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Angular Distributions of (n,d) Pickup Reactions in N^{14}, P^{31}, and S^{32} at 14 MeV*

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A double proportional counter-scintillator telescope was employed to study the angular distributions of deuterons produced by 14.1-MeV neutron-induced pickup reactions on natural targets of N^{14}, P^{31}, and S^{32}. Measurements were taken at intervals of 5°–15° over the laboratory range 0°–150°. Simultaneous measurements of E and dE/dx permitted separation of particles of different Z/M. Five angular distributions of deuterons corresponding to three ground-state and two excited-state transitions were obtained. Absolute center-of-mass differential cross sections were assigned. Neither significant isotropic contributions nor back-angle yields were observed. All spin and parity assignments were consistent with accepted values. Absolute reduced widths were extracted by the peak-fitting method and the Amado extrapolation procedure. Comparison of experimental and jj shell-model S values (relative reduced widths), in addition to observed jj-forbidden transitions, clearly indicated appreciable core excitations in the ground-state configurations of P^{31} and S^{32}. The $S^{32}(n,d)P^{31}$ (gnd.) measurements revealed a gross discrepancy in a previously reported cross section for the inverse $P^{31}(d,n)S^{32}$ reaction. An anomalously large reduced width for the transition to the 3.68-MeV level of C^{13} was qualitatively confirmed.

I. INTRODUCTION

BECAUSE of the experimental difficulties inherent in fast neutron studies, (n,d) and (d,n) reactions have received much less attention than their (p,d) and (d,p) counterparts. Of the more than 130 stripping and pickup reactions tabulated by Macfarlane and French,[1] only three are of the (n,d) type. This article reports measurements of angular distributions and absolute differential cross sections for (n,d) reactions induced in N^{14}, P^{31}, and S^{32} by bombardment with 14.1-MeV neutrons. The selection of N^{14} as a target was motivated by the apparent discrepancy noted in reference 1 between the reduced width for $N^{14}(n,d)C^{13}$ (3.68 MeV) as measured by Carlson,[2] and that for $N^{14}(p,d)N^{13}$ (3.51 MeV) as measured by Bennett.[3] Since the (p,d) result seemed reliable and much more reasonable from a theoretical standpoint, the disparity cast considerable doubt on the accuracy of the (n,d) experiment. Our observations, however, are in qualitative agreement with Carlson's, indicating that another explanation must be found to resolve the anomaly. The $P^{31}(n,d)Si^{30}$ and $S^{32}(n,d)P^{31}$ reactions have been reported recently by others,[4] but at the outset of this experiment they had been reported only in a preliminary study at this laboratory.[5] Our cross sections for these reactions are in excellent agreement with those reported by Velyukhof *et al.*,[4] but the measurements on S^{32} imply a gross error in the $P^{31}(d,n)S^{32}$ (gnd. state) cross section quoted by Calvert *et al.*[6]

II. APPARATUS AND EXPERIMENTAL PROCEDURE

Monoergic, 14.1-MeV neutrons were produced by means of the $T(d,n)He^4$ reaction using the 175-keV deuteron beam of a Cockcroft-Walton accelerator.[7] A BF_3 long counter,[8] calibrated with a Ra-α-Be source of known intensity, provided an absolute determination of the neutron flux. The observed mean variation in the calibration sensitivity of the neutron counting system was $\lesssim 1\%$.

The counter telescope (Fig. 1) consisted of two thin gas proportional counters for dE/dx measurement and a CsI(Tl) crystal cemented directly on the face of an RCA 6342A photomultiplier. This telescope, with an additional gas counter, was used previously by Hassler and Peck.[9] The crystal was cut and polished to a thickness of 46 mils, which is equivalent to a proton energy of 14.5 MeV. Great care was taken to insure that the proportional counters were free of hydrogenous contamination, surface leakage noise, and internal corona. The counters were filled with an Ar+5% CO_2 gas mixture to a pressure of 75–150 mm Hg determined by the energy of the outgoing deuterons of interest

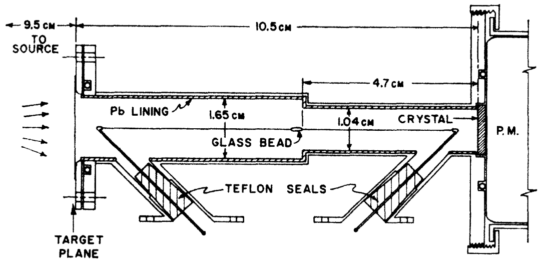

FIG. 1. Cross-sectional view of counter construction and geometry. Not shown is a thin aluminized Mylar foil which covers the CsI(Tl) crystal.

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† Submitted in partial fulfillment of the requirements for the Ph.D. degree at Brown University.

[1] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

[2] R. R. Carlson, Phys. Rev. **107**, 1094 (1957).

[3] E. F. Bennett, Phys. Rev. **122**, 595 (1961).

[4] G. E. Velyukhof, A. N. Prokof'ev, and S. V. Staroudubtsef, Soviet Phys.—JETP **12**, 395 (1961).

[5] H. P. Eubank, M. R. Zatzick, and F. L. Hassler, Bull. Am. Phys. Soc. **4**, 287 (1959).

[6] J. M. Calvert, A. A. Jaffe, A. E. Litherland, and E. E. Maslin, Proc. Phys. Soc. (London) **A68**, 1008 (1955).

[7] R. A. Peck, Jr., and H. P. Eubank, Rev. Sci. Instr. **26**, 444 (1955).

[8] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[9] F. L. Hassler and R. A. Peck, Jr., Phys. Rev. **125**, 1011 (1962).

(4–9 MeV). The telescope assembly mounting permitted rotation about a vertical axis through the target plane over a range of laboratory angle of 0°–150° in a plane normal to the deuteron beam. Source-counter geometry was relatively well defined and permitted a coincidence counting rate of approximately 4 counts/min for an assumed reaction cross section of 10 mb/sr, with a mass 30 target of thickness 10 mg/cm^2 and a neutron production rate of 2.5×10^9 n/sec into 4π. Neither chance coincidence nor dead time corrections were required for the above running rate. The observed background count rate at 0° corresponded to a minimum observable cross section of approximately 0.5 mb/sr. At large angles (120°–150°), the chance coincidence counting rate set this limit at about 2 mb/sr for practical running periods of 2–3 hours per angular setting.

The electronics system permitted two basic modes of operation: either the coincident average dE/dx pulse-height spectrum from the two gas counters could be displayed on the twenty-channel analyzer gated by a selected region of the scintillator E spectrum, or vice versa. Simultaneous measurement of E and dE/dx performed in this manner resulted in effective separation of particles of different Z/M. The ability of the counter to discriminate against protons and deuterons of the same average energy (at 12 MeV) was tested by observing the recoil proton and deuteron dE/dx spectra produced by neutron bombardment of thin polyethylene (CH_2) and deutero-paraffin (CD_2, 96% enriched) radiators. When the most probable energy loss for the 11.5–12.5 MeV deuterons was approximately 150 keV per counter, the overlap of the two pulse-height groups showed a $\approx5\%$ proton contamination for 100% deuteron count at equal particle energies and intensities. The theoretical dE/dx pulse-height spectra predicted by the Landau-Symon theory[10] for the above experimental conditions were in good agreement with the observed results.

As a precaution against systematic errors, the absolute differential cross section for (n,d) elastic scattering at a spectrometer setting of 0° (corresponding to a mean angle of $\approx6°$) was determined with the 10.5-mg/cm^2 CD_2 radiator. The measured laboratory value, 424 ± 28 mb/sr, agreed very well with the more accurate result given by Seagrave,[11] 404 ± 6 mb/sr at the same angle. The yield and energy resolution ($\approx6\%$) of the recoil deuteron pulse-height group provided a reliable and rapid check on the over-all system performance. It also permitted an accurate determination of the 0° fiducial index of the spectrometer angular scale because of the rapid fall off in differential cross section (500 to 50 mb/sr) over the first twenty degrees of laboratory angle. Targets of natural nitrogen, phosphorous, and sulfur were prepared in three different forms. Dry nitrogen gas, commercially available with a purity of 99.9%, was admitted to an evacuated brass, lead-lined, circular cylindrical cell of radius 0.95 cm and length 2.5 cm. Filling pressures of 1.2–2 atm were required to obtain useful yields. These pressures produced a convex bowing of the 2.5 mg/cm^2 titanium foil exit window which matched the concave surface of the counter window, minimizing contributions from the 1–2 mm air space between foils. However, since background measurements were made with the cell evacuated, in which case the gas cell window was also concave, a shimming spacer was used to adjust the air path to approximately the same length for both reaction and background runs.

Red phosphorus of commercial purity, supplied as a fine mesh powder, was suspended in acetone solution and allowed to settle out on a 25-mil lead backing over a known area and then dried. The thickness was determined by weighing before and after deposition. Of the three targets made, the thinnest (5.52 mg/cm^2) was selected because it provided an adequate yield and was also the most uniform. Sulfur targets prepared by the same method were intolerably nonuniform because of the formation of large grain clusters in solution. This difficulty was circumvented by utilizing the low melting point of sulfur: A molten smear was spread evenly over a freshly cleaned lead backing and quickly cooled. The resulting glassy-like surface provided a 3.6-mg/cm^2 target of excellent uniformity on the fourth attempt. A thicker target would have been desirable

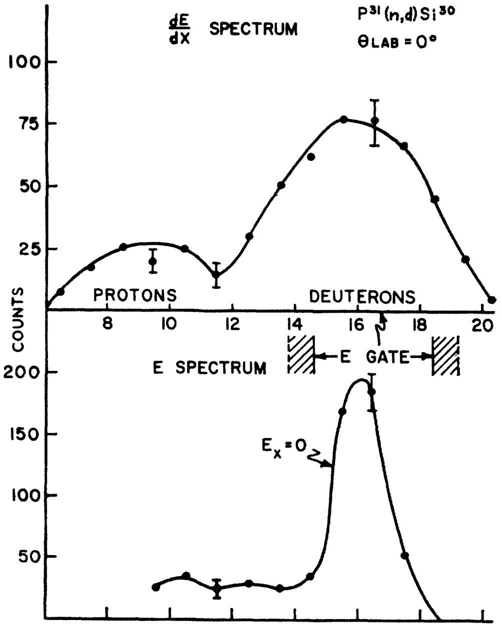

FIG. 2. Corresponding E and dE/dx spectra for the $P^{31}(n,d)Si^{30}$ (gnd.) reaction. Uncertainty in the E gate width is shown by the cross-hatched area.

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[10] K. R. Symon, Harvard University thesis, 1948 (unpublished); and B. B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952).

[11] J. D. Seagrave, Phys. Rev. **97**, 757 (1955).

TABLE I. Data summary.

Reaction	Final state E_x (MeV)	J^π	(r_0,l)	$(d\sigma/d\Omega)_{\mathrm{c.m.}}$ peak (mb/sr)	$\{C^2\}$	θ_{exp}^2 absolute	$S_{\mathrm{exp}}=\theta^2/\theta_0^2$	S_{ii}	S^*/S_g (exp)
[a] $\mathrm{N}^{14}(n,d)\mathrm{C}^{13}$	0	$(1/2)^-$	4.1, 1	10.4 ± 1.9	1/2	0.065	1.41	2.0	2.1
$E_n=14.1$ MeV	3.09	$(1/2)^+$	...	N.O. → (<0.5)					
$J_0^\pi=1^+$	3.68	$(3/2)^-$	4.1, 1	8.5 ± 1.5	1/2	0.12	3.0	2/11	
[b] $\mathrm{N}^{14}(n,d)\mathrm{C}^{13}$	0		4.5, 1	9.0 ± 1	1/2	0.05	1.1	2.0	3.64
$E_n=14.1$ MeV	3.09		...	N.O.					
	3.68		4.5, 1	12.5 ± 1	1/2	0.16	4.0	2/11	
[c] $\mathrm{N}^{14}(p,d)\mathrm{N}^{13}$	0	$(1/2)^-$	5.4, 1	$5.1\pm15\%$	1/2	0.046	1.21	2.0	0.61
$E_p=18.5$ MeV	2.37	$(1/2)^+$	5.0, 0?	$0.25\pm?$	1/2	<0.002			
	3.51	$(3/2)^-$	5.0, 1	$1.5\pm?$	1/2	0.026	0.74	2/11	
[a] $\mathrm{P}^{31}(n,d)\mathrm{Si}^{30}$	0	0^+	5.77, 0	19.3 ± 2.0	2/3	0.016	0.32	3/2	(2.5)
$J_0^\pi=(1/2)^+$	2.24	2^+	7.6, 2	1.2 ± 0.5	2/3	0.015	0.8		
[d] $\mathrm{P}^{31}(n,d)\mathrm{Si}^{30}$	0		5.1, 0	$19.2\pm15\%$	(1)	(0.012)		3/2	
$E_n=14.1$ MeV	2.24		...	N.O.?					
[a] $\mathrm{S}^{32}(n,d)\mathrm{P}^{31}$	0	$(1/2)^+$	5.71, 0	21.5 ± 2.3	1/2	0.02	0.5	4.0	
$J_0^\pi=0^+$	1.27	$(3/2)^+$	...	obs, weak (≈0.75)	1/2				
[d] $\mathrm{S}^{32}(n,d)\mathrm{P}^{31}$	0		5.1, 0	$18.2\pm15\%$	(1)	(0.011)		4.0	
$E_n=14.1$ MeV	1.27		...	obs, weak					
[e] $\mathrm{P}^{31}(d,n)\mathrm{S}^{32}$	0		5.5, 0	$1.9\pm50\%$	1/2	0.006	0.15	4.0	
$E_d=9$ MeV									

[a] This experiment. [b] See reference 2. [c] See reference 3. [d] See reference 4. [e] See reference 6. N.O. = not observed.

from the standpoint of yield, but would not have permitted adequate energy resolution of the 1.27-MeV level in P^{31}.

Since the Q value was known for each of the reactions studied, it was possible to preset the discriminator levels and the analyzer channel range in advance of each data run, thus insuring optimum counting and particle discrimination for each deuteron group. Selection of corresponding segments of E and dE/dx spectra was readily accomplished through the use of thick CH_2 and CD_2 radiators which provided a high-yield energy continuum of recoil protons and deuterons up to the maximum available energy. The shift in cutoff channels as a function of upper and lower level discriminator settings was easily observed and adjusted at moderate neutron production rates. This procedure, combined with a knowledge of the system energy losses and predetermined thin radiator deuteron energy calibration, permitted observation of the desired deuteron dE/dx pulse-height group gated by the corresponding slice of the E spectrum. A typical result of this method for the $\mathrm{P}^{31}(n,d)\mathrm{Si}^{30}$ reaction is shown in Fig. 2. Note that because of the low intensity of $\mathrm{P}^{31}(n,p)$ protons in the neighborhood of the deuteron ground-state group, proton-deuteron separation was almost complete. This was also the case for the other ground-state reactions, but was generally much less favorable for the excited states.

Comparison of the experimental angular distributions with the plane wave Butler theory[12] required introduction of a finite aperture smearing correction, since, e.g., at a spectrometer angle setting of $\theta_0=0°$, the actual scattering angle between an incident neutron and an outgoing deuteron entering the scintillator could be as much as 12°. Aperture or window functions of the spectrometer corresponding to selected angular settings were obtained by an approximate graphical-numerical procedure. They were used as weighting functions to obtain the average or smeared theoretical distribution in the laboratory system.[13] Finally, both the experimental and smeared theoretical distributions were transformed back to the c.m. system to present the comparison. The smearing correction is significant only in the region $\theta_0\leq20°$ since the width and symmetry of the aperture function about θ_0 remain relatively constant for larger counter angles.

Most of the total errors assigned to the differential cross sections were attributable to the counting statistics and to the neutron flux measurements. Under typical operating conditions, the chance count, dead time, and multiple-scattering corrections were negligible.

III. RESULTS AND DISCUSSION

Five angular distributions were measured and were fitted by plane wave Butler curves, with appropriate

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[12] S. T. Butler and O. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).

[13] F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).

aperture corrections as described above. In four cases excellent fits could be obtained using reasonable cutoff radii and assuming contributions from only a single l value. The spins and parities determined in this experiment were all in agreement with previous assignments. Each of the Butler curves was computed with the help of the Lubitz tables,[14] wherein the angle-dependent part of the Butler stripping differential cross section has been numerically tabulated in terms of the dimensionless functions, $\sigma_{\text{tab}}{}^{l}(x,y)$. When it was obvious that $l=0$, no difficulty was encountered in finding a reasonable radius for best fit. When $l\neq 0$, the graphical procedure of Lubitz was employed to determine the value of r_0, which, for the chosen l, placed the first (main) peak of the Butler curve at the same angle corresponding to the peak of the experimental distribution. The dimensionless reduced width θ^2 and the spectroscopic factor or relative reduced width $S=\theta^2/\theta_0{}^2$ were extracted as outlined in reference 1, wherein the proper empirical single-particle reduced widths $\theta_0{}^2$ have been defined and tabulated. A comparative data summary is given in Table I, which includes the pertinent published results of other workers.

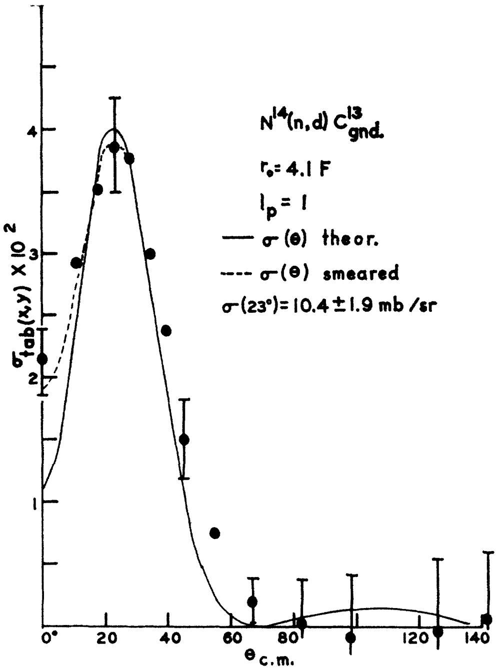

FIG. 4. Angular distribution of deuterons from the reaction $N^{14}(n,d)C^{13}$ (gnd.). The ordinate values are those of the dimensionless function $\sigma_{\text{tab}}{}^{l}(x,y)$ taken from the numerical tables of Lubitz (see reference 14). It is proportional to the square of the Wronskian and contains the entire angular dependence of the differential cross section. The error flags show statistical counting errors only.

A. $N^{14}(n,d)C^{13}$

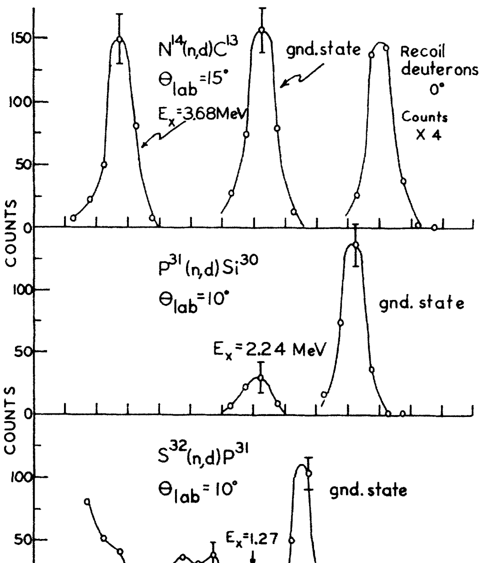

FIG. 3. Selected energy spectra for each of the indicated reactions. Each of the pulse-height groups is shown disconnected in the top and middle spectra because they were measured individually as discussed in Sec. II of the text.

The top of Fig. 3 shows the gated scintillation E spectrum of deuterons which leave C^{13} in its ground state and in its second excited level at 3.68 MeV. The first excited state at 3.09 MeV was not observed. The third peak, on the right side of the figure, is a recoil deuteron group observed with a thin CD_2 radiator. Each pulse-height group was observed individually, and the two $N^{14}(n,d)$ groups have been normalized to the same number of incident neutrons. The angular distributions of these two groups are shown in Figs. 4 and 5.

Deuterons from $N^{14}(n,d)$ reactions leaving C^{13} in its second ($3/2^-$, 3.68 MeV) and third ($5/2^+$, 3.85 MeV) excited states could not be distinguished experimentally at any one angle, so the "3.68 MeV" group undoubtedly contains some contribution from transitions to the higher level. The angular momentum selection rules restrict the possible orbital angular momenta to $l=1$ and 3 for the reaction to the 3.68-MeV state, and to $l=2$ and 4 for the transition to the 3.85-MeV state. Since the angular distribution shown in Fig. 5 is well fitted by an $l=1$ Butler curve, whereas an $l=2$ curve would peak at a larger angle, it may be concluded that the 3.68-MeV deuteron group contains no substantial contribution from reactions to the 3.85-MeV level. This is consistent with the expectation that the angular momentum barrier would inhibit a reaction in which $l=2$ relative to one in which $l=1$, apart from detailed considerations of the nuclear structure.

Of the other possible sources of contamination (to both groups) from the competing reactions $N^{14}(n;p,dn,t,He^3,\alpha)$, with Q values 0.63, -10.3, -4.01, -17.4,

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[14] C. R. Lubitz, "Numerical Table of Butler-Born Approximation Stripping Cross Sections," University of Michigan Report, 1957 (unpublished).

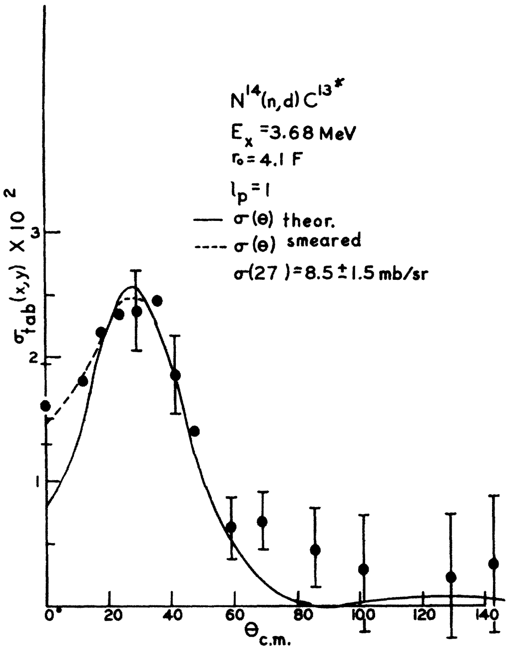

FIG. 5. Angular distribution of deuterons from the reaction $N^{14}(n,d)C^{13}$ (3.68 MeV). See caption of Fig. 4.

−0.157 MeV, respectively, only the triton contribution could not be eliminated on the grounds of Q value or mass-energy selection. Tritons from $N^{14}(n,t)$ reactions leaving C^{12} in its 0^+ (gnd.) and 2^+ (4.44 MeV) states of excitation would have laboratory energies of 9.57 and 5.32 MeV at the peak angles of the (n,d) angular distributions, $\theta_{\text{c.m.}} = 23°$ and 27°, respectively. As a result of the limited E and dE/dx resolution of the counter telescope, such tritons, if present, would not have been well separated from the desired 8.7- and 5.0-MeV deuteron groups at the corresponding angles. Because of the marginal triton discrimination and the aforementioned anomaly in the reduced width ratio, $S^*(3.68)/S(\text{gnd.})$, the possibility of triton contamination was examined in detail.

The relative energy losses of the deuterons and tritons which leave C^{13} and C^{12} in their respective ground states, taken as functions of laboratory angle, indicated that the most favorable place to observe the presence of a possible triton contribution to the angular distribution of Fig. 4 is at 0° in the E spectrum. This is also the best angle from the standpoint of the angular momentum transfer conditions, since $(l_p)_{\min} = 1$ for the (n,d) reaction, $(l_d)_{\min} = 0$ for the (n,t) reaction, and no reasonable choice of r_0 (4–8 F) will cut off the first main peak of the $l_d = 0$ distribution for the simple $j_0^2(qr)$ curve. A full Wronskian[15] and/or distorted wave treatment[16] might alter the above conditions somewhat. In any event, a separation in the E spectrum at 0° of at least 0.6 MeV, after initial losses, should have been realized, and a contribution of $>1 \pm 0.5$ mb/sr would not have escaped observation. The dE/dx separation of <100 keV would have been unresolvable. Since no irregularities of statistical significance were observed at 0°, the triton contamination at the forward angles was probably small. It is also possible that the second maximum of the $l_d = 0$ curve could overlap the first maximum of the $l_d = 2$ curve in the neighborhood of $\theta_{\text{c.m.}} = 20°–40°$ for reasonable values of r_0. If such contamination were present in this angular region, where partial separation in the E spectrum is still possible, it was not observed.

The best evidence favoring the smallness of the triton contamination of the ground-state angular distribution is the fact that the reduced width extracted from this (n,d) study, which agrees with that of Carlson[2] for the same reaction, also agrees with that of Bennett[3] for the $N^{14}(p,d)N^{13}$ (gnd.) reaction in which a triton contribution is energetically impossible. Although (p,He^3) is possible in the mirror reaction, Bennett's detector could discriminate almost perfectly against He^3 particles.

A reasonable estimate of the (n,t) differential cross section was obtained from the results of Johnston *et al.*[17] for the $C^{12}(He^3,p)N^{14}$ (gnd.) reaction (also $l = 0$, 2 allowed) measured for not too different incident and outgoing energies. The reciprocity relation gives a 0° cross section of ≈1.5 mb/sr for the (p,He^3) reaction. Except for Coulomb effects, the (n,t) cross section should have about the same value. This result is consistent with all of the above observations. It is interesting to compare the value of the measured[18] total cross section, 11±2 mb, for tritium production induced by U^{236} fission neutron bombardment of N^{14}, with the total ground-state cross section of ≈16 mb for the (p,He^3) reaction. This latter value is based on the inverse reaction of reference 17. Because of the negative Q value of the (n,t) reaction, only the fast portion ($\gtrsim 5$ MeV) of the fission neutron flux could contribute to the $N^{14}(n,t)C^{12}$ reaction, and only the transition to the ground state would contribute significantly. Thus, it appears that the (p,He^3) and (n,t) reactions leading to the same ground state of C^{12} have approximately the same total cross sections. If the angular distributions are also similar, we are again led to the conclusion that the triton contamination of the ground state deuteron angular distribution is small. Considering all of the evidence above, it seems highly unlikely that a possible triton contribution could affect the peak (n,d) cross section of Fig. 4 by more than 15%.

Quite similar arguments apply to the deuterons and tritons which leave C^{13} and C^{12} in their respective 3.68- and 4.44-MeV states of excitation. In this case, however,

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[15] S. T. Butler, Phys. Rev. **106**, 272 (1957).

[16] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[17] R. L. Johnston, H. D. Holmgren, E. A. Wolicki, and E. G. Illsley, Phys. Rev. **109**, 884 (1958). The ground-state angular distribution is quasi-isotropic with some indication of forward peaking.

[18] E. L. Fireman, Phys. Rev. **91**, 922 (1953).

the dE/dx spectrum near 0° favored possible observation of the tritons, since the deuterons and tritons were of virtually equal energy just prior to their entry into the dE/dx counter. The absence of tritons was indicated by the lack of any significant broadening of the dE/dx pulse-height group associated with the 3.68-MeV level of C^{13}. Because of the incomplete dE/dx resolution and the statistical uncertainties, however, these measurements could not easily be used to set an upper limit to the (n,t) cross section. Since the 4.44-MeV level of C^{12} has spin and parity 2^+, the allowed values of l_d are 0, 2, 4 and an (n,t) reaction to that state should have an angular distribution similar to that of an (n,t) reaction to the C^{12} ground state. The (n,t) cross section would be expected to be large at 0° and substantially smaller at the maximum of the (n,d) angular distribution. No important triton contamination of the (n,d) group would then be expected unless the cross section for the (n,t) reaction to the 4.44-MeV level of C^{12} were appreciably greater than that for the (n,t) reaction leaving C^{12} in its ground state. In view of the evidence cited above for the absence of tritons in the ground-state deuteron group, it seems reasonable to conclude that the triton contamination of the excited state deuteron group is also small. This contention is supported by the quality of the $l=1$ Butler fit of Fig. 5, as well as by the predictions of the configuration selection rules discussed below.

From the standpoint of the shell model, the 1^+ ground state of N^{14} in *jj* coupling is a C^{12} core plus $(p_{1/2})^2$, and, therefore, the unique $l=1$ transition to the $1/2^-$ ground state of C^{13} should have a large reduced width.[19] There are two equivalent nucleons (with isotopic spin formalism), and the coefficient of fractional parentage (cfp) is unity because there is only one possible parent state. Therefore, the spectroscopic factor in the limit of *jj* coupling is $S=2$. (Note that the isotopic spin coupling factor $\{C^2\}=1/2$.)

All of the other transitions to low-lying levels of C^{13} are unfavored by the model and/or the dynamics. For the transition to the 3.09-MeV $(1/2^+)$ level, only $l=0$, 2 are allowed; the first requires that the proton be picked up from an *s* state, while the second requires a *d* state, i.e., configurations $s^4p^8(2s)^2$ and $s^4p^8d(2s)$ would have to be present in the ground state. This argument is due to Standing,[20] whose study of the mirror reaction $N^{14}(p,d)N^{13}$ showed that there is essentially no contribution from these states. Accordingly, $S\approx 0$ for the (n,d) reaction to the $1/2^+$ state of C^{13}.

The results of this experiment for the $N^{14}(n,d)C^{13}$ (gnd.) and $N^{14}(n,d)C^{13}$ (3.09 MeV) reactions are in satisfactory agreement with the theoretical predictions as well as with the previous experimental (n,d) results of Carlson[2] and the (p,d) results of Bennett.[3] The observed differential cross section at the peak of the ground-state angular distribution was 10.4 ± 1.9 mb/sr, as compared to Carlson's 9 ± 1 mb/sr (or 8 ± 1 mb/sr with his isotropic component removed). The suggested weak intensity of the $p^8(2s)^2$ component[18] in the ground-state configuration of N^{14} is confirmed by the fact that no transition to the $1/2^+$ 3.09-MeV level of C^{13} was observed in either of the (n,d) experiments, and only a very small cross section was observed in the (p,d) reaction to the analog state at 2.37 MeV in N^{13}. Note that this low intensity of the $(2s)^2$ component would strongly attenuate the possible $l=0$, (n,t) transitions discussed earlier, and the other possible l values, (2,4), would be dynamically inhibited. This is consistent with the small triton contamination anticipated from the observations and arguments given earlier.

The $5/2^+$ state of C^{13} at 3.85 MeV is unfavored by both the dynamics and the model (*jj* or *LS*). Since only $l=2$, 4 are possible, the proton must be picked up from a *d* or *g* state, both of which are inhibited by the higher centrifugal barrier and incompatible with the 1^+ ground state of N^{14}. The theoretical expectation is confirmed by the observation, noted above, that no significant $l=2$ component is evident in the angular distribution of Fig. 5.

For the reaction proceeding to the 3.68-MeV $(3/2^-)$ state only $l=1$, 3 are allowed. The dynamics favors the lower value, but the model (*jj*) does not, since this would require the presence of some unlikely components in the ground state of N^{14}. The value[1] of S^* in the limit of *jj* coupling is 2/11, implying that the transition should be weak compared to that proceeding to the ground state. In the intermediate coupling model, the ratio of spectroscopic factors, S^*/S_g for the $N^{14}(p,d)$ reactions to the second excited $3/2^-$ and $1/2^+$ ground levels of N^{13} has been calculated[21] as a function of spin-orbit parameter ζ so normalized that $\zeta(N^{13})=\zeta(N^{14})$. Within the configurations $1p^n$, S^*/S_g is found to decrease monotonically from 2.26 at $\zeta=0$ (*LS* extreme) to 1/11 at $\zeta=\infty$ (*jj* extreme) for a Rosenfeld interaction. Thus, an experimental measurement of S^*/S_g for either $N^{14}(p,d)N^{13}$ or its mirror equivalent, should furnish an estimate of ζ. The measured values of S^*/S_g, given in the data summary table, indicate a value of $\zeta\approx 0$ (*LS* limit) for the (n,d) case, whereas the value $\zeta\approx 3.5$, given by the (p,d) results is closer to the usual value[1] of 4.

The large cross section for the $N^{14}(n,d)$ reaction to the 3.68-MeV level of C^{13} is in serious disagreement with the theoretical prediction and appears inconsistent with Bennett's measurement for the corresponding (p,d) reaction. This experimental result is, however, in approximate agreement with that of Carlson for the same (n,d) reaction. In the limit of *jj* coupling, the transitions to this level and to the ground state of C^{13} have theoretical spectroscopic factors in the ratio $S^*/S_g=1/11$, corresponding to a much smaller cross

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[19] J. B. French, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B.

[20] K. G. Standing, Phys. Rev. **101**, 152 (1956).

[21] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).

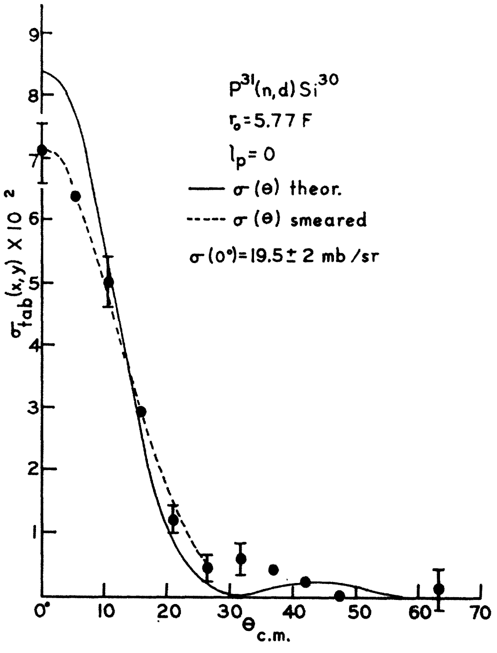

FIG. 6. Angular distribution of deuterons from the reaction $P^{31}(n,d)Si^{30}$ (gnd.). Measurements extended to 150° (lab). No significant yield observed. See caption of Fig. 4.

section for the reaction to the excited level. The experimental value of $S^*/S_g \approx 2.1$, although somewhat smaller than the value of 3.64 which follows from Carlson's data, is nevertheless an anomalous result. This latter ratio has been deduced from reference 1 without removal of the isotropic components observed in Carlson's angular distributions. Such removal would lead to approximately the same value of S^*/S_g obtained in this experiment.

Recent evidence which appears to support the observations in the (n,d) experiments is provided by the measurements of Cameron *et al.*[22] on $N^{14}(t,\alpha)C^{13}$ reactions proceeding to the several lowest levels in C^{13}. According to these authors the alpha group corresponding to the reactions to the 3.68- and 3.85-MeV levels is more intense than the ground-state alpha group by the factor 1.96.

Finally, it should be mentioned that the discussion in reference 1 of the N^{14} and C^{13} ground-state wave functions points out other discrepancies not yet understandable in the light of present theory. Evidently more experimental and/or theoretical work in the $A=13$, 14 mass region will be required to develop a more consistent picture.

B. $P^{31}(n,d)Si^{30}$

The only resolvable deuteron groups for which angular distribution studies were made are shown in Fig. 3. All sources of competing reactions could be ruled out either on the basis of Q values or mass-energy discrimination.

Figures 6 and 7 show the angular distributions of deuterons leading to the ground and first excited states of Si^{30}. The good and poor fits of the Butler curves to the respective $l=0$ and $l=2$ distributions appear to be typical of such behavior observed elsewhere[6] and consistent with the plane-wave assumptions of the theory. Measurements were also made at five angles between 90° and 150° (not shown), but no significant yield was observed.

The strong $l=0$ transition to the 0^+ ground state of Si^{30} is the only one allowed in strict jj coupling. Since it is favored by both the model and dynamics, the reduced width for separation of the P^{31} ground state into $Si^{30}(\text{gnd.})+p$ should be large. In fact, if the ground state of P^{31} were well represented by a pure $(s_{1/2})^3$ state and Si^{30} as a $(s_{1/2})^2$ state, the experimental ground-state spectroscopic factor, S_g, should approach the limiting value 3/2. This value follows from the fact that there are three equivalent nucleons (with isotopic spin formalism) outside the last closed shell and there are two parent states with $(\text{cfp})=1/\sqrt{2}$. The fact that the observed S value, 0.32, is much smaller, indicates that the above jj-state description is inadequate. The presence of the weak $l=2$ transition to the 2.24-MeV level of Si^{30} supports this conclusion, since the transition is forbidden in jj coupling. Data from stripping reactions have been used to obtain a rough estimate of the amount of core excitation in the ground-state wave function of P^{31}, which was estimated to be roughly 60–70% $(s_{1/2})^3$, with a major secondary component of about 25% $[(s_{1/2})(d_{3/2})^2]_{J,T=1,0}$. This last mixture is

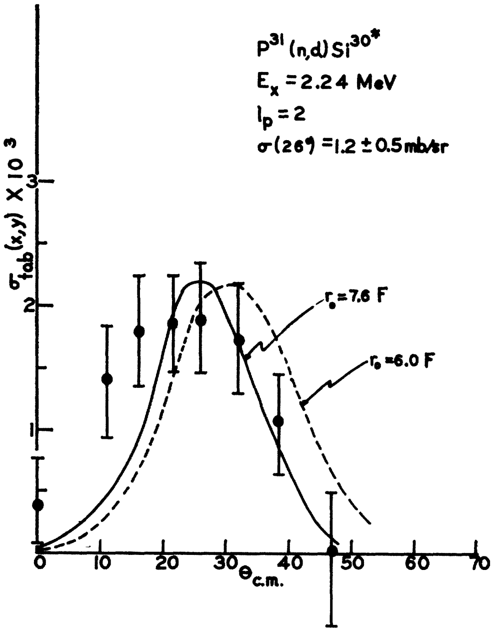

FIG. 7. Angular distribution of deuterons from the reaction $P^{31}(n,d)Si^{30}$ (2.24 MeV). See captions of Figs. 4 and 6.

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[22] L. M. Cameron, H. D. Holmgren, and R. B. Schwartz, Bull. Am. Phys. Soc. 6, 416 (1961).

just the configuration required to explain the $l=2$ transition to the 2^+ Si^{30} (2.24-MeV) level. Because of the large uncertainties in the excited-state cross section and the poor fit given by the Butler curve for this weak transition, a valid quantitative comparison could not be obtained. This point is effectively demonstrated by the large ambiguity in the reduced width determined for this reaction by the Amado extrapolation[23] shown in Fig. 8.

C. $S^{32}(n,d)P^{31}$

The energy spectrum for this reaction (Fig. 3, bottom) is quite similar to that obtained in the $P^{31}(n,d)$ case, in that there is a strong $l=0$ ground-state group, of about the same cross section, accompanied by a weak first excited state group. Unfortunately, a reliable angular distribution could not be carried out for this group. What appears to be a doublet group in channels 10–14 is, in fact, attributable to deuterons which leave P^{31} in its second excited state (2.23 MeV) plus deuterons from the ground-state transition $S^{34}(n,d)P^{33}$, $Q=-8.66$ MeV. Since the isotopic abundance of S^{34} is only 4.7%, the cross section for this reaction must be quite high if the above assignment is correct. There were no other sources of contamination from competing reactions.

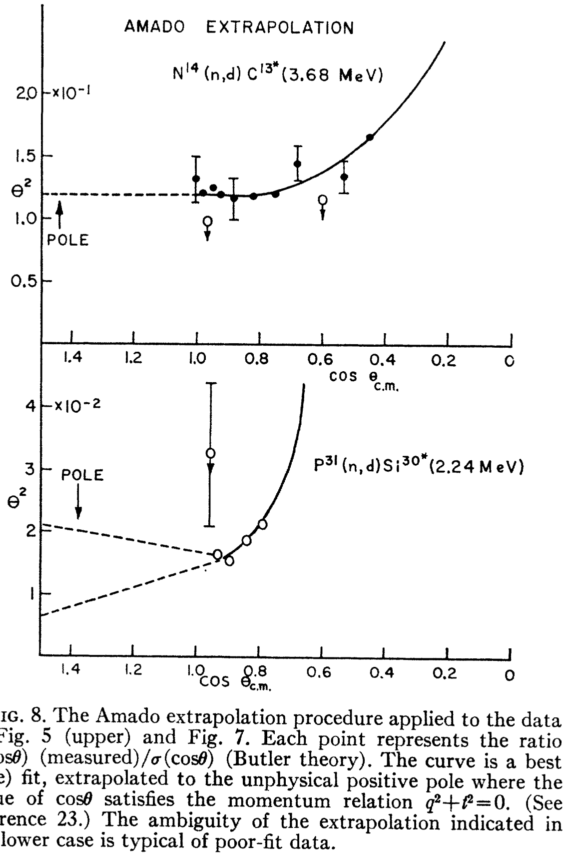

FIG. 8. The Amado extrapolation procedure applied to the data of Fig. 5 (upper) and Fig. 7. Each point represents the ratio $\sigma(\cos\theta)$ (measured)/$\sigma(\cos\theta)$ (Butler theory). The curve is a best (eye) fit, extrapolated to the unphysical positive pole where the value of $\cos\theta$ satisfies the momentum relation $q^2+t^2=0$. (See reference 23.) The ambiguity of the extrapolation indicated in the lower case is typical of poor-fit data.

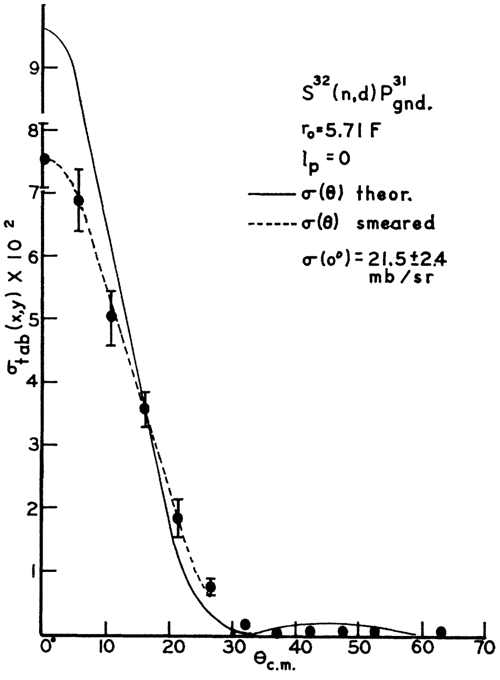

FIG. 9. Angular distribution of deuterons from the reaction $S^{32}(n,d)P^{31}$ (gnd.). See captions of Figs. 4 and 6.

The sharp rise in the count at lower channels is due mostly to protons from $S^{32}(n,p)P^{32}$.

The angular distribution of deuterons which leave P^{31} in its ground state is shown in Fig. 9. The quality of the fit is again consistent with earlier remarks given for $P^{31}(n,d)$; likewise the yield at back angles was unobservable. The $S^{32}(n,d)P^{31}$ angular distribution does not have any small secondary maximum like that at about 32° in Fig. 6.

The absolute differential cross sections measured for the $P^{31}(n,d)Si^{30}$ and $S^{32}(n,d)P^{31}$ ground-state reactions are in excellent agreement with those reported in reference 4. Before the Russian data were available to us, the only other measurement for comparison with our $S^{32}(n,d)$ cross section was that observed for the inverse reaction by Calvert *et al.*[6] Whereas the reciprocity relation predicted a ratio of $\sigma(n,d)/\sigma(d,n)=3.2$, the measured ratio was 11.2. Since the data of reference 4 support our (n,d) result, it is reasonable to conclude that the value reported for the (d,n) reaction is too small by at least a factor 3. The higher cross section for the pickup reaction arises from the spin factors in the expressions for the differential cross section.

Shell-model arguments similar to those offered for the $P^{31}(n,d)Si^{30}$ reaction apply here also. In this case, however, $S(\text{closed shells}\rightarrow s_{1/2}^{-1})=4$ is predicted for the unique $l=0$ ground-state transition. Such an S value would be expected if the ground-state configurations of S^{32} and P^{31} were well represented by a closed shell and a single hole $s_{1/2}$ state, respectively. The presence of core excitations in the S^{32} ground-state wave

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[23] R. D. Amado, Phys. Rev. Letters 2, 399 (1959).

function is clearly indicated by the small value, 0.5, of the observed S value and by the presence of excited states normally forbidden in strict jj coupling. Other observations[1] lead to the same conclusions. Unfortunately, one of the reactions used in reference 1 to set a lower limit of approximately 40% for the core excitations in S^{32} was based on the results of the (d,n) reaction of reference 6, which we now believe to be in error. A revised estimate should now be possible with the use of the new data. A quantity which should be less sensitive to the diminution in S_{jj} produced by core excitations is the ratio of the two experimental S values for the ground-state transitions induced in P^{31} and S^{32}. The difference in the spectroscopic factors reflects the presence of the extra $2s$ proton in S^{32}. The measured ratio is ≈ 1.7 compared to a predicted value of ≈ 2.7. This disagreement may not necessarily be serious, since the core excitations could be somewhat different for the two cases. Meaningful values of the ratios S^*/S_g could not be obtained, because the results for the excited-state cross sections and reduced widths were unreliable.

D. General Comments

Of the five experimental angular distributions shown in Figs. 4–8, four could be fitted very satisfactorily by using the plane wave Butler theory. It is well known that good fits have been obtained in many other cases, and this rather surprising success of the plane wave theory may be interpreted to imply either (a) that the Coulomb and nuclear distortions are small, or (b) that there is considerable degree of cancellation of the distortions produced by the (attractive) nuclear and (repulsive) Coulomb forces. The assumption of small distortion seems reasonable for the reactions studied in this work, because the incident particles were uncharged, the target nuclei were of low Z, and the bombarding energy was well above the Coulomb barrier.

Because large differential cross sections have been observed for other reactions at back angles,[24,25] the angular distribution measurements shown in Figs. 4–8 were extended in 15° steps to $\theta_{\text{c.m.}} = 155°$. In each case the cross section at large angles was too small to observe. From this result it may be concluded that heavy-particle stripping[26] is not important for these reactions at 14 MeV. Since backward-peaked angular distributions may also result from distortion of the incident and outgoing waves,[16,27] these observations also provide some evidence that such distortions are not large. According to Wilkinson,[28] the question of the conditions under which distortion and/or heavy-particle stripping become important in a given reaction is still very much open.

For each of the reactions studied here, the radius r_0 determined from the angular distribution was within 10% of the value given by the empirical formula $r_0 = 1.7 + 1.2A^{1/3}$ F. The radii obtained for the $l=0$ reactions on phosphorus and sulfur were almost exactly equal to the values given by the expression $r_0 = 4.37 + 0.042A$, which was obtained by Reynolds and Standing[29] from a survey of many (p,d) and (d,p) reactions on targets lighter than calcium.

The energy pulse-height spectra for the $N^{14}(n,d)$ reaction show a small maximum at about the right energy for deuterons which leave C^{14} in its ground state via the reaction $N^{15}(n,d)$. This maximum is too small to be statistically significant by itself, but a small bump at almost exactly the same place in the spectrum occurs in each of Carlson's[2] published pulse-height distributions. Since the abundance of N^{15} is only 0.4%, the cross section must be large if this identification is correct. Separated isotopes of N^{15} and S^{34} (discussed earlier) could easily be obtained, and (n,d) studies on these elements should be undertaken.

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[24] D. R. Maxson, Phys. Rev. **123**, 1304 (1961).

[25] H. D. Holmgren, Phys. Rev. **106**, 100 (1957).

[26] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).

[27] W. Tobocman, Phys. Rev. **115**, 99 (1959).

[28] D. H. Wilkinson, *Proceedings of the Conference on Nuclear Structure, Kingston, 1960*, edited by D. A. Bromley and E. Vogt (University of Toronto Press, Toronto, 1960), p. 2.

[29] J. B. Reynolds and K. G. Standing, Phys. Rev. **101**, 158 (1956).