Title

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STUDY OF THE ^{40}Ca(He^3,t)^{40}Sc REACTION AT 30.2 MeV[*]

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INTRODUCTION

In the last few years, the (He^3,t) reaction has been systematically used to investigate odd-odd nuclei, especially near the closed shells. In most cases, the members of low-lying spin multiplets, corresponding to the lowest shell-model configurations in the residual nucleus, have been identified using very simple empirical rules[1] for spin assignments. In these experiments, the in-shell transitions were mostly studied. It was however rather difficult to study the higher lying levels corresponding to cross-shell configurations since often no shell-model calculation was available. Nevertheless, the general trends of the (He^3,t) reaction were carefully tested on almost all the lighter nuclei, confirming the previously established properties, and some evidence seemed to appear[1,2] that the cross-shell transitions with parity change were inhibited. It was also shown[3] that a tensor force is needed in order to explain the angular distributions of the unnatural parity states.

Besides the question of whether or not cross-shell transitions with parity change are allowed, it is interesting to study, in a simple case, the

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interference of the central and tensor parts that these transitions allow, in order to better determine the force responsible for the (He^3,t) transition.

The ^{40}Ca target is well known. Its 20 protons and neutrons can be roughly supposed to fill the closed shells N = Z = 20. Thus the eventually observed states will involve both cross-shell and parity change transitions, the involved particle being transferred to an outer odd parity orbit. Moreover, one can hope to observe a series of levels corresponding to higher energy configurations in this special case where the nuclear structure can allow simple theoretical estimations for the excited levels in the residual nucleus, at least from the better known ^{40}K mirror nucleus. This can be a good case to test the spectroscopic possibilities of the (He^3,t) reaction.

The levels of ^{40}Sc nucleus are not well known. In an earlier $^{40}Ca(He^3,t)^{40}Sc$ experiment, Rickey et al.[4] have observed several triton groups corresponding to levels in ^{40}Sc. Their study of the positron decay of ^{40}Sc allowed them to establish the ^{40}Sc ground state as a 4^-.

In contrast, we have more information for the mirror nucleus ^{40}K, where the levels are known from the $^{39}K(d,p)^{40}K$ experiment of Enge et al.[5] They identified the first four states in ^{40}K, described by the configuration $\{(d_{3/2})_p^{-1}(f_{7/2})_n\}_{J^\pi=2^-\cdots 5^-}$. In addition they suggested that the position of the higher energy $\{(d_{3/2})_p^{-1}(p_{3/2})_n\}_{J^\pi=0^-\cdots 3^-}$ multiplet was near 2 MeV. Unfortunately, the low incident energy employed in this experiment distorts the spectroscopic information and leaves the reaction mechanism unclear.

In addition to the one particle-one hole states observed in this previous work, two particle-two hole states have been investigated by Wesolowski et al.[6] through the favorable $^{40}Ar(He^3,t)^{40}K$ reaction. They observed a series of nine strongly excited levels in ^{40}K, between 1.65 and 5.87 MeV energy excitations, including the 4.38 and 5.87 MeV isobaric analog states of the ground and first excited states of ^{40}Ar.

A recent study of the ^{40}Ar$(p,n\gamma)^{40}$K reaction by Twin et al.[7] confirms the previous spin and parity assignments for the low lying levels in ^{40}K. In addition they identified four positive parity states at 1.644 (0^+), 1.959 (2^+), 2.261 (3^+) and 2.290 MeV (1^+) which can be tentatively described by the $(f_{7/2})^2(d_{3/2})^{-2}$ configuration.

EXPERIMENTAL PROCEDURE AND RESULTS

The 30.2 MeV ^{3}He beam of the sector-focussed Saclay cyclotron has been used to bombard a 0.25 mg/cm^2 thick ^{40}Ca target. The outgoing particles have been detected and identified by an E-ΔE silicon solid state detector telescope (E = 3 mm and ΔE = 0.25 mm), coupled to an on-line PDP8 computer. The overall energy resolution was 70 keV. Angular distributions have been measured for 13 excited states in a 4 MeV energy range, between 11 and 70 degrees CMS. The energies are given in Table I and compared to the known ^{40}K states.

Figure 1 displays an experimental spectrum. The four strongest triton groups are at 0, 0.77, 0.89 and 2.33 MeV. For the first three groups, the energies agree roughly with the known energies of the first three excited states of ^{40}K. Both ^{40}K and ^{40}Sc have 4^- ground states. According to charge symmetry, one can assume that the 0.010 MeV group is a doublet $4^- + 3^-$, the 0.77 MeV level is a 2^- and the 0.89 MeV has $J^\pi = 5^-$. All of these levels are reasonably described by the $\{(f_{7/2})_p(d_{3/2})_n^{-1}\}_{J^\pi=2^--5^-}$ configuration.

The strongly excited 2.32 MeV level (Fig. 2) corresponds energetically to a weak doublet in the ^{39}K$(d,p)^{40}$K experiment[5] but to a strong peak observed in the ^{40}Ar(He^3,t)^{40}K reaction[6] which is expected to select two-particle-two holes states in ^{40}K. It is also close to the 2.261 (3^+), 2.290 (1^+) and 2.291

($\ell=4$) positive parity states identified in the ^{40}Ar(p,nγ)^{40}K reaction.[7]

It should also be noted that no strongly excited group was seen which would correspond to the $\{(p_{3/2})(d_{3/2})^{-1}\}$ multiplet known in ^{40}K.[5,7] Besides these main triton groups there are a lot of more weakly excited levels. The 1.64 MeV state can be compared to the 1.644 MeV 0^+ level identified by Twin et al.,[7] but its angular distribution does not show a typical 0^+ pattern. The level observed at 1.74 MeV does not correspond to any level in ^{40}K. The other measured angular distributions except the 2.64 and 3.14 MeV triton groups do not show very significant patterns. Under these conditions, it is difficult to use the ^{40}K spectrum to make a further level identification, unless an other attempt is made for spin assignment.

The low-lying levels in ^{40}Sc appear to be described by the $\{(f_{7/2})_p(d_{3/2})_n^{-1}\}$ configuration. In this experiment, they are excited through a reaction involving a parity change between the target nucleus ground state and the final states. The corresponding transitions are rather strong since the cross sections have an intensity around 100 μb/sr at forward angles. One must take into account that this reaction is not favored since the ^{40}Ca ground state has $T_z = 0$. The measured cross sections are very comparable to those measured for the ^{48}Ca(He^3,t)^{48}Sc reaction.[1] Moreover, the angular distributions obtained display significant patterns allowing spin assignment to be made either empirically[1] or by means of microscopic calculations.

MICROSCOPIC CALCULATIONS

We shall be especially interested in the lowest $\{(f_{7/2})_p,(d_{3/2})_n^{-1}\}$ states, since they are the only ones for which we can make reasonable assumptions for the microscopic structure. Such cross shell transitions allow the central and tensor parts of the force to interfer and can yield some new information on the most suitable nucleon-nucleon force v that can be used. We take

$$v = V[f(r)(1 + a_{\sigma\tau}\ \vec{\sigma}_1\cdot\vec{\sigma}_2) + \overline{\theta}(r)\ a_T\ S_{12}]\ \vec{\tau}_1\cdot\vec{\tau}_2$$

V is an effective strength determined in order to reproduce the experimental cross-section. f(r) is a Yukawa type radial form. Its range is either 1.4 or 1 fm. $\overline{\theta}(r)$ has been calculated[10] from the OPEP potential.[8] For both radial forms, the finite size of the projectile has been taken into account.[9,10] We have assumed a Serber mixture with $a_{\sigma\tau} = 1$. a_T is either 0 or 1. The different types of forces used in the calculations are summarized in Table II. We consider the 1.4 fm range Yukawa central force with an OPEP tensor part added (force 3 of Table II) to be the most realistic.[10]

The optical potentials are given in Table III. Potential 1 is derived from 30 MeV ^{3}He scattering and potential 2 from 12 MeV triton elastic scattering on ^{40}Ca (Ref. 11). The DWBA code NENESSE[12] has been used for this calculation, a tensor force is included, using the formalism of J. Raynal.[13]

We shall first study the dependence of the calculated cross-sections on the optical parameters. Several authors[14,15,16] have shown that one can, to a good approximation, use the same parameters for entrance and exit channels. For the lowest 5^- state, using the usual 1 fm range central force, we have made two calculations: For the first, an optical potential which fits the 30 MeV elastic He^3 scattering on ^{40}Ca(V_1) was used in both channels. Almost no structure appears in the calculated cross-section (Fig. 3) in sharp disagreement with experiment. On the other hand, taking a potential which fits 12 MeV elastic triton scattering on ^{40}Ca(V_2) for the exit channel, leads to angular distributions very close to the experimental one (Fig. 3), both for the 1 fm range and the 1.4 fm range Yukawa force. The choice of the optical parameters is seen to be very important, mainly because of the large Q value (-14.48 MeV) of the reaction. For all the calculations, therefore, we use V_1 for the entrance channel and V_2 for the exit channel.

The 0.89 MeV 5^- level is the only natural parity state that was measured without ambiguity since the 3^- and 4^- states are not resolved. A pure central term (force 1) with a range of 1.4 fm gives the typical L = 5 pattern, but a tensor term (force 3) is needed to explain the slow decrease of the experimental cross section at large angles (Fig. 4). The contribution of the tensor part is rather small, but is exactly what is needed to fit the angular distribution. On the other hand, a 1 fm range central part plus the OPEP tensor term (force 4) gives an angular distribution in which the tensor part dominates and which does not fit the experiment.

For the unnatural parity states 2^- and 4^-, a pure central force gives angular distributions (Figs. 5 and 6), which are in total disagreement with the experimental ones. This is as expected for (He^3,t) reactions to unnatural parity states, where a tensor force is known to be necessary.[3] Rather good fits are obtained using force 3, and indeed, the contribution of the central term is small compared to the tensor contribution. For the 4^- - 3^- doublet, a better fit can be obtained by taking the 3^- admixture into account. We have assumed that the 3^- and 4^- cross-sections are equal around 45°, as indicated by the results of Schultz <u>et al</u>.[17] The 3^- contribution is small for the angles smaller than 30° (Fig. 5), but very important at larger angles. Increasing the central contribution with respect to the tensor one will probably not change drastically the fit for the 4^- state (which is already good), but may improve the fit for the 2^- state at large angles (Fig. 6).

The strengths V needed to explain the experimental magnitude of the cross sections relative to the $\{(f_{7/2})_p(d_{3/2})_n^{-1}\}_{J^-}$ multiplet are very comparable (Fig. 7) to those needed for the $\{(f_{7/2})_p(f_{7/2})_n^{-1}\}_{J^+}$ multiplet in ^{48}Sc (Ref. 14). The strengths relative to the 4^- and 3^- components of the ^{40}Sc ground state doublet have been extracted under the previous assumptions. Some suggestions have recently been made[1,2] that the excitations involving a parity change should be inhibited in the (He^3,t) reaction. We have shown that, for the simple case we consider, the excitations presumably occur through the same mechanism, whether or not there is a parity change.

The most important consideration is whether or not the transition is of natural parity. This has been already explained since, in the first case the excitation occurs mainly through the central term of the force, and in the second case, the tensor term dominates the transition.

CONCLUSION

In this work we have considered only the first four levels in ^{40}Sc. This enabled us to define and test the force which will be used to analyze the other experimental results we have neglected here. A further experiment with a better resolution, leading to unambiguous angular distributions is needed. However, this restricted study has shown that the parity change transition is allowed in ^{40}Ca with a strength comparable to that found for the in-shell transitions in ^{48}Ca, suggesting the same reaction mechanism. In addition, we have shown that, if the tensor force is needed for the transitions leading to unnatural parity states, its contribution appears to be sensible in the cross shell transitions, even for the natural parity states.

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TABLE I. Energy levels observed in ^{40}Ca(He^3,t)^{40}Sc reaction. The previously known levels in the ^{40}K mirror nucleus are given for comparison. Indicated also are the corresponding spin and parity determinations. This list is limited to the 4 MeV range of this work.

^{40}Ca(He^3,t)^{40}Sc this work		^{39}K(d,p)^{40}K Ref. 5		^{40}Ar(He^3,t)^{40}K Ref. 6		^{40}Ar(p,nγ)^{40}K Ref. 7	
E(MeV)	J^π	E(MeV)	J^π	E(MeV)	J^π	E(MeV)	J^π
0.010	4^-+3^-	0.	4^-	0.015		0.	4^-
		0.028	3^-			0.030	3^-
0.77	2^-	0.795	2^-	0.84		0.800	2^-
0.89	5^-	0.885	5^-			0.891	5^-
1.64		1.639		1.65		1.644	0^+
1.75							
		1.954		1.96		1.959	2^+
		2.042	(3^-)			2.047	2^-
		2.064	(2^-)			2.070	3^-
		2.099	(1^-)			2.103	1^-
						2.261	3^+
		2.286		2.29		2.290	1^+
2.33						2.291	4
		2.393					
		2.415					
		2.565					
2.64		2.622	(0^-)				
		2.743					
		2.781		2.77			
		2.802					
		2.948					
		2.983					
3.01		3.021					
		3.104		3.08			
3.14		3.125					
		3.144					
		3.225					
		3.367					
		3.385					

(continued)

TABLE I. Continued

$^{40}Ca(He^3,t)^{40}Sc$ this work		$^{39}K(d,p)^{40}K$ Ref. 5		$^{40}Ar(He^3,t)^{40}K$ Ref. 6		$^{40}Ar(p,n\gamma)^{40}K$ Ref. 7	
E(MeV)	J^π	E(MeV)	J^π	E(MeV)	J^π	E(MeV)	J^π
3.45		3.412		3.44			
		3.479					
		3.599					
		3.629					
		3.657					
		3.715					
		3.738		3.73			
		3.766					
3.80		3.790					
		3.820					
		3.838					
		3.869					
		3.883					
		3.898					
		3.920					
4.04		4.017					
		4.102					

TABLE II. Forces introduced in the calculation of the cross sections. The given OPEP force is averaged over the projectile density, as explained in the text.

Force	central part	tensor part
1	1.4 fm range Yukawa Serber	no
2	1 fm range Yukawa Serber	no
3	1.4 fm range Yukawa Serber	OPEP
4	1 fm range Yukawa Serber	OPEP
5	1.4 fm range Yukawa Serber	75% OPEP

TABLE III. Optical potentials used in the cross-section calculations, both extracted from Ref. 11.

number	V (MeV)	R_V fm	a_V fm	W_W (MeV)	R_W fm	a_W fm	E (MeV)
1	167	1.16	0.715	13	1.8	0.872	30
2	172.6	1.40	0.715	50.9	1.40	0.610	12

FIGURE CAPTIONS

Fig. 1. Experimental spectrum for the ^{40}Ca(He^3,t)^{40}Sc reaction at $\theta = 25°$.

Fig. 2. Experimental angular distribution measured for the 2.33 MeV level in ^{40}Sc.

Fig. 3. Shapes of the L = 5 angular distributions for the 0.89 MeV level in ^{40}Sc, assuming two central forces (1 and 1.4 fm range, see Table II) and two different optical potentials in the exit channel, as given in Table III.

Fig. 4. Angular distribution measured for the 0.89 MeV 5^- level in ^{40}Sc. Plotted are the experimental points and four calculated angular distributions using the different forces defined in Table II.

Fig. 5. Angular distribution measured for the 0.010 MeV doublet in ^{40}Sc. Plotted are the experimental points, and four calculated angular distributions corresponding to the transitions

$(0^+ \rightarrow 4^-)$, force 1 (dotted line)
$(0^+ \rightarrow 4^-)$, force 3 (full line)
$(0^+ \rightarrow 3^-)$, force 3 (dashed line)
$(0^+ \rightarrow 4^-)+(0^+ \rightarrow 3^-)$, force 3, (dashed-dotted line). In this case the calculated angular distribution normalization is explained in the text.

Fig. 6. Angular distributions measured for the 0.77 MeV, 2^- level in ^{40}Sc. Plotted are the experimental points and two calculated curves involving a 1.4 fm range central force coupled (full time) or not (dotted line) with an OPEP tensor force.

Fig. 7. The effective force strengths V are represented as a function of the transferred spin J. The upper curve is relative to the transitions leading to natural parity states and the lower to unnatural parity states. For ^{48}Ca, the strengths for the natural parity states are taken from Ref. 14 and for the unnatural parity states from Ref. 10. The same force 3 of Table II), including the OPEP tensor term (averaged over the projectile density) has been used in the analysis of both experiments.

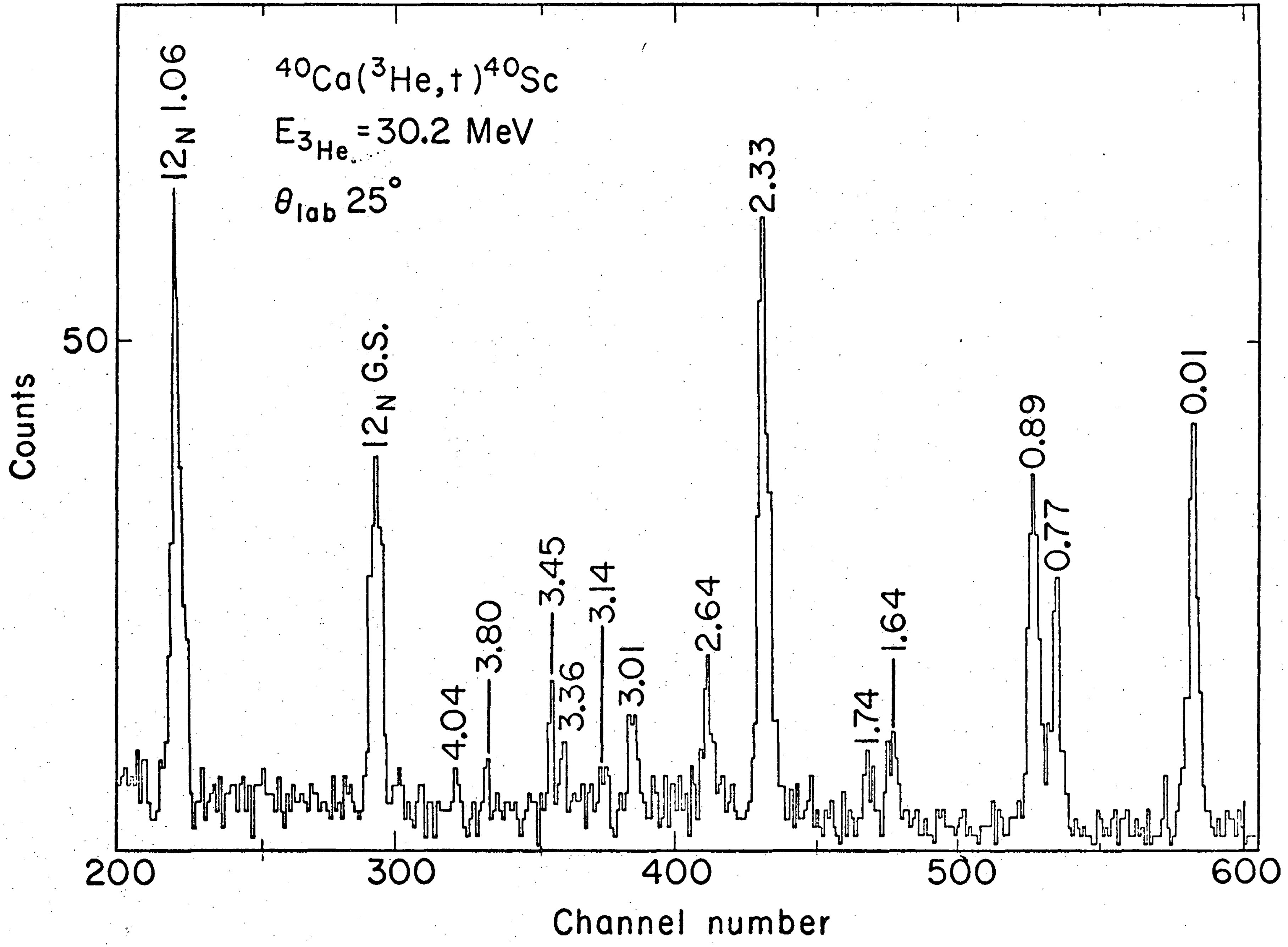

Fig. 1

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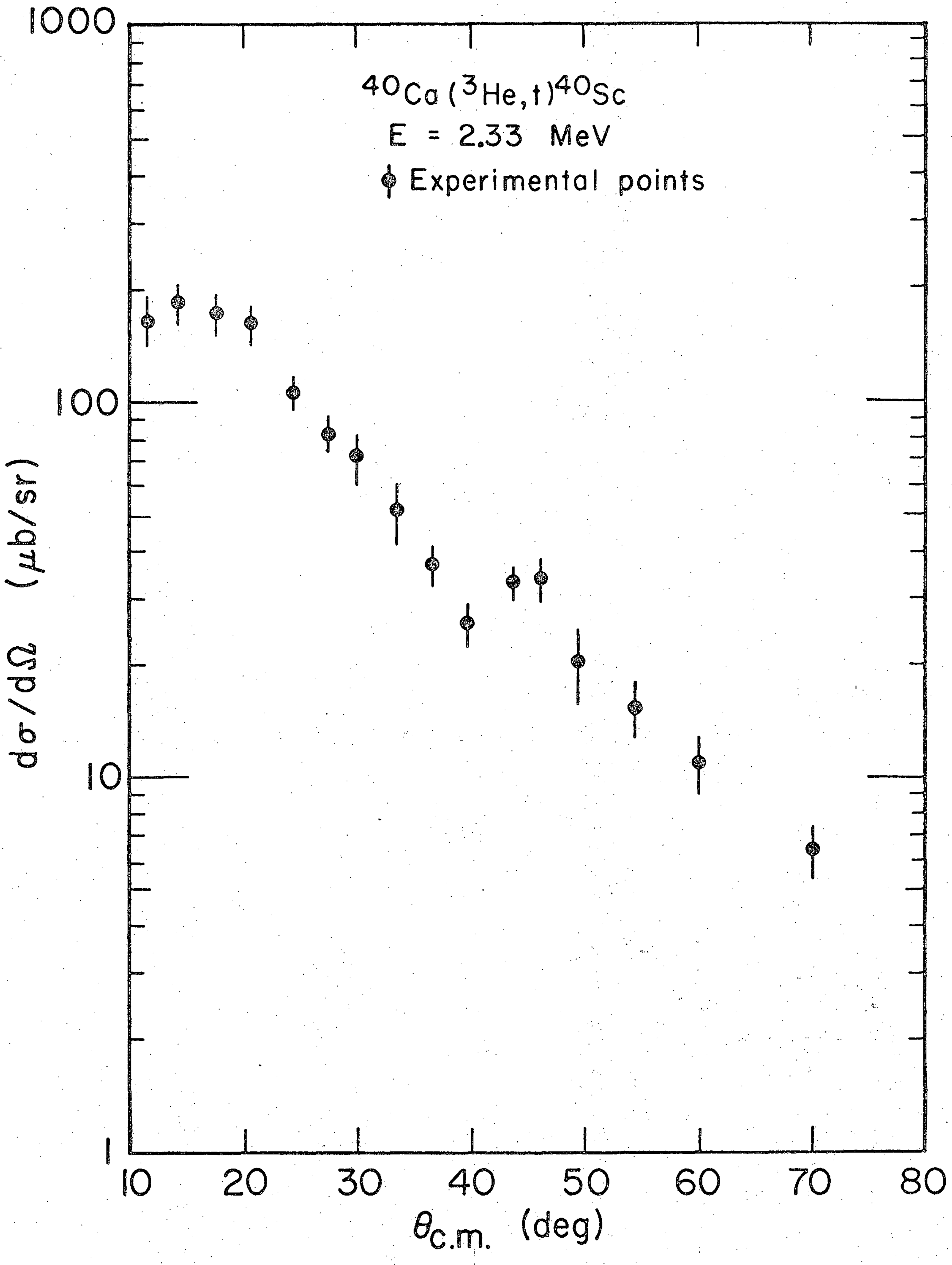

Fig. 2.

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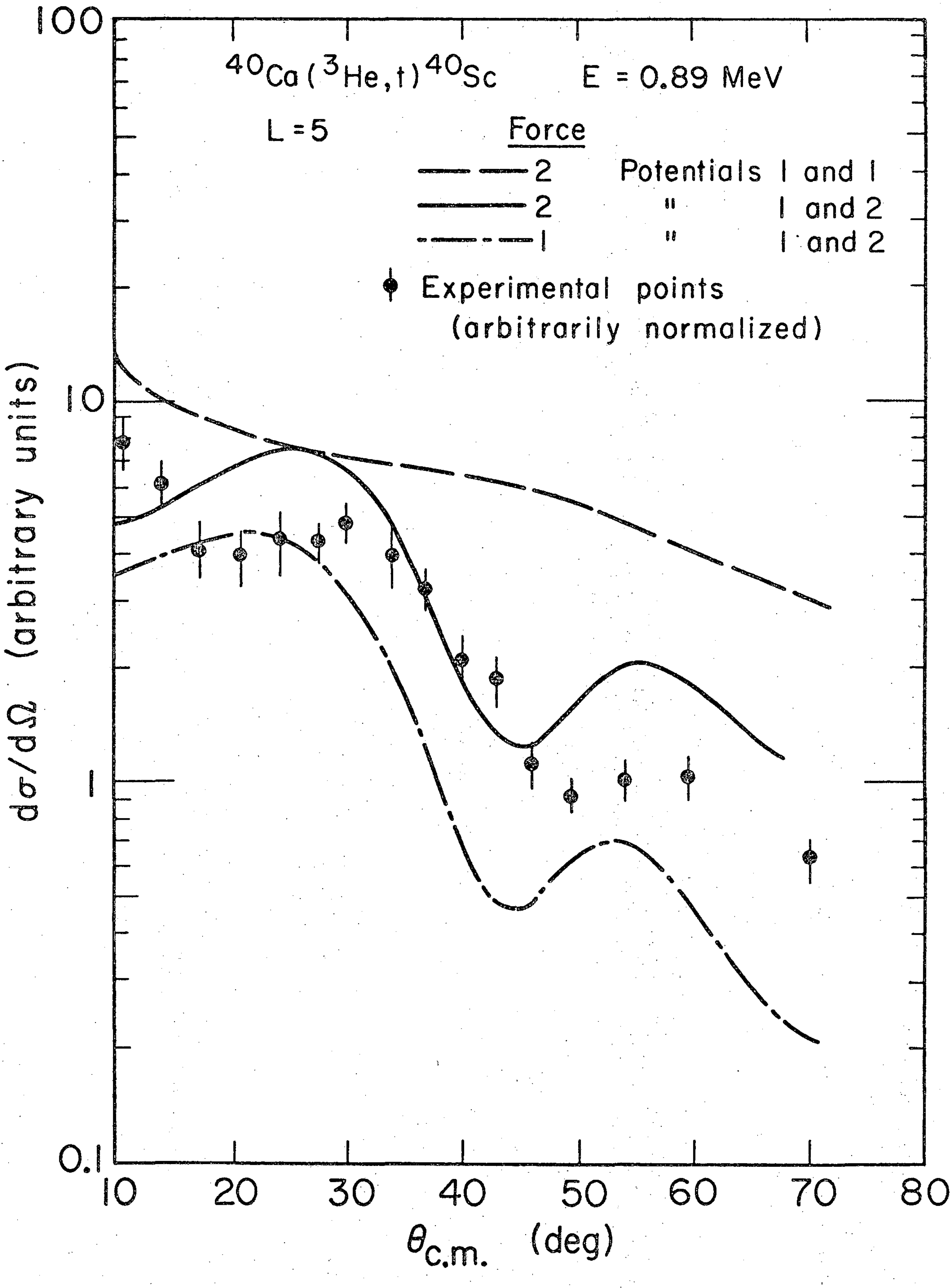

Fig. 3.

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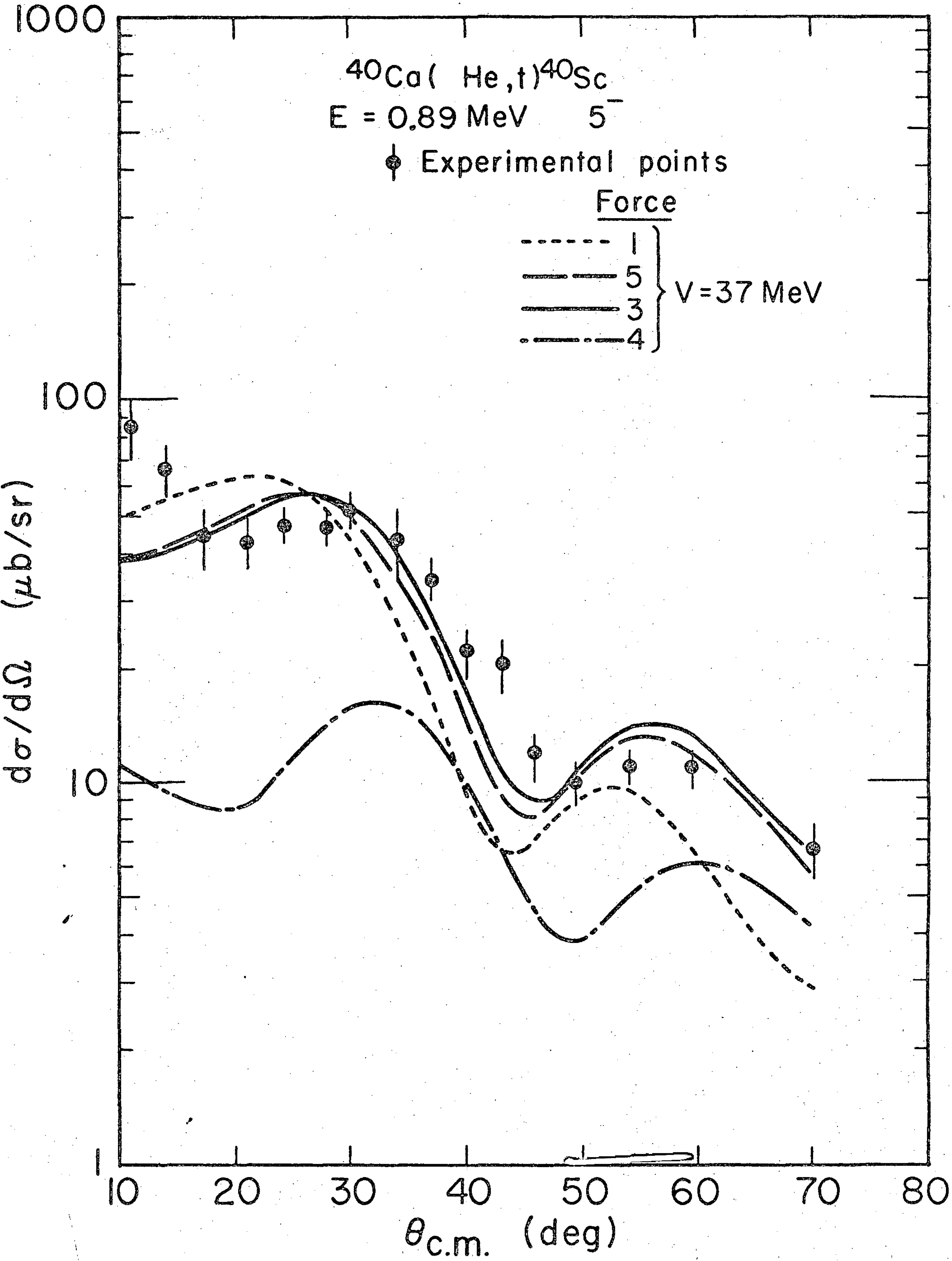

Fig. 4.

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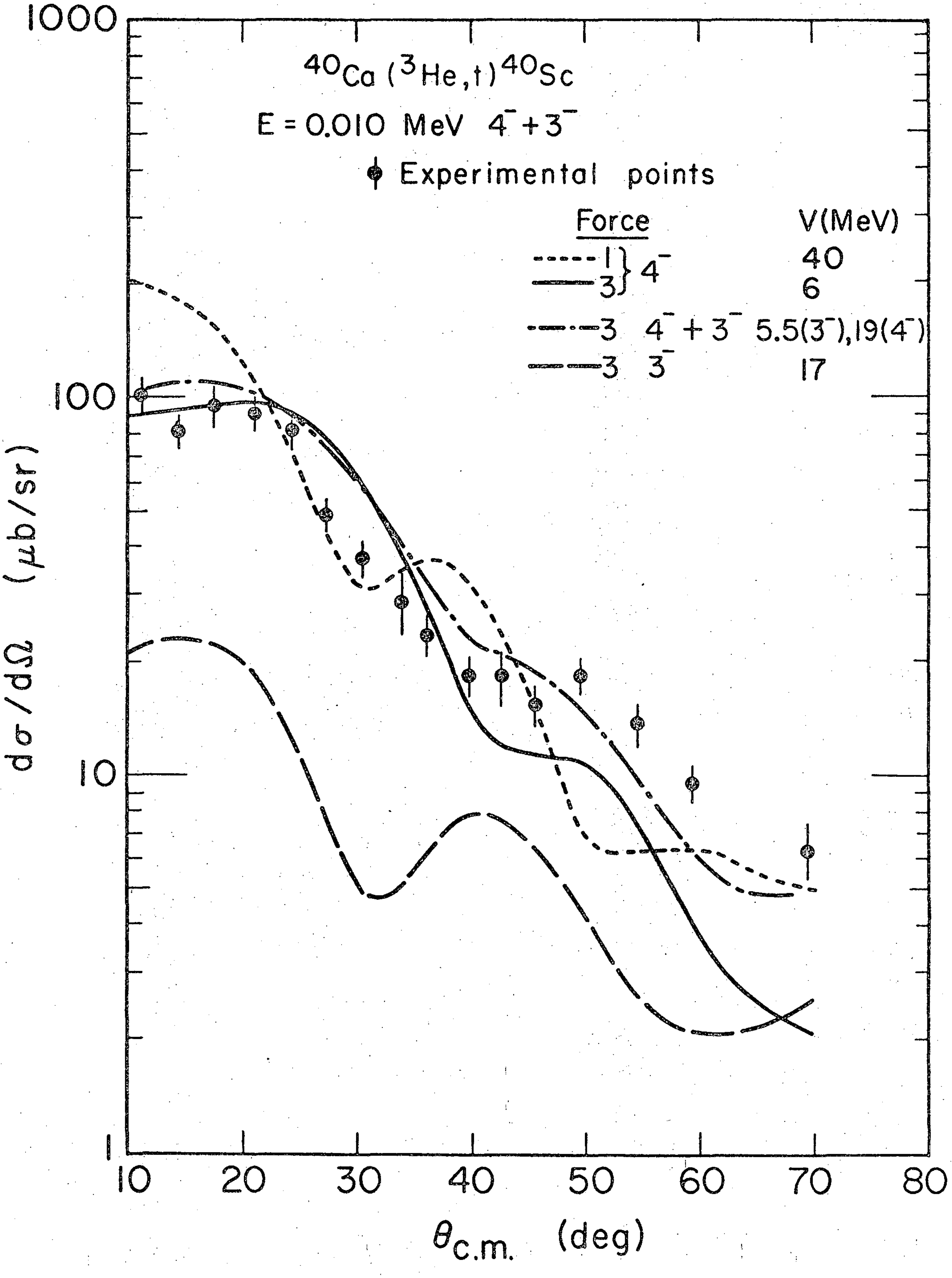

Fig. 5.

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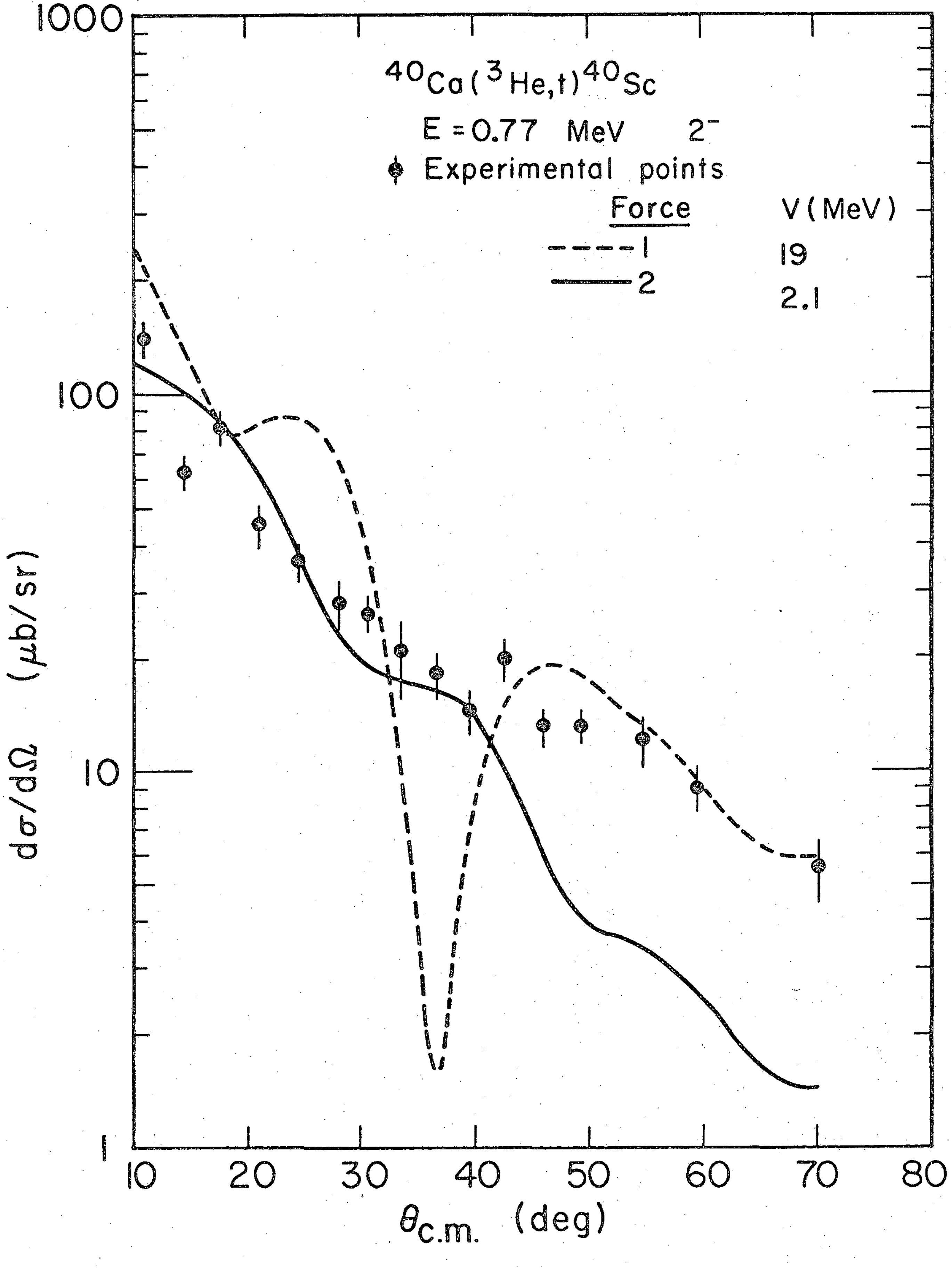

Fig. 6.

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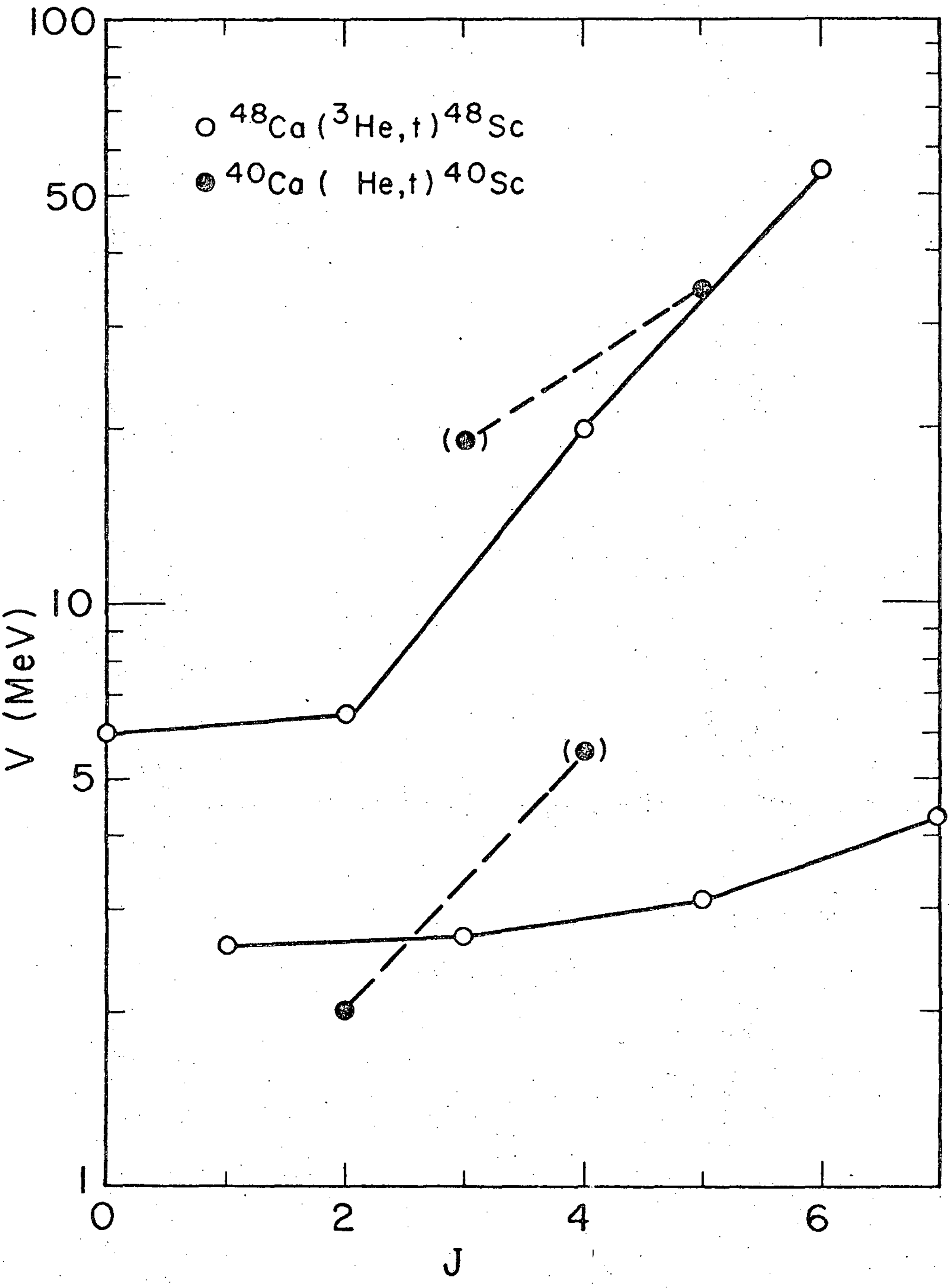

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Fig. 7.

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