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Survival of cluster correlation in dissipative binary breakup of ^{24,25}Mg*

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The role of α clustering in the binary complex fragment decay of fully energy-relaxed composites ^{24,25}Mg*, formed in ^{12,13}C + ^{12}C reactions, has been studied. The inclusive isotopic energy distributions of the emitted fragments ^{6,7}Li and ^{7,8,9}Be have been measured. The ratio of the measured fully dissipative (fissionlike) yields of each isotopic fragment obtained in the two reactions was compared with the corresponding statistical model prediction of the same. Unlike in the case of ^{6,7}Li fragments, the measured yield ratios of ^{7,8,9}Be fragments were found to deviate substantially from the statistical model predictions of the same. The observed deviations were due to the enhancement in the measured yields of ^{7,8,9}Be fragments (with respect to the respective statistical model predictions) only in specific exit channels containing either ^{16}O or ^{18}O, both well known α-cluster nuclei, as the complementary binary fragment. The present data indicated, for the first time, the survival and sustained influence of cluster correlations on dissipative binary decay of hot composites ^{24,25}Mg* at excitation energy of $\sim$2.25 MeV/nucleon.

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The phenomenon of α clustering in light nuclei and its role in the dissipative binary decay of hot composites formed in the reactions involving light self-conjugate even-even nuclei up to moderate excitation energy (typically, $E^* \lesssim 100$ MeV) is presently a very active area of research, both experimentally [1–6] as well as theoretically [7,8]. In previous years too, there have been extensive studies on this subject, where the manifestation, though somewhat indirect, of cluster structure in self-conjugate even-even nuclei was linked with the observation of dinuclear orbiting and/or quasi-molecular-resonance phenomena, leading to enhancement in the yield and/or resonance-like excitation function in a few outgoing channels around the entrance channel [9–21]. In recent years, new theoretical studies on correlated cluster structure of even-even nuclei have led to various interesting predictions about the ground-state structure in the form of a linear α-chain-like structure, compact geometric shapes, or even a lightly bound gaslike/α-condensate configuration [7,8]. This has led to a large number of experimental studies unfolding the nature of α correlation in ground as well as excited states of these nuclei around the respective cluster breakup threshold [1]. It is thus pertinent to ask at this point how the cluster correlation in light nuclei evolves with excitation energy.

To address this point, quite a few studies have been made in the recent years on self-conjugate even-even nucleus ^{24}Mg* using the ^{12}C + ^{12}C reaction. Inelastic scattering and α-transfer studies have demonstrated that, in the case of ^{24}Mg*, such correlations, leading to resonant structures in the excitation function, persisted up to an excitation energy of $\sim$45 MeV, beyond which the excitation functions became nearly structureless [2]. Recently, exclusive light particle (α, proton) measurements have been made for the reaction ^{12}C + ^{12}C at an excitation energy of 61.4 MeV [3], which indicated that α-particle emission from ^{24}Mg* in general followed the expected behavior of the fusion-evaporation reaction but for some residual deviations from the statistical behavior in two specific (less dissipative) exit channels (carbon with 3α and oxygen with 2α channels), which have tentatively been assigned due to the contamination of direct (α-transfer and pickup) reactions and/or α-structure correlation effects. This has been further confirmed in the study of entrance channel dependence with a different entrance channel ^{14}N + ^{10}B [4]. On the other hand, in the intermediate-energy domain, it has recently been predicted theoretically using a microscopic mean-field model that cluster correlation may show up in the exit channel [in the decay of hot, light, self-conjugate projectile-like fragments (PF)] [8]; interestingly, a recent experimental investigation of the decay of hot ^{16}O, ^{20}Ne, and ^{24}Mg PFs produced in the reaction ^{40}Ca (25 MeV/nucleon) + ^{12}C have also indicated the existence of such α-cluster correlation in the exit channel at typical excitation energy of $\sim$3.5 MeV/nucleon [6]. Therefore, coming to the low-energy [fusion and compound nucleus (CN)] domain, it remains to be thoroughly investigated if α-structure correlations do manifest in specific dissipative channels of self-conjugate nuclei associated with the binary complex fragment decay of a compound nucleus. However, such studies, either theoretical or experimental, have not been made in the past in the low-energy domain.

With this motivation in mind, we planned to look for the signature of cluster correlation in binary fragment decay of fully energy-relaxed composites (compound nuclei) ^{24,25}Mg* formed in ^{12,13}C + ^{12}C reactions, by comparing the isotopic fragment yields in two exit channels corresponding to two reactions, where the complementary binary product of one of the exit channels is the well-known α-cluster nucleus. Here we report our measurement of isotopic fragments

(^{6,7}Li, ^{7,8,9}Be) emission in ^{12}C (80 MeV) + ^{12}C and ^{13}C (78.5MeV) + ^{12}C reactions. The beam energies for ^{12,13}C have been chosen so as to form the composite systems at same excitation energy. The measured and the predicted ratios of isotopic fragment yields from both reactions have been compared to look for the signature of cluster correlation in highly dissipative compound nucleus decay channel. The present results, for the first time, indicate the existence and influence of cluster correlation in highly dissipative binary fragment decay of the compound nucleus even at a fairly high excitation of $E^* \sim 54$ MeV.

The experiment has been performed at BARC-TIFR Pelletron-Linac facility, Mumbai, using 80-MeV ^{12}C and 78.5-MeV ^{13}C ion beams on ^{12}C target (thickness $\sim$70 μg/cm^2). The emitted fragments have been identified using two telescopes, each consisting of $\sim$50-μm ΔE single-sided silicon strip detector (SSSD), $\sim$1000-μm E double-sided silicon strip detector (DSSD), and backed by four CsI(Tl) detectors, each of thickness 6 cm. The angular resolutions were $\sim 0.8^\circ$ and $\sim 1^\circ$ for the two telescopes placed on either side of the beam axis. The isotopic separations obtained for different fragments were quite satisfactory [5]. The inclusive energy distributions for various fragments (^{6,7}Li, ^{7,9}Be) have been measured in the angular range of 14° to 36° in the laboratory. The ^{8}Be spectra were reconstructed from 2α correlation data obtained from the telescopes (details are illustrated in the following paragraphs). A Versa-Module-Eurocard (VME)–based online data acquisition system LAMPS [22] was used for the collection of data on an event-by-event basis. Energy calibrations of the telescopes have been performed using elastically scattered ^{12,13}C ions from ^{12}C, ^{209}Bi targets at different energies (^{12}C beam of 70 and 80 MeV, ^{13}C beam of 78.5 and 82 MeV) and using the ^{229}Th α source. The systematic errors in the data, arising from the uncertainties in the measurements of the solid angles, target thickness, detector dead area, and the calibration of current digitizer, have been estimated to be $\approx$15%.

Typical inclusive double differential energy spectra, $d^2\sigma/d\Omega dE$, of different isotopes of the fragments Li and Be obtained in the reactions ^{12}C + ^{12}C (blue solid line) and ^{13}C + ^{12}C (red dash-dotted line) are shown in Fig. 1. The energy distributions are nearly Gaussian in shape (excluding the transfer channel peaks), having their centroid at the expected kinetic energies for the fission fragments obtained from the Viola systematics corrected by the corresponding asymmetry factors [23] (shown by arrows in Fig. 1). This suggests that, in all cases, the fragments are emitted from a fully energy-relaxed composite as expected for statistical decay of a compound nucleus. From Fig. 1 it has been observed that the yield of ^{9}Be is higher in the ^{13}C + ^{12}C as compared to that in ^{12}C + ^{12}C reaction. This excess emission of ^{9}Be in the case of former is indicative of a clustering effect in the exit channel, as will be discussed later.

The energy spectrum of ^{8}Be, which is unstable and decays into $^8\text{Be} \to \alpha + \alpha$, was reconstructed from the measured α-α correlation data. The relative energies of all coincident α-α pairs from all detected events have been plotted against deduced Q values assuming binary breakup, as shown in Figs. 2(a) and 3(a) for the reactions ^{12}C + ^{12}C and ^{13}C + ^{12}C,

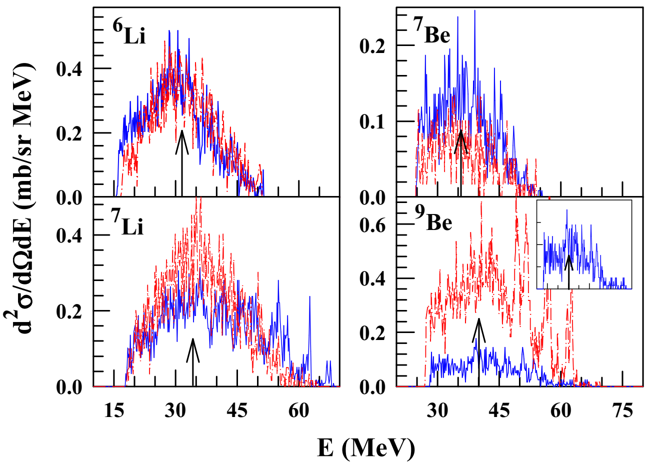

FIG. 1. Energy distributions of lithium and beryllium isotopes for the ^{12}C + ^{12}C (blue solid line) and ^{13}C + ^{12}C (red dash-dotted line) reactions at laboratory angle $\sim 15^\circ$. (Inset) Magnified energy distribution of ^{9}Be for ^{12}C + ^{12}C reaction. Arrows indicate the mean fragment kinetic energies of the fragments as obtained from Viola systematics (see text).

respectively. The ^{8}Be decay events are expected to form a band around α-α relative energy $\sim$92 keV, the Q value for breakup of ^{8}Be. The corresponding ^{8}Be energy spectra, generated by putting two-dimensional gates on the correlation plots [as shown in Figs. 2(a) and 3(a) by red rectangular boxes], have been displayed in Figs. 2(b) and 3(b). It is clear from the figures that for both the reactions, the energy spectrum of ^{8}Be follows Viola systematics, signifying equilibrium emission of these fragments from fully energy-relaxed composites.

The fragment angular distributions in the center of mass (c.m.), $d\sigma/d\Omega$, of different isotopes of Li and Be obtained as described in Ref. [12] in the above two reactions are

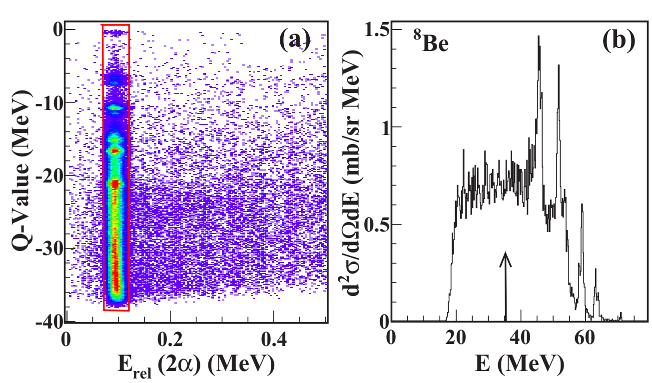

FIG. 2. (a) Typical two-dimensional plot of relative energy of 2α pairs detected in coincidence in each event vs respective reaction Q value estimated using two-body kinematics for the ^{12}C + ^{12}C reaction; (b) typical energy spectrum of ^{8}Be at 20°, reconstructed from 2α pairs within the rectangular gate shown by the red line in panel (a). Arrow indicates the mean energy of the fragment as obtained from Viola systematics (see text).

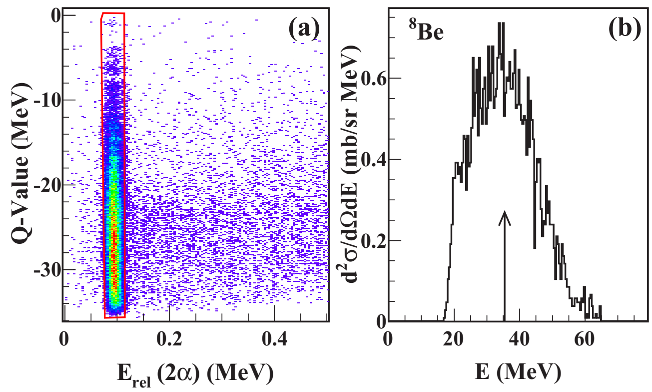

FIG. 3. Same as Fig. 2 for $^{13}C+^{12}C$ reaction (see text).

shown in Fig. 4. The angular distributions of all fragments emitted in both the reactions are found to follow $\sim 1/\sin\theta_{c.m.}$ dependence in c.m. (shown by solid lines in Fig. 4), which further demonstrated that these fragments have been emitted from a fully energy-dissipated, thermalized composite system.

The influence of neutron-to-proton ratio (N/Z) of the compound nucleus on the respective isotopic yield is also demonstrated clearly in Fig. 4. Usually, in the case of equilibrium decay, N/Z of the fragments are close to that of the compound nucleus. This trend is clearly visible here; the yields of ^{6}Li and ^{7}Be are more in the decay of $^{24}Mg^*$ than in the decay of $^{25}Mg^*$, whereas the yields of relatively neutron-rich isotopes ^{7}Li and ^{9}Be are more in the decay of $^{25}Mg^*$ than in the decay of $^{24}Mg^*$. In the case of ^{9}Be yield, the quantitative enhancement is found to be significantly higher than for all other fragments; this may be, at least partly, explained within the framework of statistical decay.

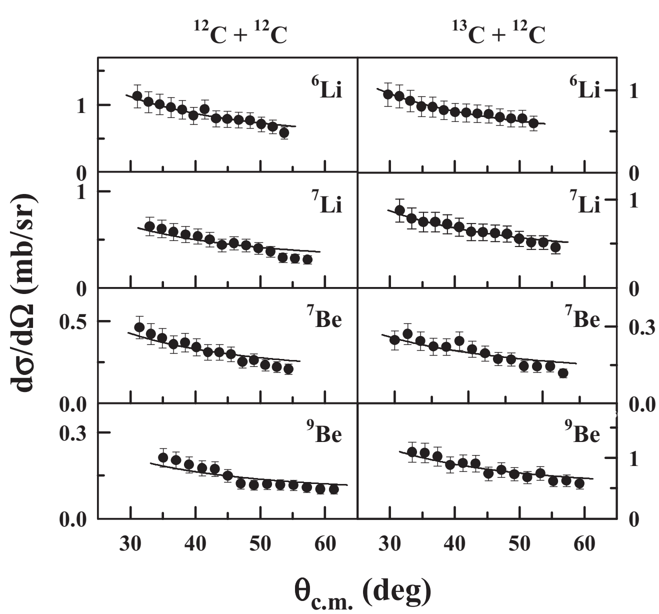

FIG. 4. The center of mass (c.m.) angular distribution of Li and Be isotopes for $^{12}C+^{12}C$ and $^{13}C+^{12}C$ reactions. The solid lines correspond to $d\sigma/d\Omega \sim 1/\sin\theta_{c.m.}$ fit to the data.

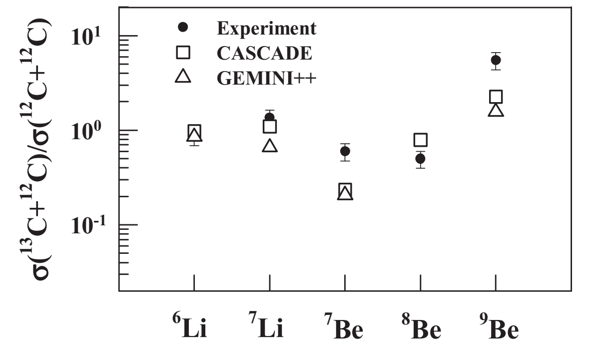

FIG. 5. Ratio of total cross sections of the fragments in $^{13}C+^{12}C$ and $^{12}C+^{12}C$ reactions. Solid circles represent the experimental data whereas open squares and triangles represent the statistical model calculations CASCADE and GEMINI++ respectively.

In order to go deeper into the comparative study of fully dissipative fragment yields between the two reactions, the experimental and the respective theoretical yields (cross sections) are displayed in Fig. 5, where the ratio of total cross section of each fragment in the two reactions [$R^{\exp(\text{th})} = \{\sigma(^{13}C+^{12}C)/\sigma(^{12}C+^{12}C)\}^{\exp(\text{th})}$] has been plotted separately for the experimental data as well as for the respective statistical model estimates obtained using two statistical model codes, CASCADE [24] and GEMINI++ [25]. The advantage of considering the ratio rather than the absolute cross section for comparison is that the effects of major experimental and computational biases are totally eliminated in the process and it brings out the physics issues more unequivocally to the forefront. It is seen from Fig. 5 that the experimental and CASCADE predicted yield ratios are completely matching for both ^{6,7}Li; in the case of GEMINI++ also, there is good agreement with data for ^{6}Li, though it slightly underpredicts the experimental yield ratio for ^{7}Li. On the other hand, the yield ratio for Be isotopes obtained using CASCADE either overpredicts (for ^{8}Be, $R^{\exp}/R^{\text{th}} \sim 0.6$) or underpredicts (for ^{7,9}Be, $R^{\exp}/R^{\text{th}} \sim 2.5$) the measured yield ratio. The code GEMINI++ also gives similar results; for both ^{7,9}Be, it underpredicts the experimental ratio and the degree of mismatch is similar to those estimated using CASCADE in both cases (GEMINI++ does not give any direct binary yield of unstable ^{8}Be, so corresponding comparison could not be made). The above results convincingly establish the fact that the measured yield ratios for Be isotopes are not in proper agreement with any of the statistical model estimates; for ^{7,9}Be, both the codes underpredict and for ^{8}Be, CASCADE overpredicts the corresponding experimental yield ratios. Though the trends of deviation in the two cases are apparently opposite to each other, we argue in the following paragraphs that the deviations observed above between the experiment and theory in all cases are due to preponderance of cluster correlation in those specific exit channels which survives at moderately high excitation of about $\sim$2.25 MeV/nucleon in the present case.

In the case of emission of ^{6,7}Li fragments, the complementary binary reaction products in the two reactions ($^{13,12}C+^{12}C$) are ^{19,18}F and ^{18,17}F, respectively. None of those fluorine isotopes is known to have any pronounced cluster structure.

Therefore, the binary fragmentation of fully energy-relaxed ^{24,25}Mg* into isotopes of Li and F is entirely determined by statistical (phase space) considerations. As a result, the experimental yields of ^{6,7}Li fragments are in very good agreement with the corresponding equilibrium decay (CACADE and GEMINI++) calculations as evident in Fig. 5. The emission of any of ^{7,8,9}Be fragments is associated with the emission of one of the isotopes of oxygen ($^{15-18}$O) as complementary fragment in the exit channel. Among them ^{16}O is well known α-cluster nucleus. The cluster structure of nonconjugate ^{18}O, where the extra valence neutrons are conjectured to stabilize quasimolecular structures, has also been fairly well established [26–28]. Therefore, in the case of ^{7}Be emission, the yield in the decay channel $^{13}\mathrm{C}+^{12}\mathrm{C} \to {}^{25}\mathrm{Mg}^* \to {}^7\mathrm{Be}+^{18}\mathrm{O}$ is expected to be higher than the corresponding statistical model value if cluster correlation due to ^{18}O survives in the exit channel and also contributes to the yield. This additional cluster correlated contribution will not be present for the $^{12}\mathrm{C}+^{12}\mathrm{C} \to {}^{24}\mathrm{Mg}^* \to {}^7\mathrm{Be}+^{17}\mathrm{O}$ decay channel. Therefore, the observed enhancement of the measured yield ratio of ^{7}Be over the corresponding statistical model yield ratio in Fig. 5 is a clear signature of the dominant role played by cluster structure at this excitation energy. The emissions of both ^{8}Be and ^{9}Be are associated with the emission of ^{16}O in the following decay channels: $^{12}\mathrm{C}+^{12}\mathrm{C} \to {}^{24}\mathrm{Mg}^* \to {}^8\mathrm{Be}+^{16}\mathrm{O}$ and $^{13}\mathrm{C}+^{12}\mathrm{C} \to {}^{25}\mathrm{Mg}^* \to {}^9\mathrm{Be}+^{16}\mathrm{O}$. So the cluster correlation in ^{16}O, if remains significant at this excitation, may boost up the yield of these respective exit channels over and above the normal statistical emission. As a result, ^{8}Be experimental yield ratio (R^{exp}) will be lower than the corresponding statistical model value (R^{th}) and it will be just opposite for ^{9}Be—which explains, at least qualitatively, the observed trend in Fig. 5.

It may be noted here that the recent studies on the effect of α-cluster correlation on exclusive light particle emission in kinematically complete measurements of $^{12}\mathrm{C}+^{12}\mathrm{C}$ reaction have indicated that the signature of α clustering was quite prominent for channels with oxygen as one of the reaction products [3]. They have also shown that the cluster correlation was present in the low dissipative (transfer-like) part of the reaction, which might be influenced by the cluster structure of particular entrance channel ($^{12}\mathrm{C}+^{12}\mathrm{C}$), as the effect reduced considerably for different (noncluster) entrance channels, producing same composite at the same excitation [4]. On the other hand, the more dissipative parts of the α spectrum were rather in agreement with the statistical decay prediction. In the present study, however, it is found that even in the decay of a fully equilibrated system with excitation energy $\sim$54 MeV, the fragment yields are substantially influenced by the cluster structure of the exit channel or more particularly of oxygen, which is contrary to our intuitive understanding that the effect of cluster correlation should die out at higher excitations. The observed survival of cluster correlation, as indicated for the first time in the present data, may due to the presence of quite a few known resonant cluster states of ^{16,18}O within the excitation energy range of these fragments; besides, there may also be interplay of dynamical evolution favoring the particular exit channel configuration [8]. In addition, the present results also point to the fact that choice of specific exit channels may be crucial to extract the signature of clustering; exit channels with known cluster configurations are likely to be more efficient in deciphering the nature of correlation and its evolution with excitation energy.

From the above discussions, it is evident that our conventional wisdom about clustering in hot nuclei is quite incomplete; some form of cluster correlation does persist in specific exit channels of hot composite decay, which are completely unwarranted as per our common understanding of CN formation and decay. However, no theoretical model for the genesis of clustering in the evolution of the hot composite towards its final exit channels is available, to the best of our knowledge, for the low-energy reactions, though recently there have been theoretical attempts to explore the possibility of occurrence of cluster correlation in the exit channel of hot PFs [8]. Even in the latter case, though the formation of $N\alpha$-cluster sources during the freeze-out phase of the PF was predicted, no quantitative estimate of the clusterlike source yield was available. In the low-energy domain, the inclusion of clustering mechanism in the evolutionary dynamics of binary fragment emission remains as a major challenge. In the absence of such a theory, no quantitative prediction of the effect of cluster correlation in the final exit-channel yield is possible. The present data at least point to the need of such a theoretical development for a deeper understanding of the low-energy nuclear reaction scenario.

In conclusion, cluster correlations in the decay of light compound systems ^{24,25}Mg*, produced through ^{12}C (80 MeV) + ^{12}C and ^{13}C (78.5 MeV) + ^{12}C reactions, have been studied from the isotopic yields of emitted fragments ^{6,7}Li and ^{7,8,9}Be. The measured fully energy dissipative fragment yields have been compared with the corresponding statistical model predictions. It has been found that the yields of ^{6,7}Li are in complete agreement with the respective statistical model (CASCADE) predictions. But, the yields of ^{7,8,9}Be for a few specific decay channels have been found to be enhanced from their respective CACADE predictions, when the complementary fragments in the exit channel were either of the isotopes of oxygen (^{16,18}O), both having prominent cluster structures. Independent cross checking of the results using the statistical model code GEMINI++ has also led to similar conclusions. So, the present results on dissipative fragment yield are indicative of the survival of the cluster correlation in the decay of hot compound system even at an excitation of 54 MeV. This is interesting, as recent light-particle (α) emission study of the same system [^{12}C (95 MeV) + ^{12}C] has indicated that the effects of cluster correlation, present at low excitations, wither away at higher excitations. Furthermore, the present study also highlighted that the choice of proper exit channel combinations may be crucial for the observation of clustering correlation in hot nuclei. These warrant further detailed investigations in the future.

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[1] M. Freer, Rep. Prog. Phys. **70**, 2149 (2007); W. von Oertzen *et al.*, Eur. Phys. J. A **36**, 279 (2008); O. S. Kirsebom *et al.*, Phys. Rev. Lett. **108**, 202501 (2012); T. K. Rana *et al.*, Phys. Rev. C **88**, 021601(R) (2013); M. Freer and H. O. U. Fynbo, Prog. Part. Nucl. Phys. **78**, 2149 (2014).

[2] A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, T. Happ, D. J. Henderson, P. Wilt, and I. G. Bearden, Phys. Rev. Lett. **68**, 1295 (1992); C. A. Bremner *et al.*, Phys. Rev. C **66**, 034605 (2002); M. Freer, J. T. Murgatroyd, S. M. Singer, N. Curtis, D. J. Henderson, D. J. Hofman, and A. H. Wuosmaa, *ibid.* **63**, 034317 (2001).

[3] L. Morelli *et al.*, J. Phys. G **41**, 075107 (2014); **41**, 075108 (2014); G. Baiocco *et al.*, Phys. Rev. C **87**, 054614 (2013).

[4] L. Morelli *et al.*, EPJ Web Conf. **66**, 03064 (2014).

[5] T. K. Rana *et al.*, EPJ Web Conf. **86**, 00036 (2015).

[6] B. Borderie *et al.*, Phys. Lett. B **755**, 475 (2016).

[7] H. Morinaga, Phys. Rev. **101**, 254 (1956); M. Chernykh, H. Feldmeier, T. Neff, P. von Neumann–Cosel, and A. Richter, Phys. Rev. Lett. **98**, 032501 (2007); A. Tohsaki, H. Horiuchi, P. Schuck, and G. Ropke, *ibid.* **87**, 192501 (2001).

[8] M. Girod and P. Schuck, Phys. Rev. Lett. **111**, 132503 (2013).

[9] S. J. Sanders *et al.*, Phys. Rep. **311**, 487 (1999), and references therein.

[10] D. Shapira, J. L. C. Ford Jr., J. Gomez del Campo, R. G. Stokstad, and R. M. DeVries, Phys. Rev. Lett. **43**, 1781 (1979).

[11] D. Shapira, J. L. C. Ford Jr., and J. Gomez del Campo, Phys. Rev. C **26**, 2470 (1982).

[12] C. Bhattacharya *et al.*, Phys. Rev. C **72**, 021601(R) (2005).

[13] A. Dey *et al.*, Phys. Rev. C **76**, 034608 (2007).

[14] W. Dünnweber, A. Glaesner, W. Hering, D. Konnerth, R. Ritzka, W. Trombik, J. Czakanski, and W. Zipper, Phys. Rev. Lett. **61**, 927 (1988).

[15] D. Shapira, R. Novotny, Y. C. Chan, K. A. Erb, J. L. C. Ford Jr., J. C. Peng, and J. D. Moses, Phys. Lett. B **114**, 111 (1982).

[16] 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).

[17] S. Kundu, A. Dey, K. Banerjee, T. K. Rana, S. Muhkopadhayay, D. Gupta, R. Saha, S. Bhattacharya, and C. Bhattacharya, Phys. Rev. C **78**, 044601 (2008).

[18] S. Kundu *et al.*, Phys. Rev. C **85**, 064607 (2012).

[19] S. Kundu, C. Bhattacharya, S. Bhattacharya, T. K. Rana, K. Banerjee, S. Muhkopadhayay, D. Gupta, A. Dey, and R. Saha, Phys. Rev. C **87**, 024602 (2013).

[20] C. Bhattacharya, S. Bhattacharya, T. Bhattacharjee, A. Dey, S. Kundu, S. R. Banerjee, P. Das, S. K. Basu, and K. Krishan, Phys. Rev. C **69**, 024607 (2004).

[21] E. Costanzo, M. Lattuada, S. Romano, D. Vinciguerra, N. Cindro, M. Zadro, M. Freer, B. R. Fulton, and W. D. M. Rae, Phys. Rev. C **44**, 111 (1991).

[22] http://www.tifr.res.in/~pell/lamps.html.

[23] C. Beck and A. Szanto de Toledo, Phys. Rev. C **53**, 1989 (1996).

[24] F. Pühlhofer, Nucl. Phys. A **280**, 267 (1977).

[25] R. J. Charity, Phys. Rev. C **82**, 014610 (2010).

[26] N. Curtis, D. D. Caussyn, C. Chandler, M. W. Cooper, N. R. Fletcher, R. W. Laird, and J. Pavan, Phys. Rev. C **66**, 024315 (2002).

[27] G. V. Rogachev *et al.*, J. Phys. Conf. **569**, 012004 (2014).

[28] E. D. Johnson, Ph.D. thesis, Florida State University, Tallahassee, FL, 2008 (unpublished).