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J. Phys. G: Nucl. Part. Phys. **25** (1999) 1897–1907. Printed in the UK PII: S0954-3899(99)99796-7

# Study of $\alpha$-transfer reaction $^{28}$Si( $^{7}$Li, t) $^{32}$S

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Received 30 November 1998, in final form 23 March 1999

**Abstract.** The $^{28}$Si( $^{7}$Li, t) $^{32}$S reaction has been studied at 48 MeV. Using a $\alpha$t potential overlap based on a microscopic cluster model, the full finite-range distorted wave Born approximation analysis was carried out for nine low-lying states; 0.0 MeV ($0^+$), 2.23 MeV ($2^+$), 3.78 MeV ($0^+$), 4.46 MeV ($4^+$), 5.01 MeV ($3^-$), 5.80 MeV ($1^-$), 6.76 MeV ($3^-$), 7.43 MeV ($1^-$) and 8.49 MeV ($1^-$) of the residual nucleus. A re-analysis was also done for the same states of $^{32}$S having an $\alpha$d overlap for the reaction $^{28}$Si ($^{6}$Li, d) $^{32}$S at 75.6 MeV. Theoretical spectroscopic factors have been calculated for the measured even-parity states of $^{32}$S using the shell model code OXBASH. The spectroscopic factors were compared for both the reactions.

## 1. Introduction

Direct transfer of one or more nucleons between the colliding nuclei is one of the most widely used means for obtaining information on the nuclear shell structure. Single-nucleon transfer is a selective and direct probe of single-particle shell structure, while two-nucleon transfer provides knowledge of pairing correlations in nuclei. Transfer reactions are very sensitive to the tail of the nuclear wavefunctions and thus to the radius and the diffusivity of the ion–ion potential. Multi-nucleon transfer reactions are extremely useful in obtaining information on nuclear structure, selectively exciting many-particle many-hole states in light nuclei. It plays a vital role in the study of the cluster states of the residual nucleus. One such interesting problem is the determination of $\alpha$-cluster states through the four-nucleon ($\alpha$-) transfer reaction.

The $\alpha$-transfer reaction is only possible with ions having $A = 6$ or more. This reaction has attracted a lot of interest because of the simplicity of the reaction mechanism involved which comes from the good spatial symmetry of the $\alpha$-particle as well as its zero spin and isospin. Since the $\alpha$-particle has a very large binding energy it behaves almost like an elementary particle and it is possible to have $\alpha$-cluster state in a nucleus.

At forward angles the $\alpha$-transfer reactions at an incident energy above the Coulomb barrier have a dependence on the transferred angular momentum [1]. These reactions also relate directly to the $\alpha$-cluster states and reveal the $\alpha$-cluster nature of the states involved. The simple way of understanding the $\alpha$-transfer reaction is through ($^{6}$Li, d) or ($^{7}$Li, t) reactions because the ground states of these projectiles can be considered to have the structure of a $\alpha$-cluster and the deuteron or triton, respectively [2]. Over a wide range of mass numbers systematic

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studies have been performed for the ($^6$Li, d) and (d, $^6$Li) reactions [3–7]. Comparative studies between ($^6$Li, d) and ($^7$Li, t) reactions [8, 9] are scarce.

In this paper we report such a comparative study of ($^7$Li, t) and ($^6$Li, d) reactions on a Si target. The ($^7$Li, t) reaction shows more features of a direct reaction mechanism compared with the ($^6$Li, d) reaction [10]. The other measurement of ($^6$Li, d) which we took from the literature was performed using the cyclotron facility and a spectrograph. There the advantage is due to high beam current. The high resolution of energy spectrum obtained in a magnetic spectrograph also helps. In our measurement with a Pelletron machine and solid-state detector telescopes we did not get enough beam current. Also, very good energy resolution to obtain sharp peaks for the weak low-lying states was not possible. Small solid angles had to be used. Because of these limitations the quality of our data is somewhat poorer than in [11]. We have measured the ($^7$Li, t) cross section data and obtained the ($^6$Li, d) data from the literature [11]. The ($^7$Li, t) reaction was studied at 48 MeV. The absolute spectroscopic factors have been derived by using microscopically calculated wavefunctions for $^7$Li and $^6$Li in the full finite-range distorted wave Born approximation (DWBA) calculations [12]. Shell model calculations were also performed to obtain the $\alpha$-spectroscopic factors of the $^{32}$S nucleus for the even-parity states using the `OXBASH` [13] computer code.

## 2. Experimental details

The experiment was performed with momentum analysed 48 MeV $^7$Li$^{3+}$ beam obtained from the 15UD Pelletron at NSC, New Delhi, and using the 1.5 m diameter general-purpose scattering chamber (GPSC). The beam intensity on the target was about 10 pnA. A self-supporting natural Si target (92.23% $^{28}$Si, 4.67% $^{29}$Si and 3.10% $^{30}$Si) was used in the experiment. The target was prepared from a thin silicon wafer by first ion-implanting up to the desired depth and then preferentially etching out this depth. Target thickness was determined by the energy loss of an $\alpha$-particle from a $^{241}$Am source. The stopping power values for this purpose were calculated from `TRIM` [14].

The experimental arrangement for the measurement of outgoing triton consisted of three $\Delta E$–$E$ telescopes, each with 1 mm $\Delta E$ and 5 mm Si(Li) $E$ detectors. The forward telescope subtended a solid angle of 0.5 msr while the one kept at a backward angle subtended a solid angle of 1 msr. Two monitor detectors were used for cross section normalization and these were placed at $\pm 9^\circ$.

Conventional particle-identification electronics was used in the experiment. The energy resolution was about 100 keV. Figure 1 shows a typical energy spectrum of tritons obtained during the experiment at 18°. It shows well-seperated peaks for all the analysed states. A Faraday cup connected to a current integrator was used to obtain the total charge. The absolute cross section was calculated using the Faraday cup counts and checked against monitor cross section which is predominantly due to Rutherford scattering.

The signals were processed through an AD811 module ADC in a CAMAC crate and the data was stored on magnetic tapes with the Micro-Vax computer system using the `ONLINE` computer program [15]. The data were collected using an event-by-event mode and stored in magnetic tapes for offline analysis. The angular distributions were measured from $\theta_{lab} = 6$–$40^\circ$ in steps of 4°.

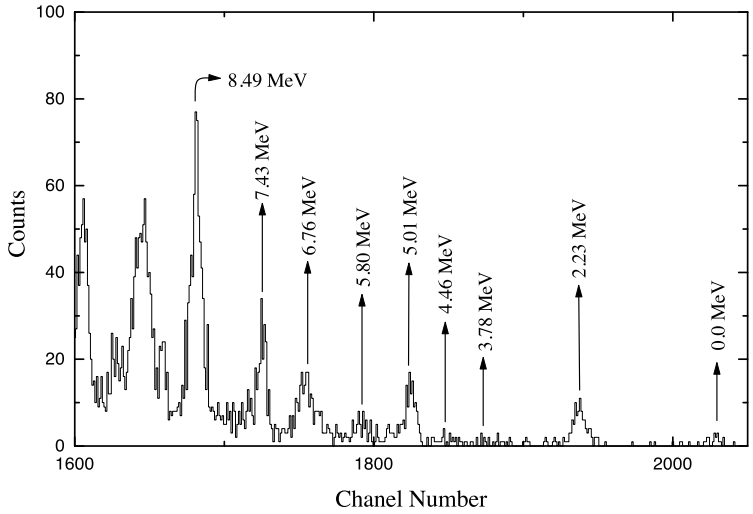


**Figure 1.** Energy spectrum obtained for tritons at 18° for the reaction $^{28}$Si( $^{7}$Li, t) $^{32}$S at 48 MeV beam energy.

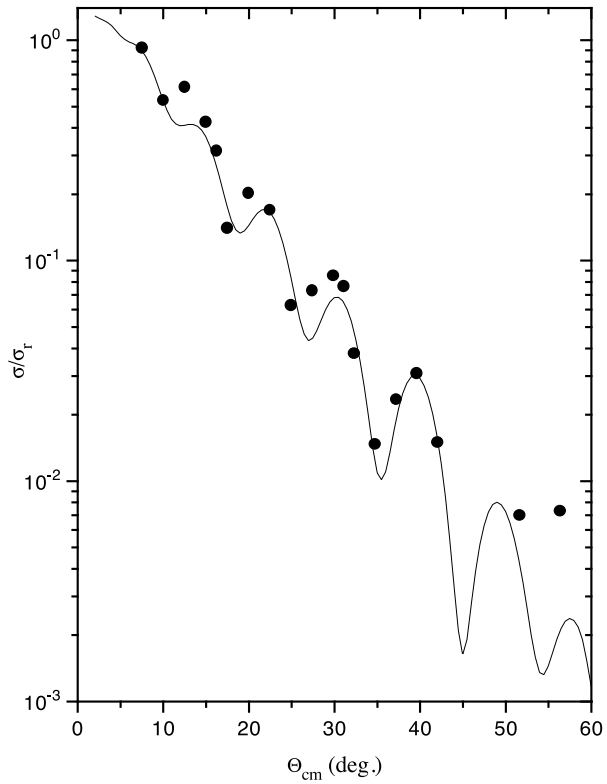


**Figure 2.** Elastic angular distribution of $^{7}$Li on natural Si at 48 MeV. The curve shows the optical model fit with the potential parameters of table 1.

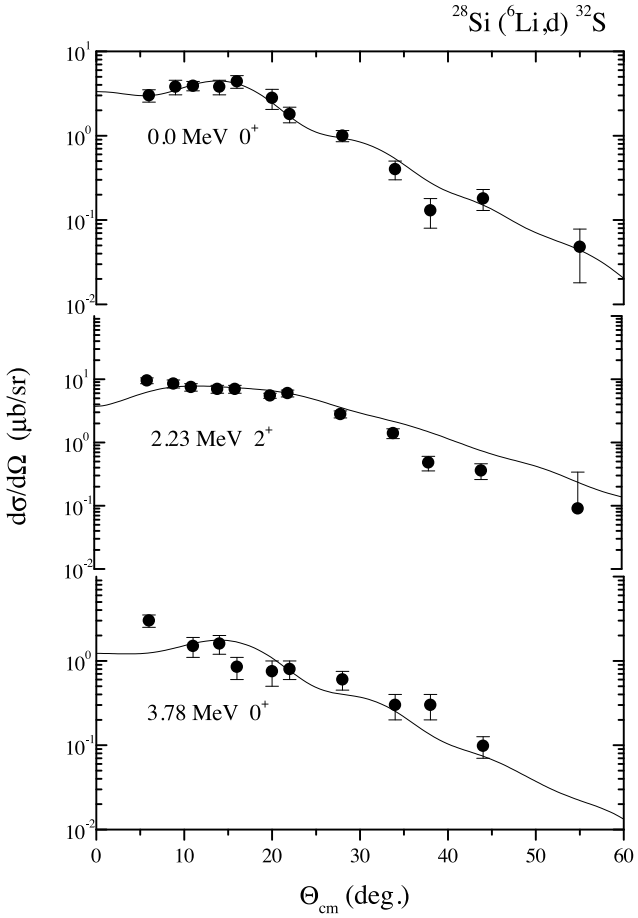


**Figure 3.** Angular distribution of the reaction $^{28}$Si($^{6}$Li, d)$^{32}$S. The solid curve represents the exact finite-range DWBA calculation.

## 3. Theoretical analysis

The angular distribution data was analysed in the framework of the DWBA using the exact finite-range computer code DWUCK5 [12]. For the determination of absolute $\alpha$-spectroscopic factors the projectile cluster overlap is very important. Therefore, in the analysis, $\alpha$t potential overlap has been calculated on the basis of a fully microscopic cluster model [16] which applies the Volkov 2 force and reproduces the exact $\alpha$t separation energy. The entrance channel wavefunction for the $^{7}$Li + $^{28}$Si reaction was calculated from optical model parameters, extracted by fitting the elastic cross section measured at 48 MeV. The computer code SNOOPY [17] was used for searching the optical model parameters. While searching the parameters GRID and SEARCH options were combined to reduce the chi-squared value to a minimum. Figure 1 shows the fit to $^{7}$Li elastic data. The exit channel parameters are taken from [18]. The parameters used for the description of the entrance- and exit-channel distorted waves are listed in table 1. For the case of the $^{6}$Li + $^{28}$Si reaction parameters given by Tanabe *et al* [11] have been employed. For the bound states of $^{32}$S a target plus $\alpha$-cluster wavefunction generated in a Woods–Saxon well of radius 1.3 $A_t^{1/3}$ and diffuseness of 0.73 fm was used. The well depth

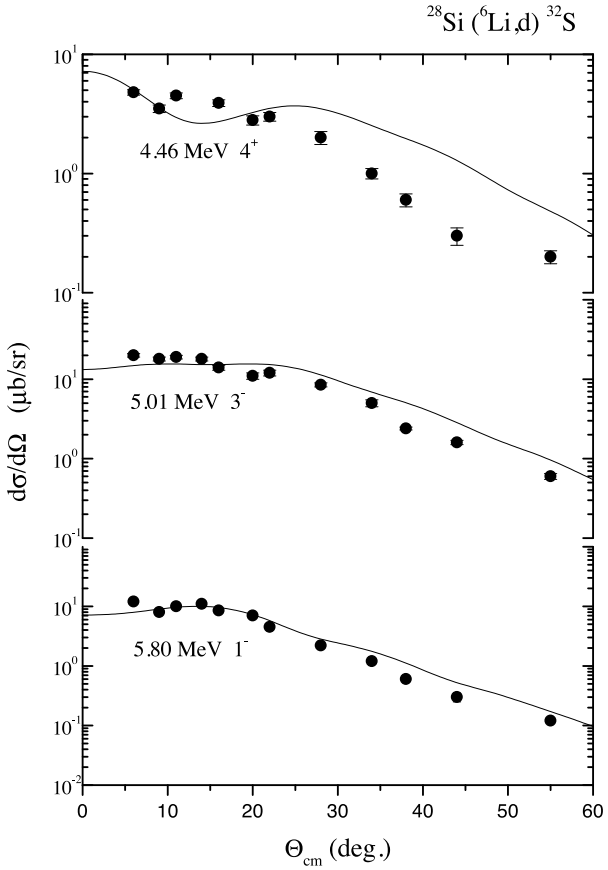


**Figure 4.** Angular distribution of the reaction $^{28}$Si($^{6}$Li, d)$^{32}$S. The solid curve shows the exact finite-range DWBA calculation.

was adjusted to reproduce the binding energy of the $\alpha$-bound levels in the final nuclear state. The single-particle configuration for the system ($^{28}\mathrm{Si}+\alpha$) was taken to be $(\mathrm{sd})^4$ and $(\mathrm{sd})^3(\mathrm{fp})^1$ for the positive and negative parity states, respectively. For the $^{6}$Li wavefunction we used an overlap wavefunction calculated microscopically [19]. The number of radial nodes $N$ was fixed by the oscillator energy conservation relation $2N + L = \sum_{i=1}^{4} 2n_i + l_i$ where $(n_i, l_i)$ are the shell model quantum numbers of the individual nucleons and $(N, L)$ describes the radial quantum number and orbital quantum number of the cluster with respect to the core. This equation gives $2N + L = 8$ and 9 for even- and odd-parity states. In the DWUCK5 code the sum over all possible $l$-values are included. So, in the ($^{7}$Li, t) case the $\alpha$ being in a $l = 1$ state is taken into account in the calculations. For the states unbound against $\alpha$-particle emission, DWBA calculations with form factors corresponding to weak binding ($E_B = -0.1$ MeV) were performed. The variation in the very small binding energy did not produce significant differences.

Shell model calculations were also performed to obtain theoretical estimates of the alpha spectroscopic factors for even-parity states using the computer code OXBASH [13]. For these calculations we have generated the single-particle states for $^{32}$S, $^{28}$Si and the $\alpha$-particle as described below. The single-particle states for $^{28}$Si and $^{32}$S have been generated using SD

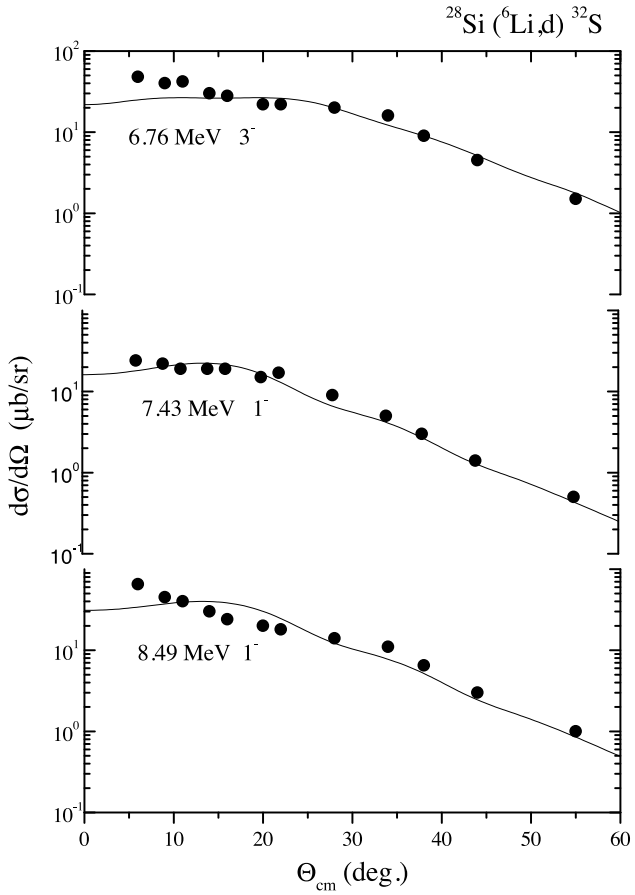


**Figure 5.** Angular distribution of the reaction $^{28}$Si($^{6}$Li, d)$^{32}$S. The solid curve shows the exact finite-range DWBA calculation result.

**Table 1.** The optical model parameters used for the DWBA calculations.

| Channel | $V$ (MeV) | $r_r$ (fm) | $a_r$ (fm) | $W$ (MeV) | $W_d$ (MeV) | $r_i$ (fm) | $a_i$ (fm) | $r_C$ (fm) |
|---|---|---|---|---|---|---|---|---|
| $^{7}$Li + $^{28}$Si | 180.72 | 1.21 | 0.832 | 12.4 | — | 2.1 | 0.756 | 1.2 |
| t + $^{32}$S | 145.0 | 1.14 | 0.73 | 19.8 | — | 1.59 | 0.8 | 1.11 |
| $^{6}$Li + $^{28}$Si | 176.5 | 1.3 | 0.7 | 32.9 | — | 1.7 | 0.9 | 1.4 |
| d + $^{32}$S | 62.833 | 1.25 | 0.7338 | 13.0 | 12.0 | 1.25 | 0.751 | 1.3 |

model space and the universal s–d interaction $W$ of Wildenthal [20]. For the cluster, the SD model space and $SU3$ interaction [21] have been used. For the ground state spectroscopic factor, the cluster and the residual nucleus are assumed to be in their respective ground states. The spectroscopic factors of the excited states have been calculated by taking the overlap between the ground state of the cluster and the excited state of the residual nucleus. Core excitation has been neglected. The excitation energies obtained as a byproduct of the spectroscopic factor calculations are found to agree with experimental values to within 200–300 keV. The spectroscopic factor values are shown in table 2. The negative-parity states

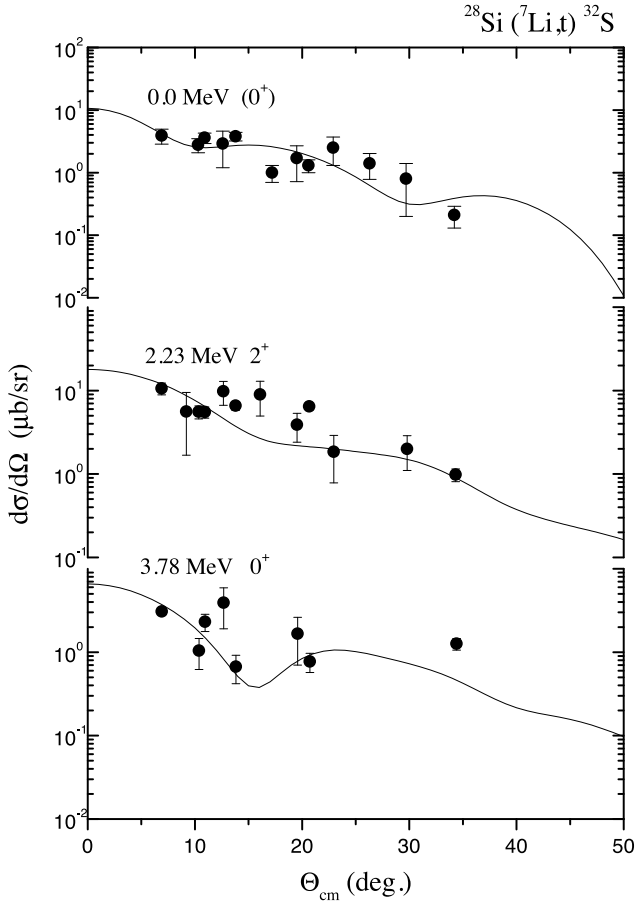


**Figure 6.** Angular distribution of the reaction $^{28}$Si($^{7}$Li, t) $^{32}$S. The solid curve shows the exact finite-range DWBA calculation.

cannot be accommodated in this scheme, because the $(sd)^3(fp)^1$ configuration requires the $\alpha$-particle to be distributed over two major shells. We did not attempt any such calculations.

## 4. Discussion and conclusion

Figures 3–8 show the experimental and theoretical ($^{6}$Li, d) and ($^{7}$Li, t) angular distributions for different states in $^{32}$S. In both the cases, except for the 4.46 MeV $4^+$ state, the calculated curves agree fairly well with the experimental cross sections. The DWBA curves calculated for the ($^{6}$Li, d) angular distributions show a systematic deviation from earlier work [11] which may be attributed to the form factors used for the $^{6}$Li which are calculated microscopically. It is observed that the population of states, especially 3.78 MeV $0^+$ and 4.46 MeV $4^+$ through the ($^{7}$Li, t) reaction, are found to be very weak. This may be because those states are not good $\alpha$-cluster states. The full finite-range DWBA curves are normalized to the experimental data through chi-squared minimization to extract the $\alpha$-spectroscopic factors for the reaction $^{28}$Si($^{7}$Li, t) $^{32}$S at 48 MeV and the values obtained through the re-analysis of the $^{28}$Si($^{6}$Li, d) $^{32}$S reaction at 75.6 MeV. The absolute spectroscopic factors of different

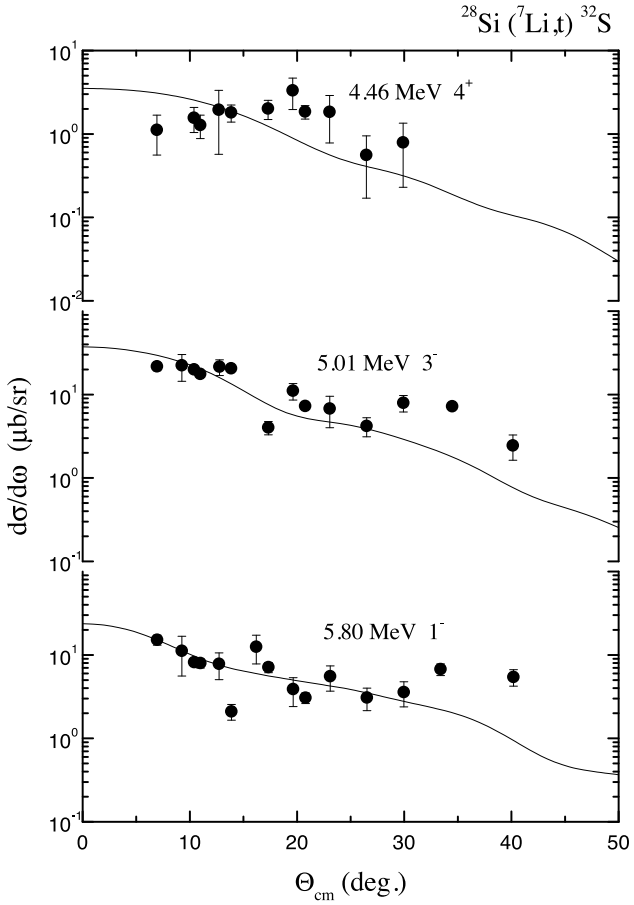


**Figure 7.** Angular distribution of the reaction $^{28}$Si($^{7}$Li, t) $^{32}$S. The solid curve shows the exact finite-range DWBA calculation.

**Table 2.** Absolute spectroscopic factors for the $\alpha$-particle transfer reaction $^{28}$Si($^{7}$Li, t) $^{32}$S at 48 MeV and $^{28}$Si ($^{6}$Li, d) $^{32}$S at 75.6 MeV, from Tanabe *et al* [11].

| | | Spectroscopic factors | | | Shell model results | |
|---|---|---|---|---|---|---|
| $E_x$ (MeV) | $J^\pi$ | ($^{7}$Li, t) | ($^{6}$Li, d) | ($^{6}$Li, d) [11] | $S_\alpha$ | Energy (calc.) |
| 0.00 | $0^+$ | 0.33 | 0.91 | 1.00 | 0.74 | 0.00 |
| 2.23 | $2^+$ | 0.11 | 0.46 | 0.45 | 0.22 | 2.15 |
| 3.78 | $0^+$ | 0.05 | 0.37 | 0.53 | 0.17 | 3.75 |
| 4.46 | $4^+$ | 0.47 | 0.17 | 0.20 | 0.01 | 4.70 |
| 5.01 | $3^-$ | 0.28 | 0.51 | 0.49 | | |
| 5.80 | $1^-$ | 0.08 | 0.51 | 0.53 | | |
| 6.76 | $3^-$ | 0.29 | 0.88 | — | | |
| 7.43 | $1^-$ | 0.57 | 1.24 | 1.2 | | |
| 8.49 | $1^-$ | 1.05 | 2.47 | 2.1 | | |

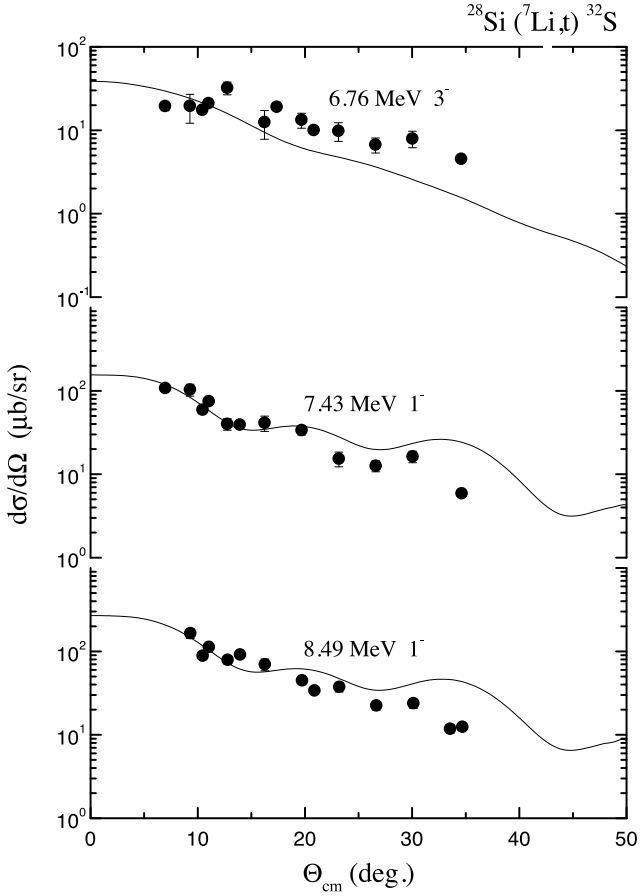


**Figure 8.** Angular distribution of the reaction $^{28}$Si($^{7}$Li, t) $^{32}$S. The solid curve shows the exact finite-range DWBA calculation.

states along with the Tanabe *et al* values are shown in table 2 (the absolute value of $S_\alpha$ for the ground state from [11] is quoted in parenthesis). In order to take into account the different overall normalization we have calculated the relative spectroscopic factors which are shown in table 3. The $S_\alpha$ values obtained through the ($^{7}$Li, t) reactions are found to be smaller than the values extracted through the ($^{6}$Li, d) reactions, especially in the case of the excited 3.78 MeV ($0^+$) and 5.80 MeV ($1^-$) states. For the 3.78 MeV $0^+$ state only a few angles are shown in the figure. This is due to the difficulties in the extraction of the cross section at certain angles where the population of the state is very weak. The cluster configuration for the excited $0^+$ state in $^{32}$S is not clear. The particles may have to cross the fp shell for this arrangement and therefore may have low probability at this excitation energy. This may be one of the reasons why the 3.78 MeV $0^+$ and 4.46 MeV $4^+$ states are weakly populated. We do not claim that the spectroscopic factors extracted for these states are very meaningful.

The theoretical fit to the ground state of $^{32}$S with our microscopic wavefunction for $^{6}$Li is found to be better than the one shown in [11]. For the 2.23 MeV $2^+$ state the theoretical fit in the case of the ($^{6}$Li, d) reaction is found to be better than in the case of the ($^{7}$Li, t) reaction. The relative spectroscopic factor of this particular state with the ($^{7}$Li, t) reaction gives a very close value to the shell model prediction. Through the ($^{6}$Li, d) reaction the value is found to

**Table 3.** The relative spectroscopic factors for the $\alpha$-transfer reactions ($^6$Li, d) and ($^7$Li, t) reaction on $^{28}$Si.

| $E_x$ | $J^\pi$ | ($^7$Li, t) | ($^6$Li, d) | Shell model |
|---|---|---|---|---|
| 0.00 | $0^+$ | 1.00 | 1.00 | 1.00 |
| 2.23 | $2^+$ | 0.33 | 0.51 | 0.30 |
| 3.78 | $0^+$ | 0.15 | 0.41 | 0.23 |
| 4.46 | $4^+$ | 1.42 | 0.19 | 0.01 |
| 5.01 | $3^-$ | 0.85 | 0.56 | |
| 5.80 | $1^-$ | 0.24 | 0.56 | |
| 6.76 | $3^-$ | 0.88 | 0.97 | |
| 7.43 | $1^-$ | 1.73 | 1.36 | |
| 8.49 | $1^-$ | 3.18 | 2.71 | |

be around 35% higher than the ($^7$Li, t) reaction. The 6.76 MeV level is found to be in good agreement for the $J^\pi = 3^-$ state. The relative spectroscopic factors of this state are found to be within 10% between the two reactions. The relative values of $S_\alpha$ for 7.43 MeV ($1^-$) and 8.49 MeV ($1^-$) states are found to be 1.73 and 3.18, respectively, in the case of ($^7$Li, t) reactions.

The $S_\alpha$ values of the low-lying states of $^{32}$S, except the 4.46 MeV $4^+$ state, obtained from the ($^6$Li, d) and ($^7$Li, t) reactions agree with shell model predictions. The differences in spectroscopic factors may be attributed partly to the influence of multistep processes.

In conclusion, we have measured the $\alpha$-spectroscopic factors of $^{32}$S through the ($^7$Li, t) reaction at 48 MeV and compared with the ($^6$Li, d) reaction. The shell model values have been calculated for the low-lying even-parity states. The relative spectroscopic factors for the strong states of $^{32}$S through the ($^7$Li, t) reaction is found to agree fairly well, within experimental errors, with the ($^6$Li, d) reaction. For the very weak, and possibly non-cluster states (e.g. 3.78 MeV $0^+$ and 4.46 MeV $4^+$), we do not claim any degree of success.

## Acknowledgments

We gratefully acknowledge the help of the NSC Pelletron crew during the experiment. We also acknowledge the partial financial support obtained from UGC for performing this study.

## References

[1] Bromley A (ed) 1984 *Treatis on Heavy Ion Science* vol 1 (New York: Plenum) p 714
[2] Kunz P D 1960 *Ann. Phys., Lpz.* **11** 275
[3] Becchetti F D, Janecke J and Thorn C E 1978 *Nucl. Phys.* A **305** 313
[4] Apagyi B and Vertse T 1980 *Phys. Rev.* C **21** 779
[5] Yamaya T, Saito M, Fujiwara M, Itahashi T, Katori K, Suechiro T, Kato S, Hatori S and Ohkubo S 1993 *Phys. Lett.* B **306** 1
[6] Gutbrod H H, Yoshida H and Bock R 1971 *Nucl. Phys.* A **165** 240
[7] Oelert W, Berg G P A, Djaloeis A, Mayer-Borieke C and Turek P 1983 *Phys. Rev.* C **28** 73
[8] Puhlhofer F, Ritter H G, Bock R, Brommundt G, Schmidt H and Bethge K 1970 *Nucl. Phys.* A **147** 258
[9] Becchetti F D, Flynn E R, Hanson D L and Sunier J W 1978 *Nucl. Phys.* A **305** 293
[10] Baranger M and Vogt E (eds) 1972 *Advances in Nuclear Physics* vol 5 (New York: Plenum) p 461
[11] Tanabe T, Yasue M, Sato K, Ogino K, Kadota Y, Taniguchi Y, Obori K, Makino K and Tochi M 1981 *Phys. Rev.* C **24** 2556
[12] Kunz P D 1978 Computer code DWUCK5 (University of Colorado Version)
[13] Brown B A, Etchegoyen A, Rae W D M and Godwin N S 1984 `OXBASH` *Computer Code*

[14] Ziegler J F, Biersack J P and Littmark V 1985 *The Stopping and Ranges of Ions in Solids* vol 1 (New York: Pergamon)
[15] Bhowmik R K, Goyal D K and Naithani S 1991 *DAE Nucl. Phys. Symp.* B **34** 393
[16] Shyam R, Lovas R G, Pal K F, Sharma V K and Nagarajan M A 1985 *J. Phys. G: Nucl. Phys.* **11** 1199
[17] Schwandt P 1984 Optical model potential code for elastic scattering analysis *IUCF Report* No. 84-X (Indiana University Cyclotron Facility)
[18] Becchetti F D Jr and Greenlees G W 1971 *Polarization Phenomena in Nuclear Reactions* ed H H Barschall and W Haeberli (Wisconsin: University of Wisconsin Press) p 682
[19] Lovas R G 1983 Private communication
[20] Wildenthal B H 1982 *Bull. Am. Phys. Soc.* **27** 725
[21] Elliot J P 1985 *Rep. Prog. Phys.* **48** 171