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$(f_{7/2})^2_{7,0}\ d^{-1}_{3/2}$ CONFIGURATION STATES IN ^{41}Ca STRONGLY POPULATED BY THE ^{39}K(α,d) REACTION

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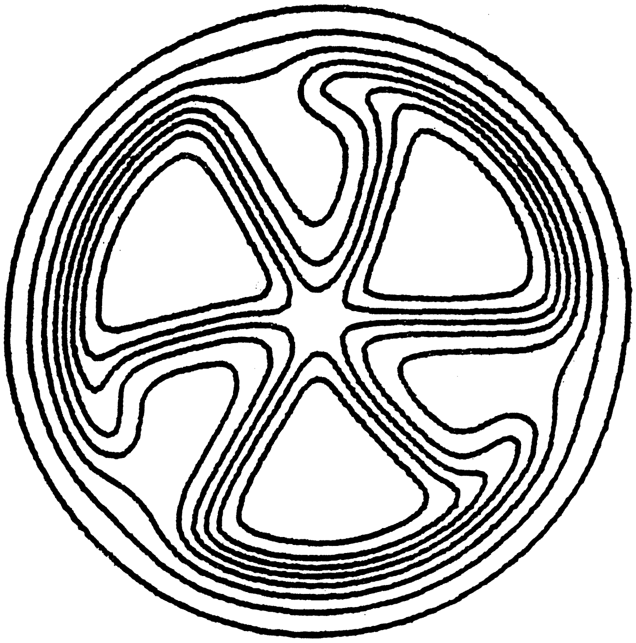

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$(f_{7/2})^2_{7,0}\ d^{-1}_{3/2}$ Configuration States in ^{41}Ca Strongly Populated by the ^{39}K(α,d) Reaction*

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ABSTRACT

Angular distributions of levels in ^{41}Ca strongly populated in the ^{39}K(α,d) reaction have been measured at E_α=40 MeV. Levels which have components corresponding to the coupling of the captured proton-neutron pair in the $(f_{7/2})^2_{7,0}$ configuration to the ground state of ^{39}K have been identified by means of their characteristic L=6 angular distributions. Evidence for the $[(f_{7/2})^2_{7,0}\ d^{-1}_{3/2}]$ 2p-1h character of the states in ^{41}Ca at 3.37, 3.83, 3.92, 3.97, 4.52, 5.22 and 5.35 MeV is discussed.

NUCLEAR REACTION: ^{39}K(α,d), E_α=40 MeV, measured $\sigma(E_d,\theta)$; natural target; deduced L-transfer.

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1. Introduction

It has been shown previously[1-3] that in the (α,d) reaction the proton-neutron pair is preferentially transferred in a completely aligned configuration. Furthermore, high values of the transferred orbital angular momentum are kinematically favoured due to momentum-mismatch. Hence levels corresponding to a $[J_i + (j_p j_n)_{J_{max}}]_{J_f}$ configuration should be populated strongly. Here J_i is the angular momentum of the target nucleus, j_p and j_n are the total angular momenta of the shell-model states into which the transferred proton-neutron pair is captured, coupled to the maximum allowed angular momentum J_{max}, and J_f is the angular momentum of the final state formed by vector coupling of J_i and J_{max}. For odd-A target nuclei where $J_i \neq 0$, $J_i \leq J_{max}$, one expects a multiplicity of $(2J_i+1)$ high-spin states to be populated. We have studied the ^{39}K(α,d) reaction in order to locate high-spin states with $11/2^+ \leq J \leq 17/2^+$ of the $[(f_{7/2})^2_{7,0}\ d^{-1}_{3/2}]$ 2p-1h configuration in ^{41}Ca. This configuration is excited by an orbital angular momentum transfer of L=6.

High-spin levels in ^{41}Ca have been studied by Gorodetzky *et al.*[4] and Lieb *et al.*[5] via γ-ray spectroscopy of heavy-ion induced reactions, but these experiments presumably yielded only information about possible spin and parity values for states along the yrast line. The present ^{39}K(α,d) experiment was undertaken to determine the possible configurations of these high-spin states and beyond that to get information about the high-spin states away from the yrast line.

2. Experimental Procedure and Results

The experiment was performed using a 40 MeV α-particle beam from the Michigan State University Cyclotron. The target was made by evaporating natural potassium metal onto a thin carbon backing and was kept under vacuum at all times. The target thickness (about 60 μg/cm^2) was determined by measuring the differential cross sections of the elastically scattered 40 MeV alpha particles and normalizing these data to calculations made with standard optical-model parameters. The reaction products were detected in the focal plane of a split-pole magnetic spectrograph with a wire-counter plastic scintillator combination.[6] A silicon detector placed in the scattering chamber allowed continuous monitoring of the target condition.

Figure 1 shows a typical spectrum. The resolution was about 60 keV full width a half maximum (FWHM). Although the known level density of ^{41}Ca is quite high in the 2 to 7 MeV excitation energy range only relatively few states are strongly excited in the (α,d) reaction. Angular distributions were obtained over the region from 6° to 55°. They are displayed in Figs. 2 and 3. Error bars, where shown, reflect only statistical uncertainties. The accuracy of the absolute differential cross section is estimated to be about ±30%.

3. Discussion

In the (α,d) reaction the proton-neutron pair is preferentially transferred with large angular momentum in a completely aligned configuration. Figure 4 shows angular distributions calculated in the distorted-wave Born approximation (DWBA) for the transfer in the $(f_{7/2})^2_{7,0}$, $(f_{7/2})^2_{5,0}$

and $(f_{7/2})^2_{3,0}$ couplings under the assumption of equal spectroscopic amplitudes. The predicted angular distributions are sufficiently different in strength and in shape to allow unambiguous identification of the transferred angular momentum. The enhanced intensity of the transfer in the $(f_{7/2})_{7,0}$ coupling relative to the other couplings is evident. Accordingly, in the ^{39}K(α,d) reaction high-spin levels with $J^\pi = 11/2^+$, $13/2^+$, $15/2^+$ and $17/2^+$ belonging to the configuration $[^{39}K(3/2^+) + (f_{7/2})^2_{7,0}]$ are expected to be strongly excited and to exhibit a distinctive L=6 angular distribution.

In order to get a pure experimental L=6 shape of an (α,d) angular distribution, the ^{40}Ca(α,d) reaction leading to the known 7^+ state in ^{42}Sc at 0.62 MeV[7] was also studied.[8] The measured angular distribution is displayed on the top of Fig. 2. The smooth curve through this angular distribution has been drawn in dashed line through other angular distributions to indicate L=6 idenfitication for the states at 3.37, 3.83, 3.92, 4.52, 5.22 and 5.34 MeV in ^{41}Ca. The weak transition to the 3.97 MeV state shows a less distinct L=6 pattern. Based on the estimate[9] that the ground state of ^{39}K is about 90% $(d_{3/2})^{-1}$ we conclude from the just discussed properties of the (α,d) reaction that these states have significant components corresponding to the $(f_{7/2})^2_{7,0}\, d^{-1}_{3/2}$ configuration.

An L=6 angular distribution can result not only from the transfer of the proton-neutron pair in the $(f_{7/2})^2$ configuration but also from the transfer in the $(d_{3/2}g_{9/2})$ and/or $(f_{7/2}f_{5/2})$ configurations. The transfer in the $(d_{3/2}g_{9/2})$ configuration can be ruled out, because none of these levels is excited in the single nucleon transfer reaction ^{40}Ca(d,p)^{41}Ca (Ref. 10) by a $g_{9/2}$ transfer. Transfers in the $(f_{7/2}f_{5/2})$ configurations are also rather unlikely, since admixtures of the $f_{5/2}$ shell in these relatively low-lying states are expected to be very weak on the basis of the experimental systematics of $f_{5/2}$ single particle strength.[11]

Aside from the above discussed transitions there are other strongly excited transitions to levels at 4.98, 5.52, 6.07 and 6.48 MeV in ^{41}Ca. They are displayed in Fig. 3 together with the ground state transitions which is predominantly L=5. In the ground state transition, the proton fills the $d_{3/2}$ hole and the neutron goes to the $f_{7/2}$ orbit. Since the ground state in ^{41}Ca nearly exhausts the $f_{7/2}$ single-particle strength, other transitions with $(d_{3/2}f_{7/2})$ transfer configurations are expected to be very weak (less than 10% of the ground state transition strength) and are not seen in the present data.

The transition to the 5.52 MeV state in ^{41}Ca exhibits a distinct L=4 angular distribution. In order to clarify this L-assignment, an experimental L=4 shape was obtained from the ^{40}Ca(α,d) reaction leading to the known 5^+ state in ^{42}Sc at 1.51 MeV and superimposed to the ^{39}K(α,d) data (dashed-dotted curve). The shapes of the 4.98, 6.07, and 6.48 MeV transitions can be explained by either pure L=5 angular distributions or a mixture of L=4 and L=6.

In order to form these states by an L=5 angular distribution, the proton must fill the $d_{3/2}$ hole and the neutron must go either into the $f_{7/2}$ or $f_{5/2}$ orbits. According to the reason given above, the $(d_{3/2}f_{7/2})$ transfer can be ruled out.

From single-nucleon transfer reactions leading to ^{41}Ca it is known that none of these states is excited by a $f_{5/2}$ transfer with noticeable strength. Accordingly, $(d_{3/2}f_{5/2})$ transitions can also be ruled out. In conclusion, transitions with cross sections larger than 20% of the ground state transition are very unlikely to show L=5 angular distributions.

We therefore fit the angular distributions as L=4+6 using the empirical shapes. The observed L=4 strength in the 4.98, 5.52, 6.07 and 6.48 MeV transitions is too large to be explained by pure $(f_{7/2})^2_{5,0}$ transfer. Most likely the $(f_{7/2}p_{3/2})_{5,0}$ configuration, which also leads to L=4 and which yields a cross section of about one order of magnitude larger than the $(f_{7/2})^2_{5,0}$ configuration, contributes also to the observed strength. As mentioned above, the L=6 admixtures in the observed angular distributions result predominantly from the transfer of the p-n pair in the $(f_{7/2})^2_{7,0}$ configuration. However in the case of the transition to the $9/2^+$ state at 4.98 MeV, the L=6 admixture can be explained as a $(d_{3/2}g_{9/2})$ transfer, since this state contains about 13% of the $g_{9/2}$ single-particle strength.[11] The observation of an L=4 and L=6 mixture for the 6.07 and 6.48 MeV transitions limits the spin and parity values for these states to $11/2^+$, $13/2^+$.

The transition strengths of these strongly excited states are summarized in Table II. Included are suggested configurations as extracted from the present work on the basis of shapes and strengths of the particular transitions. Nine states in ^{41}Ca can be assigned to have parts of the $[(f_{7/2})^2_{7,0}\, d^{-1}_{3/2}]$ 2p-1h configurations and not four as expected by the simple weak-coupling model.[12] These suggested configurations are consistent with the $^{40}K(^{3}He,d)^{41}Ca$ results of Bohne et al.[13] Since the ground state wave function of ^{40}K is predominatly $d^{-1}_{3/2}\ f_{7/2}$, states with spin varying from $1/2^{+}$ to $15/2^{+}$ and 2p-1h configurations of the type $(f_{7/2})^{2}\ d^{-1}_{3/2}$ and $(f_{7/2}p_{3/2})\ d^{-1}_{3/2}$ are preferentially excited in this reaction by transferring the proton into the $f_{7/2}$ or $p_{3/2}$ orbits. The present results confirm the conjectures for the spins and parities of the states at 3.37, 3.83, 3.92 and 5.22 MeV made in the (heavy-ion, x nγγ) work of Refs. 4 and 5. For the level at 5.22 MeV, the unambiguous L=6 angular distribution together with the fact that it has by far the largest cross section strongly suggests a $17/2^{+}$ assignment. This conclusion was also reached by Thorn et al.[14] on the basis of the states population intensity alone observed in the $^{39}K(\alpha,d)$ reaction at 28.5 MeV bombarding energy. The fact that the 5.22 MeV level is not seen in the $^{40}K(^{3}He,d)$ reaction also supports this assignment.

Assuming that the $17/2^{+}$ state at 5.22 MeV has the pure configuration $(f_{7/2})^{2}_{7,0}d^{-1}_{3/2}$, the fractions of this configuration in the wave functions of the 3.37 $(11/2^{+})$, 3.83 $(15/2^{+})$ and 3.92 $(13/2^{+})$ MeV states can be determined from the strength of the particular (α,d) transition after dividing by $[(2J_{f}+1)/(2J_{i}+1)]$. The following fractions of the $(f_{7/2})^{2}_{7,0}\ d^{-1}_{3/2}$ configuration are found: for the 3.37 $(11/2^{+})$ level 10%, for the 3.83 $(15/2^{+})$ level 32%, and for the 3.92 $(13/2^{+})$ level 37%. The application of the 2J+1 rule to two-nucleon transfer reactions seems rather dangerous, since the cross section depends coherently on the components of the wave functions

of the states involved. But in this case, as discussed above, contributions from components other than the main component in the target wave function $d^{-I}_{3/2}$ and the $(f_{7/2})^{2}_{7,0}\ d^{-1}_{3/2}$ component in the final wave functions are quite small. Even then, the above obtained fractions of the $(f_{7/2})^{2}_{7,0}\ d^{-1}_{3/2}$ configurations have to be considered as fairly uncertain.

Acknowledgements

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Table I. Results of the ^{39}K(α,d)^{41}Ca Reaction

Ex (MeV)	J^{π}	σ(10°) (μb/sr) L=4	L=5	L=6	suggested configurations
0.00	$7/2^-$		260		$f_{7/2}$
3.37	$(11/2^+)^{a,b}$			54	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
3.83	$(15/2^+)^{a,b}$			230	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
3.92	$(13/2^+)^{a}$			230	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
3.97	$(11/2^+-17/2^+)^{d}$			90	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
4.52	$(11/2^+-17/2^+)^{d}$			240	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
4.98	$9/2^+$	90		92	$g_{9/2}+(f_{7/2})^2_{5,0}d^{-1}_{3/2}+(f_{7/2}P_{3/2})_{5,0}d^{-1}_{3/2}$
5.22	$(17/2^+)^{a,b,c,d}$			800	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
5.35	$(11/2^+-17/2^+)^{d}$			340	$(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
5.52	$(7/2^+-13/2^+)^{d}$	300			$(f_{7/2})^2_{5,0}d^{-1}_{3/2}+(f_{7/2}P_{3/2})_{5,0}d^{-1}_{3/2}$
6.07	$(11/2^+,13/2^+)^{d}$	600		120	$(f_{7/2})^2_{5,0}d^{-1}_{3/2}+(f_{7/2}P_{3/2})_{5,0}d^{-1}_{3/2}+(f_{7/2})^2_{7,0}d^{-1}_{3/2}$
6.48	$(11/2^+,13/2^+)^{d}$	280		60	$(f_{7/2})^2_{5,0}d^{-1}_{3/2}+(f_{7/2}P_{3/2})_{5,0}d^{-1}_{3/2}+(f_{7/2})^2_{7,0}d^{-1}_{3/2}$

a. Ref. 4

b. Ref. 5

c. Ref. 14

d. Present work

Figure Captions

Fig. 1.--Deuteron spectrum from the $^{39}K(\alpha,d)^{41}Ca$ reaction taken at $\theta_{lab}=20°$. The contaminant ground state transition of the $^{12}C(\alpha,d)^{14}N$ reaction is cross hatched.

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

Fig. 3.--Angular distributions for other strong transitions. For further explanation see text.

Fig. 4.--Results of distorted wave Born approximation calculations for the transfer in the $(f_{7/2})^2_{7,0}$, $(f_{7/2})^2_{5,0}$ and $(f_{7/2})^2_{3,0}$ couplings assuming equal spectroscopic amplitudes.

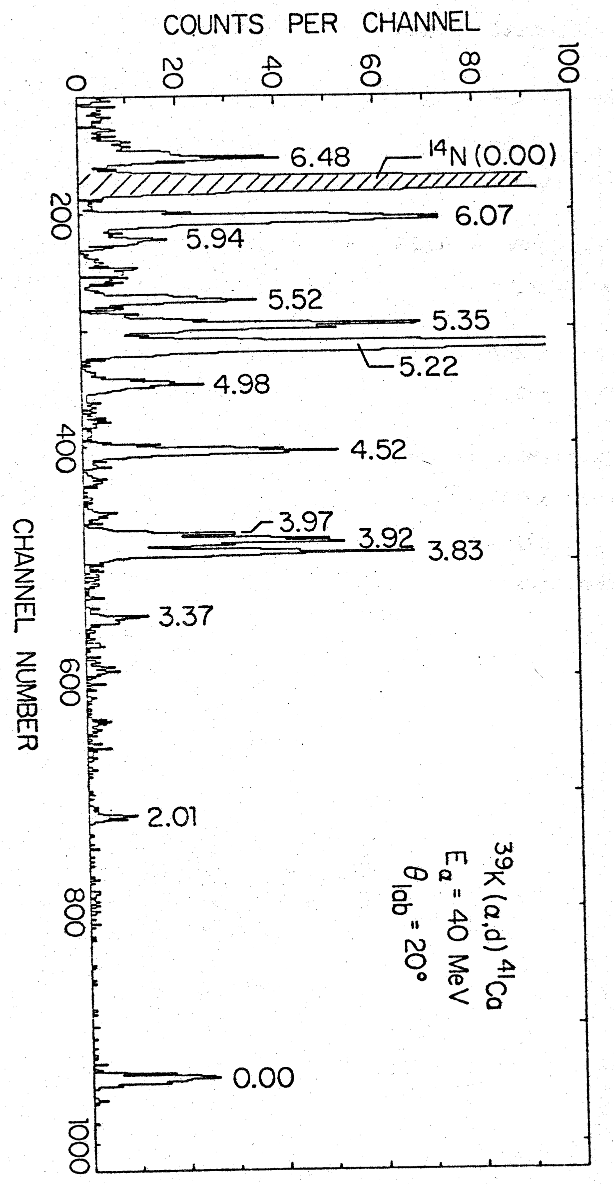

Fig. 1

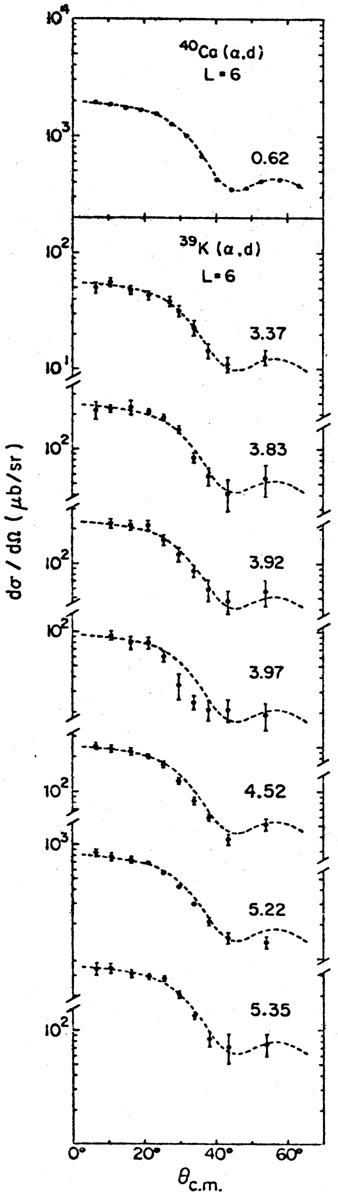
^{40}Ca (α,d)
L=6
0.62
^{39}K (α,d)
L=6
3.37
3.83
3.92
3.97
4.52
5.22
5.35
10^4
10^3
10^2
10^1
10^2
10^2
10^2
10^2
10^3
10^2
dσ / dΩ (μb/sr)
0°
20°
40°
60°
θc.m.

Fig. 2

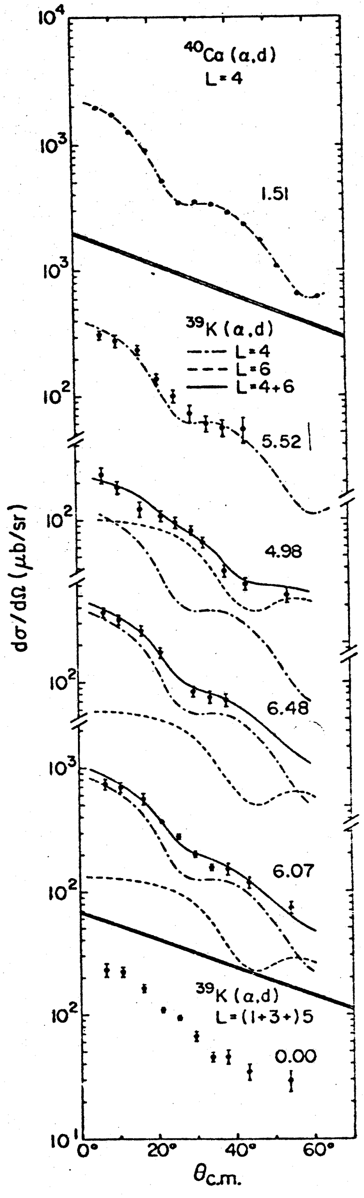
^{40}Ca (α,d)
L=4
1.51
^{39}K (α,d)
L=4
L=6
L=4+6
5.52
4.98
6.48
6.07
^{39}K (α,d)
L=(1+3+)5
0.00
10^4
10^3
10^3
10^2
10^2
10^2
10^3
10^2
10^2
10^1
dσ/dΩ (μb/sr)
0°
20°
40°
60°
θc.m.

Fig. 3

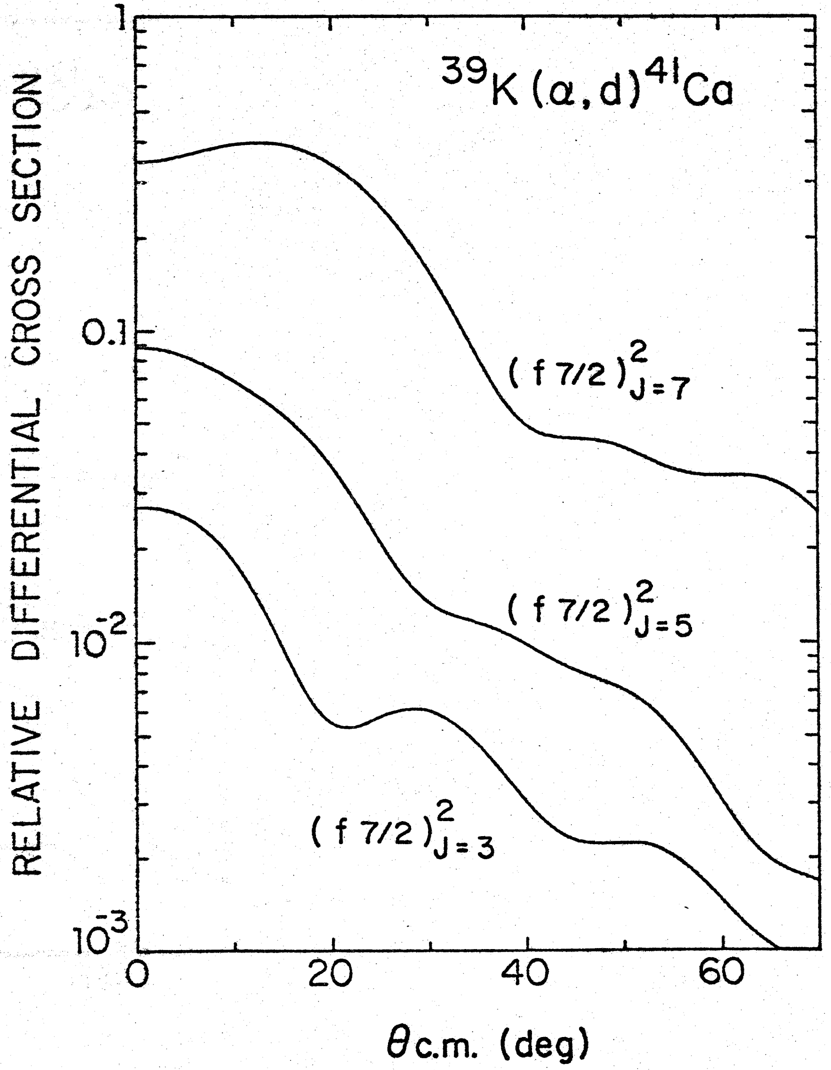
$^{39}K(\alpha,d)^{41}Ca$
RELATIVE DIFFERENTIAL CROSS SECTION
1
0.1
10^{-2}
10^{-3}
$(f\,7/2)^2_{J=7}$
$(f\,7/2)^2_{J=5}$
$(f\,7/2)^2_{J=3}$
0
20
40
60
θc.m. (deg)

Fig. 4