Survival of orbiting in ^{20}Ne (7–10 MeV/nucleon) + ^{12}C reactions

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The inclusive energy distributions of fragments with $Z \geqslant 3$ emitted from the bombardment of ^{12}C by ^{20}Ne beams with incident energies between 145 and 200 MeV have been measured in the angular range $\theta_{lab} \sim 10°–50°$. Damped fragment yields in all cases have been found to be characteristic of emission from fully energy equilibrated composites; for B and C fragments, average Q values, $\langle Q \rangle$, were independent of the center-of-mass emission angle ($\theta_{c.m.}$), and the angular distributions followed a $\sim 1/\sin\theta_{c.m.}$-like variation, signifying long lifetimes of the emitting dinuclear systems. Estimates of total yields of these fragments have been found to be much larger than those predicted by the standard statistical model. This may be indicative of the survival of an orbiting-like process in the ^{12}C + ^{20}Ne system at these energies.

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Extensive efforts have been made in recent years to understand the mechanism of complex fragment emission in low-energy ($E_{lab} \lesssim 10$ MeV/nucleon), light heavy-ion ($A_{proj.} + A_{targ.} \lesssim 60$) reactions [1–11]. In most of the reactions studied, the observed fully energy damped yields of the fragments have been successfully explained in terms of the fusion-fission (FF) mechanism [12–17]. However, there has been a noticeable exception in the reactions involving α-cluster nuclei (e.g., ^{20}Ne + ^{12}C, ^{28}Si + ^{12}C, etc.), where a large enhancement in yield and a resonance-like excitation function in a few outgoing channels were observed, for which the deep-inelastic orbiting mechanism [8,10,11], has been found to be particularly competitive. The first observation of a fully energy-damped reaction yields in light systems was reported by Shapira *et al.* [8] in an investigation of ^{20}Ne + ^{12}C inelastic scattering at backward angles, where large cross sections have been observed in inelastic scattering yields near 180°. Orbiting was then evidenced in the ^{28}Si + ^{12}C reaction [10] and detailed studies on the same system revealed that, at lower bombarding energies, the excitation spectra for the ^{12}C fragments were dominated by single excitation and mutual excitations of the ^{12}C and ^{28}Si fragments, whereas at higher bombarding energies, the dominant strength for all these channels shifted to higher excitation energies [18]. For these higher energy spectra, the most probable Q values were found

to be independent of detection angle and the resulting angular distributions were found to have a $d\sigma/d\Omega \propto 1/\sin\theta_{c.m.}$-like angular dependence, characteristic of a long-lived, orbiting, dinuclear complex. Similar results have been obtained for the ^{20}Ne + ^{12}C system [8,9], where resonance-like behavior was also found in the excitation functions for several outgoing channels, similar to what has been observed for the symmetric ^{16}O + ^{16}O system. Subsequently, enhancements of large-angle, binary reaction yields have been observed in somewhat heavier ^{28}Si + ^{28}Si and ^{24}Mg + ^{24}Mg systems [1], where a significant nonresonant background yield was observed at higher excitation energies. All these results are indicative of the fact that the enhancements are not due to a specific structure effect appearing only in a few select channels; rather, they are manifestations of the dynamics of damped nuclear reactions involving a large number of channels.

Intuitively, the enhancement in elastic and inelastic channels may be explained in terms of a long-lived dinuclear configuration that decays back to the entrance channel owing to weak absorption, which inhibits the orbiting configuration from spreading into compound nuclear states. However, weak absorption of only grazing partial waves is sufficient to explain the enhancement in the elastic channel; in contrast, the orbiting phenomenon in general suggests weak absorption for even lower partial waves between the critical angular momentum of fusion, l_{cr}, and the grazing angular momentum, l_{gr}. Furthermore, because of the rapid mass equilibration that is thought to occur during the light systems, significant mass and charge transfer should also occur during the course of evolution of the orbiting dinuclear complex. So, the rearrangement channels are also of interest in probing the dynamics of the orbiting process involving light nuclear systems.

It is clear from these observations that, though some general consensus has been arrived at regarding the occurence of orbiting and/or resonance reactions (e.g., both are strongly

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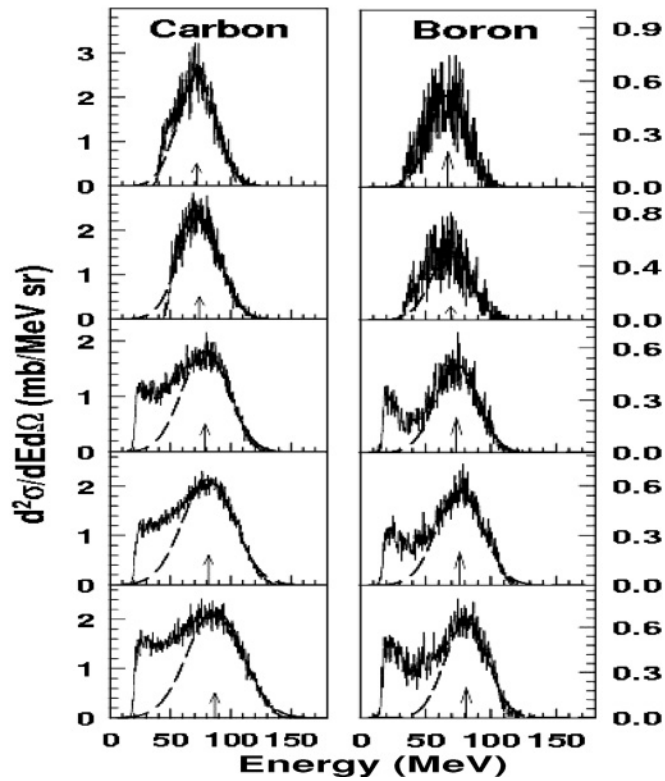
FIG. 1. Measured energy distributions of the B and C fragments emitted in the reaction ^{20}Ne + ^{12}C at E_{lab} = 145, 158, 168, 178, and 200 MeV (from top to bottom, respectively). The arrow corresponds to the position of the peak of the Gaussian distribution.

correlated with number of open reaction channels, which in turn are related to weak absorption of partial waves), the precise mechanisms of orbiting and resonance behavior are still unknown. For a better understanding of the orbiting process, it will be interesting to study how the orbiting process evolves with energy. Intuitively, the survival of a long-lived dinuclear configuration other than a fused composite is less probable at higher excitations and there are also indications that the entrance channel effect becomes smaller at higher energies [1]. Shapira *et al.* [9] made a detailed study of the ^{20}Ne + ^{12}C system in the energy range E_{lab} = 54–81 MeV and showed that there was large enhancement of strongly damped yields characteristic of a long-lived orbiting ^{20}Ne + ^{12}C dinuclear system. Our aim was to investigate whether the orbiting process would survive at even higher excitation energies, which might allow us to have a better understanding of orbiting in relation to FF processes. With this motivation, we have studied the fragment emission spectra from the reaction ^{20}Ne + ^{12}C at E_{lab} = 145, 158, 168, 178, and 200 MeV, to see whether orbiting still survives at higher energies.

The experiment was performed using accelerated ^{20}Ne beams of energies 145, 158, 168, 178, and 200 MeV, from the Variable Energy Cyclotron at Kolkata. The target used was 550 μg/cm^2 self-supporting ^{12}C. Different fragments have been detected using two solid state [Si(SB)] telescopes ($\sim$10 μm ΔE, 300 μm E) mounted on one arm of the 91.5-cm

scattering chamber. Two solid state telescopes ($\sim$50, 100 μm ΔE [Si(SB)] and 5 mm E[Si(Li)]) were mounted on the other arm of the scattering chamber for the detection of light charged particles; the same detectors were also used as monitor detectors for normalization purposes. The typical solid angle subtended by each detector was $\sim$0.3 msr. The telescopes were calibrated using elastically scattered ^{20}Ne ion from Au, Al, and a Th-α source. The systematic errors in the data, arising from the uncertainties in the measurements of solid angle, target thickness, and the calibration of current digitizer, have been estimated to be $\approx$15%. (Part of these uncertainties are due to the Gaussian fitting procedure employed to extract the fully damped yields from the sequential decay components.)

Inclusive energy distributions for various fragments ($3 \leqslant Z \leqslant 12$) have been measured in the angular range $10°$–$50°$. This covered backward angles in the center-of-mass (c.m.) frame, because of the inverse kinematics of the reactions. Typical energy spectra for B and C fragments obtained at an angle of $10°$ at E_{lab} = 145, 158, 168, 178, and 200 MeV, respectively, are shown in Fig. 1. It is evident from Fig. 1 that energy spectra of the ejectiles B and C at all bombarding energies exhibit strong peaking as a function of energy. In all cases, the energy distributions are nearly Gaussian in shape. The non-Gaussian shapes at the low-energy side of the energy spectra correspond to sequential decay processes, which can be simulated by Monte Carlo statistical-model calculations as elaborated later in the data analysis discussion. (The Gaussian fits so obtained are shown by dashed lines in Fig. 1; the centroids (shown by arrows) are found to correspond to the scission of the deformed dinuclear configuration [11,19,20]. This suggests that the fragments are emitted from a fully energy relaxed composite—as expected for both FF and orbiting processes. The increasing yields at lower energies may also be due to the second kinematical solution that is a signature of the binary nature of the emission process.

The c.m. angular distributions of the B and C fragments obtained at E_{lab} = 145, 158, 168, 178, and 200 MeV, respectively, are displayed as a function of c.m. angle in Fig. 2. The transformations from the laboratory to c.m. systems have been done with the assumption of a two-body kinematics averaged over total kinetic energy distributions. It is seen that the c.m. angular distributions of these fragments obtained at all bombarding energies follow the $1/\sin\theta_{c.m.}$-like variation (shown by solid lines), further corroborating the conjecture of emission from fully equilibrated composite.

The variations of average Q value, $\langle Q \rangle$, with c.m. emission angle for the B and C fragments obtained at different E_{lab} are shown in Fig. 3. It is observed that, for both fragments at all energies, the average Q values are independent of the c.m. emission angles. As energy increases, one expects that the contribution of a deep inelastic process should start showing up. Such a process is characterized by a sharp falloff of $\langle Q \rangle$ with angle, as observed in other light systems (^{16}O (116 MeV), ^{20}Ne (145 MeV) + ^{27}Al, ^{28}Si systems, for example, where fragment energy distribution had two components, one coming from fully energy equilibrated FF and the other from deep inelastic reactions [2,3]). In contrast, for the ^{20}Ne + ^{12}C system, the $\langle Q \rangle$ values remain nearly constant, which further suggests that, at all the angles, the
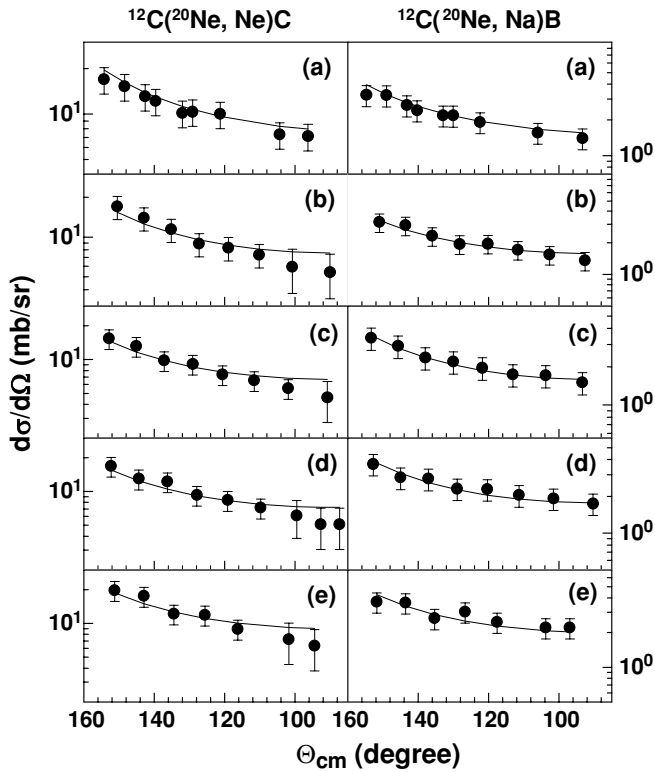
FIG. 2. The c.m. angular distributions of the B and C fragments obtained at $E_{\text{lab}} = 145$, 158, 168, 178, and 200 MeV (from (a) to (e), respectively). Solid circles correspond to experimental data and the solid curves are $f(\theta_{\text{c.m.}}) \sim 1/\sin\theta_{\text{c.m.}}$ fit to the data.

FIG. 3. Average Q values of the B and C fragments obtained at $E_{\text{lab}} = 145$, 158, 168, 178, and 200 MeV (denoted by inverted triangle square, diamond, triangle, and circle, respectively) plotted as a function of c.m. emission angle.

fragments are emitted from completely equilibrated source at all the incident energies considered here. It is quite interesting to note that ^{16}O, ^{20}Ne $+ ^{28}$Si systems, even though α-like, do not fall in line with other light α-like systems, such as ^{20}Ne $+ ^{12}$C, and ^{28}Si $+ ^{12}$C systems, for example, as far as the shape of the energy distributions, variation of $\langle Q \rangle$ values with angle, and yields of the fragments are concerned. This difference in behavior may be related to the number of open channels, which is much smaller in ^{20}Ne $+ ^{12}$C, and ^{28}Si $+ ^{12}$C systems [21].

Clearly these observations indicate that the yield of these fragments originates from fully energy relaxed events associated with the decay of either a compound nucleus or a long-lived, orbiting dinuclear system. The possibility that the B and C fragments might be produced wholly or partially through the aforementioned processes has been investigated more quantitatively by comparing the experimental yields with the theoretical predictions of the standard statistical model [22], the extended Hauser-Feshbach model (EHFM) [14]. The solid circles and triangles in Fig. 4 are the experimental angle-integrated yields of the fragments. The solid lines in Fig. 4 (left side) are the predictions of the statistical model code CASCADE [22]. The calculations, using l values up to l_{cr} at each energy ($l_{\text{cr}}(\hbar) = 24$, 24, 24, 25, and 25 for $E_{\text{lab}} = 145$, 158, 168, 178, and 200 MeV, respectively [23]), are found to underpredict the experimental yields. A similar observation has been reported by Shapira *et al.* [8,9] for the
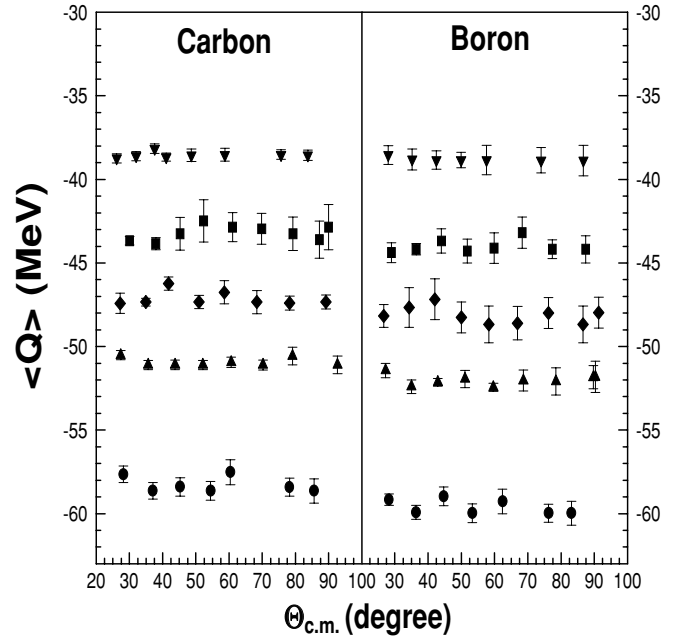
same system at lower energies. In Fig. 4 (right side), the EHFM predictions of the experimental yields of C and B (solid lines) have been displayed along with the present experimental data (filled triangles). Interestingly the EHFM predictions are also similar to those obtained from CASCADE calculations and the experimental yields are in fair excess of the theoretical estimates of both CASCADE and EHFM.

Since the statistical models do not reproduce most of the observed experimental behaviors, an additional reaction component corresponding to the orbiting mechanism has to be considered. The large measured cross sections led to the suggestion that an orbiting, dinuclear configuration is formed that decays back to the entrance channel. After the discovery of orbiting in the ^{12}C $+ ^{28}$Si system, similar enhancements of large-angle, binary-reaction yields have also been observed in the present data. It is expected that the orbiting mechanism will retain a greater memory of the entrance channel than the FF process. The trapped, dinuclear complex can either evolve with complete amalgamation into a fully equilibrated compound nucleus or, alternatively, escape into a binary exit channel by way of orbiting trajectories. Orbiting can therefore be described in terms of the formation of a long-lived dinuclear molecular complex that acts as a "doorway" state to fusion with a strong memory of the entrance channel. The equilibrium orbiting model has been used to successfully explain both the observed cross sections and total kinetic energy (TKE) values of the fully damped fragments for several lighter nuclear systems at lower energies. However, in the present case, the theoretical values of the equilibrium orbiting model [11] [shown in Fig. 4 (left side) as dash-dot-dotted curves] are also found to underpredict the experimental yields. It is, therefore,
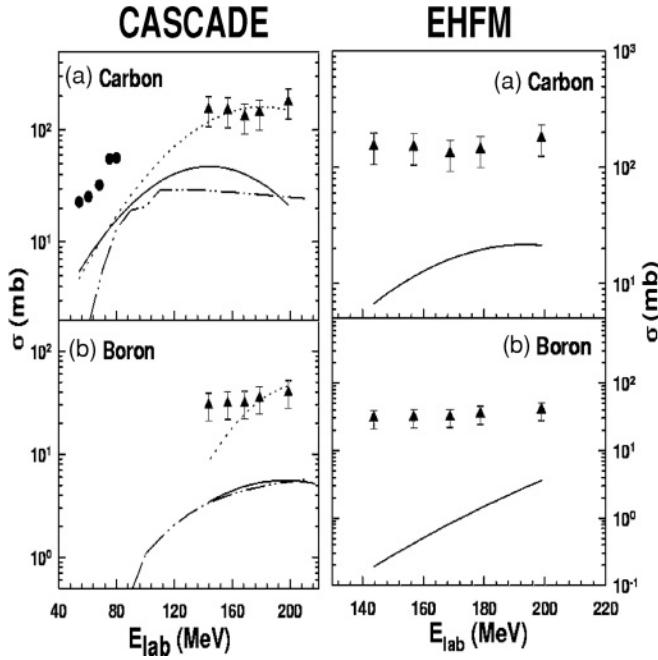
FIG. 4. The excitation functions for the angle-integrated yield of the carbon and boron fragments. Triangles are the present data; lower energy data (shown by solid points) have been taken from [8]. In the left side of the figure, solid, dashed and dash-dot-dotted curves are the predictions of the statistical model with $l = l_{\mathrm{cr}}$, $l = l_{\mathrm{gr}}$, and the equilibrium orbiting model, respectively. Solid curves in the right side of the figure are EHFM predictions.

evident that both the equilibrium orbiting and statistical decay (CASCADE, EHFM) models result in comparable disagreement with the data. It may be interesting to note here that Shapira *et al.* studied the same reaction at lower energies [8,9] and came to the conclusion that the large enhancements in the energy-damped fragment yield observed at those energies might be due to a nuclear orbiting phenomenon. The average Q values for the C and B fragments have been plotted in Fig. 5 as a function of incident energy. The linear dependence of $\langle Q \rangle$ with energy provides strong evidence that the long lifetime may be associated with an orbiting phenomenon. This linear dependence of $\langle Q \rangle$ can be expressed by the following simple equation: $\langle Q \rangle = (14.9 \pm 1.0) - (0.97 \pm 0.02)E_{\mathrm{c.m.}}$. Note that the $\langle Q \rangle$ values obtained in the present experiment between 145 and 200 MeV fall on the same straight line extrapolated from the lower energy ($\sim$50–80 MeV) data [9]. This means that the energy relaxation is complete for the fragment emission studied here up to the incident energy of 200 MeV. Moreover, it also means that the final kinetic energy ($E_{\mathrm{kin}}^{f} = \langle Q \rangle + E_{\mathrm{c.m.}}$) is nearly independent of bombarding energy—which may be due to the limitation on the maximum value of a angular momentum beyond which the formation of a dinucleus is not allowed owing to centrifugal repulsion [18].

In general, the energy distributions, the angular distributions, and the total fragment yields measured for the ^{20}Ne + ^{12}C reaction at incident energies between 145 and 200 MeV are similar to those obtained at lower incident energies ($\sim$50–80 MeV) for the same system (see Refs. [8,9]). Large energy
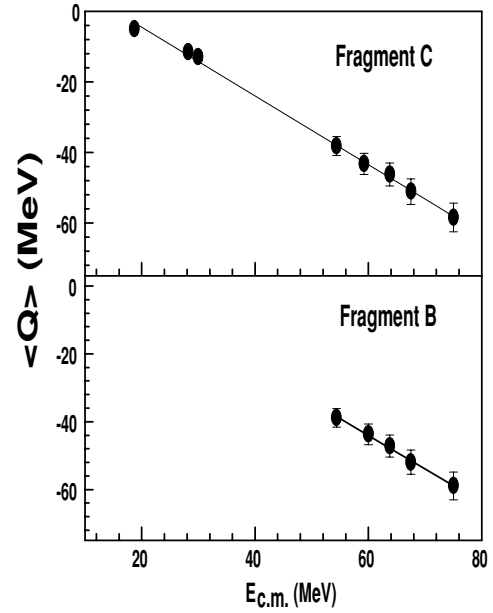

FIG. 5. Bombarding energy dependence of the average Q values. The solid line shows the linear dependence of $\langle Q \rangle$ with bombarding energy. The $\langle Q \rangle$ values at lower energies are taken from [9].

damping, a $1/\sin\theta_{\mathrm{c.m.}}$ dependence of angular distribution, and the near constancy of $\langle Q \rangle$ over a wide angular range signify that the fragment decay originates from a long-lived, fully energy equilibrated system. However, the large enhancement of fragment emission cross section over the statistical model predictions leads to the conjecture that the orbiting mechanism may still play a major role at these energies, though the equilibrium orbiting model of Ref. [11] also fails to explain the large enhancement in yield. The dash-dot-dotted curve displayed in Fig. 4 (left side) represents the "best fit" that can be obtained by the orbiting model with a reasonable choice of the Bass potential parameters (strengths, short range, and long range of the proximity potential). To check whether the enhancement in C yield could be due to feeding from the secondary decay of heavier fragments of various possible binary breakup combinations, we have performed detailed simulations of secondary decay using the Monte Carlo binary decay version of the statistical decay code LILITA [24]. The secondary decays of Ne* (binary channel ^{20}Ne + ^{12}C), Mg* (binary channel ^{28}Mg + ^{8}Be), Si* (binary channel ^{28}Si + ^{4}He), and O* (binary channel ^{16}O + ^{16}O) have been studied. Indeed the LILITA calculations (using the parameter set proposed in the appendix of Ref. [9] and assuming the excitation energy division follows the mass ratio [1]) are in qualitative agreement with the experimental results obtained at 9 MeV/nucleon by Rae *et al.* [25] for the sequential decay of ^{20}Ne + ^{12}C. It was found that even at the highest excitation energy, the secondary decays of Mg* and Si* do not reach up to C; the contribution of primary Ne* decay to C yield was estimated to be $\sim$15–20% of the primary yield. Nearly $\sim$40–45% of the primary O* produced through binary exit channel ^{16}O + ^{16}O decays to C; however, as the O binary yield is small ($\sim$10% of the binary Ne yield, as estimated from CASCADE [22]), the overall

secondary decay contribution from O is smaller than that from Ne. Moreover, the simulations of energy distributions of the secondary decay yield of C from Ne as well as O using the code LILITA show that they peak at much lower energies (typically, at ∼45–50 MeV for Ne and ∼55–60 MeV for O, compared to the peak of the experimental energy distribution at ∼70–90 MeV). Now, the Gaussian fitting procedure for the extraction of the primary C yield is fairly efficient in rejecting most of the low-energy tail (with a typical rejection ratio ∼25–30% of the total yield). It is thus evident that the secondary decay component does not interfere with the estimated primary C yield for two reasons: (i). The total secondary decay yield is not quite large, and (ii). The Gaussian fitting procedure for the extraction of primary C yield does take care, to a large extent, of the rejection of the contributions of the secondary decay components as their energy distributions are different from those of the primary components.

In conclusion, the present analysis seems to indicate that there is significant enhancement in fragment yield for ^{20}Ne + ^{12}C reactions in excess to the corresponding equilibrium model predictions [11]. The shortcomings of the equilibrium model for orbiting does not imply that the presence of an orbiting mechanism, as distinct from fission, can be ruled out. On the contrary, there may be a large orbiting-like contribution from nonfusion window ($l_{cr} \leqslant l \leqslant l_{gr}$). This is consistent, at least qualitatively, with the fact that a CASCADE

calculation [22] performed with l values up to l_{gr} ($l_{gr}(\hbar) = 31$, 33, 34, 36, and 38 for E_{lab} = 145, 158, 168, 178, and 200 MeV, respectively [26]) is found to reproduce the data fairly well [dotted lines in Fig. 4 (left side)]. Yields in the transfer channels (B, for example) are also found to be strongly affected by the orbiting process (yield enhancement), which may be due to stochastic nucleon exchanges during the long lifetime of the dinuclear system. Although ^{16}O, ^{20}Ne + ^{28}Si systems, even though α-like, do not show the characteristics of orbiting at these energies, orbiting-like behavior has been observed for the ^{28}Si + ^{16}O reaction at lower energies [16]. Thus, the enhancement in fragment yield observed in the present data is primarily believed to be due to an orbiting phenomenon; however, the equilibrium orbiting model, in its present form, seems to be inadequate to explain the whole set of data, and a more complete understanding of orbiting and its relationship angular momentum dissipation (which plays a crucial role in defining orbiting trajectories and yield) will be required.

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