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Triton Reactions near 2 MeV: $^{11}B(t,\alpha)^{10}Be$

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α-particle groups from the $^{11}B(t,\alpha)^{10}Be$ reaction have been studied using thin self-supporting boron films isotopically enriched to 98% in ^{11}B and surface-barrier detectors. Angular distributions of tritons elastically scattered by ^{11}B and of α particles leaving ^{10}Be in its ground and first-excited states were measured at triton energies ranging from 1.00–2.10 MeV. The elastic-scattering data were analyzed with the optical model, and the reaction data were analyzed with the distorted-wave Born approximation for $1p$ proton pickup. α-particle potentials having deep wells as opposed to shallow ones were found to provide best fits to the reaction data. The ratio of the spectroscopic factor of the first-excited state in ^{10}Be to that of the ground state, found from the fits to the data, is in reasonable agreement with the value obtained from shell-model calculations.

I. INTRODUCTION

IN a number of previous experiments, angular distributions for $(^3He,\alpha)$ reactions on light nuclei have been analyzed in terms of plane-wave[1,2] and distorted-wave Born-approximation[3] (DWBA) calculations of the pickup of a $1p$ neutron from the target nucleus. It is, therefore, of interest to see if a (t,α) reaction may be similarly interpreted in terms of the pickup of a $1p$ proton. This possibility is indicated by the fact that a number of (t,α) experiments on light nuclei[4–6] have yielded angular distributions with forward or backward peaking characteristic of a predominantly direct reaction mechanism.

The present experiment[7] is an investigation of the $^{11}B(t,\alpha)^{10}Be$ reaction at triton energies between 1.00 and 2.10 MeV. Measurements of the triton elastic scattering by ^{11}B were also made, and were analyzed by means of the optical model. The resulting optical parameters together with an appropriate set of α-particle optical parameters were then employed in DWBA calculations which were compared with the experimental angular distributions.

It has been suggested[8] that some states in ^{10}Be are isobaric analogs of states in ^{10}B. The spectroscopic factors obtained from the DWBA analyses were therefore compared with those predicted by shell-model calculations.[9]

II. EXPERIMENTAL PROCEDURE

A. Apparatus

Tritons from the Naval Research Laboratory 2MV Van de Graaff accelerator were focused on the target at the center of a 26.7-cm-i.d. scattering chamber. The charged particles emerging from the target were incident upon surface-barrier solid-state detectors[10] accurately positioned at 15° intervals in the walls of the scattering chamber. The relative values of the solid angles subtended by the detectors at the target center were measured both directly and by the elastic scattering from gold. The results of the two methods agreed to about 1%.

The boron targets were self-supporting films isotopically enriched to 98% in ^{11}B. They were prepared by simple evaporation of the enriched boron in the presence of a glass slide on which there was coated a thin detergent substrate. The boron powder was held in a carbon boat having extremely thin walls. Because of the high melting point of boron (~2300°C) it was necessary to water cool the current electrodes, the walls of the evaporator and the substrate during evaporation. Cooling the latter was accomplished by clamping the slide to a length of waveguide stock through which water was flowed. After evaporation the boron films were allowed to cool, and were then floated off, and mounted on frames in the usual manner. The density of the film was estimated to be 50–100 $\mu g/cm^2$ from scattering experiments.

The depletion depths of the detectors were maintained at the smallest values which both minimized the energy lost by protons and simultaneously allowed the less penetrating α particles to lose all of their energy. The charged-particle pulses were amplified

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[1] W. E. Dorenbusche and C. P. Browne, Phys. Rev. **131**, 1212 (1963).
[2] P. D. Forsyth, I. J. Taylor, and R. R. Perry, Nucl. Phys. **66**, 376 (1965).
[3] E. M. Kellogg and R. W. Zermuhle, Phys. Rev. **152**, 890 (1966).
[4] H. D. Holmgren, L. M. Cameron, and R. L. Johnston, Nucl. Phys. **48**, 1 (1963).
[5] G. D. Gutsche, H. D. Holmgren, L. M. Cameron, and R. L. Johnston, Phys. Rev. **125**, 648 (1962).
[6] R. B. Schwartz, H. D. Holmgren, L. M. Cameron, and A. R. Knudson, Phys. Rev. **134**, B577 (1964).
[7] J. D. Silverstein and G. H. Herling, Bull. Am. Phys. Soc. **12**, 33 (1967).
[8] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. **78**, 1 (1966).
[9] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).
[10] Ortec, Oak Ridge, Tenn.

and shaped with standard electronics, resulting in an over-all resolution of 40 keV. These pulses were then sorted by means of a 1024-channel analyzer, allowing spectra from up to four detectors to be accumulated simultaneously.

B. Reduction of Spectra

Sample (t,t) and (t,α) spectra are shown in Figs. 1 and 2, respectively. As is evidenced in these spectra the targets contained a significant amount of oxygen and carbon. The oxygen presumably arises from an oxide layer formed on the boron film upon its exposure to air. The carbon contamination is thought to arise mainly from the cracking of pump vapors in the scattering chamber during bombardment.

Superimposed on the triton peaks from ^{11}B and ^{12}C in Fig. 1 are the results of a computer calculation in which a search was made on the heights, widths, and locations of two summed Gaussians. In some spectra, the close proximity of the $^{16}O(t,t)$ peak necessitated the fitting of the spectrum to a sum of three Gaussians. At angles of 45° or less the $^{11}B(t,t)$ and $^{12}C(t,t)$ peaks coincided, and the contributions from each were determined with the aid of a (t,t) spectrum obtained with a carbon target. In addition to the uncertainties introduced by this subtraction process, there also existed, for some angles, an ambiguity in subtracting a complicated background which may have arisen from other reactions in the target. Published data on triton elastic scattering from ^{12}C provided a convenient guide in reducing the data obtained with the boron target. This is illustrated in Fig. 3, where the smooth curve was drawn through the data of Gutsche, Holmgren, Cameron, and Johnston[5] at 1.75 MeV, and the points are the data from this experiment obtained with a carbon contaminated boron target. The over-all agreement is seen to be good. By referring to these published data one could therefore find an unambiguous way of measuring the areas under the peaks in the boron target spectra.

The two highest energy peaks in the (t,α) spectrum (Fig. 2) arise from the ground-state reactions on ^{11}B and ^{16}O. For angles at which these two peaks coincided the contribution from each was determined with the aid of a (t,α) spectrum obtained with an oxygen target. For angles at which the two were partially resolved, the Gauss fit program mentioned above was used to determine the peak areas. The peak from the first excited 3.37-MeV state in ^{10}Be was clearly resolved at all angles. The number of counts under this peak from a detector at a fixed angle provided a convenient normalization for all the data at a given triton energy. The peak from the ground-state $^{12}C(t,\alpha)$ reaction was also resolved at all angles. The relatively large yield of this group often made it useful as an energy calibration.

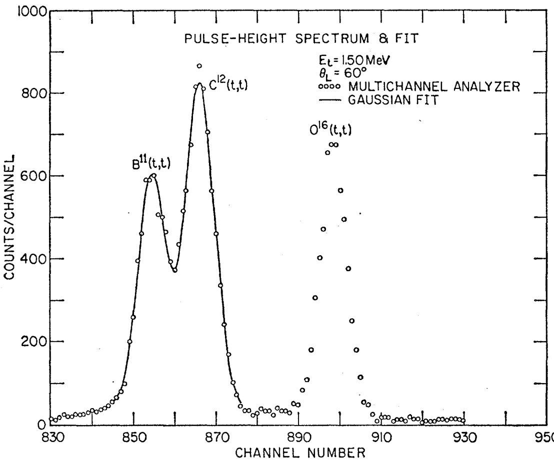

FIG. 1. Sample triton spectrum from a ^{11}B target.

The spectrum in Fig. 2 also contains an α-particle group leading to the 5.96-MeV state in ^{10}Be, which was recently found to be a 1.1-keV doublet.[11,12] Because they were weakly excited, complete angular distributions for this group and that leading to the 6.26-MeV state could not be obtained. The spectrum also contains other α groups from the carbon and oxygen contaminants.

C. Elastic-Scattering Data

The results for triton elastic scattering from ^{11}B at incident energies of 1.75 and 2.10 MeV are shown in Fig. 4. It was not possible to determine the absolute normalization of the data. The normalization at 30° is discussed in Sec. III.

The error bars represent uncertainties in the relative cross section of about 5%. At angles where there existed the aforementioned uncertainties (see Sec. II B), the errors are 10% or more. The angular distributions are seen to have similar shapes.

D. (t,α) Data

Relative differential cross sections for the (t,α) reactions leaving ^{10}Be in its ground and first excited states were measured at triton energies of 1.00, 1.40, 1.80, and 2.10 MeV. The c.m. angular distributions are shown in Fig. 5. The aboslute cross sections have not been measured, but the units for both groups at a given bombarding energy are the same, as mentioned in Sec. II B. The error bars represent uncer-

[11] F. C. Young, P. D. Forsyth, M. L. Roush, and W. F. Hornyak, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), pp. 179–182.

[12] E. K. Warburton and D. E. Alburger, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), pp. 114–145.

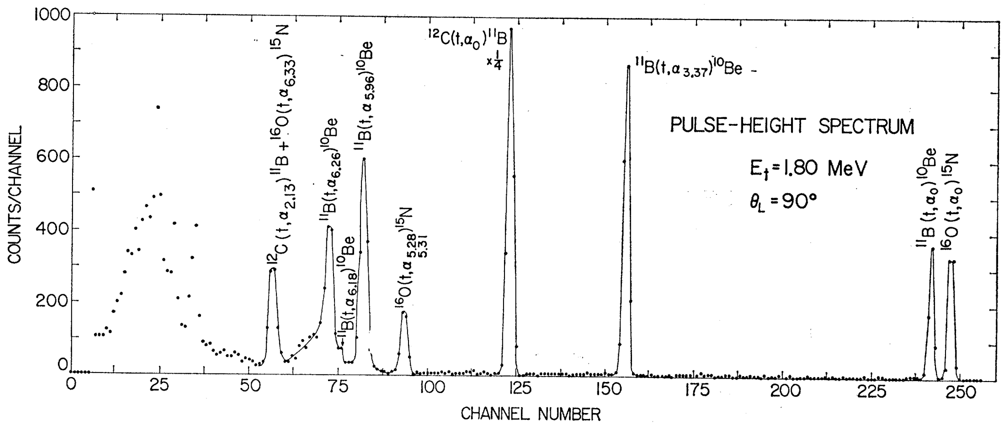

FIG. 2. Sample α-particle spectrum from a ^{11}B target.

tainties of 10% or less due to counting statistics and imperfect reproductibility in some cases. All of the ground-state angular distributions have similar shapes. The same is true of the first-excited-state angular distributions at the three higher energies. This similarity suggests the possibility of interpreting the data in terms of a direct reaction model.

III. TRITON OPTICAL-MODEL ANALYSIS

An optical-model analysis of low-energy triton elastic scattering from several light nuclei has been discussed elsewhere.[13] The optical potential used was

$$U=-Vf(x)-iWf(x')-V_{so}\lambda_\pi^2\mathbf{l}\cdot\boldsymbol{\sigma}|(d/rdr)f(x)|+V_C, \quad (1)$$

where

$$f(x)=(1+e^x)^{-1},$$
$$x=(r-r_0A^{1/3})/a,$$
$$x'=(r-r_0'A^{1/3})/a',$$

and the other symbols have their usual meanings. For each triton energy the starting point was the parameter set which yielded the best fit to ^{9}Be(t,t) data at 2.10 MeV,[14] and only the well depths were allowed to vary in searching for the best fit.

The search code employed was ABACUS,[15] which minimized χ^2, defined by

$$\chi^2=(N^{-1})\sum_{i=1}^{N}\left[\frac{\sigma_{ti}-B\sigma_{xi}}{\Delta\sigma_i}\right]^2. \quad (2)$$

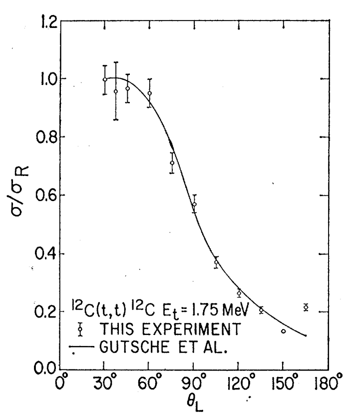

FIG. 3. Comparison between ^{12}C$(t,t)^{12}$C data arising from carbon contamination in a ^{11}B target with the data of Gutsche *et al.* (Ref. 5).

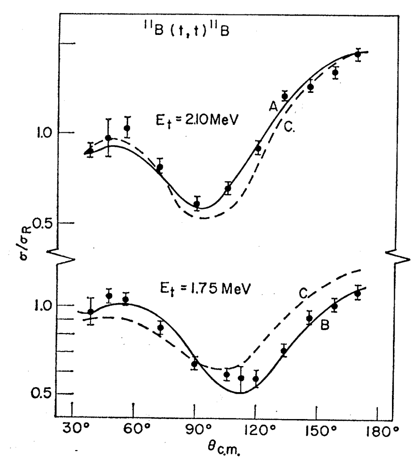

FIG. 4. Angular distributions for ^{11}B$(t,t)^{11}$B at 1.75- and 2.10-MeV triton energy. Solid curves—optical-model fits using potentials A and B of Table I; dashed curve—same using potential C of Table I.

[13] G. H. Herling, L. Cohen, and J. D. Silverstein, Phys. Rev. **178**, 1551 (1969). Also referred to as I.

[14] L. Cohen and G. H. Herling (unpublished).

[15] E. H. Auerbach (unpublished).

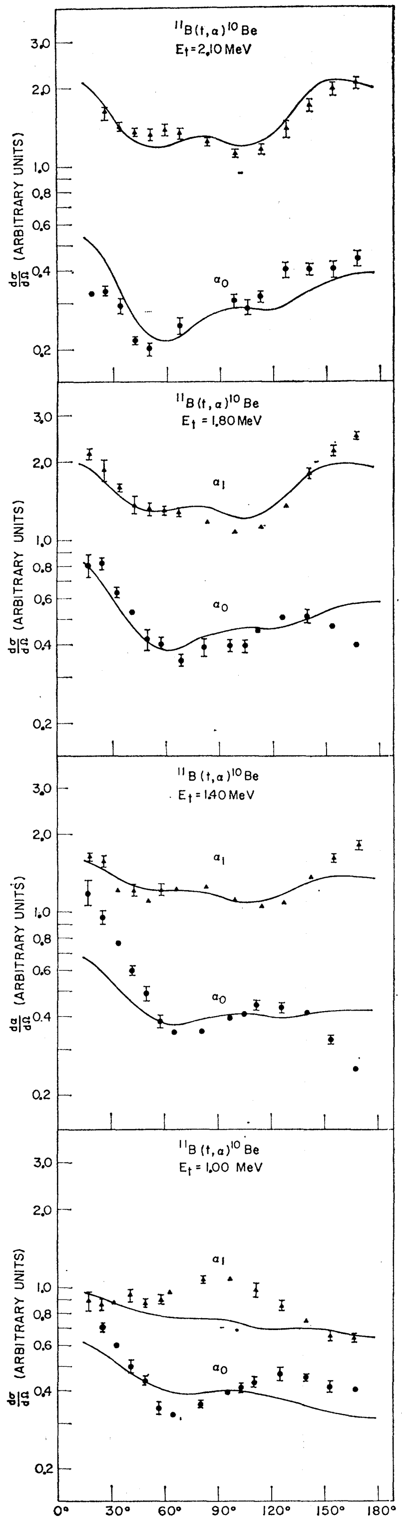

FIG. 5. Angular distributions for $^{11}B(t, \alpha)^{10}Be$ at 1.00-, 1.40-, 1.80-, and 2.10-MeV triton energy. The curves are the fits to the data arising from a DWBA analysis for $1p$ proton pickup. The optical-model parameters are given in Table I, sets C, X, and Y.

The symbol B in Eq. (2) refers to a possible renormalization of the data, and was allowed to vary between the limits 1 ± 0.15. It was not, however, optimized by the search code. If a parameter set yielded a good fit to the data with $B=1$, apart from normalization, the data were renormalized by requiring that the experimental point at 30° agree with the optical-model value. The parameters were then readjusted in order to obtain a minimum χ^2. The other symbols have their usual meanings.

The resulting best fits for each of the two energies are shown as solid curves in Fig. 4, and the parameters are given in Table I as sets A and B. Searches in which the starting set of parameters included a theoretically preferred[16,17] weaker spin-orbit potential were also performed. However, they yielded fits to the data which were either no better than or inferior to the solid curve fits in Fig. 4.

In addition, a search was made in which the data at both energies were fitted simultaneously, employing the geometry of I, and the arithmetic mean of the well depths obtained therein as a starting point. The fits obtained in this manner are shown as dashed curves in Fig. 4, and the parameters are given as set C in Table I.

IV. DWBA ANALYSIS

A. Fitting Procedure

Stock, Bock, David, Duhm, and Tamura have given a critical, detailed discussion of DWBA analyses of (^{3}He,α) reactions[18] which may be expected to apply also to (t,α) reactions. These authors have emphasized that exit channel wave functions based upon empirical α-particle optical potentials satisfying

$$U^{\alpha}\approx U^{\mathrm{He}}+U^{n} \tag{3}$$

tend to minimize finite range and nonlocal effects, and, therefore, are to be preferred. These effects are expected to be especially important for cases in which there is a significant angular momentum mismatch. They tend to decrease the contribution of the nuclear interior, and although that contribution may be reduced in a zero range, local calculation by means of a radial cut-off, both the magnitude and shape of the angular distribution are sensitive to the ambiguous value of the cutoff radius.

The $^{11}B(t,\alpha)^{10}Be$ reactions discussed here involve the pickup of an $l=1$ proton, whereas the semiclassical orbital angular momentum transfer, in units of $\hbar$, is

[16] A. Y. Abul Magd and M. El-Nadi, Progr. Theoret. Phys. (Kyoto) **35**, 798 (1966).

[17] L. R. Vesser, D. D. Armstrong, and P. W. Keaton, Jr., Bull. Am. Phys. Soc. **13**, 117 (1968).

[18] R. Stock, R. Bock, P. David, H. H. Duhm, and T. Tamura, Nucl. Phys. **A104**, 136 (1967).

TABLE I. Optical-model parameters.

Set	E (MeV)	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)	V_{so} (MeV)
				Tritons				
A	2.10	145	0.85	0.704	3.78	2.06	0.722	8.26
B	1.75	138	0.85	0.704	1.94	2.06	0.722	8.92
C [a]		142	0.85	0.704	3.11	2.06	0.722	9.16
				α particles				
X [b]		160	1.45	0.43	3.00	1.45	0.43	
Y [c]		174	1.45	0.43	3.00	1.47	0.43	

[a] Obtained by simultaneously fitting elastic scattering at both incident energies.

[b] Employed for ground-state α group at all incident energies.

[c] Employed for first-excited-state α group at all incident energies.

approximately 1.5. For the sake of definiteness no radial cutoff was used. The local, zero-range calculations reported here were performed using the code JULIE.[19] The bound-state wave function in these calculations was computed in a Saxon-Woods potential according to the separation energy prescription.

The only variations of triton parameters which have been attempted are the differences between sets A, B, and C of Table I. In an attempt to minimize possible fluctuations, set C was finally employed at all energies.

Both shallow ($V\approx 50$MeV) and deep ($V\approx 180$ MeV) types of exit channel optical potentials were considered. Elastic scattering of α particles from ^{9}Be has been analyzed by Taylor, Fletcher, and Davis[20] in terms of shallow potentials. Because of fluctuations in the optical-model parameters, and the difficulty of reliably extrapolating them among light nuclei, the real and imaginary well depths were allowed to vary in the range $45\leq V\leq 65$ MeV, $4\leq W\leq 6$ MeV in an attempt to fit the data with the published geometrical parameters[20] and sets A and B of Table I. No satisfactory fits were obtained to the ground-state group, which is not surprising in view of the preceding remarks.

A similar α-particle elastic-scattering analysis performed by Brady, Jungerman, and Young[21] has yielded deep optical potentials, but for the reasons just mentioned, parameters were allowed to vary. The variations were limited by exploiting the Vr_0^2 ambiguity together with the published fit. With W and a constant, the ambiguity defined a region $150\leq V\leq 200$ MeV, $1.45\leq r_0\leq 1.65$ fm within which any point was considered acceptable.

B. Results of DWBA Analysis

The best fits to 1.80- and 2.10-MeV data with deep α-particle potential wells are shown in Fig. 5. They were obtained using the set-C triton potential in Table I. The final values of the α parameters are given in Table I as set X and Y for α_0 and α_1, respectively. Although the first minimum of the α_0 data at 2.10 MeV is shifted by 9°, the gross features of the angular distribution persist; even if the shift is due to a resonance, its effect would appear to be small.

The fits to the 1.40- and 1.00-MeV data using the potentials C, X, and Y of Table I are also shown in Fig. 5. Small variations of the triton and α-particle potential well depths yielded an improved fit to the forward angle slope of the α_0 data at 1.40 MeV only at the expense of an inferior fit at other angles. An over-all improved fit was found, however, for the α_0 data at 1.00 MeV with the slightly different well

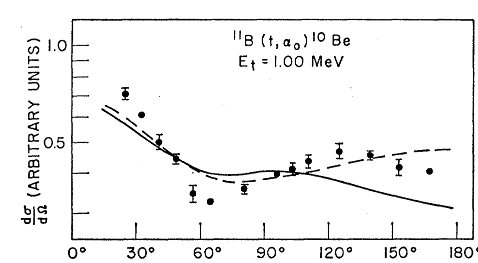

FIG. 6. Fits to ^{11}B$(t,\alpha_0)^{10}$Be reaction at 1.00-MeV triton energy with two sets of triton and α-particle optical parameters differing only in real well depths. Solid curve—$V_t=142$ MeV, $V_\alpha=160$ MeV; dashed curve—$V_t=145$ MeV, $V_\alpha=152$ MeV; other parameters are as in potential sets C and X of Table I.

[19] R. M. Drisko (unpublished).

[20] R. B. Taylor, N. R. Fletcher, and R. H. Davis, Nucl. Phys. **65**, 318 (1965).

[21] F. P. Brady, J. A. Jungerman, and J. C. Young, Nucl. Phys. **A98**, 241 (1967).

depths of 145 and 152 MeV for the triton and α particle, respectively. This is shown as the dashed curve in Fig. 6. This represents the only case for which a variation in well depths about their values in potentials C, X, and Y yielded a fit appreciably better than that in Fig. 5.

The α_1 data are seen to be satisfactorily fitted at each of the three higher energies. The failure to fit the 1.00-MeV data is not surprising, however, because rather than going through a minimum between 90° and 120° as do the data at the other energies, they go through a broad maximum there. In fact, the coefficient of $P_2(\cos\theta)$ in a Legendre Polynomial fit to the α_1 angular distribution at 1.00 MeV is opposite in sign to that of the α_1 angular distributions at the other energies.

C. Relative Spectroscopic Factors

The data and calculations allow a determination of the ratio of the spectroscopic factors S_0 and S_1 for the ground state and 3.37-MeV state of ^{10}Be, repsectively. The ratio is given by

$$\frac{S_1}{S_0}=\frac{(\sigma_1)_x/(\sigma_1)_{\rm DW}}{(\sigma_0)_x/(\sigma_0)_{\rm DW}}. \quad (4)$$

The quotients entering the numerator and denominator are taken to be the normalizations applied to the calculated angular distributions to provide the best visual fit to the data.

The first excited state of ^{10}Be is known to have $(J^\pi,T)=(2^+,1)$ and the ground state has $(0^+,1)$. It has been suggested[8] that these states are isobaric analogs of states in ^{10}B. Absolute spectroscopic factors for stripping leading to the same final states considered here,[22] and for pickup[23] leading to the ground state of ^{10}Be have been compared with shell-model predictions.

A comparison of the ratio of spectroscopic factors determined from this experiment with those predicted by the shell-model calculations of Cohen and Kurath[9] appears in Table II. The two theoretical ratios 2.65 and 3.25 depend upon the potential scheme employed. Estimates of Ref. 18 suggest that the experimental ratio has an uncertainty of the order of 40%.

TABLE II. Relative spectroscopic factors.

E_t (MeV)	2.10	1.80	1.40
$(S_1/S_0)_{\rm expt}$	3.09	2.14	2.12
$(S_1/S_0)_{\rm theoret}$	2.65[a]	3.25[b]	

[a] From the POT interaction of Ref. 9.
[b] From the 2BME interaction of Ref. 9.

V. CONCLUSIONS

Although not all details of the angular distributions have been reproduced, the agreement may be considered good in light of the angular momentum mismatch and the usual difficulties of treating light nuclei and low bombarding energies. For example, anomalies in the data such as the 9° shift of the α_0 minimum at 2.10 MeV and the gross change in shape of the α_1 angular distribution at 1.00 MeV suggest the possible existence of resonance effects in the triton energy range being considered.

Nevertheless, it has been possible to interpret the $^{11}B(t,\alpha)^{10}Be$ data in terms of simple DWBA calculations for $1p$ proton pickup. Triton optical potentials which account for the elastic-scattering data of this work as well as that from neighboring $1p$ nuclei have been employed, and the α-particle potentials are deep. The combination is similar to that expected to be best for $(^3He,\alpha)$ reactions. The result has been a reproduction of the general features of the angular distributions, and fair agreement between the relative spectroscopic factor extracted from the experiment and that predicted by the intermediate coupling shell model.

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[22] J. P. Schiffer, G. C. Morrison, R. H. Siemssen, and B. Zeidman, Phys. Rev. **164**, 1274 (1967).
[23] W. Fitz, R. Jahr, and R. Santo, Nucl. Phys. **A101**, 449 (1967).