$B^{11}(He^3, \alpha)B^{10}$ Reaction at 33 MeV*

D. DEHNHARD,† N. WILLIAMS,‡ AND J. L. YNTEMA
Argonne National Laboratory, Argonne, Illinois 60439

(Received 9 December 1968)

Differential cross sections of the $B^{11}(He^3, \alpha)B^{10}$ reaction leading to seven states up to 5.2-MeV excitation energy have been measured at forward angles at an incident energy $E(He^3) = 33$ MeV. The angular distributions have been analyzed in terms of the distorted-wave Born approximation on the assumption that the direct neutron-pickup process is predominant. Relative spectroscopic factors have been extracted and are found to be in good agreement with Cohen and Kurath's theoretical predictions and with the results of the $B^{11}(p, d)B^{10}$ experiment at 33.6 MeV.

I. INTRODUCTION

THE $B^{11}(d, t)B^{10}$ reaction[1] at 21.6 MeV and the $B^{11}(p, d)B^{10}$ reaction[2] at 18.9 MeV have revealed some inconsistencies in relative spectroscopic factors, particularly for the states at 0.717 and 2.15 MeV in B^{10}. Results for the $B^{11}(p, d)$ reaction[3] at 155 MeV and more recently[4] at 33.6 MeV have yielded spectroscopic factors in good agreement with each other and with the theoretical predictions of Cohen and Kurath.[5] The $B^{11}(d, t)B^{10}$ reaction has also been studied at 11.8 MeV[6] and at 20 MeV,[7] the data show only poor agreement with each other, probably because of the low energy of the outgoing tritons at $E_d = 11.8$ MeV. At 20 MeV the experiment was analyzed merely with the plane-wave Born approximation. The $B^{11}(p, d)$ reaction has been studied[8] at 40 MeV with poor energy resolution. The $B^{11}(He, \alpha)$ reaction has been studied previously at the rather low incident energies of 1.0–2.15[9] and 2.2–5.5 MeV.[10]

Although the forward peaking and oscillatory shapes of the angular distributions seem to indicate a direct-reaction mechanism, the relative strengths of the transitions to the various states in B^{10} are in disagreement with the values obtained from the (d, t) reaction and with theory. Distorted-wave calculations are not too meaningful for the (He^3, α) reaction at this low energy, where small contributions from compound-nucleus processes can cause the relative cross sections to fluctuate strongly with incident energy, even if the shapes of the angular distributions remain oscillatory.

The (He^3, α) reaction at higher incident energies, however, is expected to proceed predominantly by a direct neutron-pickup mechanism. This has been shown to be the case for nuclei in the $2s1d$ and $1f2p$ shells. The $B^{11}(He^3, \alpha)B^{10}$ reaction at 33 MeV may thus provide an independent check on the spectroscopic information if a direct neutron-pickup mechanism is also applicable to reactions on $1p$-shell nuclei.

II. EXPERIMENT

Self-supporting B^{11} foils of thickness ~ 50 $\mu g/cm^2$ and isotopic enrichment 92.5% were prepared by evaporation. The 33-MeV He^3 beam of the Argonne 60-in. cyclotron was focused into a 60-in. scattering chamber[11] by use of a magnetic analyzing system which reduced the energy spread of the beam to approximately 30–40 keV. A single surface-barrier detector of thickness 1000 μ was used for most of the experiment, and an over-all energy resolution of 100 keV was obtained at forward angles. At the largest angles studied, the kinematic energy spread across the detector (which had an aperture size of 3.2 mm and was placed 170 mm from the target) increased the peak width to as much as 200 keV.

A typical energy spectrum is shown in Fig. 1. All known states[12] in B^{10} below 5 MeV excitation (Fig. 2) have been resolved. The group close to 5.1 MeV may be due to the 5.17-MeV state with $J^\pi = 2^+$ and $T = 1$, the 5.11-MeV state with $J^\pi = 2^-$ and $T = 0$, or the 5.18-MeV state with $J^\pi = 1^+$ and $T = 0$. In a direct reaction, the 2^- level can only be reached by pickup of a $2s1d$ particle and is therefore probably only weakly excited. Excitation of the 1^+ level cannot be excluded, but according to Cohen and Kurath[5] the spectroscopic factor for this transition should be only 2% of that for excitation of the $J^\pi = 2^+$, $T = 1$ state. It was assumed in the analysis that only the 5.17-MeV level was excited. At excitation energies greater than 2.5 MeV, contamination

* Work performed under the auspices of the U.S. Atomic Energy Commission.

† Present address: University of Minnesota, Minneapolis, Minn.

‡ Present address: Rutgers—The State University, New Brunswick, N.J.

[1] D. Dehnhard, G. C. Morrison, and Z. Vager, in *Proceedings of the International Conference on Nuclear Physics*, edited by R. L. Becker and A. Zucker (Academic Press Inc., New York, 1967), p. 112.

[2] J. C. Legg, Phys. Rev. **129**, 272 (1963).

[3] D. Bachelier, M. Bernas, I. Brissand, C. Detraz, and P. Radvanyi, Communication au Colloque sur les Noyaux Legres, Lyon, 1966 (unpublished).

[4] L. A. Kull and E. Kashy, Phys. Rev. **167**, 963 (1968).

[5] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).

[6] W. Fitz, R. Jahr, and R. Santo, Nucl. Phys. **A101**, 449 (1967).

[7] A. A. Ogloblin, Nucl. Phys. **47**, 408 (1963).

[8] T. H. Short, Ph.D. thesis, University of Minnesota, 1965 (unpublished).

[9] J. A. Lonergan and D. J. Donahue, Nucl. Phys. **88**, 465 (1966).

[10] I. J. Taylor, F. de S. Barros, P. D. Forsyth, A. A. Jaffe, and S. Ramavataram, Proc. Phys. Soc. (London) **75**, 772 (1960); P. D. Forsyth, I. J. Taylor, and R. R. Perry, Nucl. Phys. **66**, 376 (1965).

[11] J. L. Yntema and H. W. Ostrander, Nucl. Instr. Methods **16**, 69 (1962).

[12] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. **78**, 1 (1966).

TABLE I. Optical-model parameters used in DWBA calculations.

Channel	Set	V (MeV)	W_s (MeV)	r_0 (F)	a_0 (F)	r_I (F)	a_I (F)	r_c (F)	V_{so} (MeV)	Ref.
$B^{11}+He^3$	1	169	32.1	1.14	0.675	1.82	0.566	1.40	8	a
$B^{10}+He^4$	2	69	24.0	1.57	0.700	1.57	0.700	1.57	...	b
	3	195	24.1	1.38	0.604	1.60	0.488	1.58	...	c

[a] J. C. Hiebert, E. Newman, and R. H. Bassel, Phys. Rev. 154, 898 (1967).

[b] Reference 16.

[c] H. T. Fortune (private communication).

with oxygen and a small amount of silicon impeded the evaluation of the energy spectra and a least-squares Gaussian fitting program was used to obtain angular distributions for the states at 3.58, 4.77 and 5.17 MeV.

The absolute cross section was not measured directly. Even the estimate was complicated by the presence of C^{12} impurity in the target, and the elastic scattering due to this was not resolved from that of B^{11} except at laboratory angles greater than 40°. However, the entrance-channel optical-model parameters used in the distorted-wave Born-approximation (DWBA) calculations yielded elastic-scattering cross sections which fitted the shape of the combined C^{12} and B^{11} elastic-scattering angular distribution, and both the shape and the absolute magnitude of the C^{12} elastic-scattering angular distribution observed at 29.2 MeV.[13] It was concluded that the differential cross sections due to scattering from B^{11} and C^{12} had very similar shapes at this energy. The fraction of C^{12} contained in the target was calculated from the spectra taken at angles greater than 40°, where the C^{12} and B^{11} elastic-scattering peaks were resolved. The B^{11} elastic-scattering cross section was then calculated and normalized to the optical-model prediction. The quoted error on the C^{12} scattering data[13] was ±25%; from this and other uncertainties, we estimated the error in the absolute cross section to be ±35% in the present work.

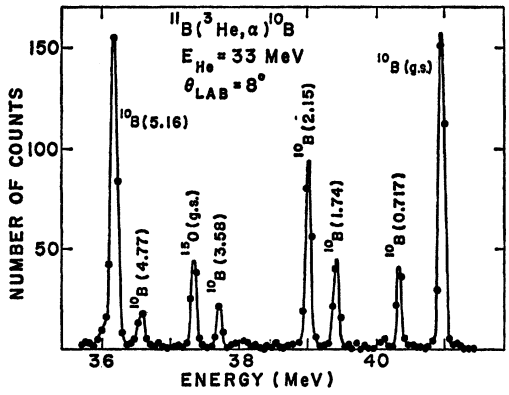

FIG. 1. Energy spectrum of the $B^{11}(He^3, \alpha)B^{10}$ reaction at $\theta_{lab}=8°$, $E(He^3)=33$ MeV.

[13] N. Williams, Ph.D. thesis, Manchester University, 1966 (unpublished).

III. RESULTS

Angular distribution of the transitions to states in B^{10} at $E_x=0.0$ MeV ($J^\pi=3^+$, $T=0$), 0.717 MeV ($J^\pi=1^+$, $T=0$), 1.74 MeV ($J^\pi=0^+$, $T=1$), 2.15 MeV ($J^\pi=1^+$, $T=0$), 3.58 MeV ($J^\pi=2^+$, $T=0$), 4.77 MeV ($J^\pi=2^+$, $T=0$), and 5.16 MeV ($J^\pi=2^+$, $T=1$) are shown in Fig. 3 along with the results of distorted-wave calculations performed with the computer code JULIE.[14] The optical-model parameters used had been obtained from elastic scattering on neighboring targets[15–17] and are given in Table I. Two different sets of He^4 potentials have been used; the fits shown in Fig. 3 were obtained with set 3. The use of set 2 resulted in a shallower minimum near $\theta_{c.m.}=40°$ and a deeper minimum near $\theta_{c.m.}=60°$. However, the relative cross sections at forward angles were almost identical for the two sets. The depth of the imaginary volume potential of set 3 was decreased with excitation energy according to the formula[17]

$$W_s(E_x)=24.1\ \text{MeV}-0.5E_x.$$

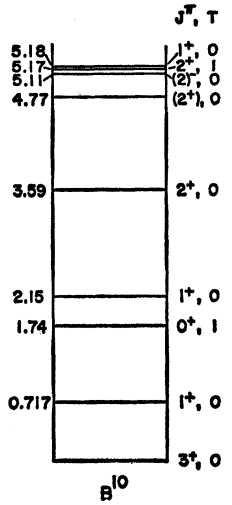

FIG. 2. Level scheme of B^{10}.

[14] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240 (unpublished).

[15] J. C. Hiebert, E. Newman, and R. H. Bassel, Phys. Rev. 154, 898 (1967).

[16] D. R. Winner and R. M. Drisko, Technical Report, University of Pittsburgh, 1965 (unpublished).

[17] H. T. Fortune (private communication).

A spin-orbit term was included in both the entrance-channel optical potential and in the well, employed in the calculation of the bound-state wave function. The radial cutoff of 4.2 F, which was used in all cases, was found to give the best fits to the locations of the maxima and minima in the angular distributions. The radius and diffuseness of the bound-state well were held constant throughout with $r_0=1.25$ F and $a=0.65$ F. A spin-orbit interaction parameter $\lambda=25$ was used.

All transitions, except that leading to the 1.74-MeV state, are mixed; they involve $p_{1/2}$ and $p_{3/2}$ and possibly some f-wave tranfer. The experimental angular distributions predominantly have shapes characteristic of $l=1$ pickup, as seen from the DWBA fits (Fig. 3) for both $j_n{}^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$. Only small differences were found between the shapes of the calculated angular distributions for $j_n{}^\pi=\frac{1}{2}^-$ and $\frac{3}{2}^-$; but the absolute cross sections differed by up to 20% for the two j values.

According to Cohen and Kurath[5] the transitions to the 0.717- and 3.58-MeV states should proceed mainly by $j_n{}^\pi=\frac{1}{2}^-$ pickup, while in the transitions to the 2.15- and 5.17-MeV states, the $j_n{}^\pi=\frac{3}{2}^-$ contribution should be stronger. However, the shapes of the experimental angular distributions leading to the ground state and the excited states shown in Fig. 3 are very similar. This indicates that there is no j dependence over the angular range studied. The ground-state transition ($J^\pi=3^+$) shows an angular distribution in which the amplitudes of the oscillations are somewhat smaller than in those leading to other states, an effect similar to that observed

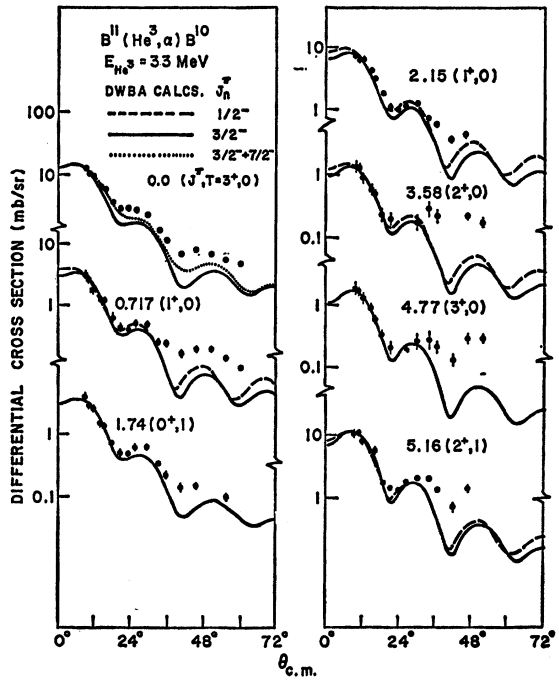

FIG. 3. Angular distributions of the $B^{11}(He^3, \alpha)B^{10}$ reaction at 33 MeV. The dotted curve for the ground-state reaction was calculated for a 10% admixture of $f_{7/2}$.

TABLE II. Relative spectroscopic factors from neutron-pickup reactions on B^{11}.

E_x (MeV)	J^π, T	$j_n{}^\pi$	Absolute S_j (theory[a])	$\Sigma_j S_j$ (theory[a])	(d,t) at 21.6 MeV[b] TSALLY	JULIE	JULIE (wtd. av.)	(p,d) at 18.9 MeV[c] TSALLY	JULIE	JULIE (wtd. av.)	(p,d) at 33.6 MeV[d] MACFIELD	(p,d) at 155 MeV[e] TSALLY	(He^3,α) at 33 MeV JULIE	JULIE (wtd. av.)
0.0	$3^+,0$	$\frac{1}{2}$	1.094										0.23	0.22
0.717	$1^+,0$	$\frac{1}{2}$	0.191	0.241	0.30	0.38	0.36	0.17	0.19	0.19	0.21	0.24	0.19	
		$\frac{3}{2}$	0.072			0.32			0.17					
1.74	$0^+,1$	$\frac{1}{2}$	0.645										0.54	0.44
2.15	$1^+,0$	$\frac{3}{2}$	0.069	0.487	0.41	0.46	0.41	0.19	0.22	0.18	0.48	0.52	0.42	
		$\frac{1}{2}$	0.462			0.40			0.17				0.09	
3.58	$2^+,0$	$\frac{3}{2}$	0.210	0.235	0.15						0.09	0.12	0.07	0.09
		$\frac{1}{2}$	0.046										0.09	
4.77	$3^+,0$	$\frac{3}{2}$	0.138	0.126	0.12						0.16		0.09	0.09
5.16	$2^+,1$	$\frac{3}{2}$	0.078										2.15	
		$\frac{1}{2}$		1.568	1.91						2.22[f]	2.67	1.79	1.81
		$\frac{3}{2}$	1.631											

[a] Reference 5.
[b] Reference 1.
[c] Reference 2.
[d] Reference 4.
[e] Reference 3.
[f] The spectroscopic factors given in Ref. 4 include the factor $C^2=\frac{1}{3}$ for the $T=1$ states.

in the $B^{11}(d, t)B^{10}$ reaction.[1] This may be the result of a spin dependence[18] or of a small f-wave contribution to that transition. A 10% $f_{7/2}$ admixture leading to the ground state results in a somewhat improved fit to the data, as shown by the dotted curve in Fig. 3.

The close similarity between the angular distributions involving pure $j_n{}^\pi=\frac{3}{2}^-$ and, according to Cohen and Kurath,[5] those involving almost pure $j_n{}^\pi=\frac{1}{2}^-$ transfer is in rather sharp contrast to the strong j dependence observed in (α, t) reactions on several $1p$-shell nuclei[19] and in the $N^{15}(He^3, \alpha)N^{14}$ reaction at 39.8 MeV.[20] However, what was thought to be j dependence in the latter reaction is now considered to be largely a Q-dependent effect.[21] Apparently the j-dependent effect varies more strongly with the energy of the He^3 particles or tritons than with the energy of the α particles. In the (He^3, α) reaction of the present investigation, the shapes of the angular distributions vary only very little with the excitation energy in B^{10}. At lower incident energies (15 and 18 MeV) a j dependence has been observed,[22] but it was not as pronounced as at 39.8 MeV. It would be of considerable interest to use a well-established j dependence to determine fractional spectroscopic factors in mixed transitions.

Spectroscopic factors S for single-neutron pickup were obtained as usual by comparison of experimental and calculated distorted-wave angular distributions, i.e., by use of the relation

$$(d\sigma/d\omega)_{\text{expt}}=NC^2S(d\sigma/d\omega)_{\text{DW}}. \quad (1)$$

Here N is the normalization constant and $C^2=(T_0, t, M_{T_0}, M_t \mid TM_T)^2$ is the Clebsch-Gordan coefficient for isobaric-spin coupling, where T_0, T, and t are the isobaric-spin quantum numbers of the B^{10} final state, of the B^{11} initial state, and of the transferred neutron, respectively, and M_T, M_{T_0}, and M_t are their z components.

Table II lists the spectroscopic factors for the three neutron-pickup reactions (d, t), (p, d), and (He^3, α) along with the theoretical values of Cohen and Kurath.[5] For the mixed transitions to the $J^\pi=1^+$ and 2^+ states, two values of S corresponding to the two $j_n{}^\pi$ values were obtained from the JULIE code on the assumption that the transition proceeds either by pure $j_n{}^\pi=\frac{1}{2}^-$ or pure $j_n{}^{1/2}=\frac{3}{2}^-$ pickup. In addition, previously published[1-4] values of S obtained with the codes TSALLY and MACEFIELD are also shown. These codes contain no spin-orbit potential in either the bound state or the entrance and exit channels, and hence only one value of S is found for each state. To facilitate a comparison of these figures, the values of S obtained from the JULIE code have in all cases been used to compute a weighted average spectroscopic factor—the weights being the theoretical strengths for the two $j_n{}^\pi$ values. These average spectroscopic factors (listed in Table II) are to be compared with the values derived by use of the codes MACEFIELD and TSALLY, and with the sum of the theoretical spectroscopic factors for the two $j_n{}^\pi$ values in each case. The figures quoted in Table II for the (He^3, α) reaction assume pure $j_n{}^\pi=\frac{3}{2}^-$ for the ground-state transition. It is expected that higher l values will be enhanced in (He^3, α) relative to the other neutron-pickup reactions. Hence, in order to make a meaningful comparison of relative spectroscopic factors, a correction for the possible $f_{7/2}$ admixture in the (He^3, α) ground-state transition must be applied. This correction factor depends upon the relative magnitudes of $(d\sigma/d\omega)_{\text{DW}}(\frac{3}{2}^-)$ and $(d\sigma/d\omega)_{\text{DW}}(\frac{7}{2}^-)$; a 10% $f_{7/2}$ admixture means that the relative spectroscopic factors given in Table II would be increased by approximately 14%.

In view of the uncertainties in the calculations of the overlap factor N of Eq. (1), it was considered more appropriate to compute this from the experimental data and the theoretical ground-state absolute spectroscopic factor. This implied a value of $N=25$ if the ground-state transition were assumed to be pure $j_n{}^\pi=\frac{3}{2}^-$, and $N=28$ if the 10% $f_{7/2}$ contribution were included.

The relative spectroscopic factors from (He^3, α) are in good over-all agreement with those from theory and from other reactions. Particularly remarkable is the good agreement between the (p, d) experiment at 33.6 MeV and the present (He^3, α) experiment. The spectroscopic factor[2] for the 2.15-MeV state from (p, d) at 18.9 MeV has the largest deviation, and Kull and Kashy[4] have suggested that the measurement may be in error. In the case of the level at 3.58 MeV, the theoretical spectroscopic factor is about twice the experimental values, although the latter are consistent among themselves.

No significant differences between the shapes of the angular distributions leading to $T=0$ and $T=1$ states have been observed, and neither has a T dependence of the spectroscopic factors. These conclusions are consistent with those of Kull and Kashy[4] for the (p, d) reaction at 33.6 MeV.

The state at 4.77 MeV has been assumed to have $J^\pi=3^+$, $T=0$, and hence is populated by $j_n{}^\pi=\frac{3}{2}^-$ and possibly by $j_n{}^\pi=\frac{7}{2}^-$. This level is usually given a tentative assignment[12] of $J=2^+$, $T=0$; but the assumption of 3^+ is more consistent with theoretical calculations[5] of its energy and spectroscopic factor.

It appears that in the present case, at least, the (He^3, α) reaction at 33.0 MeV provides a reliable basis for the determination of relative spectroscopic factors.

[18] R. H. Siemssen and D. Dehnhard, Phys. Rev. Letters **19**, 377 (1967).
[19] D. Dehnhard and R. H. Siemssen, Bull. Am. Phys. Soc. **12**, 17 (1967).
[20] G. C. Ball and J. Cerny, Phys. Letters **21**, 551 (1966).
[21] G. C. Ball and J. Cerny, Bull. Am. Phys. Soc. **12**, 1144 (1967).
[22] E. M. Kellogg and R. W. Zurmühle, Phys. Rev. **152**, 890 (1966).