Competition between the compound and the pre-compound emission processes in α-induced reactions at near astrophysical energy to well above it

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Abstract. The study of pre-compound emission in α-induced reactions, particularly at the low incident energies, is of considerable interest as the pre-compound emission is more likely to occur at higher energies. With a view to study the competition between the compound and the pre-compound emission processes in α-induced reactions at different energies and with different targets, a systematics for neutron emission channels in targets ^{51}V, ^{55}Mn, ^{93}Nb, ^{121,123}Sb and ^{141}Pr at energy ranging from astrophysical interest to well above it, has been developed.

The off-line γ-ray-spectrometry based activation technique has been adopted to measure the excitation functions. The experimental excitation functions have been analysed within the framework of the compound nucleus mechanism based on the Weisskopf-Ewing model and the pre-compound emission calculations based on the geometry dependent hybrid model. The analysis of the data shows that experimental excitation functions could be reproduced only when the pre-compound emission, simulated theoretically, is taken into account.

The strength of pre-compound emission process for each system has been obtained by deducing the pre-compound fraction. Analysis of data indicates that in α-induced reactions, the pre-compound emission process plays an important role, particularly at the low incident energies, where the pure compound nucleus process is likely to dominate.

1. Introduction

The mechanism of pre-equilibrium emission (PE), particularly at the lower incident energies, is of fundamental interest, since it is expected to occur at the higher excitation energies[1]. It reflects the dynamics of formation of an excited composite system and its evolution to the equilibrium states leading to formation of a compound nucleus (CN). A large number of nuclear reactions initiated by the light and heavy ions have been analysed in the frame work of the CN mechanism, where it is assumed that the excited composite system, formed by the absorption of incident ion lives long enough till thermodynamic equilibrium is established by the CN mechanism. However, both the experimental evidence and the intuition suggest that particle(s) emission may occur from the excited composite system formed by the absorption of the incident ion by the target

nucleus before the establishment of thermodynamical equilibrium[2, 3, 4, 5]. These particles are called PE particles and the process as PE emission. Some of the important experimental signatures of the PE emission are; (i) the presence of a larger number of high-energy particles as compared to the spectrum predicted by the CN theory, (ii) forward-peaked angular distribution of the emitted particles, (iii) slowly decreasing tails of the excitation functions (EFs) etc.

The EFs data of low energy neutron capture are very useful in accurate determination of the astrophysical reaction rates for p and γ-processes[6, 7]. With the motivation to study the reaction mechanism in a consistent and systematic way, the measurements and analysis of EFs for (α,n) reactions on various targets having odd Z and odd A nuclei have been undertaken.

2. Measurements of Excitation functions

Spectroscopically pure targets of ^{55}Mn, ^{93}Nb and ^{141}Pr have been prepared by rolling method of desired thickness and are used as the samples. The experiments have been carried out at the Variable Energy Cyclotron Centre (VECC), Kolkata, India, using a collimated α-particle beam[1]. A stack consisting of target samples sandwiched between the aluminum degraders/catchers was irradiated for $\approx$12 h. The beam current $\approx$100 nA was monitored from the current integrator count rate. The calculations for average beam energy on a given target of the stack have been performed using the stopping power program SRIM[8]. The post-irradiation analysis has been carried out by using a high resolution large volume (100 c.c.) high-purity germanium (HPGe) detector coupled to an ORTEC PC based multichannel analyzer.

3. Analysis of excitation functions

In the present work, the code ALICE-91 developed by M. Blann[9], has been used to calculate the CN and the PE emission cross-sections. The CN calculations in this code are performed by using the Weisskopf-Ewing model[10], while, the PE component is simulated from the geometry dependent hybrid (GDH) model[11]. In this code, the level density parameter $a,(a=A/K$ where, A be is the mass number of the composite nucleus and K is a free parameter), the initial exciton number n_0, and the mean free path multiplier $COST$ are some of the important parameters. The value of K=8, n_0=4 and $COST$=0.2 give satisfactorily reproduction of the experimental data. The experimentally measured EFs and calculated EFs with K=8, n_0=4 and $COST$=0.2 for the reactions ^{93}Nb$(\alpha, n)^{96}$Tc and ^{141}Pr$(\alpha, n)^{144}$Pm are shown in Fig. 1 (a-b), while for reaction ^{55}Mn$(\alpha, n)^{58}$Co is shown in Fig. 2(a). In order to get systematics in PE emission (P_{FR}) on various targets, theoretical calculations of experimental data of other reactions ^{51}V$(\alpha, n)^{54}$Mn, ^{121}Sb$(\alpha, n)^{124}$I, and ^{123}Sb$(\alpha, n)^{126}$I (which are not shown here) have also been performed by using code ALICE-91 with same set of parameters and are found in good agreement.

4. Pre-equilibrium fraction P_{FR}

The P_{FR} reflects the relative importance of the PE processes and is defined as the ratio of the difference of the cross-sections for (PCN+CN) emission and the CN emission [i.e., $\sigma_{(PCN+CN)} - \sigma_{(CN)}$] to the cross-section values of (PCN+CN) [i.e., $\sigma_{(PCN+CN)}$]. The deduced P_{FR} values are plotted as a function of the excitation energy for the reactions ^{51}V$(\alpha, n)^{54}$Mn, ^{55}Mn$(\alpha, n)^{58}$Co, ^{93}Nb$(\alpha, n)^{96}$Tc, ^{121}Sb$(\alpha, n)^{124}$I, ^{123}Sb$(\alpha, n)^{126}$I, and ^{141}Pr$(\alpha,n)^{144}$Pm and are shown in Fig. 2(b). The following conclusions are deduced from Fig. 2 (b); (i) P_{FR} for these reactions increases sharply with excitation energy for each target. The sharp increase in P_{FR} with the excitation energy shows that a very fast distribution of the excitation energy among the nucleons take a part in the PE emission, (ii) P_{FR} for presently studied reactions attains a maximum value, that particularly depends on the mass number of the target nucleus. The higher the mass of the target nuclei, lower the values of the excitation energies at which maxima occur, and (iii) there is an inconsistency in P_{FR} for similar target masses i.e., ^{51}V and ^{55}Mn. This inconsistency has been explained in terms of a shell effect.
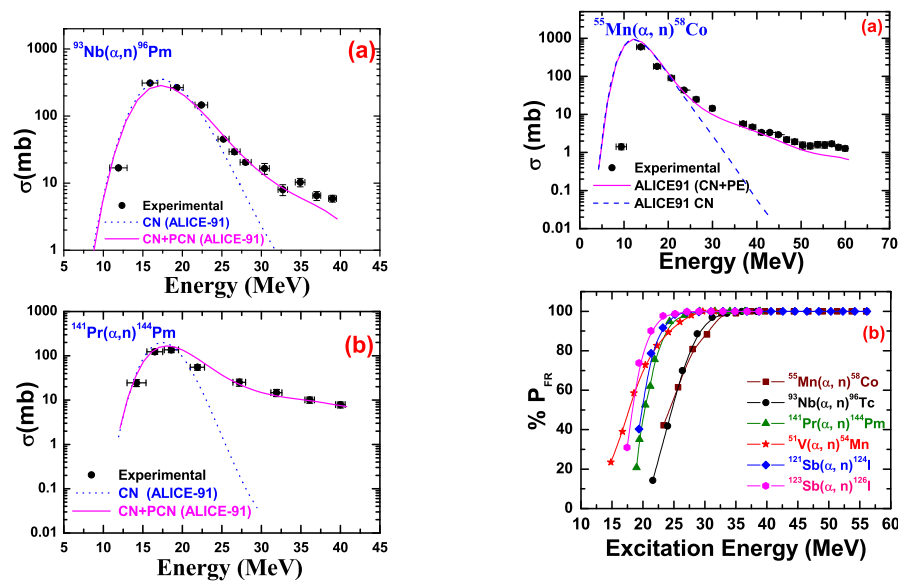
Figure 1. The experimentally measured and theoretically (ALICE-91) calculated EFs.

Figure 2. (a)The experimentally measured and theoretically (ALICE-91) calculated EFs, (b)Variation PE Fraction P_{FR} as a function of Excitation energy

5. Conclusions

The measurement and analysis EFs for reported reactions indicate that EFs could be reproduced only when the PE emission, simulated theoretically, is taken into account. The P_{FR} is found to depend on the excitation energy and structure of the target nuclei.

5.1. Acknowledgements

6. References

[1] Singh B P, Bhardwaj H D, and Prasad R 1991 *Can. J. of Phys.* **69** 1376
[2] Avrigeanu M, Avrigeanu V, Bem P, Fischer U, Honusek M, Katovsky K, . Manailescu C, Mrazek J, Simeckova E, and Zavorka L 2014 it Phys. Rev. C **89** 044613
[3] Kim K, Kim G N, Naik H, Zaman M, Yang S -C, Song T-Y, Guin R and Das S K 2015 *Nucl. Phy. A.* **935** 65
[4] Sharma M K,Bhardwaj H D, Unnati, Singh P P, Singh B P, and Prasad R 2007 *Ero Phys. J.* **31** 43
[5] Singh B P, Sharma M K, Muthafa M M, Bhardwaj H D and Prasad R 2006 *Nucl. Inst. and Methods in Phys. Res. A.* **562** 717
[6] Sauerwein A, Becker H -W, Dombrowski H, Elvers M, Endres J, Giesen U, Hasper J, Hennig A, Netterdon L, Rauscher T, Rogalla D, Zell K O and Zilges A 2011 *Phys. Rev. C.* **C84** 045808
[7] Gyurky Gy, Vakulenko M, Fulop Zs, Halasz Z, Kiss G G, Somorjai E and Szucs T 2014 *Nucl. Phy. A* **992** 112
[8] http://www.srim.org
[9] Blann M 1991 *NEA Data Bank, Gif-sur-Yvette, France.* **Report PSR-146**
[10] Weisskopf V F and Ewing D H 1940 *Phys. Rev.* **57** 472
[11] Blann M 1972 *Phys. Rev. Lett.* **28** 757