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# Pre-equilibrium particle emission in alpha induced reactions

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Study of the mechanism of pre-equilibrium particle emission in alpha particle induced reactions has been done in the present work. The cross-sections for systems $\alpha + {}^{144}Sm$ and $\alpha + {}^{154}Sm$ have been calculated using the statistical model code ALICE-91. Significant pre-equilibrium particle emission contribution has been obtained for these systems at higher projectile energy. At higher projectile energies, the pre-equilibrium particle emission has been found to affect predominantly over the equilibrated compound nucleus emissions. The contribution of pre-equilibrium particle emission is found larger for $\alpha + {}^{144}Sm$ system than that of $\alpha + {}^{154}Sm$ system. The present results indicate that the systems having spherical targets have more contribution of pre-equilibrium particle emission than that of systems with deformed targets. These results suggest that the shape of target (spherical or deformed) also affect the dynamics of pre-equilibrium particle emission at energy above the fusion barrier.

**Keywords**: Pre-equilibrium emission, Excitation functions, Pre-equilibrium fraction, Mass asymmetry, ALICE-91

## 1 Introduction

Efforts have been made to study the light and heavy ion induced reactions in the field of nuclear physics. At projectile energies of few tens of MeV, α-induced reactions are generally considered to proceed through equilibrium (EQ) as well as pre-equilibrium (PE) emission of particles[1]. The relative contributions of these processes depend on the projectile energy and the entrance channel of the system. The contribution of PE reactions can be obtained by comparing the measured excitation functions (EFs) and theoretical predictions of statistical model codes. The PE and the compound nucleus (CN) emission reactions have been studied by several researchers in past few decades[2-7]. The PE emission probably arises from the collisions between individual nucleons of the target and projectile. The energy spectra of charged particles emitted in a nuclear reaction show several discrete peaks at a particular angle and high energies. Some of these peaks are well resolved. At low energy side a broad Maxwellian distribution followed by a continuum has also been observed. The Maxwellian distribution curve indicates that the particles are emitted from the equilibrated nucleus. The isolated peaks at higher energy region may be attributed to the direct reactions. The explanation of the continuum may be attributed to some intermediate process called pre-equilibrium particle emission (PE) process[8,9]. It may be assumed that the pre-equilibrium particle emission proceeds through two body residual interactions inside the compound system. The pre-equilibrium particle emission may be considered as a bridge between two extreme reaction mechanisms. The pre-equilibrium particle emission process is characterized by (i) slowly descending tails of excitation functions, (ii) forward peaked angular distribution of emitted particles and (iii) relatively large number of higher energy particles than predicted by the compound nucleus mechanism. The first successful theory of such process was the exciton model. This model gives the energy distribution of the emitted particles and the angle-integrated cross-section of all the reactions. This semi-classical model also predicts the main features of the angular distributions of emitted particles. At very high energy the reaction may be studied using Monte Carlo simulation method. Presence of PE emissions at HI projectile energy slightly above the Coulomb barrier has also been noticed[10]. Recently, it has been observed that pre-equilibrium particle emission process may cause the emission of nuclear cluster or even fission also at moderate excitation energies[11].

In the present work, statistical model code[12] ALICE-91 has been used to calculate the excitation functions for light ion induced reactions at energy

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above the Coulomb barrier. In order to make a consistent analysis of theoretical predictions, an attempt has been made to select the adjustable parameters of the code. Further, the relative contributions of pre-equilibrium and equilibrium processes are separated and their dependence on target deformation has been studied.

## 2 Pre-Equilibrium Cross-Sections using ALICE-91

The dynamics of pre-equilibrium particle emission has been studied in α-particle induced reactions at projectile energy above the Coulomb barrier. The cross-sections for the systems α + $^{144}$Sm and α + $^{154}$Sm have been calculated using statistical model code ALICE-91. The present calc0ulations have been done for different projectiles at energy range ≈10-120 MeV. The reactions studied have been divided into two categories for ease in comparison, the reactions in which only neutrons emission take place, and those which involve both neutrons and protons emission like (α, pxn). The level density parameter 'a' (= A /K) MeV$^{-1}$, is one of the important parameter in this code, where 'A' is the mass number of the compound nucleus and 'K' is called level density parameter constant, which affects the equilibrium components. The level density parameter 'a' used for different reactions has been taken as default from literature[13]. Most of the required input parameters have been used as default except the mass and charge of the projectile and target. The present calculations are done with the view of studying the pre-equilibrium particle emission. In the ALICE-91 code, the level density parameter 'a', mean free path multiplier 'COST' and initial exciton number $n_0$ are the three important parameters, which may be varied. In general, the reactions involving in emission of only neutrons have the largest cross sections as neutron is uncharged particle and has no difficulty in passing through the Coulomb barrier. Hence, only the neutron emission channels (xn and pxn) have been considered for pre-equilibrium and equilibrium calculations in the present study.

## 3 Results and Discussion

The pre-equilibrium contributions for alpha induced reactions have been estimated from the calculated excitation function data of ALICE-91 code. An attempt has been made to study the dependence of pre-equilibrium particle emission on the deformation of target. The cross-sections have been calculated for α + $^{144}$Sm and α + $^{154}$Sm systems. The excitation functions for these reaction channels show an initial exponential rise in the cross section, with energy starting from the threshold energy of the reaction.

In these systems, the projectile is same, but the targets $^{144}$Sm and $^{154}$Sm have different structure. The target $^{144}$Sm ($\beta_2$= 0.000) is spherical, while $^{154}$Sm target ($\beta_2$= 0.270) is well deformed. The values of deformation parameters ($\beta_2$) have been taken from Mollar table[14]. The other entrance channel parameters, such as mass-asymmetry, Coulomb factor etc. is nearly same for these two systems. As such, any discrepancy in the cross-sections of these two systems will be mainly due to the effect of target deformation. The cross-section calculated from ALICE-91 code for the system α + $^{144}$Sm has been plotted as a function of projectile energy and displayed in Fig 1. In this figure, the solid lines represent the ALICE-91 calculations

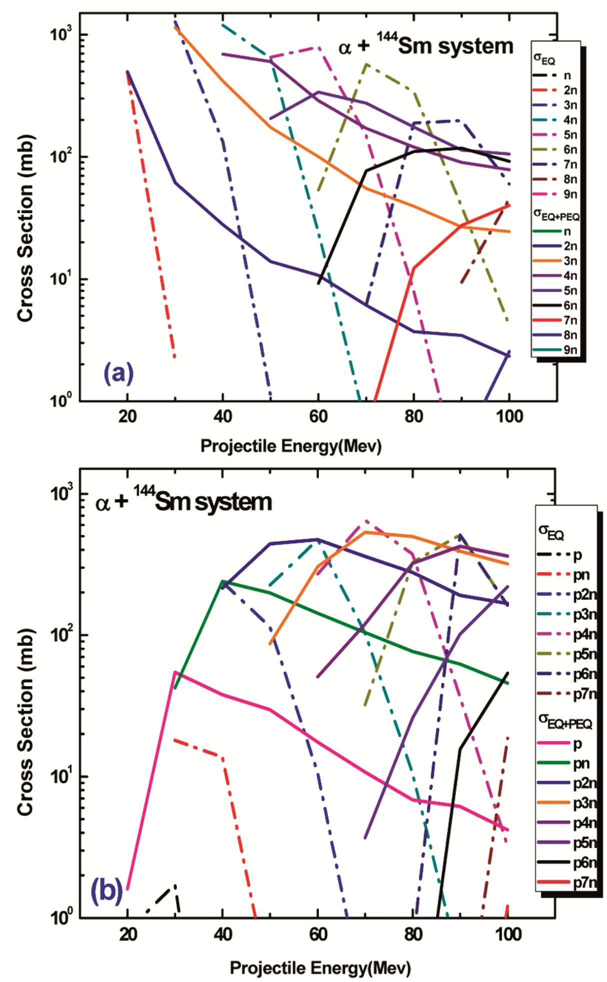


Fig. 1 – Pre-equilibrium and equilibrium cross-sections of (a) xn and (b) pxn channels for α + $^{144}$Sm system, computed using ALICE-91 code.

for equilibrium consideration only, while the dash dotted lines show the predictions of pre-equilibrium along with equilibrium calculations. It can be clearly observed from Fig. 1 that the effects of pre-equilibrium particle emission start dominating at higher projectile energies, above 40 MeV. The equilibrium compound nucleus predictions failed to predict the higher energy tail of the excitation functions for this system. Further, the total equilibrium and pre-equilibrium cross-sections have been estimated by adding the cross-sections of all channels. The total equilibrium and pre-equilibrium cross-sections for the system α + $^{144}$Sm has been plotted in Fig. 2. It can be noticed from this figure that the pre-equilibrium particle emission for the system increases with beam energy and dominates over equilibrium cross-sections at higher projectile energies.

Further, the equilibrium and pre-equilibrium cross-sections have been calculated for α + $^{154}$Sm system by ALICE-91 code at same excitation energies. The cross-sections calculated from ALICE-91 code for this system has been shown in Fig. 3. The total equilibrium and pre-equilibrium cross-sections for the system α + $^{154}$Sm has also been evaluated and plotted in Fig. 4. From these plots, it can be clearly noticed that the pre- equilibrium particle emission increases with the projectile energy. However, the contribution of pre-equilibrium particle emission is found larger in case of α + $^{144}$Sm system than that of α + $^{154}$Sm. The present results indicate that the systems having spherical targets have more contribution of pre-equilibrium particle emission than that of systems with deformed targets.

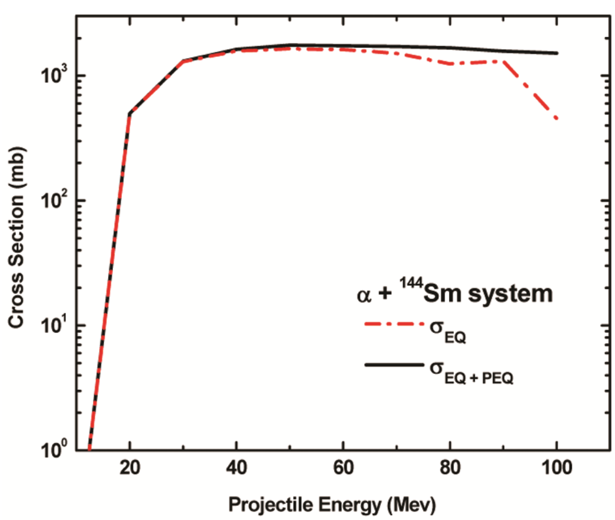


Fig. 2 – Sum of pre-equilibrium cross-sections along with equilibrium cross-sections of the xn and pxn channels for α + $^{144}$Sm system, computed using ALICE-91 code.

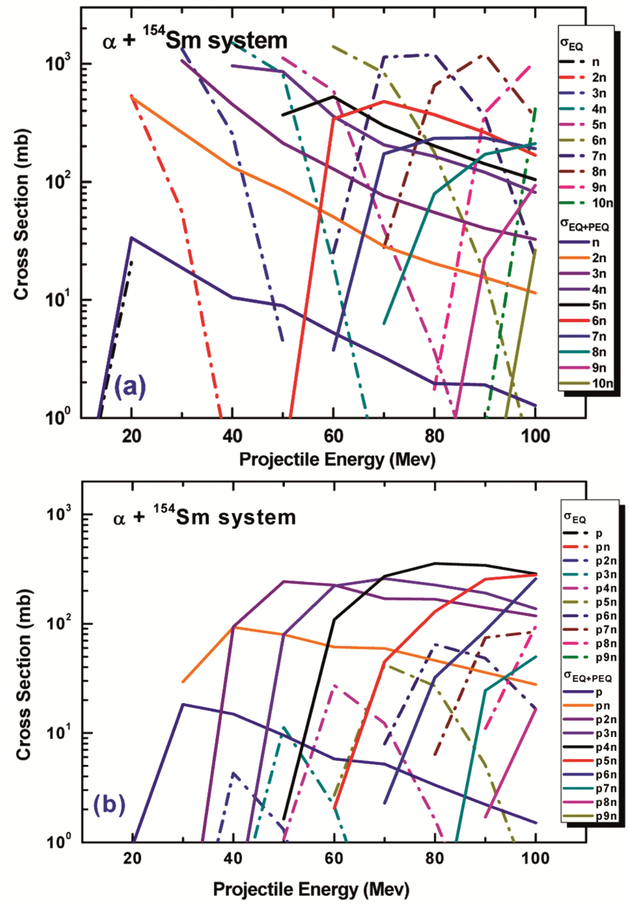


Fig. 3 – Pre-equilibrium and equilibrium cross-sections of (a) xn and (b) pxn channels for α + $^{154}$Sm system, computed using ALICE-91 code.

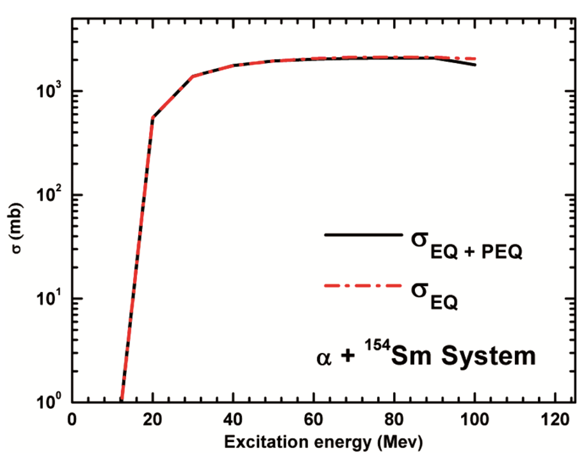


Fig. 4 – Sum of pre-equilibrium cross-sections along with equilibrium cross-sections of the xn and pxn channels for α + $^{154}$Sm system, computed using ALICE-91 code.

## 4 Conclusions

The present study has been done to understand the mechanism of pre-equilibrium particle emission and its dependence on the deformation of target. The cross-sections for systems $\alpha + {}^{144}Sm$ and $\alpha + {}^{154}Sm$ have been calculated using the statistical model code ALICE-91. At higher projectile energies, significant contribution of the pre-equilibrium particle emission effects has been found along with the equilibrated compound nucleus. The contribution of pre-equilibrium particle emission is found larger for $\alpha + {}^{144}Sm$ system than that of $\alpha + {}^{154}Sm$ system. The present results indicate that the systems having spherical targets have more contribution of pre-equilibrium particle emission than that of systems with deformed targets. These results show that the shape of target (spherical or deformed) also influence the pre-equilibrium particle emission dynamics at projectile energy above the Coulomb barrier.

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## References

1 Psychalinos C & Spanidou A, *Int J Electron Commun*, 60 (2006)168.
2 Gomez del Campo J, Shapira D, McConnell J, Gross C J, Stracener D W, Madani H, Chávez E & Ortíz M E, *Phys Rev C*, 60 (1999) 021601(R).
3 Otsuka T & Haradav K, *Phys Lett B*, 121 (1983) 106.
4 Birattari C, Bonardi M, Cavinato M, Fabrici E, Gadioli E, Erba E G, Groppi F, Bello M, Bovati C, Di Filippo A, Stevens T G, Connell S H, Sellschop J P F, Mills S J, Nortier F M, Steyn G F & Marchetta C, *Phys Rev C,* 54 (1996) 3051.
5 Delagrance H, Fleury A, Hubert F & Simonoff G N, *Phys Lett B,* 37 (1971) 355.
6 Vergani P, Gadioli E, Vaciago E, Fabrici E, Gadioli Erba E, Galmarini M, Ciavola G & Marchetta C, *Phys Rev C*, 48 (1993) 1815.
7 Cavinato M, Fabrici E, Gadioli E, Erba E G, Vergani P, Crippa M, Colombo G, Redaelli I & Ripamonti M, *Phys Rev C*, 52 (1995) 2577.
8 Hodgson P E, Heavy ion collision proceedings of International Summer School, La Rabia, Spain, (1992) 220.
9 Gadioli E & Gadioli E E, Nuclear theory for applications - 1980, IAEA -SMR 68/1, Vienna, (1981) 3.
10 Sharma M K, Bhardwaj H D, Unnati, Singh P P, Singh B P & Prasad R, *Eur Phys J A*, 31(2007) 43.
11 Prasad E, Varier K M, Thomas R G, Sugathan P, Jhingan A, Madhavan N, Babu B R S, Sandal R, Kalkal S, Appannababu S, Gehlot J, Golda K S, Nath S, Vinodkumar A M, Kumar B P A, John B V, Mohanto G, Musthafa M M, Singh R, Sinha A K & Kailas S, *Phys Rev C*, 81 (2010) 054608.
12 Blann M, NEA Data Bank, Gif-Sur-Yveette, France, Report PSR-146 (1991).
13 Mughabghab S F & Dunford C, *Int Conf Nucl Data Science Technol*, Societa Italiana Di Fisica Trieste, (1997) 985.
14 Möller P, Sierk A J, Ichikawa T & Sagawac H, *Atomic Data Nucl Data Tables*, 109 (2016) 1.