PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

Entrance channel dependence of back-angle yields: Orbiting in $^{24}Mg + ^{16}O$ reaction

A. Ray, S. Gil,* M. Khandaker, D. D. Leach,
D. K. Lock, and R. Vandenbosch
Nuclear Physics Laboratory (GL-10), University of Washington, Seattle, Washington 98195
(Received 21 December 1984)

The back-angle yields of the oxygen and carbon particles from the $^{24}Mg + ^{16}O$ reaction have been measured at $E_{lab}(^{24}Mg) = 79.5$ MeV by using reverse kinematics. Comparison with data for the $^{28}Si + ^{12}C$ reaction forming the same compound nucleus at the same excitation energy and with very similar spin distribution, demonstrates a strong entrance channel effect which is favoring the breakup into the entrance channel with large excitation energy. This result qualitatively supports the picture of the formation of a long-lived orbiting complex whose structure and decay is dependent on the entrance channel. The compound nucleus contribution is inferred to be less than 15% of the measured oxygen cross section.

Recent backward-angle measurements of strongly damped reaction products from the $^{28}Si + ^{12}C$,[1] $^{20}Ne + ^{12}C$,[2,3] $^{16}O + ^{27}Al$ (Ref. 4) reactions have indicated the formation of a long-lived orbiting complex. In these experiments large inelastic scattering cross sections have been observed at backward angles. The integrated center of mass cross sections vary as $1/\sin\theta_{c.m.}$ near 180°. These observations have been interpreted as evidence for an orbiting deep-inelastic-like process. A compound nucleus decay mechanism would however also lead to a near $1/\sin\theta_{c.m.}$ angular distribution in the limit of complete alignment of the angular momentum of the emitted particle with that of the compound nuclear system. The original claim that an orbiting rather than a compound nucleus mechanism was responsible for the back-angle yields relied heavily on comparison of compound nucleus calculations with the observed cross sections. It was argued[3] that since a Hauser-Feshbach compound nuclear calculation predicts appreciably smaller ($\approx \frac{1}{5}$) inelastic cross sections, it is not a compound nuclear reaction. These calculations however are fairly sensitive to level density and optical model parameters, the diffuseness parameter of the compound nucleus spin distribution, and the angular momentum cutoff used.

We report here an experiment to test whether the $^{28}Si + ^{12}C$ reaction goes via a compound nuclear process. We form the ^{40}Ca nucleus by the $^{24}Mg + ^{16}O$ reaction at the same excitation energy and angular momentum as formed in the $^{28}Si + ^{12}C$ reaction and compare the relative back-angle yields of carbon and oxygen with that obtained from the $^{28}Si + ^{12}C$ reaction. The observation of a strong entrance channel effect demonstrates that a noncompound nuclear process is dominant in these reactions at the backward angle. The $^{28}Si + ^{12}C$ system was previously investigated[1] using a ^{28}Si beam at $E_{lab} = 115$ MeV. We have measured the angular distribution of oxygen and carbon particles from the $^{16}O(^{24}Mg, ^{16}O)^{24}Mg$ and $^{16}O(^{24}Mg, ^{12}C)^{28}Si$ reactions at $E_{lab} = 79.5$ MeV. The excitation energy is 47.9 MeV for both systems and the $l_{critical} \approx 20\hbar$ values for the two systems as obtained from a trajectory model calculation[5] are the same within 5%. This calculation[5] uses a classical trajectory incorporating the nuclear proximity potential and one-body proximity friction with radius and diffuseness parameters for the system obtained from electron scattering results. The measured fusion cross sections for the $^{24}Mg + ^{16}O$ systems[6] and $^{28}Si + ^{12}C$ system[7,8] at the corresponding energies are equal within 10%.

A 200 $\mu g/cm^2$ Al_2O_3 target was bombarded by about 3 pna of ^{24}Mg beam obtained from the University of Washington FN tandem Van de Graaff accelerator and the spectra of the recoiling targetlike particles were studied at forward angles. This is equivalent to studying projectilelike products emitted at backward angles in the bombardment of a ^{24}Mg target by ^{16}O beams. A gas ΔE solid-state E telescope was used to measure the angular distribution of the scattered carbon, nitrogen, and oxygen particles from $\theta_{lab} = 5.6°$ to 20° in steps of 3°. A gas absorber cell was placed in front of the telescope for measurements at $\theta_{lab} = 5.6°$ and 8° to range out the elastically scattered ^{24}Mg. A solid-state detector was placed at $\theta_{lab} = 14°$ for normalization and to monitor carbon buildup on the target. Measurements were also taken at all the angles using a 200 $\mu g/cm^2$ Al target and a 50 $\mu g/cm^2$ carbon target. We subtracted the aluminum and carbon backgrounds from the Al_2O_3 spectrum and also corrected for carbon buildup on the Al target and for a layer of 10 $\mu g/cm^2$ of oxygen on the blank aluminum. The total subtraction due to aluminum and carbon background from the raw counts is not more than 45% in the worst case. The absolute normalization was obtained by bombarding the Al_2O_3 target with a 31.5 MeV ^{24}Mg beam (the Coulomb barrier for the $^{24}Mg + ^{16}O$ reaction is = 39.45 MeV) and measuring the elastic cross section.

Figure 1 shows carbon and oxygen spectra at $\theta_{lab} = 11°$. Two-body final states of $^{24}Mg + ^{16}O$ and $^{28}Si + ^{12}C$ were assumed in calculating Q values shown in the figure. Differential cross sections per MeV are obtained by averaging over 2–4 MeV Q-value bins at lower excitation energies and averaging over 0.5–1 MeV bins at higher excitation energies. Varying bin sizes are taken to get reasonable statistics. The Q value at the centroid of the bin is plotted along the x axis. The spectra are dominated by yields at high excitation energies which correspond to strongly damped processes. We have determined differential cross sections for scattered oxygen and carbon particles for several Q-value bins. They all vary as $1/\sin\theta_{c.m.}$ near 180°. We show in Fig. 2 the angular distribution for oxygen and carbon particles for two Q-value bins. The smooth curves show a $1/\sin\theta$ dependence. We could not get the angular distribution at $\theta_{lab} = 8°$ and 5.6° for the (-18.7 MeV $\leq Q \leq 0.0$ MeV) bin because of

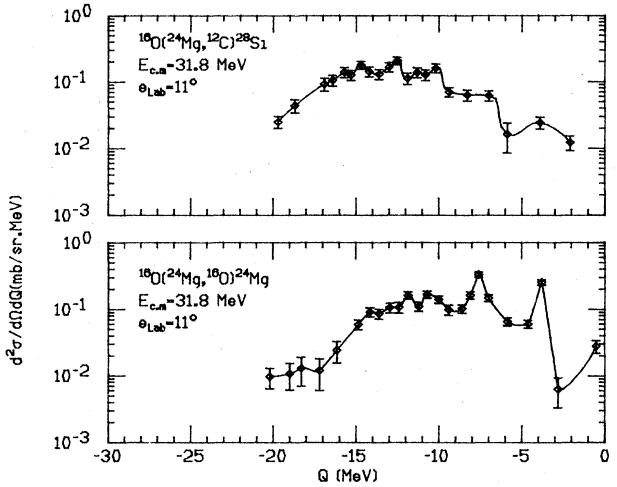

FIG. 1. Q-value spectra for carbon and oxygen particles emitted at backward angles. The solid line is only to guide the eye.

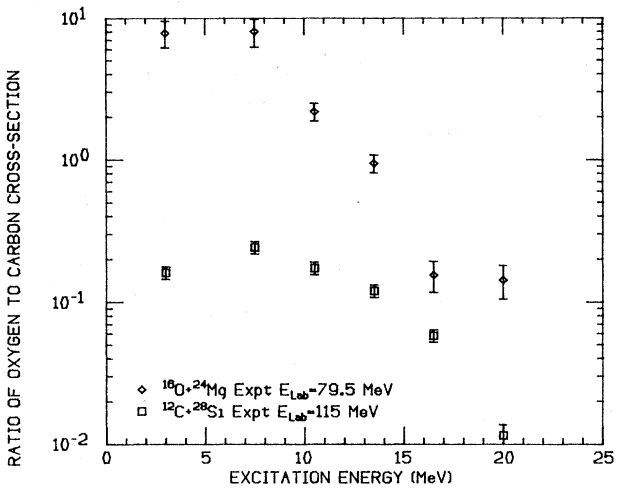

FIG. 3. Ratio of oxygen to carbon cross sections vs excitation energy for the $^{24}Mg+^{16}O$ and $^{28}Si+^{12}C$ systems.

multiple scattering and large energy losses of lower energy oxygen particles in the gas absorber cell. In the $^{28}Si+^{12}C$ reaction,[1] the carbon cross section is about four times the oxygen cross section. In the $^{24}Mg+^{16}O$ reaction, we find that the oxygen cross section is about three to four times the carbon cross section in the $(-8.5\ \text{MeV} \leq Q \leq 0.0$ MeV) region. Considering the entire Q-value spectra, we find more oxygen particles than carbon particles. In Fig. 3 we plot the ratio of oxygen to carbon cross section for several MeV wide excitation energy bins versus the corresponding excitation energy and show the results from the $^{24}Mg+^{16}O$ and $^{28}Si+^{12}C$ (Ref. 1) experiments. The lowest excitation energy point is obtained by summing over 0–6 MeV excitation energy bin and other points are obtained by summing over 3–4 MeV excitation energy bins. The ratio of oxygen to carbon cross section for the $^{24}Mg+^{16}O$ system is greater than that for the $^{28}Si+^{12}C$ system by a factor of about 10 in the lower excitation energy region and by a factor of about 4 on the average in the entire spectra. These results clearly demonstrate an entrance channel effect and are consistent with the picture of a long-lived orbiting complex formed in these reactions.

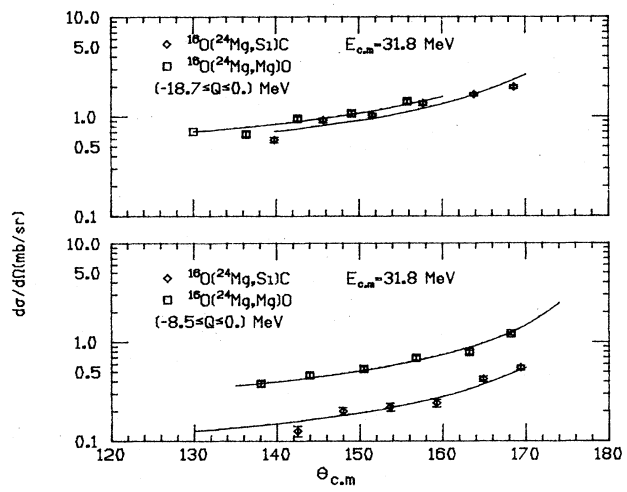

FIG. 2. The angular distributions for the yields in two Q-value bins are shown. The smooth curves show a $1/\sin\theta$ dependence.

The absolute oxygen and carbon cross sections predicted by evaporation code calculations[9] are very sensitive to the values of l_{critical} and the diffuseness parameter of the compound nucleus spin distribution. They are also sensitive to the level density parameters and the optical model parameters used for calculating transmission coefficients of emitted oxygen and carbon particles. We have found that the contributions to the cross sections for these heavy particle emissions come only from the tail of the compound-nucleus spin distribution. So the cross sections depend very much on the tail of the compound-nucleus spin distribution. However, the ratio of the two cross sections is comparatively insensitive to variation of different parameters. The ratio of the two cross sections varies by (20–25)% for 10% variation of l_{critical} and it changes by (30–35)% for varying the diffuseness parameter of the compound-nucleus spin distribution by a factor of 4. These calculations show that the large difference between the ratio of the oxygen to carbon cross section as measured for the $^{24}Mg+^{16}O$ system and the same ratio as measured for the $^{28}Si+^{12}C$ system cannot be explained in the compound-nucleus formalism by assuming a possible (5–10)% difference in the spin distributions of the compound nuclei formed by $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ reactions. These results show that a noncompound process which can produce a $1/\sin\theta_{\text{c.m.}}$ angular distribution near 180° is dominant in these reactions.

We have made a simple estimate of the compound-nucleus contribution in the measured oxygen cross section for the $^{24}Mg+^{16}O$ reaction. Let us define R_{expt} as the measured ratio of the oxygen to carbon cross section and $R_{\text{CN,calc}}$ as the ratio of oxygen to carbon cross section as calculated by the evaporation code CASCADE.[9] Let $\sigma_{\text{expt}}^{\text{oxygen}}$ and $\sigma_{\text{expt}}^{\text{carbon}}$ be the experimentally measured oxygen and carbon cross sections, respectively, $\sigma_{\text{compound}}^{\text{oxygen}}$ and $\sigma_{\text{compound}}^{\text{carbon}}$ be the compound-nucleus contribution to the oxygen and carbon cross sections, respectively, and $\sigma_{\text{noncompound}}^{\text{oxygen}}$ be the contribution from the noncompound process to the oxygen cross

section. Then

$$R_{\text{expt}}=\left[\frac{\sigma^{\text{oxygen}}_{\text{expt}}}{\sigma^{\text{carbon}}_{\text{expt}}}\right], \quad R_{\text{CN calc}}=\left[\frac{\sigma^{\text{oxygen}}_{\text{compound}}}{\sigma^{\text{carbon}}_{\text{compound}}}\right] .$$

Then since $(\sigma^{\text{carbon}}_{\text{expt}}) \geqslant (\sigma^{\text{carbon}}_{\text{compound}})$ we obtain

$$\left[\frac{\sigma^{\text{oxygen}}_{\text{noncompound}}}{\sigma^{\text{oxygen}}_{\text{compound}}}\right] \geqslant \left[\frac{R_{\text{expt}}}{R_{\text{CN calc}}}-1\right] .$$

We find by insertion of the experimental and calculated ratios and considering the uncertainties in the calculated and experimental values, that the compound nucleus contribution to the observed oxygen cross section is less than 15%.

In conclusion, these results show that a noncompound reaction mechanism is dominant for the highly inelastic process with the mass asymmetry of the entrance channel. The $1/\sin\theta$ angular distributions imply the formation of a long-lived intermediate. These observations are consistent with the original surmise[1] that an orbiting process dominates the back-angle yield.

This work was supported in part by the U.S. Department of Energy.

---

*On leave of absence from Comision Nacional de Energia Atomica, Buenos Aires, Argentina.

[1]D. Shapira *et al.*, Phys. Lett. B **114**, 111 (1982).
[2]D. Shapira, J. L. C. Ford, Jr., and J. Gomez del Campo, Phys. Rev. C **26**, 2470 (1982).
[3]D. Shapira *et al.*, Phys. Rev. Lett. **48**, 1781 (1979).
[4]D. Shapira, J. L. C. Ford, Jr., J. Gomez del Campo, and P. H. Stelson, Phys. Rev. C **21**, 1824 (1980).
[5]R. Vandenbosch, Nucl. Phys. **A339**, 167 (1980).
[6]S. L. Tabor, D. F. Geesaman, W. Henning, D. G. Kovar, K. E. Rehm, and F. W. Prosser, Phys. Rev. C **17**, 2136 (1978).
[7]K. T. Lesko, D. K. Lock, A. Lazzarini, R Vandenbosch, V. Metag, and H. Doubre, Phys. Rev. C **25**, 872 (1982).
[8]Y. Nagashima *et al.*, Phys. Rev. C **26**, 2661 (1982).
[9]F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).