MSUCL-230
December 1976

Four-Particle, One-Hole States in ^{43}Ca Strongly Populated by the ^{41}K(α,d) Reaction*

H. Nann, W.S. Chien, and A. Saha

Cyclotron Laboratory and Department of Physics
Michigan State University, East Lansing, MI 48824

ABSTRACT

Angular distributions of the ^{41}K(α,d)^{43}Ca reaction have been measured at 40 MeV bombarding energy. Four-particle, one-hole states in which the stripped proton-neutron pair occupies a $(f_{7/2})^2_{J=7,T=0}$ configuration coupled to the unperturbed ^{41}K-core were identified by their characteristic L=6 angular distributions. These states lie at 2.95, 3.37, 3.94, 4.13, 4.19, 4.59, and 4.89 MeV. Evidence for their $[(f_{7/2})^4_{J=7,T=1}d^{-1}_{3/2}]$ 4p-1h character is discussed. Several other strong transitions were observed which show mixtures of L=4 and L=6 angular distributions.

NUCLEAR REACTIONS: ^{41}K(α,d), E_α=40 MeV; measured $\sigma(E_d,\theta)$; enriched target; deduced L transfer.

---

*Work supported in part by the U.S. National Science Foundation.

I. Introduction

Previous (α,d) studies$^{1-3)}$ have shown that stretched configuration high-spin states are preferentially excited because of the geometrical coefficients in the structure factor$^{4)}$ and momentum mismatch conditions between the entrance and exit channels. This feature has been used in the present ^{41}K(α,d) reaction to locate high-spin states in ^{43}Ca of four-particle, one-hole character in which a transferred proton-neutron pair in the $(f_{7/2})^2_{7,0}$ configuration is coupled to the unperturbed two-particle, one-hole configuration of the ^{41}K-core. The transitions to these states are characterized by an orbital angular momentum transfer of L=6.

High spin levels in ^{43}Ca have been studied by Poletti, et al.$^{5)}$ via γ-ray spectroscopy of heavy-ion fusion-evaporation reactions, and decay schemes of the yrast levels together with suggested spin assignments were reported. DeVoigt, et al.$^{6)}$ measured angular distributions of the ^{43}Ca(α,α') reaction and identified states resulting from coupling of an $f_{7/2}$ neutron to the 3^- and 5^- states in ^{42}Ca. These experiments have populated some of the 4p-1h states searched for in the present investigation of the ^{41}K(α,d)^{43}Ca reaction. The juxtaposition of the three very different kinds of data should serve to illuminate the structural details of these states and, of course, to better fix their identities.

II. Experimental Procedure and Results

The present experiment was carried out using a 40 MeV α-particle beam from the Michigan State University Cyclotron.

The reaction products were detected in the focal plane of a split-pole magnetic spectrograph with a proportional-counter, plastic-scintillator combination. The proportional counter was of a slanted-cathode construction with a delay-line readout.7) The target was made by evaporating metallic potassium, enriched to 98% in ^{41}K, onto a thin carbon foil. The metallic potassium was reduced from K$_2$CO$_3$ by means of Ta powder as a part of the evaporation process. The target was kept under vacuum at all times, The thickness was about 100 μg/cm^2 and was determined by measuring the elastic differential cross sections of 40 MeV α-particles and normalizing these data to calculations made with standard optical-model parameters [e.g. ref. 8)]. A silicon detector placed in the scattering chamber allowed continuous monitoring of the target condition and the normalization of the relative cross sections at different angles.

A typical spectrum is shown in Fig. 1. The resolution obtained was about 40 keV, full width at half maximum. Although the known level density of ^{43}Ca is very high in the excitation energy region up to 6 MeV, only relatively few states are excited. Up to 2.8 MeV of excitation, only the ground and 2.05 MeV states are populated with noticeable strength. The strongest transitions lead to states between 3 and 5 MeV of excitation. The data were analyzed with the peak fitting program AUTOFIT.9) Angular distributions were taken from 6° to 55°. They are displayed in Figs. 2-5. The error bars shown reflect the statistical errors and the uncertainties in unfolding close lying states. The accuracy of the absolute differential cross section is estimated to be ±30%.

A summary of the present results is given in Table I. The excitation energies of the levels observed are listed together with the L transfer and their strength of formation. The spin and parity values reported comprise the results of the present work and of Refs. 5) and 6). As an example, the level at 4.14 MeV is populated in the ^{43}Ca(α,α') reaction6) by a mixture of $\ell=3$ and $\ell=5$, thus limiting the spin values to $\leq 13/2^+$. In the present experiment, this state is excited by a pure L=6 transfer. This restricts the spin and parity values to $11/2^+$ or $13/2^+$.

III. Discussion

The preferential transfer of the proton-neutron pair in the (α,d) reaction in a completely aligned configuration has been reported previously.1-3,10) The enhancement effects are such that, for example, the transfer in the $(f_{7/2})^2_{7,0}$ and $(f_{7/2}p_{3/2})_{5,0}$ couplings are about one order of magnitude stronger than for other couplings. Accordingly, high-spin levels belonging to the configurations $[^{41}\mathrm{K}(3/2^+) \boxtimes (f_{7/2})^2_{7,0}]$ and $[^{41}\mathrm{K}(3/2^+) \boxtimes (f_{7/2}p_{3/2})_{5,0}]$ are expected to be strongly excited by L=6 and L=4 angular distributions, respectively.

In order to identify the expected L=6 and L=4 angular distributions, experimental L=6 and L=4 shapes were obtained from the ^{40}Ca(α,d) reaction10) leading to the known 7^+ and 5^+ states in ^{42}Sc at 0.62 and 1.51 MeV,11) respectively. These shapes are superimposed on the angular distributions in Figs. 2-4.

The transitions to the states at 2.95, 3.37, 3.94, 4.13, 4.19, 4.59, and 4.89 MeV excitation energy in ^{43}Ca exhibit clear

L=6 patterns. The weak transition to the 3.28 MeV state, displayed in Fig. 4, shows a less distinct L=6 pattern. The L=6 shape associated with these states leads to the suggestion that their wave functions have significant components of the type $[^{41}\mathrm{K}(3/2^+) \boxtimes (f_{7/2})^2_{7,0}]$. Their possible spin-parity values could range from $11/2^+$ to $17/2^+$.

Besides the transfer of the proton-neutron pair in the $(f_{7/2})^2_{7,0}$ configuration, the transfer in the $(d_{3/2}g_{9/2})$ and/or $(f_{7/2}f_{5/2})$ configurations could also produce an L=6 angular distribution. For a $(d_{3/2}g_{9/2})$ transfer, the proton must fill the $d_{3/2}$ hole in ^{41}K and the neutron must go into the $g_{9/2}$ orbital. Accordingly, such states would also have to be excited in the ^{42}Ca(d,p) reaction[12] by ℓ_n=4 stripping into the $g_{9/2}$ orbital. The only ℓ_n=4 transition seen in the ^{42}Ca(d,p) reaction leads to a state at 3.92 MeV with about 12% of the total $g_{9/2}$ single-particle strength. In the present experiment this state could not be resolved from the 3.94 $(15/2^+)$ [see ref. [5]] level. Therefore, a fraction (about 20%) of the observed L=6 strength for the 3.94 MeV transition should come from the excitation of the 3.92 MeV level by a $(d_{3/2}g_{9/2})$ transfer. Transfers in the $(f_{7/2}f_{5/2})$ configurations are unlikely, since states in ^{43}Ca with $(^{41}\mathrm{K}(3/2) \boxtimes (f_{7/2}f_{5/2}))$ 4p-1h character are estimated to lie about 4 MeV higher than the $f_{5/2}$ single-particle states.

In addition to these just mentioned states which are populated with clear L=6 transitions, states at 3.50, 3.84, 4.29, 4.36, 4.46, 5.19, 5.25, and 5.70 MeV in ^{43}Ca are also observed to be strongly populated. Their angular distributions

are displayed in Fig. 3. The transitions to the 2.85 and 3.07 MeV states, displayed in Fig. 4, are less strong. The angular distribution of the 3.84 MeV state exhibits a distinct L=4 pattern, whereas the others show mixtures of L=4 and L=6 tranfers. As mentioned above, the L=6 admixture can be attributed to the transfer of the proton-neutron pair in the $(f_{7/2})^2_{7,0}$ configuration. The L=4 component can be attributed to a mixture of $(f_{7/2})^2_{5,0}$ and $(f_{7/2}p_{3/2})_{5,0}$ transfers, of which the latter configuration yields a larger cross section by more than one order of magnitude. The observation of L=4 and L=6 mixtures for these transitions limits the spin and parity values of the final states to $11/2^+$ or $13/2^+$.

The shapes of the 4.29, 4.36, 5.25, and 5.35 MeV transitions can also be fitted by an L=5 angular distribution. In order to populate these states with an L=5 transfer, the proton must fill the $d_{3/2}$ hole and the neutron must go either into the $f_{7/2}$ or $f_{5/2}$ orbit. Since none of these states is excited in the ^{42}Ca(d,p) reaction with noticeable ℓ_n=3 strength,[12] a $(d_{3/2}f_{7/2})$ or $(d_{3/2}f_{5/2})$ transfer which leads to the required L=5 angular distribution can be ruled out.

The ^{43}Ca ground state, $J^\pi=7/2^-$, and the $3/2^-$ state at 2.05 MeV are both quite strongly excited in this (α,d) reaction. This is expected, since both states have predominant $f_{7/2}$ and $p_{3/2}$ single-particle character,[12] respectively. They are populated in the ^{41}K(α,d) reaction by filling the $d_{3/2}$ proton hole in ^{41}K and transferring the neutron either into the $f_{7/2}$ or $p_{3/2}$ orbit. Based on the assumption that the ground state of ^{41}K can be described as pure $[(f_{7/2})^2_{0,1}d^{-1}_{3/2}]_{3/2^+}$ and the ground and 2.05 MeV states in ^{43}Ca as $(f_{7/2})^3_{7/2^-}$ and $(f_{7/2})^2_{0,1}p_{3/2}]_{3/2^-}$, respectively, distorted wave Born approximation (DWBA) calculations have been performed. The optical model parameters are taken from Ref. 8). The resulting angular distributions are superimposed in Fig. 5 on the data in full line. The agreement in shape is good. Taking into consideration that less than 100% of the assumed configurations are present in the real wave functions, the magnitude of the differential cross section is quite well represented (within a factor of 1.2).

The suggested configurations of the transferred proton-neutron pair as extracted from the present work on the basis of shapes and strength of the particular transitions are listed in Table I. As can be seen, the $[^{41}K(3/2^+) \otimes (f_{7/2})^2_{7,0}]$ 4p-1h configuration is spread over 17 states in ^{43}Ca. Assuming that the ground state of ^{41}K is predominantly $[(f_{7/2})^2_{0,1}d^{-1}_{3/2}]_{3/2^+}$, we suggest that these states have parts of the $[(f_{7/2})^4_{7,1}d^{-1}_{3/2}]$ 4p-1h configuration. The present results confirm the conjectures made in the heavy-ion induced γ-ray spectroscopy work of Ref. 5) for the spin and parities of the states at 2.95, 3.37, 3.94, and 4.59 MeV. They are also in good agreement with the results of the ^{43}Ca(α,α') work of DeVoigt, <u>et al</u>.6)

The present ^{41}K(α,d)^{43}Ca reaction and the ^{43}Ca(α,α') experiment excite different parts of the ^{43}Ca states wave functions. The (α,d) experiment populates, as discussed above, the simple shell-model parts of the wave function, whereas the (α,α') reaction samples those parts of the wave function which result from the coupling of a $f_{7/2}$ neutron to the 3^-

and 5^- vibrational states in ^{42}Ca. These 3^- and 5^- states in ^{42}Ca are quite strongly excited in both the ^{42}Ca(α,α') [Ref. 13)] and the ^{41}K(^{3}He,d) [Ref. 14)] reaction. This indicates that these levels can be described as a mixture of vibrational and 3p-1h configuration shell-model states. The coupling of a $f_{7/2}$ neutron to ^{42}Ca produces now the aforementioned two parts of the ^{43}Ca wave function. Levels in ^{43}Ca built upon the 2^- and 4^- members of this multiplet with mixed vibrational and 3p-1h configurations shell model states in ^{42}Ca can be excited in the (α,d) experiment but not in inelastic alpha scattering.

It is interesting to compare the present results to those of the ^{39}K(α,d)^{41}Ca reaction published previously.15) In ^{41}Ca, only 9 states are observed to be excited by L=6 transfer compared to 17 states in ^{43}Ca. According to the simple shell-model picture, only 4 states with spins ranging from $11/2^+$ to $17/2^+$ should be populated in both nuclei. However, if other states with spins $J^\pi=11/2^+-17/2^+$ arise from different configurations, the $[K(3/2^+) \otimes (1f_{7/2})^2_{J=7}]$ configuration can mix into them and the result will be more than four L=6 transitions. Hence the number of L=6 transitions will tend to follow the actual total number of states with the allowed spin values. The total (summed) L=6 strength, however, should remain constant. In the present case, these other states arise from the coupling of a $f_{7/2}$ neutron to the 2^--5^- multiplet of mixed vibrational and particle-hole shell-model configurations in ^{40}Ca and ^{42}Ca, respectively. In ^{40}Ca, the 3^- and 5^- states are much lower in energy than the 2^- and 4^-

states. In ^{42}Ca, however, the splitting of the 2^{-}-5^{-} quartet is considerably reduced and the 2^{-} and 4^{-} states lie at low excitation energy. Moreover, in ^{40}Ca the octupole strength is mainly concentrated into the lowest 3^{-} state, whereas in ^{42}Ca it is considerably fractionated.[13]) Hence, there are more states in ^{42}Ca than in ^{40}Ca serving as core states to which the $f_{7/2}$ neutron can be coupled.

The relative ^{41}K(α,d) to ^{39}K(α,d) strength for similar transitions reflects the fact that ^{41}K already has two particles in the $1f_{7/2}$ shell. The ratio of the ground state transitions where the proton-neutron pair are predominantly transferred in the $(d_{3/2}f_{7/2})$ configuration is 0.65, and that of the transitions to the $17/2^{+}$ states which proceed by pure $(f_{7/2})^2_{7,0}$ is 0.63. The ratio of the summed ^{41}K(α,d) to ^{39}K(α,d) L=6 transfer strength is 0.70, which is very close to the above values. The slightly higher value may result from some unobserved L=6 strength in the previously published ^{39}K(α,d) results. The theoretical ^{41}K(α,d) to ^{39}K(α,d) ratio for similar transitions is 0.75 assuming that the ground state wave functions of ^{41}K and ^{39}K are described as $[d^{-1}_{3/2} \otimes (f_{7/2})^2_{0,1}]$ and $[d^{-1}_{3/2}]$, respectively, and that the transferred configurations are the same in both cases.

We wish to acknowledge B.H. Wildenthal for his encouragement of our (α,d) studies, for his assistance in the early stages of the project, and for helpful discussions.

References

1. B.G. Harvey, J. Cerny, R.H. Pehl, and E. Rivet, Nucl. Phys. 39(1962)160.
2. E. Rivet, R.H. Pehl, J. Cerny, and B.G. Harvey, Phys. Rev. 141(1965)1021.
3. C.C. Lu, M.S. Zisman, and B.G. Harvey, Phys. Rev. 186 (1969)1086.
4. N.K. Glendenning, Phys. Rev. 137(1965)B102.
5. A.R. Poletti, E.K. Warburton, J.W. Olness, J.J. Kolata, and P.H. Gorodetzky, Phys. Rev. C13(1976)1180.
6. M.J.A. deVoigt, D. Cline, and R.N. Hiroshko, Phys. Rev. C10(1974)1798.
7. R.G. Markham and R.G.H. Robertson, Nucl. Instr. & Methods 129(1975)131.
8. R.M. Del Vecchio and W.W. Daehnick, Phys. Rev. C6 (1972)2095.
9. J.R. Comfort, Argonne National Laboratory (unpublished).
10. H. Nann, W.S. Chien, A. Saha, and B.H. Wildenthal (unpublished).
11. P.M. Endt and C. van der Leun, Nucl. Phys. A214(1973)1.
12. W.E. Dorenbusch, T.A. Belote and O. Hansen, Phys. Rev. 146(1966)734.
13. E.P. Lippincott and A.M. Bernstein, Phys. Rev. 163(1967) 1170.
14. J.S. Forster, K. Bearpark, J.L. Hutton, and J.F. Sharpey-Schafer, Nucl. Phys. A150(1970)30.

15. H. Nann, W.S. Chien, A. Saha, and B.H. Wildenthal, Phys. Rev. C12(1975)1524.

FIGURE CAPTIONS

Fig. 1.--Deuteron spectrum from the $^{41}K(\alpha,d)^{43}Ca$ reaction taken at $\theta_{lab}=20°$.

Fig. 2.--Angular distributions for L=6 transitions. The curves represent empirical L=6 shapes.

Fig. 3.--Angular distributions of strong transitions showing either pure L=4 or mixed L=4 plus L=6 shapes. The dashed and dashed-dotted curves represent empirical L=4 and L=6 shapes, respectively.

Fig. 4.--Angular distributions of some weak transitions.

Fig. 5.--Angular distributions for the transitions to the ground and 2.05 MeV state. The curves represent DWBA calculations as explained in the text.

TABLE I.--Results of the $^{41}K(\alpha,d)^{43}Ca$ reaction. E_x is accurate to ±10 keV.

E_x (MeV)	J^{π}	$\sigma(10^{o})$ ($\mu b/sr$)				suggested configurations of the transferred proton-neutron pair
		L=3	L=4	L=5	L=6	
0.0	$7/2^-$			150		$(d_{3/2}f_{7/2})_{J,0}$
2.055	$3/2^-$	65				$(d_{3/2}p_{3/2})_{J,0}$
2.850	$(11/2^+,13/2^+)^{b,c}$		23		20	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
2.951	$(11/2^+)^a$				76	$(f_{7/2})^2_{7,0}$
3.072	$(11/2^+,13/2^+)^{b,c}$		10		18	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
3.196	$(\ 13/2)^{+b}$		very weak			
3.278	$(11/2^+-17/2^-)^c$				24	$(f_{7/2})^2_{7,0}$
3.372	$(13/2^+)^a$				79	$(f_{7/2})^2_{7,0}$
3.500	$(11/2^+,13/2^+)^{b,c}$		130		110	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
3.838	$(7/2^+-13/2^+)^c$		60			$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}$
3.944*	$(15/2^+)^a$				135	$(f_{7/2})^2_{7,0}$
4.134	$(11/2^+,13/2^+)^{b,c}$				78	$(f_{7/2})^2_{7,0}$
4.191	$(11/2^+-17/2^+)^c$				220	$(f_{7/2})^2_{7,0}$
4.291	$(11/2^+,13/2^+)^c$		32		21	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
4.357	$(11/2^+,13/2^+)^c$		58		25	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
4.462	$(11/2^+,13/2^+)$		33		(6)	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}$
4.591	$(17/2^+)^a$				510	$(f_{7/2})^2_{7,0}$
4.701						
4.888	$(11/2^+-17/2^+)$				105	$(f_{7/2})^2_{7,0}$
5.189	$(11/2^+,13/2^+)$		20		35	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
5.246	$(11/2^+,13/2^+)$		110		28	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
5.351	$(11/2^+,13/2^+$		78		34	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})_{5,0}+(f_{7/2})^2_{7,0}$
5.696	$(11/2^+,13/2^+)^c$		42		37	$(f_{7/2})^2_{5,0}+(f_{7/2}p_{3/2})+(f_{7/2})^2_{7,0}$
6.087						
6.173						

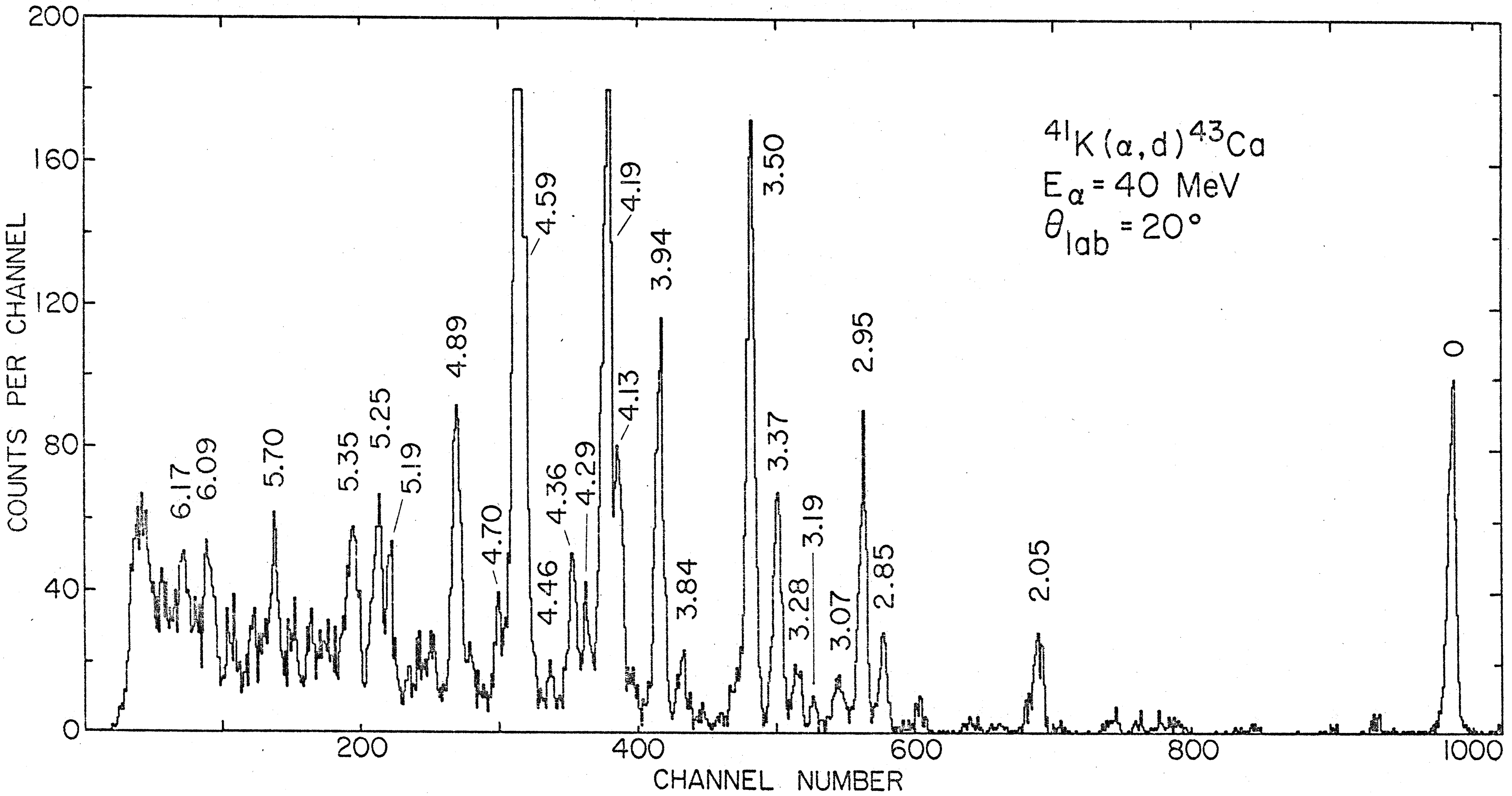
---

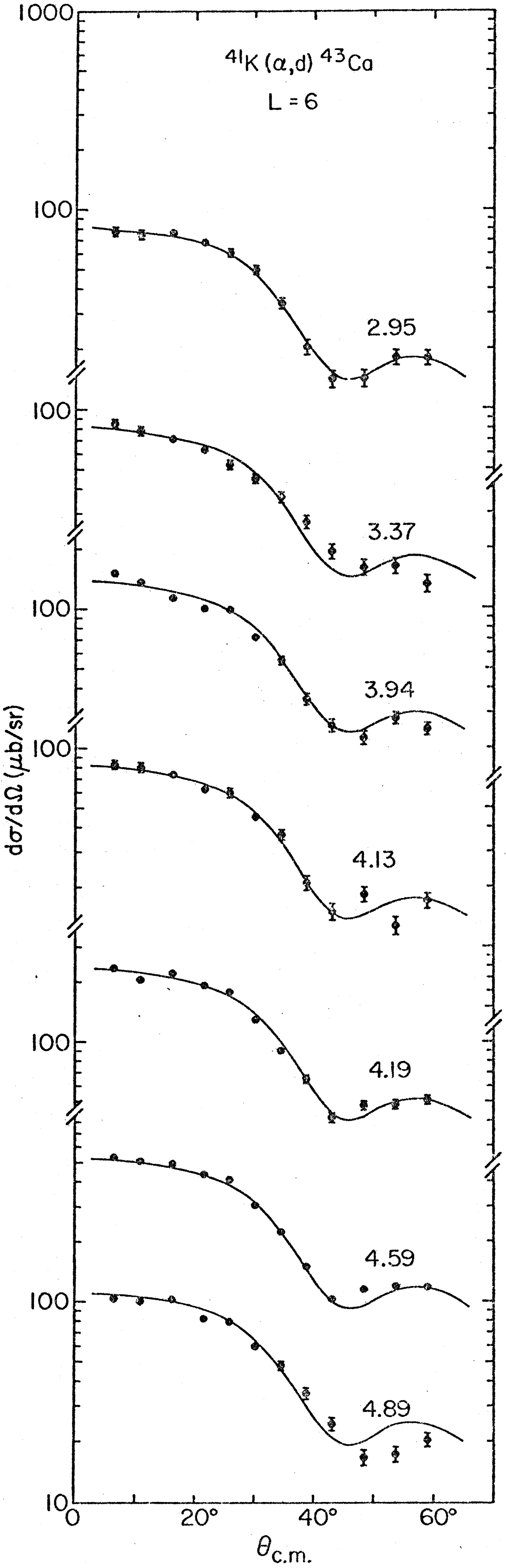
*not resolved from the 3.916 $(9/2^+)$ MeV state.

[a] Ref. 5)

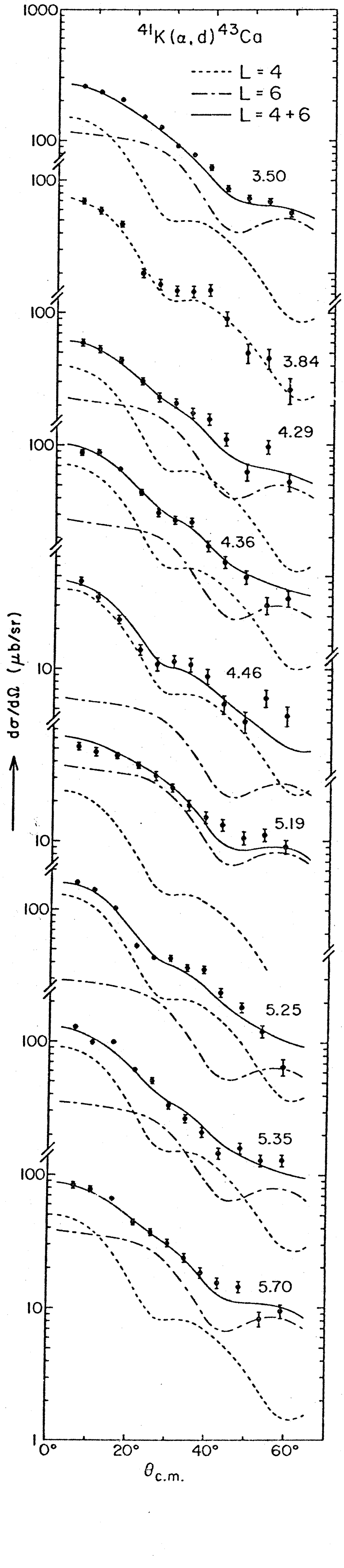
[b] Ref. 6)

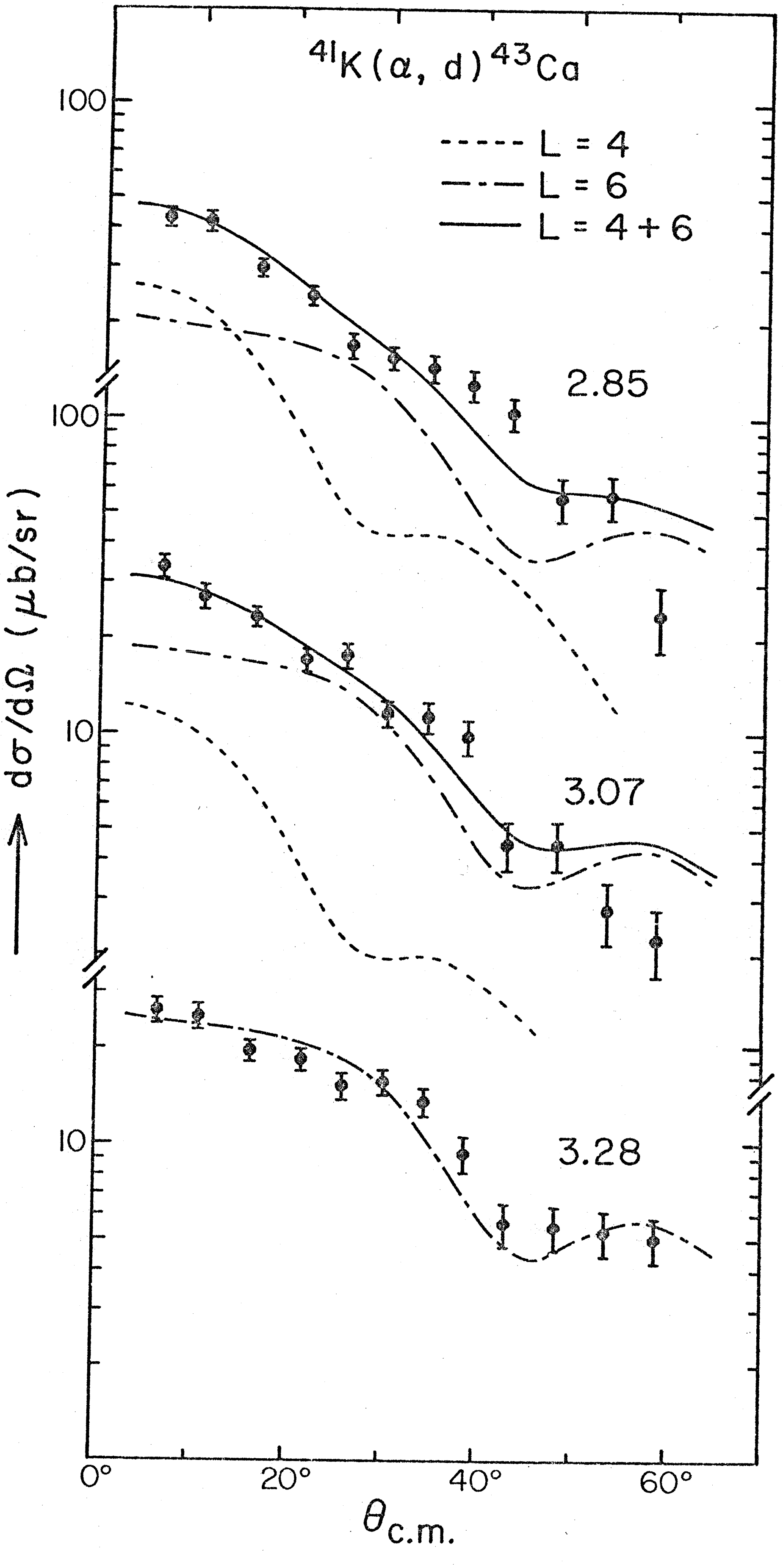
[c] Present work.


$^{41}K(\alpha,d)^{43}Ca$
$E_{\alpha} = 40$ MeV
$\theta_{lab} = 20°$
COUNTS PER CHANNEL
CHANNEL NUMBER
0
40
80
120
160
200
200
400
600
800
1000
6.17
6.09
5.70
5.35
5.25
5.19
4.89
4.70
4.59
4.46
4.36
4.29
4.19
4.13
3.94
3.84
3.50
3.37
3.28
3.19
3.07
2.95
2.85
2.05
0

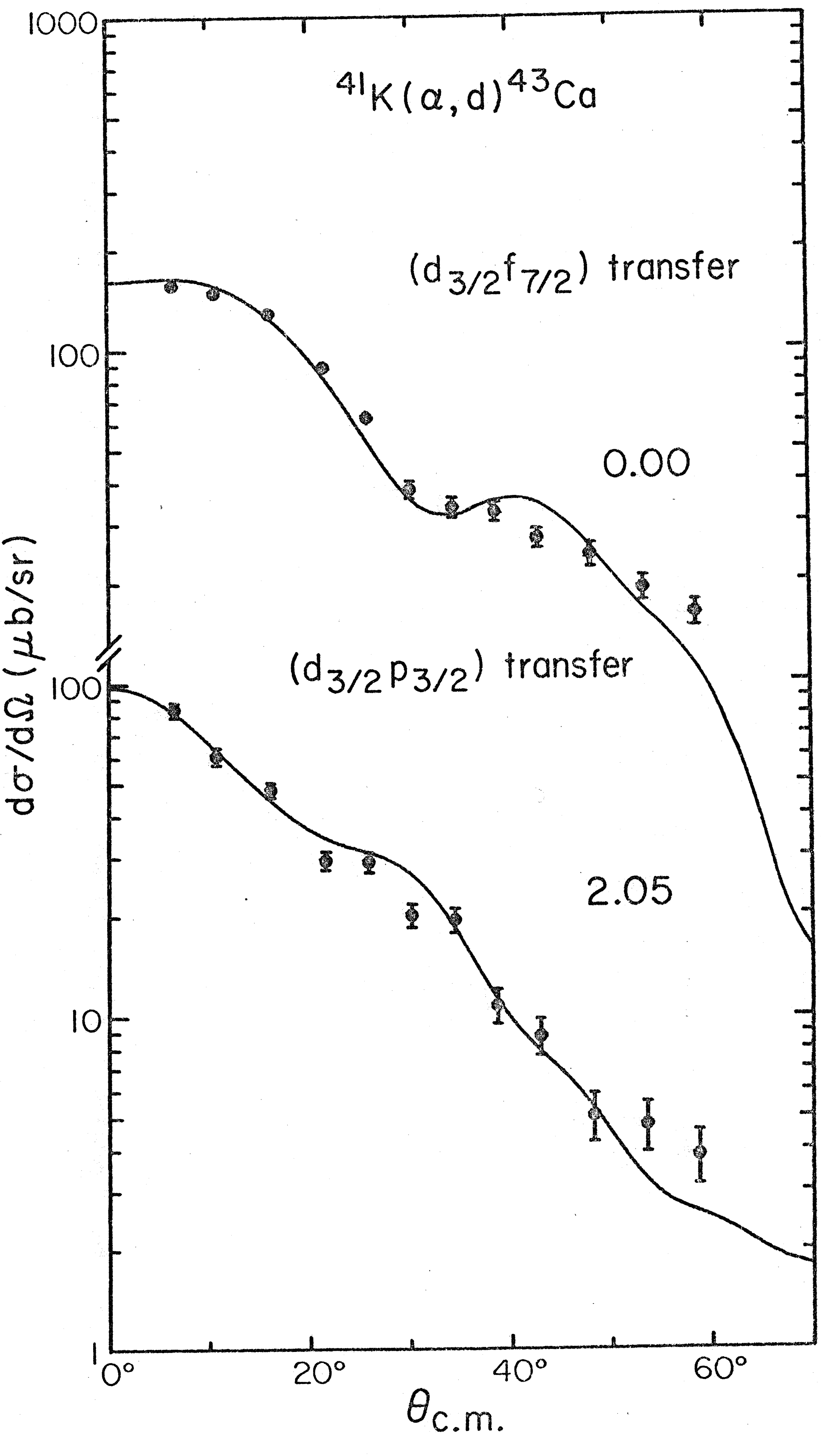


^{41}K (α,d) ^{43}Ca
L = 6
1000
100
100
100
100
100
100
10
2.95
3.37
3.94
4.13
4.19
4.59
4.89
dσ/dΩ (μb/sr)
0
20°
40°
60°
θ$_{c.m.}$


$^{41}K(\alpha, d)^{43}Ca$
L = 4
L = 6
L = 4 + 6
3.50
3.84
4.29
4.36
4.46
5.19
5.25
5.35
5.70
1000
100
100
100
100
10
10
100
100
100
10
1
0°
20°
40°
60°
$\theta_{c.m.}$
$d\sigma/d\Omega$ ($\mu b/sr$)



$^{41}K(\alpha, d)^{43}Ca$
L = 4
L = 6
L = 4 + 6
2.85
3.07
3.28
100
100
10
10
$d\sigma/d\Omega$ (μb/sr)
0°
20°
40°
60°
$\theta_{c.m.}$


$^{41}K(\alpha,d)^{43}Ca$
$(d_{3/2}f_{7/2})$ transfer
0.00
$(d_{3/2}p_{3/2})$ transfer
2.05
$d\sigma/d\Omega$ (μb/sr)
1000
100
100
10
1
0°
20°
40°
60°
$\theta_{c.m.}$