Study of Reactions $^{10}B(p,d)^{9}B$ and $^{11}B(p,d)^{10}B$†

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Excited states of ^{9}B and ^{10}B were studied by means of the (p,d) reaction, using 33.6-MeV incident protons. Deuteron groups were observed corresponding to strongly excited levels in ^{9}B at 0.0-, 2.35-, 7.1-, and 11.75-MeV excitation and in ^{10}B at 0.0-, 0.72-, 1.76-, 2.15-, 3.57-, 4.75-, 5.10-, and 6.04-MeV excitation. Small deuteron yields were observed corresponding to excited states in ^{9}B at 2.8- and 14.6-MeV excitation and ^{10}B at 6.57- and 7.5-MeV excitation. The angular distribution for the elastic scattering of 33.6-MeV protons from ^{10}B was measured and fitted with an optical-model calculation to provide parameters for a distorted-wave Born-approximation (DWBA) analysis of the (p,d) data. Angular distributions were taken for all the levels strongly excited in the (p,d) reaction, and the results compared to a DWBA calculation. Spectroscopic factors were extracted and compared with theoretical intermediate-coupling calculations in the $1p$ shell and with other (p,d) and (d,t) results. Spin assignments were made for the levels of ^{9}B strongly excited in the (p,d) reaction. Difficulties in matching the shapes of the experimental angular distributions to DWBA calculations for pickup and stripping reactions involving light nuclei are discussed.

INTRODUCTION

THIS paper describes the results from the reactions $^{11}B(p,d)^{10}B$ and $^{10}B(p,d)^{9}B$, using a 34-MeV incident proton beam. It represents the continuation of a study of neutron pickup reactions on $1p$ shell nuclei; an earlier paper describes the results of (p,d) reactions at an incident proton energy of 34 MeV with targets of ^{6}Li, ^{7}Li, and ^{9}Be.[1]

The (p,d) reactions on ^{10}B and ^{11}B have been investigated previously with incident proton energies in the range 11 to 155 MeV.[2–4] However, a considerable amount of additional information could still be obtained by using a sufficiently high incident-proton energy and a solid-state detector system with good resolution capabilities. With this arrangement, the observable range of excitation energy in the residual nucleus included those levels known to be strongly excited in this reaction, and angular distributions for these states have been measured. Spectroscopic factors were extracted from the data and compared to the theoretical calculations of Kurath[5] and Balashov.[6]

EXPERIMENTAL METHOD

The experimental setup for these measurements was the same as that described in a previous paper.[1] A proton beam with an energy of 33.6±0.2 MeV was extracted from the Michigan State University cyclotron. The reaction products were detected by a ΔE-E counter telescope; the E counter was a 3-mm-thick lithium-drifted silicon detector, and the ΔE counter was a silicon surface-barrier detector with a thickness of 270 μ. The energy resolution obtained was 160 keV for the $^{11}B(p,d)^{10}B$ deuteron spectra and 120 keV for the $^{10}B(p,d)^{9}B$ deuteron spectra. The apparatus used to measure the elastic scattering of protons from ^{10}B was identical to that described in an earlier paper.[1]

The ^{10}B target was purchased from the Nuclear Division of the Oak Ridge National Laboratory. It consisted of a self-supporting boron foil, isotopically enriched to 92.15% ^{10}B, with a thickness of 165±5 $\mu g/cm^2$. The ^{11}B target was made by evaporating isotopically enriched boron (98.05% ^{11}B) on a carbon backing $\sim$50 $\mu g/cm^2$ thick, using an electron gun. Since the Q value for the reaction $^{12}C(p,d)^{11}C$ is $\sim$7.2 MeV more negative than the Q value for $^{11}B(p,d)^{10}B$, deuterons from the carbon backing do not interfere with the observation of the strongly excited levels of ^{10}B. In addition to these targets, natural-boron targets were made using a suspension of finely ground natural boron (80.22% ^{11}B and 19.78% ^{10}B) in a polystyrene binder. The natural-born targets were used to obtain the ratio of the ground-state cross sections for the $^{11}B(p,d)^{10}B$ and $^{10}B(p,d)^{9}B$ reactions; this ratio was then used together with the $^{10}B(p,d)^{9}B$ data to normalize the differential cross sections from the $^{11}B(p,d)^{10}B$ reaction data, and yielded a value of 53±4 $\mu g/cm^2$ for the thickness of the ^{11}B deposited on the carbon backing.

EXPERIMENTAL RESULTS

$^{10}B(p,d)^{9}B$

A deuteron-energy spectrum from the reaction $^{10}B(p,d)^{9}B$ is shown in Fig. 1. Deuteron groups were observed corresponding to strongly excited levels of ^{9}B at 0.0, 2.35, 7.1, and 11.75 MeV, and small deuteron yields were noted corresponding to weakly excited levels at 2.8 and 14.6 MeV (Fig. 2). The very broad, weakly excited level observed with a ^{9}B excitation energy (E_x) of 14.6 MeV may correspond to the level observed at E_x=14.9 MeV in the same reaction, using 156-MeV

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[3] D. Bachelier *et al.*, J. Phys. (Paris) C1, 51 (1966).
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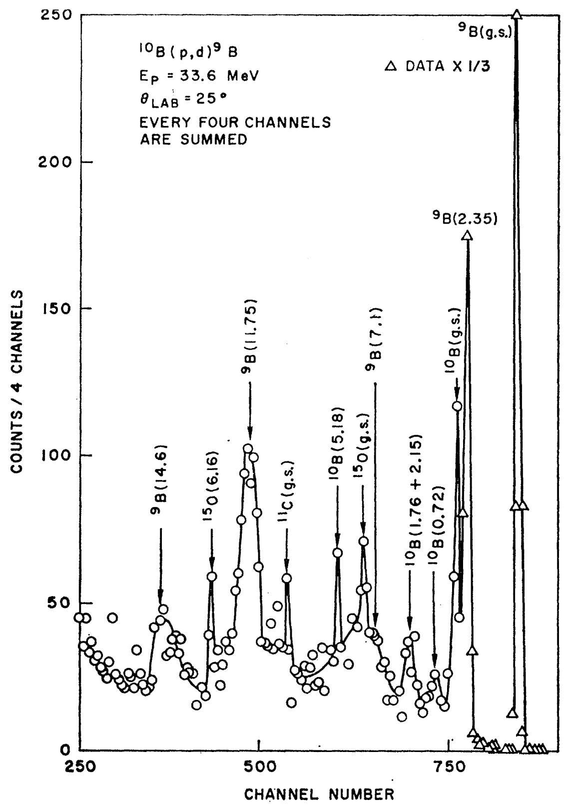

FIG. 1. ^{10}B$(p,d)^{9}$B deuteron spectrum at 25°. Deuteron groups corresponding to levels of ^{10}B are excited by the reaction ^{11}B$(p,d)^{10}$B and arise from an 8% ^{11}B impurity in the target. The counts have been summed for every four channels in order to show more clearly yields corresponding to ^{9}B levels at 7.1- and 14.6-MeV excitation.

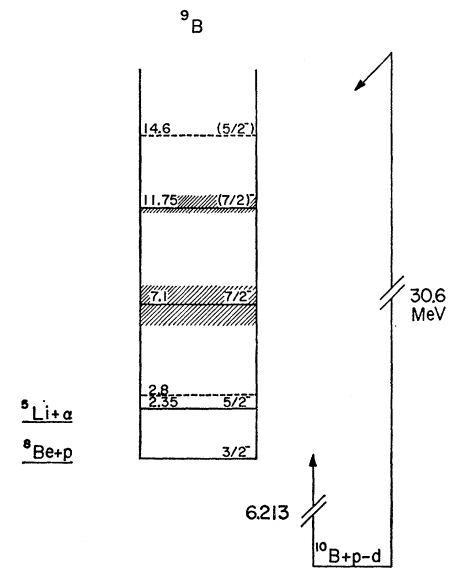

FIG. 2. Energy-level diagram of ^{9}B showing levels of ^{9}B excited in the ^{10}B$(p,d)^{9}$B reaction. Weakly excited levels are indicated with a dashed line.

protons.[3] With the higher incident proton energy, however, the 14.9-MeV level was reported to be strongly excited, with a cross section comparable to that of ground state at forward angles, whereas the present 34-MeV data show the 14.6-MeV level to have a cross section $\sim\frac{1}{10}$ that of the ground state at forward angles.

The two known positive-parity ^{9}B states at excitation energies of 1.5 MeV ($J^{\pi}=\frac{1}{2}^{+}$) and 2.83 MeV ($J^{\pi}=\frac{3}{2}^{+}$, $\frac{5}{2}^{+}$) [2,7] are of special interest, since their presence in the spectra could denote evidence of $2s$-$1d$ shell admixtures in the ground-state wave functions of stable nuclei with $A\leq10$.[1] No evidence was found for the excitation of the 1.5-MeV level, which corresponds to the 1.67-MeV level of ^{9}Be($J^{\pi}=\frac{1}{2}^{+}$); however, results from the ^{10}B$(p,d)^{9}$B reaction using 11-MeV protons show a level at 1.7 MeV very weakly excited by what appears to be a compound-nucleus mechanism.[8] While the 1.7-MeV level is not observed in this investigation, the present 34-MeV data do not rule out the possibility of the same degree of excitation.

A small deuteron group ($E_x=2.8$ MeV) with a differential cross section of approximately 120 μb/sr was observed at about 30° (center-of-mass angle), but it was difficult to follow over an extended range of forward angles because of the masking effect of levels arising from an ^{11}B impurity in the target (see Fig. 1). At 60°,

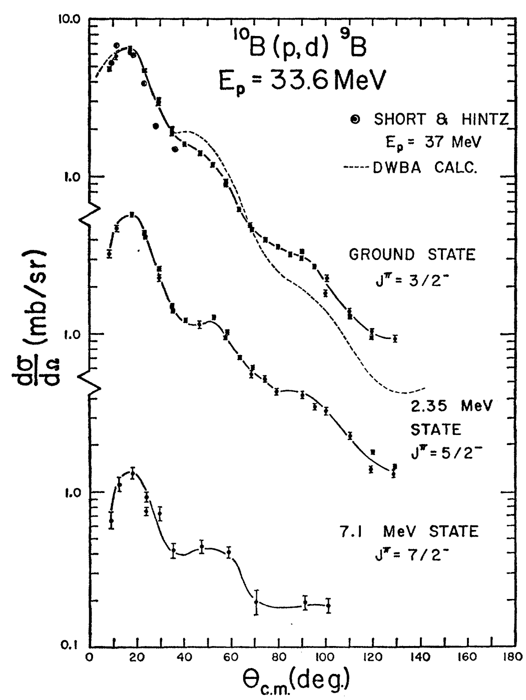

FIG. 3. ^{10}B$(p,d)^{9}$B angular distributions for deuteron groups corresponding to ^{9}B levels at 0.0, 2.35, and 7.1 MeV. The error bars only represent statistics, and the solid lines are drawn in to guide the eye. The dashed line shows the results of a DWBA calculation. Data points from work done at $E_{n}=37$ MeV (Ref. 4) are also shown.

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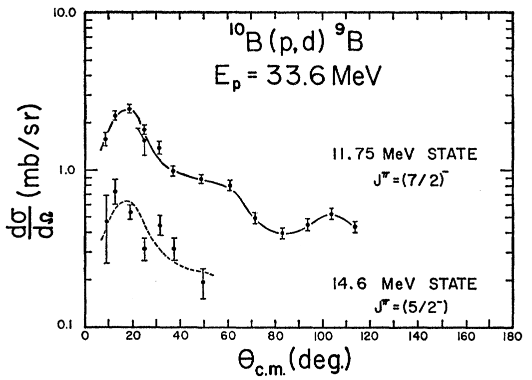

FIG. 4. $^{10}B(p,d)^9B$ angular distributions for deuteron groups corresponding to ^9B levels at 11.75 and 14.6 MeV. The dashed line drawn through the 14.6-MeV data points has the same shape as the line drawn through the 11.75-MeV data points

where it would not be masked by the deuteron groups arising from the ^{11}B impurities, it was not observed. This could signify a rapidly decreasing cross section typical of a direct-reaction process, and therefore opens the possibility for an observable $2s$-$1d$ shell admixture in the ground-state wave function of ^{10}B. The evidence, however, is scanty at best, and the only definite conclusion one can draw is that any $2s$-$1d$ admixture in the ^{10}B ground state is very small.

There are two previously reported states in ^9B at 11.62-MeV ($J^\pi=?$) and at 12.06-MeV excitation ($J^\pi=\frac{1}{2}^-$, $\frac{3}{2}^-$).[2] A single strong deuteron group was observed corresponding to an excitation energy of 11.75 MeV in ^9B. If the 12.06-MeV state has $J^\pi=\frac{1}{2}^-$, it would not be excited by a direct-reaction process due to angular-momentum selection rules. In this case, the single observed level has a measured excitation energy of

TABLE I. Measured ^9B excitation energies and widths for deuteron groups observed in the reaction $^{10}B(p,d)^9B$.

Excitation energy (MeV)	Width (MeV)
0.0	$\sim$0
2.35±0.02	
7.1 ±0.2	1.95±0.2
11.75±0.1	0.80±0.05
14.6 ±0.2	1.35±0.2

11.75±0.1 MeV, as compared with a previously determined energy of 11.62±0.1 MeV.[2] However, if the 12.06-MeV level has $J^\pi=\frac{3}{2}^-$ and is excited in the reaction, it would cause the centroid of the doublet peak to be shifted up in excitation energy from the strongly excited level at 11.62 MeV to the observed value of 11.75 MeV. The first explanation is more attractive, since the deuteron group shows no sign of a doublet structure over a wide range of angle, and the observed width of 800±50 keV is close to the previously reported width for the 11.62-MeV level of 700±100 keV.[2]

Strongly excited levels of ^9B at 0.0-, 2.35-, 7.1-, and 11.75-MeV excitation all have angular distributions with shapes characteristic of $l_n=1$ pickup (see Figs. 3 and 4), so that the parity of these levels is negative. Poor statistics for the 14.6-MeV-level data do not allow the definite assignment of the picked-up neutron's orbital angular momentum; however, the dashed curve in Fig. 4 is approximately the same shape as that observed for the 11.75 state and shows that an $l_n=1$ as-

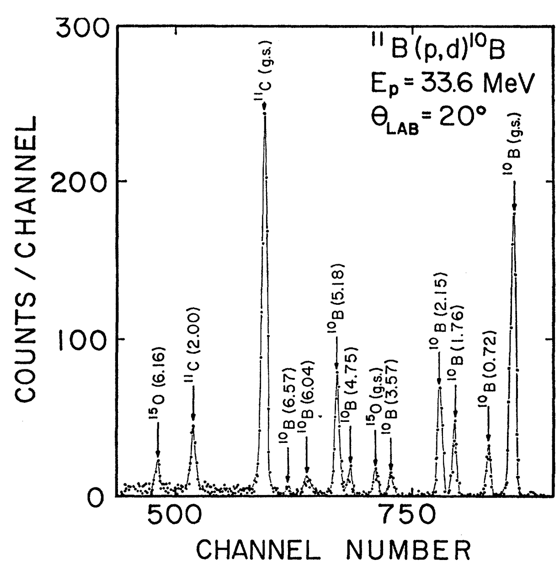

FIG. 5. $^{11}B(p,d)^{10}B$ deuteron spectrum at 20°. The target consisted of 54 $\mu g/cm^2$ of ^{11}B on a carbon backing 50 $\mu g/cm^2$ thick.

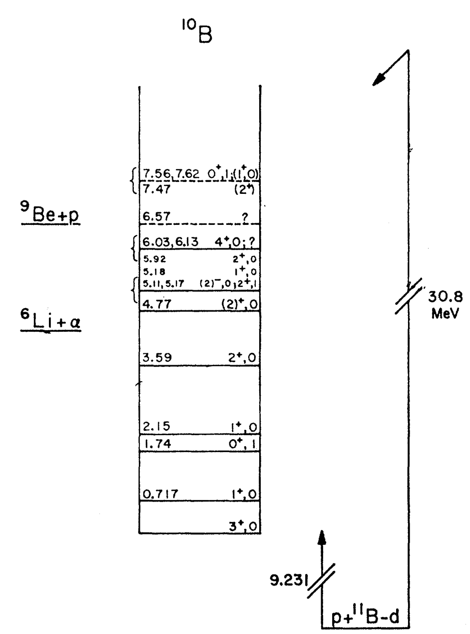

FIG. 6. Energy-level diagram of ^{10}B showing previously known levels (Ref. 2) excited in the $^{11}B(p,d)^{10}B$ reaction. Levels indicated with a dashed line are weakly excited by the reaction; the brackets indicate groups of levels which could not be separated with the energy resolution obtained in these measurements.

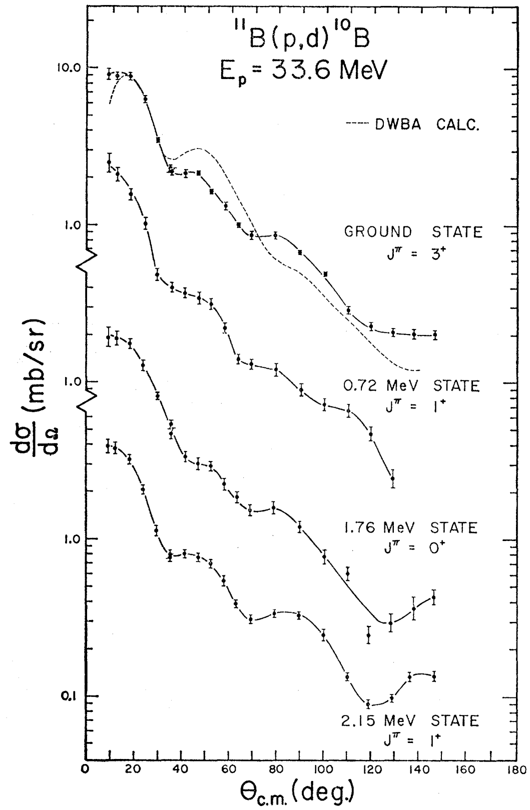

FIG. 7. $^{11}B(p,d)^{10}B$ angular distributions for deuteron groups corresponding to ^{10}B excitation energies of 0.0, 0.72, 1.67, and 2.15 MeV. The dashed line shows the results of a DWBA calculation.

signment is a reasonable possibility for the state. Total-angular-momentum assignments for all the observed states have been made on the basis of the measured spectroscopic factors for these levels and will be discussed in the next section. Table I is a list of the measured excitation energies and linewidths for the observed levels of ^9B.

$^{11}B(p,d)^{10}B$

The deuteron-energy spectrum from the $^{11}B(p,d)^{10}B$ reaction (see Fig. 5) shows deuteron groups corresponding to strongly excited levels of ^{10}B with excitation energies of 0.0, 0.72, 1.76, 2.15, 3.57, 4.75, 5.18, and 6.04 MeV; weakly excited levels of ^{10}B with excitation energies of 6.57 and 7.5 MeV were also observed. The deuteron group corresponding to a ^{10}B excitation energy of 5.18 MeV could correspond to known levels[2] of ^{10}B at 5.17-MeV ($J^\pi=2^+$), 5.18-MeV ($J^\pi=1^+$), and 5.11-MeV ($J^\pi=2^-$) excitation (Fig. 6). The 5.11-MeV level should only be weakly excited, since it can only be excited in the direct-reaction process by pickup of a $2s$-$1d$ shell neutron. The 5.17- and 5.18-MeV levels can both be excited by a direct-reaction mechanism, and deuteron groups from the two could not be separated with the 160-keV energy resolution obtained in this experiment.

The deuteron group corresponding to 6.04-MeV excitation energy in ^{10}B could correspond to previously observed levels at 5.92-MeV ($J^\pi=2^+$), 6.03-MeV ($J^\pi=4^+$), and 6.13-MeV ($J^\pi=?$) excitation.[2] The level at 6.03 MeV cannot be excited by a direct-reaction process due to angular-momentum selection rules; hence principal contributions to this group are from the 5.92- and 6.13-MeV levels. No evidence was found for the excitation of negative-parity states at 7.0-MeV ($J^\pi=1^-$), 7.8-MeV ($J^\pi=1^-$), and 8.1-MeV ($J^\pi=2^-$) excitation.[2] Any yield to these states was not masked by strongly excited positive-parity states, so that no direct evidence for sizable $2s$-$1d$ admixtures in the ground-state wave function of ^{11}B was found in this work.

The angular distributions for the ^{10}B levels at 0.0-, 0.72-, 1.76-, 2.15-, 3.57-, and 4.75-MeV excitation have shapes characteristic of the direct pickup of a $1p$ shell neutron (see Figs. 7 and 8). The deuteron groups corresponding to ^{10}B excitation energies of 5.18 and 6.04 MeV have similar angular distributions. This indicates that contributions to the 5.18-MeV group from the 5.11-MeV level ($J^\pi=2^-$) are indeed small, as previously con-

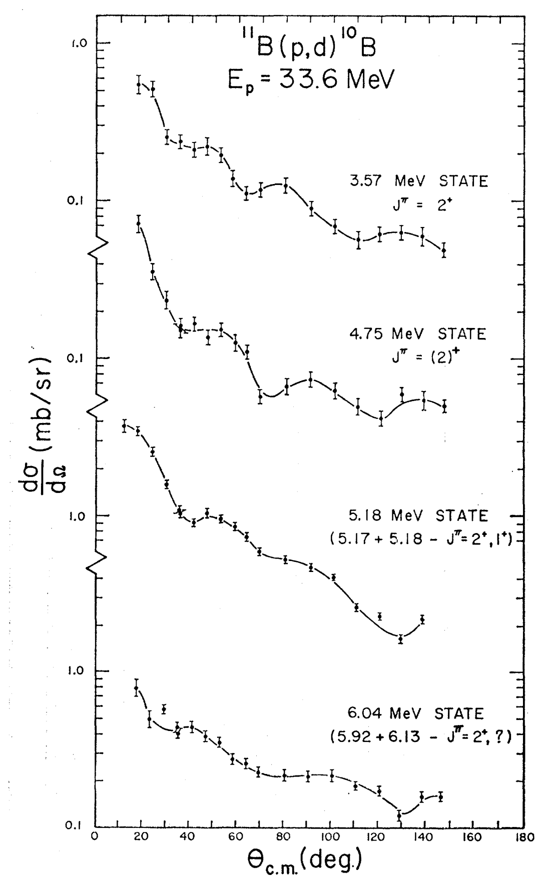

FIG. 8. $^{11}B(p,d)^{10}B$ angular distributions for the deuteron groups corresponding to ^{10}B excitation energies of 3.57, 4.75, 5.18, and 6.04 MeV.

jectured, and that if the 6.04-MeV group contains contributions from the 6.13-MeV level ($J^\pi=?$), the parity of this level is probably positive.

It was previously reported for reaction $^7Li(p,d)^6Li$ that the slopes of the angular distributions[1] first peaks for the ^6Li $T=0$ states at 0.0 and 2.15 MeV were steeper than those of the ^6Li $T=1$ states at 3.57 and 5.38 MeV.[1] No such effect was noted in comparing the angular distributions for the ^{10}B $T=0$ states at 0.72 and 2.15 MeV and the ^{10}B $T=1$ state at 1.76 MeV. The differential cross section for the transition to the ^{10}B $T=1$ level at 1.76 MeV does not fall off more rapidly beyond the first maximum than those transitions to the neighboring $T=0$ levels at 0.72 and 2.15 MeV. Such an effect was reported for these levels in the $^{11}B(d,t)^{10}B$ reaction with $E_d=11.8$ MeV.[9]

$^{10}B(p,p)^{10}B$

The angular distribution for the elastic scattering of 33.6-MeV protons from ^{10}B was measured with a proton-energy resolution of 500 to 600 keV (see Fig. 9). Proton groups corresponding to the ground state and the 0.72-MeV state of ^{10}B could not be resolved; however, data from the elastic scattering of protons from ^{10}B at incident energies of 19[10] and 185 MeV[11] show the cross section of the 0.72-MeV level to be 1 to 2% as large as that of the ground state. Since ^{11}B constituted only 8% of the target, its effect on the cross section was assumed to be small and was neglected. This is not a serious omission, assuming that the ^{10}B and ^{11}B elastic-proton distributions do not differ appreciably in shape and magnitude. The accuracy of the absolute differential cross sections is 6 to 9%.

ANALYSIS

The ABACUS computer code[12] was used to fit the measured angular distribution for the leastic scattering of protons from ^{10}B. The optical potential used was of the form

$$U=U_c-Vf(r,R,a_R)-i4a_IW\frac{d}{dr}f(r,R,a_I)$$
$$-\frac{1}{(m_\pi c)^2}\frac{V_{so}}{dr}\frac{d}{dr}f(r,R,a_R). \quad (1)$$

Here $f(r,R,a)=1/(e^x+1)$, $x=(r-RA^{1/3})/a$, and U_c is the Coulomb potential from a uniformly charged sphere of radius $RA^{1/3}$ F. The best fit to the data is shown in Fig. 9, and the optical parameters used are given below.[13]

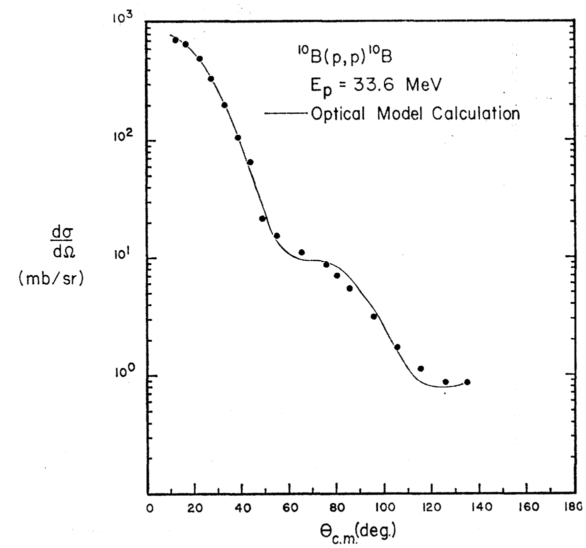

FIG. 9. $^{10}B(p,p)^{10}B$ angular distribution. The solid line shows the results of an optical-model calculation.

The DWBA calculations were carried out using the Macefield computer code. Parameters for the picked-up neutron were $a_n=0.65$ F, $R_n=1.25A^{1/3}$ F; no spin-orbit term was included in the potential. The deuteron optical parameters[14] were obtained from an outside source,[15] with a volume-absorption term instead of the surface term given in Eq. (1). One set of optical parameters was used for both the $^{10}B(p,d)^9B$ and $^{11}B(p,d)^{10}B$ DWBA calculations.

It was impossible to get reasonable fits to the experimental (p,d) angular distributions using the deuteron optical parameters given above. However, if the deuteron imaginary well is increased by a factor of 4, reasonable fits were obtained, as can be seen in Figs. 3 and 7. This same effect was observed in the (p,d) rereactions with ^6Li, ^7Li, and ^9Be.[1] The increase in the deuteron-well depth varied the amplitude of the first peak of the differential cross section by less than 20% in all cases.

The same difficulties were also encountered in attempting to fit data from (d,p) reactions with $1p$ shell nuclei[16] at an incident deuteron energy of $\sim$20 MeV. In this case, reasonable fits to the data were obtained by using a cutoff radius[17] in the DWBA calculations. It was found, however, that the amplitude of the first peak of the differential cross section varied strongly as a function of the cutoff radius. Roughly, the amplitude of the first peak of angular distribution had two maxima; the first maximum appeared at a cutoff radius of 0 F and the

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[10] G. Schrank, E. K. Warburton, and W. W. Daehnick, Phys. Rev. **127**, 2159 (1962).
[11] D. Hasselgren, P. U. Renberg, O. Sundberg, and G. Tibell, Nucl. Phys. **69**, 81 (1965).
[12] E. H. Auerbach, Brookhaven National Laboratory Report No. BNL-6562, 1962 (unpublished).
[13] Proton optical parameters: $V=53.99$ MeV, $W=6.22$ MeV, $V_{so}=6.31$ MeV, $R=1.097$ F, $a_R=0.548$ F, $a_I=0.644$ F.
[14] Deuteron optical parameters: $V=83.5$ MeV, $W=14.94$ MeV, $V_{so}=0.0$, $R=1.33$ F, $a_R=a_I=0.65$ F.
[15] D. Dehnhard, G. C. Morrison, and Z. Vager, in *Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 1966* (Academic Press Inc., New York, 1967).
[16] R. H. Siemssen, Bull. Am. Phys. Soc. **12**, 479 (1967).
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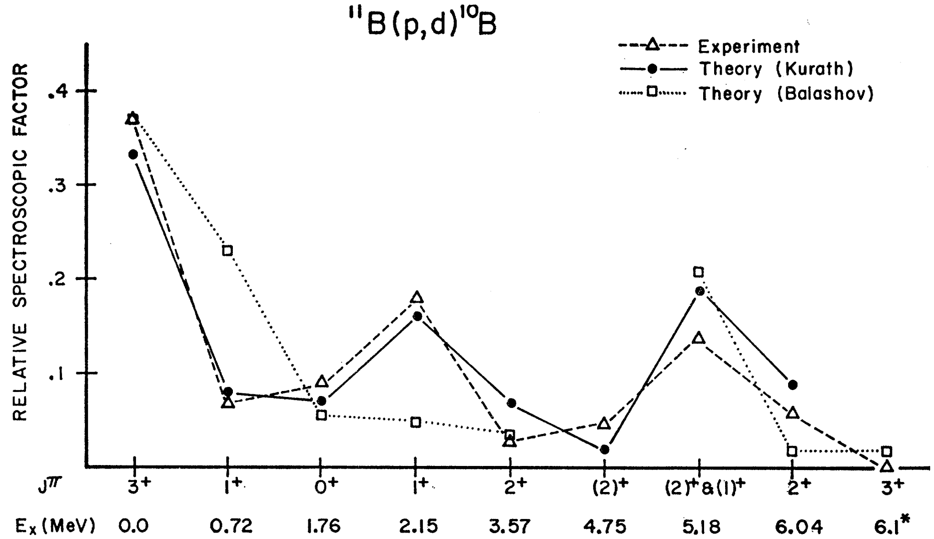

FIG. 10 Theoretical and experimental spectroscopic factors from the reaction $^{11}B(p,d)^{10}B$. A weakly excited $J^{\pi}=3^+$ level near 6.1-MeV excitation (indicated by an asterisk) is predicted by both Kurath and Balashov, but was not observed experimentally.

second at a cutoff radius from 3 to 5 F. The cross section of this peak varied by a factor of about 3 between the two maxima. Cutoff radii corresponding to the second maximum were used in the subsequent DWBA calculations, in which reasonable fits to the data were obtained.

The concern about the behavior of the amplitude of this forward-angle peak arises because the spectroscopic factor is assumed to be directly proportional to the ratio of the maxima of the DWBA and experimental angular distributions at forward angles. If the parameters of the DWBA calculation are varied in order to produce theoretical results which bear a reasonable resemblance (in shape) to the experimental data, the effect of these variations on the amplitude of the angular distribution's forward-angle peak must be considered in deciding just how meaningful the extracted spectroscopic factors are.

In summary, neither method of obtaining fits to the data explains the reason for the anomalous behavior of the DWBA in the case of light nuclei. The effect is large and reproducible, and it has been observed in the case of (d,p) and (p,d) reactions at several different bombarding energies. It deserves further study in that it may be pointing out weaknesses in the DWBA calculations which are especially emphasized in the case of light nuclei.

SPECTROSCOPIC FACTORS

Experimental spectroscopic factors were obtained by comparing the relative magnitudes of the characteristic $l_n=1$ peaks in the DWBA calculation and the experimental data. Theoretical spectroscopic factors were obtained from the coefficients of fractional parentage calculated by Kurath, using an intermediate-coupling model for the $1p$ shell nuclei[5]; a second set of theoretical spectroscopic factors was obtained from the calculations of Balashov.[6] The theoretical and experimental relative spectroscopic factors were obtained by normalizing the sum of the observed spectroscopic factors for each reaction to 1. More details concerning the method used to extract experimental spectroscopic factors and the expression used to obtain the theoretical spectroscopic factors from the coefficients of fractional parentage can be found in an earlier paper.[1]

Relatively good agreement is obtained between the theoretical calculations of Kurath and the experimentally obtained spectroscopic vactors for the $^{11}B(p,d)^{10}B$ reaction (see Fig. 10). Somewhat poorer agreement is obtained with the calculations of Balashov; in particular, there is a marked difference between the calculated and experimental spectroscopic factors for the 0.72- and 2.15-MeV levels of ^{10}B. Both Balashov and Kurath predict a weakly excited level ($J^{\pi}=3^+$) around 5–6-MeV excitation in ^{10}B. There are three known levels in the region 6.5–7.0-MeV excitation in ^{10}B with unknown spins and parities.[2] None was observed to be excited by the (p,d) reaction; however, the deuteron yield may have been very small and lost in the background. The spectroscopic factor for the deuteron group observed at a ^{10}B excitation energy of 6.04 MeV was calculated, assuming that only a 2^+ state contributed to the yield, whereas, as mentioned previously, the energy resolution could not have separated contributions from a previously observed level of ^{10}B at 6.13 MeV.

Spectroscopic factors have now been extracted for the $^{11}B(p,d)^{10}B$ reaction at incident proton energies of 18.9,[18] 155,[3] and 33.6 MeV; they have also been extracted for the $^{11}B(d,t)^{10}B$ reaction at an incident deuteron energy of 21.6 MeV.[15] The results are shown in Fig. 11, where the spectroscopic factors for the deuteron group corresponding to a ^{10}B excitation energy of 5.16 MeV have been extracted, assuming that only the 5.17-MeV level of ^{10}B ($J^{\pi}=2^+$) contributes to the yield. In all these experiments, however, the energy resolution was not good enough to separate out contributions to the observed deuteron yield from the 5.18-

[18] J. Legg, Phys. Rev. **129**, 272 (1962).

MeV level of ^{10}B ($J^{\pi}=1^{+}$). Contributions to the observed deuteron group from both levels were assumed in the calculation shown in Fig. 10. The experimental spectroscopic factor for the 5.16-MeV level of ^{10}B extracted from the $E_p=155$-MeV work also contains contributions from the 4.77-MeV level of ^{10}B ($J^{\pi}=2^{+}$), which was not resolved.

The spectroscopic factor for the 2.15-MeV level of ^{10}B obtained from the work at $E_p=18.9$ MeV appears likely to be in error, as its value is significantly different from a closely grouped series of results from (p,d) experiments performed at widely different energies, from Kurath's theoretical calculations, and from a (d,t) experiment (see Fig. 11). It was on the basis of the work done at $E_p=18.9$ MeV that a previous investigation proposed an isotopic-spin dependence in the (p,d) and (d,t) reactions, which would account for significant differences in the observed spectroscopic factors for the 2.15- and 0.72-MeV levels of ^{10}B [15]; the present work does not support this contention.

With the above-mentioned 2.15-MeV datum point ignored, a mean spectroscopic factor was calculated from the experimental data for each ^{10}B level; the results are shown in Table II.

From these results, the following general conclusions appear to be valid: (1) Relative spectroscopic factors obtained over a wide range of incident energies using a variety of DWBA procedures agree to within 15–20%. (2) Spectroscopic factors obtained from the (d,t) reaction are not significantly different from those obtained with (p,d) reactions. (3) Kurath's calculations agree with the experimental spectroscopic factors to within ~20%. (4) A reasonable absolute error for the spectroscopic factors obtained in this work falls somewhere in the region of 15–20%.

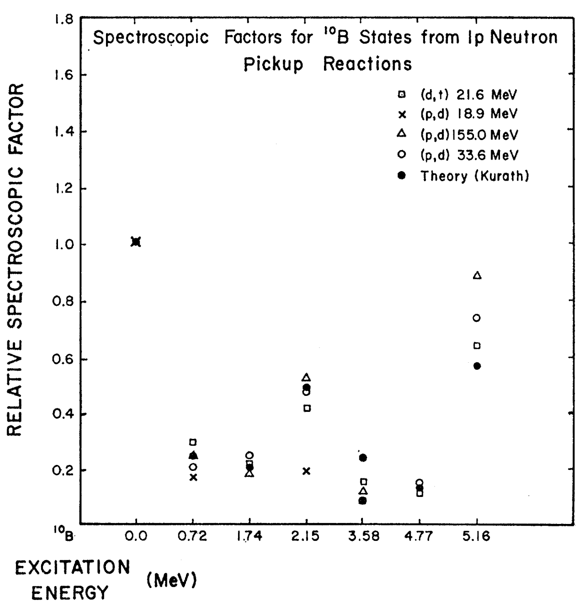

FIG. 11. A comparison of theoretical and experimental spectroscopic factors for ^{10}B states from $1p$ neutron pickup reactions. The spectroscopic factors for the ground state have been normalized to 1.

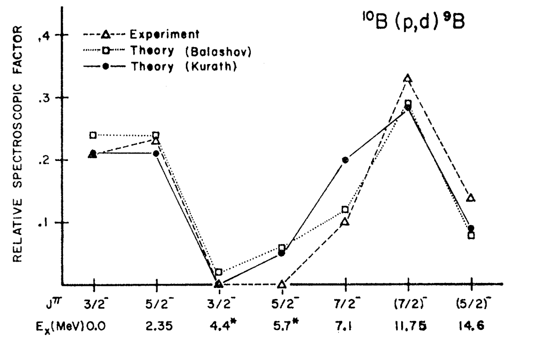

FIG. 12. Theoretical and experimental spectroscopic factors for the reaction $^{10}B(p,d)^{9}B$. Weakly excited levels near 4.4- and 5.7-MeV excitation (indicated by asterisks) are predicted by both Kurath and Balashov, but were not observed experimentally.

Note, however, that $^{7}Li(d,t)^{6}Li$ [19] data analyzed using the plane-wave Born approximation (PWBA) shows a possible isotopic-spin dependence in the spectroscopic factor for the 3.57-MeV level of ^{6}Li ($T=1$) when compared with results from $^{7}Li(p,d)^{6}Li$. Unfortunately, the consistency of the observed effect could not be checked, as results for the 5.36-MeV level of ^{6}Li ($T=1$) were inconclusive. In another case, a comparison of the results from the $^{9}Be(d,n)^{10}B$ and $^{9}Be(^{3}He,d)^{10}B$ reactions has shown that smaller relative spectroscopic factors for the $T=1$ states are extracted from the (d,n) reaction than from the $(^{3}He,d)$ reaction.[20] There is therefore some evidence for an isotopic-spin dependence in spectroscopic factors which is not included in the present theories, but the absence of any evidence for isotopic-spin effects in the present work indicates that the origin of the observed irregularities is not easily isolated.

Experimental and theoretical spectroscopic factors for the reaction $^{10}B(p,d)^{9}B$ are shown in Fig. 12. The ^{9}B levels at 4.4 and 5.7 MeV have been predicted theoretically by both Kurath and Balashov, but have not been observed experimentally. The predicted yields are small, however, and the peaks may have been lost in the high background because of three-body breakup.

The ^{9}B levels at 0.0, 2.35, 7.1, and 11.75 MeV have all been determined to have negative parity, while the

TABLE II. Average differences of spectroscopic factors from mean values of the experimental data.

Spectroscopic factors from	Average difference from mean values
(p,d) reactions	15%
(d,t) reactions	18%
Theoretical calculation (Kurath)	20%

[19] E. W. Hamburger and J. R. Cameron, Phys. Rev. **117**, 781 (1960).

[20] R. H. Siemssen, G. C. Morrison, B. Zeidman, and H. Fuchs, Phys. Rev. Letters **16**, 1050 (1966).

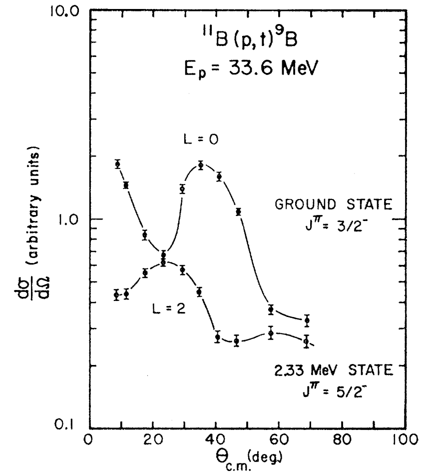

FIG. 13. $^{11}B(p,t)^{9}B$ angular distributions for the 0.0- and 2.33-MeV levels of ^{9}B.

^{9}B level at 14.6 MeV has been tentatively identified as having negative parity. Assuming the experimental spectroscopic factors agree with theoretical calculations to within $\sim$20%, the spins for the observed levels were assigned by comparing the theoretical and experimental results (see Fig. 12).

Additional evidence to support these assignments was obtained from triton-energy spectra for the reaction $^{11}B(p,t)^{9}B$. These spectra were taken with the same ^{11}B targets used in the $^{11}B(p,d)^{10}B$ reaction work, with the particle identification system adjusted to detect tritons. Angular distributions were measured for the ground state and the 2.33-MeV state of ^{9}B and are shown in Fig. 13. These data are in agreement with results from the $^{11}B(p,t)^{9}B$ reaction with $E_p=40$ MeV.[21] The shapes of the angular distributions can be explained with the following simple model for the (p,t) reaction. When the incident proton picks up two neutrons as a pair from ^{10}B, they must be in the singlet state with a total spin $S=0$, and the orbital angular momentum of the pair must be even from symmetry considerations ($L=0, 2, 4, \cdots$). Using this simple picture, the ground-state distribution for $^{11}B(p,t)^{9}B$ has a characteristic shape for the pickup of a dineutron with orbital angular momentum $L=0$. This means that the ground state of ^{9}B can only have the assignment $J^{\pi}=\frac{3}{2}^-$, in agreement with the $^{10}B(p,d)^{9}B$ work. The angular distribution for the 2.33-MeV state has a characteristic shape for the pickup of a dineutron with $L=2$, allowing for spin and parity assignment of $J^{\pi}=\frac{7}{2}^-, \frac{5}{2}^-, \frac{3}{2}^-$, or $\frac{1}{2}^-$. These values do not contradict the previous $J^{\pi}=\frac{5}{2}^-$ assignment for this state.

Note also that the assignments for the levels at 0.0, 2.35, and 7.1 MeV also coincide with the spin assignments for isobaric analog levels of ^{9}Be at 0.0-, 2.43-, and 6.6-MeV excitation.[2] There is therefore a significant amount of supplementary evidence to support the spin and parity assignments which were made on the basis of agreement between experimental and theoretical spectroscopic factors.

SUMMARY

The shapes of the experimental angular distributions for pickup and stripping reactions with light nuclei consistently disagree with DWBA calculations which use optical parameters obtained from elastic-scattering experiments. Two different methods have been used to adjust the theoretical calculations in order to obtain reasonable fits to the data: (1) The strength of the imaginary deuteron well was increased by a factor of 3 or 4 in the (p,d) calculations[1,22]; (2) a cutoff radius was used in the (d,p) calculations.[16] At the present time, there is no apparent theoretical justification for either method.

The same relatively good agreement between experimentally obtained spectroscopic factors and the intermediate-coupling calculations of Kurath was found for the reaction $^{11}B(p,d)^{10}B$ as has been observed previously for the reactions $^{7}Li(p,d)^{6}Li$ and $^{9}Be(p,d)^{8}Be$.[1] On the basis of this general accord observed between the intermediate-coupling model and experiment, spin assignments were made for the observed negative-parity levels of ^{9}B by comparing the data from the $^{10}B(p,d)^{9}B$ reaction with the model predictions. No evidence was observed for any sizable $2s$-$1d$ admixture in the ground-state wave functions of ^{10}B and ^{11}B.

A comparison of spectroscopic factors from the reaction $^{11}B(p,d)^{10}B$ with proton energies in the range 19 to 155 MeV with those from the reaction $^{11}B(d,t)^{10}B$ with $E_d=21.6$ MeV shows no significant difference between the experimental results. The comparison also indicates that relative spectroscopic factors can be determined to within 15–20%.

No noticeable difference in the shapes of angular distributions for the neighboring $T=0$ and $T=1$ states of ^{10}B was observed which could be interpreted as an isotopic-spin effect, nor were there any significant differences noted in the (p,d) or (d,t) spectroscopic factors to the $T=1$ levels of ^{10}B which could be correlated to a difference in isotopic spin. Some recent investigations of other reactions report effects in spectroscopic factors and angular distributions which are interpreted as an isotopic-spin dependence not included in the present DWBA theory. The present work shows that the observation of isotopic-spin effects is limited to specific cases, and adds to the collection of data from which some obvious patterns of regularities has yet to be recognized.

ACKNOWLEDGMENTS

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[22] N. S. Chant, P. S. Fisher, and D. K. Scott, Nucl. Phys. **A99**, 669 (1967).