Spectroscopic information from the ^{9}Be(^{7}Li,^{6}He)^{10}B and ^{9}Be(^{7}Li,^{6}Li)^{10}Be reactions*

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Elastic scattering of ^{7}Li + ^{9}Be and ^{6}Li + ^{10}B has been measured at $E(^{7}\text{Li}) = 34$ MeV and $E(^{6}\text{Li}) = 30$ MeV and the data have been described with the standard optical model. Both ^{9}Be(^{7}Li,^{6}He) and ^{9}Be(^{7}Li,^{6}Li) reaction data were measured. Extreme forward angle (^{7}Li,^{6}He) data were taken so that the j transfer (3/2 or 1/2) to the first two 1^{+} states in ^{10}B could be determined. Both states were found to be populated predominantly by $p_{1/2}$ transfers. The absolute spectroscopic factors obtained are in good agreement with 35 MeV (^{3}He,d) data, but not with 17 MeV data. Comparison between the spectroscopic factors obtained from the (d,n), (^{3}He,d), and (^{7}Li,^{6}He) reactions shows a clear need for the energy dependence of these reactions to be understood before reliable absolute spectroscopic factors for ^{10}B can be obtained. The (^{7}Li,^{6}Li) results were in good agreement with the calculations of Cohen and Kurath, in contrast to the (^{7}Li,^{6}He) results.

[NUCLEAR REACTIONS ^{7}Li+^{9}Be, 34 MeV; ^{6}Li+^{10}B, 30 MeV; measured $\sigma(\theta)$; deduced optical model parameters. ^{9}Be(^{7}Li,^{6}He)^{10}B, 34 MeV; measured $\sigma(\theta)$; deduced j transfer; ^{9}Be(^{7}Li,^{6}Li)^{10}Be, 34 MeV; measured $\sigma(\theta)$. Deduced $S(^{10}\text{B})$ and $S(^{10}\text{Be})$ from finite-range DWBA analysis.]

I. INTRODUCTION

In 1966, Siemssen *et al.*[1] reported a comparison of the ^{9}Be(d,n) and ^{9}Be(^{3}He, d) reactions which showed that the spectroscopic factor for the 0^{+}, $T=1$, 1.74 MeV state in ^{10}B is 2.5 times greater for (^{3}He, d) than for (d,n), while for the first two $T=0$ states they were the same within the experimental error. Many different explanations for this difference have been given. One of the most successful has been that given by Cotanch and Robson,[2] who considered the effect of the coupling between the $T=0$ and $T=1$ components of the entrance channel, which occurs for (^{3}He, d) but not for (d,n). The inclusion of isospin in the distorted-wave–Born-approximation (DWBA) analysis results in a decrease of the imaginary optical model potential for the (^{3}He, d) case to the $T=1$ state with a corresponding decrease in the (^{3}He, d) spectroscopic factor. A reanalysis[3] with the Cotanch-Robson model of more recent (^{3}He, d) (Ref. 4) and (d,n) (Ref. 5) data has been able to extract spectroscopic factors for the two reactions which agree to within 20% when compound nucleus contributions to the (d,n) reaction are included. In order to make certain that the (d,n) compound nucleus calculations are realistic, an alternative reaction which yields comparable spectroscopic factors has been studied. The reaction chosen is the ^{9}Be(^{7}Li, ^{6}He)^{10}B reaction. This reaction has the same isospin coupling effects as the (d,n) reaction and should yield the same spectroscopic factors. In addition, the ^{9}Be(^{7}Li, ^{6}Li)^{10}Be reaction and the elastic scattering of ^{10}B + ^{6}Li and ^{9}Be + ^{7}Li were measured. The reaction data were compared with exact finite-range distorted-wave–Born-approximation calculations in order to extract spectroscopic factors, while the elastic scattering data were analyzed with the optical model.

II. EXPERIMENTAL PROCEDURE

The Li beams, produced with a Heinicke source[6] and later with an inverted sputter source,[7] were accelerated with the Florida State University super FN tandem Van de Graaff accelerator. Typical beam currents on target were 250 nA. The ^{9}Be targets were prepared by the method described by Taylor, Fletcher, and Davis[8] and were 100–190 μg/cm^{2} thick. The product of the target thickness and the detector solid angle ($Nd\Omega$) was determined by normalizing the α particle elastic scattering yield at the lab energy of 18 MeV and angle of 85.6° c.m. to the data of Taylor *et al.*[8] A combination of the 10% error quoted in Ref. 8 and the reproducibility of the normalization data leads to an absolute error of 13% for this work. The ^{10}B targets enriched to 98.2% were self-supporting and had thicknesses between 50 and 100 μg/cm^{2}. The product $Nd\Omega$ for the ^{10}B targets was determined by normalizing 12 MeV elastic proton scattering at 110.54° c.m. to the cross section of 25 mb/sr determined by Watson *et al.*[9] The error in the absolute cross section is 16% for the present work, and arises principally from the 15% error

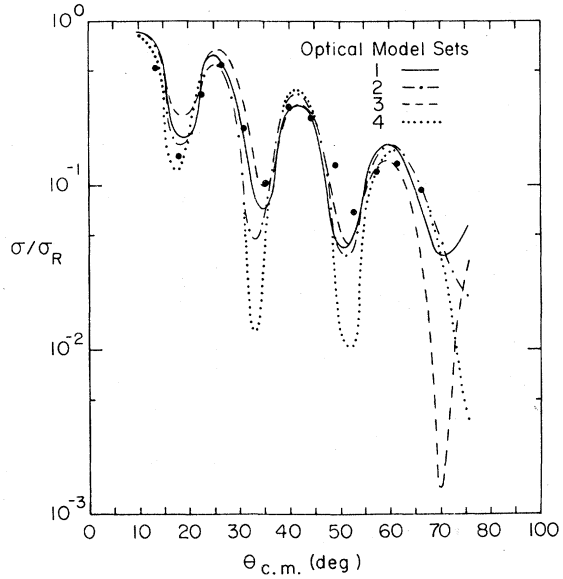

FIG. 1. Elastic scattering angular distributions for ^{7}Li+^{9}Be at $E(^7\text{Li}) = 34$ MeV plotted as the ratio to Rutherford. The optical model parameter sets used in the calculations are given in Table I. The relative error in the data is less than the size of the data points.

of Ref. 9.

For all measurements, two Si surface barrier counter telescopes consisting of 25 μm ΔE counters with 500 μm stopping counters (E) were used in a scattering chamber that permitted the counters to be cooled to -10°C. The ΔE and E signals were amplified and gated with conventional electronics and then stored in an EMR 6130 on-line computer via a CAMAC interface between the analog-to-digital converter units and the computer. Contours around the different particle types were drawn with a light pen after the $\Delta E \times E$ events were displayed on a storage scope. It was possible to sort on-line all events of interest in both telescopes with this system. Both telescopes had a solid angle of 0.3 msr and an angular resolution of 0.2°. The (^{7}Li, ^{6}He) data for angles less than 15° were taken in a quadrupole spectrometer.[10] The band pass of the instrument was 1 MeV and measurements were made with the spectrometer set to focus ^{6}He particles whose energy would correspond to states in ^{10}B at 0.5 and 2.0 MeV. The absolute cross section for this data was obtained by normalizing data taken with the quadrupole spectrometer to data taken in a scattering chamber at 12.5° and 15°. A monitor detector was used during all runs to provide a measure of target deterioration and charge integration errors. The relative errors are indicated by the error bars on the data displayed in the angular distributions.

III. ANALYSIS AND RESULTS

A. Optical model analysis

To provide optical model parameters necessary for the distorted-wave–Born-approximation analysis of the transfer data, 34 MeV ^{9}Be+^{7}Li and 30 MeV ^{10}B+^{6}Li data were analyzed with the optical model program JIB.[11] The previously published parameters for this mass region of Bassani *et al.*,[12] Schumacher *et al.*,[13] Weber *et al.*,[14] and Poling, Norbeck, and Carlson[15] were used as starting parameters in the searches. The standard form of the optical potential was used with either volume or surface imaginary potentials depending on choices made in Refs. 11–14. Reasonable descriptions of the data were found for calculations done with starting values from Bassani *et al.*,[12] Schumacher *et al.*,[13] and Weber *et al.*,[14] while it was not possible to describe the data with the potential of Poling, Norbeck, and Carlson.[15] This result is not surprising since the ^{6}Li+^{10}B data of Poling *et al.*[15] were taken at 5.8 MeV which is well below the Coulomb barrier. The ^{6}Li+^{9}Be parameters of Poling *et al.*[15] were also tried because these parameters had an energy dependent absorption. However, the calculated angular distributions for these parameters were too oscillatory and the oscillations increased in amplitude with increasing angle, in contrast to the data. The best fits to the data are shown in Figs. 1 and 2 and the parameter sets obtained are given in Table I.

B. DWBA analysis of transfer data

Representative spectra for the reactions ^{9}Be(^{7}Li, ^{6}He)^{10}B and ^{9}Be(^{7}Li, ^{6}Li)^{10}Be are shown in Figs. 3 and 4. No reduction in the cross section

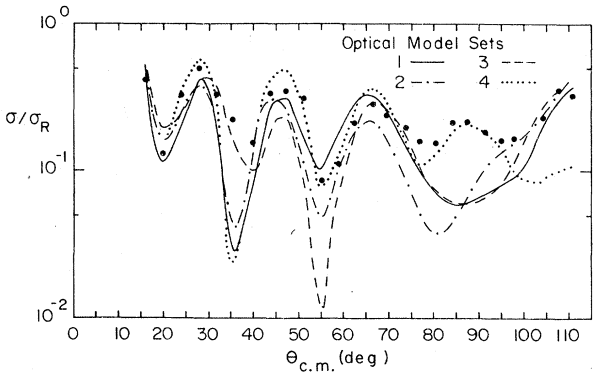

FIG. 2. Elastic scattering angular distributions for ^{6}Li+^{10}B at $E(^6\text{Li}) = 30$ MeV plotted as the ratio to Rutherford. The optical model calculations were done with the parameter sets in Table I. The size of the data points is greater than or equal to the relative error in the data.

TABLE I. Optical model parameters for ^{7}Li+^{9}Be and ^{6}Li+^{10}B. The interaction radii are given by $R_x = r_x A_T^{1/3}$.

Reaction	Set	U (MeV)	r_r (fm)	a_r (fm)	W (MeV)	r_i (fm)	a_i (fm)	r_c (fm)
^{7}Li+^{9}Be	1	173.1	1.19	0.78	8.9	2.52	0.924	1.78
	2	234.4	1.21	0.76	8.9	2.43	1.02	1.78
	3	539.0	1.05	0.67	22.0	2.11	0.893	1.78
	4	23.0	2.15	0.77	10.3	2.24	1.13	1.78
^{6}Li+^{10}B	1	173.2	1.21	0.802	8.9	2.17	0.947	1.78
	2	233.4	1.21	0.73	8.9	2.17	1.02	1.78
	3	500.0	1.05	0.66	11.0	2.11	0.893	1.78
	4	22.8	2.15	0.61	10.3	1.89	1.13	1.78

for the transition to the 0^+, $T=1$, 1.74 MeV state in ^{10}B was observed in this work. For comparison purposes, the angular distributions to the first four states in ^{10}B are shown in Fig. 5. To extract spectroscopic information from the transfer reactions, exact finite-range DWBA calculations were performed with the code MERCURY.[16] Since the elastic scattering data did not provide a clear choice for a "best" set of optical parameters, reaction calculations were done for the (^{7}Li, ^{6}He) reaction to the 3^+, 0.0 MeV and 0^+, 1.74 MeV states in ^{10}B in order to test the various possibilities. These two transitions were chosen because they involve transfers only into $1p_{3/2}$ orbits, whereas the 1^+ transitions can have both $1p_{3/2}$ and $1p_{1/2}$ contributions. The bound state wave functions were generated with Woods-Saxon potentials that had the geometry parameters $r=1.25$ fm and $a=0.65$ fm and a spin-orbit parameter $\lambda=25$. The depths of the potentials were adjusted to give the correct separation energies. $^7\text{Li} \rightarrow {}^6\text{He}+p$ was assumed to have a 0.89 spectroscopic factor for the p to be in a $p_{3/2}$ orbit.[17] The calculated angular distributions are shown in Fig. 6. The calculations for optical model set 2 are not shown because they were the same as for optical model set 1. Of the four optical model sets, set 4 gives a poor description of the forward angle data and does not decrease with increasing angle as does the data, while set 3 fits the forward angle data but does not have any structure at the larger angles. Consequently, set 1 was used for all further calculations and for the extraction of spectroscopic factors.

Previously[18] it has been shown that the (^{7}Li, ^{6}He) reaction is sensitive to the difference between $p_{3/2}$ and $p_{1/2}$ components in the final state wave function so that it should be possible to measure the $p_{3/2}$ and $p_{1/2}$ components in the transitions to the 1^+ states in ^{10}B. Figure 5, which is a comparison of the data for the four states measured in ^{10}B indicates that the first two 1^+ states in ^{10}B are predominantly $p_{1/2}$. Figure 7 shows the calculated angular distributions and the data for the 1^+, 0.72 MeV and 1^+, 2.15 MeV states in ^{10}B. The calculations were done assuming the state in ^{10}B to be reached by either $p_{3/2}$ or $p_{1/2}$ transfer. As can be seen, the forward angle data agree extremely well with the $p_{1/2}$ calculations indicating that these

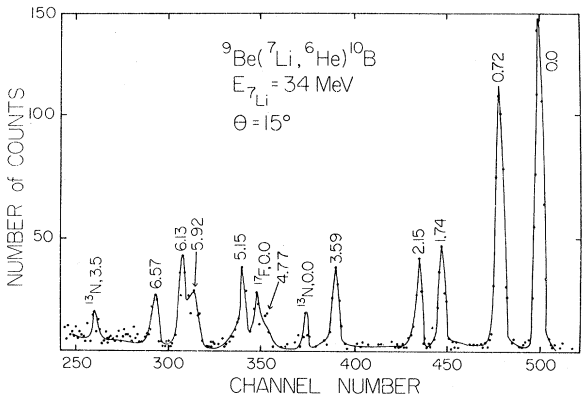

FIG. 3. Typical spectrum taken in a scattering chamber. Note the population of the 1.74 MeV, 0^+, $T=1$ state in ^{10}B.

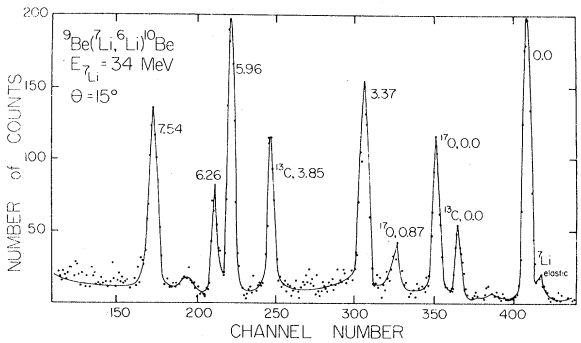

FIG. 4. Typical spectrum taken in a scattering chamber for the ^{9}Be(^{7}Li, ^{6}Li)^{10}Be reaction.

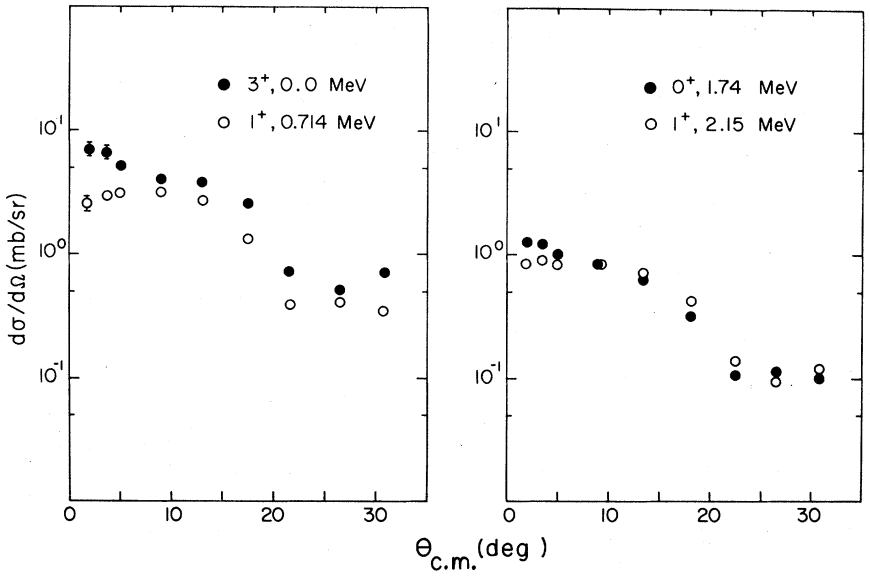

FIG. 5. Comparison of the experimental angular distributions for the ^{9}Be(^{7}Li, ^{6}He)^{10}B reaction at $E_{^{7}\mathrm{Li}}$ populating the first four states in ^{10}B. Note the difference in shape at the extreme forward angles in the 3^+ and 0^+ states which go by $p_{3/2}$ transfer and the two 1^+ states.

two states are populated almost completely by $p_{1/2}$ transfers. A recent study[19] of the ^{9}Be(^{3}He, d)^{10}B reaction with a polarized ^{3}He beam also reached the tentative conclusion that the proton is in a $p_{1/2}$ orbit for these states. The conclusions were considered tentative in the ($^{3}\vec{\mathrm{He}}$, d) work because the thick targets used to get reasonable statistics made the energy resolution so poor that the peak yield extraction contained considerable error. The present (^{7}Li, ^{6}He) result shows the trend of the ($^{3}\vec{\mathrm{He}}$, d) data to be correct. The assignment of the 2.15 MeV state as a $p_{1/2}$ transfer is in disagreement with the calculations of Cohen and Kurath.[17]

Spectroscopic factors were extracted for the 3^+, 1^+, 0^+, and 1^+ states in ^{10}B by comparing the

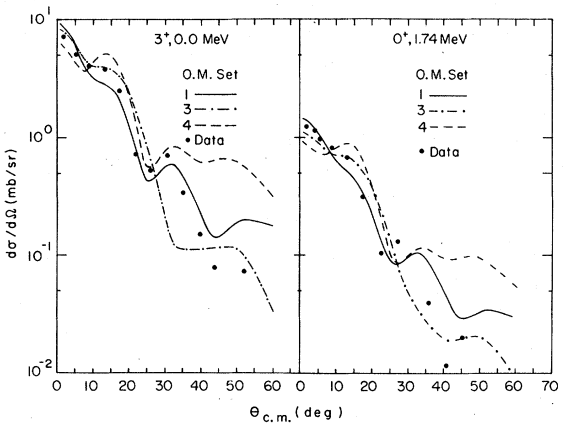

FIG. 6. Calculated and experimental angular distributions for the 3^+ and 0^+ states in ^{10}B. The DWBA calculations were done with all four sets of optical parameters but the calculations for Sets 1 and 2 were indistinguishable. The relative errors in the data are less than or equal to the size of the data points. The DWBA calculations were normalized to the total experimental cross section between 1.75° and 20° c.m.

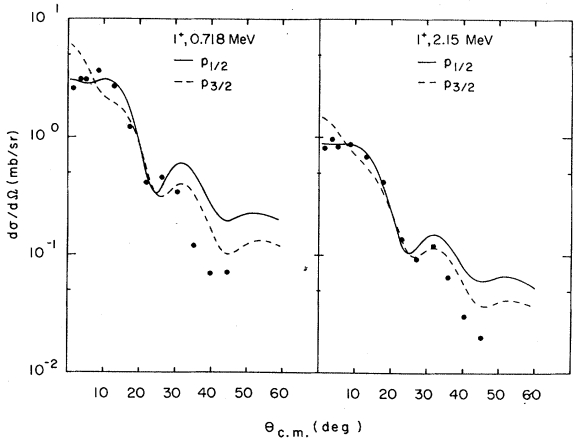

FIG. 7. Calculated and experimental angular distributions for the first two 1^+ states in ^{10}B. The DWBA calculations were done with optical parameter Set 1 of Table I. The two curves show the shape of the calculations assuming the proton transfer to be either into a $p_{3/2}$ or $p_{1/2}$ orbit. The calculations were normalized to the total experimental cross section between 1.75° and 20° c.m.

TABLE II. Absolute and relative spectroscopic factors for levels in ^{10}B.

E_x (MeV)	J^π, T	$S(^7\text{Li}, ^6\text{He})$ Abs.	Rel.	$S(d,n)$ [a] Abs.	Rel.	$S(^3\text{He}, d)$ 17 MeV [a] Rel.	35 MeV [b] Abs.	Rel.	S_{theor} [c] (C.K.) Abs.	Rel.	S_{theor} [d] (V.G.) Abs.	Rel.
0.0	$3^+, 0$	0.88	1.0	1.18	1.00	1.00	0.68	1.00	1.20	1.0	0.76	1.00
0.72	$1^+, 0$	1.38($p_{1/2}$ or $p_{3/2}$)	1.57	2.37	2.01	1.77	1.15	1.70	1.35	1.12	0.99	1.30
1.74	$0^+, 1$	1.40	1.58	1.53	1.30	2.40			2.36	1.96	0.98	1.29
2.15	$1^+, 0$	0.46($p_{1/2}$), 0.54($p_{3/2}$)	0.52($p_{1/2}$)	0.50	0.42	0.60			0.73	0.61	0.46	0.61

[a] Average of values given in Ref. 5.
[b] See Ref. 19.
[c] See Ref. 17.
[d] See Ref. 20.

total experimental cross section for this angular range. The absolute and relative spectroscopic factors are given in Table II. The largest difference between the (d,n) and $(^7\text{Li}, ^6\text{He})$ reactions is in the spectroscopic factor for the 0.72 MeV, 1^+ state which was 2.37 in the (d,n) analysis and 1.38 in the present analysis. Even if the $(^7\text{Li}, ^6\text{He})$ result is increased up by the 20% experimental error, the spectroscopic factor would only be 1.66, still short of the 2.37 (d,n) result. The $(^7\text{Li}, ^6\text{He})$ absolute spectroscopic factors agree quite well with the higher energy $(^3\text{He}, d)$ work. The extracted spectroscopic factors for $(^7\text{Li}, ^6\text{He})$ confirm the previously reported (d,n) and $(^3\text{He}, d)$ anomaly for the 0^+, $T=1$ ^{10}B state. While the absolute value of the $(^7\text{Li}, ^6\text{He})$ spectroscopic factors are closer to the Varma and Goldhammer[20] values than the Cohen and Kurath values, the fact that the $(^3\text{He}, d)$ absolute spectroscopic factors are highly energy dependent[19] means that the $(^7\text{Li}, ^6\text{He})$ reaction needs to be studied at quite different energies in order to examine the energy dependence of the spectroscopic factors obtained with it before the absolute value can be safely extracted.

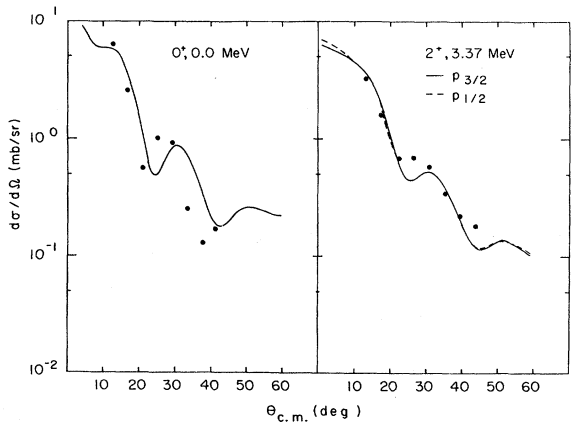

FIG. 8. Calculated and experimental $(^7\text{Li}, ^6\text{Li})$ angular-distributions. The DWBA calculations were normalized to the total experimental cross section between 12° and 30° c.m.

The $(^7\text{Li}, ^6\text{Li})$ angular distributions are shown in Fig. 8. The spectroscopic factors were extracted by comparing the total experimental cross section between 10°–30° c.m. with the theoretical cross sections. The results are given in Table III. These results are in good agreement with the calculations of Cohen and Kurath. As can be seen in Fig. 8, it is not possible to determine whether the 2^+ state is populated by a $p_{3/2}$ or a $p_{1/2}$ transition in the $(^7\text{Li}, ^6\text{Li})$ reaction.

IV. CONCLUSIONS

Optical model calculations were able to give a reasonable description of the elastic scattering data but could not reproduce all of the structure observed in the data. The $(^7\text{Li}, ^6\text{He})$ angular distributions were shown to distinguish between $p_{3/2}$ and $p_{1/2}$ components in the final stages in ^{10}B for angles less than 10° c.m. The data indicate that the first two 1^+ states in ^{10}B are populated by $p_{1/2}$ transfers in agreement with recent $(^3\text{He}, d)$ measurements.[19] These results are in disagreement with the calculations of Cohen and Kurath, which predict the first 1^+ state to be populated predominantly by $p_{1/2}$ transfer, and the second 1^+ state by $p_{3/2}$ transfer. Comparison of the $(^7\text{Li}, ^6\text{He})$ spectroscopic factors with (d,n) and $(^3\text{He}, d)$ works shows several difficulties, the most serious being the large difference in the (d,n) and $(^7\text{Li}, ^6\text{He})$ results for the 1^+, 0.72 MeV state in ^{10}B. Since both the (d,n) and $(^7\text{Li}, ^6\text{He})$ DWBA fits are reasonable at forward angles this difference needs to be investigated further. The $(^7\text{Li}, ^6\text{He})$ absolute spectroscopic factors are lower than $(^3\text{He}, d)$ results taken at $E_{^3\text{He}}=17$ MeV but are in good agree-

TABLE III. Absolute spectroscopic factors for ^{10}Be.

E_x (MeV)	J^π	$S(^7\text{Li}, ^6\text{Li})$	$S(d,p)$ [a]	S_{theor} [b] (C.K.)
0.0	0^+	2.07	1.67	2.36
3.37	2^+	0.42($p_{1/2}$), 0.38($p_{3/2}$)	0.24	0.23($p_{1/2}$)

[a] See Ref. 21.
[b] See Ref. 17.

ment with 35 MeV data.[19] The strong energy dependence of the (^{3}He, d) reaction makes it difficult to compare absolute spectroscopic factors between the (d, n), (^{3}He, d), and (^{7}Li, ^{6}He) reactions. The (^{7}Li, ^{6}Li) spectroscopic factors are in good agreement with the calculations of Cohen and Kurath. This work has reaffirmed that the energy dependence of both the light and heavy ion reactions needs to be studied in greater detail before reliable absolute spectroscopic factors for these light nuclei can be obtained.

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