The Elastic Scattering of Deuterons by Tritons*

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The differential cross section for the elastic scattering of deuterons by tritons has been measured in the energy range 0.96 Mev to 3.22 Mev. The angular range of data is between 44.3° and 126.4° in the center-of-mass system of coordinates. The values of the cross section have a minimum near 90°, and this minimum decreases steadily and moves to higher angles as the incident deuteron energy is increased. At 1.20 Mev the cross section at the minimum is equal to 0.130 barn, and at 3.22 it is 0.019 barn.

INTRDUCTION

INFORMATION concerning the interactions among the light nuclei has recently been extended at this laboratory to include a measurement of the differential cross sections for elastic scattering of deuterons by tritons as a function of scattering angle and incident deuteron energy. The range of laboratory deuteron energies is between 0.96 Mev and 3.22 Mev, and the angular range for most energies is between 44.3° and 126.4° in the center-of-mass system of coordinates.

The data presented in this paper and those in the preceding paper[1] on p-d scattering were obtained concurrently, using the same equipment. The results of the p-d scattering experiment were essential for completion of the work presented in this paper.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

A beam of collimated, monoergic deuterons from the Minnesota electrostatic generator was passed through a small volume scattering chamber filled with a mixture of hydrogen and tritium gas. Charged particles resulting from passage of the beam through the scattering chamber were detected and identified by a gas-filled proportional counter. This scattering chamber, counter, charge collection and measuring system, and pressure and temperature measuring systems have been previously described.[1,2]

The energy of the incident deuteron beam was controlled and measured by an electrostatic analyzer which operated on the molecular deuterium beam. For purposes of calibrating the energy scale and measuring the thicknesses of aluminum entrance windows to the scattering chamber, a proton beam was used to determine the point at which the 1.882-Mev[3] threshold of the $Li^7(p, n)Be^7$ reaction occurred.

TRITIUM HANDLING SYSTEM

Tritium was obtained and stored, when not in use, in the form of a sintered pellet of uranium tritide. This pellet was in turn contained in a small quartz bottle which was coupled to the scattering chamber and Wallace & Tiernan differential pressure gauge through a Pyrex stopcock.

Prior to use, the scattering chamber, pressure gauge, and quartz bottle were evacuated by an oil diffusion pump and a liquid nitrogen cold trap until a pressure of about 5×10^{-5} mm Hg was obtained. UT_3 is a stable compound at room temperatures and no measurable quantity of gas was lost by this evacuation procedure. The scattering chamber was then isolated from the pump and the UT_3 pellet was heated to about 400°C, evolving the tritium gas[4] directly into the scattering chamber and pressure gauge. When the desired pressure was attained (about 40 mm Hg) the glass stopcock was closed and the current in the heating element around the quartz bottle was reduced in order to maintain the uranium at about 100°C. At the end of 4 to 6 hours the tritium gas which had been used in the scattering chamber was purified by recycling through the uranium. The compound UT_3 was formed very rapidly if the uranium was maintained at about 100°C, and essentially all hydrogen isotopes in the gas sample were taken up within a very few minutes.

The sample of gas was composed of 98 percent tritium and 2 percent hydrogen when first obtained, but the quantity of hydrogen in the gas sample rose constantly during the experiment. The source of this hydrogen was traced to various hydrocarbons that were in or near the scattering volume. Data were taken with the fractional amount of tritium as low as 40 percent.

The method of measuring the percentage of tritium and hydrogen in the gas sample is discussed below.

IDENTIFICATION OF PARTICLES

It should be emphasized that when the deuteron beam passed through the scattering chamber filled with a mixture of tritium and hydrogen, a large number of different charged particles were observed in the proportional counter. Deuterons were scattered by tritons at all angles in the laboratory, recoil protons and recoil tritons could be counted between 0° and 90°, and at angles less than 30° two groups of deuterons which

* This research was assisted by the joint program of the ONR and AEC.

[1] Brown, Freier, Holmgren, Stratton, and Yarnell, Phys. Rev. **88**, 253 (1952).

[2] Claassen, Brown, Freier, and Stratton, Phys. Rev. **82**, 589 (1951).

[3] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).

[4] Spedding, Newton, Warp, Johnson, Nottorf, Johns, and Daane, Nucleonics **4**, 4 (1949).

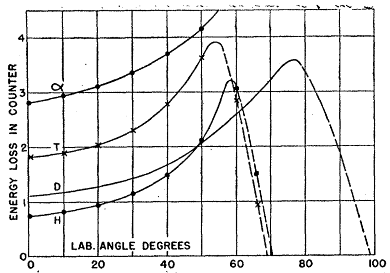

FIG. 1. Curves showing the loss of energy of scattered deuterons, recoil protons, recoil tritons, and alpha-particles in the proportional counter are plotted as a function of angle in the laboratory. The incident deuteron energy is 3.0 Mev.

were scattered by protons could be observed. In addition, alpha-particles from the reaction $T(d,n)\alpha$ were observed[5] at all angles. This last group, however, had a cross section that was small when compared to the other processes. It was absolutely necessary, therefore, that the various voltage pulses coming from the proportional counter be properly identified.

The groups of particles were identified by their relative pulse heights as recorded on a 10-channel pulse-height analyzer. These pulses were in turn proportional to the energy lost by the various charged particles when they passed through the counter. This energy loss for each group of particles was calculated as a function of angle and incident deuteron energy. The result of one such calculation is illustrated in Fig. 1. The incident beam energy in this case is 3.0 Mev. The energies lost (ΔE) by deuterons scattered from tritons, recoil protons, recoil tritons, and $T(d,n)\alpha$ alpha-particles are shown as a function of scattering angle in the laboratory system of coordinates. The ΔE for the two groups of deuterons scattered by protons at angles less than 30° are omitted. These particular curves were calculated assuming an aluminum counter window 130 kev thick for 2-Mev protons and a counter filling of 17 cm Hg of carbon dioxide and argon. Thinner counter windows and lower counter pressures were often used during this experiment, but in all cases the resulting pulse-height distributions could be interpreted by referring to Fig. 1 or similar curves.

Figures 2, 3, and 4 illustrate pulse-height distributions obtained at 34.5°, 49.8°, and 65°. Reference to Fig. 1 readily allows identification of the various groups of particles. It is of interest to note that at 34.5° the pulse resulting from a recoil proton is slightly less than that of a deuteron scattered from a triton, while at 50° the two have almost the same energy loss in the counter. At 65° (and higher angles) all particles except scattered deuterons and disintegration alpha-particles have been stopped in the counter window or produce pulses only slightly larger than normal counter noise. These data (Figs. 2, 3, and 4) were obtained by the methods described in reference 1. They represent the yield observed per mm Hg of gas pressure and per microcoulomb of incident deuteron charge collected.

[5] T. F. Stratton and George D. Freier, Phys. Rev. 88, 261 (1952).

MEASUREMENT OF THE PERCENTAGE OF TRITIUM

A study of Figs. 1, 2, and 3 shows that the pulse-height distribution resulting from the recoil protons was never completely resolved from both the scattered deuteron and recoil triton pulse-height distributions. Consequently, no direct method of obtaining the concentrations of hydrogen and tritium in the chamber could be carried out and the following somewhat indirect method was used.

At small angles in the laboratory, both recoil tritons and scattered deuterons were observed in the proportional counter. The recoil triton, at these angles, received its momentum from a deuteron scattered, in general, at some larger angle. For example, the yield of recoil tritons observed at 40° in the laboratory gave the laboratory cross section for scattered deuterons at 63.4°. In the laboratory 49.8° is the one angle where the yield of deuterons may be computed from the yield of recoil tritons or vice versa. A recoil triton which entered the detector at 49.8° had deflected a deuteron through an equal angle on the opposite side of the beam. At this angle the deuteron yields from two different peaks can then be obtained simultaneously provided the recoil triton yield is corrected for the larger solid angle presented to the tritons by the detector. The relationship in this case is $Y_D=0.750Y_T$, where Y_D and Y_T are the deuteron and triton yields, respectively. By applying this relationship to a pulse distribution such as shown in Fig. 2, the number of pulses in the left-hand peak caused by recoil protons can be determined. Utilizing this proton yield, knowing the cross section for production of recoil protons at 49.8°[1] and knowing the temperature and pressure of the gas in the chamber, the number of hydrogen scattering centers (and consequently the number of tritium nuclei) could be computed.

The tritium concentration was measured about 50 times and during the experiment was observed to decrease steadily from 98 percent tritium to 40 percent

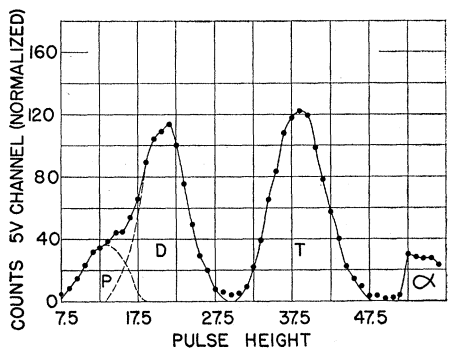

FIG. 2. Pulse-height distribution observed at 34.5°. The yields plotted are normalized per mm Hg pressure and per microcoulomb of charge collected. The abscissa is in volts. Particle groups may be identified by referring to Fig. 1.

tritium. For best resolution of the pulse-height distributions the measurement of tritium concentration was made at energies equal to or greater than 1.96 Mev. The measurement of tritium concentration was independent of the incident deuteron energy used.

METHOD OF OBTAINING DATA

The procedure after filling the scattering chamber was to first measure the percentage of tritium in the gas sample as described above. This value was used for all measurements during this chamber filling. Cross sections were obtained at least twice at each angle and energy—once for each positive and negative value of the scattering angle. If poor agreement existed, or if for some reason (e.g., low percentage tritium) one run appeared to be of doubtful value, additional data were taken. No consistent differences between positive and negative scattering angles were found, and the cross sections observed were independent of the relative amounts of tritium and hydrogen in the gas sample used in obtaining them. Since in the laboratory system of coordinates the cross section for recoil protons averaged between 3 and 7 times the cross section for scattering of deuterons by tritons, data taken with low tritium concentration were relatively less reliable and were generally repeated several times. The method of obtaining a cross section from pulse-height distributions illustrated in Figs. 2, 3, and 4 is discussed in reference 1.

Data were obtained by counting scattered deuterons at all laboratory angles and recoil tritons at small laboratory angles. Recoil tritons observed at small angles corresponded to deuterons observed at large angles (e.g., 34.5° corresponds to 71.65°). Cross sections obtained in these two different ways provided a check on the internal consistency of the data. In general, the agreement was very good, being somewhat less than the estimated errors (discussed below). At angles less than 50° (laboratory) the pulse-height distributions resulting from recoil protons and scattered deuterons were not separated and the expected yield of recoil protons

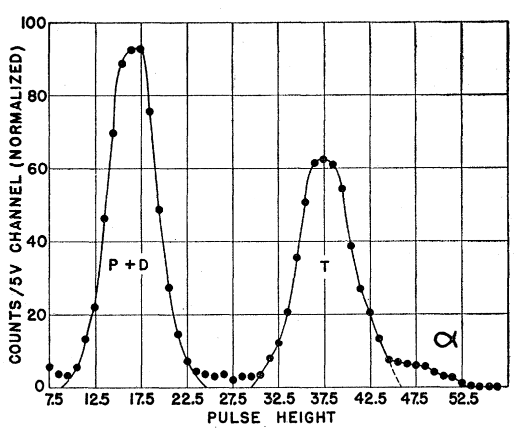

FIG. 3. Pulse-height distribution at 49.8°. At this angle protons and deuterons lose about the same amount of energy in the counter.

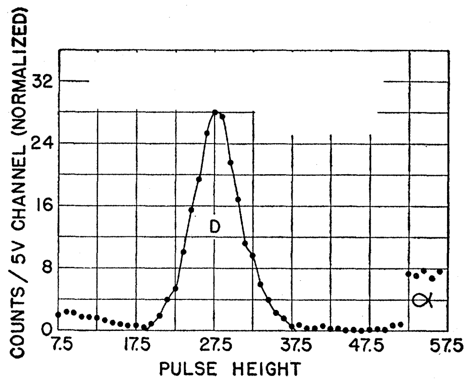

FIG. 4. Pulse-height distribution at 65°. At this angle all particles except scattered deuterons and alpha-particles from the $T(d, n)\alpha$ reaction have been stopped in the counter window.

had to be subtracted from the total peak. Since the percentage of hydrogen in the gas sample was measured for each chamber filling and the cross section for the recoil protons was known (reference 1), this could be done. Above 60°, only scattered deuterons (and alpha-particles) in general could enter the counter.

The largest laboratory angle studied during this experiment was 90° at 3.22 Mev. The maximum angle necessarily decreased as the energy was lowered. The reason for this upper limit is related to the mechanics of this scattering process and to the fact that a rare and radioactive gas, tritium, was used in the scattering chamber. At large scattering angles (above about 90°) a deuteron scattered by a triton retains only a small fraction of its original energy. In addition, it was necessary that the window in the proportional counter be made sufficiently thick in order that it be secure against breaks, leaks, and diffusion processes through it. Consequently, at high angles the deuterons were stopped in the counter window.

During the period that the gas was in the chamber, a very slow pressure rise was noticed. However, the total change in pressure was small, and several checks indicated that impurity scattering was negligible during the period of time mentioned above.

CORRECTIONS TO THE DATA

A correction to the percentage of tritium measured as discussed above was necessary. Reference to Figs. 1 and 3 shows that at 49.8° the voltage pulses resulting from a recoil triton and an alpha-particle differ only slightly. Very often (at this angle) the two pulse-height distributions were, therefore, not resolved. The differential cross section for the production of alpha-particles from the $T(d, n)\alpha$ reaction has been measured as a function of angle and energy,[5,6] and additional values were obtained during this experiment. The expected yield of alpha-particles was calculated and a small correction was made to the number of particles in the

[6] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

TABLE I. Summary of D-T scattering experiment. $\sigma(\beta')$ is the cross section in the center-of-mass system at the center-of-mass angle β', and $K^2=p^2/\hbar^2$ is the wave number squared of the incident deuteron in the c.m. system. Data were obtained by counting deuterons at the laboratory angle β or recoil tritons at the laboratory angle γ as indicated. At 90° c.m. the starred cross sections were obtained by counting deuterons while the remainder were obtained by counting tritons. The units of $\sigma(\beta')$ are barn/steradian.

Triton angle γ							45	40		34.5		31.6			26.8	
Deuteron angle β	26.8	31.6	34.5	40	45	49.8	56.3		65	75	75		80	83.8		90
Center-of-mass angle β'	44.3	52.1	56.7	65.4	73.2	80.4	90	100	102.2	110.85	115.15	116.75	121.1	125.4	126.4	131.8
Probable error of $\sigma(\beta')$	±9%	±6%	±6%	±6%	±6%	±5%	±5%	±5%	±5%	±5%	±5%	±5%	±5%	±5%	±9%	±5%
$E_D=0.96$ Mev $\sigma(\beta')$			0.195	0.204	0.158	0.181										
$k^2\sigma(\beta')$			0.650	0.680	0.526	0.603										
$E_D=1.20$ Mev $\sigma(\beta')$		0.148			0.133	0.133	0.131*					0.163				
$k^2\sigma(\beta')$		0.616			0.554	0.554	0.546*					0.678				
$E_D=1.46$ Mev $\sigma(\beta')$	0.151	0.138	0.119	0.112		0.101	0.097*	0.103	0.101	0.120		0.133				
$k^2\sigma(\beta')$	0.766	0.700	0.603	0.568		0.512	0.491*	0.522	0.512	0.608		0.674				
$E_D=1.97$ Mev $\sigma(\beta')$	0.103	0.094	0.077	0.072		0.059	0.059*	0.065	0.069	0.087		0.100			0.129	
$k^2\sigma(\beta')$	0.704	0.643	0.526	0.493		0.404	0.404*	0.445	0.472	0.595		0.684			0.882	
$E_D=2.21$ Mev $\sigma(\beta')$	0.086		0.072	0.058	0.052	0.046	0.047	0.052	0.055	0.069	0.077				0.114	
$k^2\sigma(\beta')$	0.660		0.552	0.445	0.399	0.353	0.361	0.399	0.422	0.529	0.594				0.874	
$E_D=2.46$ Mev $\sigma(\beta')$	0.090		0.067	0.056	0.050	0.036	0.034	0.038	0.042	0.055	0.069			0.112	0.113	
$k^2\sigma(\beta')$	0.768		0.572	0.478	0.427	0.308	0.290	0.324	0.359	0.470	0.589			0.959	0.966	
$E_D=2.71$ Mev $\sigma(\beta')$	0.084		0.064	0.052	0.043	0.031	0.027	0.030	0.034	0.045	0.057			0.094	0.109	
$k^2\sigma(\beta')$	0.790		0.602	0.489	0.404	0.291	0.254	0.282	0.320	0.423	0.536			0.884	1.025	
$E_D=2.99$ Mev $\sigma(\beta')$	0.091		0.060	0.044	0.041	0.028	0.023	0.024	0.025	0.036	0.047		0.070		0.099	
$k^2\sigma(\beta')$	0.944		0.622	0.456	0.425	0.290	0.239	0.249	0.259	0.373	0.487		0.726		1.027	
$E_D=3.22$ Mev $\sigma(\beta')$			0.054	0.042	0.032	0.026	0.022	0.019	0.021	0.031	0.041			0.092	0.081	0.139
$k^2\sigma(\beta')$			0.602	0.469	0.357	0.290	0.246	0.212	0.235	0.347	0.458			1.028	0.950	1.554

recoil triton peak and finally to the percentage of tritium. This correction was never greater than 2 percent.

Two corrections to the data were necessary because gas-to-wall-to-counter scattering processes produced extraneous counts. Figure 2 of reference 1 illustrates the appearance of a single group of particles as observed from this scattering chamber. A "tail" of particles whose energy when entering the counter was less than that of the principal group can be seen extending to higher pulse heights. This phenomenon was a function of angle and energy, being most significant at small angles and high energies. This "tail" of particles effected both its parent peak and any neighboring peak of higher pulse height.

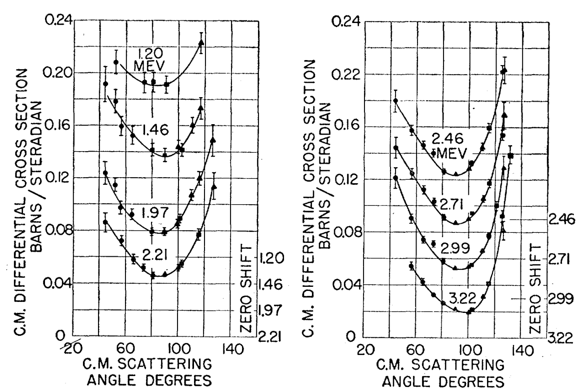

FIG. 5. The differential cross sections per unit solid angle for the elastic scattering of deuterons by tritons is plotted as a function of center-of-mass angle for various incident deuteron energies. Cross sections obtained by counting scattered deuterons which have been resolved from recoil protons are illustrated by squares. Circles represent data obtained from a pulse-height distribution consisting of recoil protons and scattered deuterons; the expected yield of protons was subtracted to obtain the yield of deuterons. Data obtained by counting recoil tritons are plotted as triangles. The zero for each energy is indicated at the right.

The first correction caused by this "tail" of particles was applied to the observed yields of recoil tritons. As is seen by Figs. 2 and 3 the pulse-height distribution resulting from the recoil tritons falls in a region which includes part of the "tail" associated with the yields of scattered deuterons and recoil protons. A correction was therefore made to all recoil triton data. This correction depended on the angle, the beam energy, the percentage tritium in the chamber, and the relative size of the voltage pulses in the two pulse-height distributions. The number of counts subtracted from the triton peak varied a great deal between individual runs. At the smallest angles it averaged about 4 percent. This correction was largest at the smallest angles, was relatively less at 45°, and was zero at all higher angles.

The second correction resulting from multiple scattering processes was applied to all data obtained at low angles. This was necessary since any one peak in the distribution had its own tail which extended into the main peak and would make the measured yield too large. As is discussed in reference 1, the corrections to be applied to these data were found by comparing p-p and d-p scattering data obtained by use of this chamber with published results.[7–9] The corrections for this second effect applied to all low angle data were −4.5 percent, −4 percent, −3 percent, −2 percent, and −1 percent at 26.8°, 31.6°, 34.5°, 40°, and 45°, respectively.

Data obtained at angles larger than 60° required a background correction since the entrance window and slits served as a source of neutrons and gamma-rays. The background counting rate caused by this radiation increased as the counter was moved to higher angles and hence nearer the source of radiation. In addition,

[7] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 553 (1948).

[8] Herb, Kerst, Parkinson, and Plain, Phys. Rev. **55**, 998 (1939).

[9] Sherr, Blair, Kratz, Bailey, and Taschek, Phys. Rev. **72**, 662 (1947).

the cross section is quite small in the angular region beyond 60°. Therefore, a background correction was made, when necessary, to data taken above 60° in the laboratory system. This correction fluctuated a great deal from run to run; it averaged about 4 percent. This effect was negligible for data obtained at angles less than 60°.

Errors in the data resulting from the finite size of the entrance slits and counter slits were negligible for this experiment.

RESULTS

The differential cross sections for the elastic scattering of deuterons by tritons in the center-of-mass system of coordinates are listed in Table I. Values of the cross section multiplied by the wave number squared of the incident particle are also included. The probable errors associated with these data (also listed in Table I) vary with angle. The error in $\sigma(\beta')$ was determined by consideration of errors in pressure measurement (± 1 percent), charge collection (± 1 percent), temperature ($\pm\frac{1}{3}$ percent), geometry (± 0.5 percent), uncertainty in measurement of tritium concentration, statistical error of each run, corrections to the data, and a consideration of the internal consistency of the data. The large error reported in data at 44.3° and 126.4° was associated with experimental difficulties which occurred in taking these data.

Figure 5 contains the results of this study in graphical form. Squares and triangles represent data obtained by counting scattered deuterons and recoil tritons, respectively, in resolved pulse-height distributions, while circles represent cross sections obtained after subtracting the expected recoil proton yield from a combined yield of recoil protons and scattered deuterons as is discussed above. The errors illustrated are probable errors. The point of the ordinate representing zero cross section for each energy is indicated on the right side of Fig. 5.

The incident deuteron energies were corrected for loss of energy in the entrance aluminum window and in the target gas. The energies are reliable to ± 20 kev at all energies except the lowest two which are considered reliable to ± 30 kev.

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The Angular Distribution of Alpha-Particles from the Reaction of Deuterons with Tritons*

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The distribution, as a function of angle, of the alpha-particles produced in the reaction of deuterons on tritons has been measured using a monoergic beam of deuterons from the Minnesota electrostatic generator. The alpha-particles were detected in the angular range of 40° to 140° in the center-of-mass system of coordinates for an incident deuteron energy of 2.21 Mev in the laboratory. The center-of-mass differential reaction cross section was flat at 8 millibarns from 40° to 90° and rose to about 13 millibarns at 140°.

INTRODUCTION

INFORMATION on the production of neutrons in the reaction of deuterons on tritons is best obtained by measurements on the yield of the associated alpha-particles. The reaction has been studied at Los Alamos[1] with incident deuterons in the energy range of 1 Mev to 2.5 Mev, and over an angular interval of 45° to 90° in the laboratory system. Interest in the reaction for theoretical considerations and as a possible source of fast monoergic neutrons caused an attempt to be made to extend the measurements on the alpha-particle yield to a wider angular range. The availability of an apparatus which allowed measurements in the angular range of 26.8° to 120° in the laboratory system of coordinates made such an investigation possible. Only one energy of incident deuterons was used, this being 2.21 Mev.

EQUIPMENT

A collimated beam of monoergic deuterons produced by the electrostatic generator was allowed to pass through a small volume scattering chamber filled with hydrogen and tritium gas. The alpha-particles produced in the reaction were detected as a function of angle by a movable proportional counter. The chamber and associated current and pressure measuring instruments have been discussed before.[2,3] The tritium handling system was discussed in the previous article.[4]

* This program assisted by the joint program of the ONR and AEC.

[1] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).

[2] Claassen, Brown, Freier, and Stratton, Phys. Rev. **82**, 589 (1951).

[3] Brown, Freier, Holmgren, Stratton, and Yarnell, Phys. Rev. **88**, 253 (1952).

[4] Stratton, Freier, Keepin, Rankin, and Stratton, Phys. Rev. **88**, 257 (1952).