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Letter

New experimental approach for developing a mass-energy systematics for precompound emission

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A systematic analysis of the experimental cross-section data in odd mass number (A) and odd atomic number (Z) nuclei is reported to reveal a novel mass-energy systematics for the pre-compound emission of fast neutrons in α-induced reactions at low energies. The experimental excitation functions have been analyzed within the framework of statistical model predictions to get information regarding pre-compound emission. The present analysis establishes for first time an interesting systematics, emphasizing that accessible excitation energy on peripheral nucleons of the systems is an exponential function of atomic mass number (A) of target nuclei. One of the most important features of this systematics is to provide a precise estimation of the pre-compound contribution for any nuclei, except closed-shell ones, over a wide range of mass number $63 \leqslant A \leqslant 109$ in the nuclear landscape. New results of the present analysis emphasize an additional subtle interconnection between the structure of nuclei and the nuclear reaction mechanism of the pre-compound emission process at low energies, where the compound nucleus process is more likely to be dominant.

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Pre-compound nucleus (PCN) decay—defined as a complex process of emitting energetic light fast particles (LFPs) from any intermediate state formed due to the initial projectile-target interaction within a nonequilibrated compound nucleus (NCN) after transferring complete projectile energy into a few degrees of freedom—has long been a subject of fundamental interest in light-ion-induced reactions [1]. The involvement of a few degrees of freedom manifests the importance of the lower matter density region at the exterior surface of the compound nucleus in the case of pre-compound emission. Such lower matter density favors the emission of LFPs in the PCN process [2,3]. The interaction trajectory of the colliding nuclei for fast particle emission determines a peripheral path that treats the reaction process as nonstatistical and inelastic in nature.

This is in contrast to the deeper particle evaporation from the core of the compound nucleus (CN), which proceeds via a large number of statistical interactions among a relatively large number of degrees of freedom within the nucleus. Involvement of a relatively very large number of degrees of freedom indicates that particles take a little longer time ($\approx 10^{-16}$ s) for their emission from the excited nucleus isotropically in the center-of-mass frame. Such emission is well explained by the statistical theory of CN decay. On the other hand, observation of a forward peaked angular distribution of the emitted particles is the dominant experimental characteristic of the PCN emission process and makes it distinguishable from the CN process. In the PCN emission, energetic particles (nucleons) residing on the periphery of the NCN system escape rapidly ($\approx 10^{-20}$ s), in times shorter than those taken by the deeper particles from the CN to traverse the entire nuclear diameter [2,4].

This indicates involvement of a relatively smaller number of degrees of freedom, which is required for emission of the

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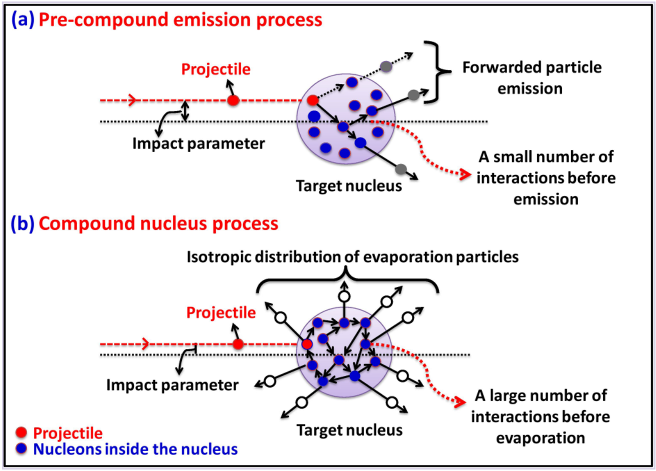

FIG. 1. A pictorial representation of pre-compound and compound nucleus processes for emitting and evaporating light nuclear particles.

pre-compound particles in peripheral interactions. At low projectile energies, depending on the interaction trajectories or the impact parameters between colliding nuclei, a distinction between dominant reaction mechanisms of particle emission in the PCN and CN processes is shown in Figs. 1(a) and 1(b). In this figure, a smaller number of interactions between projectile and target nuclei before emission of nuclear particles characterizes the PCN emission process, while a larger number of interactions before evaporation of particles corresponds to the CN decay. The phenomenon of PCN emission was studied in detail with incident particles of high energy above 10 MeV/nucleon. Later, the recent advancements in the accelerator and detector technologies gave an opportunity to study more rigorously the PCN emission process at relatively low energies, where the CN process is found to be a sole contributor.

As the process of pre-compound emission dominates at relatively higher energies, it enhances the reaction cross section and, hence, the reaction rates for the astrophysical stellar phenomenon of element creation in stars [5,6]. Since PCN emission itself is a complex phenomenon which also competes with the CN process at relatively low energy, it is rather difficult to extract its own contribution within CN reactions. It will be interesting if such PCN contribution relative to the CN components, termed the pre-compound fraction (F_{pcn}), is determined experimentally in relevnt reactions, and variation of F_{pcn} with energy is studied over a wide range of nuclei in order to see any systematics. This is important, as data on the PCN emission over a wide mass range of nuclei are required to understand the basic origin point of LFP emission from the quasiequilibrated states in reactions before proceeding to equilibrium.

Theoretically, cross sections associated with quasiequilibrated (intermediate) states of particle emission are difficult to determine, as the fluctuations in the level density of such pre-compound emission states are yet to be known precisely. Experimentally, insufficient or contradictory cross-section data on same reaction by different authors also obstruct drawing a concrete conclusion on the PCN emission process. Both these experimental and theoretical constraints create complexity in developing the systematics in the PCN emission process. Blann [7] in his pioneering theoretical work made an attempt to develop a systematics on the PCN emission process by determining the variation of pre-equilibrium/pre-compound fraction (F_{pcn}) with the excitation energy in reactions induced by α particles [7]. Nonetheless, this study [7] was not carried forward on account of non-availability of appropriate experimental data for a wide mass region. Blann [7] pointed out in the concluding remarks that it would be very much needed to deduce F_{pcn} from precise experimental data for a wide range of excitation energies and mass numbers of target nuclei. Later on, Hodgson [1] also put forward the remark that many detailed interesting features of PCN decay may emerge by performing a systematic analysis of the experimental cross-section data for several reactions.

For many years, availability of abundant experimentally measured cross-section data inspired searches for some interesting systematics on the PCN emission. The present work is an attempt to find an exclusive parameter which can satisfactorily explain the pre-compound emission for a wide range of target nuclei on the nuclear landscape at low energies. This is important in view of the fact that none of the pre-compound models are capable of explaining the complexity associated with the PCN emission with a single parameter. This is achieved by performing a systematic analysis of low energy experimental cross-section data on (α, n) reactions for several target nuclei of atomic mass number $A \approx 60$–110. In this mass region, the probability of neutron capture is high; therefore, conclusions drawn from the present analysis not only augment the understanding of the PCN reaction dynamics but also provide a scientific basis to explain the stellar enhancement in the reaction rate of astrophysical phenomena [2,4]. Furthermore, in principle, the present study of pre-compound neutron emission may also be significantly important in the formation of superheavy elements (SHE). This is because the pre-compound emission of neutrons enhances the formation cross sections of superheavy nuclei, which increases the survival probability of the evaporation residue and, hence, increases the relevant reaction cross sections [8].

With this motivation, we performed a systematic analysis of available experimental cross-section data for (α, n) reactions on odd-A and odd-Z target nuclei, viz., ^{63}Cu, ^{65}Cu, ^{69}Ga, ^{71}Ga, ^{85}Rb, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag and ^{109}Ag. The selection of α-particle beam and the target nuclei for these reactions is based on the following facts. The strongly bound α-particle beams have large reaction cross sections for neutron emitting channels, predominantly for one-neutron emission at low energies. Hence beams of α particles are the most suitable for the study of the pre-compound emission process. The choice of odd-A and odd-Z target nuclei in these reactions is to wash out the ambiguity arising due to odd-even effects, if any. In α-particle-induced reactions, the possibilities of other competing processes, viz, elastic breakup, transfer reactions, incomplete fusion, massive transfer, etc., are reduced considerably. Further, consistent experimental data of different workers are also available for these reactions in the literature

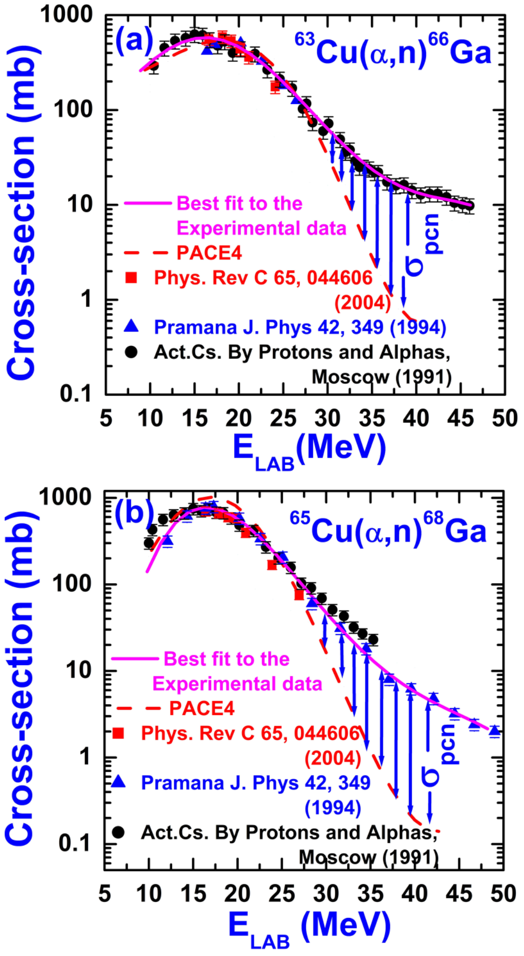

FIG. 2. Experimentally measured EFs with consistent inclusive-online Ref. [10] and exclusive-offline Refs. [11,12] data for reactions ^{63}Cu$(\alpha,n)^{66}$Ga [indicated in panel (a)] and ^{65}Cu$(\alpha,n)^{68}$Ga [panel (b)]. In these figures the theoretical calculations performed with the Monte Carlo statistical code PACE4 are also shown.

(EXFOR data library) [9] and have less experimental uncertainty.

Keeping the above facts in mind, the plots of measured excitation functions (EFs) for the chosen reactions have been obtained by using a consistent set of experimental cross-section data. As typical examples, the EFs for reactions ^{63}Cu$(\alpha,n)^{66}$Ga and ^{65}Cu$(\alpha,n)^{68}$Ga are shown in Figs. 2(a) and 2(b), respectively, where solid curves guide the eye to the best fit of the experimental data taken from Refs. [10–12]. The theoretical calculations for these reactions have also been performed with the Monte Carlo statistical code PACE4 [13,14] and are shown in Figs. 2(a) and 2(b) by dashed curves. The code PACE4 [13,14] is based on Hausher-Feshbach (HF) theory [15] and calculates cross section by using Bass formulations [16]. As can be seen from these figures, the statistical calculations reproduce the experimental data up to the peak region; however, observed enhancement of the experimental data as compared to PACE4 predictions in the tail portion of measured EFs has been attributed to the sole contribution of pre-compound emission.

The sole contribution of the PCN emission (σ_{pcn}) is observed by subtracting CN cross section ($\sigma_{cn} = \sigma_{pace4}$) from experimental data ($\sigma_{exp} = \sigma_{cn+pcn}$), i.e., $\sigma_{pcn} = (\sigma_{cn+pcn} - \sigma_{cn})$, at each energy. Such contribution of the PCN emission (σ_{pcn}) is shown by vertical arrows in Figs. 2(a) and 2(b). As can be seen from this figure, the contribution of PCN (length of arrows) goes on increasing with respect to the CN prediction at relatively higher energies. This is because the phenomenon of PCN emission is dominant at relatively high energies. In a similar way, the PCN contribution has also been deduced for the presently studied reactions ^{69}Ga$(\alpha,n)^{72}$As, ^{71}Ga$(\alpha,n)^{74}$As, ^{85}Rb$(\alpha,n)^{88}$Y, ^{89}Y$(\alpha,n)^{92}$Nb, ^{93}Nb$(\alpha,n)^{96}$Tc, ^{103}Rh$(\alpha,n)^{106}$Ag, ^{107}Ag$(\alpha,n)^{110}$In, and ^{109}Rh$(\alpha,n)^{112}$In.

After deducing the contribution of pre-compound emission in reactions, a quantity termed the pre-compound fraction, F_{pcn} [$= (\sigma_{pcn}/\sigma_{cn+pcn})\times 100\%$], is defined that indicates the relative importance of PCN emission in the CN process. In order to establish systematics in the PCN emission with mass number, F_{pcn} is plotted as a function of the center-of-mass energy ($E_{c.m.}$) for each target nuclei in Fig. 3(a). Here, $E_{c.m.}$ washes out the effects arising due to the individual masses of projectile and target nuclei by converting the two-body system into a one-body system. As can be seen from Fig. 3(a), initial value of F_{pcn} increases very rapidly with $E_{c.m.}$. The steep rise of F_{pcn} at lower energies indicates sensitive dependence of pre-compound decay on $E_{c.m.}$. Further, a small variation in $E_{c.m.}$ produces a large change in F_{pcn}, which implies complexity of the PCN process. In this energy region, it is indeed difficult to extract the exact contribution of the PCN emission in reactions. Furthermore, the slower rate of F_{pcn} with $E_{c.m.}$ indicates the saturation of first PCN particle emission and the opening of the threshold of second particle emission in the PCN process.

It may be observed that the values of $E_{c.m.}$ at which F_{pcn} starts and attains maximum are different for different targets. As indicated in Fig 3(a), F_{pcn} starts increasing at a lower value of $E_{c.m.}$ for heavier mass target nuclei (^{109}Ag) and vice versa; i.e., with increasing mass of nuclei, a relatively smaller energy is required to emit one neutron as a pre-compound particle from the composite system. This is expected as the Q value of neutron emission for α-induced reactions for highest mass number nuclei (i.e., Q value $= -6.376$ MeV for ^{109}Ag) is less negative as compared to the lightest target nuclei ^{63}Cu (Q value $= -7.502$ MeV). However, data collected for the target nuclei, viz., ^{69}Ga, ^{71}Ga, ^{85}Rb, ^{89}Y, ^{93}Nb, ^{103}Rh, and ^{107}Ag, do not follow a systematic trend of F_{pcn}. Therefore, no clear systematic dependence on $E_{c.m.}$ with mass number of target nuclei can be obtained. Nevertheless, the peculiarity in trend of all curves along with unique behavior, as no curve superposes over another, is a clue for existence of systematics in the PCN emission process with target mass number.

In a nuclear reaction, the static effects arising due to different projectile-target combinations influence the reaction cross section considerably. Such effects are washed out by including the Q value of the reaction in the energy ($E_{c.m.}$). As a result, the excitation energy ($E^* = E_{c.m.} + Q$) can be used as another important parameter in place of $E_{c.m.}$ to derive the mass dependent systematics in the PCN emission. With the aim of gaining

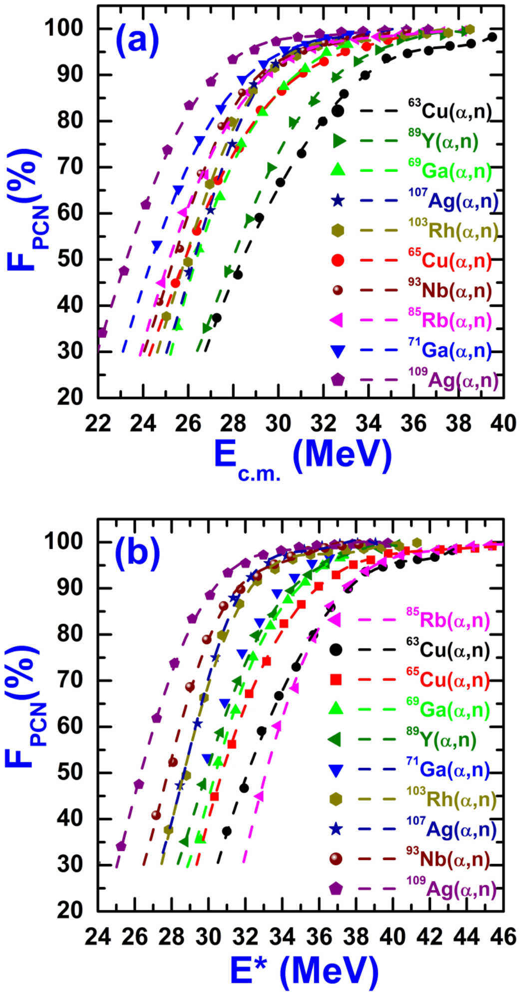

FIG. 3. The fraction of pre-compound emission F_{pcn} as a function of center-of-mass energy ($E_{c.m.}$) and excitation energy (E^*) for α-induced reactions on target nuclei ^{63}Cu, ^{65}Cu, ^{69}Ga, ^{71}Ga, ^{85}Rb, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag, and ^{109}Ag.

strong confidence in the systematic study of PCN emission, F_{pcn} is plotted as a function of the excitation energy (E^*) for the aforesaid reactions in Fig. 3(b). The only observation which can be made in this case is that the threshold value of the excitation energy at which F_{pcn} starts is lower for the heavier target ^{109}Ag; but this is not the case for the lower mass target nuclei, as higher value of E^* corresponds to the ^{85}Rb as compared to the ^{63}Cu target nucleus. Further, the nuclei ^{71}Ga and ^{93}Nb again do not follow the systematic trend of the F_{pcn} with excitation energy (E^*). These results are found to be far away from the expectation of Blann [7] and Hodgson [1], as they looked for some systematic trends of PCN decay with excitation energy experimentally.

As mentioned, the emission of LFPs in the PCN process is strongly governed by interaction trajectories and matter density. The impact parameters of the colliding nuclei curb the interaction trajectories between projectile and target, while matter density, somehow, may influence the emission of pre-compound particles. As a matter of fact, a relatively lower value of matter density (larger value of impact parameter) produces a lower number of nuclear interactions (excitons) within the nucleus and may enhance the pre-compound emission. Consequently, in PCN emission the participation of nucleons on the periphery of the composite system is more probable, where matter density is relatively smaller, as compared to the nucleons well inside the nucleus. As a result, the excitation energy available to the nucleons at the periphery of nucleus may play a crucial role in emission of LFPs in the PCN process.

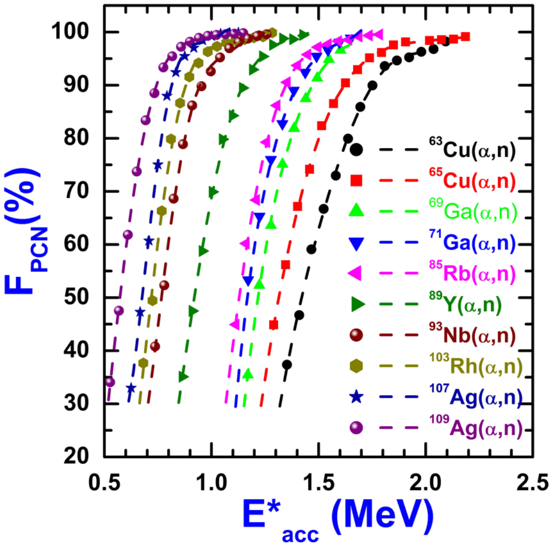

FIG. 4. The fraction of pre-compound emission F_{pcn} as a function of excess energy E^*_{acc} for α-induced reactions on target nuclei ^{63}Cu, ^{65}Cu, ^{69}Ga, ^{71}Ga, ^{85}Rb, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{107}Ag, and ^{109}Ag.

In addition to the role played by the nucleons at the periphery of the nucleus in PCN emission, the Coulomb effect (Z_1Z_2) may also be considered to be important for the parametrization of energy. Consequently, the accessible excitation energy over the Coulomb barrier ($E^* - V_b$) per surface nucleon of the composite system [$E^*_{acc} = (E^* - V_b)/A^{2/3}$] may influence the pre-compound emission process significantly [8]. Considering the above facts, we took a step towards an interesting systematics on the PCN dynamics with mass number by plotting F_{pcn} as a function of E^*_{acc}. These plots are shown in Fig. 4 for the presently studied reactions. As can be seen from this figure, a systematic trend of F_{pcn} in terms of mass number A of the target nuclei and E^*_{acc} has been revealed: successive decrease in the value of E^*_{acc} with increase in the mass number (A) of target nuclei from $^{63}_{29}$Cu to $^{109}_{47}$Ag. Figure 4 gives a clear picture of the pre-compound emission process, indicating the involvement of surface nucleons in such reactions. Surface nucleons may be considered to follow the interaction trajectories with relatively larger value of impact parameter and to have significant influence on the emission of pre-compound neutrons for the presently studied target nuclei ($63 \leqslant A \leqslant 109$).

The conclusions drawn from Fig. 4 on the interesting mass-energy systematics in pre-compound emission are summarized in Fig. 5. The value of E^*_{acc} corresponding to each target nucleus is deduced from Fig. 4 to obtain the mass-energy systematics. As a typical example of mass-energy

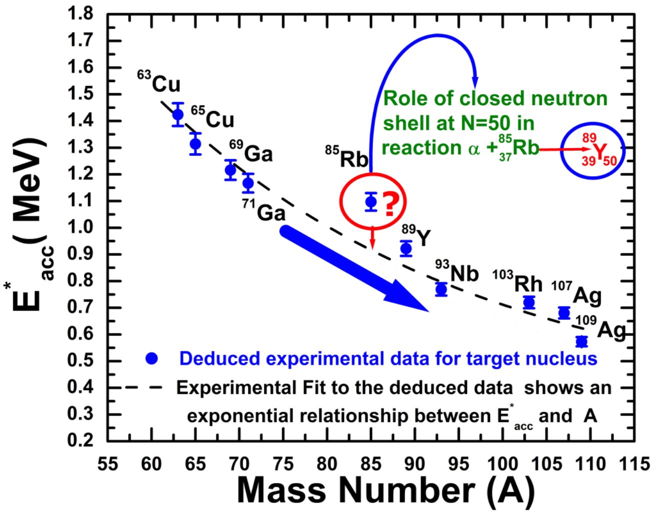

FIG. 5. Mass-energy systematics in pre-compound emission reactions, indicating that excess excitation energy E^*_{acc} is an exponential function of mass number of target nuclei for a wide $A \approx 63$–107 region.

systematics, the variation of E^*_{acc} with mass number A ($63 \leqslant A \leqslant 109$) for a definite value of the pre-compound fraction (say 50%) is shown in Fig. 5. As can be seen from this figure, E^*_{acc} goes on decreasing almost exponentially (dashed curve) with mass number (A) of the target nuclei for a given value of pre-compound fraction. A lower value of E^*_{acc} is needed to emit a neutron as a pre-compound particle from higher mass target nuclei, and vice versa. This exponential relationship in the PCN emission process is significantly important and gives a way to correlate the pre-compound contribution for (α, n) reactions at low energies, where the CN emission is generally considered to be dominant.

The target nucleus ${}^{85}_{37}$Rb (red circle in Fig. 5) needs to be specially mentioned. The higher value of E^*_{acc} corresponding to nucleus ${}^{85}_{37}$Rb shows an interconnection between the nuclear structure and reaction dynamics of neutron emission in pre-compound emission that indicates another success of the mass-energy systematics. The deviation of E^*_{acc} for ${}^{85}_{37}$Rb may be explained by the closed neutron shell at $N = 50$ (magic number) of the excited compound nucleus ${}^{89}_{39}$Y formed as a result of fusion of an α particle with the target nucleus ${}^{85}_{37}$Rb (i.e., $\alpha + {}^{85}_{37}\mathrm{Rb} \Rightarrow {}^{89}_{39}Y_{50}$). Since the compound nucleus ${}^{89}_{39}\mathrm{Y}_{50}$ has a closed neutron shell ($N = 50$, a magic neutron nucleus), it requires more excitation energy to emit one neutron as compared to the neighboring nucleus ${}^{89}_{39}$Y, even when it is used as a target in the $\alpha + {}^{89}_{39}\mathrm{Y} \Rightarrow {}^{93}_{41}\mathrm{Nb}_{52}$ reaction.

To conclude, it has been stated that particles interacting on the nuclear periphery, where an average lower nucleon density is present, may have a better chance of being emitted as pre-compound particles, compared to particles passing through the entire diameter of the target nucleus; an underlying effect of a lower density nuclear matter region. In this reagrd, the systematics obtained from the present analysis is interesting, and offers additional insight into the existing reaction dynamics of the low energy pre-compound emission process.

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