SYSTEMATIC INVESTIGATION OF PRECOMPOUND EMISSION OVER COMPOUND EVAPORATION IN α+^{89}Y REACTION*

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The exciton model and the hybrid Monte-Carlo simulation method have been used to investigate the effect of pre-equilibrium emission over compound evaporation in the α+^{89}Y reaction. The pre-equilibrium excitation functions of ^{92m,91m,90,89}Nb, ^{89,88}Zr and ^{88,87}Y radionuclides populated via xn, pxn, and αxn channels, respectively, were evaluated over a wide energy range, starting from the threshold and up to 100 MeV. The results show that the inclusion of a precompound model is essential to reproduce the measured data. Our calculations are in a good agreement with the most of the experimental data reported earlier.

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1. Introduction

Systematic theoretical and experimental studies are necessary to understand the nuclear deexcitation processes, namely pre-equilibrium (PEQ) and equilibrium (EQ), observed in the reactions induced by medium-energy light- and heavy-ion projectiles [1–6]. Concurrently, the performance of various reaction models and parametrizations implemented in popular codes like TALYS1.8 or Alice14 must be examined by comparison with the available experimental results. Reliable calculations of reaction cross sections induced by the light/heavy-ion projectiles are needed to provide proper nuclear reaction data for applications in various fields of science. Among the others, the optimization of the production parameters for radionuclides is nowadays important in medicine, industry, agriculture, biology, *etc.*

Investigation of the reactions induced by α-particles on the Y target over a wide energy range is important to estimate the contribution of PEQ processes in the production of residues that may aid to optimize the pro-

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duction of radionuclides such as ^{88}Y, ^{87}Y, ^{88}Zr (precursor of ^{88}Y), ^{89}Zr, ^{90}Nb, which have found application in treating liver tumours, investigating slow metabolic processes, have a capability for labeling antibodies, *etc.* [7, 8]. The production of ^{92}Nb from α+^{89}Y was first reported by Hansen *et al.* in the 10–15 MeV energy range; then, a threshold anomaly in the 10.4–10.8 MeV energy range was discussed by Richter *et al.* [9, 10]. Isomeric cross-section ratio (ICR) of ^{90g,m}Nb populated via ^{89}Y(α,3n) reaction was investigated by Smend *et al.* [11] within 34–54 MeV. The excitation functions of ^{92m,90}Nb were reported by Mukherjee *et al.* [1] for α+^{89}Y up to 50 MeV and compared with the Blann's hybrid model calculation for PEQ processes. Chaubey *et al.* [12] examined the neutron evaporating channels up to 60 MeV and observed non-equilibrium effects comparing with the model calculations. Furthermore, Singh *et al.* [2] measured the production of ^{89}Nb, ^{89}Zr, ^{88,87}Y up to 50 MeV and compared them with the hybrid PEQ model calculations. The isomeric cross-section ratio for ^{89m,g}Nb was reported by Naik *et al.* [13] within 38–43 MeV. Recently, Shahid *et al.* [3] investigated experimentally the population of various neutron, proton, and α-emitting channels, and compared them with the theoretical values obtained from the TALYS1.6 code.

However, the experimental work on the α+^{89}Y system is so far limited to energies below 60 MeV. Therefore, an extensive theoretical investigation has been carried out over a wide energy range starting from the threshold, using the relatively new EQ–PEQ models and parametrizations. This comparative study of different theoretical approaches and models with the data would provide the confidence to estimate the production of ^{88}Y from its precursor, ^{88}Zr, for which measured data are still not available.

2. Comparison of TALYS1.8 and Alice14

Recent versions of the nuclear reaction model codes, namely TALYS1.8 and Alice14, consisting of various PEQ and EQ models, were chosen to compare with the available experimental data. TALYS1.8 contains two semi-classical, one-component exciton models [14], a two-component exciton model, which is used in the present study [15, 16], and a quantum-mechanical multi-step direct and multi-step compound (MSD-MSC) model for PEQ processes. TALYS1.8 includes the transfer and knockout reaction processes in addition to the Exciton Model (EM) in the pre-equilibrium emission cross-section calculation. The Hauser–Feshbach mechanism (HF) is used for evaporation of particles from the fully equilibrated compound nucleus [14]. It also estimates the direct reaction contribution using a coupled-channel analysis, which is small in the energy range reported here. Both phenomenological and microscopic level density models can be selected. The phenomenological ones are: the backshifted Fermi gas model (BFG), the Gilbert–Cameron

(GC) level density with Ignatyuk systematics and the Generalized Superfluid Model (GSM). The microscopic level density models are the Skyrme force from Goriely's tables (SFG) and the temperature-dependent Hartree–Fock–Bogolyubov (HFB) framework using the Gogny force from Hilaire's combinatorial tables *etc.* The two-component exciton model (EM) for PEQ emissions and the backshifted Fermi gas model (BFG) were chosen for the cross-section calculations in the present work.

On the other hand, Alice14 is built on the hybrid Monte Carlo simulation (HMS) [17] for the PEQ emission of particles and the Weisskopf–Ewing model (WE) for the compound mechanism. It can be used for light- as well as heavy-ion induced reactions up to 200 MeV energy range [18]. It calculates isomeric cross sections and isomeric cross-section ratio (ICR) separately along with the ground state of the product yield. The Fermi gas (FG) level density was used for the estimation of residual populations. Moreover, cluster emission such as ^{2,3}H, ^{3,4}He, ^{7}Be for the PEQ and EQ processes was considered. The mean free path parameter was chosen as 1.5.

3. Results and discussion

A comparative analysis of cross sections for ^{92m,91m,90,89}Nb, ^{89,88}Zr, and ^{88,87}Y radionuclides produced via xn, pxn, and αxn channels, respectively, in the $\alpha+^{89}$Y reaction, has been performed using different PEQ and EQ models up to 100 MeV starting from the threshold energy. In order to discriminate the PEQ emissions from the EQ process, the cross sections for the residues were estimated for the pure EQ process using the HF mechanism from TALYS1.8, and the combined effect of EQ and PEQ processes using both Alice14 and TALYS1.8. The results are shown in Figs. 1 and 2 along with the experimental observations [1–3, 12, 19]. The measured data are denoted by symbols and the theoretical estimations by curves.

3.1. xn channels

Comparisons of the theoretical and experimental excitation functions of the residues, ^{92m,91m,90,89}Nb, produced through the neutron-emitting channels are depicted in Figs. 1 (a), (b), (c), (d), respectively. In Fig. 1 (a), HF+EM reproduced the experimental cross-section data of ^{92m}Nb quite well in comparison to the WE+HMS model estimation towards the high-energy tail of the excitation function. However, the theoretical results underestimate the cross-section values reported by Mukherjee *et al.* [1] throughout the entire energy range. The measured production of the ^{91m}Nb residue, shown in Fig. 1 (b), is not properly described by any of the model calculations. In Fig. 1 (c), the HF model in the low-energy range and HF+EM in the high-energy region (≥ 55 MeV) reproduce the experimental observations indicating the PEQ contribution appearing in addition to the compound pro-

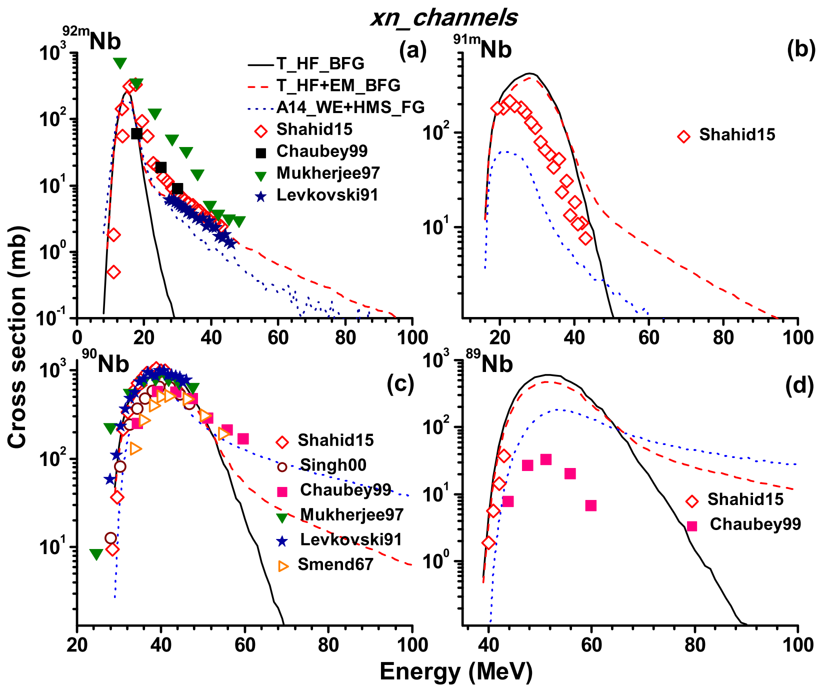

Fig. 1. Excitation functions for xn channels of the $\alpha+^{89}$Y reaction obtained using HF and WE models for EQ emissions, and EM and HMS for PEQ emissions, compared with the experimental data. (T and A14 represent TALYS1.8 and Alice14; BFG/FG indicate the backshifted Fermi gas and Fermi gas level densities, respectively).

cess. However, the Alice calculation reproduces the Chaubey *et al.* [12] and Singh *et al.* [2] data fairly well throughout the measured energy range. In Fig. 1 (d), the recent measurement by Shahid *et al.* [3] is well-reproduced, indicating that the theoretical estimates match the data in the low-energy region ($\leq$ 43 MeV); however, the reported result of Chaubey *et al.* [12] is significantly lower compared to the model calculations. Thus, in all the discussed (α, xn) channels, significant deviations from their traditional shapes of the compound process with a broad maximum have been observed towards the high-energy tail of the excitation function, which confirms a substantial PEQ emission of neutrons in addition to the evaporated neutrons.

3.2. pxn, αxn channels

Limited experimental results are available for the residues produced in the proton-emitting channels, presented in Figs. 2 (a), (b). The cross sections for the residues are mainly available in the EQ emission energy region and they are well-reproduced by the model calculations; however, Singh *et al.* [2] data show an overproduction up to $\sim$ 12–13 times relative to other measured and theoretical estimates. Nevertheless, the theoretical calculations indicate significant PEQ emissions compared to EQ towards the high-energy region.

On the other hand, in the α-emitting channels, both TALYS and Alice can explain the measured cross sections up to $\sim$ 28 MeV, as shown in Fig. 2 (c). The overestimation of measured data if only EQ is used, and their reproduction by the EQ+PEQ calculation using TALYS indicates the occurrence of the PEQ process towards the high energy region. The theoretical calculations with TALYS significantly underestimate the result of Singh *et al.* [2] in the entire measured energy range, while they match the other measurements. However, Alice14 also underpredicts the data to a great extent within $\sim$ 37–47 MeV. TALYS and Alice reproduce the experimental data reasonably well in the $\alpha 2n$ channel, presented in Fig. 2 (d). Experimental data are unavailable beyond 60 MeV to conclude on the PEQ emission; nevertheless, the theory predicts significant PEQ emissions in the high-energy region. It is observed from the theoretical calculation that the production of ^{88}Zr is high around 75 MeV. Since ^{88}Zr is the precursor of ^{88}Y, it is important to examine experimentally the optimized production of ^{88}Y radionuclides.

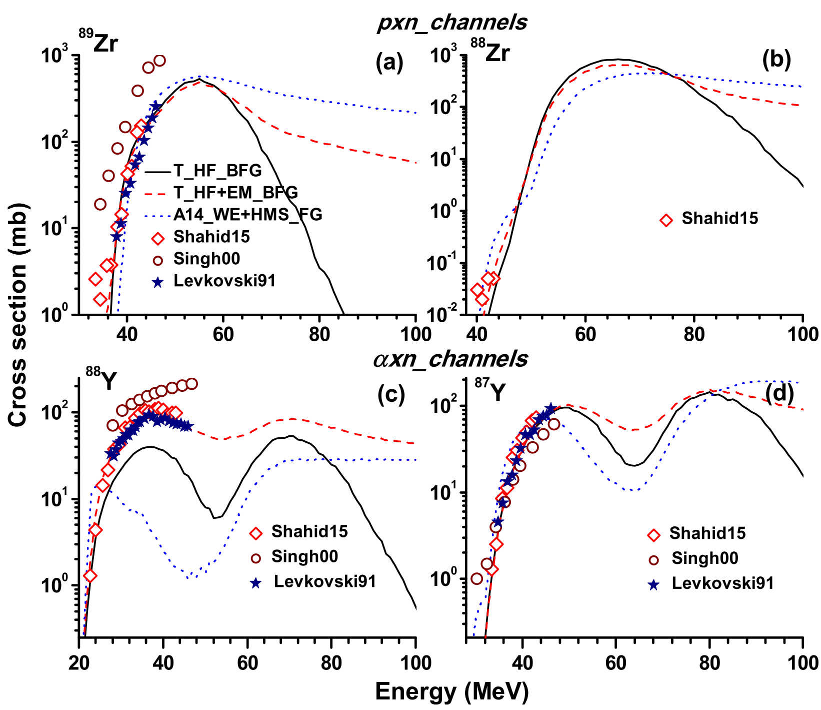

Fig. 2. Comparison of measured and theoretical excitation functions for pxn and αxn channels using different PEQ–EQ models. Notation is the same as in Fig. 1.

4. Summary

In this article, a comparative study of the theoretical and measured cross sections for the residues produced in the $\alpha+^{89}$Y reaction was carried out up to 100 MeV incident energy using the Hauser–Feshbach and Weisskopf–Ewing models for the EQ process, while the Hybrid model using Monte-Carlo simulation and the exciton model were used for the PEQ emissions. Apart from some exceptions, the theoretical estimations appeared reliable when compared with the available measured data. The EQ–PEQ models predict substantial PEQ emissions in addition to the EQ process towards the high-energy region for the ^{92m,91m,90,89}Nb, ^{89,88}Zr, and ^{88,87}Y residues populated through neutron, proton, and α-emitting channels. Overall, TALYS1.8 allows for a better reproduction of the measured data in comparison to Alice14.

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