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THE $C^{12}(\alpha,d)N^{14}$ REACTION*

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Abstract

The energy spectra of deuterons from the $C^{12}(\alpha,d)N^{14}$ reaction have been studied up to an excitation of 21 MeV. The reaction was induced by 53-MeV alpha particles from the Berkeley 88-inch spiral ridge cyclotron, and the reaction products were distinguished by a new type of particle identifier. The observed selectivity of final state population is correlated with the predicted configurations for many N^{14} levels and several new assignments are made.

1. Introduction

The two-nucleon transfer, (α,d), reaction leading to states of N^{14} is especially interesting for two reasons. A) A detailed investigation may provide the basis for an understanding of the observed selectivity of final state population in α, d (or He^3,p) reactions in general, since extensive theoretical studies of this nucleus, most recently by True[1]) provide the wave functions necessary for cross section predictions. The preceding paper by N. K. Glendenning[2]) delineates and tests this possibility. B) High resolution studies of the $C^{12}(\alpha,d)N^{14}$ reaction, continuing to high excitation (> 15 MeV), can extend our knowledge of the N^{14} levels, particularly exploring states of two excited nucleons around the target "core" that are inaccessible in single-nucleon transfer experiments.

2. Experimental

The $C^{12}(\alpha,d)N^{14}$ reaction was induced by a beam of 53-MeV alpha particles from the Berkeley 88-inch spiral ridge cyclotron. The general beam optical system has been described previously[3]); measurements were made in a 36-inch scattering chamber. In the present experiment no beam collimation was used after the second quadrupole doublet. Removal of the collimator did not affect the resolution but the background decreased.

A block diagram of the counting equipment is presented in Fig. 1. Particles were detected by a counter telescope that consisted of two Li-drifted surface barrier counters: a 14 mil transmission counter backed by a 120 mil stopping counter. To increase the effective counter thickness the counter telescope was rotated 40° with respect to a radial line from the center of the scatter chamber. Deuterons of up to 37.5 MeV could be stopped by this system. The counters were positioned so that the two surface barriers faced each other to lessen the dead layer between the counters, since there was an approximately 3-mil dead layer on the mesa side of the transmission counter.

The reaction products were distinguished by a new type of particle identifier[4] that employs the empirical relationship,

$$\text{Range} = a\ E^{1.73} \ ,$$

where a depends on the type of particle, and E is the incident energy. A typical particle-identifier spectrum is shown in Fig. 2. The asymmetry of the proton peak was caused by high energy protons that were not stopped in the counter telescope. Total-energy pulses were fed into a Nuclear Data pulse-height analyzer which was appropriately gated so that the deuteron and triton spectra were recorded simultaneously, each spectrum in a 1024 channel group. The proton-deuteron valley was also recorded in the analyzer to measure any small but possible loss of deuterons. No loss was observed with the gates set as shown in Fig. 2. The average energy resolution for the deuterons was 170 keV. (Optimum resolution was 145 keV.) The particle identifier output was observed continuously on another pulse-height analyzer. Since no variation of peak or valley position occurred, the gate settings were not changed during the experiment.

The beam intensity, which ranged from 15 to 200 mμ amp depending on the angle of observation, was measured by means of a Faraday cup and integrating electrometer. An additional Li-drifted surface barrier counter, placed at a fixed angle (≈ 20 deg), detected the alpha particles scattered from the target. Measuring the ratio of the inelastic peak heights to the general background was useful in determining the "quality" of the beam.

Thus the effect of changes in the beam optical system could be quickly ascertained. In addition, monitoring the elastic peak provided a continuous check of the target thickness and/or the beam position and angle. Very little variation was observed.

Carbon targets were prepared by diluting a "Dag" solution (colloidal graphite in isopropyl alcohol and acetone) with ethanol and acetone. This solution was poured on a glass mirror and allowed to dry. When the mirror was submerged in water the carbon film would rise to the surface. The film was then collected on cellophane and the water allowed to evaporate. When dry, self-supporting films about 0.3 mg/cm^2 thick and as large as 4 by 4 in. could be peeled from the cellophane. Most of the oxygen impurity was removed by heating the targets to 1400°C in a vacuum for several hours and then allowing them to cool to below 200°C before exposure to air. However, as noted in Figs. 3 and 4 a small oxygen impurity is present. (The 1.1 MeV level of F^{18} made by the $O^{16}(\alpha,d)F^{18}$ reaction is a "giant peak"[5], and therefore even a very small impurity is observable.)

3. Results

Figures 3 and 4 illustrate deuteron energy spectra at laboratory scattering angles of 30 and 60 deg, respectively. The angular range studied covered from 12 to 80 deg (lab), and the observable excitation in N^{14} extended up to 21 MeV at small angles. Lists of the N^{14} levels identified are presented in Tables I and II. Table I also includes the integrated cross sections and dominant shell-model configurations for many of the levels. The absolute cross section values were obtained by normalizing to the earlier (poor resolution) data at 48 MeV taken at the late Crocker Laboratory 60-inch cyclotron[11]. Although such a normalization would not be expected to introduce a significant error, the uncertainty of these absolute values may be as great as ± 30%; however, the uncertainty in the relative cross sections of the different levels is less than 10%. The angular distributions of the deuterons corresponding to formation of the N^{14} ground state, 3.95-, 5.10-, 5.83-, 6.44-, 7.03-, 7.97-, 8.47-, 9.00-, and 9.41-MeV levels are shown in Figs. 5 through 9.

4. Discussion

Transitions involving high energy incident and outgoing particles are expected to go predominately by a direct reaction mechanism. The $C^{12}(\alpha,d)N^{14}$ reaction should preferentially populate those N^{14} levels whose configurations are an unchanged C^{12} core coupled to a neutron-proton pair since direct-stripping transitions involving excitation of the core are relatively unlikely[12]. Further selectivity of the (α,d) reaction arises from the fact that the wave function of the neutron-proton pair in the captured state must have a high degree of overlap with the wave function of that neutron-proton pair in the α particle[2].

Extensive theoretical studies of the N^{14} nucleus have been made. For example, Warburton and Pinkston[7], by a careful analysis of experimental data, have given shell-model assignments for most of the levels in N^{14} up to 10.50 MeV. True[1] has arrived at very similar results from a conventional two-particle shell-model calculation of the energies of the various possible configurations, assuming that C^{12} was an inert core with a $(1s_{1/2})^4\,(1p_{3/2})^8$ configuration.

Noting Table I, in general our results are in excellent agreement with the shell-model assignments. The 3.95- and 7.03-MeV hole states, which cannot be formed by the addition of two nucleons to C^{12} in a $(s_{1/2})^4 (p_{3/2})^8$ configuration, are formed with relatively small cross sections. These levels could, however, be formed through the $(p_{3/2})^6 (p_{1/2})^2$ minor component of the C^{12} ground state[13]. The only level that was not populated approximately to the extent expected was the $(p_{1/2}\, d_{3/2})_{2-}$, T = 0 state at 7.97 MeV; in addition the unassigned level at 8.47 MeV was highly populated. It has been speculated that this $p_{1/2}\, d_{3/2}$ configuration possibly should be assigned to the 8.47-MeV level[14]. However, a more tenable assignment of the 8.47-MeV level which is also in agreement with its large population can be made. If C^{13} is pictured as a $p_{1/2}$ neutron moving around a C^{12} core, the resonance states in the $C^{13}(p,\gamma)N^{14}$ and $C^{13}(p,p)C^{13}$ reactions that should be observed are those having some $p_{1/2}$ component. Only two of the established states between 7.97 and 10.42-MeV excitation have not been observed in the resonance experiments: the states at 8.47 and 9.00 MeV[6]. (Midget resonances for these two levels were recently found[15]). In this region of excitation only two of True's configurations have no $p_{1/2}$ component: the $(d_{5/2})^2_{5+}$, T = 0 state predicted to lie at 9.32 MeV and associated with the level at 9.00 MeV; and the $(s_{1/2}\, d_{5/2})_{2+}$, T=0 state predicted to lie at 9.45 MeV and associated with the level at 10.09 MeV[1]. However, the latter assignment is incorrect if the spin of the 10.09-MeV level is 1+ as Kashy, et al.[10] report. Furthermore a resonance corresponding to this level was clearly observed in the $C^{13}(p,p)C^{13}$ reaction[10]. Thus the $(s_{1/2}\, d_{5/2})_{2+}$, T = 0 configuration probably should be associated with the 8.47-MeV level. Determination of the parity of this state would be most valuable in clarifying the assignment. Glendenning's relative cross section predictions for the (α,d) transitions agree qualitatively with the suggested assignment.

At no angle was a deuteron group observed that corresponded to formation of the 0+, T = 1 level at 2.31 MeV. This transition is forbidden on the basis of angular momentum and parity conservation in addition to isospin conservation[11]. None of the known T = 1 levels that could be experimentally observed were populated above the general background. However, several of the T = 1 levels lie so close to T = 0 levels that any population would have been obscured. The failure to populate many of the levels whose isospin is unknown cannot necessarily be considered strong evidence for a T = 1 assignment since the (α,d) transition probability to states involving extreme core excitation is also very small[12].

Observation of the 8.47-, 9.41-, and 9.71-MeV states indicates that these levels have T = 0. Further evidence for the T = 0 nature of these levels comes from a recent study of the $O^{16}(d,\alpha)N^{14}$ reaction in which these levels were populated relatively strongly[14]. A previously unreported level at 10.71 ± 0.10 MeV was populated fairly strongly and thus should be assigned T = 0. The possibility that the peak associated with 10.71 MeV excitation actually corresponds to the unobserved level at 10.55 MeV is not considered likely. Such a discrepancy would correspond to a consistent error of about four channels in the energy calibration.

As previously noted[5], the peak at 9.0 MeV excitation dominates the energy spectra. In the earlier $C^{12}(\alpha,d)N^{14}$ investigation[11] this peak was associated with the 1+ level at 8.99 MeV and because of the large population it was suggested that this was a T = 0 level. This peak is now associated with the $(d_{5/2})^2_{5+,\ T=0}$ level that is calculated to lie at about 9.32 MeV[1] since such a configuration will be preferentially populated[16] and the statistical factor 2J + 1 favors the formation of a high spin state. Obviously no information concerning the nature of the 8.99-MeV level can be obtained since it is completely obscured by the giant peak. A comparison of the angular distributions demonstrates that the transition to the 9.00-MeV level has a distinctive shape. Further, the angular distributions of very highly populated states observed in other (α,d) reactions exhibit a similar, non-oscillatory, shape. A complete discussion of these giant levels and their spectroscopic configuration is available elsewhere (Ref. 5 and 17).

The other angular distributions presented are oscillatory and fairly similar in appearance with no apparent characteristics that would enable one to distinguish one type of level from another.

Above 11 MeV excitation (Table II) a number of levels are populated fairly strongly. In this region deuterons could be produced via the break-up of $N^{14} \rightarrow C^{12} + d$(Q = 10.272 MeV) but the general background was not appreciably higher. Any increase in the "background" could probably be accounted for by the higher level density. When considering levels in this region of excitation $f_{7/2}$ states should be included. Though True's published results[1] do not include such states, a recent representative calculation including them has been made available to us.[18]

The large, broad peak centered at 12.76 ± 0.10 MeV probably corresponds to the same level (or levels since the peak appears to be a doublet or triplet) that Sachs, et al.[19] identified at 13 MeV from an investigation of the $C^{12}(B^{11},Be^{9})N^{14}$ reaction ($E_{B}11 = 115$ MeV). However, their tentative assignment, $(d_{5/2})^2_{4+}, T = 1$, appears doubtful since the (α,d) reaction also populates this level. Nagatani and Bromley[20] have also observed a strong population to a state at 13 MeV in the $C^{12}(\alpha,d)N^{14}$

reaction (E_α = 42 MeV). A more likely assignment is a 4+, T = 0 state of strongly mixed $(d_{3/2}\, d_{5/2})$ and $(p_{1/2}\, f_{7/2})$ configurations, which is calculated to fall in this region. These configurations both possess large ^3G components which should enhance the transition probability. (See the preceding paper for a further discussion of this state.)

Another large peak arises at 15.1 ± 0.10 MeV. The only T = 0 high spin configuration in this excitation region that has not been correlated with a specific level is the $(d_{5/2}\, f_{7/2})_{6-}, T = 0$ configuration which is calculated to lie at about 15 MeV.[18] This configuration is pure ^3H which should also enhance the transition probability.

We are indebted to Norman K. Glendenning and William W. True for many valuable discussions. We also wish to thank Fred Goulding and Don Landis for invaluable assistance with the electronics.

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[*] This work was done under the auspices of the U. S. Atomic Energy Commission.

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16. The $(d_{5/2})^2_{5+}$ configuration is strongly favored by the kinematics of the reaction. For 53 MeV incident alpha particles, the angular momentum transferred in a surface interaction is about 4 to 6 $\hbar$ when the deuteron escapes at 0 degrees. Consequently transitions to levels formed by capturing both of the stripped nucleons into shells having orbital angular momentum values of 2 or 3 $\hbar$ should be enhanced. Formation of a $(d_{5/2})^2$ level requires that ℓ_n and ℓ_p both be equal to 2 $\hbar$. A value of 4 $\hbar$ for the sum of ℓ_n and ℓ_p permits the maximum overlap between the radial wave functions of the two nucleons so that their final state is as similar as possible to their initial state. Ignoring spin—flipping interactions, the captured nucleons will retain their initial triplet configuration. Thus states with a strong ^3G amplitude will be favored at small angles. Likewise states whose configurations have large ^3H and ^3I amplitudes should also be preferentially populated. That this is a necessary—but not always a sufficient—requirement to guarantee preferential population, is demonstrated in the preceding paper.[2]

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Table I.

Comparison of the N^{14} levels observed at excitations less than 11 MeV with those previously reported.[a] Shell-model configurations and integrated cross sections are also included.

Levels identified (MeV)	Cross section (mb)	Previously reported levels			Dominant configuration[b]
		energy (MeV)	J^{π}	T	
0	0.98	0	1+	0	$(p_{1/2})^2$
		2.31	0+	1	$(p_{1/2})^2$
3.95	0.31	3.945	1+	0	$(p_{3/2})^{-1}$ $(p_{1/2})^{-1}$
4.91	1.58[c]	4.91[d]	(0)-	0	$p_{1/2}$ $s_{1/2}$
5.10		5.10[d]	2-	0	$p_{1/2}$ $d_{5/2}$
5.69	1.64[c]	5.69[d]	1-	0	$p_{1/2}$ $s_{1/2}$
5.83		5.83[d]	3-	0	$p_{1/2}$ $d_{5/2}$
		6.05			?
6.21	1.69[c]	6.21	1+	0	$(s_{1/2})2$
6.44		6.44[e]	3+	0	$s_{1/2}$ $d_{5/2}$
		6.70			?
7.03	0.32	7.03[d]	2+	0	$(p_{3/2})^{-1}$ $(p_{1/2})$-1
		7.40			?
		7.60			?
7.97	0.31	7.97	2-	0	$p_{1/2}$ $d_{3/2}$
		8.06	1-	1	$p_{1/2}$ $s_{1/2}$
8.47	1.08	8.47		(0)[h]	?
		8.63	0+	1	$(s_{1/2})^2$
		8.71	0-	1	$p_{1/2}$ $s_{1/2}$
		8.91	3-	1	$p_{1/2}$ $d_{5/2}$
		8.99	1+	(0)[i]	?
9.00	5.67	9.00[f]	5+	0	$(d_{5/2})^2$
		9.17	2+	1	$(s,d)+(p_{3/2})^{-1}(p_{1/2})^{-1}$

Table I
Continued

Levels identified (MeV)	Cross section (mb)	Previously reported levels			Dominant configuration[b]
		energy (MeV)	J^{π}	T	
9.41	0.81	9.41	1-	h	$p_{1/2}\ d_{3/2}$ (?)
		9.51	2-	1	$p_{1/2}\ d_{5/2}$
9.71	0.37	9.71	1+	h	$(d_{5/2})^2$
10.02	0.49	10.09	(1+)	0	$s_{1/2}\ d_{5/2}$[g]
		10.22	1-		?
		10.43	2+	1	$s_{1/2}\ d_{5/2}$
10.55		10.55	1-		
10.71	0.97			h	

[a] Reference 6.

[b] References 1, 7, 8.

[c] Members of the doublet were not resolved but careful analysis of peak position and shape strongly indicates that the transition proceeds primarily to the higher spin component.

[d] The parity assignments for these levels were taken from reference 5.

[e] The parity assignment for this level was taken from reference 9.

[f] Reference 5.

[g] The assigned configuration is wrong if the spin of this level is 1+ as recently reported, instead of 2+ as previously thought (ref. 10).

[h] The observation of this level indicates (confirms) a T = 0 assignment.

[i] The previous suggestion (ref. 11) of a T = 0 assignment to this level should be disregarded.

Table II.
Comparison of the N^{14} levels observed at excitations greater than 11 MeV with those previously reported[a]

Levels identified (MeV)	Previously reported levels			Intensity[b]
	Energy (MeV)	J^{π}	T	
11.06 (?)	11.06	1+	0	Very weak
	11.23	3-	1	
11.40	11.29	2-	0	Very small, broad peak arises at this excitation
	11.39	(1+)	0	
	11.51	3+		
	11.66			
11.75 (?)	11.74	1+		Very weak
	11.80	(2+)		
	11.97	(2-)		
	12.05			
12.30	12.21	3-		Weak
	12.29			
	12.41	4-		
	12.52			
12.76	12.61	3+		Large (2.74 mb), broad peak arises at this excitation
	12.69	3-		
	12.80	4+		
	12.83	4-		
	12.95	(4+)		
	13.17	0-		
	13.23			
	13.30			
13.45 (?)				Very weak
	13.72	3		
	14.22			

Table II.
(Continued)

Levels identified (MeV)	Previously reported levels Energy (MeV)	J^π	T	Intensity[b]
14.7	14.4 14.84 14.91			Small, broad peak
15.1	15.00			Large, sharp peak
15.5	15.5			Weak
16.0				Weak
16.3				Medium
17.1				Medium
17.7				Medium

[a] Reference 6.

[b] Level classified weak corresponds roughly to a cross section slightly less than the cross section to the 3.95-, 7.03-, and 7.97-MeV levels, whereas medium indicates an equal or slightly larger cross section.

Figure Captions

Figure 1. Block diagram of counting equipment for recording energy spectra.

Figure 2. Particle identifier spectrum at a scattering angle of 15 deg (lab) from bombardment of C^{12} with 53-MeV alpha particles. The discriminator settings are represented by lines 1, 2, and 3.

Figure 3. Deuteron energy spectrum from the $C^{12}(\alpha,d)N^{14}$ reaction.

Figure 4. Deuteron energy spectrum from the $C^{12}(\alpha,d)N^{14}$ reaction.

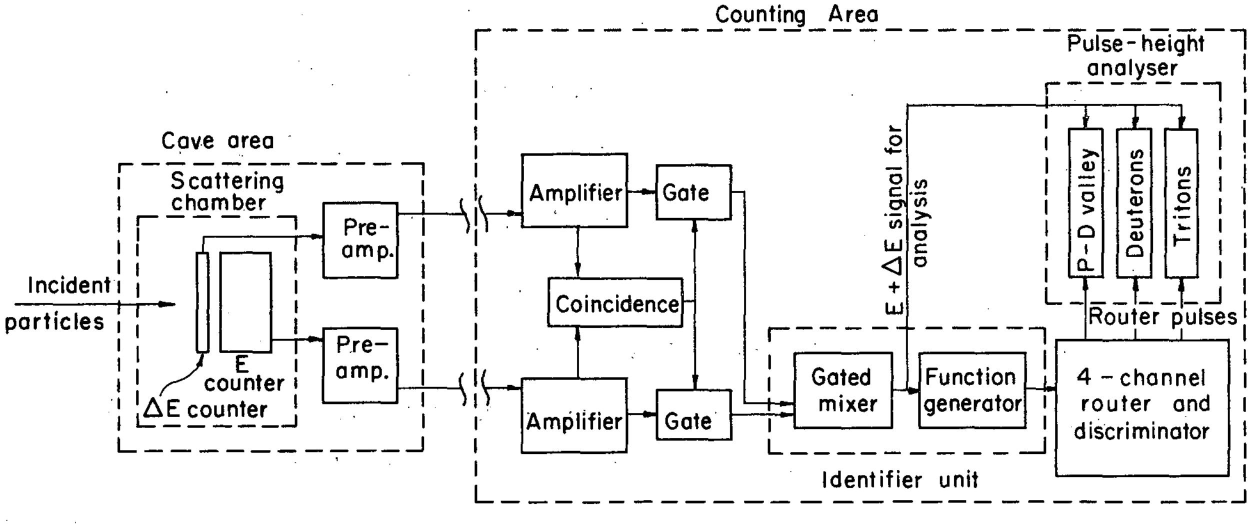
Figure 5. Angular distributions of deuterons from formation of the ground state and 6.44-MeV levels of N^{14}. The latter includes a small contribution from the 6.23-MeV level.

Figure 6. Angular distributions of deuterons from formation of the 5.10- and 5.83-MeV levels of N^{14}. Small contributions from the 4.91- and 5.69-MeV levels, respectively, are included.

Figure 7. Angular distributions of deuterons from formation of the 3.95- and 7.03-MeV levels of N^{14}.

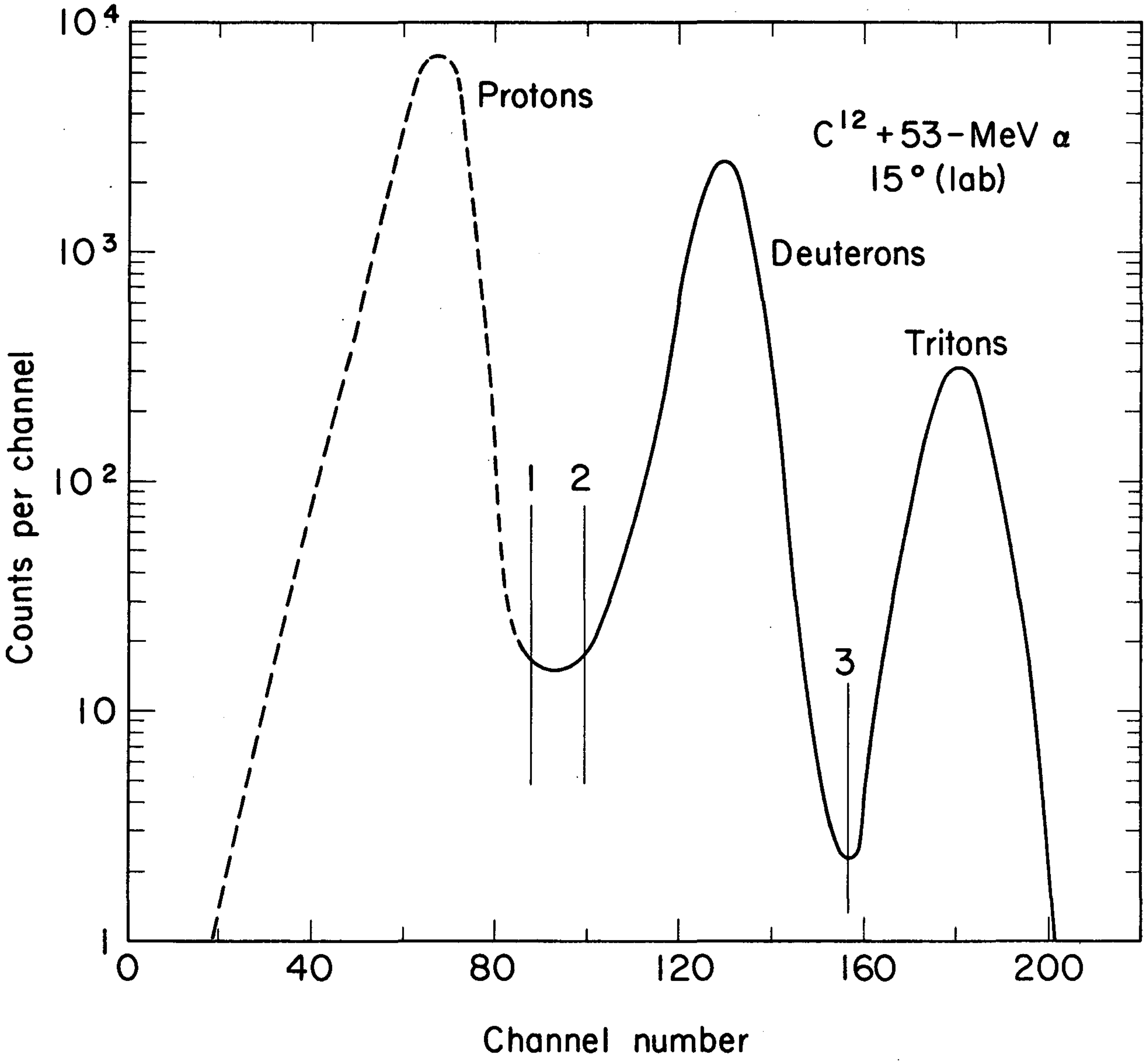
Figure 8. Angular distributions of deuterons from formation of the 7.97-, 8.47-, and 9.41-MeV levels of N^{14}.

Figure 9. Angular distribution of deuterons from formation of the 9.00-MeV level of N^{14}.



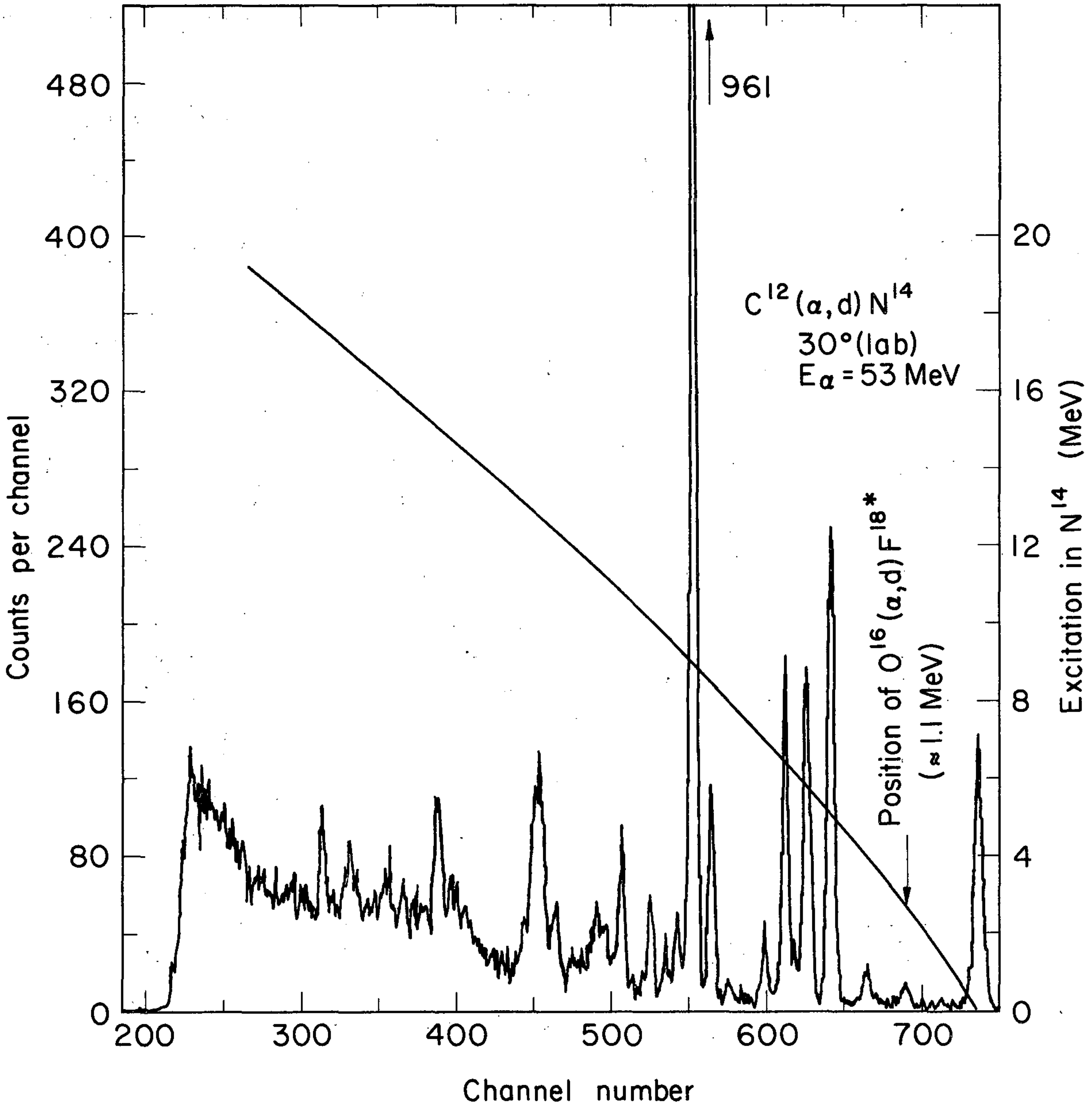
MUB-3251

Fig. 1



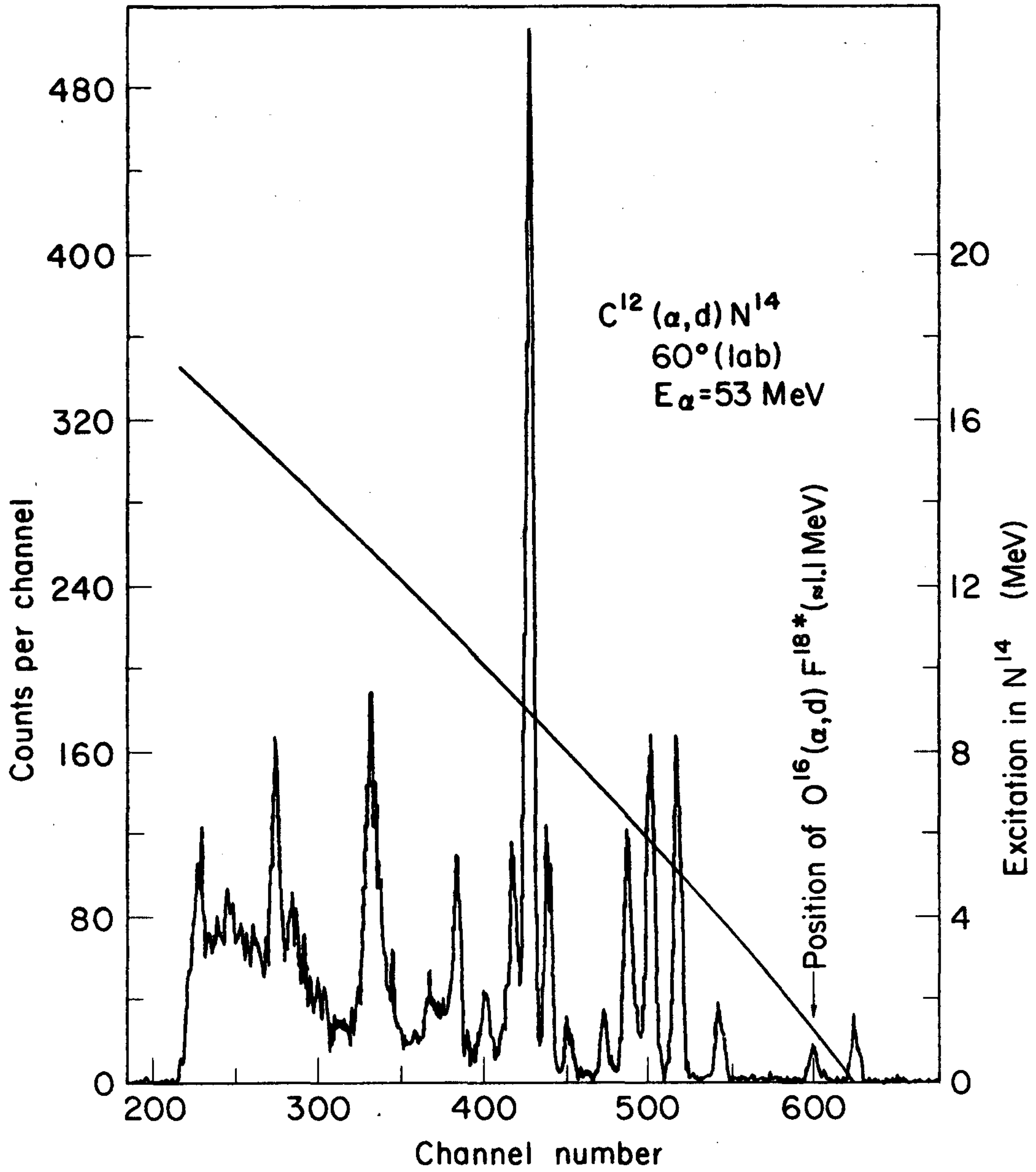
MUB-3252

Fig. 2



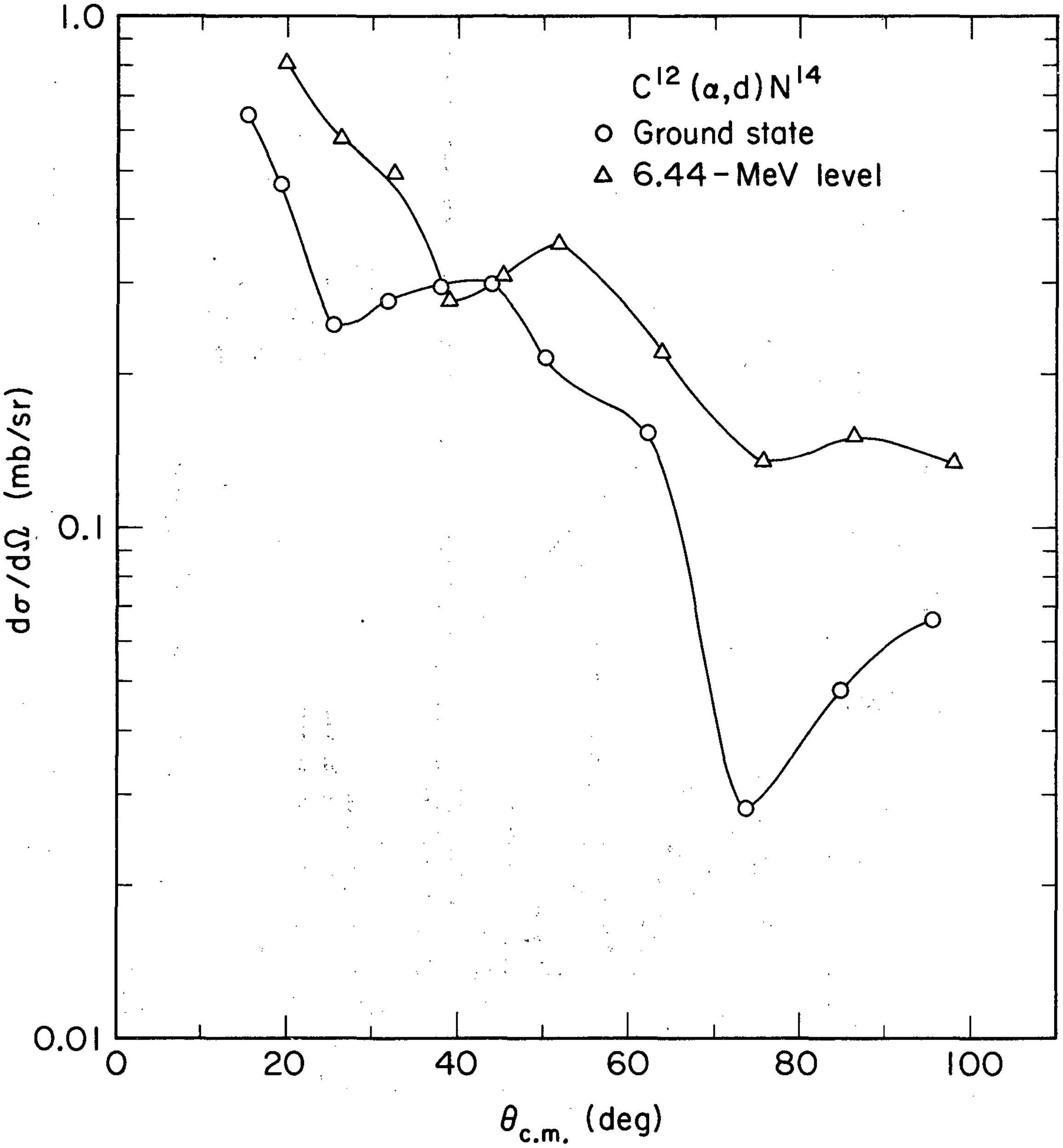
MUB-3253

Fig. 3



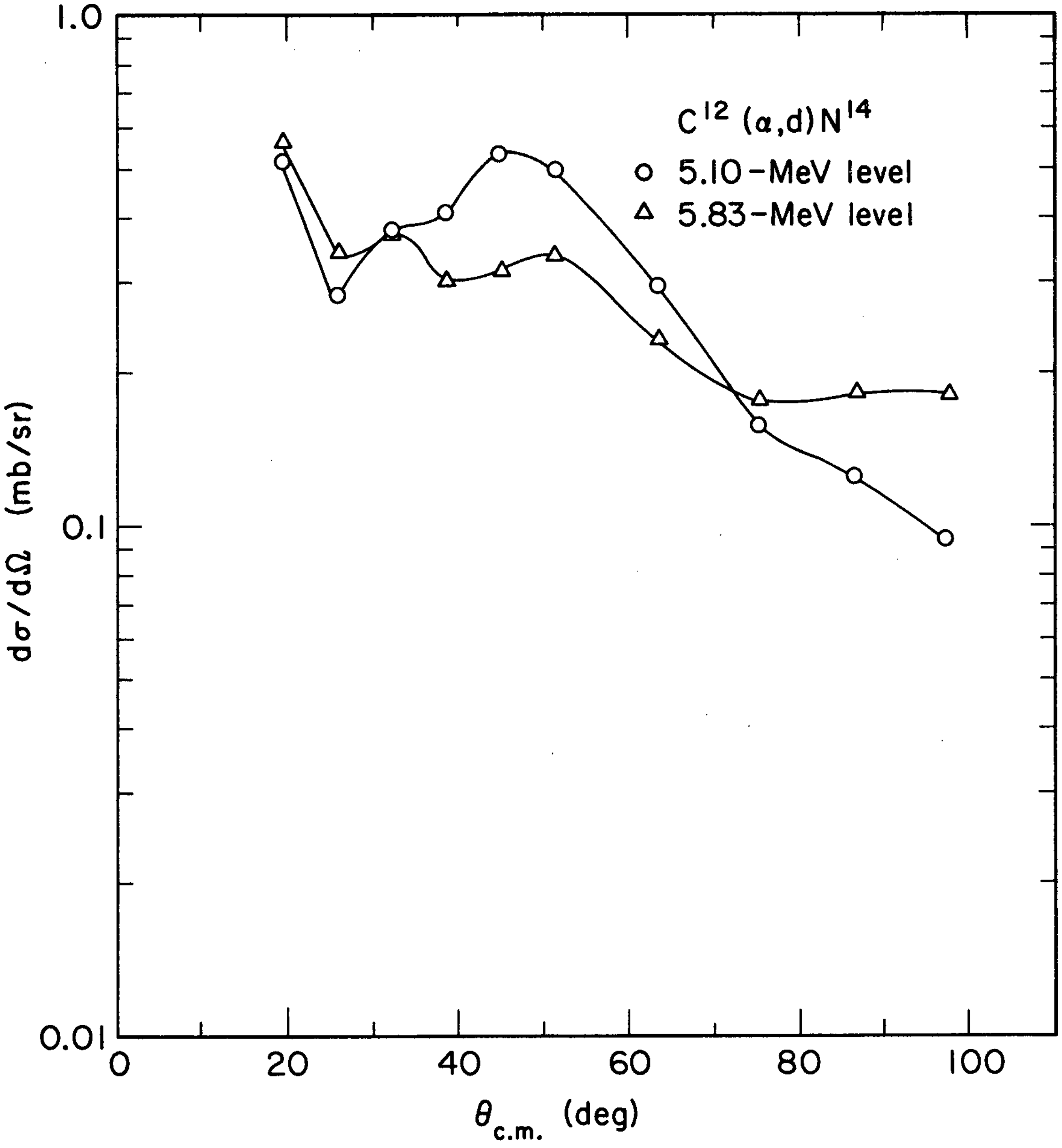
MUB-3254

Fig. 4



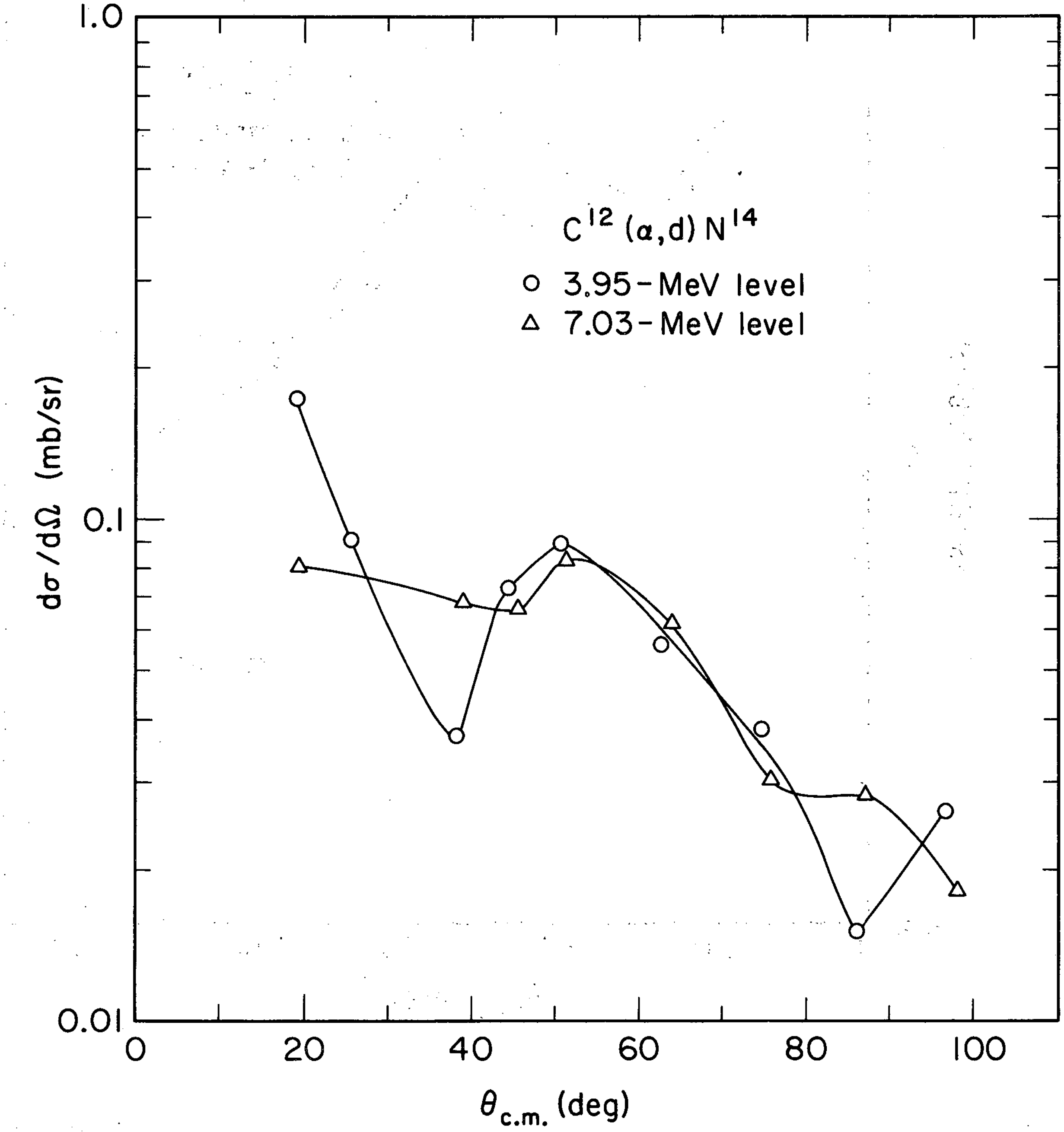
MUB-3248

Fig. 5



MUB-3249

Fig. 6



MUB-3247

Fig. 7

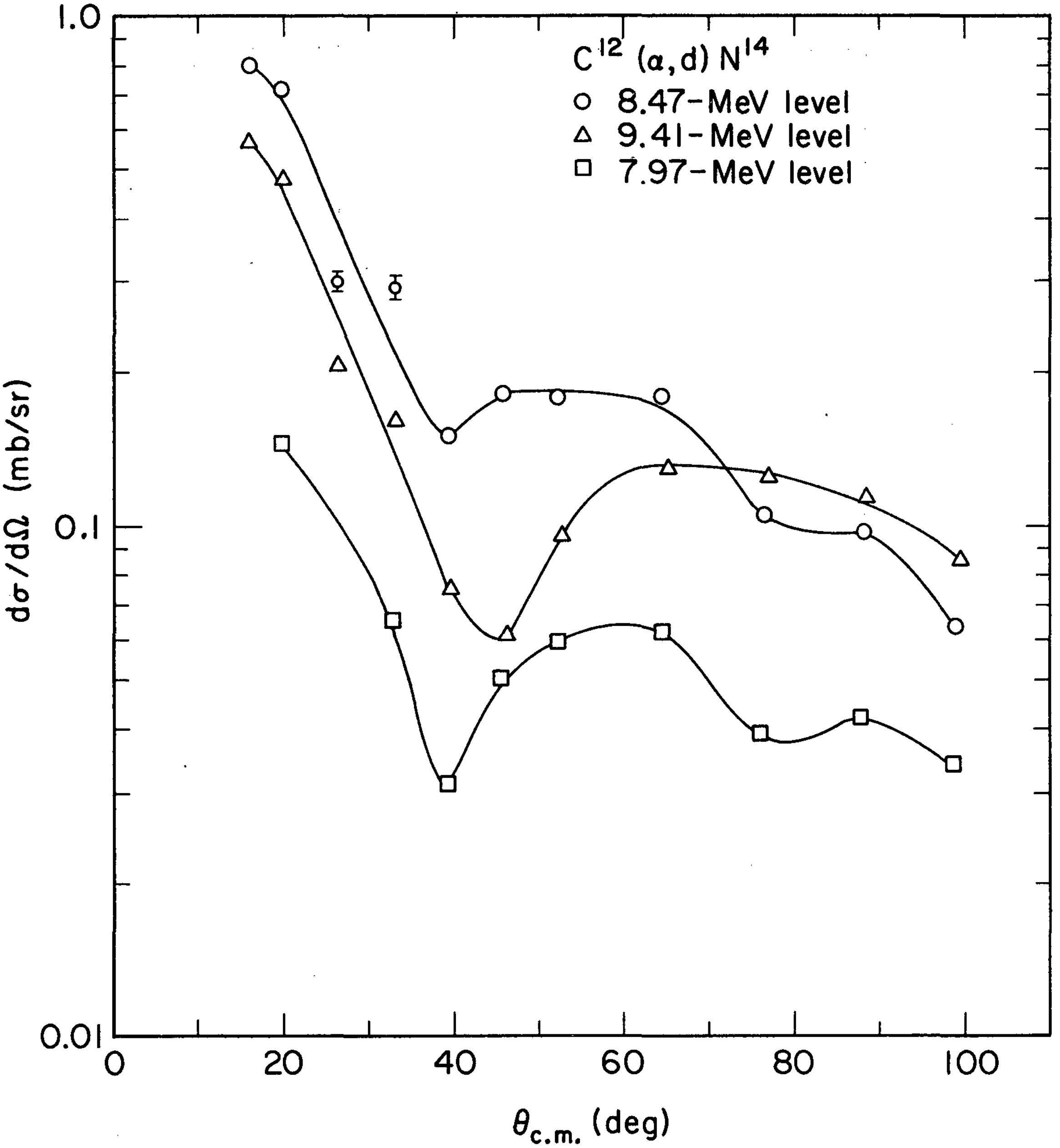


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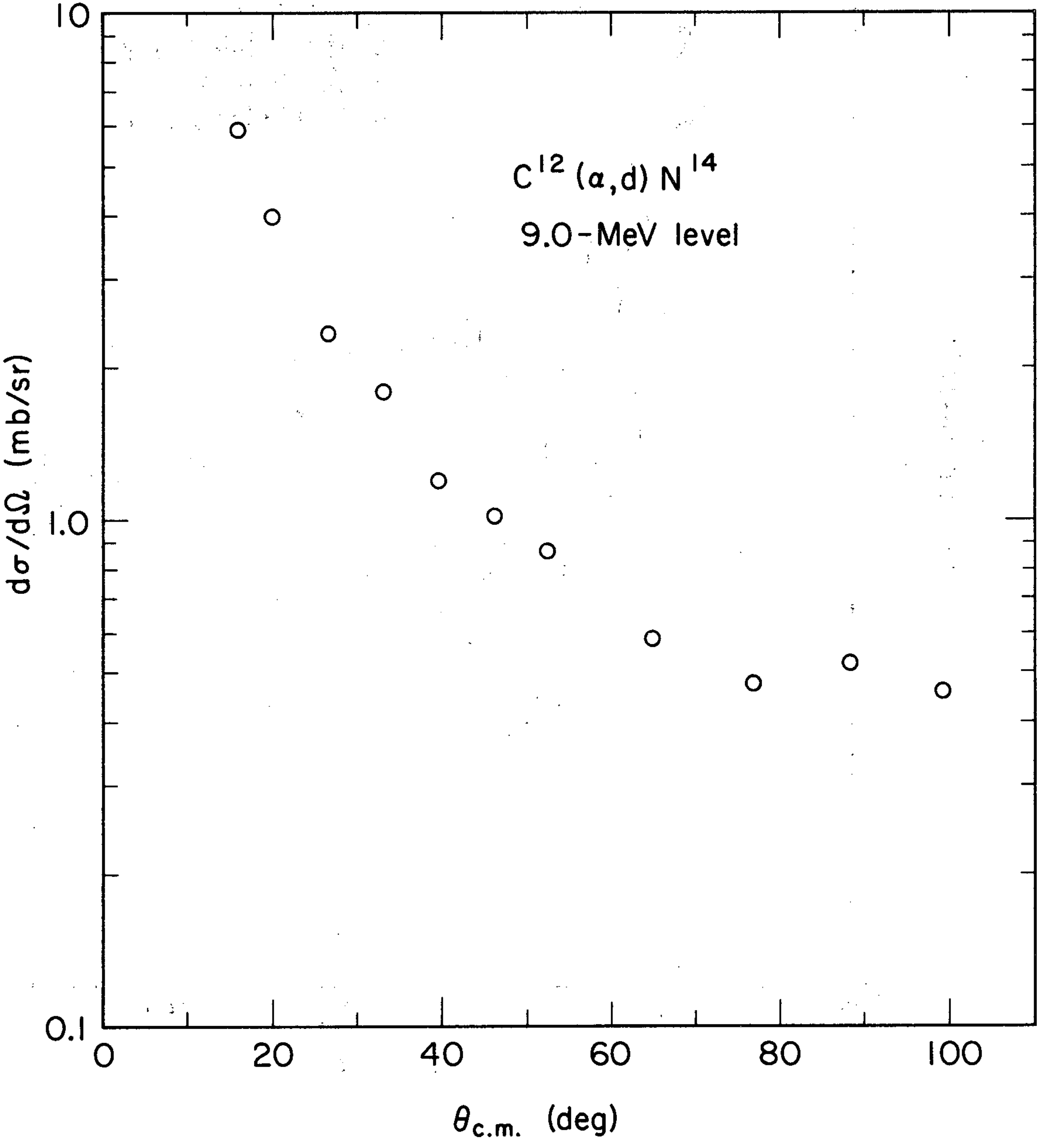
Fig. 8



MUB-3250

Fig. 9