Reactions ^{48}Ti$(n,d)^{47}$Sc, ^{16}O$(n,d)^{15}$N, ^{19}B$(n,d)^{9}$Be, and ^{6}Li$(n,d)^{5}$He at 14.4 MeV*

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(Received 11 March 1965)

The reactions ^{48}Ti$(n,d)^{47}$Sc, ^{16}O$(n,d)^{15}$N, ^{10}B$(n,d)^{9}$Be, and ^{6}Li$(n,d)^{5}$He have been studied at 14.4 MeV. The absolute differential cross sections have been analyzed using the distorted-wave method and assuming simple proton pickup. The effects of finite range, nonlocality, and radial cutoff have been investigated. Good fits obtained for the reactions ^{16}O$(n,d)^{15}N$(g.s.), ^{10}B$(n,d)^{9}$Be(g.s.), and ^{10}B$(n,d)^{9}$Be(2.43 MeV) yield spectroscopic factors in close agreement with shell-model predictions. The shape of the angular distribution of the reaction ^{48}Ti$(n,d)^{47}$Sc is well explained, but a discrepancy in absolute magnitude of about a factor 4 is not yet understood. The agreement between theory and experiment for the reaction ^{6}Li$(n,d)^{5}$He(g.s.) is not satisfactory, and this may indicate the importance of other processes such as knock-on.

I. INTRODUCTION

Experimental difficulties have made the (n,d) reaction the least investigated of all deuteron-stripping and pickup reactions. Until now only a few angular distributions of (n,d) reactions have been measured[1–4] and often the uncertainties were large both in the shape and in the absolute magnitude. The advent of counter telescopes[5,6] and multidimensional analyzers offers the possibility of performing extensive quantitative measurements of (n,d) reactions. Features of these measurements are good discrimination between various charged particles, low background, and the determination of the absolute cross section to an accuracy of approximately 10%. Now it becomes worthwhile to apply the distorted-wave method to the analysis of (n,d) reactions. They then become a valuable tool of nuclear spectroscopy, since they probe the proton configurations, while the commonly studied (d,p) and (d,t) reactions are concerned with the neutron configuration.

We undertook a systematic survey of (n,d) reactions at $E_n=14.4$ MeV: ^{6}Li$(n,d)^{5}$He; ^{7}Li$(n,d)^{6}$He; ^{10}B$(n,d)^{9}$Be; ^{14}N$(n,d)^{13}$C; ^{16}O$(n,d)^{15}$N; ^{19}F$(n,d)^{18}$O; ^{48}Ti$(n,d)^{47}$Sc; ^{51}V$(n,d)^{50}$Ti; ^{59}Co$(n,d)^{58}$Fe; and ^{197}Au$(n,d)^{196}$Pt. The angular distributions exhibit the characteristic features of direct interactions. The general trend of the differential cross section is to decrease as the atomic number of the target nucleus increases, the forward maximum being of the order of 10 mb/sr for $A\approx 10$ and decreasing to approximately 0.5 mb/sr for $A\approx 50$. Only an upper limit of 0.08 mb/sr can be placed for $A\approx 200$.

The first reaction we studied was ^{51}V$(n,d)^{50}$Ti, discussed in Ref. 7. Since that time a considerable improvement in the experimental arrangement has been achieved, primarily through the use of multidimensional analyzers. In the present work we extend the study of (n,d) reactions from medium-weight to light nuclei: ^{48}Ti, ^{16}O, ^{10}B, and ^{6}Li. Advances have also been made in the application of the distorted-wave method to the analysis of stripping reactions since the V(n,d) reaction was studied. It is now established that this method gives reliable results for medium-weight and heavy targets.[8] We have little reason to doubt that it will be equally successful if applied consistently to lighter nuclei, although some of the difficulties which arise in practice are discussed in Sec. IV.

The Q value for the reaction ^{48}Ti$(n,d)^{47}$Sc is $Q=-9.2$ MeV. There are no other data available for this reaction, although recently the reaction ^{48}Ti$(d,{}^{3}\text{He})^{47}$Sc was investigated.[9]

The reaction ^{16}O$(n,d)^{15}$N has the Q value -9.9 MeV. The angular distribution of deuterons was measured[2] at $E_n=14$ MeV and the authors claim a large differential cross section which reaches 75 mb/sr at the peak. This result contradicts the measurement[10] of the total cross section for the ^{16}O(n,d) reaction at 14 MeV, which yields 15 mb; it also disagrees with the measurement[11] of the inverse reaction ^{15}N$(d,n)^{16}$O. The measured exci-

* Research partly sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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[9] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).

[10] A. B. Lillie, Phys. Rev. **87**, 716 (1952).

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tation curve for the reaction $^{15}N(d,n)^{16}O$ does not give indications of sharp resonances in this energy region.

The Q value for the reaction $^{10}B(n,d)^{9}Be(gs)$ is -4.358 MeV. Using a beam of 14.4-MeV neutrons, levels of ^{9}Be up to 6.5 MeV of excitation can be investigated. The low-lying levels of ^{9}Be have been extensively studied. Inelastic scattering of protons,[12] deuterons,[13] alpha particles,[13] and electrons[14,15] at various energies from $\sim$10 MeV up to 185 MeV show that the levels at 2.43 and 6.8 MeV are in all cases strongly excited, while other levels are not. There is good reason to describe these two levels as the second and the third members of the rotational band with $K=\frac{3}{2}^-$ based on the ground state. The state at 1.75 MeV is still subject to discussion. Spencer *et al.*,[16] are inclined to interpret the anomaly at 1.7 MeV in the spectrum of inelastically scattered protons on ^{9}Be not as a state in the usual sense, but as "an aspect of spatial localization." According to the work of Jacobson[17] the spins and parities of the levels at 3.04 and 4.74 MeV are $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The only previous measurement of the reaction $^{10}B(n,d)^{9}Be$ is that of Ribe and Seagrave[3] at $E_n=14.4$ MeV.

The reaction $^{6}Li(n,d)^{5}He$ has the Q value -2.43 MeV. The angular distribution of deuterons leaving ^{5}He in the ground state and in the excited state has been measured[4] at $E_n=14$ MeV using nuclear emulsions.

II. EXPERIMENTAL ARRANGEMENT

In the arrangement used in this experiment the discrimination between various charged particles was such that, for example, a group of protons introduces only $\sim$2% uncertainty in a deuteron group of the same energy but of 10 times less intensity. The background, which was mainly due to random coincidences and charged particles from the reaction of neutrons with ^{16}O (propotional counters used to identify the charged particles were filled with CO_2), was low enough to permit detection of a group of deuterons with a cross section greater than or equal to 0.1 mb/sr, provided their energy was higher than 6 MeV. This limit gradually increases as the energy is reduced, and is $\sim$0.8 mb/sr at 4 MeV. The energy of a particular deuteron group can be measured with an accuracy of about 100 keV. However, in order to have a reasonable counting rate, one has to use poor geometry and thick targets, which prevent a good energy resolution. Two deuteron groups could be resolved if their separation was not smaller than 0.5 MeV. The accuracy of the absolute cross-section measurement was believed to be better than 10%.

In the present experiment charged particles were detected with the counter telescope[6] which is a combination of three gas (CO_2) proportional counters and a CsI(Tl) scintillation counter. The first proportional counter is placed in front of the target. Its role is to reject the detection of charged particles generated by neutrons in the front wall of the counters. This counter is therefore in anticoincidence with the other three counters, which follow the target. The second proportional counter is located immediately after the target. It reduces the background, helps to collimate the charged particles, and also prevents the large volume of gas in which the target is placed from acting as an additional target. The third proportional counter is used to determine the energy loss ΔE of a particle which passed through it. The scintillation counter, which follows this proportional counter, measures the residual energy of the same particle.

After the amplification stage, pulses from the proportional counters and from the scintillation counter are led into the coincidence-anticoincidence gating unit, wherefrom two pulses are derived, one proportional to ΔE and the other to E. These ΔE and E pulses are analyzed by a two-dimensional 100×100 channel analyzer.[18] The amplitude-to-time converter transforms these two pulses into numbers read by two independent scalers, and these are printed on paper tape by a printer. The neutron monitor and the analyzer input are gated off for the time the printer takes to print and reset, this time being about 0.4 sec. An electronic computer was used to sort the data in the final tables giving frequency of data versus ΔE and E.

The main advantage of this arrangement is the simultaneous display of proton, deuteron, and triton spectra in the final tables. The three-dimensional display of frequency of data versus ΔE and versus E enables one to distinguish different particles very accurately. The discrimination between different particles depends upon the resolution of the ΔE counter. In the present experiment the width of the ΔE spectrum at half-maximum for 7-MeV protons was 25%. For every E channel one can calculate the ΔE spectrum of various particles using the Landau-Symon theory.[19] The energy-loss spectra and the comparisons with the theoretical calculations for deuterons are shown in Fig. 1.

The calibration of the energy-loss counter and the energy counter was made using polythene and heavy paraffin targets partially covered with Al absorbers of known thickness. The resolution of the scintillation counter was found to be 4% for 14.4-MeV protons.

The angular resolution of the arrangement can be described by the width of the window function at half-

[12] G. Schrank, E. K. Warburton, and W. W. Daehnick, Phys. Rev. **127**, 2159 (1962); J. Benveniste, R. G. Finke and E.A. Martinelli, *ibid.* **101**, 655 (1956).
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[18] M. Konrad and B. Turko, Nucl. Instr. Methods **13**, 29 (1961); M. Konrad and V. Radeka (to be published).
[19] See, for example, B. B. Rossi's *High Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952).

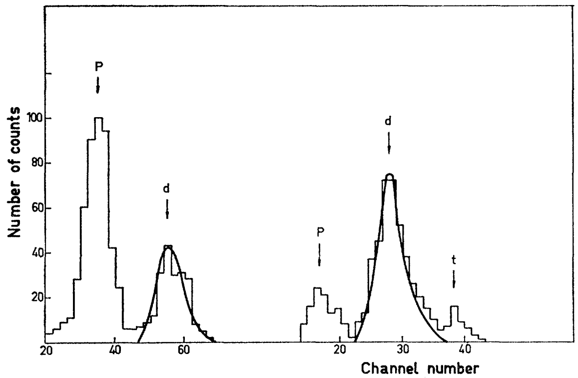

FIG. 1. Spectrum of energy losses ΔE for protons, deuterons and tritons in the dE/dx counter. The left side shows 4.5-MeV-protons and deuterons from the reaction $n+^{16}O$; the right side shows 7-MeV protons, deuterons and tritons from the reaction $n+^{10}B$.

maximum, which, for example, at 15 deg was 10 deg. The absolute cross sections were determined by comparing the number of deuterons detected for a given number of incident 14.4-MeV neutrons with the numbers of elastically scattered protons and deuterons from the polythene and heavy paraffin targets.[20] The over-all accuracy in the measurement of the absolute cross section was $\sim 8\%$ for the Li, B, and O targets and 15% for the Ti target.

The present experiment was performed using the Cockcroft-Walton 200-keV accelerator[21] at the Institute "Ruder Bošković." The 14.4-MeV neutrons were obtained from the $^3H(d,n)^4He$ reaction. The average neutron yield was 1.5×10^9 n/sec. The neutron flux was constantly monitored by counting the associated alpha particles with a scintillation counter. In order to control the stability of the monitoring system an additional discriminator was used, its lower limit being set at the alpha peak.

The scattering of neutrons from the surrounding wall produces neutrons degraded in energy and incident obliquely on the target. The relative amount of these neutrons compared with the monoenergetic 14.4-MeV group was estimated, using polythene and heavy paraffin targets, to be altogether less than 10%. Charged particles produced by these degraded neutrons result in a nearly flat background. The correction for this effect cannot be performed accurately. However, several checks showed that the error introduced into a particular deuteron group could not exceed 1 or 2%, and therefore it was neglected.

Targets

The titanium target was of TiO_2, 3.85 mg/cm^2 thick, deposited on a 28-mg/cm^2-thick gold foil by electrophoresis. For the measurement of the background a gold foil of the same size and thickness was used.

Two different oxygen targets were used. One was the above-mentioned TiO_2 target. The second target was the gas CO_2 with which the second proportional counter of the telescope is filled. The main problem was to determine the active volume of the CO_2 gas. On one side the volume is well defined by a 28-mg/cm^2 gold foil on the target wheel which divides the first anticoincidence counter from the second proportional counter. The determination of the total effective length of the gas target is based on the consideration of the minimum path through the second proportional counter necessary to obtain a pulse amplitude sufficient to trigger the coincidence unit. Also, only part of the counter volume is visible from the scintillation counter. On these considerations the total active volume of the gas CO_2 was estimated to be 53% of the entire quantitity of gas present in the counter. The pressure of CO_2 was 7.2 cm Hg. The total thickness of the CO_2 target was (0.6 ± 0.1) mg/cm^2.

Other elements like tungsten (anode wire), carbon (graphite lining of the proportional counters), silicon (glass ball on the end of the anode) etc., are also targets. The relative contribution of deuterons produced from (n,d) reactions on these elements was proved to be negligible.

The measurement of the reaction $^{197}Au(n,d)^{196}Pt$ yields an upper limit for the cross section ~ 0.08 mb/sr,[22] so that one can neglect the effect of the gold foil as well.

Bearing in mind that the gas target is eccentric relative to the rotation axis of the telescope which passes through the target wheel, we took care to correct the neutron-source–gas-target distance. The effective angle for every setting angle of the telescope was computed.

The boron target was made by depositing 94% enriched ^{10}B powder from a solution in acetone on a gold foil 16 mg/cm^2 thick. The thickness of the boron target was 2.33 mg/cm^2, its area 4.1 cm^2. To secure mechanical rigidity of the boron, a small quantity of celloidin was added.

The boron target contains 6% of ^{11}B. However, the Q value for $^{11}B(n,d)^{10}Be$ is -9.01 MeV, whereas for $^{10}B(n,d)^9Be$ it is -4.36 MeV. Deuterons from the $^{11}B(n,d)Be^{10}$ reaction could therefore influence only the low- energy part of the deuteron spectra, i.e., that part which corresponds to the transitions to the levels of ^9Be above ~ 5 MeV of excitation; and the influence could only be slight.

The presence of other impurities in boron powder, of which iron is the most abundant ($\sim 0.07\%$), could safely be ignored because of the relatively small cross sections for the $Fe(n,d)Mn$ reactions.

Hydrogen contained in celloidin results in a rather large number of recoil protons. However, neither these

[20] T. Nakamura, J. Phys. Soc. Japan **15**, 1359 (1960); M. D. Goldberg, V. M. May and J. R. Stehn, Brookhaven National Laboratory Report No. BNL-400, Vol. I, 1962 (unpublished).

[21] M. Paic, K. Prelec, P. Tomaš, M. Varicak, and B. Vosicki, Glasnik Mat.-Fiz. Astron., Ser. II **12**, 269 (1957).

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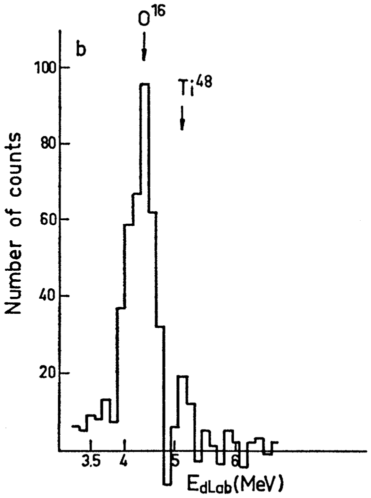

FIG. 2. The energy spectrum of deuterons induced by the neutron bombardment of the solid TiO_2 target. The background has been subtracted.

protons leaking into the deuteron region, nor deuterons produced by the capture process $n+p \rightarrow d+\gamma$, could appreciably distort the deuteron spectra.

The lithium target was of LiF, 5.1 mg/cm² thick, deposited on a lead foil. The Q value for the reaction $^6Li(n,d)^5He$ is -2.43 MeV, while for $^{19}F(n,d)^{18}O$ it is -5.74 MeV. Therefore, deuterons from (n,d) reactions on fluorine do not influence the ground-state group from ^6Li.

The background was measured using

(a) a PbF_2 target, 5.3 mb/cm³ thick, on a lead foil, and

(b) a lead foil identical to the ones on which the LiF and PbF_2 were deposited.

III. RESULTS

The energy spectra and angular distributions obtained in this experiment are shown in Figs. 2 through 12. The error bars on the experimental points in the angular distributions indicate only the statistical errors.

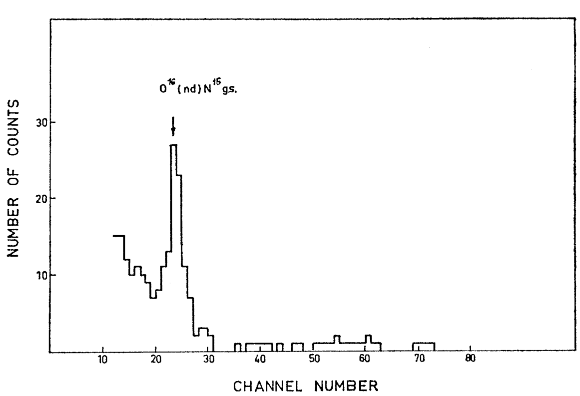

FIG. 3. The background spectrum at 0 deg. The group around channel 25 is due to the reaction $^{16}O(n,d)^{15}N$ (GS).

A. $^{48}Ti(n,d)^{47}Sc$

The spectrum of deuterons obtained at 0 deg from the neutron bombardment of the TiO_2 target is shown in Fig. 2. The $^{48}Ti(n,d)^{47}Sc$ (gs) group is just resolved from the pronounced $^{16}O(n,d)^{15}N$ (gs) group. The differential cross sections were measured at 9 angles between 0 and 105 deg (Fig. 7). At backward angles the cross section is certainly not bigger than 0.1 mb/sr.

B. $^{16}O(n,d)^{15}N$

The spectrum of deuterons from the $^{16}O(n,d)^{15}N$ reaction using the TiO_2 target is shown in Fig. 2.

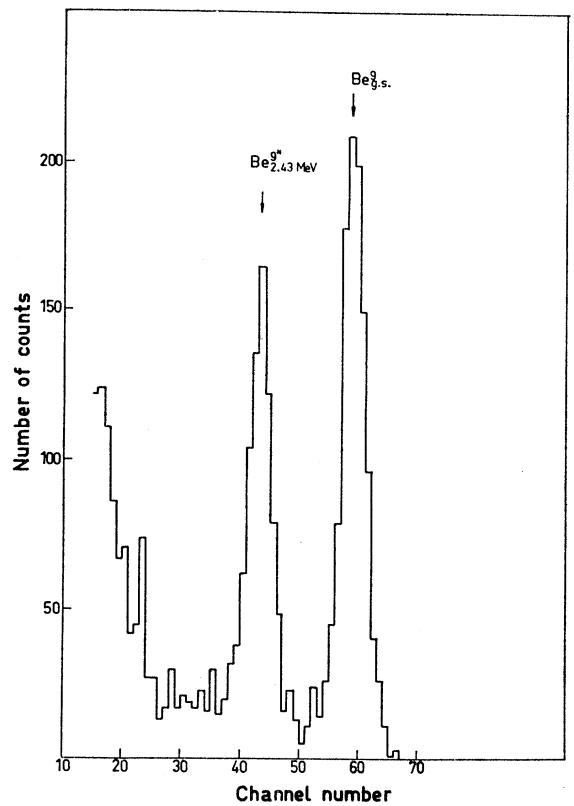

FIG. 4. The energy spectrum of deuterons from the reaction $^{10}B(n,d)^9Be$ at 0 deg, after the background has been subtracted.

Figure 3 shows the "background" spectrum (gas CO_2 in the second proportional counter), wherefrom the deuteron group corresponding to the reaction $^{16}O(n,d)^{15}N$ (gs) was extracted. The differential cross sections were measured at 12 angles from 0 to 70 deg (c.m.) (Fig. 9). It should be mentioned that the agreement between the results obtained with gas and with TiO_2 targets was very good.[23]

C. $^{10}B(n,d)^9Be$

The deuteron spectra from the reaction $^{10}B(n,d)^9Be$ reveal two pronounced peaks. They correspond to the

[23] G. Paić, I. Šlaus and P. Tomaš, Phys. Letters **9**, 147 (1964).

ground state and 2.43-MeV state in ^{9}Be. Figure 4 shows the spectrum obtained at 0 deg. The 2.43-MeV-state group is superimposed on a continuous spectrum which in that region is quite small but increases steeply at lower deuteron energies. The continuous spectrum is due to the fact[24] that above 1.66-MeV excitation, ^{9}Be can disintegrate into ^{8}Be$+n$. The sharp increase in intensity at low deuteron energy can be attributed to the simultaneous breakup into four particles: $\alpha+\alpha+n+d$, and to the contribution of the 6.76-MeV excited state in ^{9}Be. This region of the spectrum is also influenced by the presence of ^{11}B in the target.

There is no evidence in this experiment of any structure around 1.75- or 3.04-MeV excitation in ^{9}Be. The

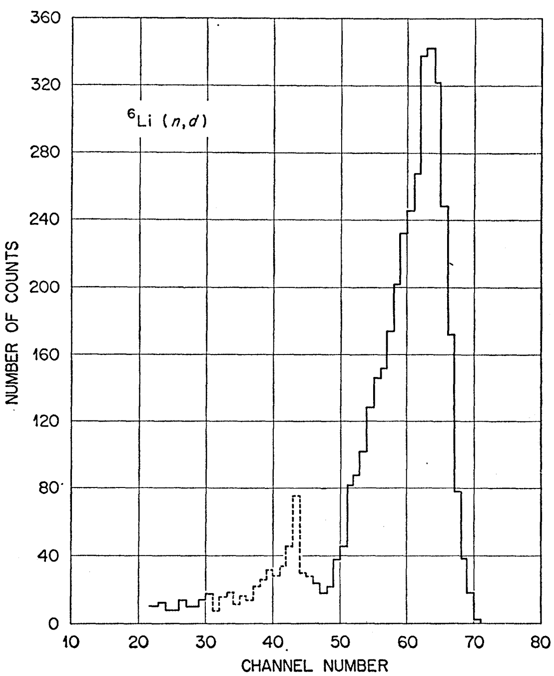

FIG. 5. The spectrum of deuterons from the reaction ^{6}Li$(n,d)^5$He. The target used was ^{6}LiF. The background and the contribution from the reaction ^{19}F$(n,d)^{18}$O have been subtracted. The region where the uncertainty in subtraction is larger than the statistical error is indicated by a dotted line.

upper limits for the cross sections for (n,d) reactions leading to excitations of 1.75 and 3.04 MeV are 0.08 0.08 mg/sr and 0.1 mb/sr, respectively.

The angular distributions of deuterons leaving ^{9}Be in the ground state and in the 2.43-MeV state are shown in Fig. 11.

D. ^{6}Li$(n,d)^5$He

Figure 5 shows the deuteron spectrum from a LiF target after the background and the contribution from the reaction ^{19}F$(n,d)^{18}$O were subtracted. The differential cross section was measured at eight angles from

[24] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).

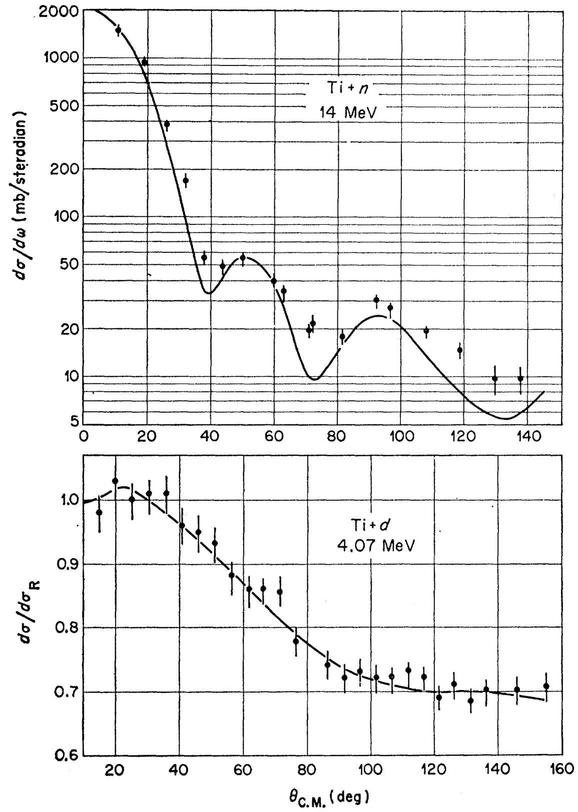

FIG. 6. Elastic scattering of neutrons (Ref. 30) and deuterons (Ref. 31) from Ti compared with the predictions of the optical potentials used in the present calculations.

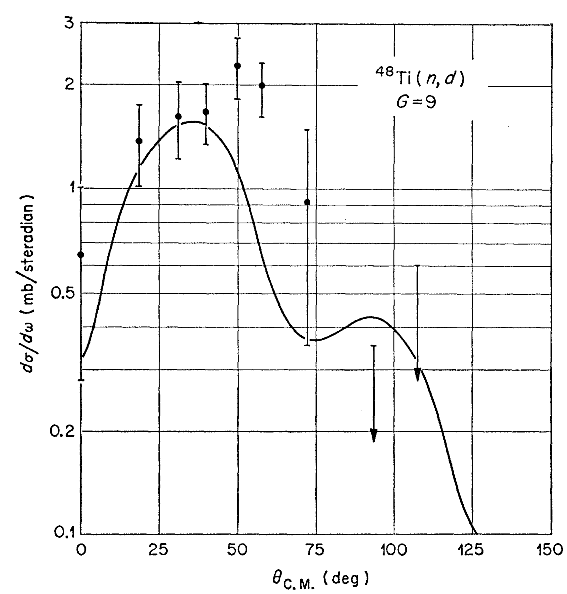

FIG. 7. Measured differential cross sections for ^{48}Ti(n,d) compared with zero-range distorted-wave predictions. The theoretical curve has been smeared to take into account the experimental angular resolution.

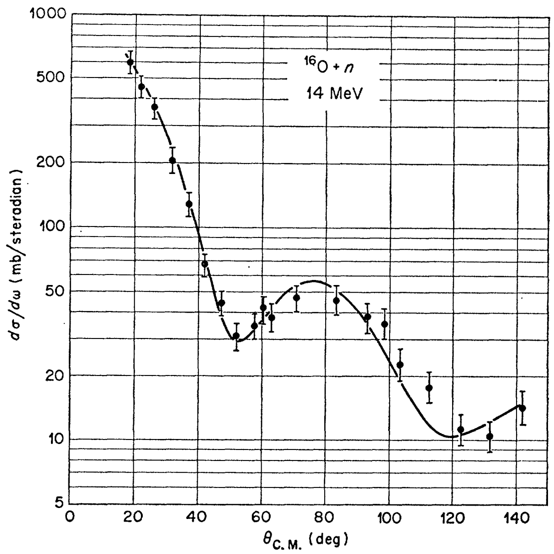

FIG. 8. Elastic scattering of neutrons (Ref. 33) from ^{16}O compared with the predictions of the optical potential used in the present calculations.

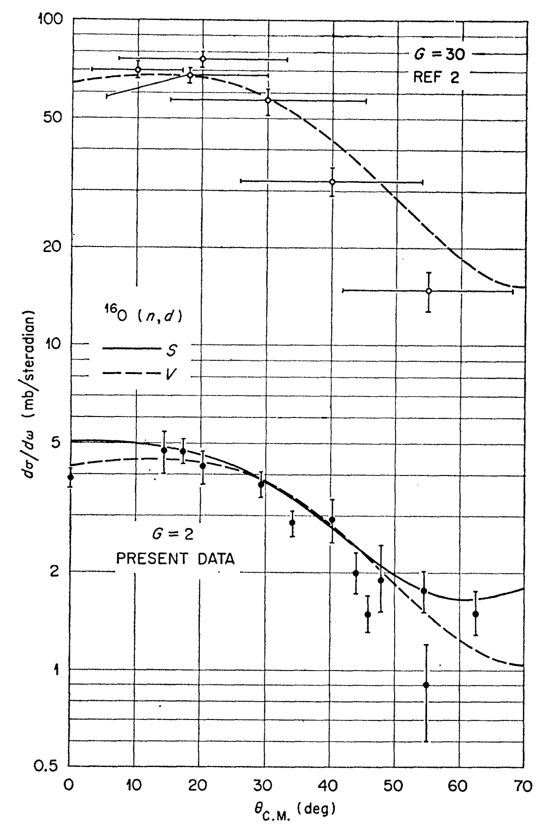

FIG. 9. Measured differential cross sections for ^{16}O(n,d) compared with distorted-wave predictions. The theoretical curves take exact account of finite range. S and V refer to the two deuteron potentials given in Table I. The effects of finite angular resolution are negligible in this case.

0 to 105 deg. The angular distribution of deuterons leaving ^{5}He in its ground state is given in Fig. 12.

IV. DISTORTED-WAVE ANALYSIS

Differential cross sections for the reactions considered here were calculated using the distorted-wave method[8,25] and assuming simple proton pickup. The predicted cross sections may be written in the form

$$d\sigma/d\omega=\sum_{lj} G_{lj}\sigma_{lj}(\theta)\,,$$

where l,j are the orbital and total angular momentum of the picked-up proton. When both the target and residual nuclear spins are nonzero, and configuration mixing is present, more than one value of l or j may

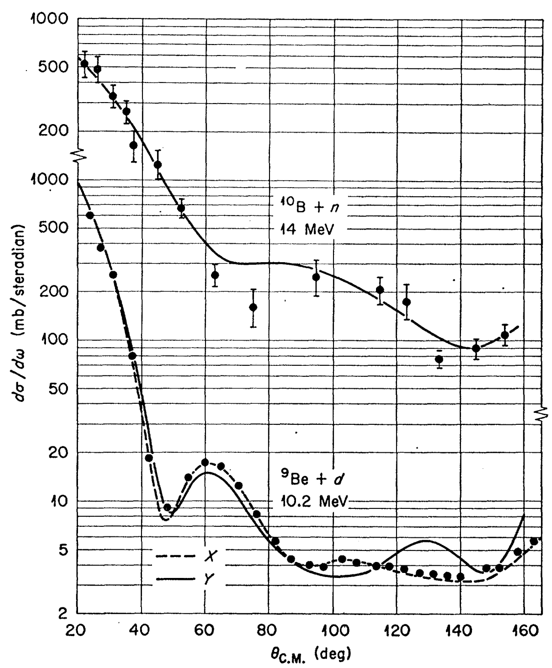

FIG. 10. Elastic scattering of neutrons from ^{10}B and deuterons from ^{9}Be compared with the predictions of the optical potentials used in the present calculations. X and Y refer to the two deuteron potentials given in Table I.

contribute. The quantity σ_{lj} is the "reduced" or single-particle cross section, and G_{lj} is the partial strength[26] for excitation of this particular final state by pickup from the l,j obrit. In principle σ should be calculated using optical-model potentials, which give a good account of the observed elastic scattering in the entrance and exit channels. In practice a compromise is often necessary, especially for the light nuclei studied here. The elastic scattering of 14-MeV neutrons has

[25] G. R. Satchler, Nucl. Phys. **55**, 1 (1964).

[26] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960); J. B. French and M. H. Macfarlane, Nucl. Phys. **26**, 168 (1961). The partial strength G is comprised of two factors, $G=S(C)^2$, where S is the spectroscopic factor and C the isospin Clebsch-Gordan coefficient.

been measured for many of these nuclei, and optical-model fits have been obtained. In most cases reasonable agreement is obtained using a potential similar to that of Perey and Buck,[27] although optimum fits often result from somewhat different parameters. Fortunately the predicted pickup cross sections are not greatly sensitive to the neutron potential used. This is not generally true of the deuteron potential, however. Although a large number of data are available for the elastic scattering of deuterons from light nuclei, and although it is usually possible to find good optical-model fits to these data,[28] a consistent set of parameters has not yet been found to give a good description of the scattering at different energies from the same nucleus, or from neighboring nuclei at the same energy. Perhaps it is not surprising to find fluctuations from nucleus to nucleus in this region, and it is also known that at the lower energies the cross sections for a given nucleus often exhibit strong fluctuations with changes in energy. In addition, the predicted scattering from these light nuclei is sensitive to quite small changes in the parameters.

This situation introduces considerable uncertainties into the parameters to be used in a reaction calculation when these have to be extrapolated from other nuclei and other energies. However, the main characterstics of the potentials are well established[28] and follow the trends exhibited by heavier nuclei,[29] namely a small radius and large surface diffuseness for the real part and a large radius for the imaginary part. For these reasons, the calculations reported here use parameters which are representative of these potentials and which do not necessarily give a very good fit to any particular observed scattering.

The potentials used have the form

$$U(r)=-V(e^x+1)^{-1}-i[W-4W_D(d/dx')]\times(e^{x'}+1)^{-1}+(\hbar/m_\pi c)^2V_s r^{-1}(d/dr)(e^x+1)^{-1}\mathbf{L}\cdot\boldsymbol{\sigma},$$
$$x=(r-r_0A^{1/3})/a,\quad x'=(r-r_0'A^{1/3})/a',$$

plus the Coulomb potential from a uniformly charged sphere of radius $r_cA^{1/3}$. For deuterons $\boldsymbol{\sigma}$ is the actual spin, and for nucleons it is the Pauli spin operator. The parameter values used are given in Table I. The bound proton is assumed to be moving in a potential of the same form as the real part of the optical potential, with the depth V adjusted to give a binding energy equal to its separation energy $(2.23-Q)$ MeV. Except where otherwise stated, the parameters $r_0=r_c=1.25$ F, $a=0.65$ F, and $V_s=8$ MeV were used for the bound proton. A general discussion of some of the uncertainties of distorted-wave calculations has been given elsewhere.[8]

[27] B. Buck and F. G. J. Perey, Nucl. Phys. 32, 353 (1962).
[28] G. R. Satchler (unpublished).
[29] E. C. Halbert, Nucl. Phys. 50, 353 (1964); C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

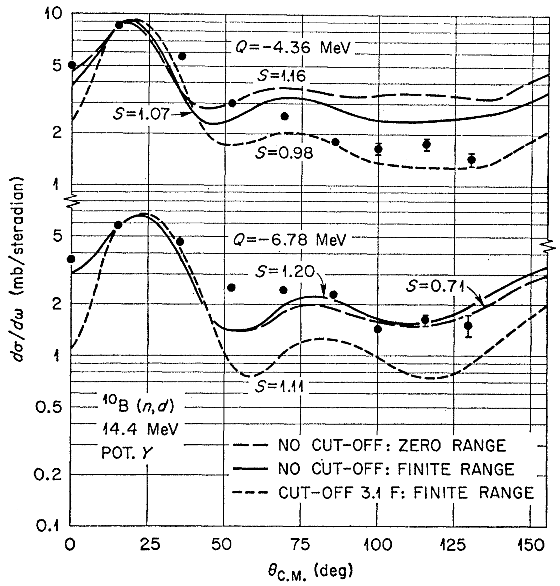

FIG. 11. Measured differential cross sections for the $^{10}B(n,d)$ reaction to the ground and first excited states of ^9Be. The theoretical curves are distorted-wave predictions using the spectroscopic factors quoted in the figure; they have been smeared to take into account the experimental angular resolution. Nonlocality and finite-range effects were calculated in the local energy approximation (Ref. 34). Deuteron potential Y (Table I) was used; potential X gives similar results.

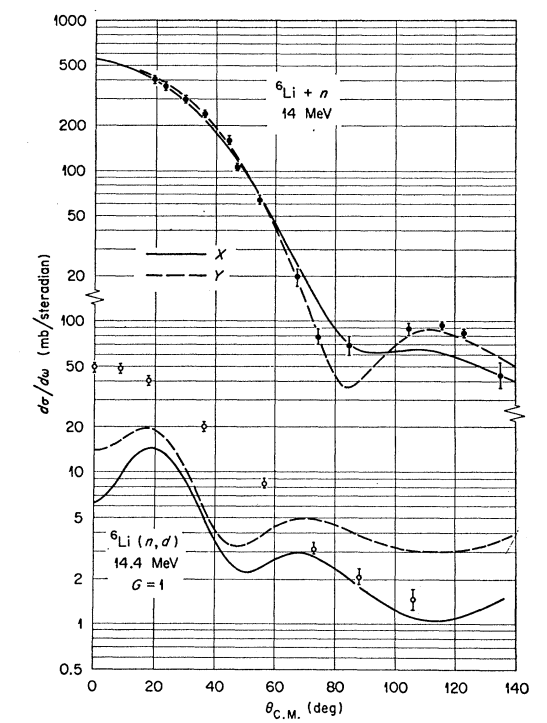

FIG. 12. Measured cross sections for the elastic scattering of neutrons (Ref. 37) from ^6Li and the $^6Li(n,d)$ reaction. The theoretical curves correspond to the two neutron potentials in Table I. The distorted-wave predictions were made in zero-range approximation, and do not include corrections for the experimental angular resolution.

TABLE I. Optical-model potential parameters.

	V (MeV)	r_0 (F)	a (F)	V_s (MeV)	W (MeV)	W_D (MeV)	r_0' (F)	a' (F)	r_c (F)
^{48}Ti									
d	100	1.00	0.90	6	0	17.5	1.50	0.60	1.3
n	44	1.25	0.65	6	0	9.5	1.25	0.47	···
^{16}O									
$d(V)$	110	1.00	0.80	6	3	0	2.34	0.47	1.3
$d(S)$	100	1.00	0.90	6	0	10	1.85	0.50	1.3
n	47	1.25	0.65	6	0	6	1.25	0.47	···
^{10}B									
$d(X)$	53.4	1.292	1.00	8	18.7	0	1.548	0.617	1.3
$d(Y)$	80	1.00	1.00	6	30	0	1.00	0.80	1.3
n	48	1.25	0.65	6	0	6	1.25	0.47	···
^{6}Li									
d	100	1.00	1.00	6	0	12.5	1.90	0.50	1.3
$n(X)$	44	1.25	0.65	6	0	9.5	1.25	0.47	···
$n(Y)$	42.8	1.40	0.48	5	0	9.5	1.40	0.44	···

A. ^{48}Ti$(n,d)^{47}$Sc

The optical-model parameters are quite well determined in this case. Both neutron[30] and deuteron[31,32] scattering from Ti have been measured at energies close to those met with in the (n,d) experiment, and the optical-model fits are shown in Fig. 6. Although the deuteron channel involves scattering from ^{47}Sc, this is not expected to introduce any significant changes. The calculated cross section is compared with experiment in Fig. 7. There is reasonable agreement in shape within the experimental uncertainties, but the strength $G=9$ required is much larger than the $G=2$ expected for an $(f_{7/2})^2$ proton configuration and measured previously in the ^{48}Ti$(d,^3$He) reaction.[9] The reason for this discrepancy is not understood at the present time. Previous (n,d) experiments on nuclei in this mass region have yielded cross sections of the correct order of magnitude.[1,7]

B. ^{16}O$(n,d)^{15}$N

An optical-model fit to 14-MeV neutron scattering[33] from ^{16}O is shown in Fig. 8. Deuteron scattering from ^{14}N at 10.9 and 11.8 MeV, and from ^{16}O at 8, 10.9, and 11.8 MeV, has been measured and analyzed, and the parameters given in Table I are representative of the results. The corresponding distorted-wave calculations give excellent agreement with the measured (n,d) cross section (Fig. 9), with the expected strength $G=2$ for pickup from the filled $p_{1/2}$ shell. These calculations include finite-range effects exactly[8]; a Gaussian-range function of range 1.25 F reduces the cross section calculated in zero-range approximation by a factor 0.76, without changing the shape by more than a few percent. No radial cutoff was used[8]; introducing one reduces the predicted cross section considerably and spoils the agreement in shape.

[30] C. St. Pierre, M. K. Machave, and P. Lorrain, Phys. Rev. **115**, 999 (1959).

[31] I. Šlaus and W. P. Alford, Phys. Rev. **114**, 1054 (1959).

[32] O. Hansen (private communication).

[33] R. Bauer, J. D. Anderson, and L. J. Christensen, Nucl. Phys. **47**, 24 (1963).

Nonetheless, the agreement in magnitude found here must be regarded, at least in part, as fortuitous. For example, calculations with another surface absorption potential for the deuterons led to $G\simeq 3$, although in the absence of the appropriate scattering data it appeared to be an equally acceptable potential. (It should be emphasized that all three potentials gave somewhat different elastic scattering for the exit channel, namely ^{15}N$+d$ at 3.713 MeV.) In addition, including the effects of nonlocality in the local energy approximation of Perey and Saxon[34] reduces the zero-range cross section by approximately $\frac{1}{3}$, although the effect would be less in a finite-range calculation. Nonlocality lengths of 0.85 F for the neutron and proton, and 0.54 F for the deuteron, were adopted without changing any of the other parameters.

Also shown in Fig. 9 are the results of another measurement[2] on this reaction at 14 MeV. Although the angular distribution is in good agreement with the present data, the cross sections appear to be too large (requiring $G\simeq 30$).

C. ^{10}B$(n,d)^{9}$Be

Figure 10 compares the measured 14-MeV neutron scattering from ^{10}B with the predictions of the optical model used in the present calculations. Data for deuteron scattering from ^{9}Be are available at 8 and 10.2 MeV, close to the energies (7.71 and 10.67 MeV) of the two deuteron groups observed in the present experiment. Good optical-model fits to these data can be obtained,[28] but unfortunately a single potential to fit both sets has not yet been found. The distorted-wave calculations presented here use two potentials, one (X) which gives a good fit to the 10.2-MeV data, and one (Y) which is representative of the other potentials, but which gives only qualitative agreement with the scattering data (see Fig. 10). Fortunately, the two give very similar (n,d) predictions, and only the curves for potential Y are shown here (Fig. 11).

Three theoretical curves are shown for each group in Fig. 11. The two broken curves were computed using the zero-range approximation, but did include the effects of nonlocality in the local energy approximation,[34] with nonlocal ranges of 0.85 F for the nucleons and 0.54 F for the deuteron. Nonlocality damps the contributions from the nuclear interior; for the ground-state group this reduces somewhat the cross section at angles greater than 40 deg, while the effect on the excited state group is to enhance and narrow the main peak at 20 deg. Finite range (using a range 1.25 F) further reduces the interior contributions, and calculations including this, also in the local energy approximation, are shown as solid curves in Fig. 11. The ground-state cross section is further reduced at wide angles, improving the fit to experiment, while the effect on the excited-state group

[34] F. G. Perey and D. S. Saxon, Phys. Letters **10**, 107 (1964); P. J. A. Buttle and L. B. J. Goldfarb, Proc. Phys. Soc. (London) **83**, 701 (1964).

is an almost uniform reduction in cross section by a factor of approximately 0.6. Also shown in Fig. 11 are the effects of using a radial cutoff which eliminates all contributions from inside 3.1 F; the corresponding curves for zero range are almost identical except for a reduction in magnitude of about 30% for the excited group and an increase of about 9% for the ground group. The cutoff gives better agreement for the ground state, but the excited-state cross section is now too low at wide angles. The use of an arbitrary and sharp cutoff is not very physical, but its effects give some indication of the contributions from the nuclear interior. The strengths G required are approximately $\frac{1}{2}$ for both transitions. Since the isospin Clebsch-Gordan coefficient[26] is $C^2=\frac{1}{2}$ in this case, the corresponding spectroscopic factors S are approximately unity, with that for the excited state approximately 10% larger. This is in excellent agreement with the values suggested by shell-model calculations.[26]

It has been suggested that there might be substantial contributions from $l=3$ pickup and stripping with these light nuclei, due to their being, in some sense, strongly deformed.[35] There are considerable uncertainties in the calculation of such contributions; the potential well of depth about 50 or 60 MeV which binds a $1p$ proton in ^{10}B does *not* bind a $1f$ proton. Adjusting the potential depth to bind a $1f$ proton by the separation energy (hence giving the correct asymptotic form to the proton wave function) requires a depth of over 100 MeV. Strictly both the $1p$ and $1f$ components of the proton wave function should be computed self-consistently, for example within a nonspherical potential well of finite depth. Such calculations are not available at present. In addition, invoking strong deformation effects of this type also suggests the possibility that second-order reaction mechanisms, involving inelastic scattering as well as pickup, may not be negligible.[36] In view of these remarks, it is not possible to deduce from the present data whether large $l=3$ admixtures are present. The angular distribution for a conventional $l=3$ pickup from ^{10}B is found to be rather structureless using the potentials described above.

[35] H. C. Meyer, W. T. Pinkston, and G. R. Satchler, Bull. Am. Phys. Soc. **8**, 553 (1963).

[36] S. K. Penny and G. R. Satchler, Nucl. Phys. **53**, 145 (1964); P. Iano and N. Austern, Bull. Am. Phys. Soc. **9**, 665 (1964).

D. ^{6}Li$(n,d)^5$He

Neutron scattering from ^{6}Li is compared in Fig. 12 to optical-model predictions for two potentials, one of which (Y) has been given as a best fit to the data.[37] Of course, data are not available for deuterons on ^{5}He but, for orientation, calculations were made using two deuteron potentials which describe the scattering from ^{9}Be. A volume-absorption potential gave unacceptable angular distributions which tend to peak at large angles; the predictions for the two neutron potentials with the surface-absorption deuteron potential are compared with experiment in Fig. 12, using a partial strength $G=1$; the proton is assumed to be moving in the same well as the neutron. If ^{6}Li consisted simply of a ^{4}He core plus a $(p_{3/2})^2$ configuration, we should have $G=1$. However, this is surely a gross oversimplification, and G is likely to be smaller. Inclusion of finite-range and nonlocality effects is expected to reduce the cross section further.

Further, it is not clear how well justified the usual truncated version of the theory[8] is when the target nucleus is so light. For example, the popular model of ^{6}Li as a ^{4}He core plus a deuteron might suggest appreciable contributions from a knock-on mechanism. Reliable calculations of these would require adequate treatment of the finite range of the *n-d* interaction, but this is not currently possible. Further, it is not clear at present what strength this interaction should have. The angular distribution for such a knock-on process is expected to be rather similar to that for pickup shown in Fig. 12.

ACKNOWLEDGMENTS

We are indebted to R. M. Drisko for making available the distorted-wave code "JULIE" and to J. K. Dickens and F. G. Perey for calculating the nonlocality and finite-range corrections in the local energy approximation.

[37] H. F. Lutz, J. B. Mason, and M. B. Karvelis, Nucl. Phys. **47**, 521 (1963).