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Evolution towards equilibration in orbiting interactions

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We have studied the evolution towards mass equilibration in ^{24}Mg+^{16}O orbiting interactions. ^{24}Mg beams of energies between 75 and 115 MeV were used to bombard targets of ^{16}O. Targetlike particles were detected at forward angles to determine the yields from orbiting interactions. The ratio of the orbiting yields of ^{12}C and ^{16}O exit channels rises continuously with energy from values below unity to above. The data are interpreted as demonstrating a strong entrance channel dependence at low energies, and an evolution towards mass equilibration with increasing energy.

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I. INTRODUCTION

The small impact parameter interactions between heavy ions, at energies of several MeV per nucleon, have been assumed traditionally to result in the formation of an equilibrated compound nucleus. This is a composite object having a mass which is the sum of the masses of the interacting nuclei. The compound nucleus is created with a large amount of excitation energy, and deexcites predominantly via the emission of photons or light nuclei. This picture, though fairly successful in describing most of the features of a large body of data, fails to explain observations in certain light heavy ion systems such as ^{28}Si+^{12}C, ^{24}Mg+^{16}O, ^{24}Mg+^{12}C, etc. Here, significant yields of fragments with masses close to those of the target and projectile have been observed. A consideration of these data leads to the following question: Are these complex fragments emitted by a dinuclear composite prior to fusion, or after? We will use our measured energy dependence of the yields of ^{16}O and ^{12}C nuclei emitted from ^{24}Mg+^{16}O interactions to argue that what we are seeing is the outward decay of a dinuclear object prior to fusion.

II. PREVIOUS MEASUREMENTS AND INTERPRETATIONS

The observed characteristics of the data in question are the following. There are large yields (~100 mb) of projectilelike and targetlike fragments. The kinetic energies of these fragments are independent of the center-of-mass angle, and the center-of-mass yields are isotropic ($\frac{d\sigma}{d\theta}$ is a constant and $\frac{d\sigma}{d\Omega}$ varies as $1/\sin\theta$). These data have been interpreted as supporting both orbiting and fusion-fission reaction mechanisms, as will be discussed below.

In order to describe these observations we proposed the formation of a rotating dinuclear composite. This is an object that lives long enough to execute one or more revolutions. Its dinuclear configuration makes it extremely deformed (axis ratios in excess of 2:1). It evolves through a complex series of changes towards equilibration of its various attributes: energy, angular momentum, charge and mass asymmetry, and shape. Of these, we believe the shape degree of freedom takes the longest to approach equilibrium values. We conjectured that, since the data indicated an abundance of targetlike and projectilelike fragments far in excess of what was expected from evaporation from a compound nucleus, we were seeing the outward decay of a dinuclear composite. We refer to these processes as orbiting, emphasizing their similarity to molecular resonances.

An extensive study of the ^{28}Si+^{12}C system has established the cross sections for the orbiting process, its energy, and its angular dependence [1]. This study has also demonstrated that the data are consistent with there being a maximum angular momentum that any orbiting dinuclear composite can sustain. This maximum angular momentum is attained at a center-of-mass energy where the exit channel kinetic energy shows saturation. Increases in center-of-mass energy above this value result in equivalent increases in the excitation energy of the orbiting constituents. The ^{40}Ca orbiting composite formed

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in ^{28}Si+^{12}C interactions decays predominantly to the ^{28}Si+^{12}C exit channel. The ^{24}Mg+^{16}O system was investigated, independently, at one energy, to populate the same composite object, ^{40}Ca, at an excitation energy and angular momentum similar to the ^{28}Si+^{12}C measurement [2]. This decay was predominantly to the ^{24}Mg+^{16}O exit channel. Figure 1 shows the orbiting cross sections for these two systems plotted as functions of center-of-mass energy. In all data sets the exit channel yields were dominated by nuclei resembling the target and projectile, even though phase-space considerations favor the ^{12}C channel over the ^{16}O. These results that indicate a strong entrance channel dependence are qualitatively consistent with orbiting and are in variance with the expectations of fusion-evaporation or fusion-fission.

Experiments investigating ^{24}Mg+^{32}S and ^{16}O+^{40}Ca interactions found that the exit channel yields in these systems depended only weakly on the entrance channel. These measurements were made at two energies for several exit channels. The investigators concluded that their data could be explained best by the reaction mechanism of fusion followed by fission, or fusion-fission [3]. Recently, back-angle ^{12}C and ^{16}O yields have been measured in the ^{31}P+^{16}O and ^{35}Cl+^{12}C systems, and no significant entrance channel dependences have been observed [4].

We assert that the features that distinguish processes that precede and follow fusion is a consequence of the equilibration of the mass, charge, and shape degrees of freedom. The process of formation of a compound nucleus erases all memory of the entrance channel beyond those constraints imposed by energy, angular momentum, mass, and charge conservation.

Are there two distinct reaction mechanisms in operation in the nuclear reactions described above, or are the orbiting and fusion-fission interpretations really two descriptions of the same underlying theme? Experimentally, it is the demonstration of a strong entrance channel dependence in the exit channel yields that distinguishes the two processes. This was done at one energy for the ^{28}Si+^{12}C and ^{24}Mg+^{16}O systems. However, this comparison has been criticized by the proponents of the fusion-fission interpretation as being very susceptible to the presence of molecular resonances, which are known to exist in such systems. We address this issue herein.

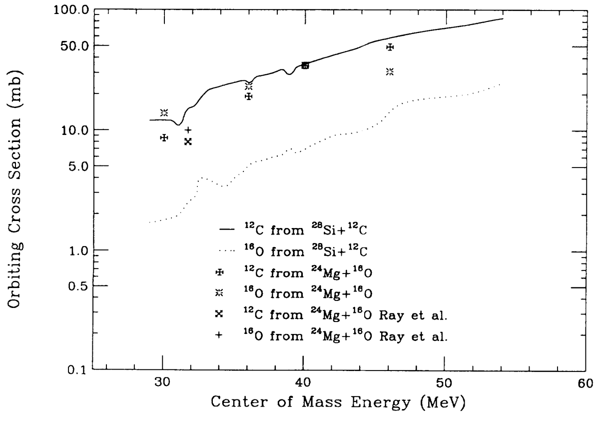

FIG. 1. The orbiting cross sections measured for the ^{28}Si+^{12}C, and ^{24}Mg+^{16}O interactions.

We believe that an understanding of the underlying reaction mechanisms in these interactions requires detailed measurement of mass distributions of exit channels, for different entrance channels populating the same composite system, *as functions of bombarding energy.* This is the primary motivation behind the measurement discussed below. We hope to complement our rather extensive data on ^{28}Si+^{12}C interactions with measurements of ^{24}Mg+^{16}O. Our data can also be compared with the previous measurement for ^{24}Mg+^{16}O at one energy. We use the measured energy dependence of the ratio of the ^{12}C to ^{16}O exit channel yields to answer the questions raised above.

The existence of a long-lived dinuclear stage prior to fusion has also been shown in studies of few nucleon transfer and exchange [6, 7] and fusion near the Coulomb barrier [8, 9]. These results complement those we describe below.

III. THE DATA

Our data were measured using the Oak Ridge National Laboratory HHIRF Tandem accelerator. Beams of ^{24}Mg nuclei of energies 75, 90, 105, and 115 MeV, respectively, were incident on a ^{16}O target. Reaction products were detected in the focal plane of an Enge spectrograph using a hybrid ionization chamber. The detector measures energy loss, total energy, and the particle trajectory, to identify the particles by charge and mass. Projectilelike particles, including the beam, were prevented from entering the detector by placing a combination of foil and gas energy degraders in front of the focal plane detector. The targetlike reaction products traversed the absorber, and were detected in the chamber. Two field settings were used at each beam energy to provide the dynamic range necessary to detect both carbon and oxygen nuclei efficiently.

The entrance aperture to the spectrometer was covered by a thin nickel foil to strip the reaction products to as high a charge state as possible. For the targetlike ions, this resulted in charge state distributions which were peaked at the maximum allowable charge states for each of the species detected, and increased the efficiency in their measurement.

The ^{16}O targets were obtained using a supersonic gas jet apparatus [10]. Pumping on oxygen requires the use of special pump oils, and additional safety precautions. We decided to circumvent some of these problems by sending ^{16}O to the gas jet, and mixing ^{14}N with the ^{16}O downstream of the gas target, and before the pumps. This way, the gas mixture seen by the pumps looked like air. Flow controllers were interlocked such that the flow of ^{16}O would be stopped if for some reason the flow of ^{14}N were stopped. The target operation was stable, reliable, and successful.

Figure 2 is a spectrum of the position of hits on the front wire of the hybrid ionization chamber in the spectrograph. The peaks correspond to different charge states

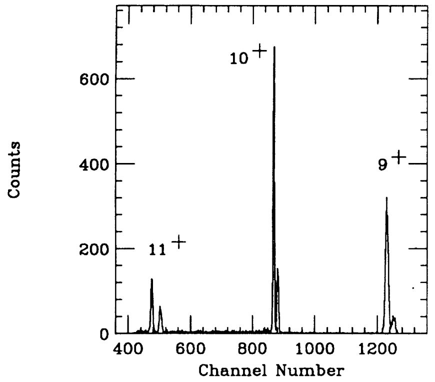

FIG. 2. Position spectra measured on the front wire of the focal plane detector for elastically scattered ^{24}Mg ions from the ^{16}O/Xe target mixture. The labels near the peaks indicate the atomic charge states of the ^{24}Mg ions entering the detector.

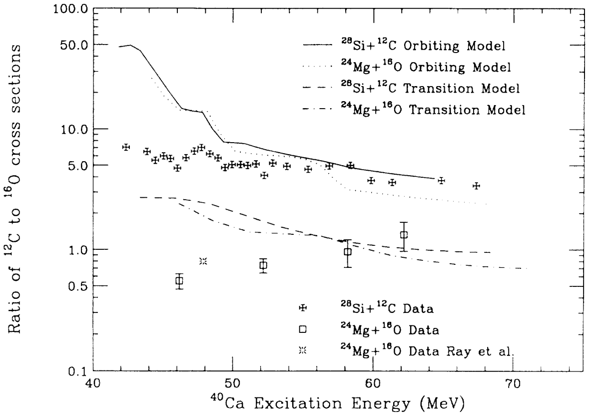

FIG. 3. Ratios of ^{12}C to ^{16}O orbiting cross sections plotted as functions of the excitation energy in the composite ^{40}Ca nucleus. The curves are the predictions of the equilibrium orbiting and the transition state models.

of 105 MeV ^{24}Mg ions scattered at 4.6 degrees from a target mixture of 99% ^{16}O and 1% Xe. The data were collected without the absorber in front of the ionization chambers. They show the purity of the target. There is no significant yield in the spectrum from nuclei other than ^{16}O and Xe. Under the assumption that the observed yields are a consequence of Rutherford scattering, we can calculate the thickness of the target. This resulted in a target thickness of 1.8×10^{16} atoms/cm^2.

The data were analyzed using the techniques developed for a previous experiment [11]. Their quality was similar to those described in the same reference. As before, the total yields for each type of reaction product were corrected for detection efficiencies and charge-state distributions. Figure 1 shows the ^{12}C and ^{16}O orbiting cross sections obtained in this measurement plotted as functions of center-of-mass energy. These were obtained by integration over the full solid angle assuming that the yields of targetlike nuclei are emitted isotropically in the center-of-mass frame. This assumption was tested explicitly at one energy, and has also been confirmed by previous measurements [1, 2, 5]. Also shown in the figure are the measurements of Ray *et al.* The agreement between the two data sets is encouraging. Since we do not have a measurement at the same energy, it is hard to quantify this comparison. The previous measurement had to rely on the use of solid targets and, therefore, had to do significant background subtraction (at the level of 50%) to account for materials other than ^{16}O in the target. Our present measurement does not suffer from target related backgrounds. The absolute cross section values we report have uncertainties at the level of 10–15 %.

Figure 3 is a plot of the ratio of the ^{12}C to ^{16}O cross sections for the ^{28}Si+^{12}C and ^{24}Mg+^{16}O systems. Also shown is the ratio measured by Ray *et al.*, for the ^{16}O+^{24}Mg system. The curves are the predictions of the equilibrium orbiting model, and the transition state model, to be described below. The data clearly show a strong entrance channel dependence. The yield in the exit channel ^{16}O is greater than the yield in the ^{12}C channel for the ^{16}O+^{24}Mg interaction at all but the highest energy. The ratio differs from that of the ^{28}Si+^{12}C data by a factor of 10 at an excitation energy of 50 MeV, and a factor of 3 at 66 MeV. It bears emphasis that over this energy range the fusion cross sections for the two entrance channels are within 10% of each other, indicating similar angular momenta and total spin. The data therefore clearly indicate a significant difference in the ratios of ^{12}C to ^{16}O exit channel yields for the two entrance channels, at all energies in this measurement. The difference decreases with increasing energy. The above observations are not at all consistent with the expectations of fusion-fission, and demonstrate, unlike previous suggestions (see discussions about ^{28}Si+^{12}C in [3]), that significant fractions of the observed yields are not coming from fusion-fission. The observed yields are consistent with our orbiting interpretation.

IV. INTERPRETATION

As discussed in Ref. [5], there are few exit channels open to the ^{40}Ca composite system when populated at small excitation energies via the ^{24}Mg+^{16}O or ^{28}Si+^{12}C entrance channels. This allows for a simplified theoretical interpretation of the data. Our qualitative expectations from this measurement were the following. If the orbiting picture is correct, at small excitation energies in a dinuclear orbiting composite, there are few exit channels available. One then expects the exit channel yields to show an entrance channel dependence reflecting the few modes of particle exchange allowed. With increasing excitation energy, several exit channels become accessible, and the exit channel yields then become independent of the entrance channel populating the mass 40 composite. The yields become determined by available phase space for decay. If, on the other hand, fusion-fission is the correct interpretation, and if a resonance were affecting the previous ^{24}Mg+^{16}O measurement, the exit channel yields for the ^{24}Mg+^{16}O and ^{28}Si+^{12}C interactions would be consistent with there being no entrance channel dependence (barring isolated fluctuations due to resonances). The data clearly demonstrate a strong entrance channel dependence.

There are two models that attempt a quantitative description of the exit channel yields in such interactions. They are the equilibrium orbiting model, and the transition state model. The equilibrium orbiting model whose predictions are shown in Fig. 3 assumes that an orbiting dinuclear composite is formed in such collisions. It then takes into account the energetics in such interactions, and determines a dinuclear potential energy surface. The exit channel yields are determined by the phase space accessible to the dinuclear exit channels. Simultaneously, the model explores the phase space available to fusion. In this manner both the orbiting and the fusion yields are predicted. The model has been applied fairly successfully to calculate the fusion and orbiting yields from the ^{28}Si+^{12}C system [11] and the orbiting cross sections for the ^{28}Si+^{14}N system [5, 12]. The model assumes that energy, angular momentum, and mass are equilibrated in the dinuclear phase space. Further, the interacting nuclei are described as being trapped in a sticking configuration. These assumptions dictate how energy and angular momentum are shared between the two nuclei constituting the orbiting composite. Studies of spin distributions and alignment in the ^{28}Si+^{12}C system, at center-of-mass energies of 43.5 and 48 MeV, have already indicated that these assumptions need refinement [13].

The top two curves shown in Fig. 3 are the predictions of this model for the ^{28}Si+^{12}C and ^{24}Mg+^{16}O interactions, respectively. The differences between the two curves show the small entrance channel dependence expected even in equilibrium models on account of the differences in angular momenta brought into the interacting systems. The ^{24}Mg+^{16}O data deviate significantly from the model predictions at all energies. The orbiting model, being of equilibrium nature, does not include any entrance channel dependence. It is therefore not surprising that it predicts the ratio of ^{12}C to ^{16}O exit channel yields to be independent of the entrance channel, barring small effects due to differences in channel angular momenta. The ^{28}Si+^{12}C interaction data seem to be well described by the model at energies above 52 MeV, perhaps indicating that energy angular momentum and charge are being equilibrated. The model predictions deviate rather significantly from the ^{24}Mg+^{16}O data. With increasing center-of-mass energy, however, the data seem to be approaching ratios expected when energy, angular momentum, mass, and charge are equilibrated. The inability of the model to describe the low energy behavior in the ^{28}Si+^{12}C interaction is probably attributable to the nonequilibration of energy and angular momentum, features which are not included in its formalism. Also, the way this model calculates the accessible phase space is only reliable at higher excitation energies in the dinuclear composite. There are other characteristics of such data such as spin alignment that are not described by this model.

The two lower curves in the same figure are the predictions of the transition state model developed by Sanders to calculate the exit channel yields from a fusion-fission approach [15]. A simple double spheroid approximation is used to calculate the fission barriers of the composite objects, in this case, ^{40}Ca. The fission cross sections are then calculated within a statistical model. The model has been applied very successfully to describe the composite fragment yield from objects of mass > 45. This is accomplished by assuming scission shapes that are essentially dinuclear. It does rather well in also describing the yields from ^{28}Si+^{14}N interactions. However, when applied to the ^{28}Si+^{12}C system, the observed cross sections in the carbon channel are underpredicted by a factor of 3. Shown in Fig. 3 are the results of this calculation for the ratios of yields in the ^{12}C and ^{16}O exit channels in ^{28}Si+^{12}C and ^{24}Mg+^{16}O interactions. The model predicts that the exit channel yields are independent of the entrance channel, in contradiction to what is evident in the data.

Since both models fail to provide a quantitative description of the data, we suggest improvements to the calculations to better describe our observations. In the orbiting interpretation, the total energy in the interacting composite system is divided into collective rotational motion, and the excitation of the constituent nuclei. The excitation energy in the nuclei varies from about 8 to 15 MeV for a center-of-mass energy variation from 30 to 40 MeV, respectively. These numbers can be obtained from the measured kinetic energy distributions of the detected fragments. At the lowest center-of-mass energies, the excitation energy is not sufficient to populate very many exit channels in the dinuclear phase space. In such a potential energy surface, the two exit channels under consideration can be thought of as valleys with ridges separating them. If there is not enough energy available to surmount these ridges, the entrance channel configuration is confined to remain in a valley, and should therefore dominate the exit channel yields. An improved formulation of the equilibrium orbiting model should be able to describe entrance channel dependences. The present assumption of equilibration in this model is tantamount to allowing the system to travel between valleys even in situations where the available excitation energy should have been inadequate to allow for such excursions. Such changes would not be appropriate for a fusion-fission calculation, since what we are proposing is a formalism for an entrance channel effect. We believe that only a dynamical model which describes the time evolution of the entrance channel to fusion, and at each stage considers all possible decay channels, including light particle emission from the two fragments, will succeed in providing a quantitative description of our data. A nonequilibrium formalism for performing such calculations has, in principle, been elucidated [14], but calculations using this approach have not yet been done.

Having demonstrated that the data support an orbiting interpretation, we note that the total orbiting cross sections shown in Fig. 1 are $\sim$100 mb, and are larger than predictions of fusion-fission and compound-nucleus models. This suggests that the measured yields could be coming from a dinuclear object whose shape degree of freedom is not equilibrated. In all systems, we believe there is competition between dinuclear orbiting and fusion. In those systems where several exit channels are accessible even at low excitation energies, particle exchange and shape equilibration probably occur more easily, and lead to decreased orbiting cross sections, and increased fusion. This is the case for the heavier systems studied elsewhere [3, 4]. It is also likely that the shape degree of freedom is less easily equilibrated in dinuclear objects made of compact nuclei like ^{12}C and ^{16}O. One should note that large orbiting cross sections are also observed for the ^{12}C+^{20}Ne system [16]. In heavier systems such as ^{28}Si+^{28}Si, the magnitudes of the complex fragment emission is smaller than in the lighter systems, and consistent with the expectations of fusion-fission interpretations of the exit channel yields [3].

V. SUMMARY AND CONCLUSIONS

We have measured the ratio of orbiting yields of ^{12}C and ^{16}O nuclei from ^{24}Mg+^{16}O interactions using a clean ^{16}O supersonic gas jet target. As functions of center-of-mass energy, this ratio increases continuously from below unity to above. Studies of the same ^{40}Ca composite object populated in ^{28}Si+^{12}C interactions show the same ratio staying well above unity at all energies. We interpret this observation as evidence for a strong entrance channel dependence at low energies and the evolution towards mass and charge equilibration at high energies. In these systems, the magnitude of the orbiting yields suggests that even at the highest energies measured, the shape degree of freedom is probably still not equilibrated. The data are qualitatively consistent with the outward decay of an orbiting complex, and at variance with the expectations of fusion-fission. However, there still does not exist a quantitative model that can describe all of the observed features of such interactions, namely, the large yield, entrance channel dependences, and the alignment of the reaction products. The few exit channels available in these systems probably inhibits the speed of shape equilibration at low energies. It would be worthwhile investigating whether orbiting is peculiar to systems in which the participant nuclei are tightly bound, as is the case for light nuclei with masses an integral multiple of the alpha particle mass. These are also the systems which have shown evidence for the presence of molecular resonances. This study also suggests the usefulness in extending the ^{24}Mg+^{16}O measurement to higher energies to establish whether the exit channel yields in this and the ^{28}Si+^{12}C interaction become identical. At a time when nuclear spectroscopists are actively engaged in studies of superdeformation in the rare-earth mass region, it is interesting to note that the present study reaffirms the probable existence of long-lived hyperdeformed configurations in the mass 40 systems. Further studies of their stability and nuclear structure could prove to be very rewarding.

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