Letter

Signature of fusion suppression in complex fragment emission

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The effect of weak binding of ^{9}Be on complete fusion has been explored through the study of complex fragment emission in ^{20}Ne + ^{9}Be reaction. The yields of the fragments ^{6,7}Li and ^{7,9}Be emitted from the excited compound nucleus ^{29}Si* have been compared with the respective statistical model predictions. Emission of same fragments from another close-by compound nucleus ^{28}Si* at similar excitation energy, formed by the fusion of two strongly bound nuclei, ^{16}O + ^{12}C, has been studied for comparison. It has been observed that for the system ^{16}O + ^{12}C, the yields of ^{6,7}Li and ^{7,9}Be fragments are close to the predictions of the statistical model. However, for the ^{20}Ne + ^{9}Be system, although the experimental yield pattern follows the statistical model prediction, there is substantial reduction in yield for all detected fragments. These observations have been attributed to the suppression of complete fusion in ^{20}Ne + ^{9}Be system due to the weak binding of ^{9}Be, a dynamical effect which is not incorporated in the conventional statistical models. It is the first time that a clear signature of the suppression of complete fusion in light systems involving weakly bound nucleus has been observed in complex fragment emission from fully equilibrated composite produced in fusion well above the barrier.

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The cluster structure of weakly bound nucleus plays an important role in modifying the process of complete fusion and the subsequent decay of the resultant compound nucleus (CN). This effect is, in particular, crucial to understand the reactions involving the weakly bound unstable nuclei near the drip lines. Stable weakly bound nuclei, like ^{6,7}Li and ^{9}Be, with breakup thresholds ranging from 1.48 to 2.55 MeV, serve well to provide an insight of the fusion mechanism with center of mass (c.m.) energies ($E_{\text{c.m.}}$) ranging from near barrier (Coulomb) to far above the barrier. Therefore, extensive systematic studies, theoretical as well as experimental, have been made in the recent years to reveal the nature of the inclusive breakup process and its influence on complete fusion in various mass domain [1–18]. These studies have clearly demonstrated the importance of particle and cluster transfers in complete fusion of weakly bound nuclei, particularly, d, t and n, α transfers for ^{6,7}Li and ^{9}Be, respectively. Thus, the general consensus one can arrive at from these studies is that, in contrast to the intuitive expectation of the two-step process of breakup of the projectile into its constituent clusters followed by full/partial absorption, direct capture from the projectile ground state dominates the suppression of complete fusion involving weakly bound stable nuclei at above barrier energies [17,18].

The generic breakup of the weakly bound nucleus is followed by either partial capture causing incomplete fusion (ICF) or no capture break up (NCBU) reaction; both these processes contribute to the suppression of complete fusion cross section (σ_f). In addition, there may be full capture of all breakup components, contributing to the complete fusion yield. The σ_f in turn influences the output of the CN decay, namely evaporation, complex or intermediate mass fragment (IMF; $2 < Z_{\text{IMF}} < Z_{\text{CN}}/2$) emission, and fission. Therefore, probing any of these three mechanisms can provide information about the σ_f of a reaction. Among these studies, complete fusion suppression as high as ≈30% was observed in case of very heavy and medium heavy ion induced reactions with $E_{\text{c.m.}}$ above the Coulomb barrier (V_B) [5–16]. A few attempts have also been made to study the effect of weak binding of ^{9}Be on fusion involving light systems at above barrier energies [1–4]. These experiments effectively measured total fusion cross sections, as finite resolutions of the detecting systems did not permit the separation of the overlapping evaporation residues originating from complete and incomplete fusion reactions. However, it was shown that the ICF fraction may sometimes be quite small and the measured total fusion yield may be taken as complete fusion yield [2]. It is interesting to note that a few of the above studies indicated significant fusion hindrance which is strongly correlated with the cluster separation energy of the weakly bound nucleus in the entrance channel [1,2]; however, some other studies indicated the absence of any effect of breakup on fusion cross section [3,4].

It is clear from the above that the fusion of light weakly bound systems (typically, $A_{\text{CN}} \lesssim 40$; A is the mass number)

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TABLE I. Details of experimental parameters.

Beam	Target	E_{lab} (MeV)	$E_{\text{c.m.}}$ (MeV)	V_B (MeV)	E^*_{CN} (MeV)	ℓ_{cr} ($\hbar$)
^{20}Ne	^{9}Be	157.2	48.8	6.58	75.0	19
^{16}O	^{12}C	135.9	58.2	7.95	75.0	21
^{20}Ne	^{9}Be	193.0	59.9	6.58	86.1	21
^{16}O	^{12}C	161.6	69.3	7.95	86.0	23

needs further investigation. This was the motivation behind the present study, and the fusion of weakly bound ^{9}Be (thresholds for the dominant breakup channels, n + ^{8}Be and α + ^{5}He, being 1.66 and 2.31 MeV, respectively) was chosen for the present experiment. It may be mentioned here that all studies reported so far mostly used evaporation residue (ER) as the main observable to extract fusion extraction function and its suppression for weakly bound systems. The choice of ER is naturally driven by the fact that it dominates the CN decay for all systems except for the heaviest ones. However, for light systems, as was pointed out earlier, ERs of complete fusion and ICF have a strong overlap, rendering it difficult to isolate the contributions of each individual component. Therefore, we plan to take up the alternative route of CN decay via IMF emission to study the effect of fusion suppression in weakly bound systems. In recent times there have been extensive studies on IMF emission involving tightly bound clustered, (i.e., α clustered) nuclei [19–28]; however, the correlation between IMF emission and fusion for weakly bound clusters has not been explored so far, to the best of our knowledge, as IMF is only a small fraction of the total CN decay. Here we show for the first time that IMF emission can also be used as a probe to study fusion suppression phenomenon in light weakly bound systems.

With this aim, we report IMF mesurement for ^{20}Ne + ^{9}Be reaction at two bombarding energies (157.2 and 193.0 MeV), both well above V_B ($E_{\text{c.m.}} \gtrsim 7V_B$). To compare the above yields with those of a similar but tightly bound system, a projectile and target combination of ^{16}O + ^{12}C has been chosen to produce a nearly same nucleus at similar excitation energies. The same system (^{16}O + ^{12}C) has been studied earlier by Kundu *et al*. [29], which has been used for checking the consistency of the present measurement. The yields of the fragments, ^{6,7}Li and ^{7,9}Be, have been measured and compared with the respective statistical model calculations for the two systems to look for the signature of fusion suppression.

The experiment was performed at the Variable Energy Cyclotron Centre, Kolkata, using ^{20}Ne and ^{16}O ion beams on ^{9}Be and ^{12}C targets, respectively. The detailed target projectile combinations and related energy values are tabulated in Table I. Both the targets were self-supporting and thickness of ^{12}C target was $\approx$100 μg/cm^2 while that of ^{9}Be was $\approx$1.78 mg/cm^2. The emitted fragments have been identified using two telescopes of the ChAKRA array, each consisting of ΔE $\approx$ 50 μm, single-sided silicon strip detector (SSSD), E $\approx$1000 μm, double-sided silicon strip detector (DSSD), and backed by four CsI (Tl) detectors, each of thickness 6 cm [30]. The angular resolution of each strip of the telescopes

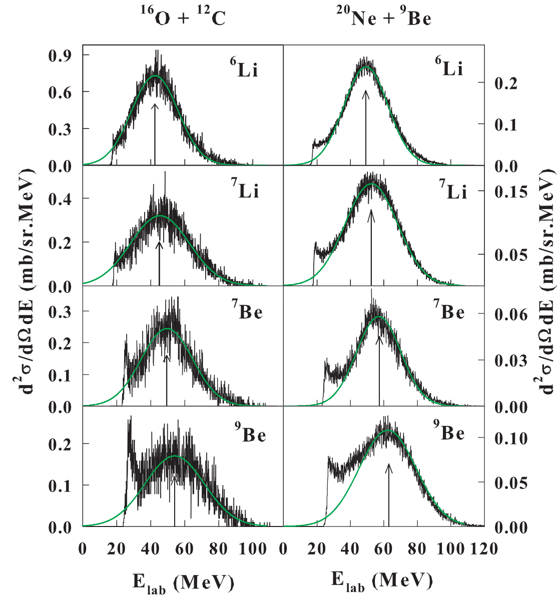

FIG. 1. Energy distributions of Li and Be isotopes fitted with Gaussian function (solid green lines) for the ^{16}O (135.9 MeV) + ^{12}C and ^{20}Ne (157.2 MeV) + ^{9}Be reactions at laboratory angle $\approx$16°. Arrows indicate the mean kinetic energies of the fragments as obtained from Viola systematics.

was $\approx$0.9°. Different emitted fragments were well separated, isotopically, in $\Delta E - E$ telescope as shown in Ref. [31]. The inclusive energy distributions of the fragments ^{6,7}Li and ^{7,9}Be have been measured in the angular range of 15° to 28° in laboratory frame. There are some uncertainties in the measurement of various parameters like detector solid angle, the thickness of the target, and the calibration of current digitizer which contribute to the error in the data. Also there are errors coming from the extrapolation of angular distribution beyond the measured angular range and from counting statistics. Total error arising from these sources has been been estimated typically as $\approx$15%.

Typical inclusive energy spectra of the isotopes of Li and Be fragments obtained in the reactions ^{16}O + ^{12}C and ^{20}Ne + ^{9}Be are shown in Fig. 1 at an excitation energy 75 MeV of the composites. The Gaussian nature of the energy spectra are quite evident in this figure, and centroids of the Gaussians are found to conform to the expected kinetic energies for fission fragments from the completely fused composite as predicted by asymmetry-modified Viola systematics [32,33]. This signifies that the emission of fragments are from a fully energy relaxed compound nucleus. There are some enhancements in yields at lower energy part, which are due to dissipative reactions, sequential decay of the excited primary fragments, and second kinematical solution for inverse kinematic nature of the reactions. Nevertheless, the width of the Gaussian has been estimated from the high-energy part of the distribution beyond the centroid of the Gaussian to minimize the contribution of the enhanced low-energy part.

The fitted Gaussian to the energy spectrum was integrated to get the differential cross section, which has been transformed to c.m. frame assuming two body kinematics averaged

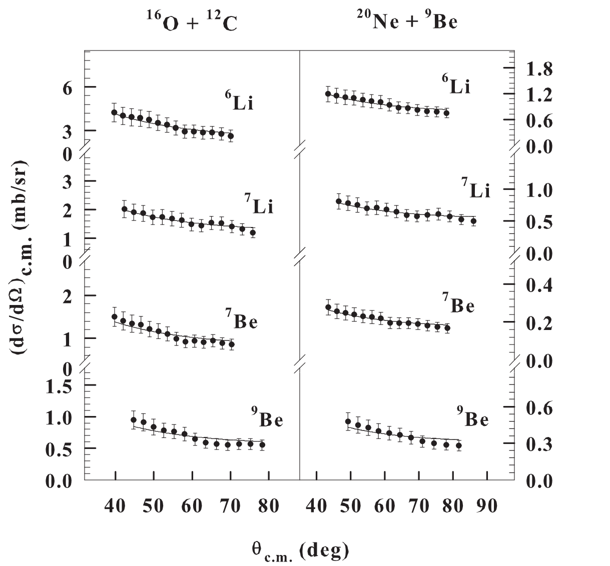

FIG. 2. The center of mass (c.m.) angular distribution of Li and Be isotopes for ^{16}O (135.9 MeV) + ^{12}C and ^{20}Ne (157.2 MeV) + ^{9}Be reactions. The solid lines correspond to $d\sigma/d\Omega \approx 1/\sin\theta_{\text{c.m.}}$ fit to the data.

over whole range of the kinetic energy distributions. The differential cross sections in c.m., $(d\sigma/d\Omega)_{\text{c.m.}}$, for the two systems have been plotted with respect to center-of-mass angle ($\theta_{\text{c.m.}}$) in Figs. 2 and 3 at two different excitation energies, 75 and ≈86 MeV, respectively. The angular distributions of all the fragments of ^{6,7}Li and ^{7,9}Be for both the systems at both energies are found to follow $\approx 1/\sin\theta_{\text{c.m.}}$ (Figs. 2 and 3). This behavior is also characteristic of fission-like decay from an equilibrated composite.

All the observations so far indicate that these fragments originated from the binary decay of a long-lived, fully energy relaxed source. The angular distributions $(d\sigma/d\Omega)_{\text{c.m.}}$ were

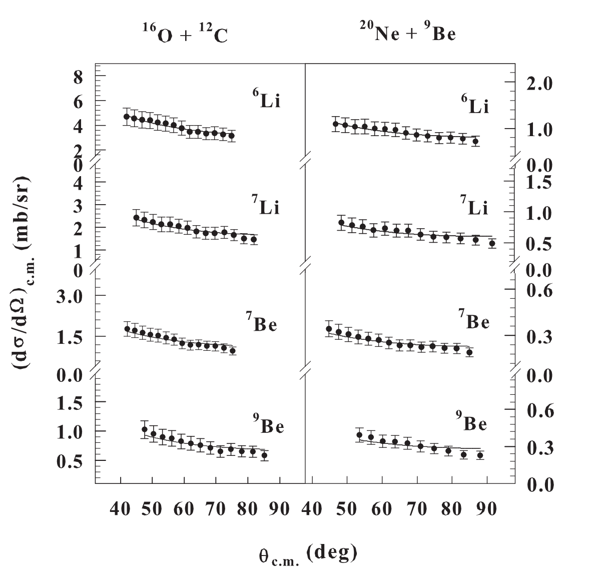

FIG. 3. Same as Fig. 2 for ^{16}O (161.6 MeV) + ^{12}C and ^{20}Ne (193.0 MeV) + ^{9}Be reactions.

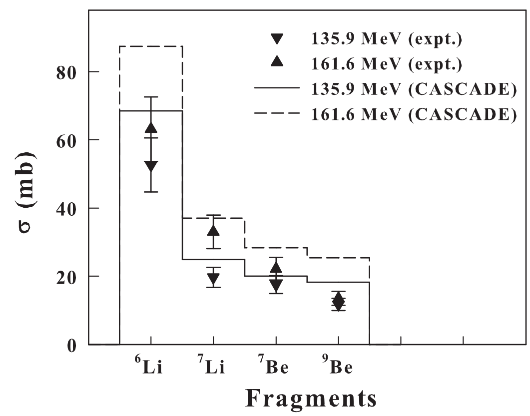

FIG. 4. Comparison of experimental yield with statistical model prediction for $^{16}\text{O} + ^{12}\text{C}$ reaction. The solid triangle down (up) represents 135.9 MeV (161.6 MeV) data points and corresponding CASCADE values are shown by solid (dashed) line.

integrated to get the total cross section. The comparisons of the experimental cross sections of different fragments with those predicted using the code CASCADE [34] are shown in Fig. 4 for $^{16}\text{O} + ^{12}\text{C}$ reaction at incident beam energies of 135.9 and 161.6 MeV. The calculations have been done with the angular momentum (l) up to the critical angular momentum of fusion, l_{cr}. The input parameters used in CASCADE calculations are given in Table II. The yields of all the fragments are found to be quite close to the predicted values and their relative trend is also matching with the statistical model prediction. Similarly, Fig. 5 shows the same comparison for the weakly bound system i.e., $^{20}\text{Ne} + ^{9}\text{Be}$ at the energies of 157.2 and 193.0 MeV. Here, although the trend is matching, the experimental yields in all cases are found to be a factor of 2–3 less than the respective predicted values.

To address the results obtained in this study, the cross sections of Li and Be fragments obtained from earlier works as a function of excitation energy ($\mathbf{E_x}$) have been plotted along with the present data in Fig. 6. There are not much data available in this mass region and at such high excitation energy of CN. Here, we have presented the fragment yield data for the decay of ^{28}Al*, formed through various entrance channels up to an excitation energy of ≈50 MeV [35]. The data from Ref. [29] on $^{16}\text{O} + ^{12}\text{C}$ reaction in the similar excitation energy region have also been incorporated for comparison. The earlier data did not have any isotopic separation of fragment yields, so the present isotopic yields have been summed up to get the total fragment yield for comparison. The present data on $^{16}\text{O} + ^{12}\text{C}$ reaction perfectly match with the earlier data [29]. The sharply increasing trend of fragment yield at lower

TABLE II. Input parameters for CASCADE. All other parameters including deformation etc. have been calculated internally.

Radius parameter ($r_\circ$) = 1.29 fm	
Level density parameter (a) = $A/8$ MeV^{-1}	
Critical angular momentum (ℓ_{cr}) as in Table I	
Diffuseness parameter ($\Delta\,\ell$) = $2\hbar$	

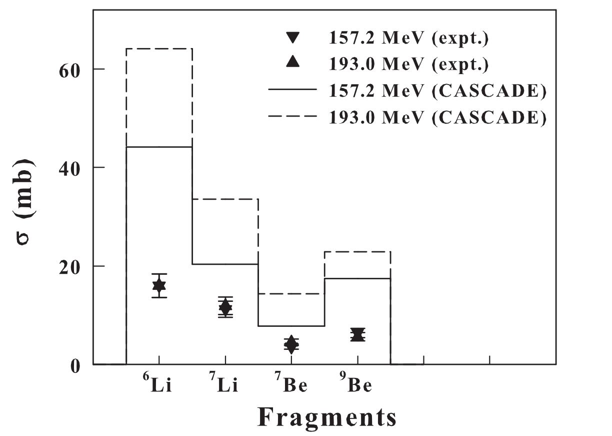

FIG. 5. Same as Fig. 4 but for ^{20}Ne + ^{9}Be reactions at beam energies of 157.2 and 193.0 MeV.

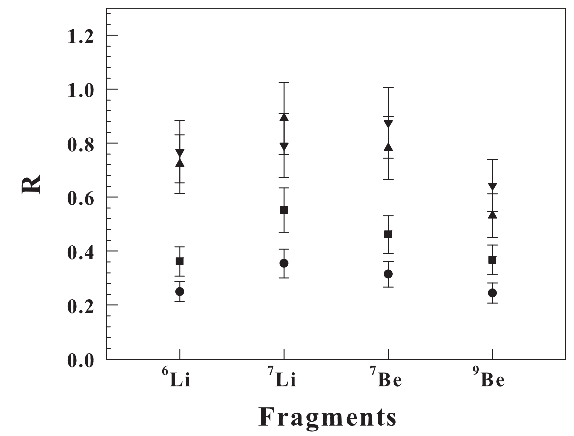

FIG. 7. Ratio of experimental to theoretical (CASCADE) cross sections for ^{16}O + ^{12}C (down, up triangles for $E^*_{\mathrm{CN}} \approx 75$, 86 MeV, respectively) and ^{20}Ne + ^{9}Be (square, circle for $E^*_{\mathrm{CN}} \approx 75$, 86 MeV, respectively) reactions.

excitation energy is seen to get considerably flattened off at higher excitation domain of the present experiment in both cases. This is due to the fact that at higher excitations, the domain of saturation of fusion cross section is already reached; therefore the growth of decay yield slows down significantly and the weak slope is mostly due to the variation of fragment partial decay width with available excitation energy, which varies from case to case. However, it is interesting to observe that for both fragments, the yields from the ^{20}Ne + ^{9}Be system deviate and lie well below the general systematic trend. A previous study on fragment emission for the reaction ^{20}Ne + ^{12}C in the similar energy range has not seen any deviation of the yields of Li and Be fragments from systematics [23]. Therefore, it seems that the lower fragment yields in the case of ^{20}Ne + ^{9}Be reaction are solely due to the weakly bound

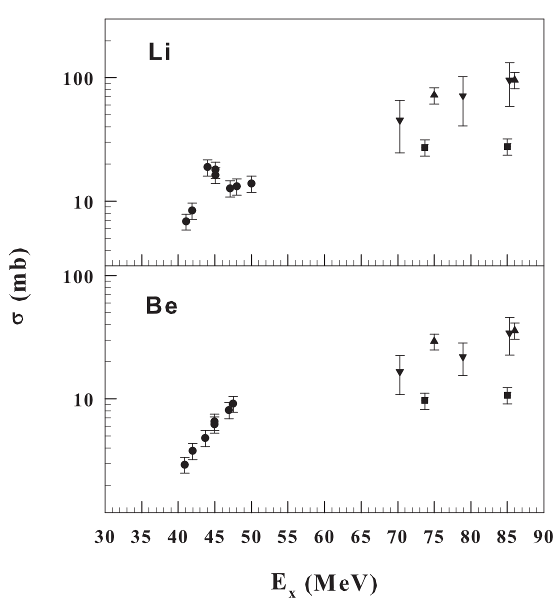

FIG. 6. Comparison of present data (^{16}O + ^{12}C: up triangle, ^{20}Ne + ^{9}Be: square) with data from Ref. [35] (circle) and Ref. [29] (down triangle) for the fragments Li and Be (see text).

nature of ^{9}Be, indicative of the suppression of fusion in this case.

To get an idea of the extent of suppression, the ratio of experimental cross sections to the corresponding theoretical (CASCADE) values have been calculated for all the fragments, given by

$$\mathbf{R} = (\sigma_{\mathrm{exp}}/\sigma_{\mathrm{th}}). \tag{1}$$

These values are shown in Fig. 7 for ^{6,7}Li and ^{7,9}Be fragments for the two systems at two excitation energies. One can see that the ratios are well below 1.0 for the ^{20}Ne + ^{9}Be reaction, whereas in comparison they are rather close to 1.0 for the ^{16}O + ^{12}C reaction. The value of **R** is seen to vary to some extent from one isotope to other. This may be due to minor variation of actual exit channel condition between the fragments which the theoretical model does not take care of. In spite of the variations, it is evident that the ratios for the two reactions fall in two distinct bands and the band for ^{20}Ne + ^{9}Be is clearly at a lower position than that of ^{16}O + ^{12}C. If we assume that the cross sections obtained for ^{16}O + ^{12}C reaction (which have been cross checked with previous measurements) represent no-suppression yields and normalize the theoretical values accordingly, then the **R** values of ^{20}Ne + ^{9}Be reaction should be scaled up by the same factor. The **R** value of each fragment for ^{20}Ne + ^{9}Be reaction ($\mathbf{R}_{\mathbf{Ne+Be}}$) has been divided by the corresponding value of the ^{16}O + ^{12}C reaction ($\mathbf{R}_{\mathbf{O+C}}$) and plotted in Fig. 8. This gives an idea of the normalized reduction of fragment yield in weakly bound Ne + Be system, which lies typically, except for a deviation in one ^{7}Li point, within the range of $\approx 35-55(\pm 12)\%$ for different fragments.

It is clear from the above that there is substantial reduction in equilibrium yields of the fragments ($Z = 3, 4$) from the respective statistical model predictions for the reaction ^{20}Ne + ^{9}Be. One is tempted to attribute this reduction to the suppression of fusion involving weakly bound system ^{9}Be in this case. To investigate this point further, we look into all possibilities that affect fragment emission. Fully equilibrated

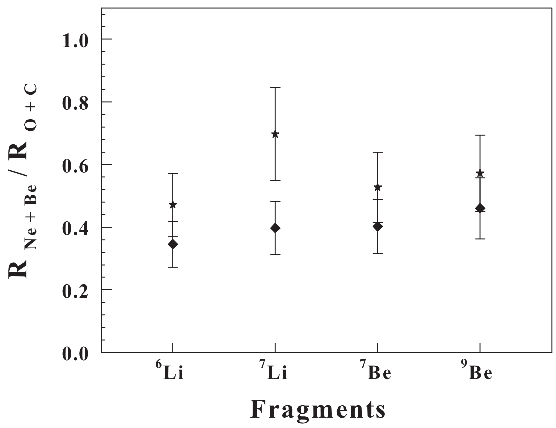

FIG. 8. **R** for ^{20}Ne + ^{9}Be reactions normalized with respect to that of ^{16}O + ^{12}C at $E^*_{\mathrm{CN}} \approx 75$ MeV (star) and 86 MeV (diamond) (see text).

fragment emission considered here may come from either complete or incomplete fusion. In the present case of weakly bound ^{9}Be, the flux from complete fusion channel may be removed due to the breakup (direct or transfer induced) of ^{9}Be to contribute to incomplete fusion. There are three possibilities as follows:

(i) all the break up fragments fuse with ^{20}Ne leading to complete fusion after break up (CF$_{\mathrm{BU}}$),
(ii) one or more fragments fuse with ^{20}Ne (ICF), or
(iii) all the fragments fly away without fusing with ^{20}Ne (NCBU).

The outcome of (i) (CF$_{\mathrm{BU}}$) is indistinguishable from CF. Incompletely fused composite formed by (ii) will also contribute to equilibrium fragment yield, whereas (iii) will leave the original nucleus at relatively low excitations with negligible probability of fragment emission. So, we need to discuss more about (ii) to look into the contribution of ICF in the observed fragment spectra. There are the following possibilities for the breakup of ^{9}Be and formation of ICF in ^{20}Ne + ^{9}Be reaction:

(a) $n + {}^{8}$Be and only ^{8}Be gets fused,
(b) $n + {}^{8}$Be ($\rightarrow \alpha + \alpha$) and one α gets fused,
(c) $n + {}^{8}$Be ($\rightarrow \alpha + \alpha$) and only n gets fused,
(d) ^{5}He $+\alpha$ and only ^{5}He or α gets fused.

As discussed earlier, it is well known that the loosely bound clustered structure and the resulting transfer of those constituent clusters play a major role in complete fusion suppression and formation of ICF composite involving light weakly bound nuclei. In the case of ^{9}Be, recent experimental studies show that most dominant cluster configurations are $n + {}^{8}$Be ($\leqslant 69\%$) and $\alpha + {}^{5}$He ($\leqslant 25\%$) [36]. Recent theoretical study also demonstrated significant contributions of n and α transfer in ICF formation for the system ^{9}Be + ^{28}Si [37]. Therefore it suffices to probe further into the contributions of ICFs due to n and α transfer only to the observed fragment yields. At the highest incident energy (193.0 MeV), the excitation energies of CF, ICF (n transfer), and ICF (α transfer) composites are calculated to be 86.0, 15.8, and 40.9 MeV, respectively. Because of this large reduction in excitation energy, corresponding IMF yield would fall off sharply; CASCADE calculations predict total (Li + Be) fragment yields in the three cases as ≈ 109, 0, and ≈ 3 mb, respectively, so it is clear that the observed fragment yields are those originating from CF only. To look further into the effect of IMF yield from ICF on the energy spectra, we try to check the peak positions of those IMFs in the observed energy spectra (Fig. 1). The peaks of the observed distributions were shown to correspond to the Viola systematics for the CF. Had there been any contribution from the two ICF processes mentioned above, the respective energy distributions, typically for the ^{9}Be fragment, would have peaked around 79 MeV (n transfer ICF) and 74 MeV (α transfer ICF) in Fig. 1 (compared to the corresponding CF peak at 63 MeV). For other fragments too there would be similar shifts in energy peaks. However, closer inspection of the spectra reveals that all spectra look like perfect single Gaussians without any hump or distortion on the higher energy side of the spectra due to ICF contributions and can be fitted nicely with single Gaussian peaking at CF peak position. So it can be concluded that the fragment yields extracted in the present experiment originated only from complete fusion of ^{20}Ne + ^{9}Be and, therefore, the reduction in fragment yield observed here is indicative of the suppression of complete fusion due to the weakly bound nature of ^{9}Be in ^{20}Ne + ^{9}Be reaction.

In conclusion, the yields of IMFs produced in ^{20}Ne + ^{9}Be reaction are found to be reduced to $\approx$ 35-55($\pm$12)% of the prediction of the statistical model normalized with respect to the fragment yields from a similar composite (1n less) at same excitation energy formed in ^{16}O + ^{12}C reaction. It was shown that the fragments originate mostly from complete fusion and the contribution of ICF (formed by breakup and/or transfer) in the observed fragment yield is negligible. Therefore, the large reduction of fragment yield seen here may be attributed to the suppression of complete fusion in the weakly bound system ^{20}Ne + ^{9}Be. It may be noted here that, though fusion suppression in heavy and medium heavy weakly bound systems at above barrier energies has been well studied to arrive at consensus on significant suppression of complete fusion, results presently available for light systems ($A_{\mathrm{CN}} \lesssim 40$) are not conclusive. It is interesting that, for the first time, a direct correlation between the suppression of complete fusion in weakly bound nucleus and reduction in IMF yield is reported. The present experiment indicates that IMF emission can also be used as a sensitive probe of complete fusion suppression studies and more work, theoretical as well as experimental, is needed to establish IMF emission as a quantitative measuring tool for complete fusion suppression in weakly bound systems.

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