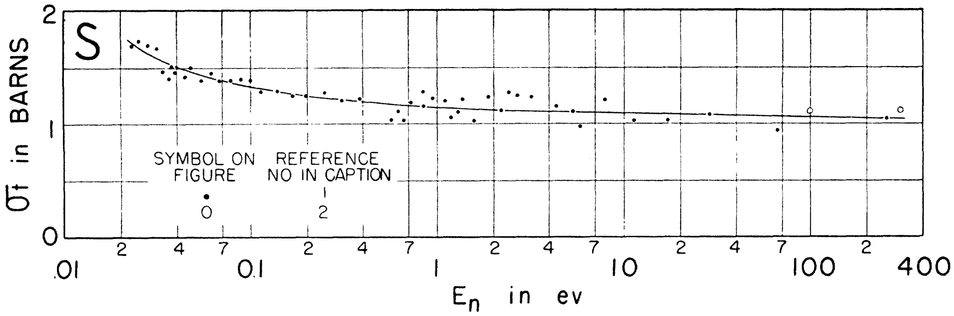


FIG. 39. (1) Rainwater, Havens, Dunning, and Wu, Phys. Rev. **73**, 733 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

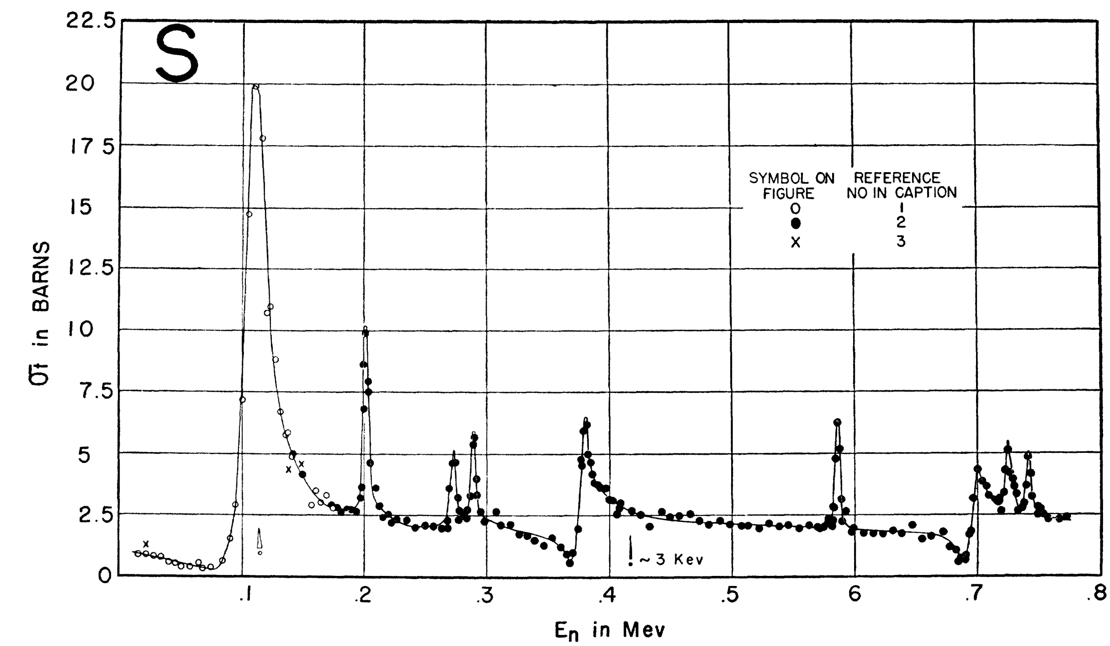


FIG. 40. (1) Adair, Bockelman, and Peterson, Phys. Rev. **76**, 308 (1949). (2) Peterson, Barschall, and Bockelman, Phys. Rev. (to be published). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

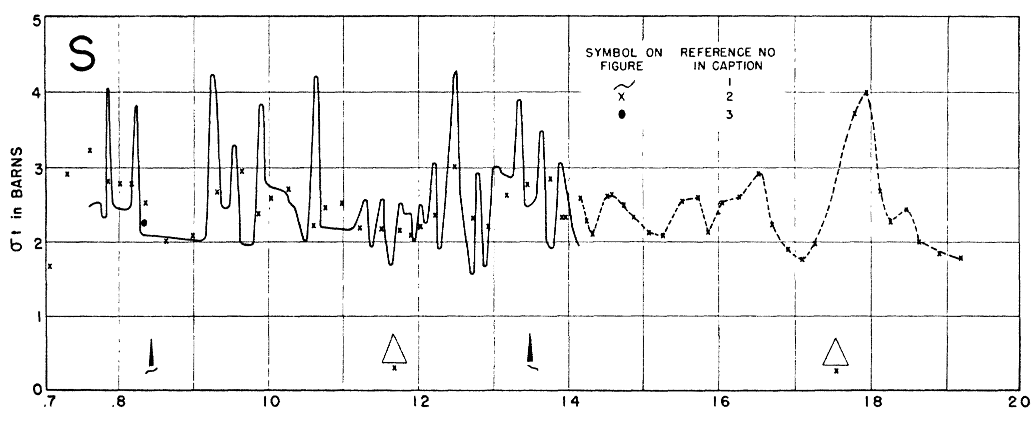


FIG. 41. (1) Peterson, Barschall, and Bockelman, Phys. Rev. (to be published). (2) Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

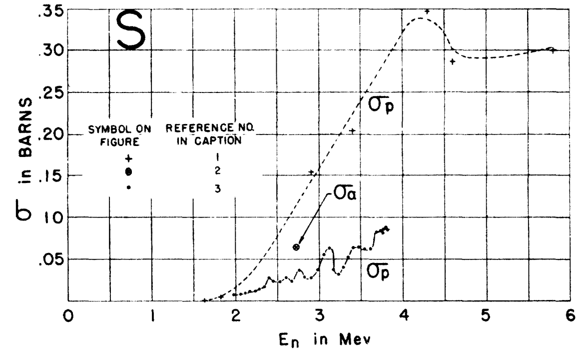


FIG. 42. (1) E. D. Klema and A. O. Hanson, Phys. Rev. **73**, 106 (1948). (2) P. Huber, Helv. Phys. Acta **14**, 163 (1941). (3) E. Bleuler, Helv. Phys. Acta **20**, 519 (1947).

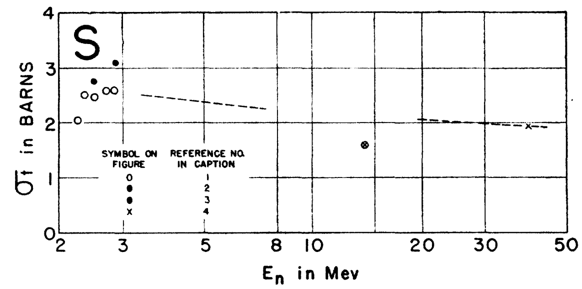


FIG. 43. (1) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (2) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (3) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (4) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).

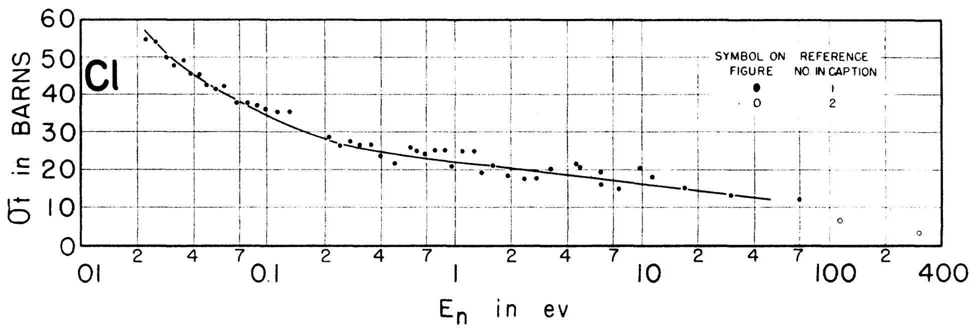


FIG. 44. (1) Columbia Velocity Selector (unpublished). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

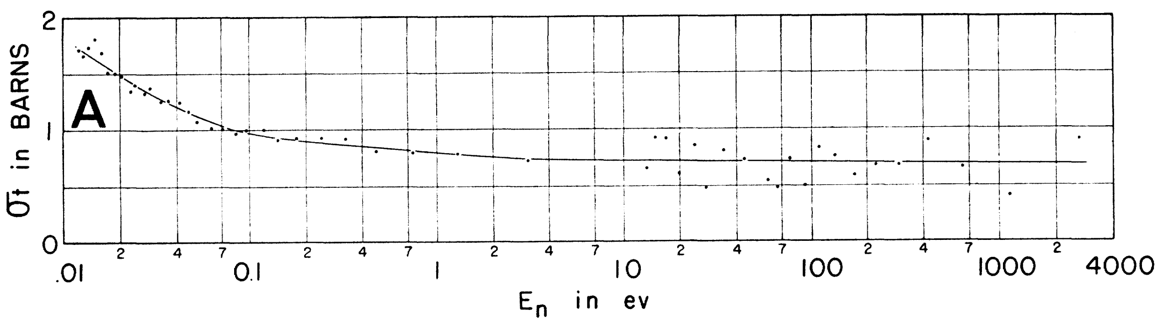


FIG. 45. Edward Melkonian, Phys. Rev. **76**, 1750 (1949); Melkonian, Rainwater, Havens, and Dunning, Phys. Rev. **73**, 1399 (1948).

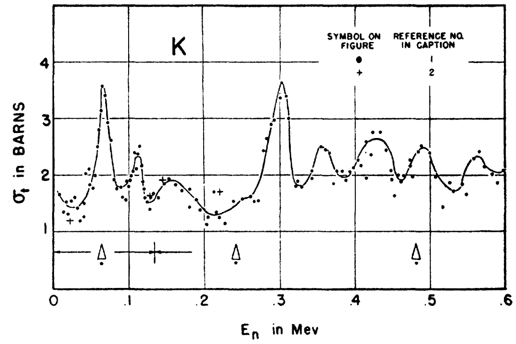


FIG. 46. (1) R. E. Peterson, Phys. Rev. **77**, 747 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1949). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939); Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).

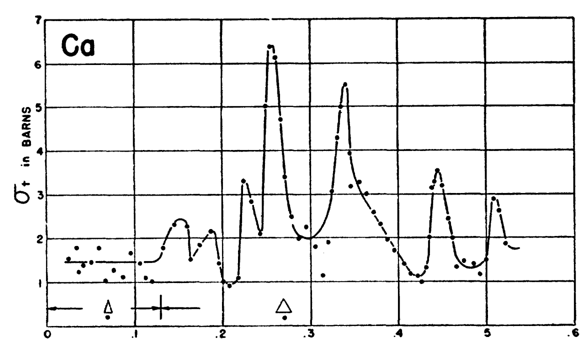


FIG. 47. Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949). Also see C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949) (epithermal cross sections). Also see H. H. Barschall, Am. J. Phys. **15** (1950).

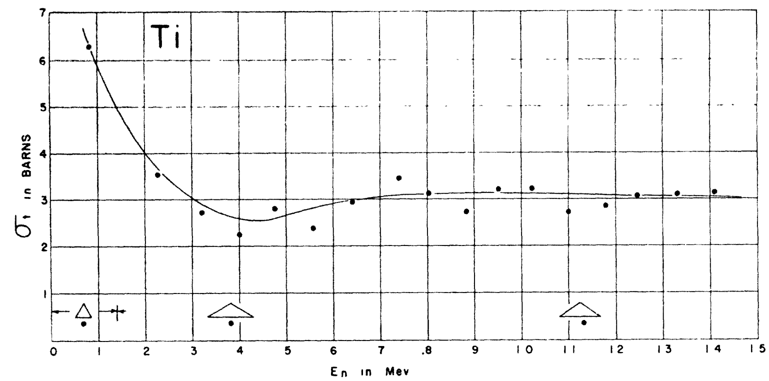


FIG. 48. R. K. Adair, Phys. Rev. **77**, 748 (1950). Also see C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949) (epithermal cross sections).

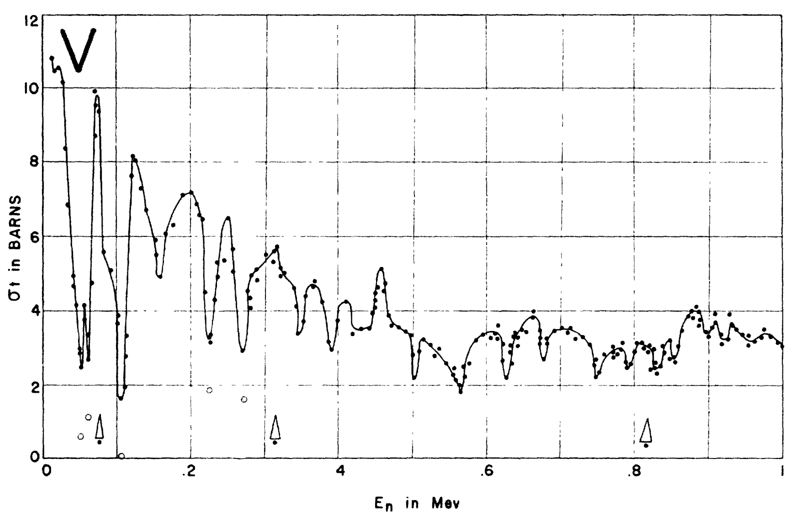


FIG. 49. J. M. Blair and J. R. Wallace, Phys. Rev. **79**, 28 (1950).

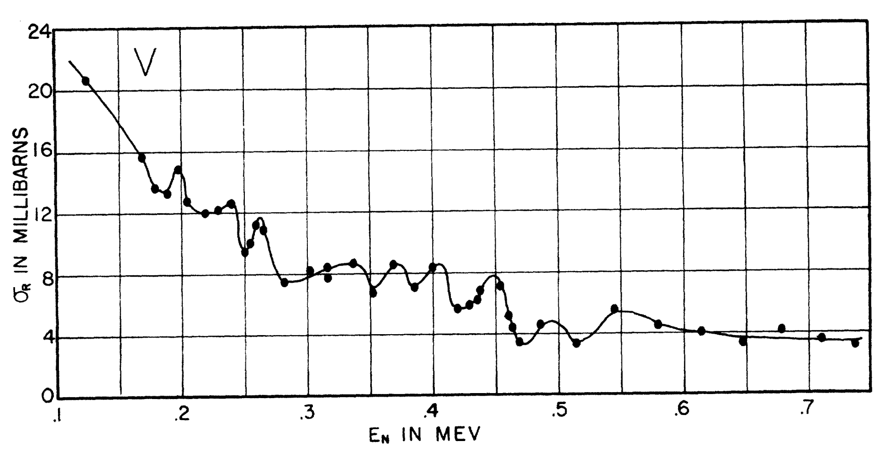


FIG. 50. R. L. Henkel and H. H. Barschall (unpublished).

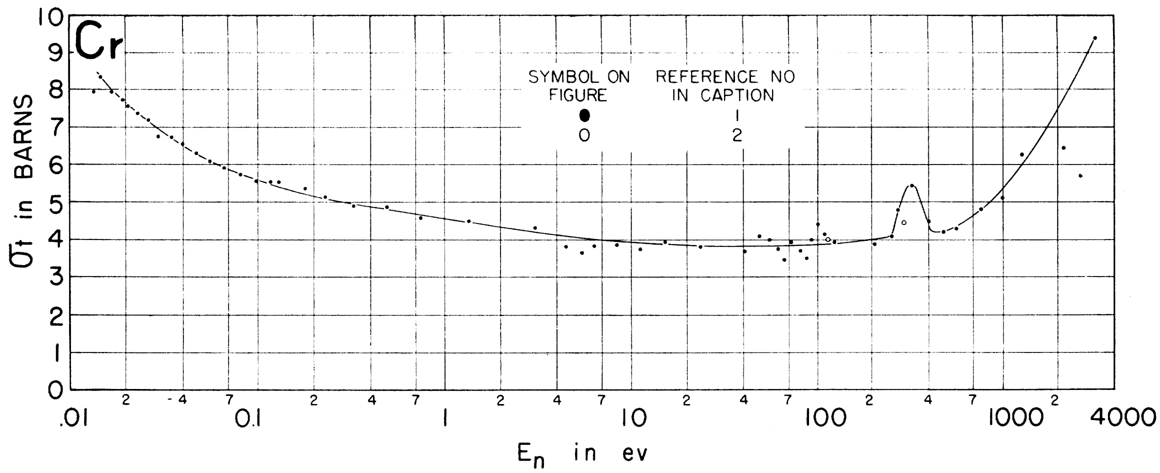


FIG. 51. (1) Columbia Velocity Selector (unpublished); W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

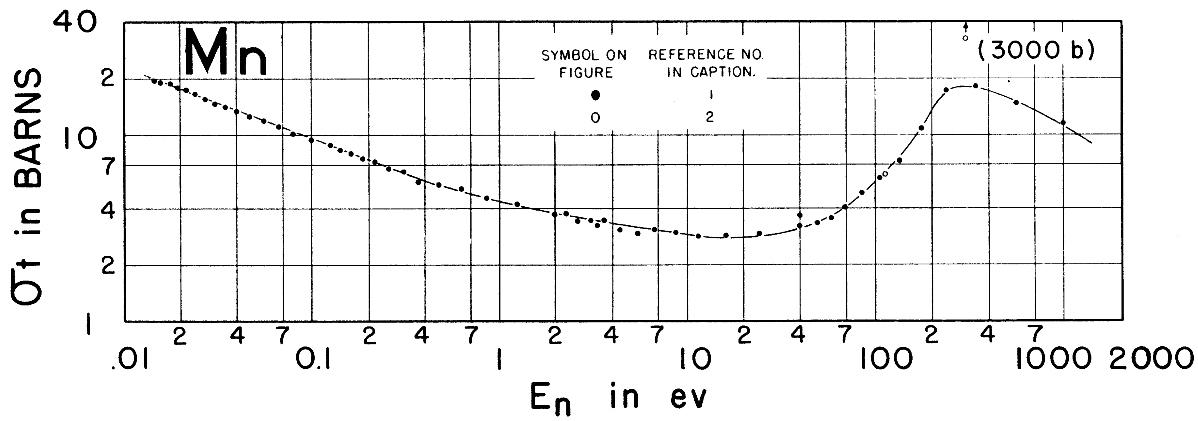


FIG. 52. (1) Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

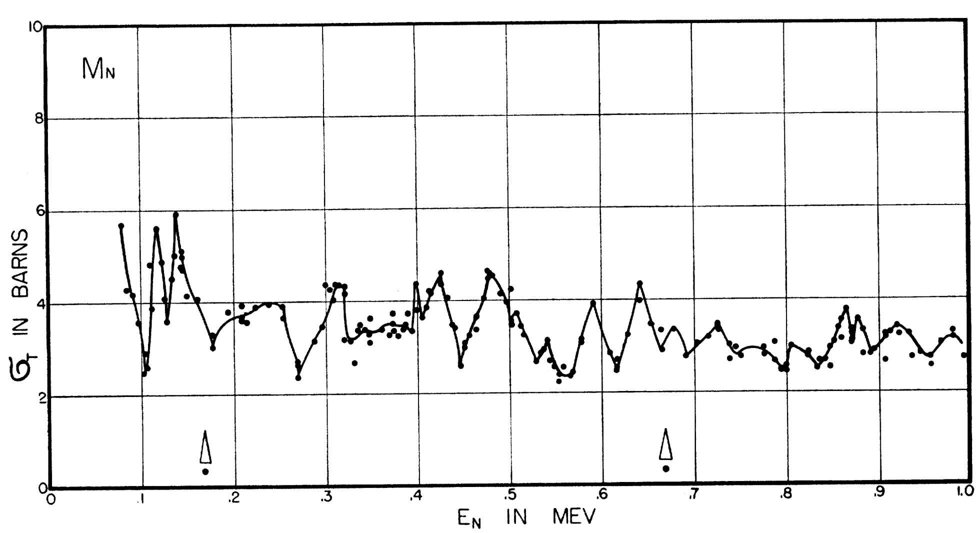


FIG. 53. W. F. Stubbins *et al.* (unpublished).

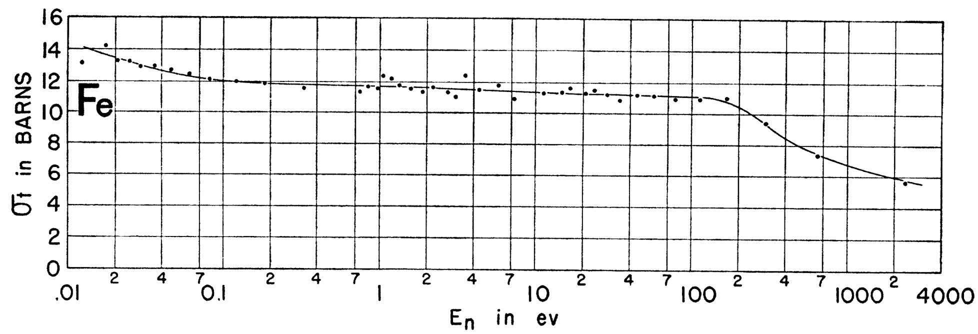


FIG. 54. Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948); W. W. Havens, Jr., and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949).

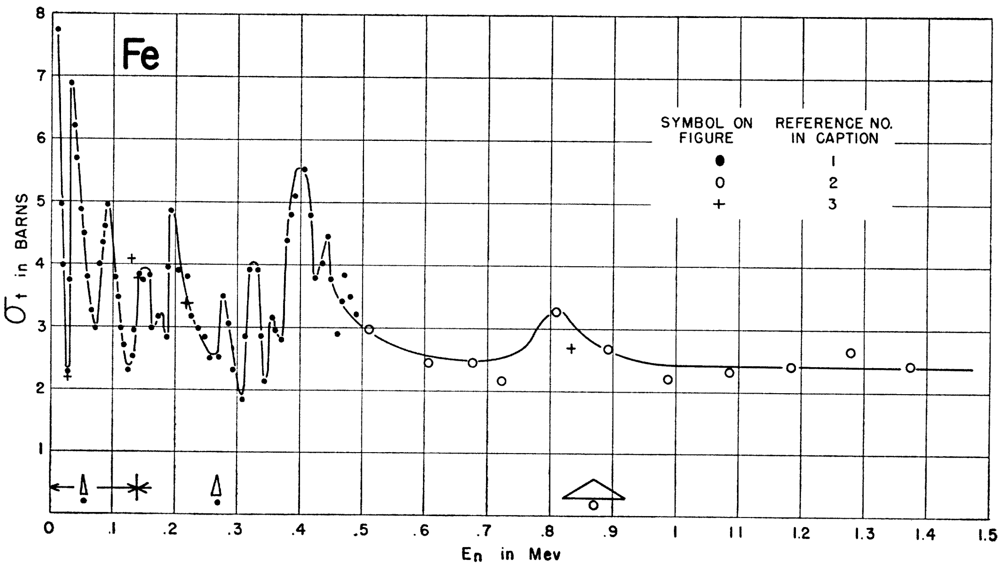


FIG. 55. (1, 2) Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). Also see H. H. Barschall, Am. J. Phys. **15** (1950).

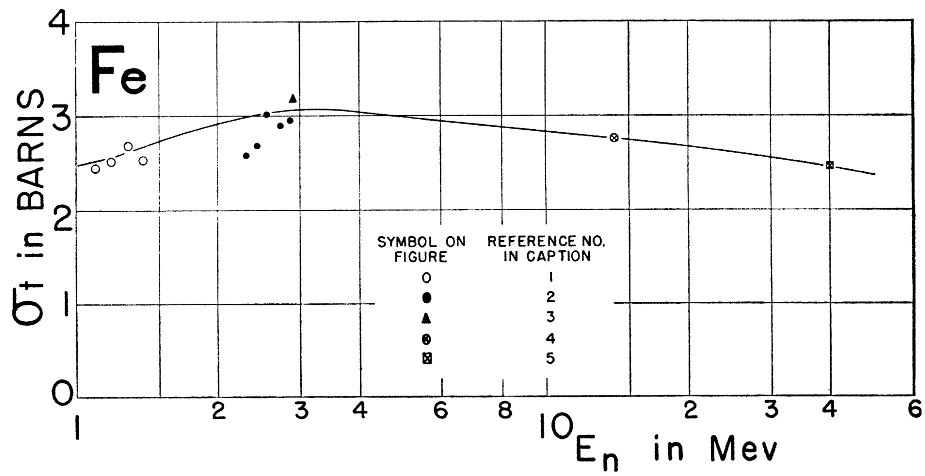


FIG. 56. (1) Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).

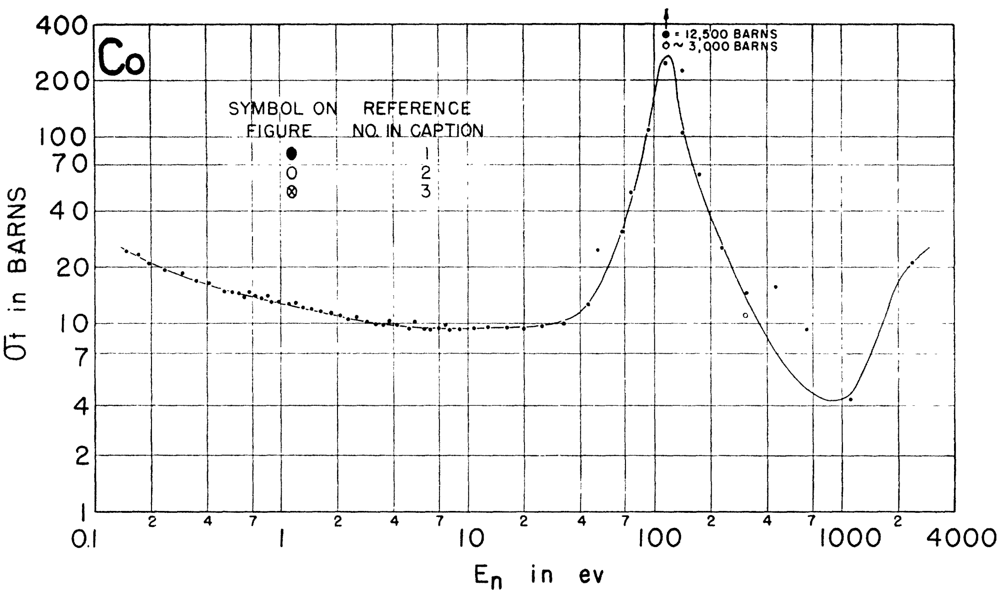


FIG. 57. (1) Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) F. G. P. Seidl, Phys. Rev. **75**, 1508 (1949).

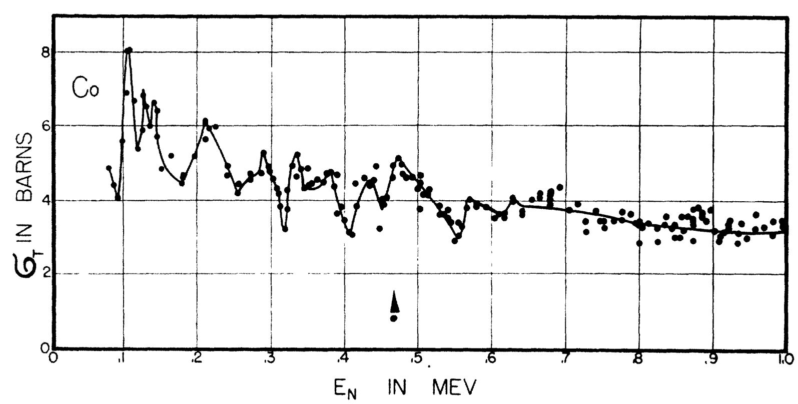


FIG. 58. W. F. Stubbins *et al.* (unpublished).

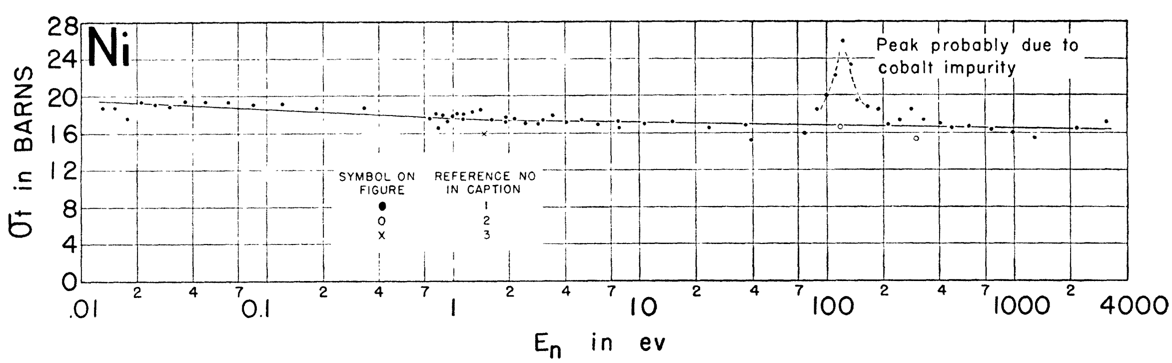


FIG. 59. (1) Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948); W. W. Havens and L. J. Rainwater, Phys. Rev. **75**, 1296 (1949). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) H. B. Hanstein, Phys. Rev. **59**, 489 (1941).

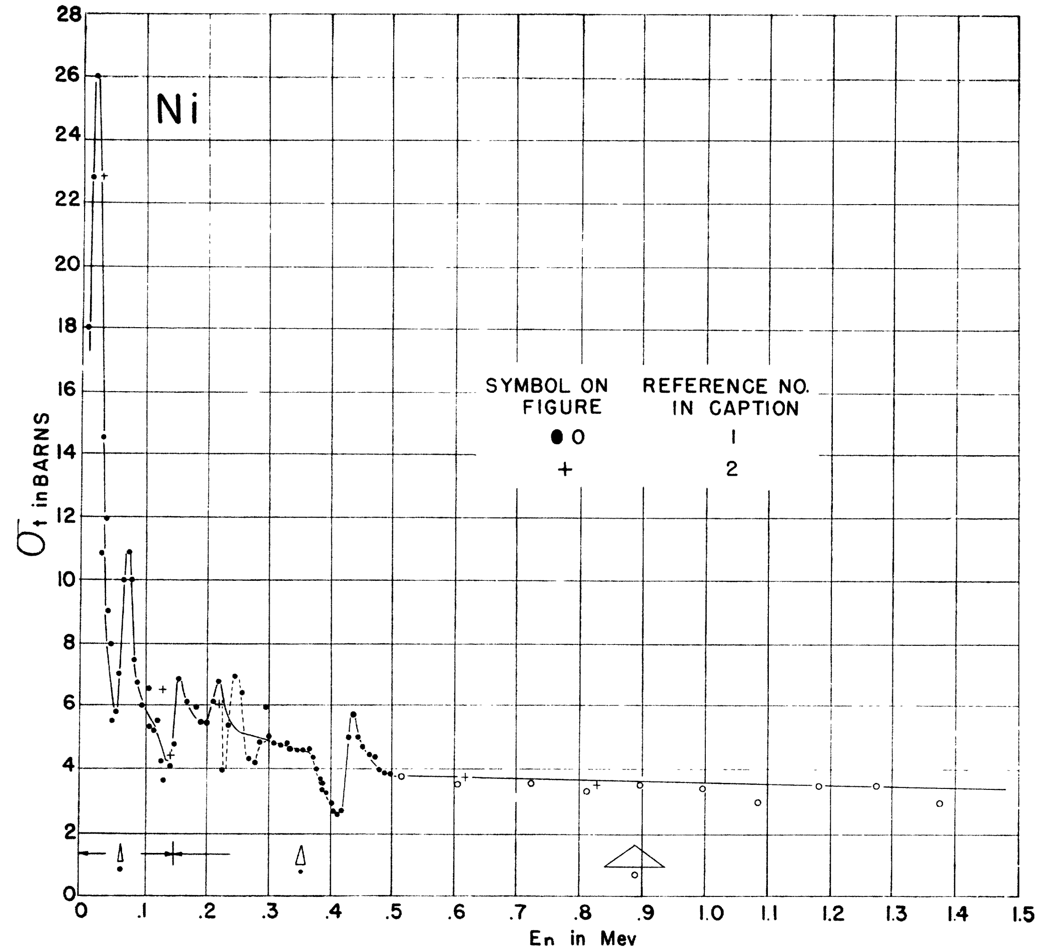


FIG. 60. (1) Barschall, Bockelman, and Seagondollar, Phys. Rev. **70**, 659 (1948). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

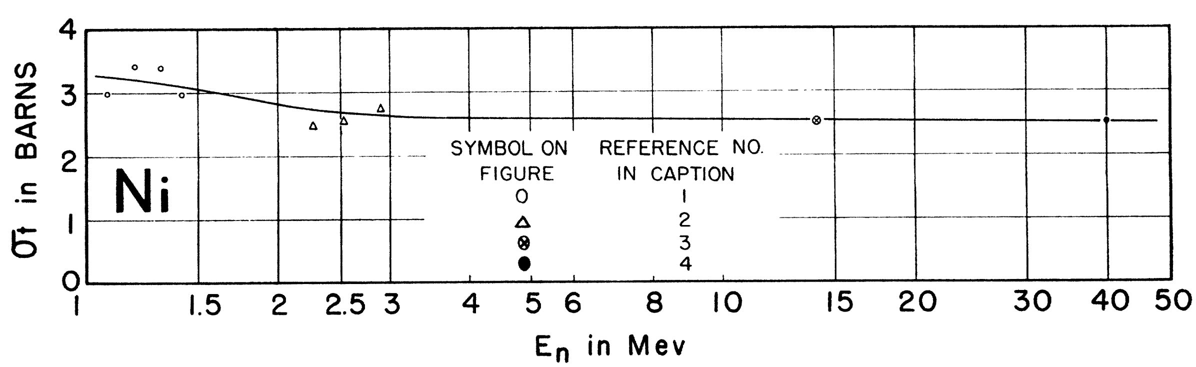


FIG. 61. (1) Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (4) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).

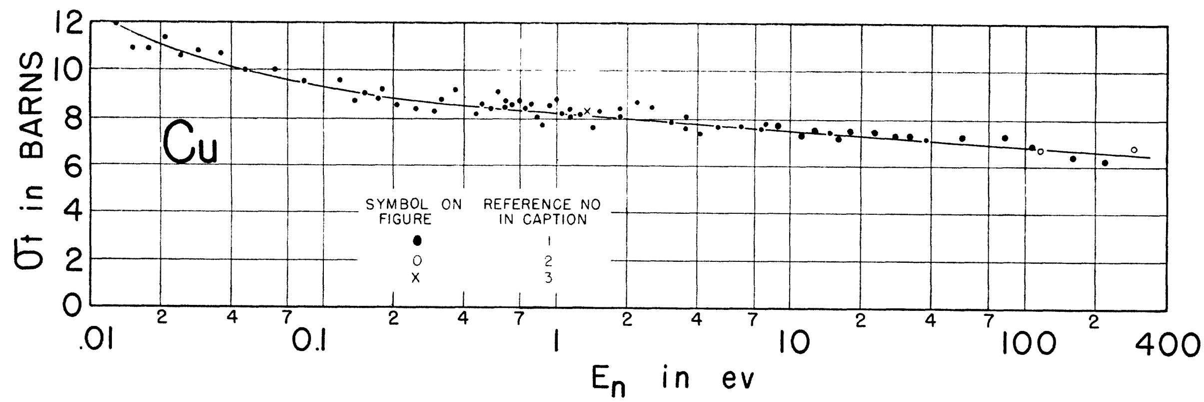


FIG. 62. (1) Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) H. B. Hanstein, Phys. Rev. **59**, 489 (1941).

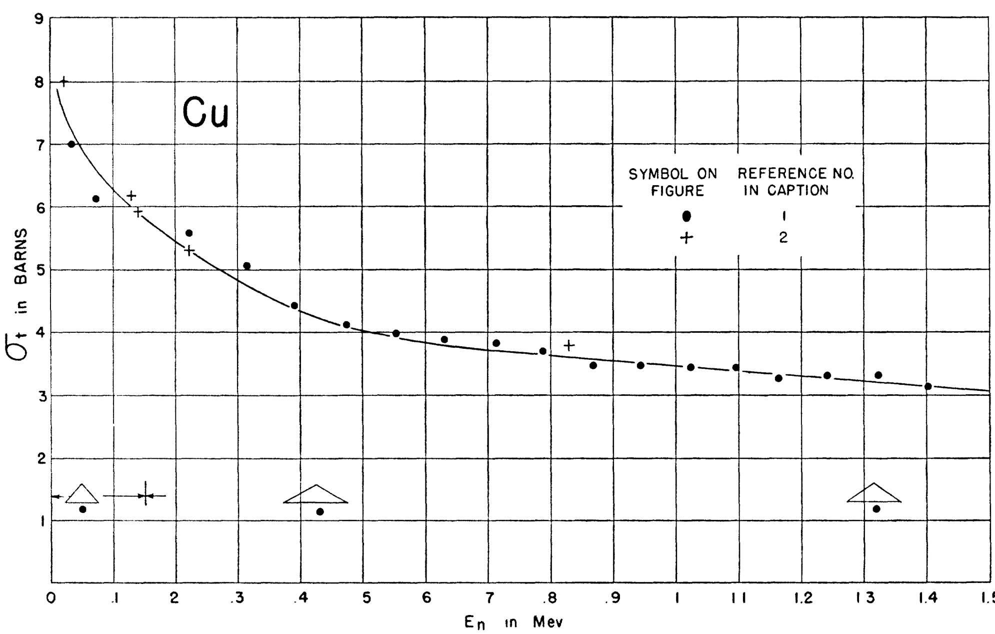


FIG. 63. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

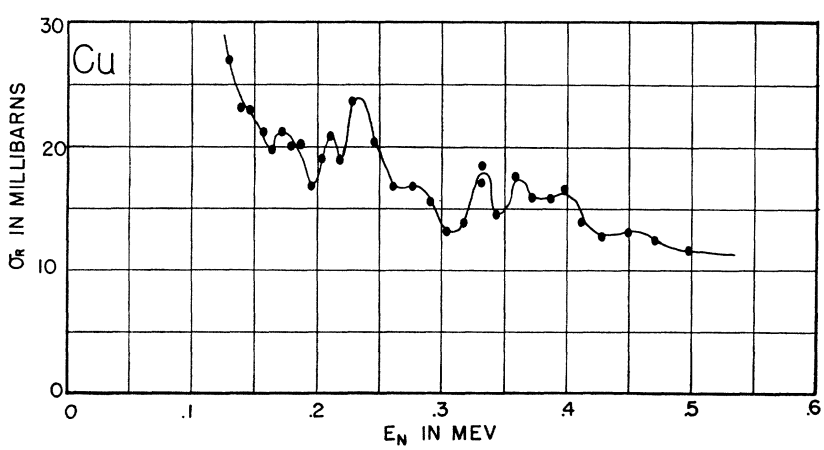


FIG. 64. R. L. Henkel and H. H. Barschall (unpublished). Also see E. Bretsher and D. H. Wilkinson, Proc. Camb. Phil. Soc. **45**, 141 (1949) (σ_p).

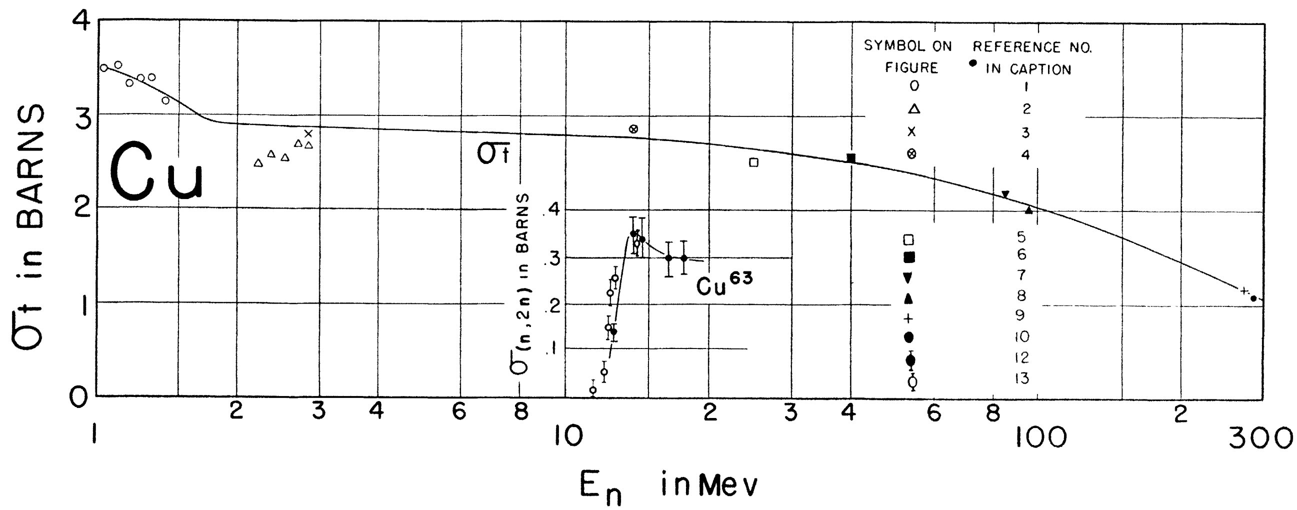


FIG. 65. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. Sherr, Phys. Rev. **68**, 240 (1945). (6) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (7) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (8) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (9) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (10) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949). (12) H. T. Gittings *et al.*, Los Alamos (unpublished). (13) J. L. Fowler and J. M. Slye, Jr., Phys. Rev. **77**, 788 (1950).

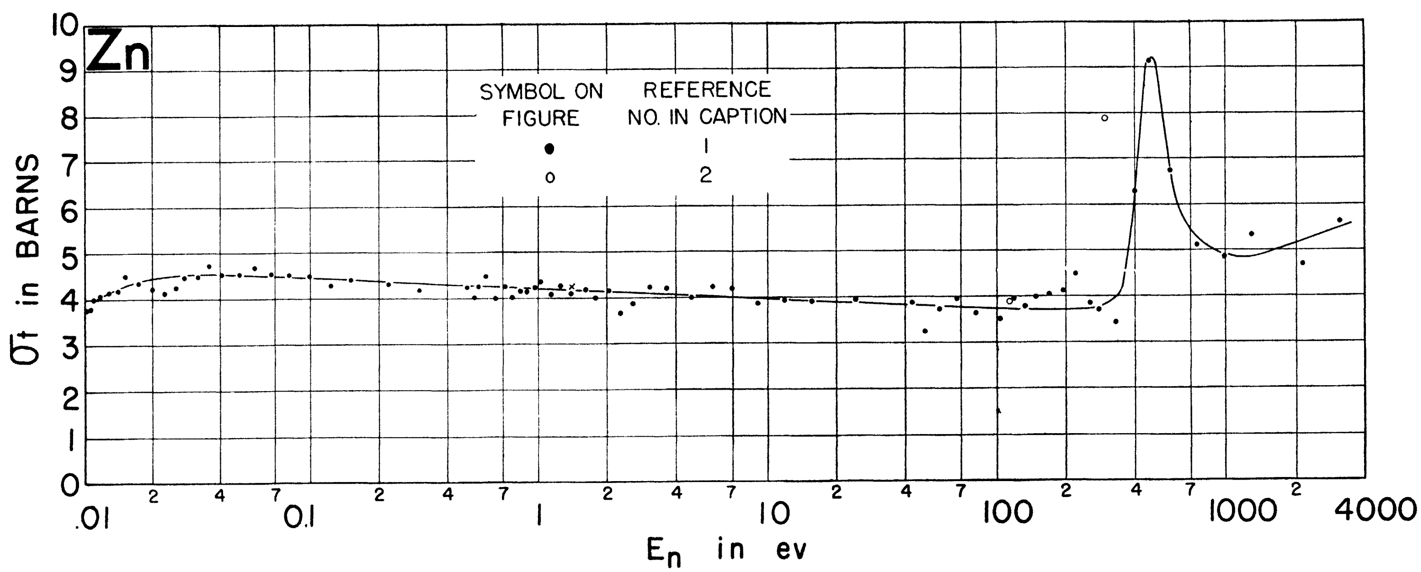


FIG. 66. (1) Columbia Velocity Selector (unpublished). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

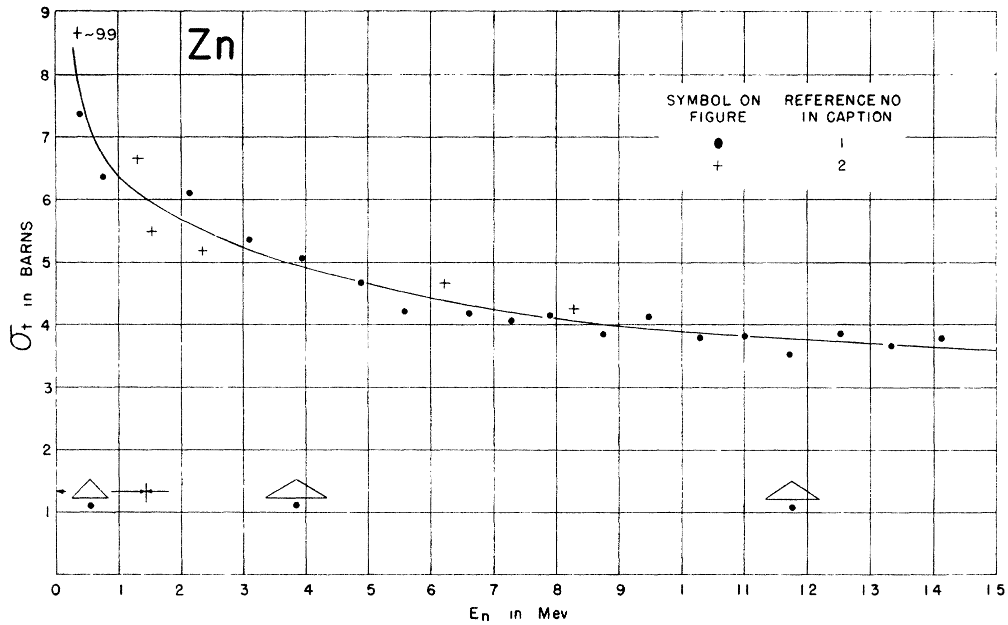


FIG. 67. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

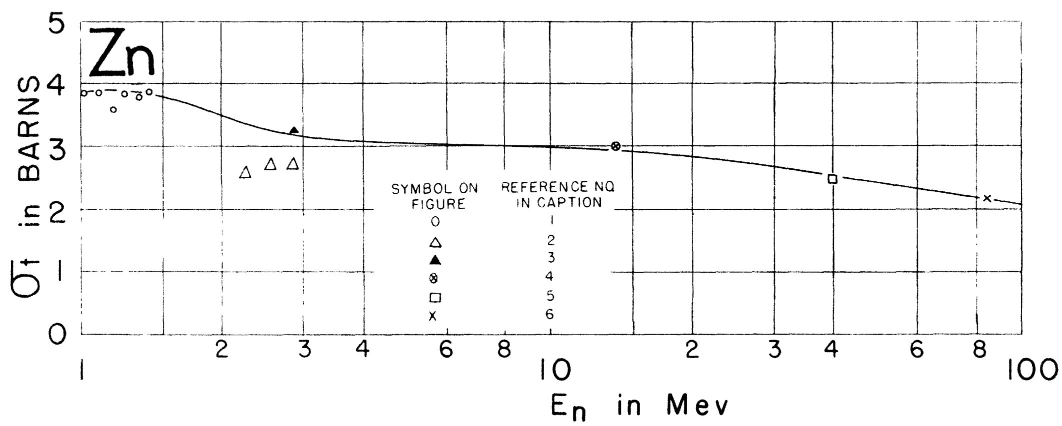


FIG. 68. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). Also see E. Bretscher and D. H. Wilkinson, Proc. Camb. Phil. Soc. **45**, 141 (1949).

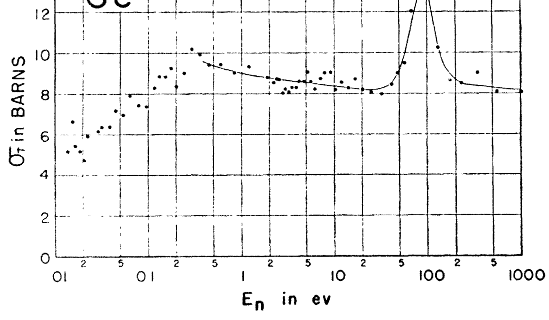


FIG. 69. Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).

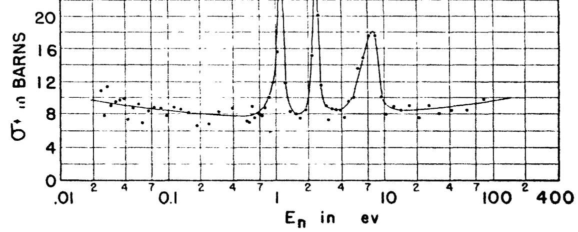


FIG. 70. Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947).

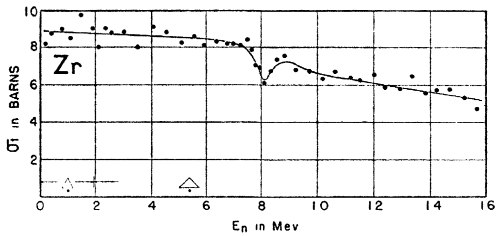


FIG. 71. Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).

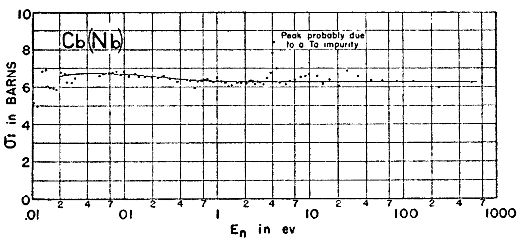


FIG. 72. Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).

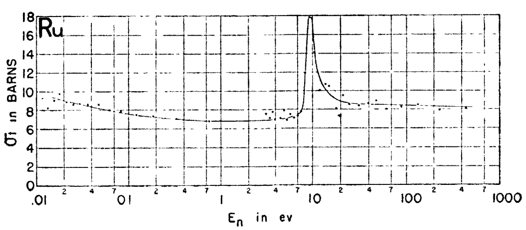


FIG. 73. Columbia Velocity Selector (unpublished).

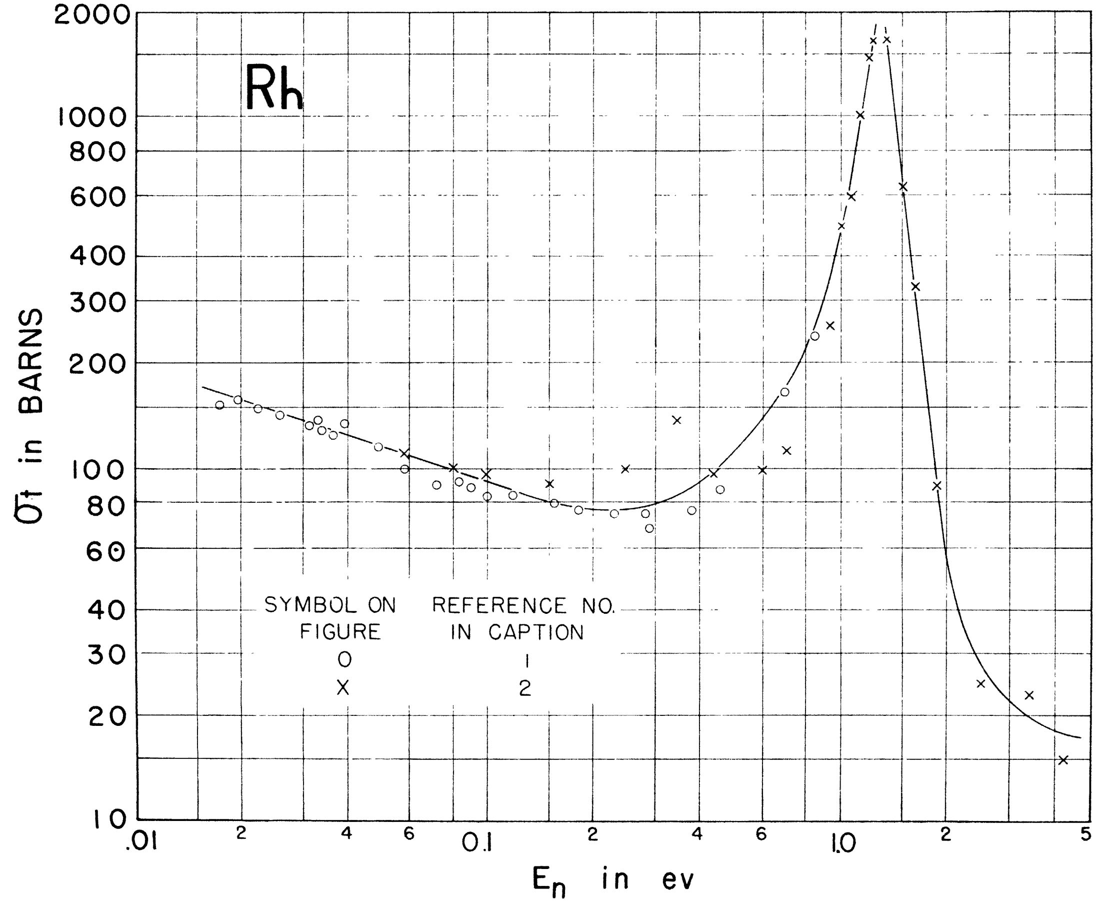


FIG. 74. (1) Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).
(2) W. J. Sturm, Phys. Rev. **71**, 757 (1947).

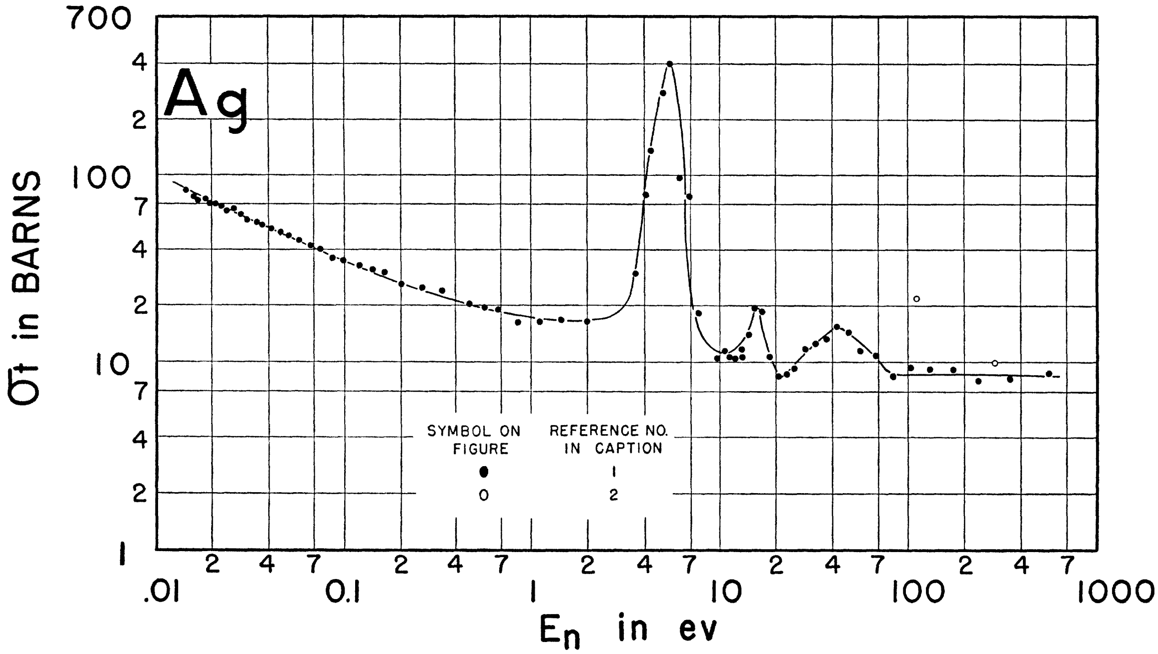


FIG. 75. (1) Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). Also see W. Selove, Phys. Rev. **77**, 557 (1950).

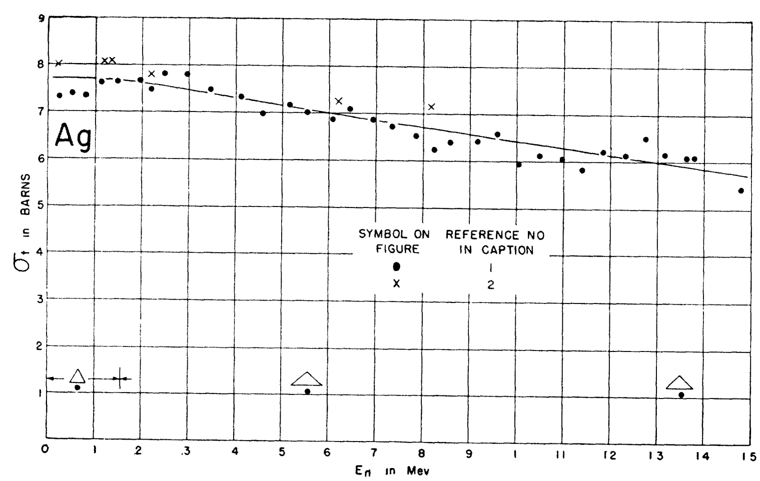


FIG. 76. (1) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

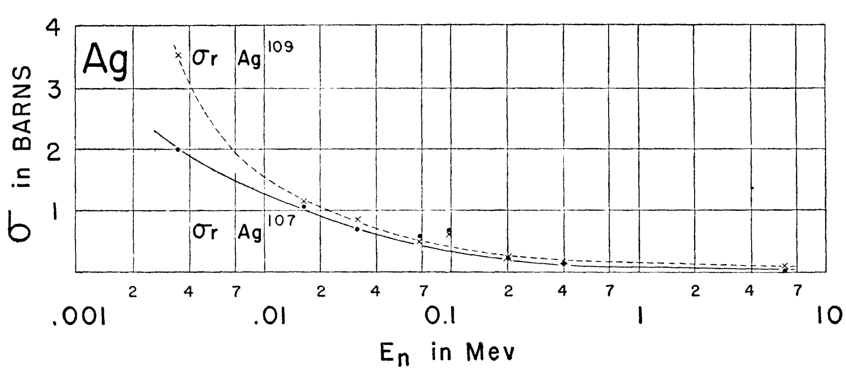


FIG. 77. Segrè, Greisen, Linenberger, and Miskel, MDDC 228.

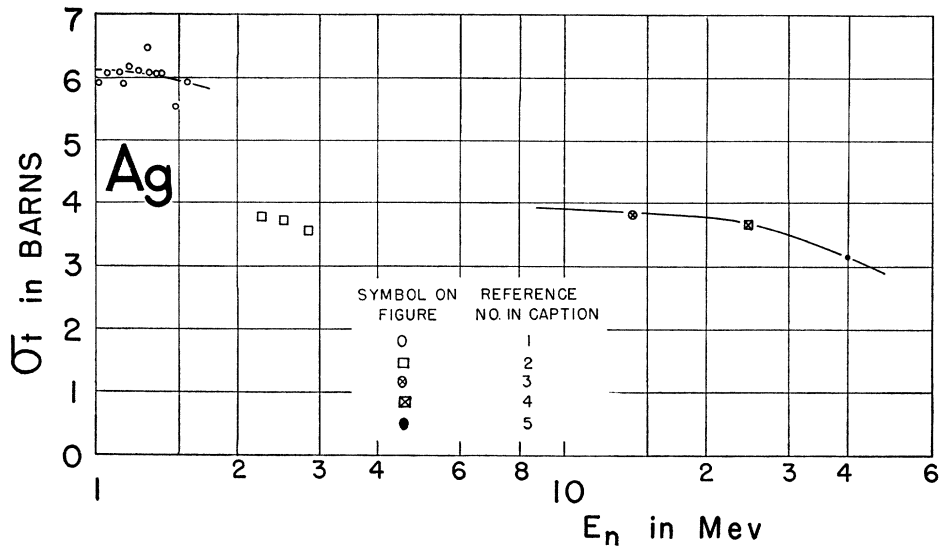


FIG. 78. (1) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (4) R. Sherr, Phys. Rev. **68**, 240 (1945). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).

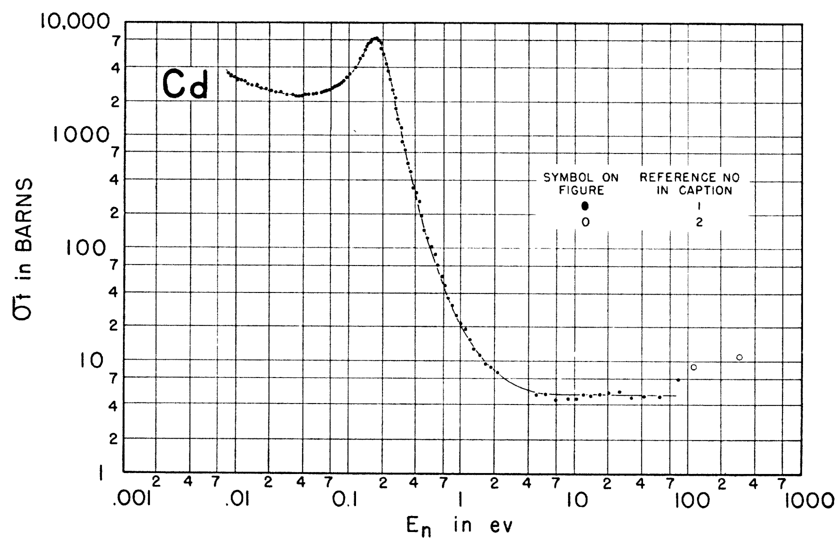


FIG. 79. (1) Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). Also see W. H. Zinn, Phys. Rev. **71**, 575 (1947); Sawyer, Wollan, Bernstein, and Peterson, Phys. Rev. **72**, 109 (1947).

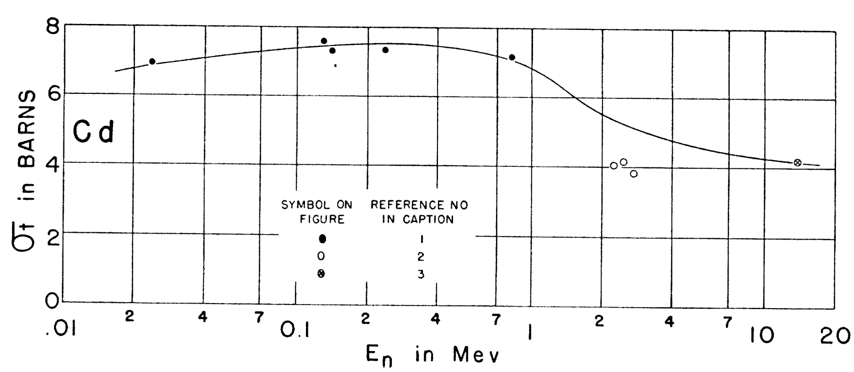


FIG. 80. (1) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946).

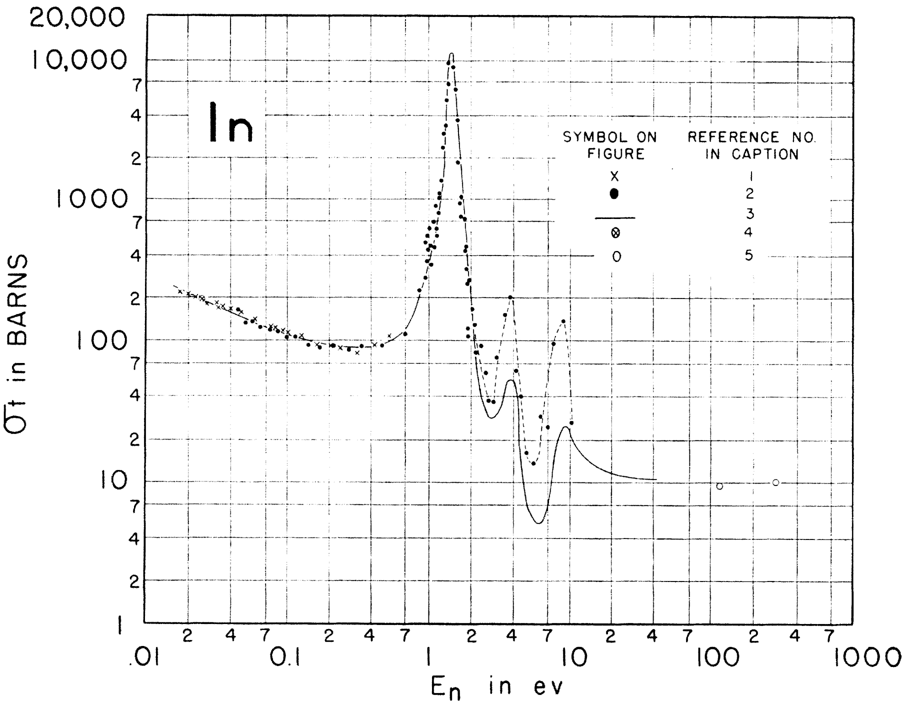


FIG. 81. (1) Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946). (2) Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947). (3) B. D. McDaniel, Phys. Rev. **70**, 832 (1946). (4) E. Fermi and L. Marshall (unpublished). (5) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

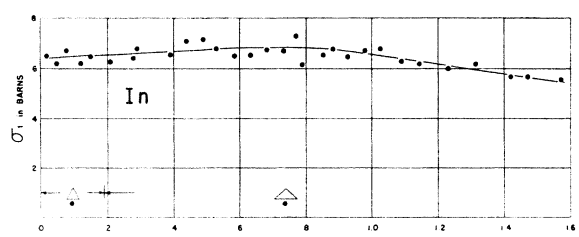


FIG. 82. Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).

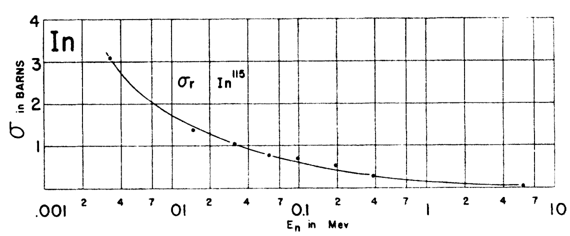


FIG. 83. Segrè, Greisen, Linenberger, and Miskel, MDDC 228. Also see S. G. Cohen, Nature **161**, 475 (1948).

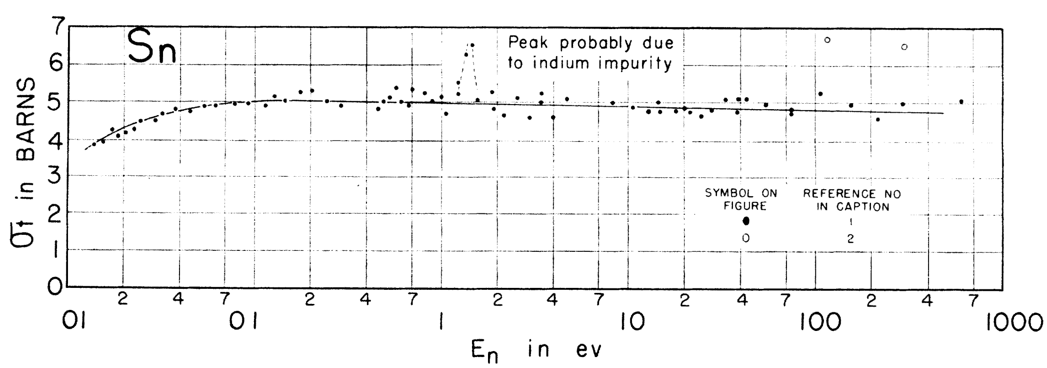


FIG. 84. (1) Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

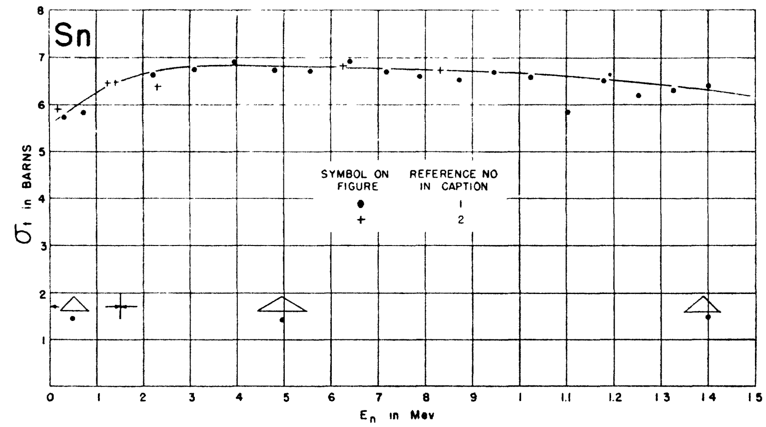


FIG. 85. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

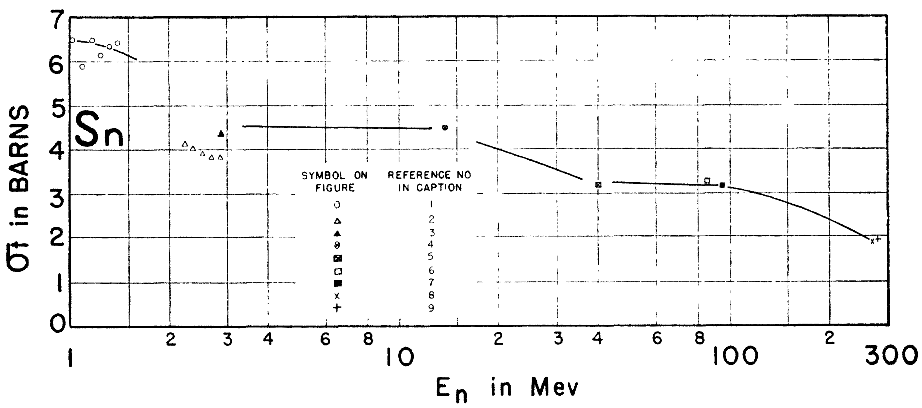


FIG. 86. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (7) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (8) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (9) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

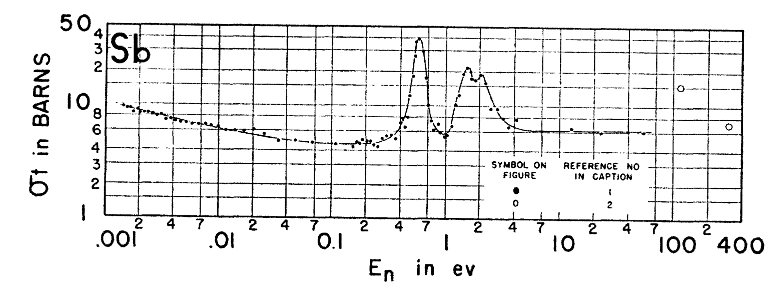


FIG. 87. (1) Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

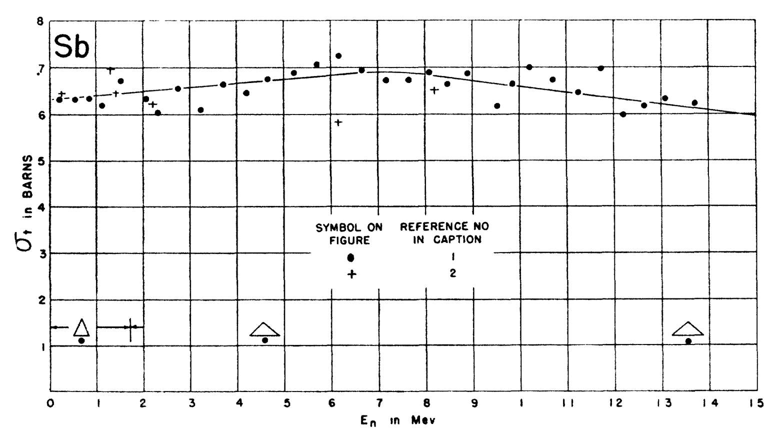


FIG. 88. (1) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939); Amaldi, Bocciarelli, Cacciapuota, and Trabacchi, Nuovo Cimento **3**, 203 (1946).

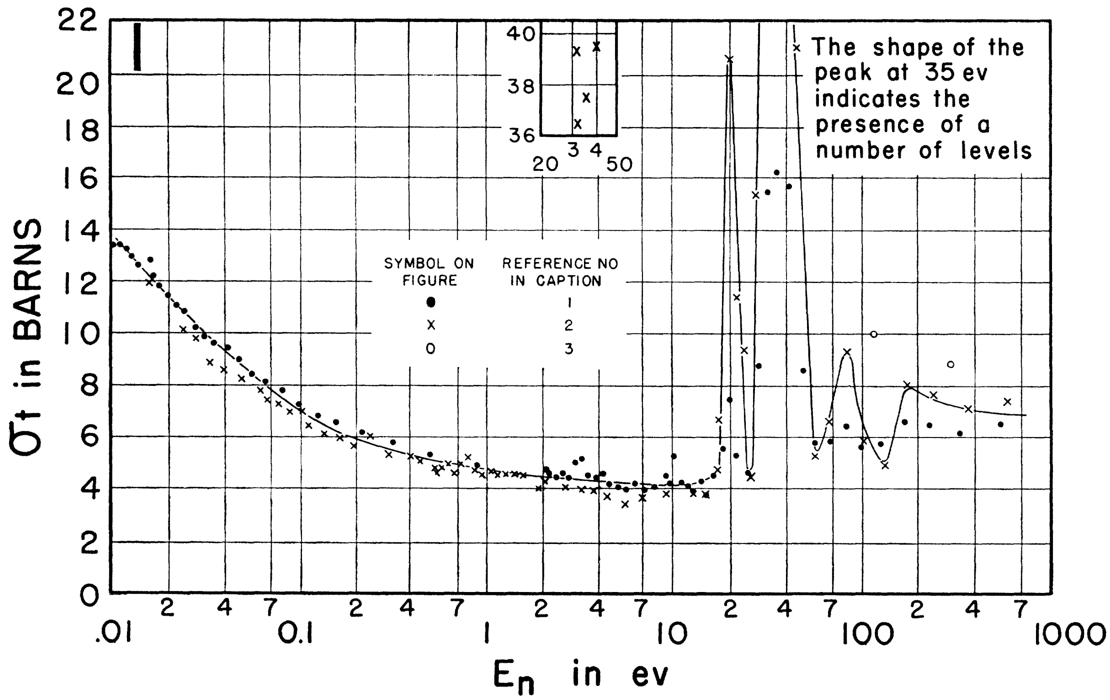


FIG. 89. (1) Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947). (2) W. B. Jones, Jr., Phys. Rev. **72**, 362 (1947). (3) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

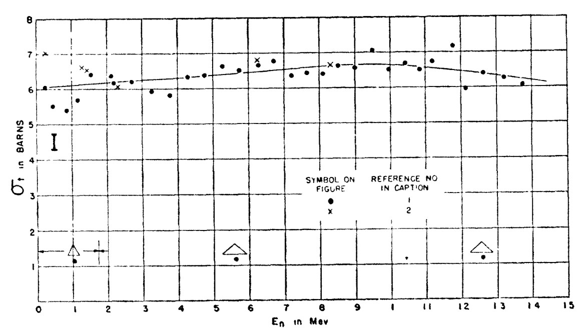


FIG. 90. (1) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).

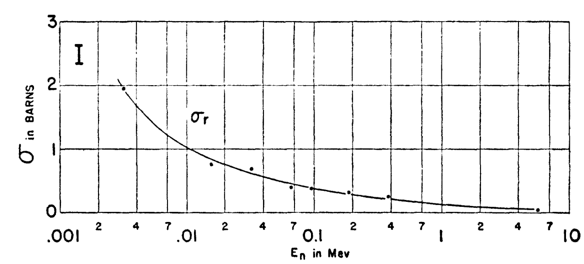


FIG. 91. Segrè, Greisen, Linenberger, and Miskel, MDDC 228.

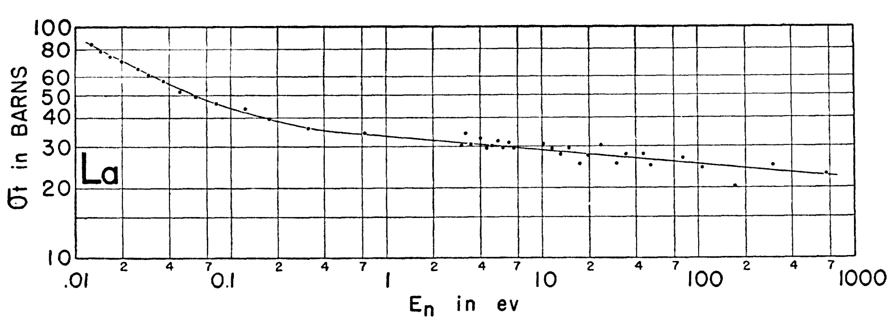


FIG. 92. Columbia Velocity Selector (unpublished).

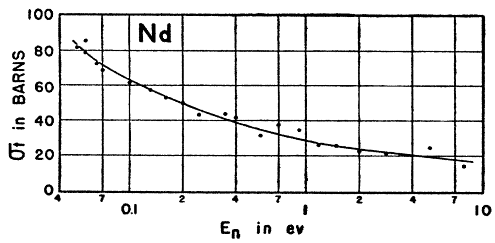


FIG. 93. W. J. Sturm and G. P. Arnold, Phys. Rev. **71**, 556 (1947).

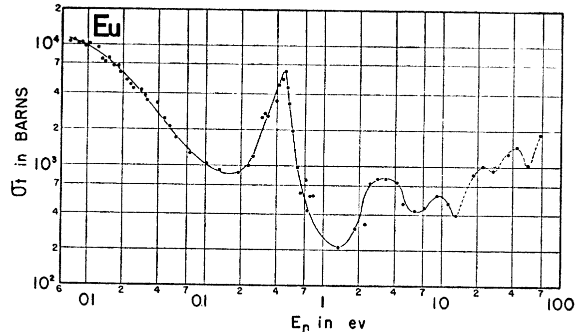


FIG. 95. W. J. Sturm, Phys. Rev. **71**, 757 (1947). See also Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).

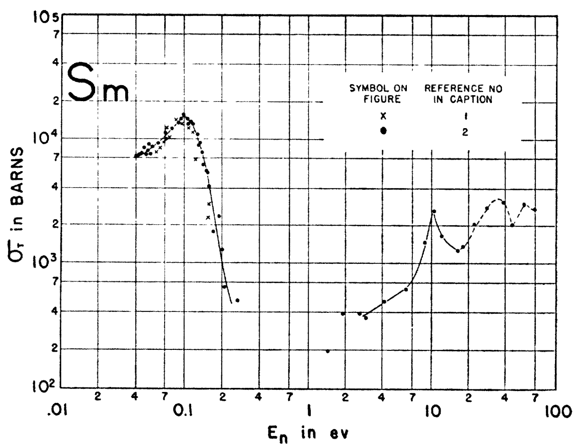


FIG. 94. (1) Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946). (2) W. J. Sturm, Phys. Rev. **71**, 757 (1947).

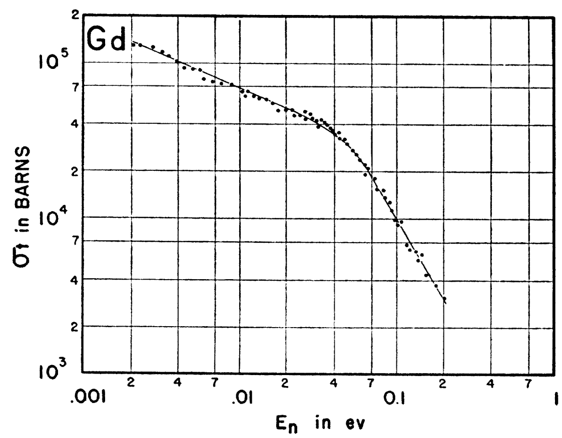


FIG. 96. W. J. Sturm, Phys. Rev. **71**, 757 (1947).

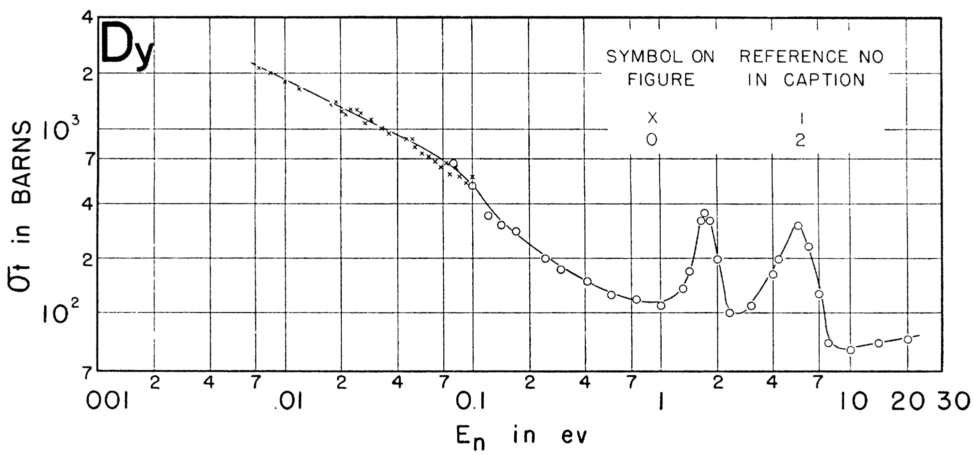


FIG. 97. (1) T. Brill and H. V. Lichtenberger, Phys. Rev. **72**, 585 (1947). (2) W. J. Sturm and G. P. Arnold, Phys. Rev. **71**, 556 (1947). Also see W. J. Sturm, Phys. Rev. **71**, 757 (1947).

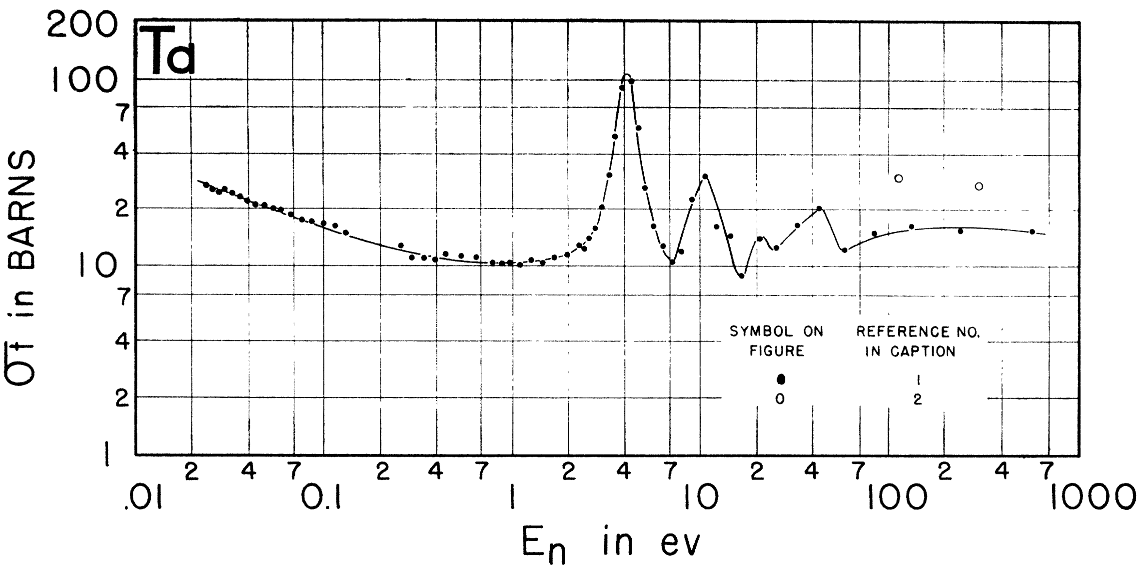


FIG. 98. (1) Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

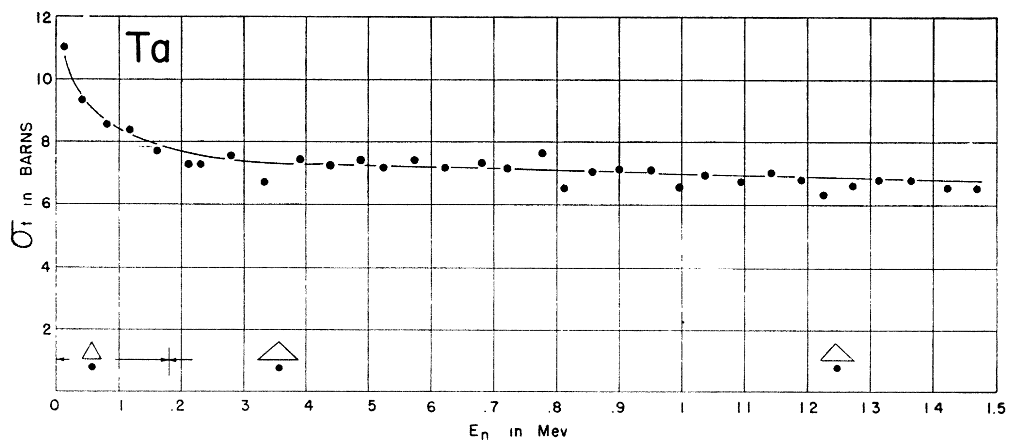


FIG. 99. Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949).

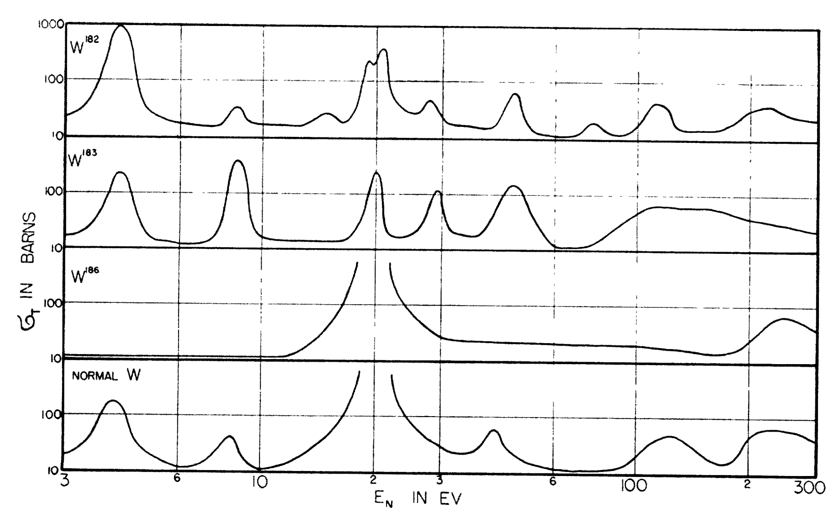


FIG. 100. Walter Selove (unpublished).

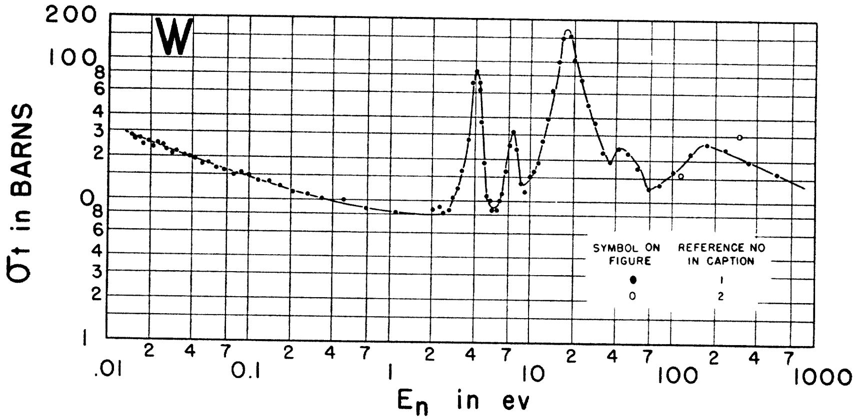


FIG. 101. (1) Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

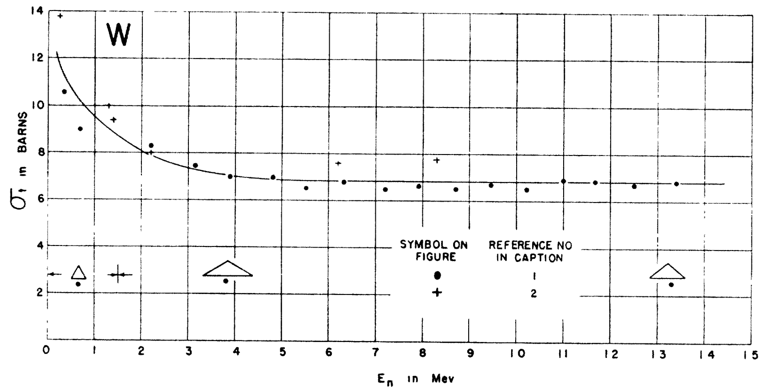


FIG. 102. (1) R. K. Adair, Phys. Rev. **77**, 748 (1950). (2) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947). Also see H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).

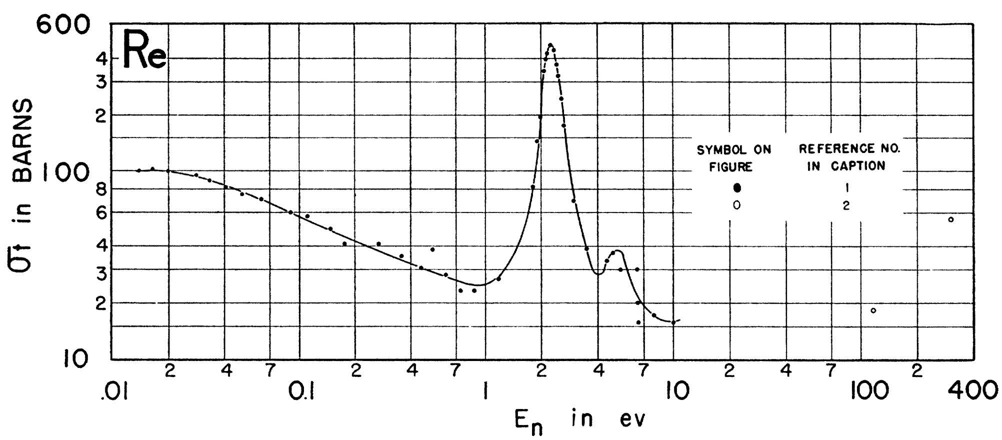


FIG. 103. (1) Argonne Mechanical Velocity Selector and Crystal Spectrometer (unpublished). (2) C. T. Hibdon and C. O. Muelhause, Phys. Rev. **76**, 100 (1949).

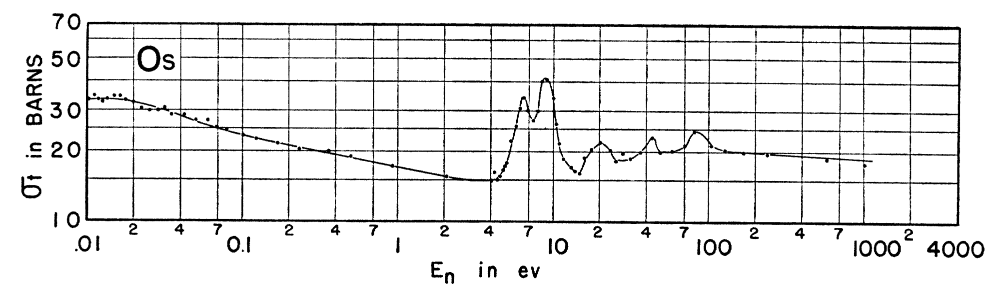


FIG. 104. Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947).

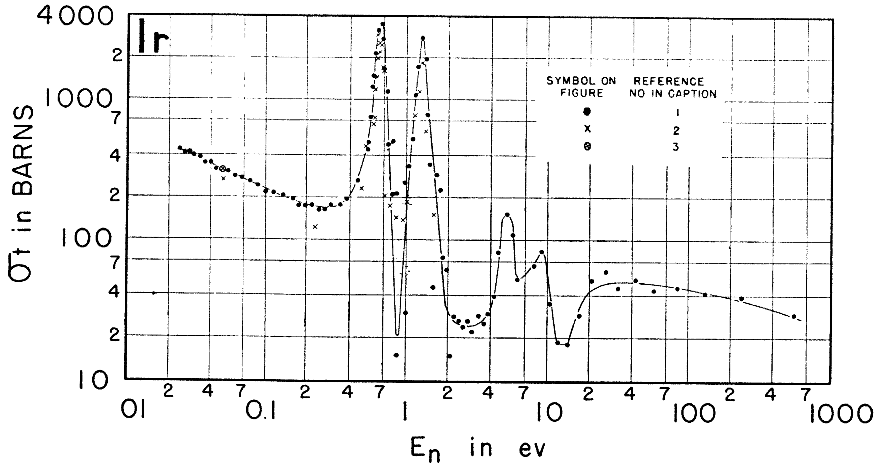


FIG. 105. (1) Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947). (2) Sawyer, Wollan, Bernstein, and Peterson, Phys. Rev. **72**, 109 (1947). (3) Powers, Goldsmith, Beyers, and Dunning, Phys. Rev. **53**, 947 (1938).

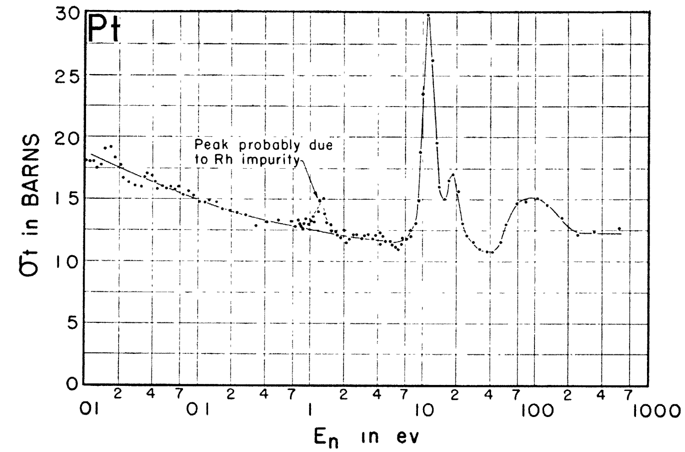


FIG. 106. Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947).

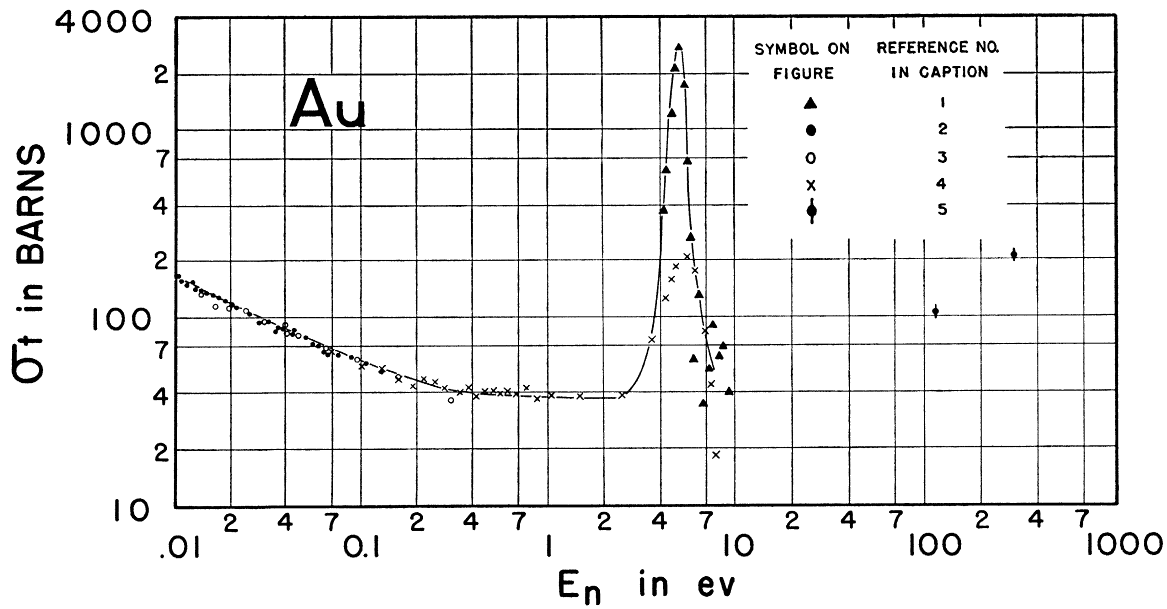


FIG. 107. (1) Havens, Wu, Rainwater, and Meaker, Phys. Rev. **71**, 165 (1947). (2) T. Brill and H. V. Lichtenberger, Phys. Rev. **72**, 585 (1947). (3) McDaniel, Sutton, Lavatelli, and Anderson, Phys. Rev. **70**, 154 (1946). (4) W. J. Sturm, Phys. Rev. **71**, 757 (1947). (5) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

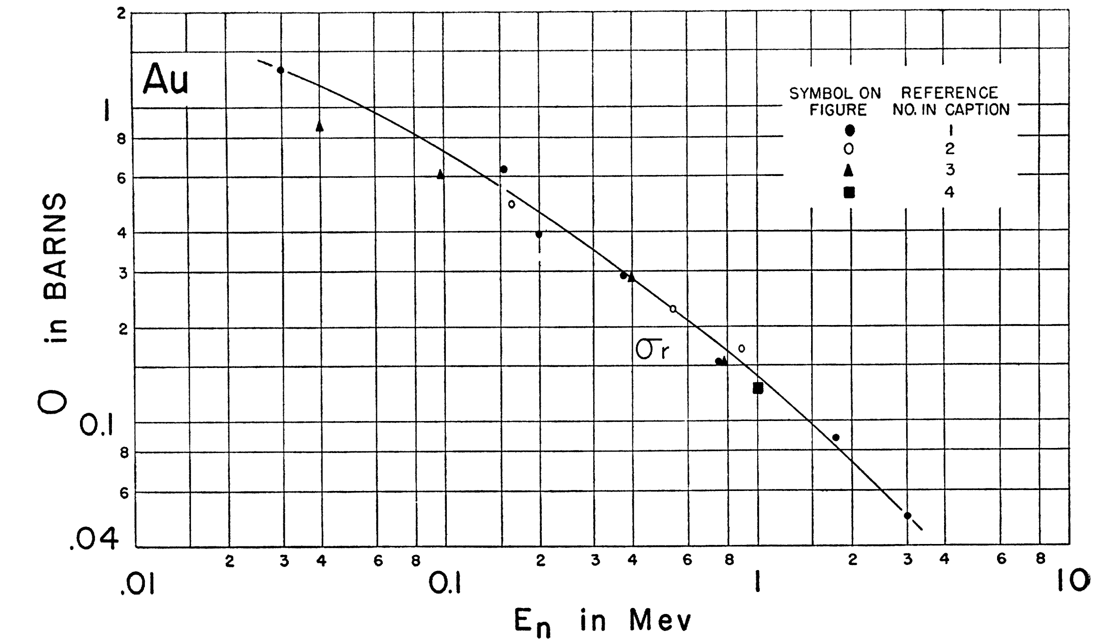


FIG. 108. (1) K. I. Greisen *et al.*, LADC 158. (2) R. L. Henkel and H. H. Barschall (unpublished). (3) Segrè, Greisen, Linenberger, and Miskel, MDDC 228. (4) Hughes, Spotz, and Goldstein, Phys. Rev. **75**, 1781 (1949). Also see Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946) (σ_t).

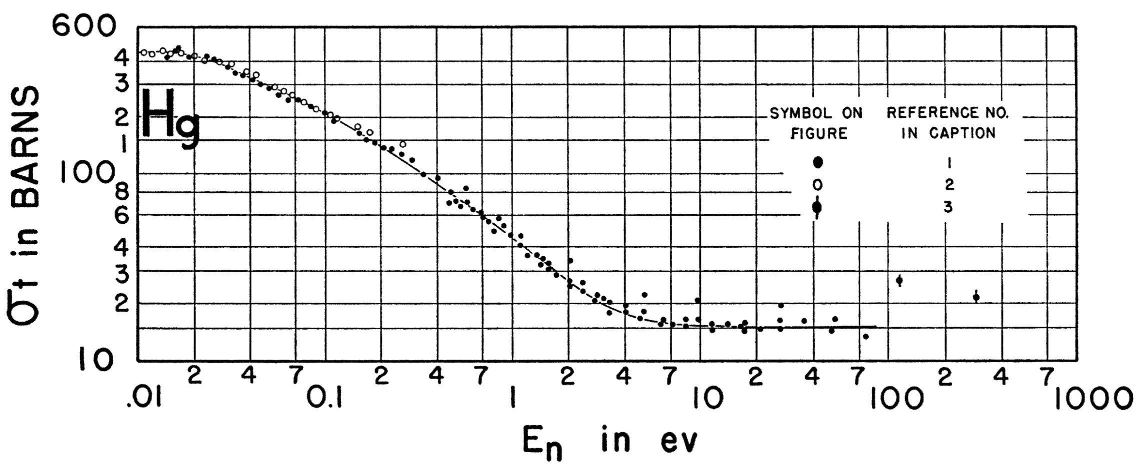
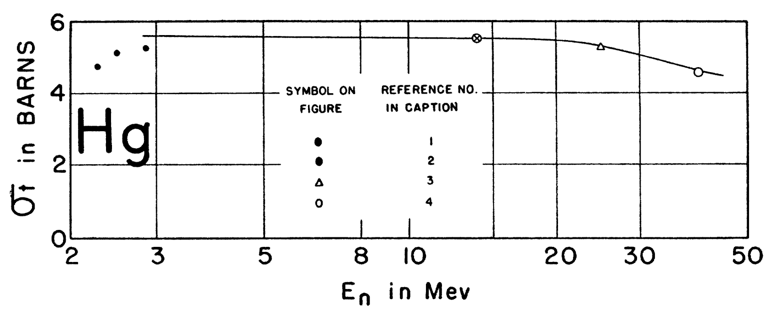


FIG. 109. (1) W. W. Havens, Jr. and L. J. Rainwater, Phys. Rev. **70**, 154 (1946). (2) L. B. Borst *et al.* (unpublished). (3) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

FIG. 110. (1) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (2) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (3) R. Sherr, Phys. Rev. **68**, 240 (1945). (4) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).



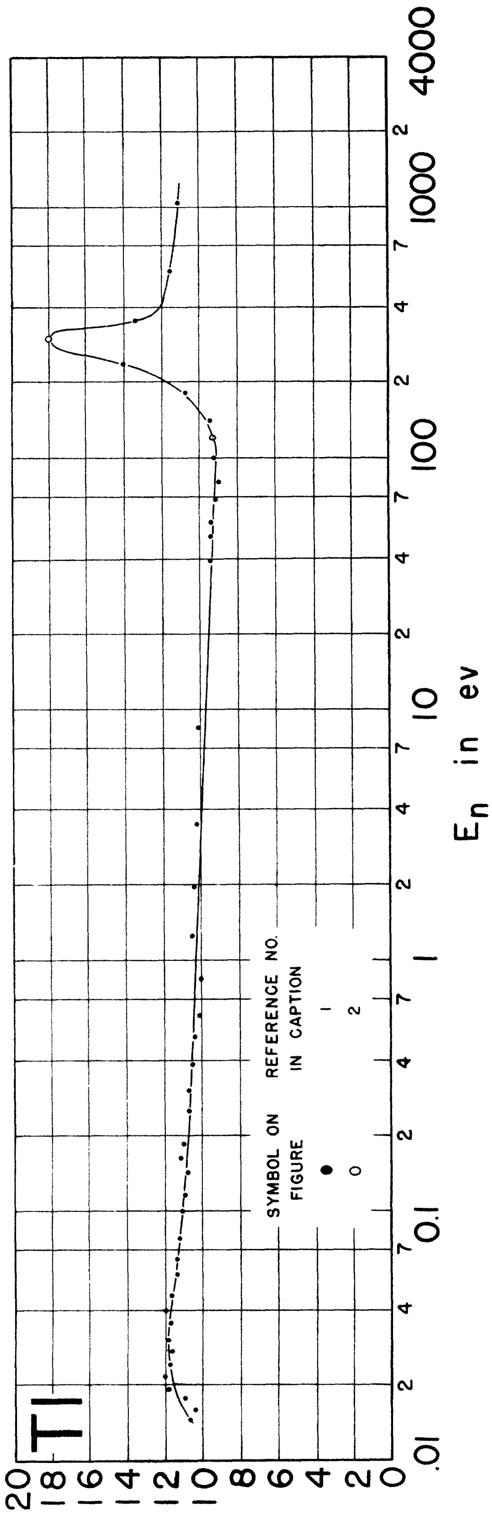


FIG. 111. (1) Wu, Rainwater, and Havens, Phys. Rev. **71**, 174 (1947). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

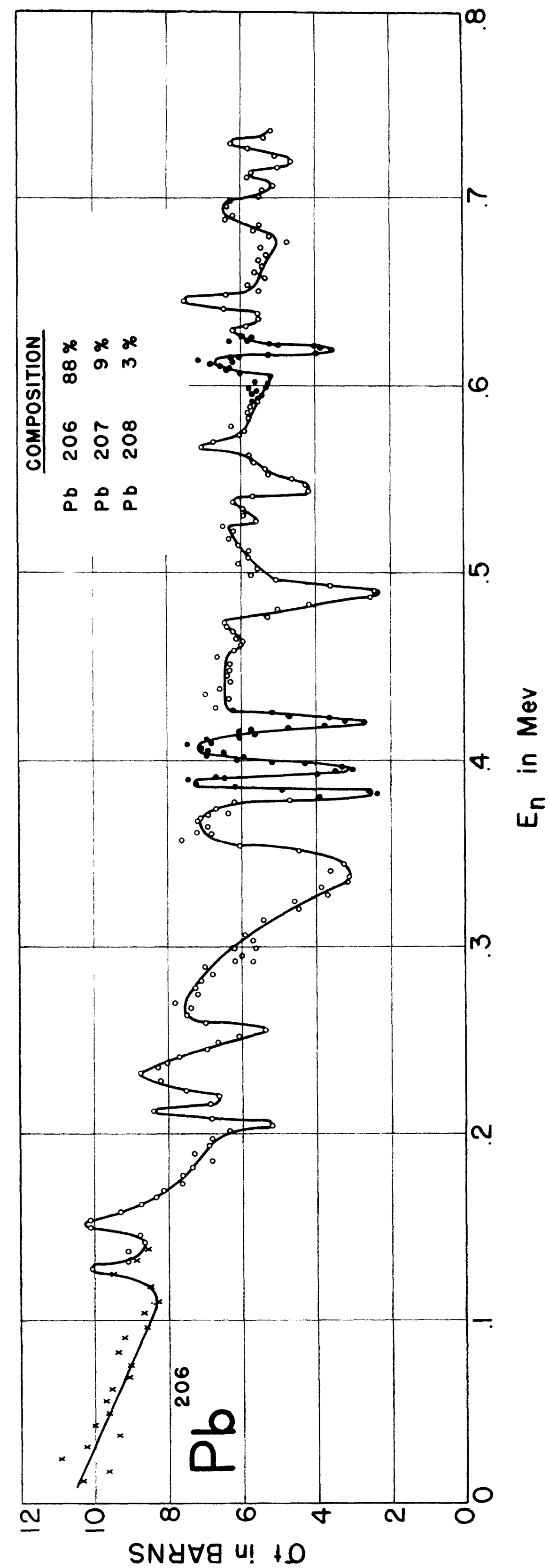


FIG. 112. Peterson, Adair, and Barschall (unpublished).

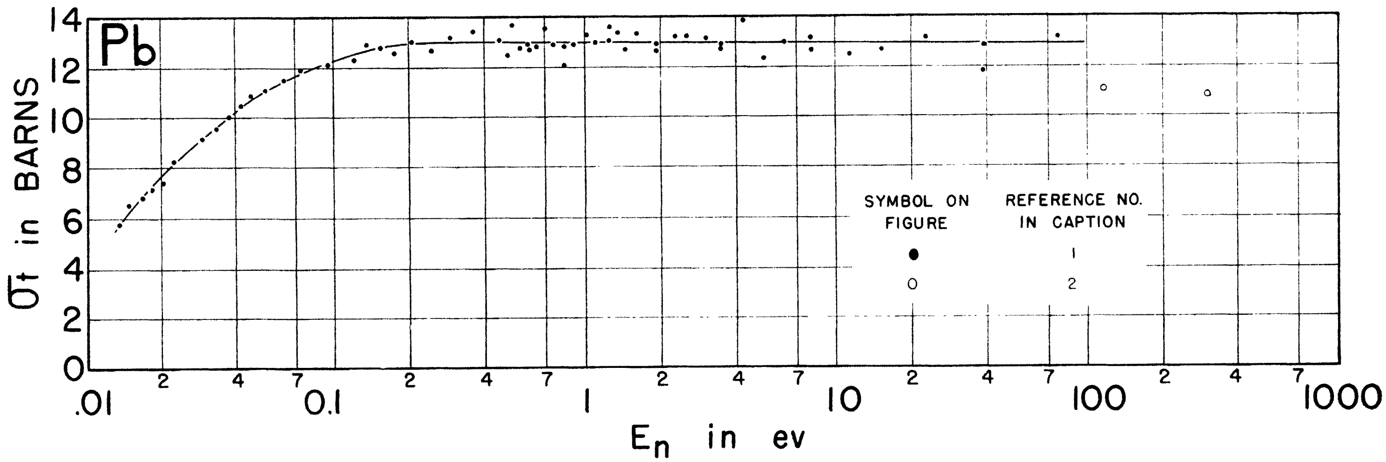


FIG. 113. (1) Columbia Velocity Selector (unpublished). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949).

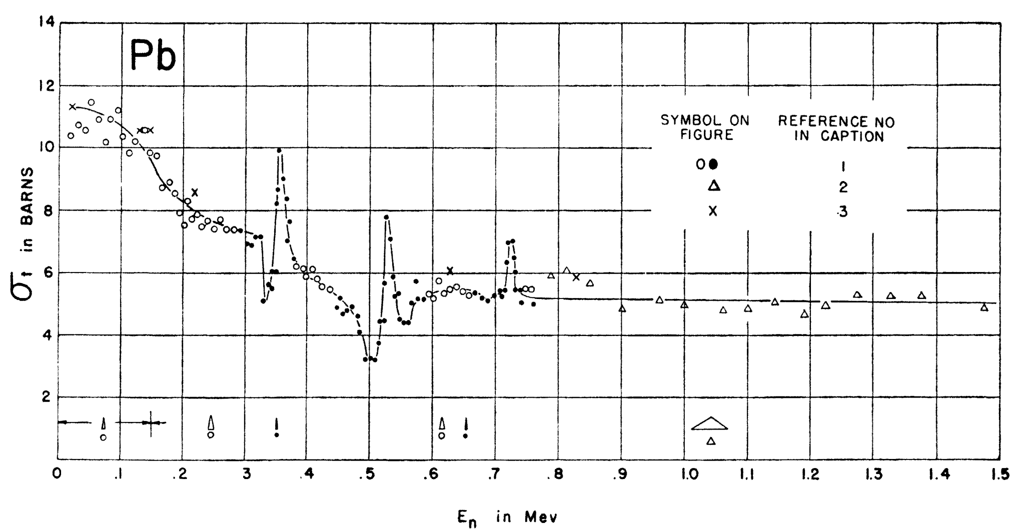


FIG. 114. (1) Barschall, Bockelman, Peterson, and Adair, Phys. Rev. **76**, 1146 (1949). (2) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

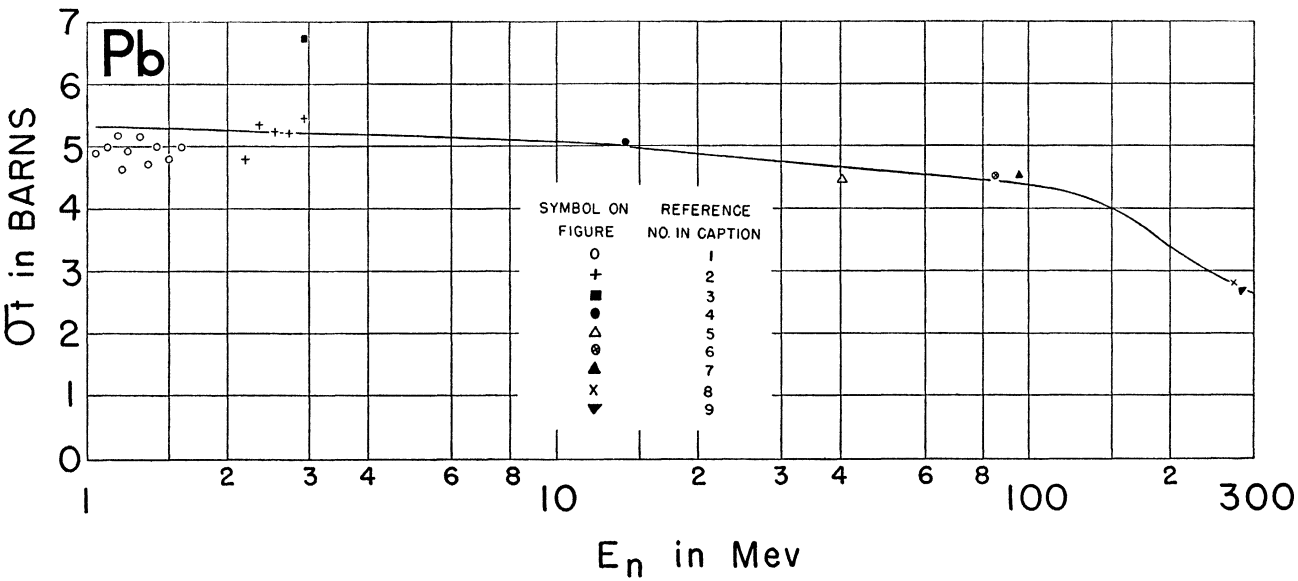


FIG. 115. (1) Bockelman, Peterson, Adair, and Barschall, Phys. Rev. **76**, 277 (1949). (2) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (3) Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). (4) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (5) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (6) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (7) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (8) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (9) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

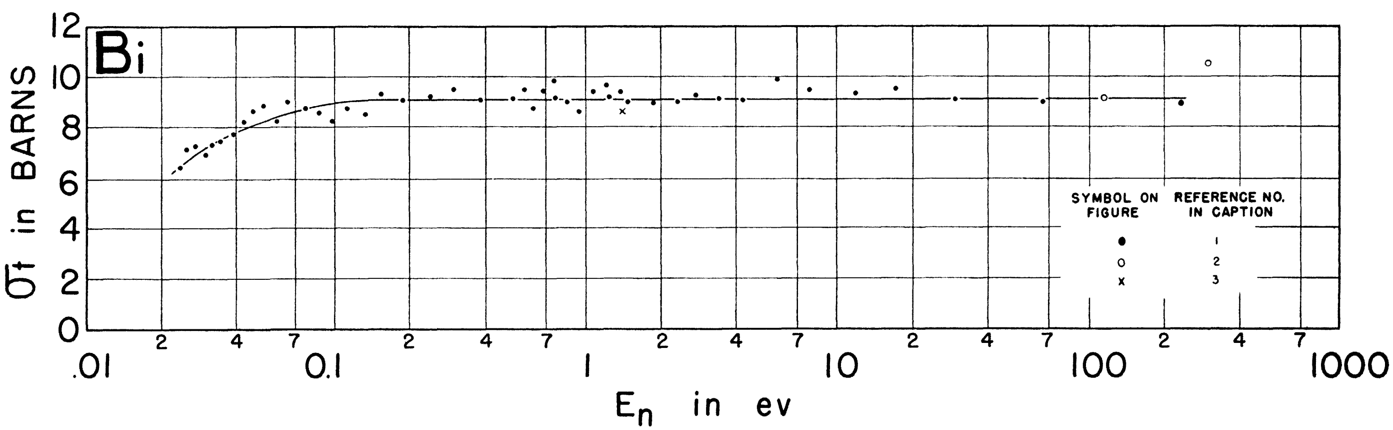


FIG. 116. (1) Havens, Rainwater, Wu, and Dunning, Phys. Rev. **73**, 963 (1948). (2) C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **76**, 100 (1949). (3) J. Hanstein, Phys. Rev. **59**, 489 (1941).

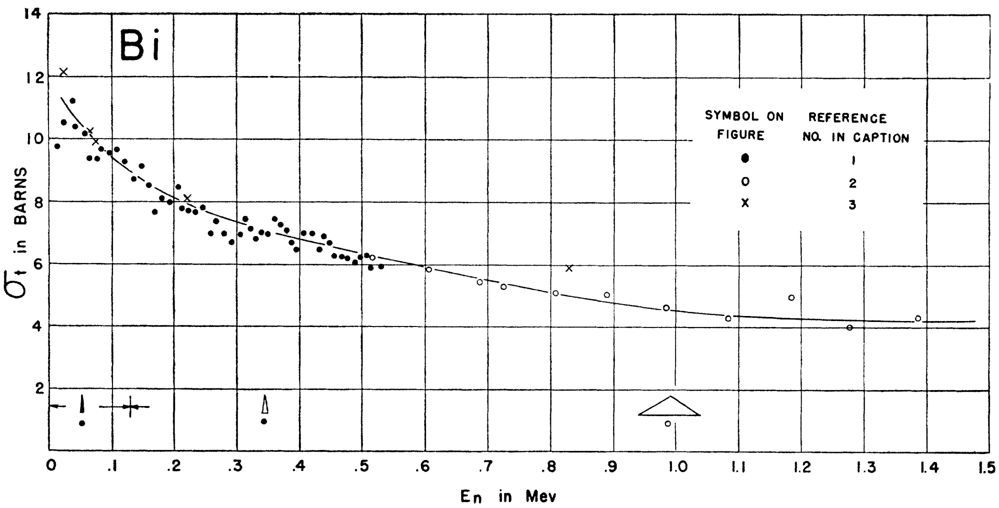


FIG. 117. (1) Barschall, Bockelman, Peterson, and Adair, Phys. Rev. **76**, 1146 (1949). (2) Barschall, Bockelman, and Seagondollar, Phys. Rev. **73**, 659 (1948). (3) Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).

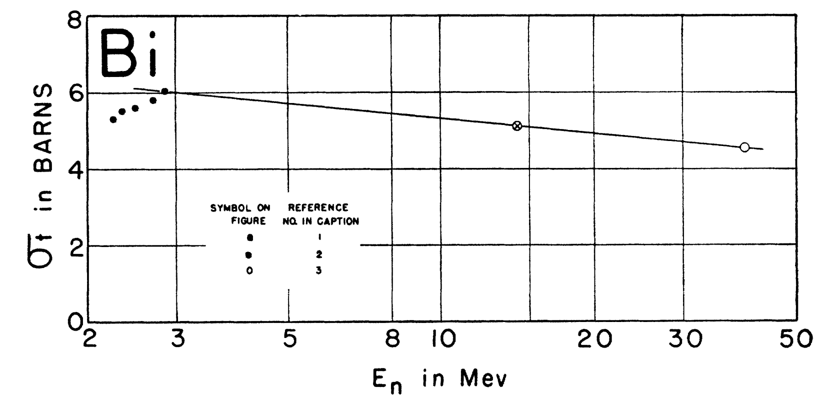


FIG. 118. (1) H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939). (2) Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946). (3) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949).

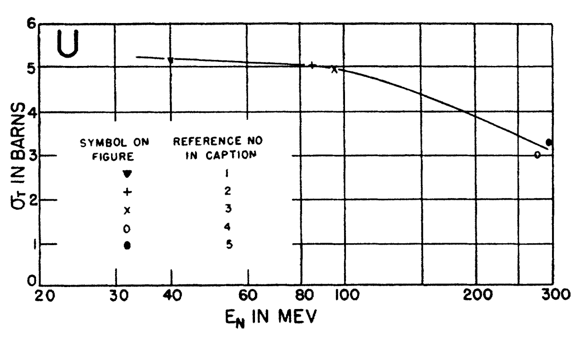


FIG. 119. (1) R. H. Hildebrand and C. E. Leith, Phys. Rev. **76**, 587 (1949). (2) Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949). (3) J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950). (4) DeJuren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949). (5) Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

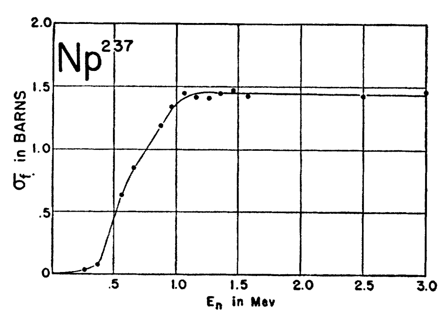


FIG. 120. E. D. Klema, Phys. Rev. **72**, 88 (1947).

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