BRIEF REPORTS

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Compound nucleus origin of back-angle yields in the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ reactions

A. Ray
Joint Institute for Heavy Ion Research, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

D. Shapira, J. Gomez del Campo, and H. J. Kim
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

C. Beck, B. Djerroud, and B. Heusch
Centre de Recherches Nucléaires, Université Louis Pasteur, Boîte Postale No. 20, F67037 Strasbourg, CEDEX, France

D. Blumenthal and B. Shivakumar
Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511
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The back-angle yields of the oxygen and carbon particles from the $^{31}P+^{16}O$ reaction have been measured at $E_{lab}(^{31}P)=135.6$ MeV by using reverse kinematics. Comparison with similar data for the $^{35}Cl+^{12}C$ reaction forming the same compound nucleus at the same excitation energy and with a very similar spin distribution shows very small entrance-channel dependence of back-angle yields. These results are in contrast to a similar study of the reactions $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$. It is evident that the oxygen and carbon yields from the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ reactions have a predominantly compound nucleus origin in contrast to those from the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ reactions. Possible connection of this nonequilibrium entrance channel dependence with the presence of nuclear molecular resonances is discussed.

Backward-angle measurements of damped reaction products from the reactions $^{24}Mg+^{12}C$ [1], $^{28}Si+^{12}C$ [2], $^{24}Mg+^{16}O$ [3], and $^{28}Si+^{14}N$ [4] have indicated the formation of a long-lived orbiting complex. In these reactions large inelastic cross sections have been observed at backward angles and the center-of-mass cross sections integrated over large-Q-value regions vary as $1/\sin\theta_{c.m.}$ near 180°. However, a compound-nucleus decay mechanism can also lead to a $1/\sin\theta_{c.m.}$ angular distribution. Measurements of the $^{32}S+^{24}Mg$ [5] and $^{35}Cl+^{12}C$ [6] systems show smaller yields of ^{12}C and similar products. A detailed comparison of the observed cross sections with a compound-nuclear decay calculation awaits knowledge of the mass-asymmetric fission barriers which have to be incorporated in the statistical calculations. Progress has been recently made by Sanders *et al.* [7] who have performed such a calculation of the ^{56}Ni nucleus. Despite the uncertainties in the optical-model parameters, the level-density parameter, the diffuseness parameter of the compound-nucleus spin distribution, and the angular momentum cutoff used, the authors of Refs. [6] and [7] claim that asymmetric fission is dominant in accounting for the yields of ^{12}C and similar products in $^{32}S+^{24}Mg$ [5,7] and $^{35}Cl+^{12}C$ [6] reactions.

One of the criteria to distinguish between compound-nuclear and orbiting reactions should be the entrance-channel dependence of back-angle yields. If a compound nucleus has been formed, then its decay should be independent of how it was formed. On the other hand, the decay of an orbiting complex should depend strongly on how it was formed. We rely on this criterion to distinguish between compound-nucleus and orbiting reactions, because this criterion is free from the uncertainties of calculation of absolute cross section for the light-ion compound nucleus reaction. The observation [3] of a strong entrance-channel dependence of back-angle yields of $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ reactions supports the picture of the formation of a long-lived dinuclear complex whose structure and decay is dependent on the entrance channel. It is interesting to find out whether the entrance-channel dependence of back-angle yields is a general characteristic of the light heavy-ion reactions in this energy regime or whether this effect shows up only in some systems.

We report here an experiment to test whether the back-angle ^{16}O and ^{12}C yields of $^{35}Cl+^{12}C$ and $^{31}P+^{16}O$

reactions are originating in a compound-nucleus process. We form the ^{47}V nucleus by the ^{31}P+^{16}O reaction at the same excitation energy and angular momentum as formed in the ^{35}Cl+^{12}C reaction [6] and compare the relative back-angle yields of carbon and oxygen with that obtained from the ^{35}Cl+^{12}C reaction. The absence of any significant entrance-channel effect would demonstrate that the back-angle yield is dominated by a compound-nucleus process. The ^{35}Cl+^{12}C system was previously investigated [6] using a ^{35}Cl beam at $E_{lab}=180$ MeV. We have measured the angular distribution of oxygen and carbon particles from the ^{16}O (^{31}P, ^{16}O)^{31}P and ^{16}O(^{31}P, ^{12}C)^{35}Cl reactions at $E_{lab}=135.6$ MeV. The excitation energy is 59.1 MeV for both systems, and the $l_{crit}=(27-28)\hbar$ for the two systems as obtained from a trajectory model calculation [8] is the same within 4%. This calculation [8] 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 l_{crit} value extracted from the ^{35}Cl+^{12}C evaporation residue measurement [6,9] is in good agreement with the model calculation.

A supersonic gas-jet ^{16}O target [10] was bombarded by about 10 particle nA of ^{31}P beam from the Oak Ridge National Laboratory HHIRF tandem accelerator, and the spectra of the recoiling targetlike particles were studied at forward angles. This is equivalent to studying the reaction at backward angle in the center-of-mass frame. The carbon and oxygen particles were detected by using a hybrid ionization and focal plane detector [11] in a Enge spectrograph from $\theta_{lab}=6.5°$ to 18.5° in steps of 3°. Carbon and oxygen particles pass through 100 μg/cm^2 of aluminum stripper foil before entering the magnetic spectrograph. We find that the carbon ions are essentially fully stripped and the charge states of oxygen ions are distributed between 8^+ and 7^+ states. The contributions from different charge states are added to obtain the cross section for that ion. The absolute normalization was obtained by bombarding the ^{16}O gas-jet target with a 70-MeV ^{31}P beam (Coulomb barrier = 71.6 MeV) and measuring the Rutherford elastic cross section at $\theta_{lab}=6.5°$ and 8°.

Figure 1 shows the differential cross sections for oxygen and carbon particles integrated over a $-30<Q<0$ MeV bin in the center-of-mass frame. They can be approximated by $1/\sin\theta_{c.m.}$ angular distribution as shown by the smooth curves. In Fig. 2(a) we plot the ratio of oxygen to carbon cross section for bins several MeV wide in excitation energy versus the corresponding exit-channel excitation energy and show the results from ^{31}P+^{16}O and ^{35}Cl+^{12}C [6] reactions. To obtain reasonable statistics, the lowest excitation energy point is obtained by summing over a 0–11.5-MeV-wide bin in excitation energy

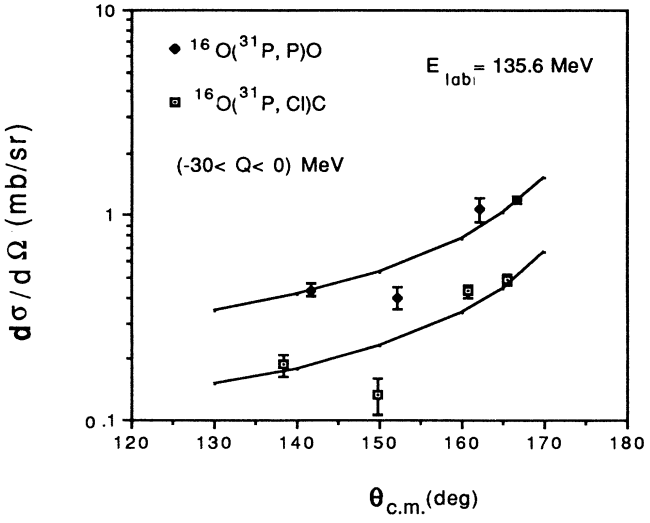

FIG. 1. Angular distributions for carbon and oxygen yields in the $-30<Q<O$ MeV bin in the center-of-mass frame are shown. The smooth curves show $1/\sin\theta$ dependence.

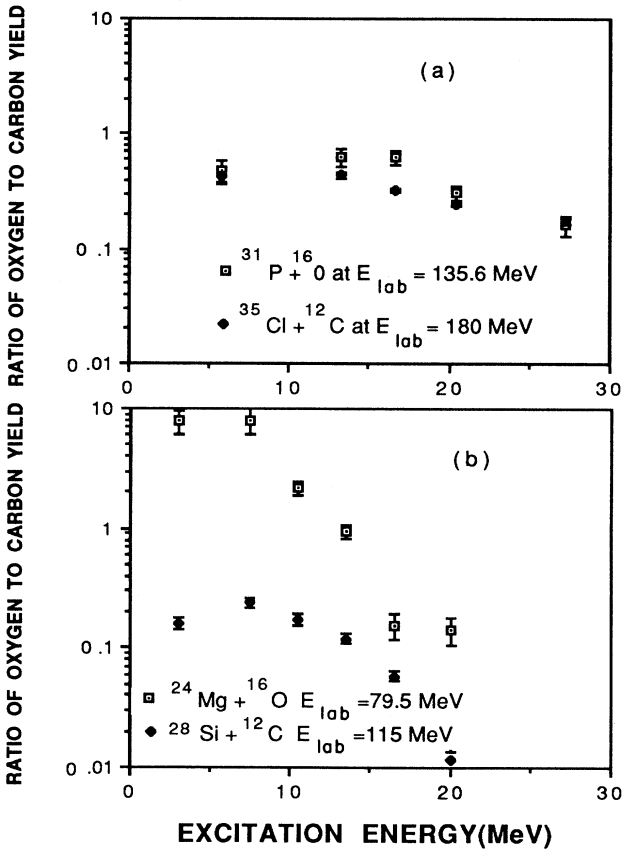

FIG. 2. Ratio of oxygen to carbon cross sections versus excitation energy for the (a) ^{31}P+^{16}O and ^{35}Cl+^{12}C systems and (b) ^{24}Mg +^{16}O and ^{28}Si+^{12}C systems.

and other points are obtained by summing over 3–4-MeV-wide bins. In Fig. 2(b) we plot the ratio of oxygen to carbon cross section for several MeV wide bins in excitation energy versus the corresponding exit-channel excitation energy for $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ reactions [3]. The $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ reactions were performed at $E_{lab}(^{28}Si) = 115$ MeV and $E_{lab}(^{24}Mg) = 79.5$ MeV, respectively. The strong entrance-channel effect observed in the comparison of $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems continues to exist at higher energy also [12]. We do not find any significant entrance-channel effect in the comparison of $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems compared to that observed in the comparison of $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems.

The absolute oxygen and carbon cross sections predicted by the statistical model [13] are sensitive to the values of l_{crit} and diffuseness parameters of the compound-nucleus spin distribution, because the contributions to the cross section for these heavy-particle emissions come only from 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 oxygen to carbon cross sections varies by (20–25)% for a 10% variation of l_{crit}, and it changes by (30–35)% if the diffuseness parameter of the compound-nucleus spin distribution is varied by a factor of 4. So the observed small difference in back-angle yields of oxygen and carbon particles from the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems can be mostly explained as a result of the small difference [(5–10)%] in the spin distributions of the two systems.

The absolute energy and angle-integrated total cross sections of carbon and oxygen for the $^{31}P+^{16}O$ reaction at $E_{lab}(^{31}P) = 135.6$ MeV are 3.34 and 1.45 mb, respectively. The uncertainty in determining the absolute cross section is estimated to be about 20%. The absolute cross sections of carbon and oxygen as observed [6] in the $^{35}Cl+^{12}C$ system at $E_{lab}=180$ MeV are 2.98 ± 0.6 and 0.85 ± 0.35 mb, respectively. So the absolute cross sections of carbon and oxygen for $^{35}Cl+^{12}C$ and $^{31}P+^{16}O$ systems are comparable. However, these yields are much smaller than the yields expected from the equilibrium orbiting model [14] (8.76 and 5.86 mb for carbon and oxygen, respectively). Using the method described in Ref. [3], we find that the contribution of the orbiting yield is less than 15% of the observed oxygen yield in the $^{31}P+^{16}O$ system. We conclude that the backward-angle-damped yields of $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems are dominated by the formation of the ^{47}V compound nucleus followed by an asymmetric fission process and that there is no significant entrance-channel effect.

The entrance-channel dependence is one of the main criteria of the orbiting reaction. It is very interesting to contrast the dominance of entrance-channel dependence and orbiting yield in the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems and the lack of this effect in the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems. The equilibrium orbiting model [14] can explain the large damped orbiting yield of binary fragments from the $^{28}Si+^{12}C$ system, but fails to explain the observed entrance-channel dependence of the orbiting yield and the lack of large damped orbiting yield for the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems. One of the main assumptions of the equilibrium orbiting model [14] regarding the formation of an equilibrated sticking configuration of orbiting nuclei is questionable in view of the recent alignment measurements [15] in the orbiting system. However, orbiting characteristics [3,15] as seen in certain systems are clearly manifestations of a long-lived noncompound process taking place in those systems. Although there is no overall quantitative understanding of these effects, we can still make a few interesting observations. It is known that the grazing angular momenta are mostly responsible for the back-angle binary fragment yields. An estimate of the number of open channels available to carry away the grazing angular momentum has been made [9,16] following the method suggested by Abe and Haas [17]. The number of open channels for each system was obtained by a triple summation over all possible two-body mass partitions in the exit channels, over all possible angular momentum couplings, and over all possible energy distributions between fragments and normalized to 1 mb of the grazing partial-wave flux. The calculation shows that for the $^{35}Cl+^{12}C$ and $^{31}P+^{16}O$ systems, the number of open channels available to carry away the grazing angular momenta is about 300 times larger than the number available in the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems. So the emission of binary fragments at back-angle from the $^{35}Cl+^{12}C$ and $^{31}P+^{16}O$ systems is mostly dominated by statistical compound-nucleus processes. In fact, it appears that the orbiting yield is dominant in α-like systems having small number of open channels, where strongly oscillatory angular distributions and highly regular gross structures in the excitation function have been observed [18] at back-angles for the ground and first excited states. Recently, structures [19] have been seen in the excitation function of back-angle-damped yield of the $^{24}Mg+^{12}C$ system. Although the interpretation of these gross structures is far from being clear, it has been suggested [18, 20] that the presence of quasimolecular states might be responsible for the observed structure and oscillatory angular distribution. These resonances have a dominantly noncompound dinuclear characteristic and might be responsible for the large orbiting yield and observed entrance-channel effect in $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems. It also appears that the fusion-fission compound-nuclear yield dominates in those systems where a very large number of open channels is available and resonance characteristics are strongly suppressed.

In conclusion, contrary to the strong entrance-channel effect observed in the ^{40}Ca composite system populated by the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems, the back-angle yields measured in the $^{35}Cl+^{12}C$ and $^{31}P+^{16}O$ systems are the result of the statistical decay of a ^{47}V compound nucleus. The disappearance of orbiting yield for the $^{31}P+^{16}O$ and $^{35}Cl+^{12}C$ systems suggests that the orbiting process might be connected to the presence of quasimolecular resonance states and the orbiting process is dominant in systems where the number of open channels is small. However, the orbiting characteristics might also arise from nonresonant processes such as nucleon exchange, α exchange mechanisms, etc., and the origin of

orbiting mechanism is still an open question at the present time.

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