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Total Neutron Cross Sections near 14.1 Mev*

JERRY P. CONNER
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

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Total cross sections of C, Ca, Ti, Ba, La, Ce, Nd, Sm, Gd, Er, Ta, Au, and Pb for neutrons of energies between 13.1 and 15.6 Mev have been measured by the transmission technique with good geometry. The range of neutron energy was achieved by observing neutrons at various angles from thin tritium targets bombarded by deuterons of energy up to 450 kev. Geometry was such that a scattering in the sample of more than about 2° removed the neutron from the beam to the stilbene scintillation detector. The total cross section of carbon for neutrons was found to vary from 1.41 barns at 13.1 Mev to a minimum of 1.31 barns at 14.2 Mev to 1.49 barns at 15.6 Mev. Other elements showed smaller cross-section variation with energy.

I. INTRODUCTION

A NUMBER of measurements of total cross sections of various elements for 14-Mev neutrons have been reported.[1–12] A comparison between experimental total cross sections and results of a theory of nuclear cross sections is often made by plotting the nuclear radius derived from the experimental cross section against the cube root of the atomic weight. For neutron energies near 14 Mev, such a graph shows an absence of data in the region of atomic weights from about 140 to 180, the rare-earth region. Although the theory of Feshbach and Weisskopf,[13] which gives an approximately linear relationship between the square root of the total cross section and nuclear radius, does not fit experimental data perfectly, it indicates the trend of total cross section *vs* atomic weight up to about atomic weight 140 for a particular choice of parameters. Total cross sections of elements of atomic weight above 180 are significantly less than those calculated by the theory if the same parameters are used. Knowledge of the total cross section in the intermediate region of atomic weight from 140 to 180 would therefore be of considerable importance in developing a more refined theory of nuclear cross sections. In the experiments to be reported in this paper total cross-section measurements have been extended through the rare-earth region. Measurements on a number of other elements, the total cross sections of which have been previously measured, have been made in order to have a comparison between this experiment and others.

Sharp resonances in the cross section as a function of energy are not expected to occur at energies near 14 Mev. However, it has been observed that total cross sections are not constant with energy in this energy range.[11,12] The availability of thin targets used with the $T(d,n)He^4$ reaction as a neutron source has made it possible to make measurements at neutron energies significantly different from, but near, 14 Mev with energy resolution of from 50 to 130 kev.

II. APPARATUS AND PROCEDURE

A conventional transmission technique with good geometry was used to determine the total cross section of the elements for neutrons. From the transmission T of a specimen, total cross section σ_t was determined from the relation $e^{-\sigma_t n t}=T=(C-B)/(A-B)$, where n is the number of atoms per cubic centimeter of the specimen, t is the length of the specimen traversed by the neutrons, C is the detector count per monitor count with specimen in between source and detector, A is the detector count per monitor count with specimen out, and B is the detector count per monitor count due to background neutrons scattered around the specimen.

Neutrons were produced by the $H^3(d,n)He^4$ reaction with the Los Alamos Cockcroft-Walton accelerator. Accelerator energy and angle of observation of neutrons with respect to the neutron beam were varied according to the neutron energy desired. Thin targets of tritium were prepared by absorbing tritium into a titanium film which had been evaporated onto a tungsten disk.[14] In order to have a well-defined target thickness and resulting neutron energy spectrum, it was necessary to have the surface of the tungsten disk smooth compared to the thickness of the titanium film, which contained the tritium. To achieve this condition the tungsten disks were polished before receiving the deposit of titanium. Thick targets were used for producing 14.1-Mev neutrons, since at 90° to the deuteron beam, the

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[1] E. O. Salant and N. F. Ramsey, Phys. Rev. **57**, 1075 (1940).

[2] Amaldi, Bacciarelli, Cacciapuoti, and Trabacchi, Nuovo cimento **3**, 203 (1946).

[3] Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947).

[4] W. Sleator, Jr., Phys. Rev. **72**, 207 (1947).

[5] A. H. Lasday, Phys. Rev. **81**, 139 (1951).

[6] D. F. Meyer and W. Neyer, Los Alamos Report 1279, 1951 (unpublished).

[7] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).

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

[9] L. S. Goodman, Phys. Rev. **88**, 686 (1952).

[10] Ageno, Cortellessa, and Querzoli, Nuovo cimento **10**, 281 (1953).

[11] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 651 (1954).

[12] Bonner, Alba, Fernandez, and Mazari, Phys. Rev. **97**, 985 (1955).

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

[14] A. B. Lillie and J. P. Conner, Rev. Sci. Instr. **22**, 210 (1951); Conner, Bonner, and Smith, Phys. Rev. **88**, 468 (1952).

TABLE I. Total cross section and standard deviation of 13 elements for neutrons of energy E_n. The numbers indicated by an asterisk give the neutron energy spread from thin targets. The number indicated by a double asterisk gives the standard deviation in neutron energy from thick targets.

Element \ E_n Mev	13.14±0.05*	13.60±0.07*	14.10±0.04*(0.12**)	14.59±0.11*	15.12±0.13*	15.60±0.13*
C	1.413±0.021	1.391±0.018	1.309±0.016	1.340±0.018	1.432±0.019	1.487±0.022
Ca	2.35 ±0.04	2.28 ±0.04	2.24 ±0.03	2.20 ±0.04	2.22 ±0.04	2.20 ±0.04
Ti	2.42 ±0.04	2.35 ±0.03	2.32 ±0.02	2.28 ±0.03	2.27 ±0.03	2.27 ±0.04
Ba	5.01 ±0.09		5.02 ±0.07			4.97 ±0.10
La	4.81 ±0.08	4.78 ±0.07	4.79 ±0.07	4.77 ±0.07	4.73 ±0.08	4.69 ±0.08
Ce	4.99 ±0.08		5.01 ±0.07			5.00 ±0.09
Nd	4.92 ±0.09		5.09 ±0.08			5.06 ±0.11
Sm	5.10 ±0.09		5.14 ±0.08			5.24 ±0.10
Gd	5.33 ±0.13		5.14 ±0.09			5.40 ±0.14
Er	5.37 ±0.09		5.37 ±0.08			5.41 ±0.10
Ta	5.27 ±0.09	5.30 ±0.08	5.31 ±0.08	5.39 ±0.08	5.30 ±0.09	5.45 ±0.10
Au	5.34 ±0.09	5.34 ±0.08	5.40 ±0.08	5.42 ±0.09	5.42 ±0.09	5.52 ±0.10
Pb	5.47 ±0.10	5.38 ±0.09	5.40 ±0.08	5.53 ±0.09	5.52 ±0.10	5.61 ±0.11

deuteron energy has little effect on neutron energy. Thick targets were prepared by absorbing tritium into a zirconium film melted onto a tungsten disk.[15]

Specimens were elemental, cylindrical in shape, 1.6 cm in diameter, and except Nd and Gd, of such length to have a transmission of approximately 0.5. The Nd specimen with a transmission of 0.58 and Gd specimen with a transmission of 0.67 were shorter because of flaws in the castings. Specimens of La, Ce, Nd, Sm, Gd, and Er were cast, those of Ca, Ba, Au, and Pb compacted and sintered. Commercial bar stock was used for the Ti specimen. Two carbon specimens were obtained from high-purity reactor-grade graphite. All specimens were machined to size. No corrections were applied for the small amount of impurities determined by spectroscopic analysis and from the source of materials.

A 1.6-cm diameter, 28-cm long tantalum bar with a calculated transmission of 0.0003 was inserted in place of the specimen to measure background radiation, which varied from ½ to 3% depending primarily on the angle of observation.

A correction to the data has been applied to compensate for small-angle single scattering by the specimen into the detector. The largest inscattering correction applied was 1.1% for lead. No corrections have been applied for multiple scattering effects. Single- and multiple-scattering formulas are considered in the appendix.

Light produced by recoiling protons in a ½-inch diameter, ½-inch long stilbene crystal placed 100 cm from the neutron source was converted and amplified by a Dumont 6292 photomultiplier tube to serve as the neutron detector. The primary monitor was a similar stilbene crystal and photomultiplier placed 30 cm from the neutron source at 90° with respect to the incident deuteron beam. In addition, a gas proportional counter counted α particles from the $\mathrm{H}^3(d,n)\mathrm{He}^4$ reaction at 135° to the deuteron beam. The amplified outputs of the photomultipliers were fed to pulse-height analyzers, which were used to keep track of gain drifts and spectrum changes, if any. Such effects were negligible. For thick targets a counting-rate loss correction of up to 1.6% was necessary. Under proper operation conditions, the two monitors consistently agreed within statistics. The sensitivity of the scintillation counters to γ rays was such that the largest radium γ-ray pulse was about 30% of the maximum of the neutron pulse-height distribution. Electrons from higher energy γ rays would go out of the scintillator and would not give larger pulses.

The specimen holder, which was halfway between the neutron source and detector, together with the detector could be rotated as a unit around the neutron source. Alignment of the system to within 0.03 cm was possible with a small telescope with a barrel of the same diameter as the specimens.

III. RESULTS

In Table I are the final corrected values of total cross section for neutrons of the energies indicated. The errors quoted should be regarded as standard deviations. The quoted errors are the square root of the sum of the squares of the following: (a) the statistical standard deviation, (b) the magnitude of the inscattering correction, (c) one-half the magnitude of the counting rate loss correction, (d) allowance for suspected impurities in the case of the Ca specimen, which during the course of the experiment, gained approximately 2% in mass, presumably of oxygen, which would not be detected in the spectroscopic analysis, (e) one-half percent for nonuniformity of the carbon specimens, the stock for which had a maximum of ½% radial density variation in a piece 5 cm long, (f) allowance for suspected cavities in the cast specimens below the level of resolution, about 0.05 cm, of a radiographic analysis, (g) one percent allowance for total of other errors which are individually negligible

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[15] Graves, Rodriques, Goldblatt, and Meyer, Rev. Sci. Instr. **20**, 579 (1949).

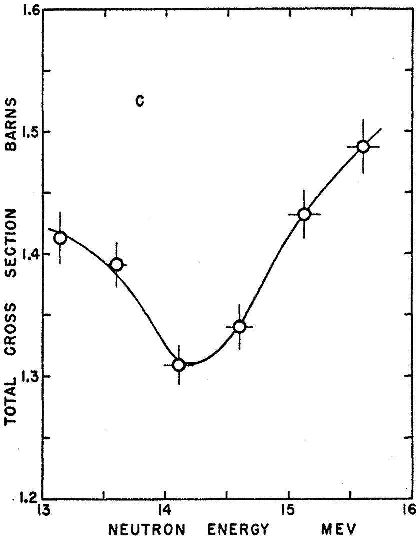

FIG. 1. Total cross section of carbon for neutrons from neutron energy of 13.1 to 15.6 Mev.

but may be significant in combination. Such errors are those due to impurities, dimensional changes with temperature, neutron scattering in the air displaced by the specimen, differential shielding of air and specimen holder by shadow-bar and specimen, multiple scattering, etc.

The number given for neutron energy spread should be regarded as very nearly the total spread in neutron energy for thin targets. For thick targets there is considerable energy spread of the emerging neutrons due to multiple scattering of the deuterons in the target material. The effect has been estimated by Thomas, who found that the neutron energy spectrum is approximately Gaussian and therefore can be characterized by a standard deviation in energy.[16] The neutron energy spread given in Table I for thick-target measurements is the standard deviation in energy.

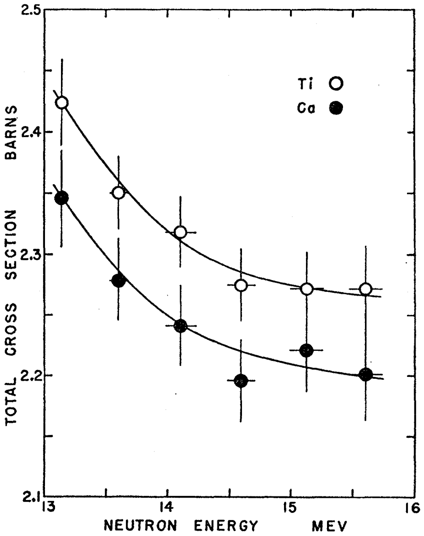

FIG. 2. Total cross section of calcium and titanium for neutrons from neutron energy of 13.1 to 15.6 Mev.

In Fig. 1 is a plot of the total cross section of carbon for neutrons as a function of the energy of the neutrons. In Fig. 2 are similar plots for calcium and titanium. For other elements the variation of total cross section with energy has been approximated by a straight line of the form $\sigma_t = A + B(E_n - 14.1 \text{ Mev})$ where the coefficients A and B have been determined by a weighted least-squares analysis of the data. Table II gives the values of the coefficients.

In Table III the measurements at 14.1 Mev described in this paper are compared with previous measurements. Except for lanthanum, agreement with Coon, Graves, and Barschall is very good.

This experiment shows that the total cross section of carbon has a minimum value at about 14.2 Mev. Coupled with data at lower energies,[17] this result indicates a broad maximum in the total cross section at an energy below 13 Mev. Cook and Bonner find a broad maximum of the total cross section at about 16 Mev, although their absolute values are slightly less.[11] These fluctuations in total cross section suggest a variation in the density of levels of the compound nucleus C^{13} in the excitation energy range of from 18 to 20 Mev. About the same region of excitation of C^{13} can be reached by the $B^{11}(d,n)C^{12}$ and $B^{11}(d,p)B^{12}$ reactions. However, experiments have indicated that these reactions are largely stripping processes and give no information about the compound nucleus.[18] The total cross section of calcium and titanium for neutrons decreases smoothly with energy between 13 and 16 Mev. The variation with energy of total cross section of barium through lead is small though significant. The variation is largest for lead and gold, which have a cross section increasing with neutron energy. Bonner and co-workers

TABLE II. Coefficients in the relation $\sigma_t = A + B(E_n - 14.1 \text{ Mev})$, where A and B were determined from a least-squares analysis of the experimental data. Errors of cross sections computed by the formula are comparable to those quoted in Table I.

Element	A	B
Ba	5.00	−0.02
La	4.77	−0.04
Ce	5.00	+0.01
Nd	5.02	+0.06
Sm	5.15	+0.06
Gd	5.25	+0.04
Er	5.38	+0.02
Ta	5.32	+0.05
Au	5.38	+0.07
Pb	5.46	+0.08

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[16] R. G. Thomas (unpublished).

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

[18] Burke, Risser, and Phillips, Phys. Rev. **93**, 188 (1954); Marion, Bonner, and Cook, Phys. Rev. **100**, 847 (1955).

have observed a similar total cross section variation for lead.[12]

IV. ACKNOWLEDGMENTS

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TABLE III. Comparison of results of present experiments to previous experiments. Since the cross section of carbon varies appreciably near 14 Mev, the comparison for carbon was limited to those experiments using 14.1-Mev neutrons from the $H^3(d,n)He^4$ reaction. *TP* indicates results of the experiment described in this paper.

Material	σ in barns	Reference
C	1.309±0.016	*TP*
	1.32 ±0.02	8
	1.279±0.004	7
	1.29 ±0.02	11
	1.20 ±0.04	9
Ca	2.24 ±0.03	*TP*
	2.19 ±0.04	8
Ti	2.32 ±0.03	*TP*
	2.28 ±0.04	8
	2.2 ±0.2	9
Ba	5.02 ±0.07	*TP*
	5.17 ±0.10	8
La	4.77 ±0.07	*TP*
	5.18 ±0.10	8
Ce	5.01 ±0.07	*TP*
	5.08 ±0.10	8
Ta	5.31 ±0.08	*TP*
	5.24 ±0.10	8
Au	5.36 ±0.08	*TP*
	5.31 ±0.11	8
	5.06 ±0.14	10
	4.68 ±0.9	2
Pb	5.40 ±0.08	*TP*
	5.48 ±0.11	8
	5.1 ±0.4	9
	5.82 ±0.17	10
	5.05 ±0.08	2

V. APPENDIX

Inscattering Corrections

The observed transmission T of the specimen can be considered equal to $T_0+T_1+T_2\cdots$, where T_0 is the true transmission of unscattered neutrons, T_1 is the ratio of counting rate of neutrons singly scattered by the specimen reaching the detector to the counting rate without specimen, etc. The dimensions of the specimen are assumed small compared to the distance from source to detector. The rate at which neutrons are singly scattered into the solid angle $d\omega$ and emerge in the direction of the detector is given by

$$\int_{x=0}^{t}\left[Q\pi\left(\frac{d}{L}\right)^2 e^{-\sigma_t n x}\right]\left[n dx \sigma_e(0) d\omega\right]\left[e^{-\sigma_t n(t-x)}\right],$$

where the brackets set off the processes involved, neutrons penetrating to depth x, scattering in dx, and penetration of the remaining specimen. Q is the rate of production by the source of neutrons per unit solid angle in the direction of specimen and detector, L is the distance from source to detector, d and t are the diameter and length respectively of the specimen, n is the number of specimen atoms per cubic centimeter, and $\sigma_e(\theta)$ is the differential elastic scattering cross section of the specimen atoms. T_1 is given by

$$\frac{T_1}{T_0}=4\pi\left(\frac{d}{L}\right)^2 n t \sigma_e(0).$$

This result agrees with that found by other workers.[19] The relative correction for single inscattering to be applied to the measured cross section is given by

$$\frac{\Delta\sigma}{\sigma_t}=4\pi\left(\frac{d}{L}\right)^2\frac{\sigma_e(0)}{\sigma_t}.$$

The elastic differential scattering cross section at 0° used for calculating corrections has been given by Feld *et al.*[20]

$$\sigma_e(0)=(kR+1)^4/4k^2,$$

where k is the neutron wave number and R is the radius of the bombarded nucleus. Recent experiments indicate that this formula gives approximately correct cross sections for light elements and for lead, but values somewhat too small for intermediate elements.[21]

Multiple Inscattering

An idea of the effect of multiple scattering may be obtained from consideration of double scattering. Those neutrons destined to be scattered twice have a history in the specimen as follows: unscattered neutrons entering the specimen are attenuated until the first scattering takes place into solid angle $d\omega_1$ at angle θ, the singly scattered neutrons are further attenuated until the occurrence of the second scattering into $d\omega_2$, also at angle θ if the neutrons are to have a chance of entering the detector, and finally the doubly scattered neutrons are attenuated by the remaining part of the specimen. In this case θ may actually have all possible values, but because of the strong forward scattering, the most frequent values of θ are small; therefore we

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[19] R. B. Day and R. L. Henkel, Phys. Rev. **92**, 358 (1953).

[20] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, U. S. Atomic Energy Commission Report NYO-636, 1951 (unpublished).

[21] J. H. Coon (to be published).

assume $\cos\theta=1$ and $\sin\theta=\theta$. Also we neglect the effect of leakage of singly scattered neutrons out the side of the specimen. Consider the first scattering to occur at x_1 and the second at x_2. The rate at which neutrons are scattered twice into $d\omega_2$ and emerge in the direction of the detector is as follows, where the brackets indicate the individual processes mentioned above:

$$\int_{\omega_1}\int_{x_2=0}^{t}\int_{x_1=0}^{x_2}\left[Q\pi\left(\frac{d}{L}\right)^2 e^{-\sigma_t n x_1}\right]\left[n dx_1 \sigma_e(\theta) d\omega_1\right]$$
$$\times\left[e^{-\sigma_t n(x_2-x_1)}\right]\left[n dx_2 \sigma_e(\theta) d\omega_2\right]\left[e^{-\sigma_t n(t-x_2)}\right].$$

Integration over x_1 and x_2 is straightforward. Since $\sigma_e(\theta)$ is large only for small values of θ, the integral over ω_1 can be evaluated approximately by setting $\sigma_e(\theta)=\sigma_e(0)$ and integrating up to some θ_m which includes the forward lobe of the scattering angular distribution. An appropriate value of θ_m is $1/kR$ according to Feld *et al.*[20] The contribution to the observed transmission due to double scattering is given by

$$T_2/T_1=\tfrac{1}{2}\pi n t \sigma_e(0)\theta_m^2.$$

For 14.1-Mev neutrons on a lead specimen of 50% transmission, this ratio is 0.06.

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Nucleon Exchange Effects in the $B^{10}(d,p)$ Stripping Reaction

N. T. S. Evans,* *Cavendish Laboratory, Cambridge, England*

AND

A. P. French, *Physics Department, University of South Carolina, Columbia, South Carolina*

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The consequences of an exchange contribution to a specific stripping reaction are worked out in some detail. The particular transition considered is that which leads to the first excited state of B^{11} and which is forbidden by the angular momentum restrictions of ordinary stripping theory. The exchange calculation provides a fair measure of agreement with experiment on the angular distribution, yield, and energy dependence of the reaction. The relation of the present analysis to treatments of heavy-particle and spin-flip stripping is briefly discussed.

I. INTRODUCTION

IN 1954 Evans and Parkinson[1] reported a study of the $B^{10}(d,p)$ reaction at deuteron energies between 6 and 8 Mev. The angular distributions of the various groups of outgoing protons could be best fitted, using stripping theory, by assuming that the B^{10} nucleus captures a neutron with $l=1$ in order to form the ground state or any of the first four excited states of B^{11}. This conforms to shell model theory, according to which B^{11} will have the properties of the polyad p^7 and will, with increasing excitation, pass successively through the total angular momentum states $\frac{3}{2}$ (ground state), $\frac{1}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ under reasonable conditions of intermediate coupling.[2,3] There is the special difficulty, however, that conservation of angular momentum does not permit formation of a state $J=\frac{1}{2}$ by simple addition of a p-neutron to B^{10} ($J=3$). Thus it would appear that the first excited state of B^{11} could not be produced in a stripping reaction by this means if its spin is indeed $\frac{1}{2}$.

Experimental evidence supports the theoretical expectation that $\frac{1}{2}(-)$ is the correct spin/parity assignment to the 2.14-Mev level of B^{11}. The spin value is implied by the relative gamma-ray transition probabilities in $Li^7(\alpha,\gamma)$,[4] and by the isotropy of the p-γ angular correlation in the reactions $B^{10}(d,p\gamma)$ [5] and $B^{11}(p,p'\gamma)$.[6] More recently Wilkinson[7] has shown that the gamma-ray transition from the first excited state to the ground state of B^{11} is fast; from this and other evidence he concludes that it is $M1$ and hence that the excited state has odd parity. It is the concern of the present paper to fit the results of the deuteron stripping experiments into this scheme of things.

II. POSSIBILITY OF NUCLEON EXCHANGE

It was recognized at the time of the original stripping measurements on $B^{10}(d,p)$ that the angular distribution of the proton group Q_1 (leading to the first excited state of B^{11}) is distinctly anomalous and can only with difficulty be reconciled with $l_n=1$. To illustrate the anomalous character, we show in Fig. 1 an angular distribution of the ground-state protons Q_0 (extended

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* Now at Hammersmith Hospital, London, England (Medical Research Council).

[1] N. T. S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) **A67**, 684 (1954).

[2] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

[3] D. Kurath, Phys. Rev. **101**, 216 (1956).

[4] G. A. Jones and D. H. Wilkinson, Phys. Rev. **88**, 423 (1952), amended in Revs. Modern Phys. **27**, 77 (1955).

[5] J. Thirion, Ann. phys. **8**, 489 (1953).

[6] Bair, Kington, and Willard, Phys. Rev. **100**, 21 (1955).

[7] D. H. Wilkinson, Phys. Rev. **105**, 666 (1957).