Indian Journal of Pure & Applied Physics
Vol. 57, August 2019, pp. 580-583

Pre-equilibrium particle emission due to heavy and light ion interactions

D Singh[a*], Sneha B Linda[a], Pankaj K Giri[a], Amritraj Mahato[a], Utkarsh[a], Pramod K Shrotriya[b], A K Mishra[c] & M Afzal Ansari[d]

[a]Department of Physics, Central University of Jharkhand, Ranchi 835 205, India
[b]KSRMV Inter College, Atrauli, Aligarh 202 280, India
[c]Department of Applied Science (Physics), SATI, Vidisha 464 001, India
[d]Department of Physics, Aligarh Muslim University, Aligarh, 202 002, India

Received 8 April 2019

To understand the mechanism of pre-equilibrium particle emission using light and heavy ion beams with different targets at energy above the Coulomb barrier, a study has been done. The cross-sections for twelve systems ^{4}He + ^{59}Co, ^{4}He +^{124}Sn, ^{4}He + ^{165}Ho, ^{12}C + ^{59}Co, ^{12}C +^{124}Sn, ^{12}C + ^{165}Ho, ^{16}O + ^{59}Co, ^{16}O + ^{124}Sn, ^{16}O + ^{165}Ho, ^{19}F + ^{59}Co, ^{19}F + ^{124}Sn and ^{19}F + ^{165}Ho have been calculated using the statistical model code ALICE-91. Significant pre-equilibrium particle emission contribution has been obtained for lighter systems at higher projectile energy. It has also been found that the pre-equilibrium particle emission affects predominantly over the equilibrated compound nucleus emissions at high projectile energies. Pre-equilibrium fraction (F_{PEQ}) has been deduced from the excitation function data for different systems at different projectile energies. The present results indicate that the probability of pre-equilibrium particle emission depends not only on a single entrance channel parameter, but it also depends on various entrance channel parameters, namely: projectile energy, mass of the projectile, mass of the target and entrance-channel mass asymmetry. The present analysis of the data also suggests that the pre-equilibrium particle emission contributes significantly at higher projectile energy for lighter mass projectile and target.

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

1 Introduction

Great effort has been employed in the study of light and heavy ion induced reactions in the field of nuclear physics. The pre equilibrium (PE) particle emission process has been found to affect the dynamics of heavy ion induced reactions at high energies >10 MeV/nucleon[1]. 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 energy spectrum of charged particles emitted during a nuclear reaction, at a particular angle and high energies several discrete peaks are observed. Some of these peaks are well resolved. At low energy side a broad Maxwellian distribution followed by a continuum has been found. The curve shows that the reaction has taken place in several steps, which indicates that the particles are emitted from the equilibrated nucleus. The isolated peaks at higher energy side may be attributed to the direct reactions without the formation of compound nucleus (CN). The explanation of the continuum may be attributed to some intermediate processes 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 mechanism is characterized by slowly descending tails of excitation functions, forward peaked angular distribution of emitted particles and 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

*Corresponding author (E-mail: dsinghcuj@gmail.com)

projectile energy slightly above the Coulomb barrier has also been noticed[10]. Recently, it has been observed that pre-equilibrium particle emission mechanism may cause emission of nuclear cluster or even fission also at moderate excitation energies[11].

In the present study, statistical model code[12] ALICE-91 has been used to calculate the excitation functions for light and heavy ion induced reactions at energy 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 various entrance channel parameters has been studied. Interesting pattern of the pre-equilibrium fraction as a function of projectile energy has been observed.

2 Pre-Equilibrium Cross-Sections using ALICE-91

In the present work, an attempt has been made to understand the pre-equilibrium particle emission in light and heavy ion induced reactions at projectile energy above the Coulomb barrier. The cross-sections for the twelve systems $^{4}He + ^{59}Co$, $^{4}He + ^{124}Sn$, $^{4}He + ^{165}Ho$, $^{12}C + ^{59}Co$, $^{12}C + ^{124}Sn$, $^{12}C + ^{165}Ho$, $^{16}O + ^{59}Co$, $^{16}O + ^{124}Sn$, $^{16}O + ^{165}Ho$, $^{19}F + ^{59}Co$, $^{19}F + ^{124}Sn$ and $^{19}F + ^{165}Ho$ have been calculated using statistical model code ALICE-91. The present calculations have been done for different projectiles at energy range ≈10-120 MeV. The reactions studied in the present work are divided into two categories for ease in comparison: (i) those involving only neutrons emission, such as (α, xn) and (ii) those involving 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 nucleus. 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. The neutron is uncharged particle and has no difficulty in passing through the Coulomb barrier. In general, the reactions involving in emission of only neutrons have the largest cross sections. Keeping this in view, only the neutron emission channels (xn and pxn) have been taken for the study of pre-equilibrium and equilibrium reaction mechanism in the present study. The excitation functions for these reaction channels are characterized by an initial exponential rise in the cross section, with energy beginning from the threshold energy of the reaction. As a representative case, the cross-section as function of projectile energy for the systems $^{4}He + ^{59}Co$ and $^{12}C + ^{59}Co$ has been plotted and shown in Figs 1-2. In these figures, the dash dotted lines show the ALICE-91 prediction with pre-equilibrium consideration, whereas the solid lines represent the predictions without pre-equilibrium calculations. It can be noticed from Fig. 1 that beyond the projectile energy 40 MeV pre-equilibrium effects predominate, whereas the equilibrium compound nucleus predictions failed to predict the higher energy tail of the excitation function for this system. Similarly in Fig. 2, the pre-equilibrium emission can be clearly seen in higher energy side. Further, it can also be noticed that pre-equilibrium particle emission is larger for the system $^{4}He + ^{59}Co$ than that of $^{12}C + ^{59}Co$ system. This indicates that the pre-equilibrium effects are more dominant than that of equilibrium process in case of lighter nuclei.

3 Results and Discussion

The pre-equilibrium contribution of the cross-section has been estimated from the calculated excitation function data and to study the dependence

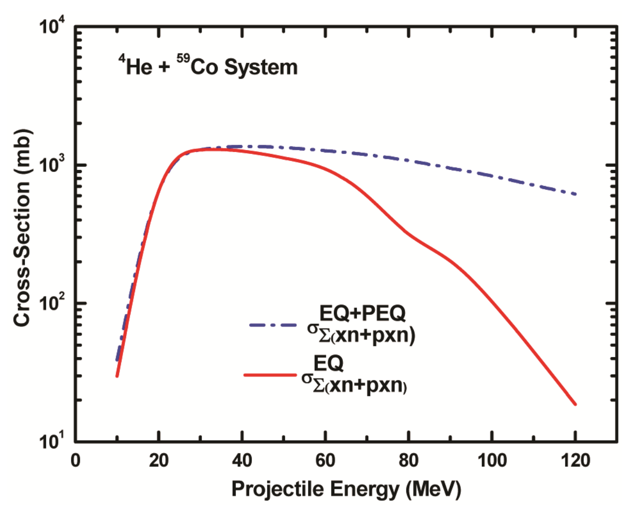

Fig. 1 – Sum of pre-equilibrium cross-sections along with equilibrium cross-sections of the xn and pxn channels in the $^{4}He + ^{59}Co$ system, calculated using ALICE-91 code.

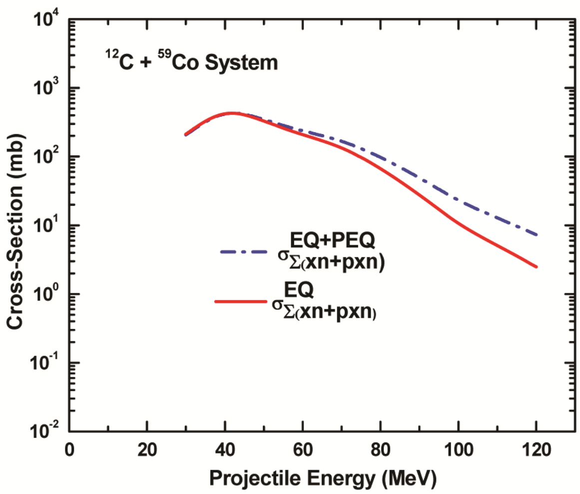

Fig. 2 – Sum of pre-equilibrium cross-sections along with equilibrium cross-sections of the xn and pxn channels in the ^{12}C + ^{59}Co system, calculated using ALICE-91 code.

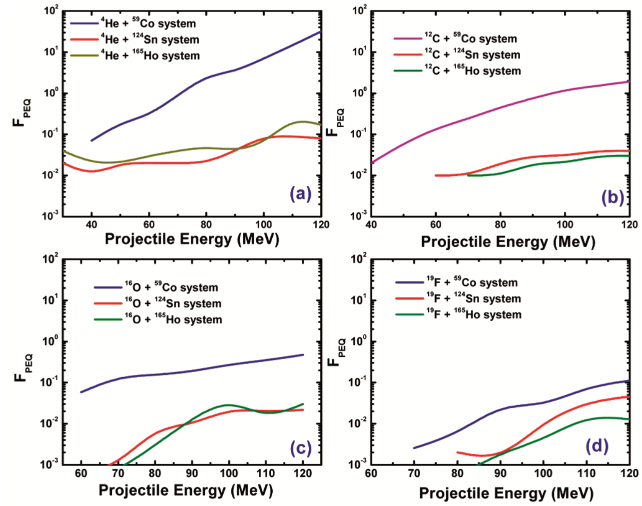

Fig. 3 – Pre-equilibrium fraction (F_{PEQ}) as a function of projectile energy for various systems.

of pre-equilibrium particle emission on various entrance channel parameters, namely; projectile energy, mass of projectile, mass of target and entrance channel mass-asymmetry between interacting partners. For this purpose, the pre-equilibrium fraction (F_{PEQ}) has been calculated.

The pre-equilibrium fraction (F_{PEQ}) for the particular reaction channel is defined as $F_{PEQ} = \frac{\sigma_{PEQ} - \sigma_{EQ}}{\sigma_{EQ}}$,

where σ_{PEQ} is the cross section of the production of evaporation residue including equilibrium and pre-equilibrium particle emission contributions while σ_{EQ} is the cross section calculated as statistical equilibration of the compound nucleus without pre-equilibrium particle emission in a nuclear reaction. The pre-equilibrium fraction (F_{PEQ}) has been plotted as a function of incident projectile energy above the Coulomb barrier for various systems and shown in Fig. 3(a - d). In this figure the systems having same projectiles are shown in one common graph. From all the plots, it can be clearly observed that the pre-equilibrium particle emission increases with the projectile energy. The contribution of pre-equilibrium particle emission is found to increase with projectile energy for both α and heavy ion induced reactions. However, the pre-equilibrium fraction (F_{PEQ}) is found to be different for light and heavy projectiles with different targets. It may be due to when the projectile reaches in the nuclear field of the target, the Q-value the reaction will also come in to picture. In all the cases, F_{PEQ} increases slowly with projectile energy in the initial region and thereafter it increase sharply. The slow increase in the beginning may be due to the statistical distribution of energy among the participating nucleons. Further, it has been also noticed that there is a sharp increase in the pre-equilibrium fraction with increase in projectile energy in case of lighter target nuclei namely, ^{59}Co. However, in case of heavier targets ^{124}Sn and ^{165}Ho, the rate of increase of F_{PEQ} is not significant in the present energy regime.

4 Summary and Conclusions

The present study has been done with the aim to understand the mechanism of pre-equilibrium particle emission. A large number of systems at projectile energy above the Coulomb barrier have been studied. The cross-sections for the twelve systems ^{4}He + ^{59}Co, ^{4}He +^{124}Sn, ^{4}He + ^{165}Ho, ^{12}C + ^{59}Co, ^{12}C +^{124}Sn, ^{12}C + ^{165}Ho, ^{16}O + ^{59}Co, ^{16}O + ^{124}Sn, ^{16}O + ^{165}Ho, ^{19}F + ^{59}Co, ^{19}F + ^{124}Sn and ^{19}F + ^{165}Ho have been calculated using the statistical model code ALICE-91. Significant contribution of pre-equilibrium particle emission has been observed for light systems at higher projectile energy. At higher projectile energies, the pre-equilibrium particle emission effects have been found to be predominant over the equilibrated compound nucleus. Further, an attempt has been made to estimate the pre-equilibrium contribution from the calculated excitation function data and to investigate the dependence of pre-equilibrium particle emission on various entrance channel parameters, namely;

projectile energy, mass of projectile, mass of target and entrance channel mass-asymmetry. In this respect pre-equilibrium fraction (F_{PEQ}) has been deduced from the data for different projectile-target systems at each projectile energy. The present results indicate that the probability of pre-equilibrium particle emission on various entrance channel parameters, namely: incident projectile energy, mass of the projectile, mass of the target and entrance-channel mass asymmetry. The present analysis of the data suggests that the pre-equilibrium particle emission contribute significantly at higher projectile energy with lighter mass projectile and target.

Acknowledgement

The authors are thankful to Vice-chancellor, Central University of Jharkhand (CUJ), Ranchi. Authors express their thanks to the Head, Department of Physics, CUJ, Ranchi, for their motivation and support throughout the work.

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 - Ebra 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, International Conference on Nuclear Data for Science and Technology, p 985, Societa Italiana Di Fisica Trieste, 19-24 May, (1997).