PHYSICAL REVIEW C **78**, 044601 (2008)

Fragment emission studies of the $^{16}O + ^{12}C$ reaction

S. Kundu, A. Dey,* K. Banerjee, T. K. Rana, S. Muhkopadhayay, D. Gupta,† R. Saha, S. Bhattacharya, and C. Bhattacharya‡
Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata-700 064, India
(Received 23 April 2008; published 1 October 2008)

The inclusive energy distributions of the fragments ($3 \leqslant Z \leqslant 5$) emitted in the reaction $^{16}O + ^{12}C$ have been measured in the angular range 9° to 29°, at the energies 117, 125, 145, and 160 MeV, respectively. The centroids of the fragments energy distributions follow Viola systematics, which suggest that the fragments are emitted from a fully energy relaxed composite—as expected for both FF and orbiting processes. The center of mass angular distributions of the fragments B, Be, and Li obtained at all the bombarding energies follow $1/\sin\theta_{c.m.}$ like variation—which further corroborates the conjecture of emission from fully equilibrated composite. The average $\langle Q \rangle$ values for the fragments B, Be, and Li are found to be independent of the center of mass emission angles, which further suggest that at all angles, the fragments are emitted from completely equilibrated source at all incident energies considered here. The yields of the fragments Li and Be are in agreement with statistical-model predictions. The enhanced yields of entrance channel fragment B indicate the survival of orbiting-like process in $^{16}O + ^{12}C$ system at these energies.

DOI: 10.1103/PhysRevC.78.044601 PACS number(s): 25.70.Jj, 24.60.Dr, 25.70.Lm

I. INTRODUCTION

In recent years, extensive studies have been made to understand the fragment emission mechanisms in low energy ($E_{lab} \leqslant 10$ MeV/nucleon) light heavy-ion ($A_{proj.} + A_{tar.} \leqslant 60$) reactions [1–19]. These fragments are found to be emitted from quasielastic (QE)/projectile breakup [2,3], deep-inelastic (DI) transfer, and orbiting [4–7,9,15–19] to fusion-fission (FF) [20–25] processes; and in some cases the structure of the nuclei has been found to play an important role. Though in most of the reaction studied, the energy damped yields of the fragments have been successfully described in terms of fusion-fission (FF) process [20–25], however, there are exceptions in the reactions involving α-cluster nuclei (e.g., $^{20}Ne + ^{12}C$ [15,16], $^{24}Mg + ^{12}C$ [19], $^{28}Si + ^{12}C$ [17,26], etc.) where the observations of large enhancement in yield and/or resonance-like excitation function in a few outgoing channels (near to the entrance channel) have indicated the competitive role played by the deep-inelastic orbiting mechanism [15–18]. Deep inelastic orbiting is described in terms of the formation of a long-lived, dinuclear molecular complex [18], with a strong memory of the entrance channel. In addition, in the case of the light heavy-ion systems, the shapes of the orbiting dinuclear complexes are quite similar to the saddle and scission shapes obtained in course of evolution of the FF process. Both orbiting and fusion-fission processes occur on similar time scales and hence the distinction between the signatures of the two processes is real challenge.

The first observation of the enhancement of fully energy damped yields in light systems was reported by Shapira *et al.* [15] in the study of $^{20}Ne + ^{12}C$ inelastic scattering at backward angles where large cross sections have been observed in inelastic scattering yields near 180°. Subsequently, orbiting was observed in $^{28}Si + ^{12}C$ [17,26] and $^{24}Mg + ^{12}C$ [19] reactions. Recently, in an extensive study for $^{20}Ne + ^{12}C$ system [4,7] in the energy range 145–200 MeV revealed that, even at higher bombarding energies, the signatures of equilibration persists, i.e., the most probable Q-values for the fragments were found to be independent of detection angles and the resulting angular distributions of the fragments were found to have $d\sigma/d\Omega \propto 1/\sin\theta_{c.m.}$—like angular dependence; however, the enhancement in the fully energy damped fragment yields near the entrance channel over the statistical model predictions, indicated the survival of orbiting at higher excitation energies. Enhancements of large angle, binary reaction yields have also been observed in somewhat heavier $^{28}Si + ^{28}Si$, $^{24}Mg + ^{24}Mg$ systems [1], where significant nonresonant background yield was observed at higher excitation energies. These studies clearly indicate that the enhancements are manifestations of dynamics of damped nuclear reactions involving a large number of channels, rather than due to specific structure effect appearing only in a few select channels.

The deep-inelastic orbiting phenomenon in general suggests weak absorption in the angular momentum window between the critical angular momentum of fusion, l_{cr}, and the reaction grazing angular momentum, l_{gr}. In addition, substantial mass and charge transfer, would also occur during the evolution of the orbiting dinuclear complex. So, the study of rearrangement channels will give opportunity to probe the dynamics of the orbiting process involving light nuclear systems. Though the phenomenon of deep-inelastic orbiting reaction have been described in terms of observation of small number of open reaction channels [27], or, alternatively, to weak absorption, the precise mechanism of the process is still unknown.

The deep-inelastic orbiting process has been observed in several light α-like systems, for example, $^{20}Ne + ^{12}C$

*Present address: Saha Institute of Nuclear Physics, 1/AF, Bidhan Nagar, Kolkata-700 064, India.
†Present address: Bose Institute, Dept. of Physics and Centre for Astroparticle Physics and Space Science, Sector V, Block EN, Bidhan Nagar, Kolkata-700 091, India.
‡chandana@veccal.ernet.in

[15,16], $^{24}Mg + ^{12}C$ [19], $^{28}Si + ^{12}C$ [17,26], $^{28}Si + ^{16}O$ [28] systems, where the number of open channels are small ($\sim$10) [27]. However, the ^{16}O (116 MeV) $+^{28}Si$ reaction [9] showed different behavior so far as the shape of the energy distributions, variation of $\langle Q \rangle$ values with angle and yields of the fragments are concerned. For a better understanding of the orbiting process, it is important to study how the orbiting process evolves with energy. In light-heavy-ion systems, it is conjectured that the long-lived molecular resonance phenomena evolve as a function of bombarding energy into shorter lived orbiting processes leading to the formation of dinucleus with nucleon exchange affecting the exit channel configuration significantly. Recently, a detailed study of the competition between direct and dissipative processes in binary channels in the sytems $^{16}O + ^{12}C$, $^{18}O + ^{12}C$ have been made by Szilner *et al.* [6] in the energy range 5–7.7 MeV/nucleon. For both the systems, resonant structure has been observed at lower energies and refractive effects at higher energies, which may be considered as the signature of the orbiting process.

In the present work, we report a study of fragment emission from $^{16}O + ^{12}C$ reaction in the bombarding energy range 7–10 MeV/nucleon with the aim to explore the role of different mechanisms (FF, DIO, etc.) in the yields of various exit channels. A significant mass and charge transfer should occur, during the course of evolution of rotating dinuclear complex, which leads to typical deep-inelastic reaction yields. Therefore, the study of the rearrangement channels offer a special interest in probing the dynamics of the long-lived dinuclear complex. With this motivation, a detailed study of fragment energy spectra have been made for the reaction $^{16}O + ^{12}C$ at different bombarding energies viz. $E_{lab} = 117$, 125, 145, and 160 MeV, respectively.

The article has been arranged as follows. The experimental setup is described in Sec. II, in brief. The experimental results and analysis are presented in Sec. III. The results are discussed in details in Sec. IV. Finally, the summary and conclusion are given in Sec. V.

II. EXPERIMENT

The experiment was performed at the Variable Energy Cyclotron Centre, Kolkata, using ^{16}O ion beams of energies of 117, 125, 145, and 160 MeV, respectively. The target used was 514 μg/cm^2 self-supporting ^{12}C. Different fragments were detected using two Si(SB) telescopes ($\sim$10 μm ΔE, $\sim$ 300 μm E, and $\sim$10 μm ΔE, $\sim$5 mm E,). Typical solid angle covered by each detector was $\sim$0.3 msr. The calibration of telescopes were done using elastically scattered ^{16}O ion from Au target. Inclusive energy distributions for the various fragments ($3 \leqslant Z \leqslant 5$) have been measured in the angular range 9° to 29° [which covered the angular range 25°–90° in the center-of-mass (c.m.) frame]. The systematic errors in the data have been estimated to be $\approx$15%. These include the errors arising from the uncertainties in the measurements of target thickness, solid angle and the calibration of current digitizer. Part of these uncertainties are due to Gaussian fitting procedure employed to extract the energy damped yields.

III. RESULTS

A. Energy spectra

The energy spectra for the fragments B, Be, and Li obtained at an angle of 15° at $E_{lab} = 117$, 125, 145, and 160 MeV, respectively, are shown in Fig. 1. It is clear from Fig. 1 that the energy spectra of the fragments Be and Li, obtained at different incident energies, are typically Gaussian in shape and their centroids correspond to the expected kinetic energies for the binary breakup obtained from the Viola systematics corrected by the corresponding asymmetric factors [29,30]. The Gaussian fit so obtained are shown by solid lines in Fig. 1 with centroids shown by solid arrows. In the case of the B ejectile also, the binary-reaction yield may still be extracted as a Gaussian distribution having energy centroid obtained from Viola systematics (as shown in Fig. 1), though there is significant enhancement in yield at lower energy part of the spectrum which increases with bombarding energy. The width of the Gaussian distributions were extracted by constructing the fit to higher energy part of the spectrum (above the centroid energy), to minimize the contamination from enhanced low energy part of the spectrum.The enhanced yields at lower energy part of the spectrum may be partly due to the contributions from sequential decay of excited primary fragments which has been simulated by Monte Carlo statistical code LILITA [31] as discussed in detail in Sec. IV. In addition, the enhanced yields at low energy near the experimental threshold may arise from the second kinematical solution, which is a signature of binary nature of the emission process.

B. Angular distributions

The differential cross sections for each fragments B, Be, and Li were obtained by integrating the respective energy distributions under the fitted Gaussian. The c.m. angular distributions $(d\sigma/d\Omega)_{c.m.}$ of the fragments B, Be, and Li,

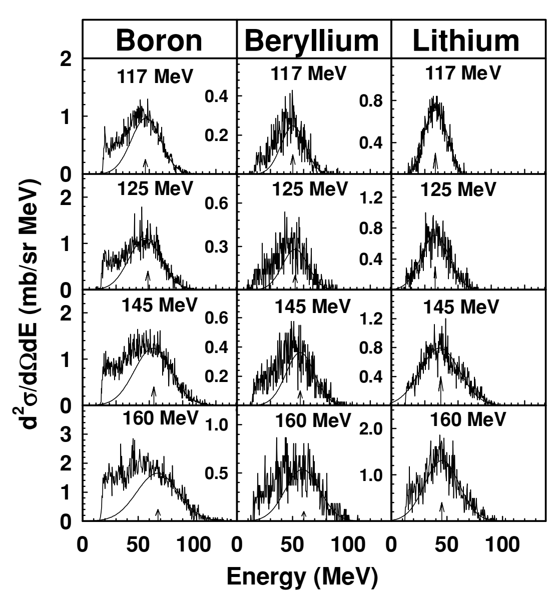

FIG. 1. Typical energy spectra of emitted fragments (B, Be, and Li) detected at an angle $\theta_{lab} = 15°$ at respective E_{lab}. Arrows indicate the centroid of the Gaussian distributions.

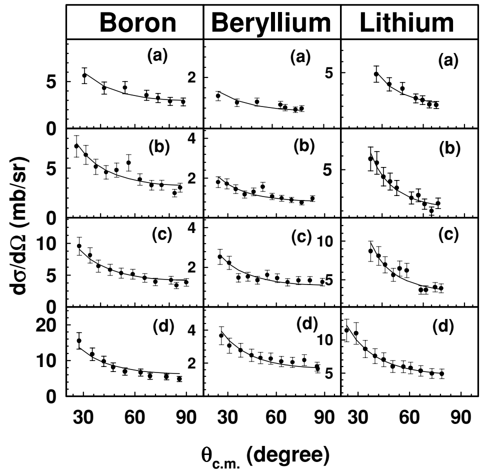

FIG. 2. The c.m. angular distributions of the B, Be, and Li fragments obtained at $E_{\text{lab}} = 117, 125, 145$, and 160 MeV [from (a) to (d), respectively]. Solid circles correspond to experimental data and solid lines show fit to the data obtained using the function $f(\theta_{\text{c.m.}}) \propto 1/\sin\theta_{\text{c.m.}}$.

obtained at $E_{\text{lab}} = 117, 125, 145$, and 160 MeV, respectively, have been displayed as function of c.m. angle in Fig. 2. The transformation from the laboratory to c.m. systems has been done assuming a two-body kinematics averaged over total kinetic energy distributions. The angular distribution of the fragments B, Be, and Li obtained at all bombarding energies are found to follow $1/\sin\theta_{\text{c.m.}}$ dependence in c.m. frame (shown by solid lines in Fig. 2.), which is characteristic of the fission like decay of an equilibrated composite system.

C. Average Q-value distributions

The angular variation of the average Q values of the fragments, provides information on the degree of equilibration. The variation of average Q values, $\langle Q\rangle$, with c.m. angle for the fragments B, Be, and Li obtained at different energies are shown in Fig. 3. It is observed that $\langle Q\rangle$ values for all the fragments obtained at different bombarding energies, are independent of center of mass emission angles. Similar results have also been observed in the case of fragments emitted in ^{20}Ne + ^{12}C system [4,7]. However, this is in contrast to the observation made earlier for the other light system [^{16}O(116 MeV) + ^{27}Al, ^{28}Si, ^{20}Ne (145, 158, 200, 218 MeV) + ^{27}Al], [5,8,9] where sharp falloff of $\langle Q\rangle$ with c.m. emission angles have been seen. For each fragments at all bombarding energies, the $\langle Q\rangle$ values remain same at all c.m. angles, which further suggests that the fragments are emitted from a completely equilibrated source at all the incident energies considered here.

D. Cross sections

All these observations indicate that the extracted binary-reaction yield of these fragments originate from the decay of a long-lived fully energy relaxed source, which may either be a CN or a long-lived orbiting dinuclear system. A detailed investigation have been made to decipher the role played by aforementioned processes in the fragment yield by comparing the extracted binary-reaction yields (obtained by

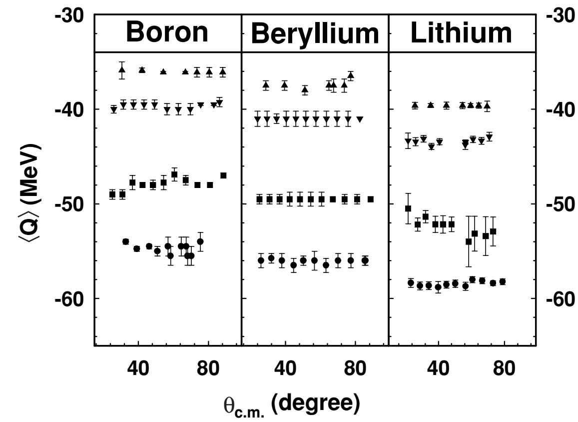

FIG. 3. Average Q values of the fragments B, Be, and Li obtained at $E_{\text{lab}} = 117, 125, 145$, and 160, MeV (denoted by triangle up, triangle down, square, and circle, respectively) plotted as a function of c.m. emission angle, $\theta_{\text{c.m.}}$.

integrating the fitted Gaussian distribution) with the theoretical predictions of the standard statistical model code CASCADE [32] and extended Hauser-Feshbach model (EHFM) [22]. The extracted angle integrated binary-reaction yields of the fragments emitted in the ^{16}O + ^{12}C reaction at different bombarding energies have been shown in Fig. 4 by solid circles. The solid lines in Fig. 4 are the theoretical predictions

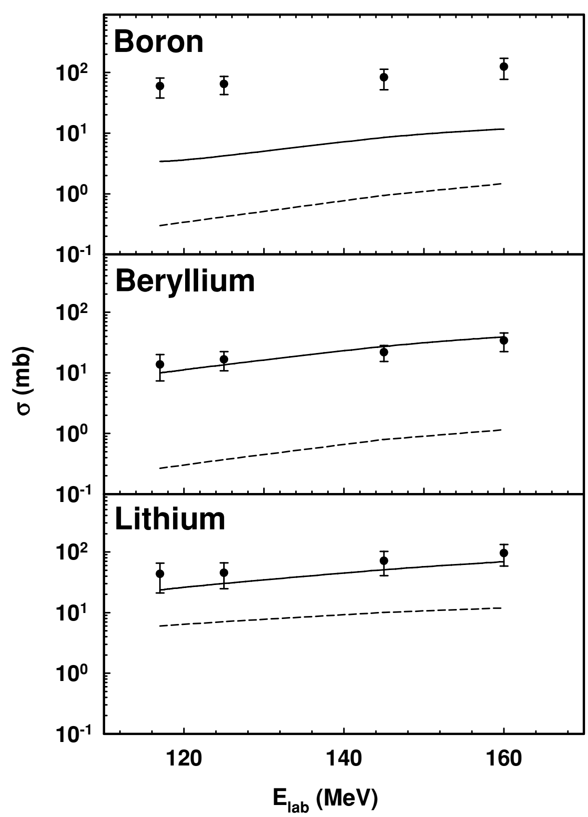

FIG. 4. Excitation functions for the angle-integrated (over the range $0^\circ \leqslant \theta_{\text{c.m}} \leqslant 180^\circ$) cross section of the B, Be, and Li fragments. Solid curves are the predictions of the statistical model with $l = l_{\text{cr}}$. Short dashed curves are the prediction from EHFM [22].

of the statistical model code CASCADE [32]. The calculations have been done using l values up to l_{cr}, the critical angular momentum for fusion, at each energy ($l_{cr}(\hbar) = 20, 21, 22$, and 23 for $E_{lab} = 117, 125, 145$, and 160 MeV, respectively [33]), and the CASCADE predictions are found to underpredict the experimental yields of the fragment B. However, for the fragments Be and Li, the experimental yields are nearly same as the respective CASCADE predictions. On the other hand, EHFM predictions (shown by short dashed line in Fig. 4) are found to be always smaller than the respective extracted binary yields and the mismatch is found to increase as one moves from Li to B.

It is evident from the above that, there is significant enhancement in B yield as compared to the respective statistical models prediction. For Li and Be fragments, too, the extracted binary yield are well explained by CASCADE, though they are underpredicted by EHFM. However, it may be noted here that the magnitude of mismatch (difference between the extracted and the predicted yields) increases progressively from Li to B, which clearly indicates, increasing additional contributions from other reaction mechanism as one moves from Li to B. So, notwithstanding the limitations of the statistical model calculations extended to light nuclear system, it is evident that there is clear signature of an enhancement in the yield of B as compared to the predicted yield. Such enhancement in the experimental binary yield with respect to respective theoretical predictions near entrance channel configuration is indicative of the formation of an orbiting dinuclear complex. As orbiting is usually 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, it is expected that the orbiting mechanism will retain a greater memory of the entrance channel than the FF process. Orbiting have first been established in the system $^{28}Si + ^{12}C$ by observing enhancements of large-angle, binary-reaction yields near to the entrance channel, similar enhancements of large-angle, binary-reaction yields have also been observed in the present data.

E. Excitation energy dependence

The variation of $\langle Q \rangle$, with incident energies for the B, Be, and Li fragments have been shown in Fig. 5. It is found that for all the fragments, the $\langle Q \rangle$ vary linearly with energy. This linear dependence provides strong evidence for the complete energy relaxation for the fragment emission studied here up to the incident energy of 160 MeV. This linear dependence of $\langle Q \rangle$ can be expressed by the following simple equation: $\langle Q \rangle = (12.5 \pm 0.3)–(1.005 \pm 0.005)E_{c.m.}$ for the fragment Be. Moreover, this linear dependence also means that the final kinetic energy ($E^{f}_{kin} = \langle Q \rangle + E_{c.m.}$) is nearly independent of bombarding energy. Similar linear dependence of $\langle Q \rangle$ have also been observed in the fragment emission in $^{20}Ne + ^{12}C$ in the energy range 50–200 MeV [4,7,16]. This may be due to the limitation on the maximum value of angular momentum beyond which the formation of a dinucleus is not allowed owing to centrifugal repulsion [26].

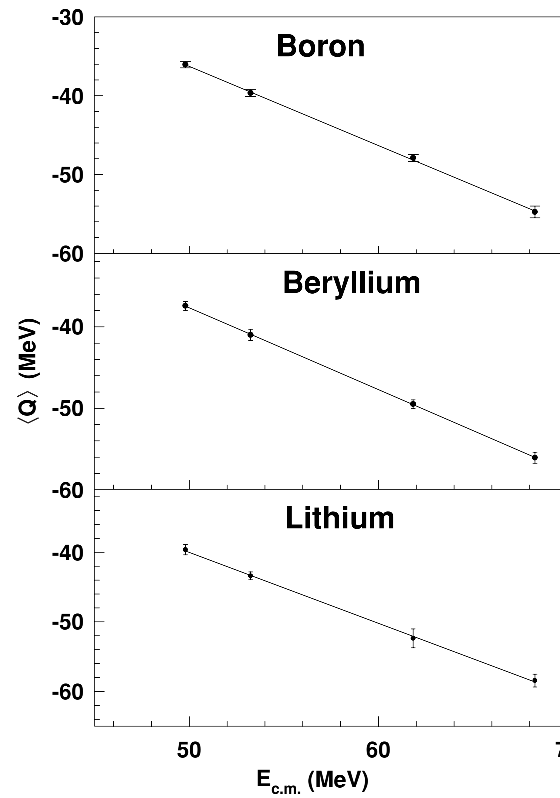

FIG. 5. Variation of average $\langle Q \rangle$ values with $E_{c.m}$. The solid lines shows the linear dependence $\langle Q \rangle$ value with bombarding energy for the fragments B, Be, and Li, respectively.

IV. DISCUSSIONS

In general, the energy distributions and angular distributions of the fragments B, Be, and Li measured in the reactions $^{16}O + ^{12}C$ up to the incident energy 160 MeV have similar shape. The observations viz., large energy damping, $1/\sin\theta_{c.m.}$ dependence of angular distribution and the near constancy of $\langle Q \rangle$ over a wide angular range, indicate that the fragment decay originates from a long-lived, fully energy equilibrated system. Similar equilibrated features have already been observed in case of fragments emission in the reactions $^{20}Ne + ^{12}C$ at energies 145–200 MeV, where, the enhancement in yield of the fragments over statistical model predictions was conjectured due to the survival of orbiting mechanism at such high excitation energies (100 MeV) [4,7]. In the present measurement also, the fragments are found to be emitted from an equilibrated system. It has been observed that there is significant enhancement in the yield of the fragment B over the statistical model predictions, suggesting additional contribution from other reaction mechanism (e.g., orbiting). On the contrary, for Li and Be, the binary yields are explained well by CASCADE, whereas, they are underpredicted in EHFM. However, it is interesting to point out that the mismatch between the extracted binary-reaction yield and respective EHFM predictions increases systematically as one approaches from Li to B, indicating the survival for orbiting in $^{16}O + ^{12}C$ system at the excitation energies considered here.

An enhancement in the fragment yield may also be partly contributed by secondary deexcitation of excited primary heavy fragments, it is therefore essential to investigate into the role of secondary decay in the fragment yield. In order to delineate whether the enhancement is due to feeding from the secondary de-excitation of heavier fragments or from orbiting mechanism, a detailed investigation have been performed and are described in the following subsections.

A. Number of open channels

In FF and orbiting processes, only a few partial waves near the grazing angular momentum are involved. Therefore, the number of open channels (NOC) available to carry away the grazing angular momentum l_{gr} of the compound nucleus is likely to play an important role in determining the mechanism of its decay. For many light heavy-ion systems, a strong correlation has been observed between the existence of very low NOC and the occurrence of resonant behavior and back angle enhancement in the elastic, inelastic, or a transfer channels [27].

The calculated NOC for the system $A = 28$, i.e., $^{16}O + ^{12}C$ [27] have been plotted in Fig. 6 as a function of grazing angular momentum l_{gr}. For the sake of comparison, the calculated NOC for two neighboring systems viz. A = 28, 31, i.e., ($^{18}O + ^{10}B$ and $^{19}F + ^{12}C$ [27]) have also been plotted in the same figure. It is seen from Fig. 6 that the NOC for the systems $^{18}O + ^{10}B$ and $^{19}F + ^{12}C$ respectively, are much higher (e.g., $\sim 10^4$ times larger) than those for the $^{16}O + ^{12}C$ system at all the grazing angular momentum. Though for the present reaction the values of $l_{gr}(\hbar)$, at the energies 117, 125, 145, and 160 MeV are 27, 28, 31, and 33, respectively, are larger than the value ($l_{gr} = 25(\hbar)$) at which the NOC for the system $^{16}O + ^{12}C$ shows a characteristic minimum, the corresponding NOC are much less compared to those for the other two nearby systems viz. $^{18}O + ^{10}B$ and $^{19}F + ^{12}C$. The large NOC values for $^{18}O + ^{10}B$ and $^{19}F + ^{12}C$ systems are in consistent with the fact that no resonances have been observed for this systems [27,34,35]. In a detailed study of the energy damped yield of the binary fragments emitted in the reactions $^{19}F + ^{12}C$ and $^{18}O + ^{10}B$, it was observed that fragments were originated from FF rather than through deep-inelastic orbiting processes, which is also in agreement with the observation of large NOC for these systems [10,36]. In contrast to these systems, resonances have been observed for the system $^{16}O + ^{12}C$ having lower NOC values. Since, the quasimolecular resonances at lower energies and orbiting mechanisms at higher energies appear to be, conceptually, very closely related, one might expect the system which shows resonances, should also show orbiting phenomena. In a recent study of the competition between direct and dissipative processes in binary channels in the reactions $^{16}O + ^{12}C$, $^{18}O + ^{12}C$ at energies of 5–7.7 MeV/nucleon [6], the observation of resonant structure at lower energies and presence of refractive effects at higher energies, may be considered as the signature of the orbiting process. In the present study also, the enhancement in the yield of the fragment B over the CASCADE and EHFM predictions may be due to the presence of orbiting phenomena.

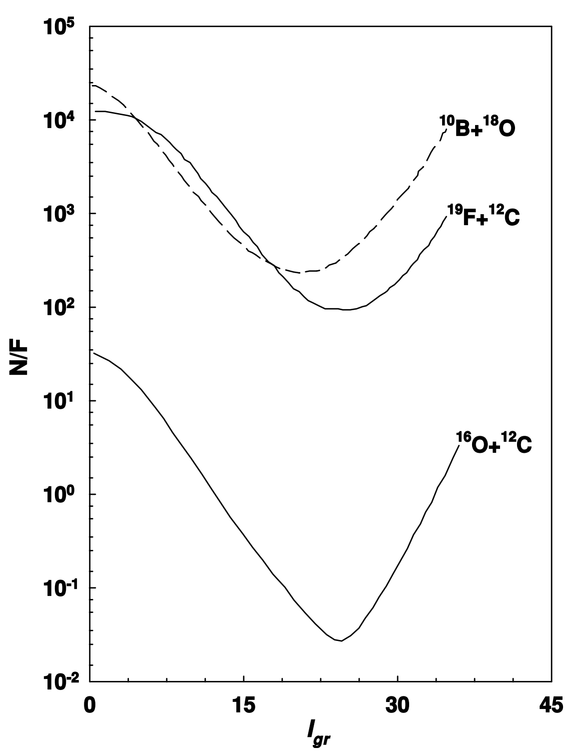

FIG. 6. Number of open channels (NOC) for decay of compound nucleus $^{28}Si^*(^{16}O + ^{12}C)$, $^{31}P^*(^{19}F + ^{12}C)$ and $^{28}Al^*(^{10}B + ^{18}O)$ [27] normalized to ihe incident flux, N/F, plotted as a function of grazing angular momentum l_{gr}.

B. Secondary decay of heavier fragments

The enhancement in the experimental fragment yield may also be, at least partially, due to feeding from secondary deexcitation of heavier fragments. A detailed simulations of secondary decay have been performed using the Monte Carlo code LILITA [31] as described in Refs. [4,7]. Secondary decays of different primary binary channels viz., O*(binary channels $^{15,16,17}O + ^{11,12,13}C$), F* (binary channels $^{17,18,19}F + ^{11,10,9}B$), Ne* (binary channels $^{20,21}Ne + ^{8,7}Be$), Na* (binary channels $^{21,22}Na + ^{7,6}Li$), and Mg* (binary channels $^{24,25}Mg + ^{4,3}He$), respectively, have been studied at the highest excitation energy. It has been observed that secondary decays of Mg*, Na*, and Ne* do not reach up to B. However, a significant yield of the fragment B arises due to the the secondary decay of the primary fragments $^{19}F^*$($\sim$49%;), $^{16}O^*$($\sim$48%) and ^{15}O($\sim$0.4%). The simulations of the energy distributions of the secondary decay yield of B from $^{19}F^*$, $^{16}O^*$, and $^{15}O^*$ have been done using the code LILITA and are found to peak at much lower energies $\sim$32–39 MeV.

The fact that the energy distributions of the secondary decay components are very different from those of the primary fragment components, the contributions of these secondary decay have been eliminated by the Gaussian fitting procedure for the extraction of primary B yields as shown in Fig. 7. First, the width of Gaussian is determined by fitting the higher energy tail of the spectrum with a Gaussian having its

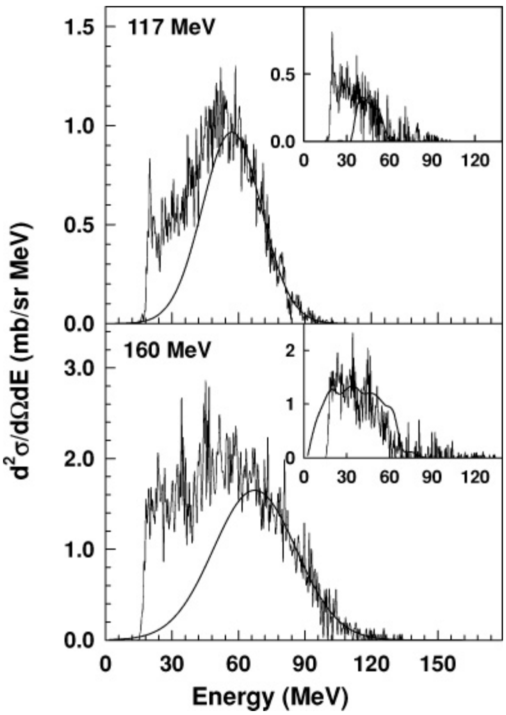

FIG. 7. Secondary decay contribution to B fragment estimated from LILITA [31] at energies 117 and 160 MeV, respectively. The energy distribution of B at these energies at $\theta_{\rm lab} = 15^\circ$ are shown along with fitted Gaussians. (Inset) The difference spectra (Gaussian subtracted from total spectra) where solid curve represents the total secondary decay contribution estimated using LILITA [31].

centroid at energies obtained from Viola systematics. In the next step, the total energy spectrum is fitted with a Gaussian to extract the primary fragment component. It is seen that there is significant enhancement in yield at lower energy part which increases with bombarding energy. The difference spectra obtained by subtracting the Gaussian fitted spectra from the experimental spectra are shown in the inset of Fig. 7. It has been found that the difference spectra obtained at 160 MeV are well reproduced by the secondary decay distributions (solid line in the inset) obtained from LILITA. However, the lower energy tail of the difference spectra obtained at 117 MeV is not explained by the secondary decay distributions, which may originate from other sources. It is thus evident that Gaussian fitting procedure for the extraction of primary fragment yield is sufficient to reject the contributions of the secondary decay components if any as their energy distributions are different from those of primary fragments [4,7].

V. SUMMARY AND CONCLUSION

The inclusive double differential cross section for fragments having $Z = 3$–5 emitted in the reaction $^{16}O + ^{12}C$ at the energies 117, 125, 145, and 160 MeV have been measured. The energy distributions of all the fragments obtained at different incident energies, have nearly Gaussian in shapes with their centroids at the expected kinetic energies for the binary break up obtained from the Viola systematics corrected by the corresponding asymmetric factors. The c.m. angular distributions $(d\sigma/d\Omega)_{\rm c.m.}$, of the fragments B, Be, and Li, obtained at energies $E_{\rm lab} = 117, 125, 145$, and 160 MeV, respectively, are found to follow $1/\sin\theta_{\rm c.m.}$ dependence, which signifies the emission of these fragments from a long-lived equilibrated composite. It has been observed that for each fragments, at all bombarding energies, the average Q values are independent of emission angle, which further suggests that the fragments are emitted from a completely equilibrated source at all the incident energies considered here. Total elemental cross-section for the fragments Li to B have been estimated from the experimental distributions. At all incident energies, a significant enhancement in the yield of the fragment B have been observed over the theoretical predictions of CASCADE and EHFM calculations. The yield of the fragments Li and Be are in good agreement with the theoretical predictions of the statistical model code CASCADE, though they are underpredicted by EHFM calculations. However, the magnitude of mismatch (difference between the extracted and the predicted yields by EHFM) increases progressively from Li to B, which clearly indicates, increasing additional contributions from other reaction mechanism or possible enhancement to the energy damped yield near the entrance channel configuration. The above observation is consistent with the fact that the NOC values for this system are much smaller than those for other two near by systems—which is indicative of the formation of an orbiting dinuclear complex in the system $^{16}O + ^{12}C$ at the energies studied here.

ACKNOWLEDGMENTS

The authors wish to thank the cyclotron operating staff for smooth running of the machine and H. P. Sil for the fabrication of thin Si detectors for the experiment.

[1] S. J. Sanders, A. Szanto de Toledo, and C. Beck, Phys. Rep. **311**, 487 (1999), and references therein.
[2] N. Carlin Filho *et al.*, Phys. Rev. C **40**, 91 (1989).
[3] S. J. Padalino *et al.*, Phys. Rev. C **41**, 594 (1990).
[4] Aparajita Dey *et al.*, Phys. Rev. C **76**, 034608 (2007).
[5] Aparajita Dey *et al.*, Phys. Rev. C **75**, 064606 (2007).
[6] S. Szilner *et al.*, Nucl. Phys. **A779**, 21 (2006).
[7] C. Bhattacharya *et al.*, Phys. Rev. C **72**, 021601(R) (2005).
[8] C. Bhattacharya *et al.*, Phys. Rev. C **66**, 047601 (2002).
[9] C. Bhattacharya *et al.*, Phys. Rev. C **69**, 024607 (2004).
[10] C. Bhattacharya *et al.*, Phys. Rev. C **54**, 3099 (1996).
[11] C. Beck *et al*. Eur. Phys. J. **A2**, 281 (1998).
[12] C. Beck *et al.*, Phys. Rev. C **54**, 227 (1996).
[13] S. P. Barrow *et al.*, Phys. Rev. C **52**, 3088 (1995).
[14] K. Farrar *et al.*, Phys. Rev. C **54**, 1249 (1996).
[15] D. Shapira, J. L. C. Ford, Jr., J. Gomez del Campo, R. G. Stokstad, and R. M. Devries, Phys. Rev. Lett. **43**, 1781 (1979).
[16] D. Shapira, J. L. C. Ford, Jr., and J. Gomez del Campo, Phys. Rev. C **26**, 2470 (1982).
[17] D. Shapira, R. Novotny, Y. C. Chan, K. A. Erb, J. L. C. Ford, Jr., J. C. Peng, and J. D. Moses, Phys. Lett. **114B**, 111 (1982).

[18] B. Shivakumar, S. Ayik, B. A. Harmon, and D. Shapira, Phys. Rev. C **35**, 1730 (1987).
[19] W. Dünnweber *et al*., Phys. Rev. Lett. **61**, 927 (1988).
[20] L. G. Moretto, Nucl. Phys. **A247**, 211 (1975).
[21] S. J. Sanders, Phys. Rev. C **44**, 2676 (1991).
[22] T. Matsuse, C. Beck, R. Nouicer, and D. Mahboub, Phys. Rev. C **55**, 1380 (1997).
[23] A. K. Dhara, C. Bhattacharya, S. Bhattacharya, and K. Krishan, Phys. Rev. C **48**, 1910 (1993).
[24] A. Szanto de Toledo, S. J. Sanders, and C. Beck, Phys. Rev. C **56**, 558 (1997).
[25] A. Szanto de Toledo, B. V. Carlson, C. Beck, and M. Thoennessen, Phys. Rev. C **54**, 3290 (1996).
[26] D. Shapira, D. Schull, J. L. C. Ford, Jr., B. Shivakumar, R. L. Parks, R. A. Cecil, and S. T. Thornton, Phys. Rev. Lett. **53**, 1634 (1984).
[27] C. Beck, Y. Abe, N. Aissaoui, B. Djerroud, and F. Haas, Phys. Rev. C **49**, 2618 (1994).
[28] J. M. Oliveira *et al*., Phys. Rev. C **53**, 2926 (1996).
[29] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).
[30] C. Beck *et al*., Z. Phys. A **343**, 309 (1992).
[31] J. Gomez del Campo and R. G. Stokstad, LILITA, a Monte Carlo Hauser-Feshbach code, ORNL-TM 7295.
[32] F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).
[33] S. Bhattacharya, K. Krishan, S. K. Samaddar, and J. N. De, Phys. Rev. C **37**, 2916 (1988).
[34] N. Aissaoui, F. Haas, R. M. Freeman, C. Beck, A. Morsad, B. Djerroud, R. Caplar, G. A. Monnehan, A. Hachem, and M. Youlal, Z. Phys. A **348**, 237 (1994).
[35] N. Aissaoui, F. Haas, R. M. Freeman, C. Beck, A. Morsad, B. Djerroud, R. Caplar, and A. Hachem, Phys. Rev. C **55**, 516 (1997).
[36] R. M. Anjos, C. Tenreiro, A. Szanto de Toledo, and S. J. Sanders, Nucl. Phys. **A555**, 621 (1993).