Comprehensive analysis of multiple neutron evaporation channels in heavy ion-induced nuclear reactions

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Introduction

The study of heavy ion (HI) interactions is of great research interest due to the richness of the reaction phenomena which include complete and incomplete fusion, fission, quasi-fission, and direct reactions. The compound nuclear reactions are mostly observed after projectile-target fusion in low and intermediate-energy regions. At these energies, a compound nucleus (CN) is formed when the energy as well as momentum of the projectile is shared among all the nucleons of the composite nucleus leading to the statistical equilibrium. It is assumed that the mode of decay of the excited CN is independent of the mode of its production which is Bohr's independence hypothesis. The excited CN then decays by the emission of protons, neutrons, etc. The emission of these particles provides important insights into the dynamics of an excited composite system and the mechanism that leads to statistical equilibrium.

Understanding the kinetics of nuclear reactions and the properties of decay of excited CN at energies close to and much above the Coulomb barrier has been made possible through the study of HI-induced reactions. Utilizing the stacked foil activation technique, several experiments have been done on nuclear reactions induced by heavy ions and these experiments give considerable information about the deexcitation of the CN as multiple channels are populated and can be analyzed simultaneously through offline gamma-spectroscopy. Many studies in the literature explain the significance of obtaining the cross-section values using theoretical models when it is not possible to obtain them experimentally for various factors [1]. In this context, it is highly helpful to update and develop these models to compare the cross-section values that are derived using the theoretical models with the experimental results.

Theoretical Formalism

Neutron emission in HI-induced reactions is a fascinating topic of study because it is the most advantageous particle emission pathway due to its zero Coulomb barrier. The neutron evaporation process from an excited CN may be considered as a sequence of discrete and random events since the number of neutrons emitted in a given fraction of excitation energy from a CN does not depend on the number of neutrons emitted in any other excitation energy intervals [2]. With respect to the variation in excitation energy and the number of emitted nucleons from a given CN, the mean excitation energy $'\varepsilon'$ carried away by the emitted neutron keeps a constant value [3]. The evaporation process may be characterized by the mean number of emitted neutrons per unit excitation energy or $1/\varepsilon$. In statistics, the Poisson distribution is used to predict the outcomes of random and independent events. This simply means that the occurrence of a given event does not affect the probability of another event happening in the same time interval. By the similarities between neutron evaporation from an excited nucleus and Poisson distribution, we may assume that the probability of emitting *'x'* number of neutrons may be described using the Poisson distribution law. Thus, the probability of *'x'* neutrons being emitted from the excited nucleus may be given by the following function:

$$P(E^*,x) \propto \frac{1}{x!}\left(\frac{E^*-\sum B_n}{\varepsilon}\right)^x \exp\left[-\left(\frac{E^*-\sum B_n}{\varepsilon}\right)\right] \qquad (1)$$

Where, $E*$ is the excitation energy of the nucleus after the initial nuclear reaction, $\sum B_n$ is the sum of the binding energies of the *'x'* emitted neutrons and ε is the average excitation energy of the CN. In the Bohr compound nucleus hypothesis, it is assumed that the de-excitation of the CN is

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Electronic address: sanjana143takar@gmail.com* independent of the mode of production. The cross-section for the x neutron emission may thus be given by

$$\sigma_{xn} = C\sigma_c P(E^*,x) \quad (2)$$

Where σ_c is the cross-section for the CN formation calculated by the incident energy, radius, and Coulomb barrier of the interacting ions and $P(E^*,x)$ is the probability of x neutron emission given by Poisson distribution law. The constant C may be obtained by normalizing the peaks of the excitation function. So the cross-section assuming Poisson random distribution for a typical xn channel may be given as [2]

$$\sigma_{xn}=\frac{\pi R^2 C}{x!}\left(1-\frac{V_c}{E_i}\right)\left(\frac{E^*-\sum B_n}{\varepsilon}\right)^x \exp\left[-\left(\frac{E^*-\sum B_n}{\varepsilon}\right)\right] \quad (3)$$

The parameters C and ε may be varied to fit the data obtained by Poisson random distribution with the experimental data. The parameter ε may be determined from the position of the peaks of the excitation functions, where $d\sigma_{xn}/dE^*|_{E^*=E_p^*} = 0$. The expression can be used to find ε. Also, with the assumption that the dependence of average excitation energy ε on A^* is linear, a least square fit for $A^* \geq 83$ leads to the following relation [3]

$$\varepsilon = (8.98 - 2.40A^*/100)\ \text{MeV} \quad (4)$$

Where A^* is the mass number of CN. $\sum B_n = xB_n$, here we ignore the variation in the binding energies of the evaporated neutrons at higher excitation energies as the shell and pairing effects play a minor role. Binding energy B_n of the emitted neutrons may be calculated by the following relation [4]

$$B_n = \left[ZM_p + NM_n - A - \alpha A + \frac{\beta I^2}{A} + \gamma A^{2/3} + \left(\frac{3e^2}{5R_0}\right)\frac{Z^2}{A^{1/3}}\right]c^2 \quad (5)$$

Where the symbols have their usual meanings.

Results and Conclusion

In the present work, an attempt has been made to calculate the cross-sections employing the Poisson random distribution approach. A program has been developed for the analysis of cross-sections of multiple neutron evaporation channels in HI-induced reactions. The experimental data [5] for neutron emission channels in the reaction induced by ^{16}O on ^{169} Tm has been analyzed within the framework as discussed above.

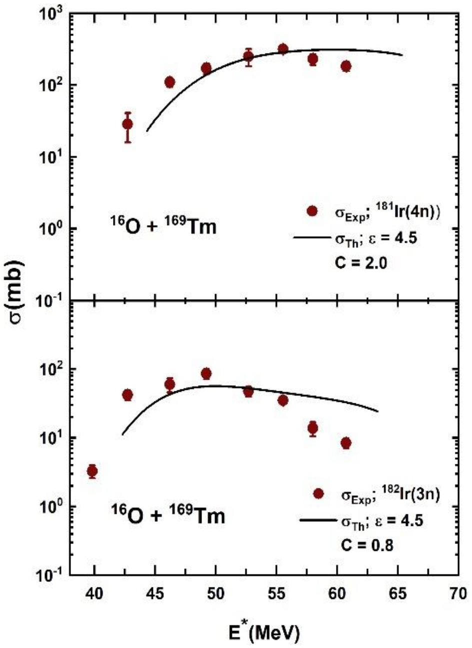

Fig.1 Experimentally measured and theoretically calculated excitation functions assuming that neutron evaporation follows Poisson random distribution.

The experimental cross-section data for ^{169}Tm(^{16}O, 3n)^{182}Ir and ^{169}Tm(^{16}O, 4n)^{181}Ir reaction channels have been compared with theoretically obtained cross-sections using the above description in Fig.1. The best-fit value of the parameter ε is found to be 4.5 MeV which matches with the value obtained from eq.4. The theoretical cross-sections obtained considering neutron evaporation events from CN formed in HI-induced reactions as Poisson random distribution, are found to be in good agreement with the experimental data. Further details of the obtained values and parameters will be presented.

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