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Observation of unexpected orbiting behavior for $^{16}O+^{89}Y$ and $^{16}O+^{93}Nb$ reactions

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We have studied the emission of projectilelike fragments from $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions forming the same compound nucleus ^{105}Ag at the same excitation energy (E_X=76 MeV) and with very similar spin distributions. A strong entrance channel dependence favoring breakup into the entrance channel with large excitation energy has been seen for $^{16}O+^{89}Y$ system, but not for $^{12}C+^{93}Nb$ system. In the case of $^{16}O+^{93}Nb$ reaction also, unexpectedly, large back-angle oxygen yield has been seen. The results indicate formation of orbiting complex for reactions between spherical nuclei such as $^{16}O+^{89}Y$ and $^{16}O+^{93}Nb$ at large orbital angular momentum near ℓ_{crit}.

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It is known from the work of Moretto *et al.* [1] and others [2] that the emission of complex fragments from a compound nucleus can be understood very well using transition-state method calculations. The surprising success of the transition-state method calculations has prompted many attempts to identify regimes in which deviations might be expected. The preequilibrium and presaddle emission of neutrons [3], charged particles [4,5], and electric dipole γ rays [6] during the formation period of compound nucleus can lower the temperature of the equilibrated compound nucleus and so the spectra of proton and α particles emitted from the compound nucleus could be softer and fission rate reduced, in apparent contradiction to the transition-state model calculations. Another scenario [2,7–9] for departure from transition-state model could be due to the formation of a long-lived ($\approx 5 \times 10^{-21}$ s) dinuclear complex with a large orbital angular momentum so that the nuclei maintain their identities and then break apart without ever forming a fully equilibrated compound nucleus. The spectra and angular distribution of emitted fragments from such a dinuclear complex are essentially identical to that of a compound nucleus because of its long lifetime. However such a dinuclear complex should predominantly break into the entrance channel in contrast to the decay of an equilibrated compound nucleus. The evidence of dinuclear orbiting was seen earlier for a few systems such as $^{28}Si+^{12}C$, $^{24}Mg+^{16}O$, and $^{28}Si+^{16}O$, etc. reactions [7–9] at (4–7 MeV/nucleon) bombarding energies (laboratory) in the case of emission of projectilelike or targetlike fragments.

The physics of the formation of dinuclear orbiting complex is rather poorly understood, although the general concept of the dinuclear system is often used to qualitatively explain different nuclear reaction anomalies [2,10–13]. A typical total nucleus-nucleus potential $V(r)$ has a pocket having both a maximum and minimum. The orbiting is expected to take place at a high orbital angular momentum (near ℓ_{crit}) when the minimum distance between the nuclei is such that $V(r)$ corresponds to the maximum of the potential pocket. However this is a necessary but not sufficient condition for orbiting. Another required criterion [2,14] is that the total number of open channels of the system, which is related to the surface transparency and absorption of nuclei, should be small. This qualitative criteria is successful [2,14] in explaining the presence and absence of dinuclear orbiting in light heavy ion systems. According to this criterion, orbiting is not expected to take place in heavy systems (total mass A $\sim$100), because the total number of open channels for such a system is very large. In this paper, we present evidence of dinuclear orbiting for reactions between spherical nuclei (total mass A$\sim$100) such as $^{16}O+^{89}Y$ and $^{16}O+^{93}Nb$ for orbital angular momenta near their critical angular momenta (ℓ_{crit}).

We formed the same compound nucleus ^{105}Ag at the same excitation energy (E_X=76 MeV) and with very similar spin distributions (ℓ_{crit} equal within 10%) by $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions. A 10 pna ^{16}O beam with 95.9 MeV energy from BARC-TIFR pelletron machine in Mumbai, India was incident on a 1 mg/cm^2 thick ^{89}Y target and all the emitted particles from α to oxygen were detected using four ΔE-E solid-state telescopes placed between 145° to 175° in the center of mass frame. Similarly a 10 pna ^{12}C beam with 85.5 MeV energy from Nuclear Science Center, New Delhi, India was incident on a 1 mg/cm^2 thick ^{93}Nb target and all the emitted particles were detected using three ΔE-E solid-state telescopes placed between 130° to 165° in the c.m. frame. We have also studied the back-angle fragment emissions from the reactions between spherical nuclei $^{16}O+^{93}Nb$ by bombarding a 1.2 mg/cm^2 thick ^{93}Nb target with a 5 pnA 116 MeV ^{16}O beam from Variable Energy Cyclotron Center, Kolkata, India and detecting emitted particles from α to oxygen in the angular region from $\theta_{\text{c.m.}}$=100° to 150° using a ΔE-E telescope.

In Fig. 1, we show the angular distributions of carbon and oxygen particles in the center of mass frame integrated over $0 \leq E_X \leq 45$ MeV and $0 \leq E_X \leq 39$ MeV, respectively, from $^{16}O+^{89}Y$ reaction at $E_{\text{c.m.}}$=81.3 MeV. The corresponding $1/\sin(\theta)$ fits are also shown. The angular distributions of oxygen and carbon particles from $^{12}C+^{93}Nb$ and $^{16}O+^{93}Nb$ re-

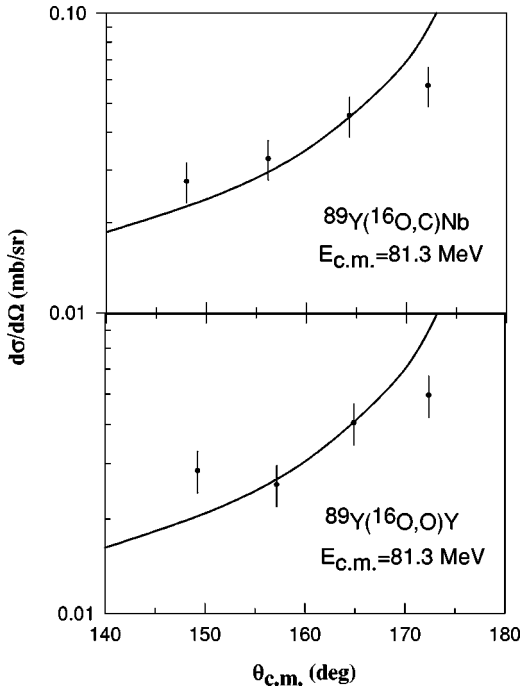

FIG. 1. Angular distributions of carbon and oxygen particles integrated over $0 \leqslant E_X \leqslant 45$ MeV and $0 \leqslant E_X \leqslant 39$ MeV exit channel excitation energy bins respectively in the c.m. frame. The solid lines are $1/\sin(\theta)$ fits.

actions also show similar trends. So the observed back-angle angular distributions of oxygen and carbon particles in the c.m. frame follow approximately a $1/\sin(\theta)$ function implying the formation of a long-lived intermediate state which could be either a compound nucleus or orbiting complex. In Fig. 2, we have plotted exit channel excitation energies versus the ratios of angle-integrated oxygen to carbon yields for $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions in different excitation energy bins. A strong entrance channel dependence has been found in the highly damped region starting from around exit channel excitation energy $E_X \geqslant 30$ MeV. The observation of this entrance channel dependence (favoring breakup into the entrance channel) along with a $1/\sin(\theta)$ angular distribution implies the formation of a long-lived intermediate orbiting complex. In the lower exit channel excitation energy region ($E_X \leqslant 29$ MeV), the ratios of oxygen to carbon yields for $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions overlap with each other implying no entrance channel dependence and hence no significant orbiting yield in this excitation energy region. The corresponding calculation using statistical model code CASCADE [15] is also shown in Fig. 2. We find that the statistical model calculations agree reasonably well with $^{12}C+^{93}Nb$ reaction data in all excitation energy regions. It also agrees with $^{16}O+^{89}Y$ reaction data in the lower excitation energy region ($E_X \leqslant 29$ MeV), but disagrees completely in the higher excitation energy region. The absolute oxygen yield obtained by integrating over energy and $1/\sin(\theta)$ angular distribution in the c.m. frame is about 1 mb for $^{16}O+^{89}Y$ reaction and this is about two orders of magnitude larger than the statistical compound nucleus model calculations. However the absolute yields of carbon and oxygen particles obtained from $^{12}C+^{93}Nb$ reactions (0.1 mb and 0.01 mb, respectively) are in agreement with statistical model calculations. So for both oxygen and carbon emissions, $^{12}C+^{93}Nb$ reaction data are consistent with the formation of a statistical compound nucleus, in agreement with the observation and conclusion of Charity *et al.* [16]. Jing *et al.* also studied [17] many other reactions such as $^{78,82,86}Kr+^{12}C$, $^{90,94,98}Mo+^{12}C$, and found good agreement with statistical transition-state model calculations for the emission of all types of particles emitted at backangles in the c.m. frame.

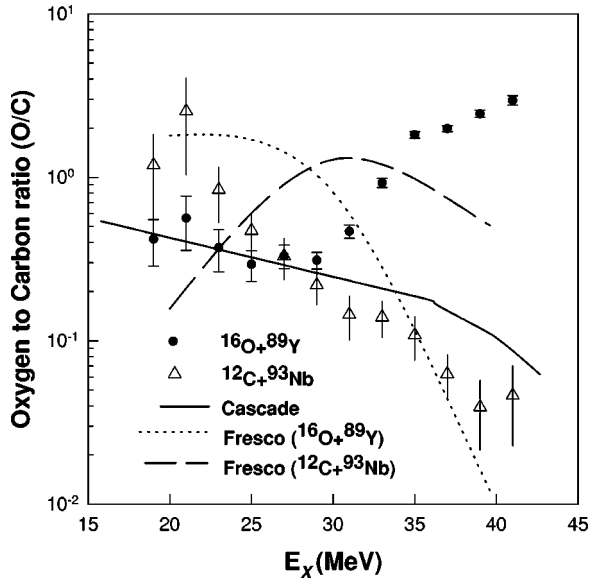

FIG. 2. Exit channel excitation energy (E_X) vs the ratios of angle-integrated oxygen to carbon yields for $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions at $E(^{16}O)_{lab}=95.9$ MeV and $E(^{12}C)_{lab}=85.5$ MeV respectively. CASCADE and FRESCO code calculations are also shown.

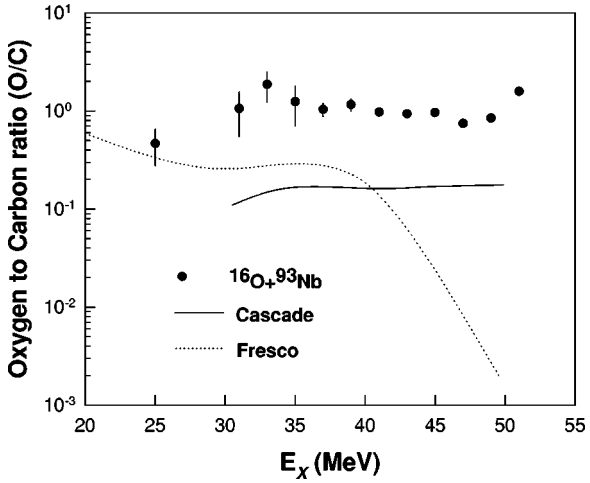

FIG. 3. Exit channel excitation energy (E_X) vs the ratios of angle-integrated oxygen to carbon yields for $^{16}O+^{93}Nb$ reaction at $E(^{16}O)_{lab}=116$ MeV. CASCADE and FRESCO code calculations are also shown.

In Fig. 3, we show the ratios of angle-integrated oxygen to carbon yields with exit channel excitation energy for $^{16}O+^{93}Nb$ reaction at $E(^{16}O)_{lab}=116$ MeV and the corresponding

statistical model CASCADE code calculations. We find that the observed oxygen to carbon ratios are higher than the calculated ratios by about a factor of 10 on average in the entire excitation energy region implying dominance of orbiting over compound nucleus yield. However the differences between experimental results and statistical model calculations are not as large (Fig. 3) as seen for the lower energy ^{16}O $+^{89}$Y reaction (Fig. 2), implying that the compound nucleus contribution compared to orbiting increases significantly at higher bombarding energy. The absolute oxygen yield obtained by integrating over energy and angular distribution is about 4 mb and this is more than an order of magnitude higher than the statistical compound nucleus model calculations.

We conclude from our present work and earlier works [16,17] that for reactions with ^{12}C, statistical compound nucleus is formed even when large orbital angular momenta (close to ℓ_{crit}) are involved, whereas for reactions with ^{16}O involving large ℓ, orbiting has been found to be dominant. However, even for reactions with ^{16}O, the relative importance of compound nuclear contribution compared to orbiting seems to increase rather rapidly at higher energy as we found from higher energy ^{16}O+^{93}Nb reaction.

We have done coupled channel calculations using FRESCO code [18] to study whether the coupling among different states and Q value differences between ^{12}C and ^{16}O induced reactions might explain our experimental results. In our coupled channel calculations, two low-lying excited states of ^{93}Nb (E_X=0.74 MeV, J^π=7/2$^+$, β=0.12 and E_X=0.809 MeV, J^π=5/2$^+$, β=0.024) and ^{89}Y (E_X=1.51 MeV, J^π=3/2$^-$, β =0.05 and E_X=2.22 MeV, J^π5/2$^+$, β=0.105) having non-negligible deformation parameters, first excited states of ^{16}O and ^{12}C along with one high energy excited state (E_X $\geqslant$10 MeV) have been included. We assumed excited states of ^{89}Y at E_X=10 MeV, J^π=9/2$^+$; E_X=20 MeV, J^π=11/2$^+$; E_X=30 MeV, J^π=11/2$^+$; E_X=40 MeV, J^π=11/2$^+$; E_X =50 MeV, J^π=7/2$^+$. The excited states of ^{93}Nb nuclei were assumed at E_X=10 MeV, J^π=9/2$^+$; E_X=20 MeV, J^π=13/2$^+$; E_X=30 MeV, J^π=17/2$^+$; E_X=40 MeV, J^π=21/2$^+$; E_X =50 MeV, J^π=17/2$^+$. The potentials for the elastic channels are taken to be double folded potential calculated using standard nucleon density distribution. The coupling between each excited channel and elastic channel has been considered. In addition, the coupling between first excited state of the projectile and excited states of the target nucleus have also been considered. Using FRESCO code, the oxygen and carbon yields for ^{16}O+^{89}Y and ^{12}C+^{93}Nb reactions were calculated at back angles (from 130° to 170° in the c.m. frame) when ^{89}Y or ^{93}Nb goes to one of the above highly excited states ($E_X \geqslant$10 MeV). The angular distributions for all those high energy states show back-angle rise. In Figs. 2 and 3, we show the results of FRESCO code calculations for the ratios of back-angle-integrated oxygen to carbon yields versus E_X. These results also show that the ratios of back-angle-integrated oxygen to carbon yields decrease at higher E_X. FRESCO code calculations have been repeated by changing the spin and parities of the unknown highly excited states and also by coupling more than one highly excited state with low-lying states, but the results qualitatively remain unchanged. So we find that the coupled channel calculations cannot even qualitatively reproduce the observed oxygen to carbon ratios for the reactions studied in our experiments.

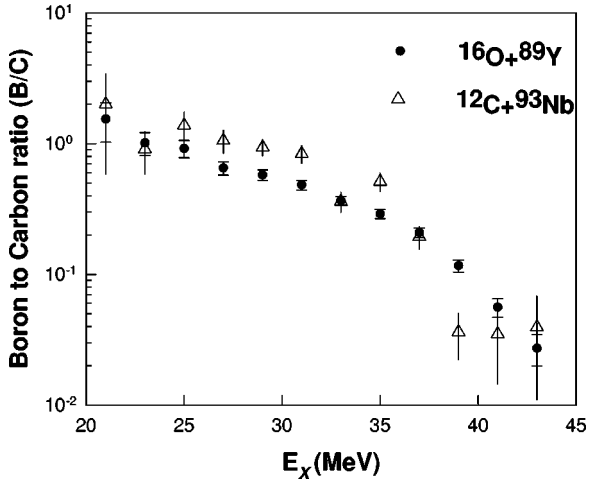

FIG. 4. Exit channel excitation energy (E_X) vs the ratios of angle-integrated boron to carbon yields for ^{16}O+^{89}Y and ^{12}C $+^{93}$Nb reactions at $E(^{16}\mathrm{O})_{lab}$=95.9 MeV and $E(^{12}\mathrm{C})_{lab}$=85.5 MeV, respectively.

We have also studied the ratios of boron to carbon yields, beryllium to carbon yields, lithium to carbon yields, etc. for both ^{16}O+^{89}Y and ^{12}C+^{93}Nb reactions. In Fig. 4, we show the ratios of angle-integrated boron to carbon yields versus exit channel excitation energy for ^{16}O+^{89}Y and ^{12}C+^{93}Nb reactions and find that the data sets overlap with each other. Similar plots for the ratios of angle-integrated beryllium to carbon and lithium to carbon yields also show that the corresponding data sets for the two reactions overlap with each other. These results show that there is no significant entrance channel effect for other channels implying that lithium, beryllium, boron, and carbon particles come from an equilibrated compound nucleus. So the orbiting effect is significant only in the entrance channel at high exit channel excitation energy region for reactions between spherical nuclei such as ^{16}O+^{89}Y, ^{16}O+^{93}Nb, etc.

The temperatures of the intermediate complexes and Coulomb barriers of the emitted carbon and oxygen particles have been determined by fitting oxygen and carbon spectra from ^{16}O+^{89}Y, ^{12}C+^{93}Nb and ^{16}O+^{93}Nb reactions with Moretto's algebraic formula [19] for statistical emission of particles as given below.

$$P(x) \propto \exp(-x/T)erfc\left(\frac{p-2x}{2\sqrt{pT}}\right), \qquad (1)$$

where x=E_{kin}(c.m.)$-V_c$. Here V_c, E_{kin}(c.m.), p and T are the Coulomb barrier energy, exit channel center of mass kinetic energy, amplification parameter and temperature of the compound nucleus respectively. In Fig. 5, we show angle integrated (assuming 1/sin(θ) angular distribution) carbon and oxygen spectra from ^{16}O+^{89}Y reaction in the c.m. frame and the corresponding fits using Eq. (1). The extracted temperature of the intermediate complex from carbon spectrum of ^{16}O+^{89}Y reaction is about 3 MeV and

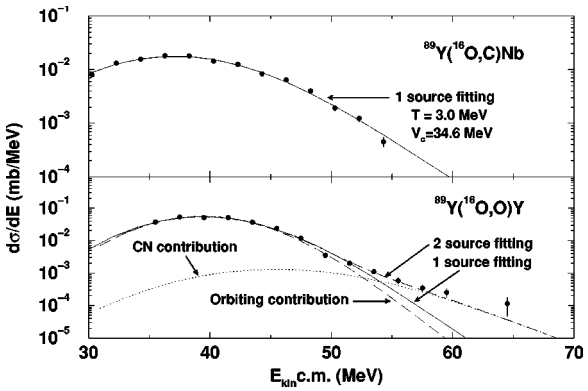

FIG. 5. Angle-integrated carbon and oxygen spectra in the center of mass frame for $^{16}O+^{89}Y$ reaction at $E(^{16}O)_{lab}=95.9$ MeV. E_{kin} c.m. is the exit channel kinetic energy in the center of mass frame. The orbiting and compound nuclear contributions to oxygen spectrum are shown.

$V_c=34.6$ MeV, which is consistent with the idea of formation of a compound nucleus at $E_X=76$ MeV, as we found from our earlier study [20] of α particle evaporation from the same compound nucleus. However a similar one source fit of the oxygen spectrum from $^{16}O+^{89}Y$ reaction yields $T=1.74$ MeV and $V_c=37.86$ MeV implying that the bulk of the oxygen particles comes from a significantly lower temperature source and the extracted V_c is also about 5 MeV lower than the expected Coulomb barrier for oxygen. In the case of the formation of an orbiting $^{16}O+^{89}Y$ complex, both ^{16}O and ^{89}Y maintain their identities and a large fraction of the total energy is stored as potential energy of the nuclei, thus reducing the excitation energy of the orbiting complex. Hence the temperature of the orbiting complex is expected to be lower than that of the corresponding compound nucleus. Moreover, for such an orbiting complex, the transmission coefficients of orbiting oxygen particle are expected to be large (compared to the corresponding compound nucleus case) implying that it sees a lower Coulomb barrier as we obtain from Fig. 5. We also find from the oxygen spectrum that one source (orbiting source) fit misses high exit channel kinetic energy points and clearly a two source fit by adding another term similar to Eq. (1) should improve the quality of fit. So we have attempted a two source fit that should decompose the oxygen spectrum into orbiting and compound nucleus parts. However, there is arbitrariness in such decomposition and so certain constraints based on physical considerations have to be put in. Based on our carbon spectrum analysis and CASCADE code calculations, we fixed the value of V_c for one of the sources (compound nuclear source) to 42.85 MeV and the corresponding parameter p that determines the width of the oxygen spectrum to $p=22$ MeV. The remaining parameters were floated freely to obtain the decomposition shown in Fig. 5. We find that considering the entire spectrum, the compound nucleus contribution is about a factor of 100 lower than the orbiting contribution, but the compound nucleus contribution is dominant in the higher kinetic energy region as found in Fig. 2 also. Our two source fitting yields $T=1.5$ MeV and $V_c=38$ MeV for the orbiting source, and $T=3.1$ MeV and $V_c=42.85$ MeV (kept fixed) for the compound nucleus source.

In the case of $^{16}O+^{93}Nb$ reaction, one source fit of the angle-integrated carbon spectrum yields $T=3.5$ MeV and $V_c=37.6$ MeV, in agreement with statistical compound nucleus model as we found from our earlier study [20] of α particles from the same compound nucleus. However, one source fit of the angle-integrated oxygen spectrum from $^{16}O+^{93}Nb$ reaction yields $T=2.9$ MeV, $V_c=43.0$ MeV. The lower values of T and V_c for oxygen spectrum are indicative of an orbiting complex source as discussed before.

So for reactions between spherical nuclei involving ^{16}O, the back-angle contribution to the entrance channel comes dominantly from a long-lived orbiting complex formed at a considerably lower temperature than the expected compound nucleus temperature and the extracted V_c is also lower. In the case of lower energy $^{16}O+^{89}Y$ reaction, the compound nucleus contribution has been found to be dominant at higher exit channel kinetic energy. We find from the analysis of different exit channels such as boron, beryllium, lithium, α, etc. that they dominantly come from a statistical compound nucleus. We have also found that all particle spectra including both oxygen and carbon spectra from $^{12}C+^{93}Nb$ reaction are consistent with the formation of a statistical compound nucleus. No significant orbiting contributions to any of those spectra have been found.

We have seen for the first time the evidence of entrance channel dependence and dinuclear orbiting in the heavier mass region ($A\approx100$) where the number of open channels is very large. These observations are qualitatively different from the earlier concept of fast or dynamical fission [11,12] reported in this mass region, which was basically a statistical process where no entrance channel dependence was seen. Our observations also cannot be understood by any kind of variation of statistical model such as equilibrium orbiting model of Shivakumar *et al.* [21] , because these models cannot produce any significant entrance channel effect and increase of oxygen over carbon yield [22].

In order to study preequilibrium emission of particles from these reactions, the formation time of the equilibrated compound nucleus (^{105}Ag) was calculated for both $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions near ℓ_{crit} at $\ell=40\hbar$ using nucleon exchange code HICOL [23]. The equilibration time has been found to be about the same (4×10^{-21} s) for both the reactions indicating that the preequilibrium emission of particles cannot be the reason for the observed entrance channel effect between $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions. HICOL code also shows that at high orbital angular momentum ($\ell=40\hbar$) for the reactions under consideration, nucleon flow takes place from the bigger nucleus to the smaller nucleus and the two nuclei reach approximately equal size at the time of equilibration.

We speculate that nuclear deformations might play important roles in determining whether orbiting would take place. The ground state of ^{12}C nucleus has a large intrinsic oblate deformation and takes all possible quantum mechanically indistinguishable orientations in space, thus appearing to be spherical-like ^{16}O, but increasing the effective surface thickness of ^{12}C. Hence for $^{12}C+^{93}Nb$ reaction, the attractive

nuclear force between the two nuclei should be stronger compared to that between similar spherical nuclei (with no intrinsic deformation) for orbital angular momentum near ℓ_{crit}, thus initiating fusion. Hence for reactions between spherical nuclei with large intrinsic deformation, fusion is expected to prevail over orbiting for large orbital angular momentum near ℓ_{crit}.

In the case of $^{16}O+^{89}Y$ reactions with high orbital angular momenta (that cause orbiting), we think that the nuclei do not overlap when they come closest to each other. At that configuration, ^{89}Y would be significantly deformed and take a prolate shape. But ^{16}O is not expected to be significantly deformed. If we assume that the tip of the deformed prolate-shaped ^{89}Y would have a lower nucleon density and hence lower Fermi momentum compared to that of the nucleons at the edge of ^{16}O, then the flow of nucleons from ^{89}Y to ^{16}O (as predicted by HICOL code) should be impeded, thus favoring orbiting over statistical compound nucleus formation. The formation of a compound nucleus might be favored when the nuclei are slightly further apart and ^{89}Y is less deformed so that the Fermi momentum of nucleons is similar at the edge of the two nuclei and hence the nucleon flow from ^{89}Y to ^{16}O is easier. In the case of reaction with lower orbital angular momenta, the two nuclei would overlap significantly at their closest configuration and then off course, the nuclei would fuse forming a statistical compound nucleus. Similarly the observation of orbiting for $^{16}O+^{93}Nb$ reaction at large ℓ might also be qualitatively understood.

In conclusion, we find orbiting in the $A\sim100$ mass region for spherical nuclear systems such as $^{16}O+^{89}Y$ and $^{16}O+^{93}Nb$ despite their large absorption probability. The orbiting effect has been found only in the entrance channel. However, ^{12}C induced reactions do not show any orbiting behavior in this mass region. Our observations cannot be explained by statistical model calculations, coupled channel calculations, or preequilibrium emissions. We speculate about the role of intrinsic deformation in initiating fusion and a possible drop in nucleon density at the tip of deformed prolate-shaped ^{89}Y and ^{93}Nb in inhibiting fusion and increasing orbiting probability.

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