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# The $^{40}$Ca(α,d)$^{42}$Sc Reaction*

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Angular distributions of the $^{40}$Ca(α,d)$^{42}$Sc reaction at $E_\alpha$ = 40 MeV have been measured for states in $^{42}$Sc up to an excitation energy of 5.2 MeV. Assignments of the L transfer are made on the basis of the characteristic shapes of the angular distributions. A strong L = 6 transition to a state at 3.61 MeV in the $^{42}$Sc is observed. Evidence for the fragmentation of the $(f_{7/2})^2_{5,0}$ and $(f_{7/2}p_{3/2})_{5,0}$ configurations into the $5^+$ states at 1.51 and 3.09 MeV is discussed.

NUCLEAR REACTION $^{40}$Ca(α,d), $E_\alpha$ = 40 MeV, measured $\sigma(E_d,\theta)$; enriched target; deduced L transfer.

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## I. Introduction

The low-lying states of $^{42}$Sc can be described in the terms of the simple shell model as a proton and a neutron in the $f_{7/2}$ orbital outside the doubly closed $^{40}$Ca-core. These states are important in providing the $(f_{7/2})^2$ matrix elements of the residual two-body nuclear interaction for shell-model calculations.[1-3] However the relation of the experimental situation to the simple $(f_{7/2})^2$ model is not so simple, since there exist low-lying states which originate from core-deformed configurations mixed with the two-particle shell-model states.[4] Even without these core-deformed configurations, admixtures of the $(f_{7/2}p_{3/2})$ configurations into the $(f_{7/2})^2$ configurations complicate the extraction of reliable $(f_{7/2})^2$ two-body matrix elements.

Two-nucleon transfer reactions such as ($^3$He,p) or (α,d) are well suited to investigate the two-particle nature of the low-lying states of $^{42}$Sc. Angular distributions of the $^{40}$Ca($^3$He,p)$^{42}$Sc reaction have been analyzed in the past with distorted-wave Born approximation (DWBA) calculations based on shell-model wave functions by Barz et al.[5] and Pühlhofer.[6] These wave functions describe the $^{42}$Sc states alternatively with and without excited-core configurations. Fair agreement between the calculated and experimental differential cross sections was obtained in these studies.

The $^{40}$Ca(α,d)$^{42}$Sc reaction has been studied to a lesser extent. Rivet et al.[7] observed several strong deuteron groups leading to low-lying, high spin, T = 0 states in $^{42}$Sc. Recently, Thomas and Skouras[8] measured $^{40}$Ca(α,d) angular distributions for transitions to the first few states in $^{42}$Sc and compared them to

DWBA predictions based on the wave functions of Flowers and Skouras[4], who describe the $^{42}$Sc states as a mixture of deformed and spherical shell-model configurations.

The $(f_{7/2})^2$ and $(f_{7/2}p_{3/2})$ configurations in the $^{42}$Sc states can also be studied via the single-proton stripping reaction on the radioactive $^{41}$Ca target. The results of a recent $^{41}$Ca($^3$He,d)$^{42}$Sc experiment have not yet been published[9]. Other information on the nature of levels in $^{42}$Sc comes from the investigation of the $^{42}$Ca($^3$He,t) reaction by Sherr et al.[10] and a subsequent analysis of the measured angular distributions by Schaeffer[11] using the wave functions of Pühlhofer[6] and Flowers and Skouras[4].

The present study of the $^{40}$Ca(α,d) reaction was undertaken in order to extend the existing information concerning the two-particle nature of levels in $^{42}$Sc. The features of the (α,d) reaction are such that stretched configuration, high-spin, $T = 0$ levels are predominantly excited. For example, the $(f_{7/2}p_{3/2})_{J=5}$ transfer is enhanced over the $(f_{7/2})^2_{J=5}$ transfer by more than one order of magnitude. This provides a special sensitivity to admixtures of the $(f_{7/2}p_{3/2})$ configuration to the $(f_{7/2})^2$ configuration in the $5^+$ states.

## II. Experimental Procedure and Results

The $^{40}$Ca(α,d) experiment was performed using a 40 MeV alpha-particle beam from the Michigan State University cyclotron. The target was made by evaporating metallic calcium, enriched to 99.9% in $^{40}$Ca, onto a thin carbon backing. The metallic calcium was reduced from $CaCO_3$ by means of Zr powder as a part of the evaporation process. The target was kept under vacuum at all times. The thickness was about 190 μg/cm$^2$ and was determined by measuring the differential cross sections of the elastically scattered 40 MeV alpha-particles and normalizing these data to calculations with standard optical model parameters[12]. The accuracy of the absolute differential cross sections thus obtained is estimated to be ± 25%. The reaction products were detected in the focal plane of a split-pole magnetic spectrograph with a position sensitive resistive-wire proportional counter. A silicon detector placed in the scattering chamber allowed continuous monitoring of the target condition.

A spectrum obtained at $\theta_{lab} = 6°$ is shown in Fig. 1. The resolution was about 50 keV full width at half maximum. The spectra were analyzed with the peak-fitting program AUTOFIT[13]. Angular distributions were measured over the region from 6° to 60°. They are displayed in Fig. 2-4. Error bars, where shown, reflect the statistical errors and the uncertainties in unfolding close lying peaks.

The excitation energies of the levels observed in the present experiment are given in Table I. Also shown are data from the compilation of Endt and van der Leun[14]. Above 3.8 MeV of excitation many new states have been found in the present $^{40}Ca(\alpha,d)^{42}Sc$ experiment. Some of these states may correspond to levels observed in the $^{41}Ca(^{3}He,d)^{42}Sc$ reaction (see Ref. 9). However, because of the high level density in this region of excitation energy, more information about the properties of these levels is needed to make such correspondences with security.

The measured angular distributions are strongly structured and show distinct dependences on the transferred orbital angular momentum L. The curves through the data points in Figs. 2-4 represent shapes for various L transfers which have been obtained by averaging data from transitions involving known angular momentum transfers. Nine levels with excitation energies up to 5.12 MeV are observed to be populated by L = 2 transitions (see Fig. 2). This limits their possible spin and parity values to $1^+$, $2^+$, or $3^+$. The angular distributions for 11 transitions exhibit characteristic L = 4 patterns. They are shown in Fig. 3. The selection rules yield spin and parities of $3^+$, $4^+$, or $5^+$ for these states. Combining the present results for the 1.51 and 3.09 MeV states with the possible spin values given in Ref. 14 yields a unique $J^{\pi} = 5^+$ assignment for these levels. In addition to the transition to the $7^+$ state at 0.62 MeV, another L = 6 angular distribution has been observed for the transition to a state at 3.61 MeV. These two L = 6 transitions are displayed in Fig. 4.

## III. Discussion

The $(\alpha,d)$ and $(^{3}He,p)$ reactions excite final states quite differently, although both reactions transfer a proton-neutron pair. In particular, due to momentum mismatch between the entrance and exit channels, the $(\alpha,d)$ reaction favors larger values of the transferred orbital angular momentum than does the $(^{3}He,p)$ reaction. Furthermore, the selection rules allow only a S = 1, T = 0 transfer of the pn pair in the $(\alpha,d)$ reaction, whereas both S = 1, T = 0 and S = 0 ,T = 1 transfers are possible in the $(^{3}He,p)$ reaction. Consequently, in the $^{40}Ca(\alpha,d)^{42}Sc$ reaction only T = 0 states of high spin are expected to be strongly excited in contrast to the $^{40}Ca(^{3}He,p)^{42}Sc$ reaction where these states are rather weakly populated.

In order to elucidate the dependence of the shape and the magnitude of the $(\alpha,d)$ differential cross sections on different configurations of the transferred proton-neutron pair, DWBA calculations have been performed with the assumption of equal spectroscopic amplitudes. The optical-model parameters for calculating the distorted waves in the entrance and exit channels are taken from the literature[12]. The resulting differential cross sections are displayed in Fig. 5. The different couplings predict sufficiently distinguished angular distributions to allow unambiguous identification of the transferred orbital angular momentum L. If two L values are allowed for any given transferred configuration, the contribution from the smaller L value always dominates that from the larger value by an order of magnitude. This results in nearly pure L patterns characteristic of the smaller of the two allowed L values. The enhanced intensity of the transfer in a completely aligned configuration is also evident. The $(f_{7/2}p_{3/2})_{5,0}$ and $(f_{7/2}p_{1/2})_{4,0}$ transfers which lead to L = 4 angular distributions (see left half of Fig. 5) yield cross sections of about one order of magnitude larger than the $(f_{7/2})^2_{5,0}$ and $(f_{7/2}p_{3/2})_{4,0}$ transfers. The same feature is observed for the L = 2 angular distributions in the right half of Fig. 5; the $(p_{3/2})^2_{3,0}$ and $(p_{3/2}p_{1/2})_{2,0}$ configurations give the by far largest cross sections.

Since direct two-nucleon transfer reactions populate essentially two-particle shell-model configurations coupled to an unperturbed target core, it is this aspect of the $^{42}Sc$ levels which is principally examined in the $^{40}Ca(\alpha,d)$ reaction. The actual low-lying levels of $^{42}Sc$ are presumably mixtures of "deformed" 4p - 2h and simple two-particle states such as proposed by Federman[15], Gerace and Green[16], or Flowers and Skouras[4] for the description of the observed level scheme of $^{42}Sc$. Those states whose parentage is dominantly 4p - 2h are assumed to be excited in the $^{40}Ca(\alpha,d)$ reaction via the two-particle components in their wave functions. The excitation of the 4p - 2h components themselves via particle-hole components in the target ground state should be less important and will be neglected in the following discussion of the strongest transitions.

According to the selection rules for a direct, single step $(\alpha,d)$ reaction, the excitation of the T = 1 states in $^{42}Sc$ is forbidden. In fact, the ground state ($J^\pi = 0^+$; T = 1), for example, is not visibly populated in the present $^{40}Ca(\alpha,d)^{42}Sc$ experiment, as can be seen in the spectrum of Fig. 1, where its position is

marked by an arrow. The upper limit of the differential cross section for the ground state transition at $\theta_{c.m.} = 6.4°$ is about 1 μb/sr. This is confirming evidence for our present assumption that at 40 MeV bombarding energy the $^{40}Ca(\alpha,d)^{42}Sc$ reaction has a single-step direct mechanism.

The $7^+$ state at 0.62 MeV, which has a wave function characterized by a nearly pure $(f_{7/2})^2_{J=7}$ configuration, is populated by the strongest transition observed in the present $^{40}Ca(\alpha,d)^{42}Sc$ reaction. The transition exhibits an L = 6 angular distribution (see Fig. 4). The contributions to the measured values of this transition from the unresolved nearby lying $1^+$ state at 0.61 MeV, which has a predominant $(f_{7/2})^2_{J=1}$ configuration, are negligible because of the special property of the $(\alpha,d)$ reaction discussed above. The opposite situation is obtained in the $^{40}Ca(^3He,p)^{42}Sc$ reaction, where the transition strength to the $7^+$ state represents only a small fraction of the observed strength for the $1^+ - 7^+$ doublet[6]. There, the shape of the angular distribution is dominated by the L = 0 transfer originating from the excitation of the $1^+$ member. In the present experiment another L = 6 angular distribution is observed for a transition to a state at 3.61. The strength of this second L = 6 transition is about 10% of the 0.62 MeV transition. The 3.61 MeV state is populated in the $^{41}Ca(^3He,d)^{42}Sc$ reaction[9] by a weak $\ell_p = 3$ transfer. Since the spin of this state is not known, the observed L = 6 angular distribution can be explained by either a $(f_{7/2})^2_{J=7}$ or a $(f_{7/2}f_{5/2})_{J=6}$ transfer. If it is a $7^+$ state, then it originates predominantly from a core-deformed configuration mixed with the $(f_{7/2})^2_{J=7}$

two-particle shell-model state. The ($\alpha$,d) strength then gives the amount of this $(f_{7/2})^2_{J=7}$ admixture. The other possibility is also reasonable, since $(f_{7/2}f_{5/2})_{J=6}$ levels are expected to lie only a few MeV above the $(f_{7/2})^2_{J=7}$ two-particle state.

The $5^+$ state at 1.51 MeV is very strongly excited by an $L = 4$ angular distribution (see Fig. 3). Again, the contribution from the close lying $3^+$ level at 1.49 MeV is negligible for similar reasons as discussed above. The transition to the other known $5^+$ state at 3.09 MeV exhibits also a strong $L = 4$ angular distribution, but its strength is a factor of 4 smaller than that of the 1.51 MeV transition.

In terms of the simple shell-model, the 1.51 MeV state should be described by a pure $(f_{7/2})^2_{J=5}$ configuration and the 3.09 MeV state by a pure $(f_{7/2}p_{3/2})_{J=5}$ configuration. However, these assumptions cannot explain the observed strengths for these two states, since as discussed above the $(f_{7/2}p_{3/2})_{J=5}$ transfer yields an order of magnitude larger cross section than the $(f_{7/2})^2_{J=5}$ transfer. The observed strengths lead to the suggestion that the $(f_{7/2})^2$ and $(f_{7/2}p_{3/2})$ configurations are mixed in the two states. This is supported by the results of the $^{41}Ca(^3He,d)^{42}Sc$ reactions[9] where the two $5^+$ states are excited by a mixture of $\ell_p = 1$ and $\ell_p = 3$ transfer.

If it is assumed that the transitions to the two $5^+$ states at 1.51 and 3.09 MeV involve only a mixture of $(f_{7/2})^2_{J=5}$ and $(f_{7/2}p_{3/2})_{J=5}$ transfer, then, in the view of the sensitivity of the two nucleon transfer cross sections to the wave functions of the states involved, the relative strengths of the $(f_{7/2})^2$ and

$(f_{7/2}p_{3/2})$ configurations can be estimated from the experimental data. For the transition to the 1.51 MeV state which is assumed to be predominantly $(f_{7/2})^2_{J=5}$, DWBA calculations have been carried out with a form factor

$$\alpha(f_{7/2})^2 + \sqrt{1-\alpha^2}\,(f_{7/2}p_{3/2})$$

Using the transition strength to the $(f_{7/2})^2_{J=7}$ configuration state at 0.62 MeV as a normalization for the data, a value of $\alpha = 0.81 \pm 0.04$ was deduced. Describing the form factor of the transition to the 3.09 MeV state by

$$\alpha(f_{7/2}p_{3/2}) - \sqrt{1-\alpha^2}\,(f_{7/2})^2$$

with the above value of $\alpha$ one obtains a cross section which is a factor of 1.5 smaller than for the 1.51 MeV transition. This is in disagreement with the experimental ratio of 3.9. Therefore, we conclude that the $(f_{7/2})^2_{J=5}$ and $(f_{7/2}p_{3/2})_{J=5}$ configurations are split over more than two $5^+$ states and that most probably the $(f_{7/2}f_{5/2})_{J=5}$ configuration also has to be included to fully describe these states.

The wave functions of Barz et al.[5], Pühlhofer[6], and Flowers and Skouras[4] were used to calculate the cross section ratios of the 1.51 and 3.09 MeV transitions. We obtained the values 2.9, 1.5, and 14, respectively. Only the wave functions of Barz et al. come close to the experimental ratio of 3.9, but they overpredict the magnitude of the cross section for the 1.51 MeV transition relative to the strength of the 0.62($7^+$) MeV transition by a factor of 1.7.

The remaining L = 4 and all L = 2 transitions are much weaker than the transitions discussed above. In addition, they lead to states with unknown spins. This and the lack of distinguishing features in the transitions make it impossible to draw inferences about configurations of these states from the present data.

## IV. Conclusion

In this paper the $^{40}Ca(\alpha,d)^{42}Sc$ reaction was studied in order to investigate the two-particle configuration, T = 0 states in $^{42}Sc$. The observed angular distributions show clearly distinguishable patterns which allowed unambiguous identification of the transferred orbital angular momenta. Two L = 6 transitions have been observed, one leading to the known $7^+$ state at 0.62 MeV, the other to a state at 3.61 MeV. It is suggested that the latter state is either a $J^\pi = 7^+$ "deformed" 4p - 2h state with about 10% $(f_{7/2})^2_{J=7}$ two-particle admixture or contains part of the $(f_{7/2}f_{5/2})_{J=6}$ configuration. The states at 1.51 and 3.09 MeV are strongly excited by L = 4 angular distributions. The observed strengths suggest a considerably mixing of the $(f_{7/2})^2_{J=5}$, $(f_{7/2}p_{5/2})_{J=5}$ configurations in these states. The other transitions show no significant strengths which allow, even combined with other available results, an inference on the particle configurations of these states.

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Table 1--Energy levels observed in the $^{40}Ca(\alpha,d)^{42}Sc$ reaction, compared with previous data. The excitation energies have an estimated uncertainty of ± 10 keV.

|  | Present Work |  |  | Reference 14 |  |
|---|---|---|---|---|---|
| $E_x$(MeV) | L | $J^\pi$ | $\sigma_{int}$ | $E_x$(MeV) | $J^\pi$ |
| 0.618 | 6 | $(5-7)^+$ | 294 | 0.617 | $7^+$ |
| 1.514 | 4 | $(3-5)^+$ | 145 | 1.511 | $(5^+,\geq 6)$ |
| 1.849 |  |  |  | 1.846 |  |
| 2.182 | 2 | $(1-3)^+$ | 3.8 | 2.188 | (1-3) |
| 2.384 | 2 | $(1-3)^+$ | 4.4 | 2.389 |  |
| 2.844 | 2 | $(1-3)^+$ | 2.8 | 2.848 |  |
| 2.918 | 4 | $(3-5)^+$ | 2.5 | 2.910 |  |
| 3.001 | 4 | $(3-5)^+$ | 3.8 |  |  |
| 3.091 | 4 | $(3-5)^+$ | 34.5 | 3.090 | $(5^+,\geq 6)$ |
| 3.182 | 4 | $(3-5)^+$ | 4.4 |  |  |
| 3.307 | 4 | $(3-5)^+$ | 3.7 | 3.312 |  |
| 3.395 | 2 | $(1-3)^+$ | 15.5 | 3.393 | $\leq 4$ |
| 3.607 | 6 | $(5-7)^+$ | 28.0 |  |  |
| 3.701 |  |  |  |  |  |
| 3.794 | 4 | $(3-5)^+$ | 4.9 | 3.807 |  |
| 3.896 | 4 | $(3-5)^+$ | 4.0 |  |  |
| 4.067 | 4 | $(3-5)^+$ | 2.3 |  |  |
| 4.252 |  |  |  |  |  |
| 4.391 | 2 | $(1-3)^+$ | 18.6 |  |  |
| 4.467 | 2 | $(1-3)^+$ | 6.3 |  |  |
| 4.748 | 4 | $(3-5)^+$ | 8.5 |  |  |
| 4.800 |  |  |  |  |  |
| 4.868 | 2 | $(1-3)^+$ | 3.6 |  |  |
| 4.996 | 2 | $(1-3)^+$ | 7.5 |  |  |
| 5.053 | 4 | $(3-5)^+$ | 4.0 |  |  |
| 5.122 | 2 | $(1-3)^+$ | 4.6 |  |  |

Figure Captions

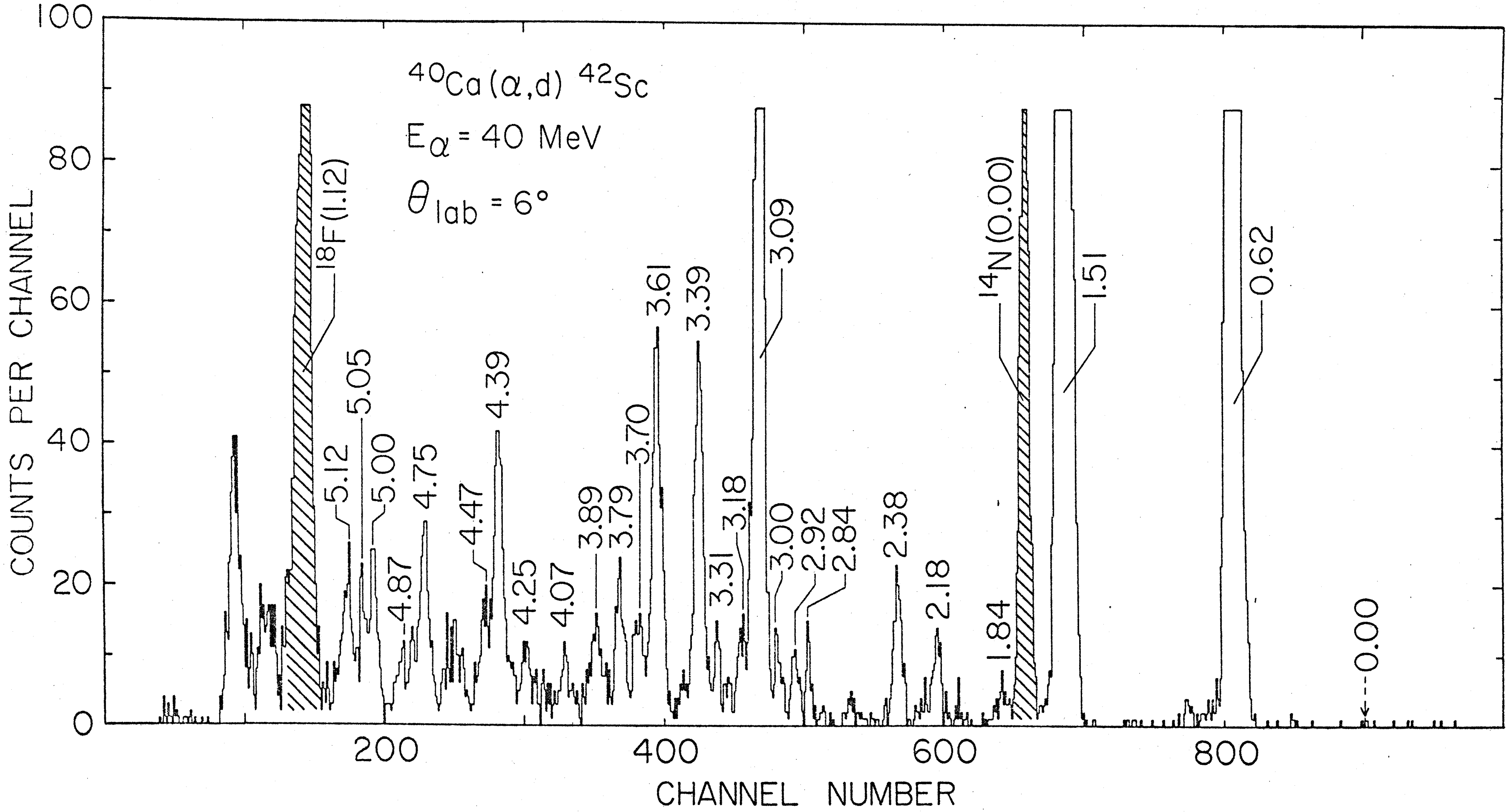
Fig. 1. Deuteron spectrum of the $^{40}Ca(\alpha,d)^{42}Sc$ reaction at 40 MeV bombarding energy.

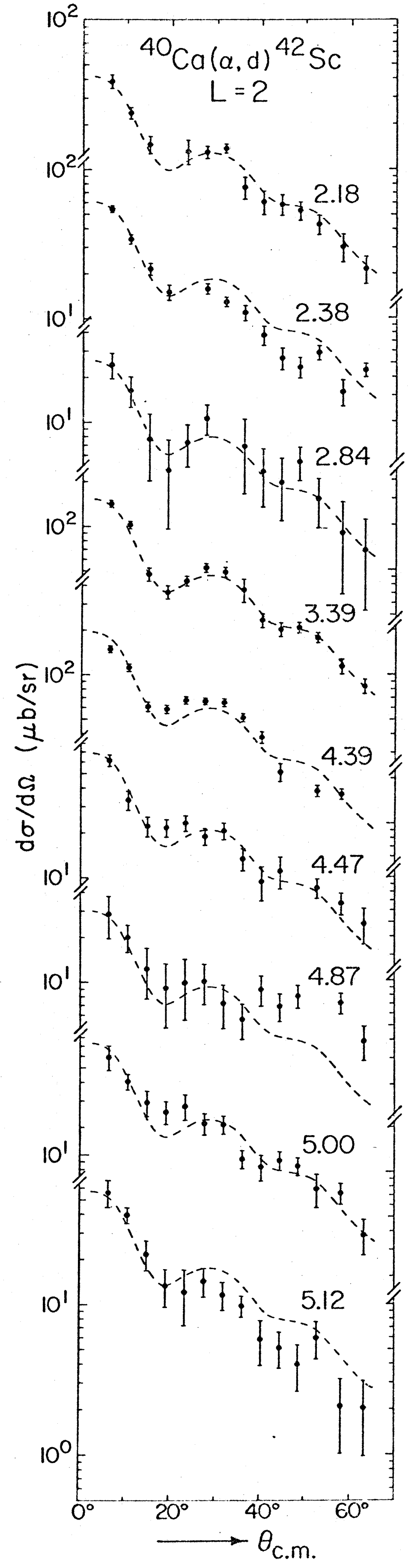
Fig. 2. Angular distribution for $L = 2$ transitions. The dashed curves represent empirical $L = 2$ shapes.

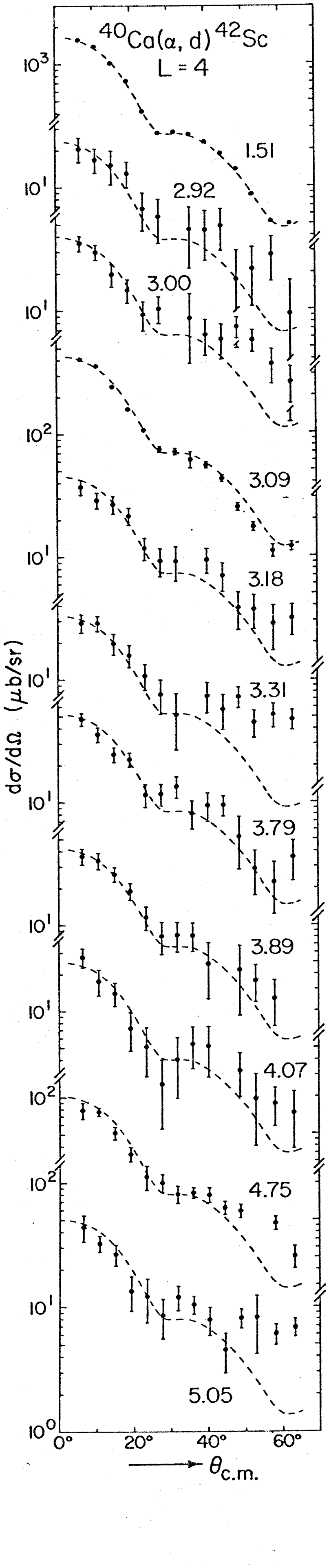
Fig. 3. Angular distributions for $L = 4$ transitions. The curves represent empirical $L = 4$ shapes.

Fig. 4. Angular distributions for $L = 6$ transitions. The curves are empirical $L = 6$ shapes.

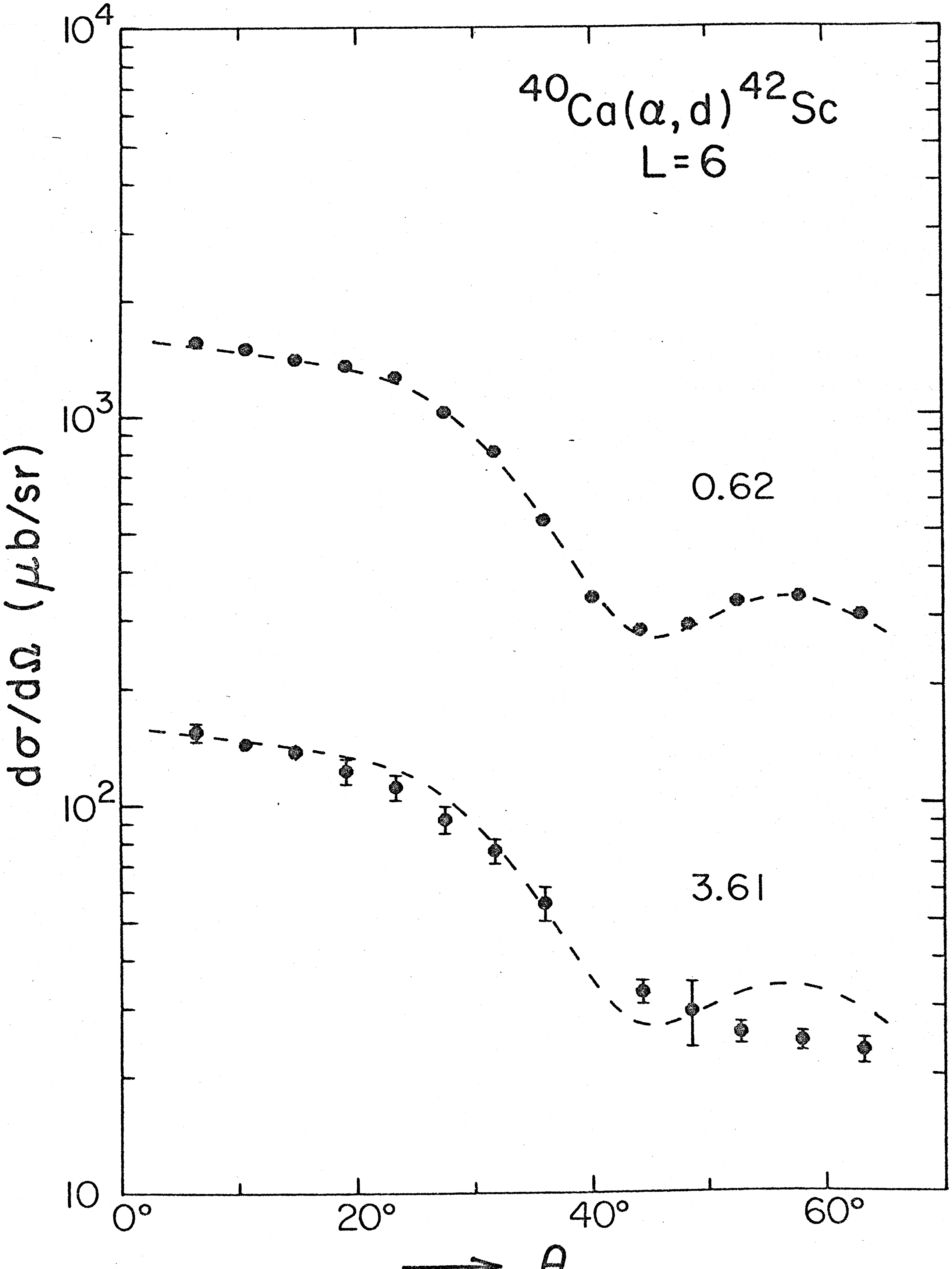
Fig. 5. Calculated DWBA curves for various transferred configurations. The cross sections shown do not include the spin statistical factor $(2J + 1)$.


$^{40}Ca(\alpha,d)\,^{42}Sc$
$E_\alpha = 40$ MeV
$\theta_{lab} = 6°$
COUNTS PER CHANNEL
CHANNEL NUMBER
0
20
40
60
80
100
200
400
600
800
$^{18}F(1.12)$
5.12
5.05
5.00
4.87
4.75
4.47
4.39
4.25
4.07
3.89
3.79
3.70
3.61
3.39
3.31
3.18
3.09
3.00
2.92
2.84
2.38
2.18
1.84
$^{14}N(0.00)$
1.51
0.62
0.00

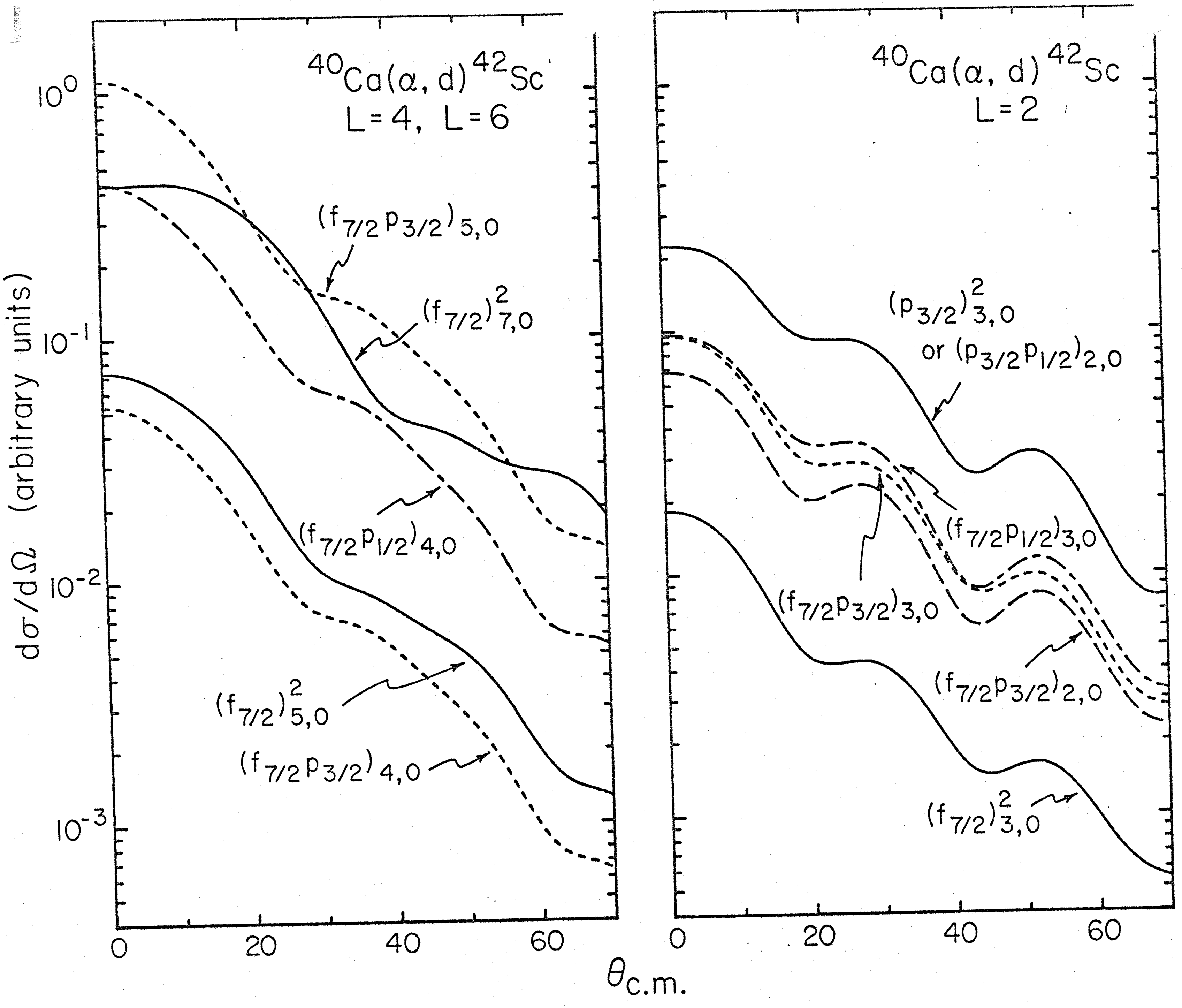

$^{40}Ca(\alpha,d)^{42}Sc$
L = 2
2.18
2.38
2.84
3.39
4.39
4.47
4.87
5.00
5.12
$10^2$
$10^1$
$10^0$
$d\sigma/d\Omega$ ($\mu b/sr$)
0°
20°
40°
60°
$\theta_{c.m.}$



$^{40}$Ca(α, d)$^{42}$Sc
L = 4
1.51
2.92
3.00
3.09
3.18
3.31
3.79
3.89
4.07
4.75
5.05
$10^3$
$10^1$
$10^1$
$10^2$
$10^1$
$10^1$
$10^1$
$10^1$
$10^1$
$10^2$
$10^2$
$10^1$
$10^0$
dσ/dΩ (μb/sr)
0°
20°
40°
60°
$\theta_{c.m.}$



$^{40}Ca(\alpha,d)^{42}Sc$
L=6
0.62
3.61
$d\sigma/d\Omega$ ($\mu$b/sr)
$10^4$
$10^3$
$10^2$
10
0°
20°
40°
60°
→ $\theta_{c.m.}$


$^{40}Ca(\alpha, d)^{42}Sc$
L=4, L=6
$(f_{7/2}p_{3/2})_{5,0}$
$(f_{7/2})^2_{7,0}$
$(f_{7/2}p_{1/2})_{4,0}$
$(f_{7/2})^2_{5,0}$
$(f_{7/2}p_{3/2})_{4,0}$
$^{40}Ca(\alpha, d)^{42}Sc$
L=2
$(p_{3/2})^2_{3,0}$
or $(p_{3/2}p_{1/2})_{2,0}$
$(f_{7/2}p_{1/2})_{3,0}$
$(f_{7/2}p_{3/2})_{3,0}$
$(f_{7/2}p_{3/2})_{2,0}$
$(f_{7/2})^2_{3,0}$
$d\sigma/d\Omega$ (arbitrary units)
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
20
40
60
0
20
40
60
$\theta_{c.m.}$