Systematic study of pre-equilibrium emission at low energies in ^{12}C- and ^{16}O-induced reactions

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Background: The role of pre-equilibrium emission within the heavy-ion fusion process has not been fully characterized. An accurate description of this process is important for understanding the formation of the compound nucleus in fusion reactions.

Purpose: We develop a systematic description, based on experimental measurements, of the strength of the pre-equilibrium process in heavy-ion fusion reactions.

Method: With a view to study pre-equilibrium emission process, the excitation functions for some neutron emission channels occurring in the fusion of ^{12}C with ^{128}Te and ^{169}Tm, and of ^{16}O with ^{159}Tb, ^{169}Tm, and ^{181}Ta, respectively, have been measured at incident energies from near the Coulomb barrier to ≈7 MeV/nucleon. The off-line γ-ray spectrometry–based activation technique has been used for the measurements of excitation functions. The measured excitation functions have been compared with theoretical predictions based on pure statistical model code PACE4 and Geometry Dependent Hybrid (GDH)-based code ALICE-91. The strength of pre-equilibrium emission has also determined from comparison of the experimental excitation functions and the PACE4 calculations.

Results: The measured excitation functions are satisfactorily reproduced by the PACE4 calculations in the energy region up to the peak position. However, at relatively higher energies, the enhancement of experimental cross sections in the tail portion of excitation functions as compared to the theoretical predictions of code PACE4 has been observed. The observed deviation may be attributed to the pre-equilibrium emission of particles during the thermalization of the compound nucleus. Further, ALICE-91 calculations which include PE emission satisfactorily reproduce the experimental data even at higher energies, indicating the significant contribution of pre-equilibrium emissions.

Conclusions: Analysis of data clearly indicates that pre-equilibrium emission is an important reaction mechanism even at low projectile energies where the compound nucleus reaction mechanism dominates, and pre-equilibrium fraction 'P_{FR} strongly depends on excitation energy available for surface nucleons in composite systems above the Coulomb barrier and the mass of the composite system.

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I. INTRODUCTION

There has been renewed interest in the emission of light fast particles (LFPs) in light-ion and heavy-ion (HI)–induced reactions [1]. The decay mechanism of LFP emission in such reactions reflects the dynamics of the formation of excited systems and their evolution to the equilibrium state. The LFPs emitted prior to the establishment of thermodynamic equilibrium of the composite system are termed pre-equilibrium (PE) particles and the reaction mechanism is referred to as the PE process [2–7]. The study of PE emission has attracted considerable attention recently from both the theoretical [3,8] and experimental [1,2,4–6,9,10] aspects, after the observation of LFPs at low energies, where a pure evaporative process is greatly favored. At moderate excitation energies in HI reactions, one expects interplay between the compound nucleus (CN) and the PE emission processes. In such processes the heavy residues may be formed with charge equal to or one unit less than the composite nucleus, via xn and pxn emission channels. At relatively high beam energies, breakup fusion or incomplete fusion (ICF) processes are also dominant over the CN and PE emission processes [6,11–15]. The light HI beams, i.e., ^{12}C and ^{16}O ions, which may have finite probability of breakup into fragments, are reported [6] to be suitable for studying many reaction processes in HI interaction.

The phenomenon of PE emission may also be understood as follows: When two heavy nuclei fuse together, they form a composite nucleus far from the statistical equilibrium, and a large fraction of its energy is considered to be in the form of an orderly translational motion of the nucleons of the projectile and the target nuclei. This orderly motion transforms slowly into chaotic thermal motion through a series of two-body interactions. The thermalization process completes when the composite nucleus reaches a state of thermal equilibrium, referred to as the compound nucleus. During the thermalization of an excited composite system, it may be possible that a single

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nucleon or a cluster of nucleons having considerable energy is ejected into the continuum. As soon as the state of thermal equilibrium is attained, the accumulation of sufficient energy on a single nucleon or a cluster of nucleons may occur in a random sequence of events and hence may require much longer emission times, favoring the emission of low-energy particles. The time scale at which PE emissions occur is very short, $\approx 10^{-21}$ s, while further evaporations from the equilibrated nucleus take a longer time, $\approx 10^{-16}$ s. The rate of emission of the PE nucleons depends on the sensitivity of the mean-field interaction between the projectile and the target nucleus [6]. This determines the initial energy distribution among the nucleons in the projectile and the target nuclei, which starts a cascade of nucleon-nucleon interactions as soon as the two nuclei touch each other. Some of the important experimental signatures of PE emission are (i) the presence of a larger number of high-energy particles as compared to the spectrum predicted by the compound nucleus model, and hence considerable reduction of CN excitation energy, (ii) forward-peaked angular distribution of emitted particles, and (iii) slowly descending tails of excitation functions (EFs), resulting in the increase in the width of the EFs.

The other processes that play dominant roles in HI reactions may be categorized simply on the basis of impact parameter of the two interacting nuclei. High values of the impact parameter that corresponds to the direct reactions lead to a few-nucleon transfer process. However, at relatively smaller values of impact parameter, the complete and incomplete fusion processes along with the PE emission process may be dominant. With the availability of medium-energy light HI beams, it is possible to study the mentioned reaction processes. Thus, at moderate beam energies the reaction cross sections of fusion processes are generally shared in the following processes: those leading to complete fusion, incomplete fusion, PE emission, and quasifission.

At moderate energies, the investigation of the reaction cross-section data at the relatively high-energy tail region of EFs is expected to give significant information on the study of PE emission. Several authors [4–6,8,11,16] have reported a variety of data on the study of the PE emission process at high energy, $\approx 10-20$ MeV/nucleon, using particle-γ coincidence and off-line γ-ray-spectroscopy-based activation techniques. However, at low beam energies (<7 MeV/nucleon) such measurements are scarce in the literature. Holub *et al.* [4], in a particle-γ coincidence experiment, measured the ejectile spectra in the interaction of ^{20}Ne with ^{165}Ho system in the energy range $\approx 11-20$ MeV/nucleon. Vergini *et al.* [11] measured the EFs of several reactions in the fusion of ^{12}C and ^{16}O with heavy nuclei. They have reported that even at incident energies slightly above the Coulomb barrier, pre-equilibrium neutrons are subsequently emitted during the thermalization of excited composite system [11]. Cavinato *et al.* [6] have carried out the experiments for measuring excitation functions for production of reaction residues in the interaction of ^{12}C with ^{181}Ta and ^{197}Au and of ^{16}O with ^{165}Ho and ^{181}Ta target nuclei, respectively, at incident energy ≈ 10 MeV/nucleon. The analysis of excitation functions provides evidence for the emission of pre-equilibrium nucleons during the thermalization of the composite system at ≈ 10 MeV/nucleon [6]. Birattari *et al.* [16] have also performed the analysis of measured excitation functions with a view to study pre-equilibrium emissions occurring in the fusion reactions of ^{12}C with ^{103}Rh at relatively higher energy, ≈ 20 MeV/nucleon. Further strength to the PE emission study was provided by Amorini *et al.* [7], who observed the contribution of pre-equilibrium emission in both the CF and ICF processes in a $^{12}\mathrm{C} + {}^{64}\mathrm{Ni}$ system at ≈ 95 MeV. They have reported that the measured γ spectra in coincidence with fast, forward-emitted α particle indicated a contribution of pre-equilibrium emission in the first stage of collision [7].

In order to study PE process, theoretical work has also been performed. Nandi *et al.* [8] have developed a model for determination the angular distribution of pre-equilibrium nucleons in HI-induced reactions at high energies. This model successfully reproduces the angular distribution of pre-equilibrium nucleons emitted in $^{12}\mathrm{C} + {}^{165}\mathrm{Ho}$ and $^{20}\mathrm{Ne} + {}^{165}\mathrm{Ho}$ reactions at 300 and 600 MeV, respectively [4,5]. Thus, both experimental and theoretical evidence indicate the interplay between fusion and PE emission process at beam energies as low as just above the Coulomb barrier. This leads to a renewed interest in the study of the PE emission process in HI reactions. Although there are several methods available to study PE emission, measurement and analysis of EFs are particularly interesting, because the features of the EFs at low, medium, and high energies can directly reveal the reaction mechanism involved. The low-energy portion of EF is dominated by the CN mechanism; however, with increasing projectile energy, the PE process become important. As such, the measurements and analysis of EFs may provide information of considerable values on the study of PE emissions in HI reactions. Though a large amount of data and several models exist, no systematic study on PE emission with respect to excitation energy and mass of composite system is available.

With the motivation to study the PE process in a consistent and systematic way, in the present work, the strength of PE process P_{FR} is deduced from the measurement and analysis of excitation functions for $3n$ emission channels in the $^{12}\mathrm{C} + {}^{128}\mathrm{Te}$, $^{12}\mathrm{C} + {}^{169}\mathrm{Tm}$, $^{16}\mathrm{O} + {}^{159}\mathrm{Tb}$, $^{16}\mathrm{O} + {}^{169}\mathrm{Tm}$, and $^{16}\mathrm{O} + {}^{181}\mathrm{Ta}$ systems using the stacked foil activation technique. The present study uses relatively low bombarding energies, varying from around the Coulomb barrier to >7 MeV/nucleon, where the CN process dominates. The simulation of the data has been performed within the framework of the pure CN process using code PACE4 [17]; however, in order to explain the high-energy tail portion of the EFs, calculations for PE emission have been performed using code ALICE-91 [18]. Analysis of the data for the presently studied reactions provides evidence for emission of pre-equilibrium neutrons prior to the establishment of thermal equilibrium of the composite system at $\approx 5-7$ MeV/nucleon. The experimental details are given in Sec. II, while Sec. III deals with the analysis of data. The conclusions drawn from the analysis are given in Sec. IV of this paper.

II. MEASUREMENTS OF EXCITATION FUNCTIONS

The HI beams obtained from the 15 UD Pelletron accelerator have been used to perform the experiments at the Inter University Accelerator Centre (IUAC), New Delhi, India.

TABLE I. Details of the system studied, including measured thickness of the samples, Coulomb barrier, and energy of interest

Serial number	System studied	Measured thickness (mg/cm^2)	Coulomb barrier (MeV)	Energy studied (MeV)	Reaction channels	$T_{1/2}$	Energy (E_γ) (keV)	Branching ratio (%)
1	$^{12}C^{6+} + {}^{128}Te$	0.92	42.2	≈42−80	$^{128}Te(^{12}C,3n)^{137}Ce$	13 h	254.29	11.0
2	$^{12}C^{6+} + {}^{169}Tm$	0.50	51.5	≈55−85	$^{169}Tm(^{12}C,3n)^{178}Re$	13.2 m	106.0, 237.0	23.4, 44.5
							351.5	5.5
3	$^{16}O^{7+} + {}^{159}Tb$	1.80	63.8	≈68−95	$^{159}Tb(^{16}O,3n)^{172}Ta$	38.8 m	214.0, 318.7	55.0, 49.0
							1109.2	14.9
4	$^{16}O^{7+} + {}^{169}Tm$	0.50	67.2	≈70−95	$^{169}Tm(^{16}O,3n)^{182}Ir$	12 h	126.9 273.8	34.4, 43.0
5	$^{16}O^{7+} + {}^{181}Ta$	1.72	70.5	≈75−100	$^{181}Ta(^{16}O,3n)^{194m}Tl$	32.8 m	636.1	99.0
					$^{181}Ta(^{16}O,3n)^{194g}Tl$	33.0 m	636.1	15.3

Spectroscopically pure, rolled self-supporting foils of ^{159}Tb and ^{181}Ta of desired thickness were used as the targets. The samples of ^{128}Te and ^{169}Tm were prepared employing vacuum evaporation technique by depositing the material on the Al foils. The Al foils serve as energy degraders as well as catcher foils, where the recoiling residues from the composite system may be trapped. In the stacked foil activation technique, an energetic beam traverses through the samples with degrading beam energies. Thus, it is possible to bombard the stack of samples at different energies in a single irradiation. The details of systems studied, including measured thickness of the samples, Coulomb barrier, energy range of interest, and pertinent decay data [19] required for cross-section measurements of the reaction residues are given in Table I.

The irradiations of the target catcher assembly have been carried out in a specially designed general purpose scattering chamber (GPSC) of 1.5 m diameter that can be used for both the on-line and off-line studies and has an in-vacuum transfer facility. In the present work, the stacked foil activation technique has been employed for measuring the excitation functions of radioactive residues produced in the projectile-target combinations. Further details of the experiments are given elsewhere [13–15,20]. The activities produced in each target catcher assembly have been measured using a high-resolution large-volume (100 c.c.) high-purity germanium detector (HPGe) γ-ray spectrometer. In order to check the energy resolution and the stability of the electronics, the efficiency spectra for ^{137}Cs and ^{60}Co sources were also recorded for several weeks. The reaction residues produced during the interaction of projectile and target nuclei were identified by their characteristic γ rays and measured half-lives. The cross sections of the production residual nuclei were determined after proper background correction from the observed γ activity using the standard formulation [15].

III. ANALYSIS OF EXCITATION FUNCTIONS

Information regarding the reaction mechanism involved in $^{12}C + {}^{128}Te$, $^{12}C + {}^{169}Tm$, $^{16}O + {}^{159}Tb$, $^{16}O + {}^{169}Tm$, and $^{16}O + {}^{181}Ta$ systems may be obtained by comparing the experimentally measured cross-section data to the theoretical model calculations. In the present paper, the theoretical calculations of measured excitation functions have been performed using two different computer codes, viz., PACE4 [17] and ALICE-91 [18], respectively. Brief details of these codes along with their important parameters are discussed in the following subsections.

A. Calculations with code PACE4

The calculations for the measured cross sections of the evaporation residues have been performed using code PACE4 [17], which is based on a statistical approach. The de-excitation of the compound nucleus is followed by a Monte Carlo procedure. In this code the angular momentum projections are calculated at each stage of de-excitation, which enables the determination of angular distribution of the emitted particles. The cross sections of evaporation residues are calculated using the Bass formula [21].

The optical model parameters for neutron, proton, and α emission were taken from Perey and Perey [17]. The γ-ray strength functions for $E1$, $E2$, and $M1$ transitions were taken from the tables of Endt [22]. The present version of the code uses the excitation-energy-dependent level density parameter from Kataria *et al.* [23]. The level density used in this code is calculated from the expression $a = (A/K)$, where A is the mass number of the compound nucleus and K is a free

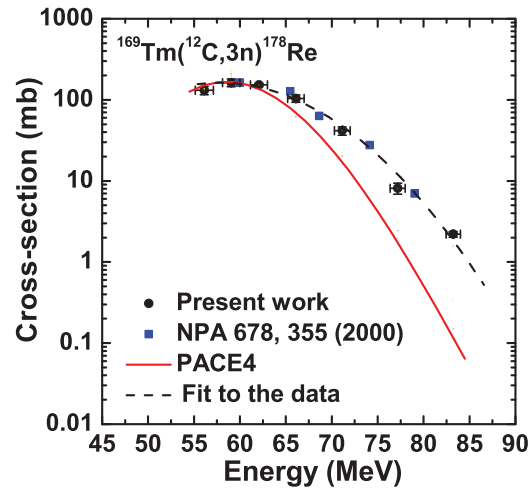

FIG. 1. (Color online) The experimentally measured and theoretically calculated EFs for reaction $^{169}Tm(^{12}C,3n)^{178}Re$ using Monte Carlo–based code PACE4. The measured cross sections for the residues ^{178}Re by Chakrabarty *et al.* [12] are also shown for comparison.

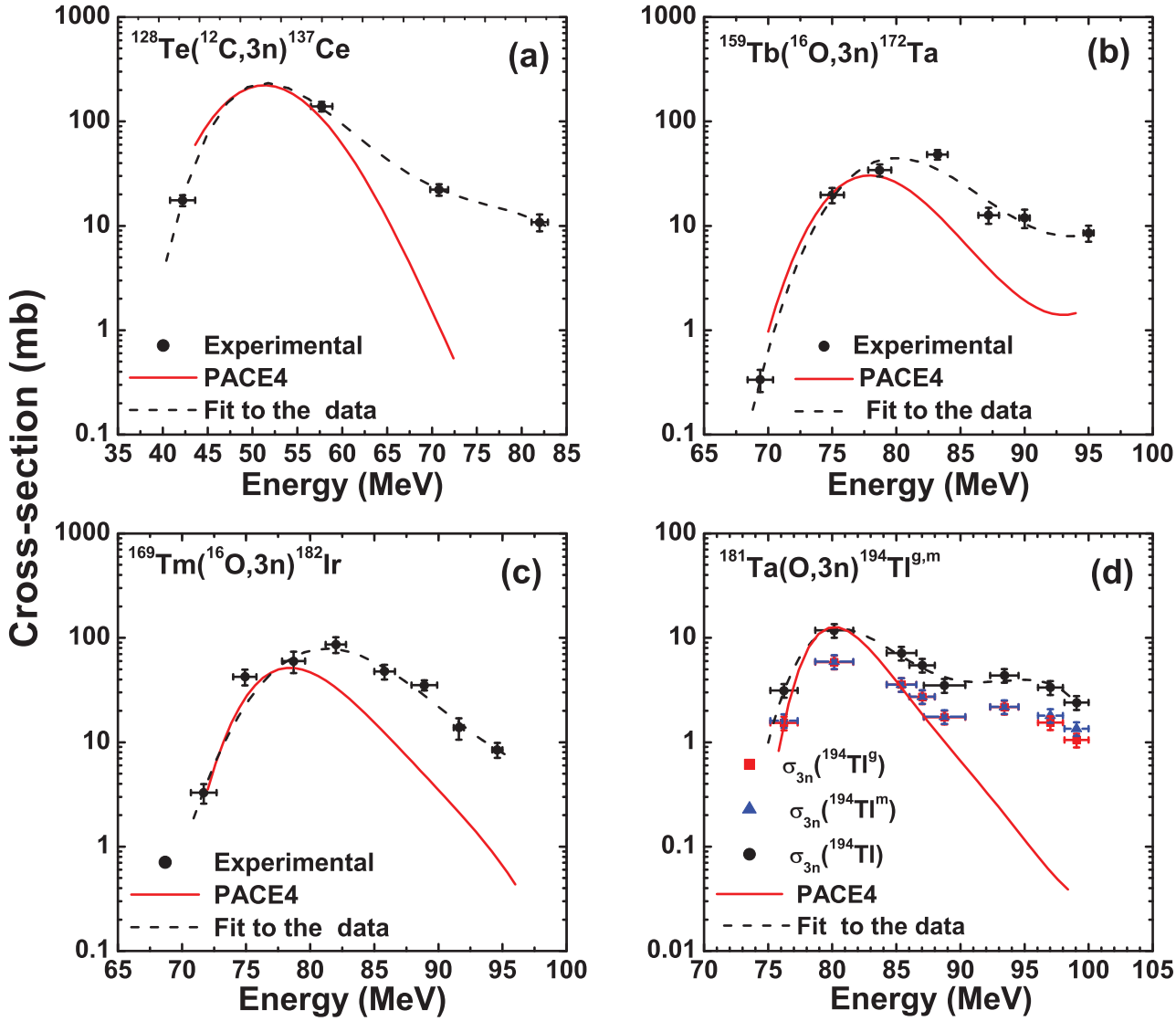

FIG. 2. (Color online) The experimentally measured and theoretically calculated EFs for reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl using Monte Carlo–based code PACE4. The parameters used in this calculations are discussed in the text.

parameter known as a level density parameter constant. In the present work, a value of $K = 8$ is taken in the calculations, which is widely accepted.

The experimentally measured and theoretically calculated EFs for reaction ^{169}Tm(^{12}C,3n)^{178}Re is shown in Fig. 1, while reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl are shown in Figs. 2(a)–2(d), respectively. The dashed curves represent the fitted experimental data guide to the eye, while solid curves represent calculations of the code PACE4. As can be seen from these figures, the theoretical calculations agree well with the experimental data up to the peak portion. In the tail portion of EFs, deviation of the experimental data as compared to PACE4 calculations has been observed. The higher values of experimental cross sections in the tail portion of EFs for these reactions as compared to the theoretical calculations may be attributed to the PE emission process, which is a dominant mode of mechanisms in xn reaction channels at relatively higher energies and is not considered in the PACE4 calculations. However, it may be pointed out that the experimental data for other xn channels, where $x > 3$, occurring in the fusion of ^{12}C with ^{128}Te and ^{169}Tm and of ^{16}O with ^{159}Tb, ^{169}Tm, and ^{181}Ta target nuclei, respectively, are satisfactorily reproduced by PACE4 calculations using the same set of parameters, indicating a negligible contribution of PE emissions in higher nucleon evaporation channels. This is expected as PE emission is more likely in the first step of de-excitation and leaves the residual nucleus in an excited state from where emission of more neutrons is less likely. It may be pointed out that at relatively low energies there may not be enough energy available to have significant pre-equilibrium emission to end up with a total of 4 neutrons emitted, but if the energy is increased at some point the possibility of 4n channel exhibiting pre-equilibrium emission may also be observed. However, for

$3n$ channel (emission of one pre-equilibrium neutron followed by two compound nucleus neutrons), PE emission from the excited composite systems during the first projectile target interaction in the reaction channels ^{128}Te, ^{169}Tm (^{12}C,$3n$) and ^{159}Tb, ^{169}Tm, ^{181}Ta(^{16}O, $3n$) is quite possible at low projectile energies. Since PE emission is not taken into account in the code PACE4, at relatively higher energies (tail portion of EFs) the observed enhancement of the measured data as compared to the theoretical predictions indicates significant contributions of PE processes, which may be confirmed by comparing the measured EFs with the calculations done by the code ALICE-91, discussed in Subsec. III B of this paper.

B. Calculations with code ALICE-91

The calculations of cross-sections of the residues produced via compound nucleus as well as pre-equilibrium emission in both light and heavy ion induced reactions can be performed using the code ALICE-91. The compound nucleus calculations are done using the Weisskopf-Ewing model [24], while simulations for PE components are performed using geometry-dependent hybrid (GDH) model [25]. In the present calculations, the optical potentials of Becchetti and Greenlees [26] have been used. The level densities of the residual nuclei may be calculated either from the Fermi gas model or from the constant temperature form [27].

Although there are many parameters in this code, the level density parameter a, the mean free path multiplier COST, and initial exciton number n_0 are some of the important parameters. The initial exciton number n_0 and mean free path multiplier COST govern mainly the pre-equilibrium components, while the level density parameter a affects mainly the equilibrium component. The level density parameter a is calculated from the expression $a = A/K$, where A is the mass number of the compound nucleus and K is an adjustable parameter. In the present calculations, the effect of variation of parameter K on measured EFs has also been studied. As a typical case, the experimentally measured and theoretically calculated EFs for reaction ^{169}Tm(^{12}C,$3n$)^{178}Re using different values of parameter $K = 10$, 12, 14, and 16 in ALICE-91 calculations are also shown in Fig. 3.

When ALICE-91 calculations with the abovementioned values of parameters are compared with their experimental counterparts, it is observed that the maxima of the measured EFs are at higher energies than those of the calculated EFs. This is expected, since in ALICE-91 calculations the angular momentum effects have not been taken into account. In HI-induced reactions, the incident particle imparts relatively larger angular momentum to the composite system. If, in the last stages of nuclear de-excitation, higher angular momentum inhibits particle emission more than it does γ emission, then the peak of excitation function corresponding to the particle emission mode will be shifted to higher energies [28]. The effect is more pronounced in HI reactions as compared to the light ion reactions, since the rotational energy is much greater in the case of HI reactions. An estimate of the possible shift due to angular momentum effects may be made from the nuclear rotational energy. For a rigid body, the rotational energy is given by $E_{rot} \approx (m/M)E_{lab}$. Here, m/M is the ratio of the projectile and the target nucleus masses and E_{lab} is the incident energy [28]. Since the angular momentum effects have not been considered in the Weisskopf-Ewing calculations of the present version of ALICE-91 code, it is desirable to shift the calculated excitation functions by the amount approximately equal to E_{rot} as calculated above. As such, in the present work, the calculated EFs have been shifted by E_{rot} on the energy scale. As an example, the calculated EF with an energy shift equal to E_{rot} for reaction ^{169}Tm(^{12}C,$3n$)^{178}Re is shown in Fig. 4. As observed from Fig. 4, the theoretically calculated EF with $K = 16$ agrees satisfactorily well with the measured ones after incorporating

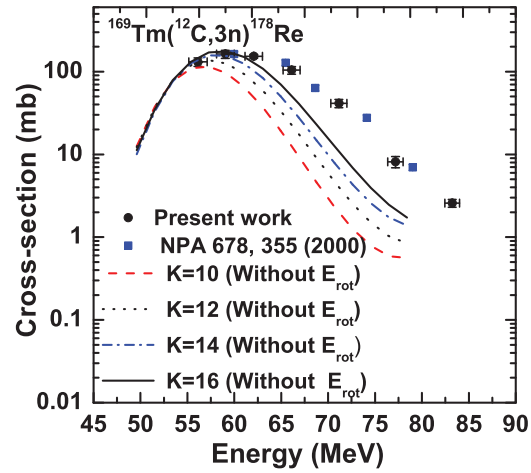

FIG. 3. (Color online) The experimentally measured and theoretically calculated EFs for reaction ^{169}Tm(^{12}C,$3n$)^{178}Re using code ALICE-91. The effects of variation of parameter $K = 10$, 12, 14, and 16, respectively, in ALICE-91 calculations are shown and are discussed in the text. The measured cross sections for the residues ^{178}Re by Chakrabarty *et al.* [12] are also shown for comparison.

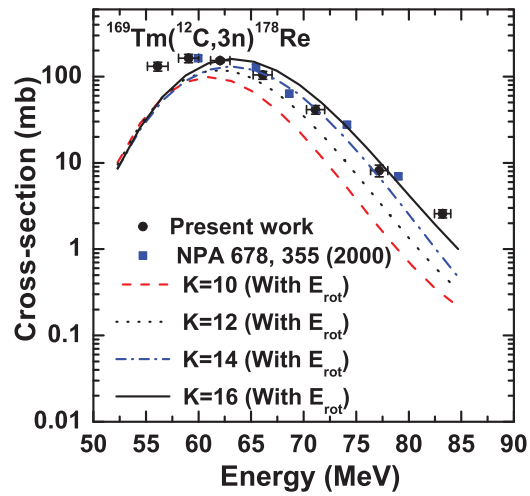

FIG. 4. (Color online) The experimentally measured and theoretically calculated EFs for reaction ^{169}Tm(^{12}C,$3n$)^{178}Re using code ALICE-91. The effects of rotational energy E_{rot} in ALICE-91 calculations are shown in this figure and discussed in the text. The measured cross sections for the residues ^{178}Re by Chakrabarty *et al.* [12] are also shown for comparison.

rotational energy shifts for all cases, in general. A higher value of parameter K is quite reasonable with the point of view of physics. Since in the PE emissions the temperature of the composite system is greater than that of the fully equilibrated compound system, the temperature-dependent level density may be used. As the temperature of the composite system increases, the value of level density a is lower and hence the value of parameter K is higher. It may be pointed out that the code ALICE-91 has been used mostly for light-ion-induced reactions, where, in general, it gives satisfactory representation of the experimentally measured data.

In code ALICE-91, the intermediate states of the system are characterized by the excitation energy E, number n_p of excited particles, and n_h of excited holes. Particles and holes are defined relative to the ground state of the nucleus and are called excitons. The initial configuration of the compound system defined by the exciton number $n_0 = (n_p + n_h)$ is an important parameter of PE formalism. In the present work, values of $n_0 = 13$ with configuration $(6p + 6n + 1h)$ for ^{12}C and $n_0 = 17$ with configuration $(8p + 8n + 1h)$ ^{16}O have been found to satisfactorily reproduce the experimental data, where p, n, and h represent the number of excited protons, neutrons, and holes, respectively. The configurations of $n_0 = 13$ (12 particles + 1 hole) and $n_0 = 17$ (16 particles + 1 hole), respectively, for ^{12}C and ^{16}O ions may be justified, assuming that the first interaction gives rise to the excitation of one particle above the Fermi energy, leaving behind a hole in the excited state [29]. The code ALICE-91 calculates two-body nuclear transition rates using Pauli corrected free nucleon-nucleon scattering cross-section data. The actual mean free path (MFP) inside the nucleus may be quite different from the one calculated using free nucleon-nucleon scattering data. In order to compensate for this difference, the parameter COST is provided in the code ALICE-91. A value of COST greater than zero means a smaller value of actual MFP for nucleon-nucleon scattering inside composite excited nucleus. As a representative case, the effect of variation of parameter COST on the calculated EF for the reaction ^{169}Tm(^{12}C,3n)^{178}Re is shown in Fig. 5. In the present work, a value of COST = 2 is found to reproduce the experimental data satisfactorily.

The experimentally measured and theoretically calculated (ALICE-91 calculations) EFs for the reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl are shown in Figs. 6(a)–6(d), respectively. As can be seen from these figures, the values $K = 16$, mean free path multiplier COST = 2, and $n_0 = 13$ for ^{12}C and $n_0 = 17$ for ^{16}O are satisfactorily reproduced in the experimental data, indicating significant contribution of PE emission in these reactions. However, in the case of ^{128}Te(^{12}C,3n)^{137}Ce reaction, there is considerable difference between the measured and calculated excitation functions at 82 MeV, even with inclusion of PE emission [3]. In the study of the role of precompound decay in heavy-ion reactions, Blann [3] has indicated that the significant contribution to PE emission may come from the multiple precompound emission at higher energies and also from equilibration collision if they take place in the low-density region. It has also been pointed out that in heavy-ion reactions all partial waves do not contribute to the fusion, and the spherical shape for corresponding moment of inertia may not be appropriate. Blann [3] has shown that the descending tails of measured excitation functions in HI reactions are expected to lie above the theoretical calculations performed using hybrid model for pre-equilibrium decay.

IV. PRE-EQUILIBRIUM FRACTION P_{FR}

The pre-equilibrium fraction P_{FR} is a measure of relative strength of PE component required to reproduce the experimental EFs. P_{FR} reflects the relative importance of equilibrium and PE processes. P_{FR} at a given energy for a given channel may be defined as the ratio of the difference of the cross-sections for (PE+CN) emission and the CN cross sections [i.e., $\sigma_{(PE+CN)} - \sigma_{(CN)}$] to the cross-section values of (PE+CN) [i.e., $\sigma_{(PE+CN)}$]. However, it may be pointed out that in literature no definite trends for the variation of P_{FR} with excitation energy E^* or mass number of the composite system are reported. The phenomenon of PE emission critically depends on energy imparted by the projectile to the composite nucleus. It is reasonable to assume that P_{FR} is strongly a function of excitation energy. The pre-equilibrium fraction P_{FR} has been calculated as $[\{\sigma_{(PE+CN)} - \sigma_{(CN)}\}/\sigma_{(PE+CN)}] \times 100\%$, where $\sigma_{(PE+CN)}$ is the experimentally measured cross section (CN+PE) and $\sigma_{(CN)}$ is compound nucleus cross section obtained from the prediction of pure statistical model code PACE4. In the present work, the PE cross section σ_{PE} has been deduced from the difference of experimentally measured cross section $\sigma_{(PE+CN)}$ and cross-section value σ_{CN} obtained from pure statistical model code PACE4. Thus, the calculated P_{FR} values are plotted as a function of excitation energy for the reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{169}Tm(^{12}C,3n)^{178}Re, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl respectively and are shown in Fig. 7(a). The following conclusions may be drawn from Fig. 7(a):

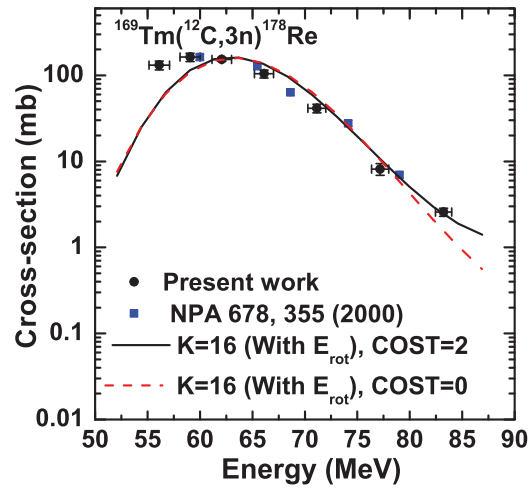

FIG. 5. (Color online) The experimentally measured and theoretically calculated EFs for reaction ^{169}Tm(^{12}C,3n)^{178}Re using code ALICE-91. The effects of different values of mean free multiplier COST = 0 and COST = 2 in ALICE-91 calculations are shown in this figure and discussed in the text. The measured cross sections for the residues ^{178}Re by Chakrabarty *et al.* [12] are also shown for comparison.

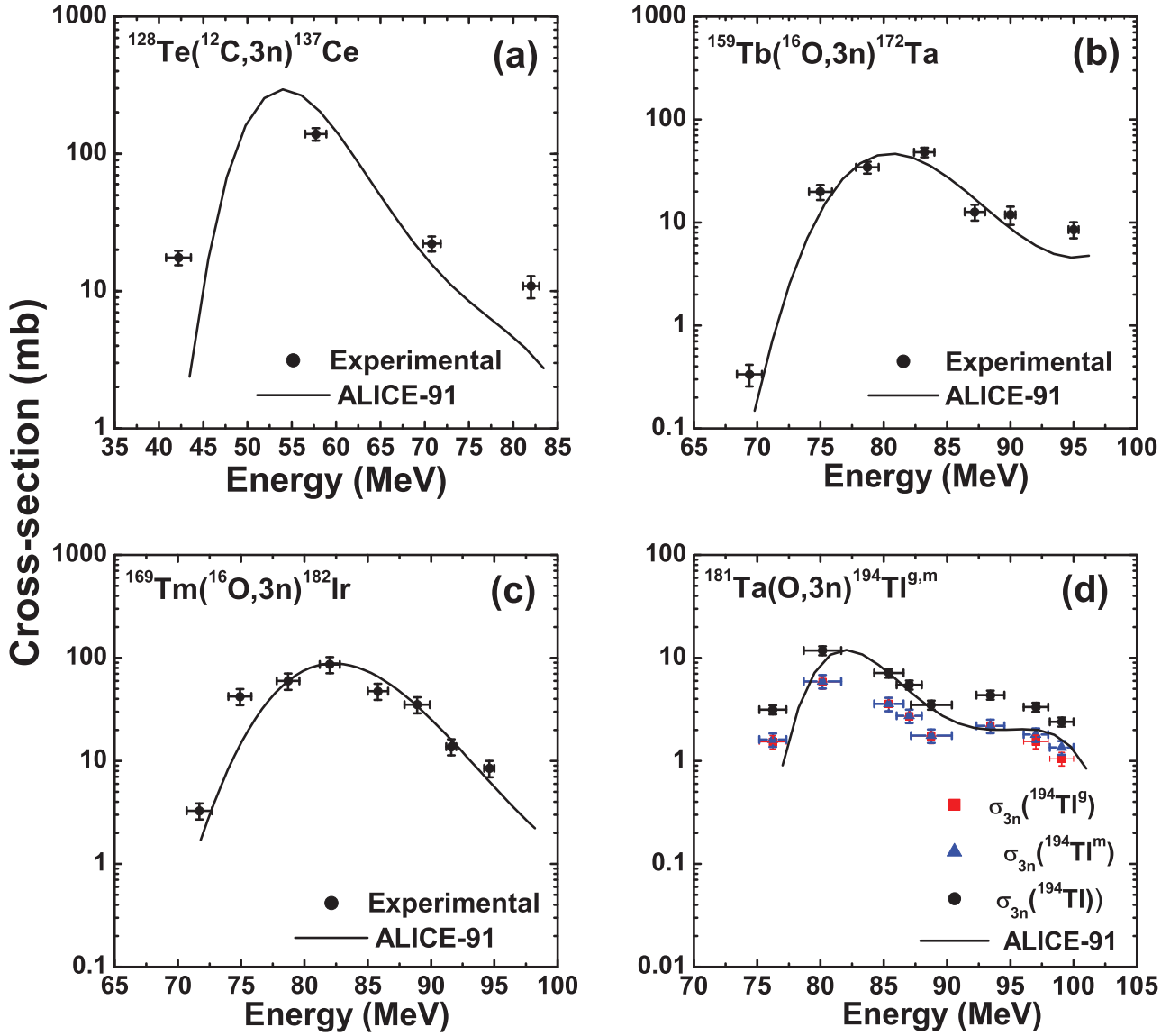

FIG. 6. (Color online) The experimentally measured and theoretically calculated EFs for reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl using code ALICE-91. The parameters used in this calculations are discussed in the text.

(1) The thresholds for PE emission are different for different projectile-target combination, being lower for lower target mass number, as expected. The values of threshold in these reactions are ≈52 MeV and ≈60 MeV for (^{12}C,3n) on ^{128}Te and ^{169}Tm; however, for reactions (^{16}O,3n) on ^{159}Tb, ^{169}Tm, and ^{181}Ta these are ≈70, 70, and 75 MeV, respectively.

(2) P_{FR} for these reactions increases sharply with excitation energy. The sharp increase in initial stage of P_{FR} shows that the statistical distribution of excitation energy among the nucleons participating in PE emission in the beginning stage may be very fast.

(3) P_{FR} for these reactions attains a maximum value, which particularly depends on the mass of the composite nucleus. As an example, for residues ^{137}Ce, formed in the interaction of ^{12}C with ^{128}Te nucleus, the maximum value (≈100%) of P_{FR} is found to be at ≈70 MeV of excitation energy, while in case of other reaction residues, the saturation is expected at relatively higher excitation energies.

(4) There is inconsistency in P_{FR} on the mass of composite system with respect to the excitation energy. As an example, the curve for P_{FR} in the emission of three neutrons in system ^{12}C + ^{169}Tm leading to composite nucleus ^{181}Re is at lower excitation energy than that of ^{16}O + ^{159}Tb system, leading to composite nucleus ^{175}Ta at higher excitation energy.

In order to obtain a systematic trend in PE emission, P_{FR} is plotted as a function of excitation energy per nucleon A of the composite system (i.e., E^*/A) and excitation energy per nucleon at the surface of composite system (i.e., $E^*/A^{2/3}$) as shown in Figs. 7(b) and 7(c), respectively. As can be observed from Figs. 7(b) and 7(c), no systematic trend of P_{FR} in terms of mass number of composite system and excitation energy per nucleon at the surface of composite system is obtained; only

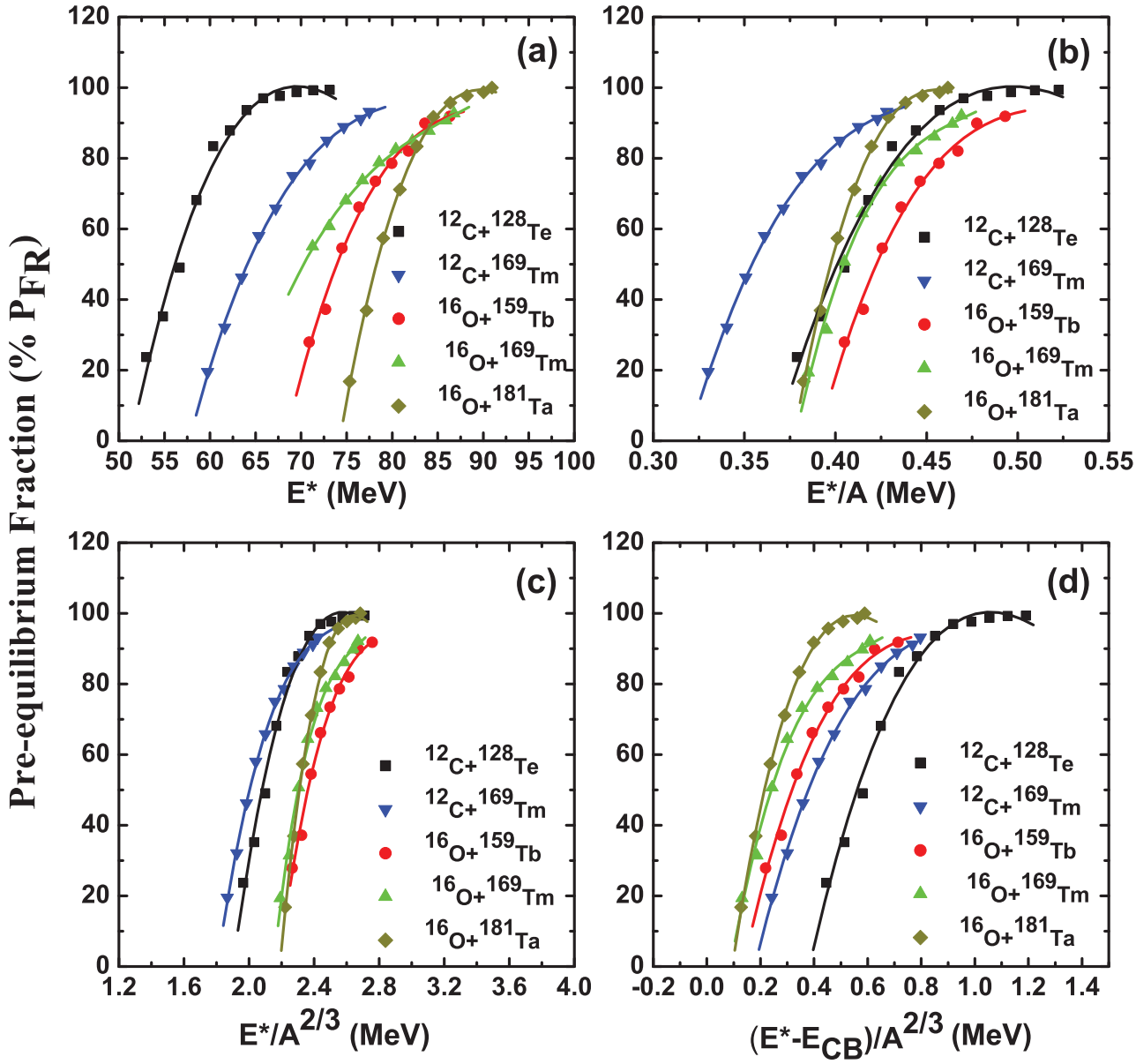

FIG. 7. (Color online) (a) Variation PE fraction P_{FR} as a function of excitation energy E^* of composite system, (b) variation PE fraction P_{FR} as a function of excitation energy E^* per nucleon A, (c) variation PE fraction P_{FR} as a function of excitation energy per nucleon A at the surface of the composite system, i.e., $E/A^{2/3}$, and (d) variation PE fraction P_{FR} as a function of excitation energy in excess of the Coulomb barrier nucleon A at the surface of the composite system, i.e., $(E^*–E_{CB})/A^{2/3}$. The solid rectangle, down triangle, circle, up triangle, and stars represent the data for the $3n$ channel in $^{12}C + ^{128}Te$, $^{12}C + ^{169}Tm$, $^{16}O + ^{159}Tb$ $^{16}O + ^{169}Tm$, and $^{16}O + ^{181}Ta$ systems, respectively

a considerable reduction in the spread of curves is observed in Fig. 7(c). As such, it may be concluded that the excitation energy may not equally distributed among all the nucleons of the composite system. Therefore, E/A may not be a good parameter for characterizing PE emission. This may lead to an additional justification that in PE emission all the nucleons of the composite system are not involved in the reaction mechanism. There is a possibility of surface effect in the presently studied cases, by assuming that the PE emission may have significant effect from the surface interaction. It is better to assume with the physics point of view that the particles passing through the nuclear periphery may have a better chance for inducing PE emission compared to the particles passing through the entire diameter of the target. In order to check whether there is influence of surface effect on the PE emission and to eliminate the effect of the Coulomb barrier, P_{FR} is plotted against excess excitation energy above the Coulomb barrier per surface nucleon of the composite system, i.e., $(E^*–E_{CB})/A^{2/3}$ and is shown in Fig. 7(d). As can be seen from this figure, for heavier composite systems P_{FR} starts at a smaller value of the excess excitation energy above the Coulomb barrier per surface nucleon of the composite system. However, for light composite systems, it starts at relatively higher values of $(E^* - E_{CB})/A^{2/3}$. This systematic

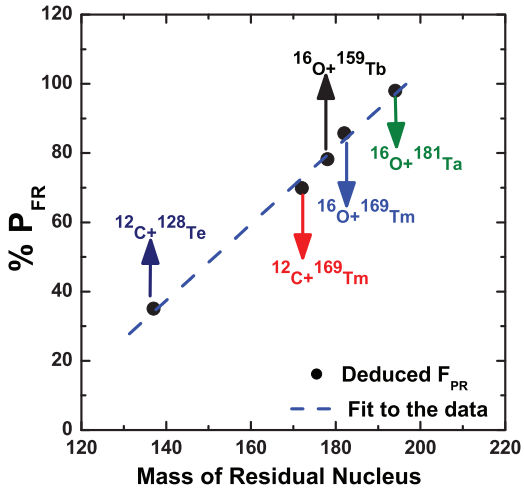

FIG. 8. (Color online) The variation of P_{FR} with the mass number of residual nucleus at 0.5 MeV excitation energy excess of the Coulomb barrier nucleon A at the surface of the composite system, i.e., $(E^*–E_{CB})/A^{2/3}$.

trend indicates the importance of the excess excitation energy above the Coulomb barrier per surface nucleon. As such, it may be concluded that this excess energy is distributed among the surface nucleons which take part in PE emission. The conclusions drawn from this study provide confidence and a systematics for PE emission and are shown in Fig. 8. This figure reflects a linear relation between P_{FR} and mass of the residual nuclei by plotting P_{FR} as a function of mass of the residual nuclei at a particular value of $(E^* - E_{CB})/A^{2/3} = 0.5$ MeV, for all these reactions. As can be seen from this figure, P_{FR} for the presently studied systems linearly increases with mass of the residual nuclei systematically. Further, the role of the projectile is also important.

V. CONCLUSIONS

In order to study the PE emission, the excitation functions for reactions ^{128}Te(^{12}C,3n)^{137}Ce, ^{169}Tm(^{12}C,3n)^{178}Re, ^{159}Tb(^{16}O,3n)^{172}Ta, ^{169}Tm(^{16}O,3n)^{182}Ir, and ^{181}Ta(^{16}O,3n)^{194}Tl have been measured in the energy range from threshold to ≈7 MeV/nucleon energies. The analysis of the excitation functions of individual fusion reactions indicates the presence of pre-equilibrium emission at such low energies. Theoretical calculations performed using the geometry-dependent hybrid (GDH) model of code ALICE-91 satisfactorily reproduce the measured excitation functions. The high-energy tails of the measured EFs cannot be accounted for by the pure compound nucleus mechanism and have significant contributions from PE emission. Proper admixture of equilibrium and pre-equilibrium processes is needed for better reproduction of the experimentally measured excitation functions in heavy-ion-induced reactions for neutron emission channels. Pre-equilibrium fraction has been found to be depend on excitation energy available above the Coulomb barrier and mass number of the composite system.

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[1] J. Pal, S. Saha, C. C. Dey, P. Banerjee, S. Bose, B. K. Sinha, M. B. Chatterjee, and S. K. Basu, Phys. Rev. C **71**, 034605 (2005).
[2] M. Blann, Ann. Nucl. Sci. **25**, 123 (1975).
[3] M. Blann, Nucl. Phys. A **235**, 211 (1974).
[4] E. Holub, D. Hilscher, G. Ingold, U. Jahnke, H. Orf, and H. Rossner, Phys. Rev. C **28**, 252 (1983).
[5] E. Holub, D. Hilscher, G. Ingold, U. Jahnke, H. Orf, H. Rossner, W. P. Zank, W. U. Schröder, H. Gemmeke, K. Keller, L. Lassen, and W. Lücking, Phys. Rev. C **33**, 143 (1986).
[6] M. Cavinato, E. Fabrici, E. Gadioli, E. Gadioli Erba, P. Vergani, M. Crippa, G. Colombo, I. Redaelli, and M. Ripamonti, Phys. Rev. C **52**, 2577 (1995).
[7] F. Amorini, M. Cabibbo, G. Cardelaa, A. Di Pietro, P. Figuera, A. Musumarra, M. Papa, G. Pappalardo, F. Rizzo, and S. Tudisco, Phys. Rev. C **58**, 987 (1998).
[8] M. Nandy, S. Ghosh, and P. K. Sarkar, Phys. Rev. C **60**, 044607 (1999).
[9] S. Mukherjee, N. L. Singh, G. K. Kumar, and L. Chaturvedi, Phys. Rev. C **72**, 014609 (2005).
[10] B. P. Singh, M. K. Sharma, M. M. Muthafa, H. D. Bhardwaj, and R. Prasad, Nucl. Inst. Methods Phys. Res. A **562**, 717 (2006).
[11] P. Vergani, E. Gadioli, E. Vaciago, E. Fabrici, E. Gadioli Erba, M. Galmarini, G. Ciavola, and C. Marchetta, Phys. Rev. C **48**, 1815 (1993).
[12] S. Chakrabarty, B. S. Tomar, A. Goswami, G. K. Gubbi, S. B. Manohar, A. Sharma, B. Bindukumar, and S. Mukherjee, Nucl. Phys. A **678**, 355 (2000).
[13] M. K. Sharma, B. P. Singh, S. Gupta, M. M. Muthafa, H. D. Bhardwaj, and R. Prasad, J. Phys. Soc. Japan **72**, 1917 (2003).
[14] M. K. Sharma, Unnati, B. K. Sharma, B. P. Singh, H. D. Bhardwaj, R. Kumar, K. S. Golda, and R. Prasad, Phys. Rev. C **70**, 044606 (2004).
[15] M. K. Sharma, Unnati, B. P. Singh, H. D. Bhardwaj, R. Kumar, K. S. Golda, and R. Prasad, Nucl. Phys. A **776**, 83 (2006).
[16] C. Birattari, M. Bonardi, M. Cavinato, E. Fabrici, E. Gadioli, E. Gadioli Erba, F. Groppi, M. Bello, C. Bovati, A. Di Filippo, T. G. Stevens, S. H. Connell, J. P. F. Sellschop, S. J. Mills, F. M.

Nortier, G. F. Steyn, and C. Marchetta, Phys. Rev. C **54**, 3051 (1996).
[17] A. Gavron, Phys. Rev. C **21**, 230 (1980).
[18] M. Blann, Report PSR-146, NEA Data Bank, Gif-sur-Yvette, France,1991.
[19] E. Browne and R. B. Firestone, *Table of Radioactive Isotopes* (Wiley, New York, 1986).
[20] D. P. Singh, Unnati, P. P. Singh, A. Yadav, M. K. Sharma, B. P. Singh, K. S. Golda, R. Kumar, A. K. Sinha, and R. Prasad, Phys. Rev. C **80**, 014601 (2009).
[21] R. Bass, Nucl. Phys. A **231**, 45 (1974).
[22] P. M. Endt, At. Data Nucl. Data Tables **26**, 47 (1981).
[23] S. K. Kataria, V. S. Ramamurthy, and S. S. Kapoor, Phys. Rev. C **18**, 549 (1978).
[24] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[25] M. Blann, Phys. Rev. Lett. **27**, 337 (1971).
[26] F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).
[27] M. Blann and H. K. Vonach, Phys. Rev. C **28**, 1475 (1983).
[28] D. Bodansky, Annu. Rev. Nucl. Sci. **12**, 79 (1962).
[29] C. Kalbach, Z. Phys. A **283**, 401 (1977).