Energy-averaged angular distributions for $^{16}O + ^{12}C \rightarrow \alpha + ^{24}Mg$

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Energy-averaged angular distributions have been measured for the reaction $^{16}O + ^{12}C \rightarrow \alpha + ^{24}Mg$, covering the c.m. bombarding-energy range 12.86–14.53 MeV in 40 equal steps. Angular distributions are approximately symmetric about 90° and are qualitatively reproduced by Hauser-Feshbach calculations.

[NUCLEAR REACTIONS $^{16}O(^{12}C, \alpha)$, $E=22.5$–25.5 MeV; $^{12}C(^{16}O, \alpha)$, $E=30$–34 MeV. Measured $\sigma(E_\alpha, \theta)$. Energy-averaged angular distributions. Hauser-Feshbach calculations.]

I. INTRODUCTION

In studies[1-3] of the $^{12}C(^{12}C, \alpha)^{20}Ne$ reaction, for a wide range of bombarding energies, the reaction mechanism is found to be dominantly compound for most final states, but members of the core-excited 0^+ rotational band (with bandhead at 7.20 MeV) are selectively populated—suggesting that they are excited partially by a direct eight-nucleon transfer mechanism. There should exist in ^{24}Mg a similar set of core excited states, of the configuration $(sd)^{12}(1p)^{-4}$. These twelve-particle-four-hole (12p-4h) states might be selectively excited in a reaction that adds twelve nucleons to a ^{12}C target, but should not be populated in a reaction that adds eight nucleons to an ^{16}O target. We have searched for these states by studying the reaction $^{16}O + ^{12}C \rightarrow \alpha + ^{24}Mg$. On average, this reaction is known[4,10] to be mostly compound, but it might be that the special 12p-4h states (if they exist) possess a measurable direct component. The signature of such states would be selective population at forward angles in the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$, but not at backward angles in the same reaction. This assumes that such twelve-nucleon transfer, if it exists, has forward-peaked angular distributions.

II. EXPERIMENTAL PROCEDURE

We have measured complete angular distributions for the reaction $^{12}C + ^{16}O \rightarrow \alpha + ^{24}Mg$ by using both combinations of target and projectile. We present all the angular distribution data in the frame of the $^{16}O(^{12}C, \alpha)$ reaction. The signature of direct population of 12p-4h states would then be *backward peaked* angular distributions in this frame.

The reaction was performed with ^{16}O and ^{12}C beams from the University of Pennsylvania tandem accelerator. Targets were enriched foils of ^{12}C, and ^{16}O gas contained in a gas cell with no entrance window. Outgoing α particles were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Data were obtained in angular steps of 7.5°, beginning at 7.5°.

Because the cross sections for $^{16}O + ^{12}C \rightarrow \alpha + ^{24}Mg$ are known[4] to fluctuate greatly with bombarding energy, it is necessary to obtain energy-averaged angular distributions. We have done this by changing the spectrograph field when we changed the beam energy, thereby collecting energy-averaged spectra. It is possible to do this and still maintain good resolution for a span of about 5 MeV in excitation. The experiment consisted of four separate exposures. In the first, data for the $^{12}C(^{16}O, \alpha)$ reaction were collected over the laboratory energy range 30.0 to 31.9 MeV in 100-keV steps. In the second, data for the same reaction were collected for $E(^{16}O) = 32.0$ to 33.9 MeV, again in 100/keV steps. Then the $^{16}O(^{12}C, \alpha)$ reaction was studied for $E(^{12}C) = 22.5$ to 23.925 MeV and from $E(^{12}C) = 24.0$ to 25.425 MeV, both in 75-keV steps. Thus, the c.m. bombarding energy was the same in both reactions, and each set of data contained an average of forty different bombarding energies 42.9 keV apart in the range 12.86 to 14.53 MeV. Spectra for runs 1 and 3, covering half the energy range, are compared in Fig. 1. These cover the states in the excitation energy range 5.22 to 10.06 MeV, inclusive. Excitation energies, spins, and parities for these states[5] are listed in Table I. In this limited range of data, there is selective population of certain states, notably the 0^+ state at 6.44 MeV, which is much stronger in the $^{12}C(^{16}O, \alpha)$ reaction than in

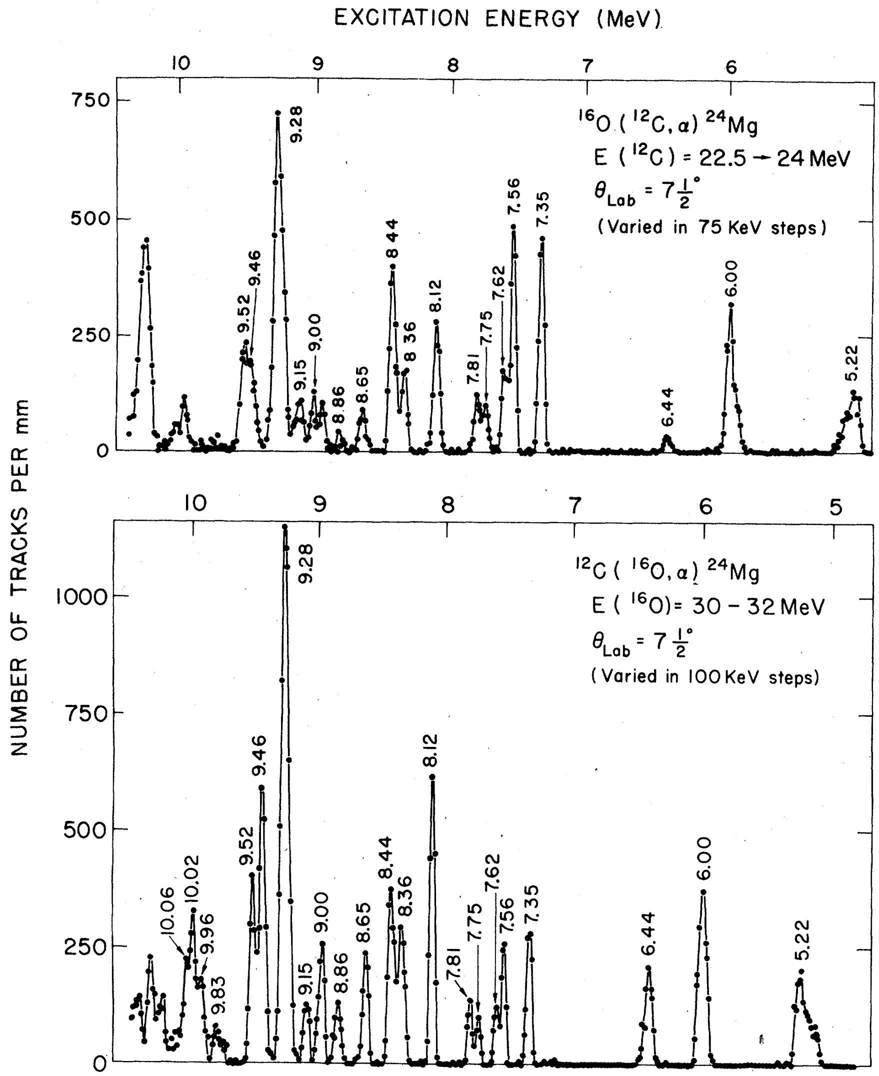

FIG. 1. Energy-averaged spectra for the reactions ^{16}O(^{12}C:α) (top) and ^{12}C(^{16}O, α) (bottom), both at a laboratory angle of 7.5°. In the center of mass, the step size and energy range covered are the same for both spectra.

^{16}O(^{12}C, α).

However, for the other half of the bombarding-energy region, the selectivity is opposite, so that most of the selectivity disappears when the full range of data is considered. The full angular distributions are displayed in Fig. 2 for six excited states. There is virtually no asymmetry in any of the angular distributions. Thus in the present range of data, we find no evidence for selective population of 12p-4h states.

In order to investigate the mechanism further, we have performed calculations with the statistical-model code STATIS[6] which uses the Hauser-Feshbach expression[7] to evaluate the energy-

TABLE I. Excitation energies and J^π in ^{24}Mg.

Literature[a] E_x (keV)	J^π	Present label[b]
5236.0 ± 0.3	3^+	5.22
6010.3 ± 0.4	4^+	6.00
6431.8 ± 0.6	0^+	6.44
7347.9 ± 0.7	2^+	7.35
8120 ± 10	(6^+)	8.12
9282.5 ± 2.0	2^+	}
9300.0 ± 0.9	$(3,4)^+$	} 9.28
9300 ± 3	(4^-)	}

[a]Reference 5.
[b]Refers to the labels in Figs. 1–3.

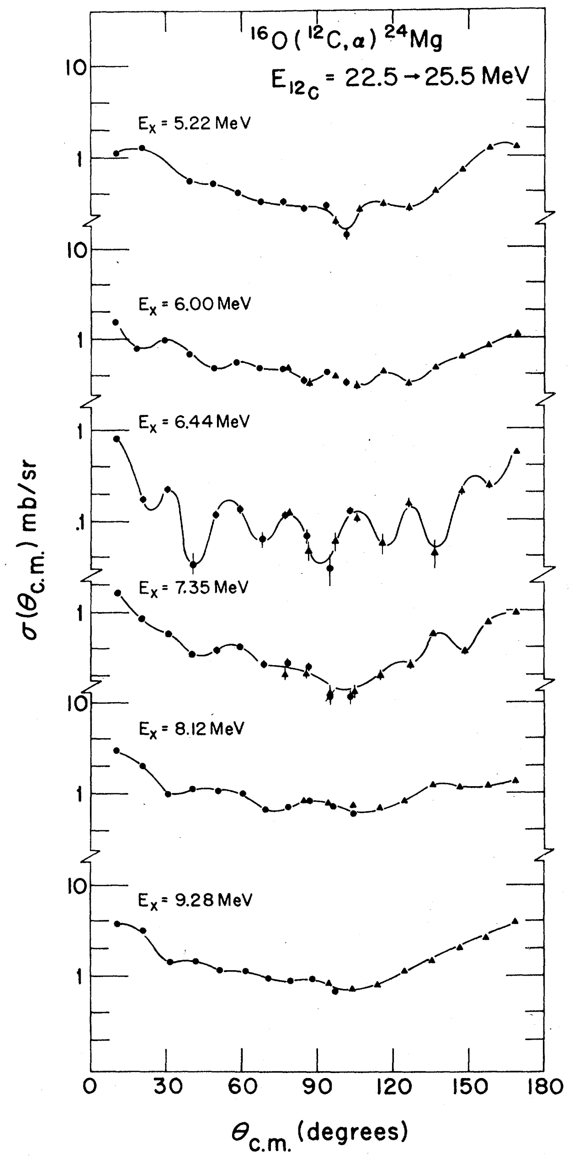

FIG. 2. Energy-averaged angular distributions for six strongly excited states in $^{16}O(^{12}C, \alpha)^{24}Mg$. Data cover the bombarding energy range 12.86–14.53 MeV (c.m.) in forty steps of 42.9 keV each.

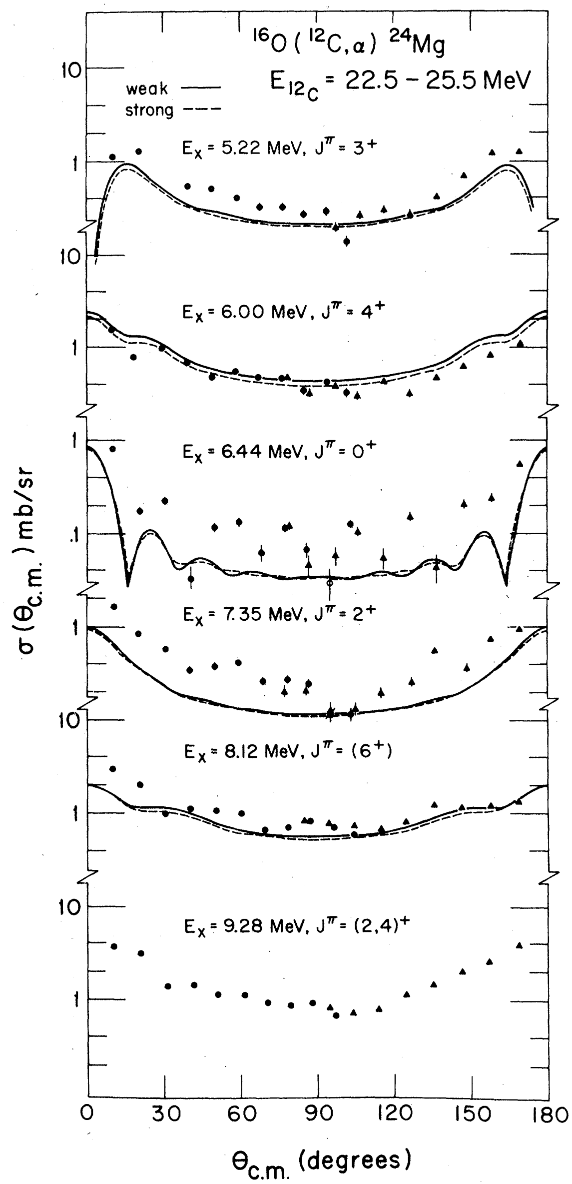

FIG. 3. Data from Fig. 2 compared with results of Hauser-Feshbach calculations. Labels weak (solid) and strong (dashed) refer to the absorptive properties of the optical potential in the entrance channel.

averaged differential cross section for population of specific final states. A comparison of statistical model predictions to recent experimental data for the *sd* shell mass region, as well as a description of this type of calculation, is given in Ref. 8. Earlier statistical-model analyses have been performed for the $^{12}C(^{12}C, \alpha)^{20}Ne$ reaction[9] and the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction.[10] In the present work, the optical model parameters used for the calculation of transmission coefficients and the level density parameters for the residual nuclei were similar to those of Ref. 10. An important difference in the present calculation in comparison to that of Ref. 10, however, is that we do not assume a $(\sin\theta)^{-1}$ approximation for the angular distribution, but calculate it explicitly. No adjustment of the parameters was made in order to improve the agreement with the experimental data. The results of the calculations are compared to experiment in Fig. 3. Dashed curves were computed with the potentials of Ref. 10, solid curves with the weakly absorbing potential of Ref. 11 in the entrance channel. The calculations show good agreement with the data, except for a slight underprediction of the cross section for low-spin states. For natural-parity states, the measured cross sections rise more steeply at forward and backward angles for low-spin states than for states of higher spin. This feature is also present in the calculations. Thus, the mechanism in the present data appears to be dominantly one of statistical compound-nucleus formation and decay.

The 9.28-MeV state is actually a triplet of unresolved levels. The observed ratio of cross section at forward angles and at 90° for this set of states is similar to that for the 2^+ state at 7.35 MeV. The magnitude of the cross section is 4 times that for the 2^+ state, and about twice that measured for the 6.00-MeV 4^+ state. If these states are also formed by a compound mechanism, then our data suggest that their combined spins are $\sum J = 7-10$. This is consistent with tentative J^π's of $(3,4)^+$ and $(4)^-$, respectively, for two levels at 9.3 MeV. A state at 9.28 MeV has $J^\pi = 2^+$.

In summary, we have measured complete, energy-averaged, angular distributions for the reaction $^{16}O + ^{12}C \rightarrow \alpha + ^{24}Mg$, leading to states between 5 and 10 MeV excitation in ^{24}Mg. All angular distributions are symmetric about 90°, and cross sections are what one would expect for a compound-nucleus process. We find no evidence for a direct eight- or twelve-nucleon transfer process. It would be interesting to extend this study to significantly higher bombarding energies, where the compound cross section for a given final state should be substantially smaller.

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