Pre-Equilibrium Emission: a Tool to Study Dynamic Effects and Clustering Structure in Exotic Nuclei

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INTRODUCTION

The neutron-rich radioactive beams which will be produced by the SPES facility of the Laboratori Nazionali di Legnaro will give an excellent opportunity to study the emission mechanisms in the low and intermediate energy heavy-ion reactions. Our research is focused on study of the pre-equilibrium, evaporative emission processes and alpha-cluster structure in the exotic nuclei. The theoretical model, developed recently by our group, describes simultaneously evaporative (thermal equilibrium) and pre-equilibrium emission of the light particles in heavy-ion reactions. Hybrid exciton model is used for the description of the pre-equilibrium stage of the compound nucleus formation, while the equilibrium evaporation process is analyzed in the framework of the statistical theory of heavy-ion reactions. Within the hybrid exciton model the alpha-particle preformation probabilities are taken into account while calculating the final yields and total spectral shapes.

The pre-equilibrium process plays an important role on the dynamics of heavy-ion fusion reactions in the early stages and also characterizes the features of the hot fused source. The knowledge on the fast emission processes includes dependence on both the entrance channel mass-asymmetry and on the beam velocity, but it is still far from being complete. The pre-equilibrium process becomes evident at the projectile energy of 6 MeV/u concerning the neutron emission and at the projectile energies larger than 8 MeV/u for protons and alpha particles emission. In our previous works [1-6] emission mechanisms were studied for the reactions with the different mass-asymmetries in the projectile energy region from 8 to 16 MeV/u. The analyses using the recently developed theoretical model, described below, put in evidence interesting features concerning the probabilities of either pre-equilibrium or evaporative emission and considering clusterization in nucleus. The 11 MeV/u ^{132}Sn + ^{27}Al reaction covers all regions of our interest including the study of pre-equilibrium and evaporative reaction mechanisms in the neutron-rich projectile induced reactions, the study of alpha clusterization and its influence on the initial exciton configuration of the non-equilibrium particles in the exotic system and the study of alpha-particle preformation probabilities in the compound nucleus.

THEORETICAL MODEL

The main assumption in the model of pre-equilibrium processes is that the incident beam loses its energy gradually. Thus, a distinction can be made after each collision between the fast particle, and the nucleons excited by the collision from states below the Fermi energy. Let n be the number of excitons (i.e. particles and holes). In the Griffin's exciton model [7] of nuclear reactions, relaxation of the composite nuclear system to equilibrium is described by the master equation:

$$\frac{d}{dt}q(n,t)=\sum_{m=n-2}^{m=n+2}\lambda_{m\to n}\,q(m,t)-q(m,t)\left(w(n)+\sum_{m=n-2}^{m=n+2}\lambda_{n\to m}\right), \qquad (1)$$

where $q(n,t)$ is the occupation probability for the composite nucleus state n, $w(n)$ is the emission rate of light particles (in our case – neutrons, protons and α-particles), $\lambda_{m\text{-}n}$ is the internal transition rate. The positive terms at the right-hand side of Eq. (1) describe the feeding to the state n from all possible states m, and the negative terms account for the losses of the system due to emission and transitions to other exciton states. The internal transition rates, $\lambda_{m\text{-}n}$, are determined by the matrix element of the transitions, $\langle|M|^2\rangle$, and the densities of the exciton states to that the transitions occur, $\omega_{0,}(n,E)$. In the model the densities of the exciton states are determined by the single particle level density g. The last one is related with the level density parameter of the Fermi-gas model a. For these parameters we used the same values as in the evaporation case. The details of the transition rate calculations used in our approach can be found in [8].

We regard as free parameters the following values: n_0, k, g. k is a parameter connected with the transition matrix element $\langle|M|^2\rangle$. It determines the transition rate of the emitted particle into continuum. This parameter is varied in the range from 200 to 800 MeV^3. The single particle level density g (which is used to determine the densities of exciton states) is connected with the level density parameter in the Fermi-gas model by the relation $g=6a/\pi^2$. The parameter a was chosen in the frame of the Fermi-gas model or the level-density phenomenological model [9] with the Grudzevich parameterization [10]. n_0 is the exciton number mentioned above. The initial exciton configuration from which the equilibration process starts can be expressed as $n_0=p_0+h_0$ and can be determined from the following Eq. (2) representing the empirical Cindro-Betak trend observed in [11-12]:

$$E^*/n_0 = 6.8 + 0.54(E_{CM} - V_C)/A_P, \quad (2)$$

where E^* is the excitation energy of the compound nucleus, E_{CM} and V_C are the center-of-mass energy and the Coulomb barrier, respectively, and A_P is the mass of the projectile nucleus.

In the frame of Griffin model we calculate the equilibrium and pre-equilibrium particles ejection probabilities and the energy spectra of pre-equilibrium particles (neutrons, protons and α-particles). In the following step using Monte-Carlo simulations we obtain the kind of pre-equilibrium particle (neutron, proton or α-particle) with its energy. Using the optical model and Monte-Carlo simulations we determine the angular momentum of the emitted particles. On the first step of our investigations for the pre-equilibrium particles we use a special method to cut off the low angular momenta [3]. For the certain angular momentum values we estimate the particle ejection angles in the frames of the standard PACE procedure using the corresponding associated Legendre functions.

RESULTS

The pre-equilibrium spectra could provide information on the alpha-particle preformation probabilities in compound nucleus. We performed theoretical model calculations for the reaction 1452 MeV (11 MeV/u) ^{132}Sn+^{27}Al with the initial exciton configuration (*27 particles, 2 holes,* n_0*=29*) considering two cases. In the first one the preformation probability was supposed to be $\psi_0=0$, while in the second case we assumed $\psi_0=0.12$ taking as a starting point analytic expression for alpha particle preformation calculation in cold heavy nuclei [13]. The calculated evaporative, pre-equilibrium and total multiplicities for neutrons, protons and alpha particles in the two cases are shown in Table 1. The pre-equilibrium alpha-particle multiplicity is growing by 42% in the case of $\psi_0=0.12$ with respect to the case of $\psi_0=0$. Considering the calculated pre-equilibrium alpha-particle cross-section of 38 mbarn for $\psi_0=0$, this effect becomes experimentally feasible considering the provided intensity of the SPES ^{132}Sn beam. It is interesting to notice that the pre-equilibrium neutron and proton multiplicities are also changing in the two cases. These changes can be attributed to the change in average energy of the ensemble constituents. The calculated spectra of alpha particles are shown in Fig. 1.

CONCLUSION

The results of the theoretical model calculations for the evaporative and pre-equilibrium particle multiplicities and spectral shapes suggest to consider the reaction 1452 MeV (11 MeV/u) ^{132}Sn+^{27}Al to be a good candidate for study the clustering structure and dynamic effects in exotic nuclei using the novel method proposed in this report.

Table 1. Calculated evaporative, pre-equilibrium and total multiplicities of neutrons, protons and alpha particles in the 11 MeV/u ^{132}Sn+^{27}Al reaction for the alpha-particle preformation probability $\psi_0=0$ and $\psi_0=0.12$.

ψ_0	M_n			M_α			M_p		
	Evap	Preeq	Total	Evap	Preeq	Total	Evap	Preeq	Total
0.00	**11.70**	**0.805**	**12.51**	**0.525**	**0.031**	**0.556**	**0.316**	**0.164**	**0.480**
0.12	**11.76**	**0.729**	**12.49**	**0.515**	**0.044**	**0.559**	**0.303**	**0.226**	**0.529**

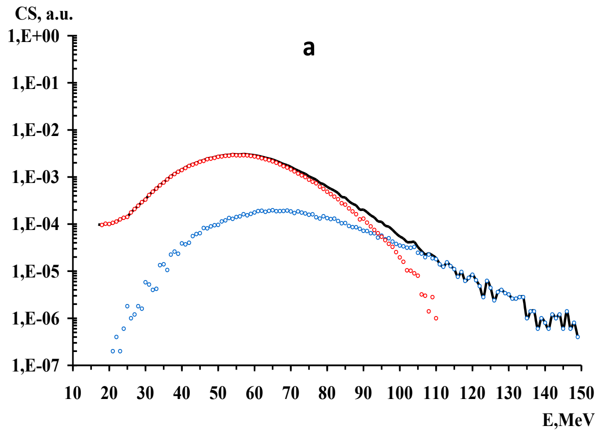

Fig. 1. Calculated pre-equilibrium (blue), evaporative (red) and total (black) spectra for alpha particles in the reaction 11 MeV/u ^{132}Sn+^{27}Al for $\psi_0=0.12$ and angular range 29-41 degrees.

On the basis of this work we propose to consider the possibility to measure light charged particles and neutrons emitted in the 11 MeV/u ^{132}Sn + ^{27}Al reaction in two parallel experiments using GARFIELD and RIPEN apparatuses, respectively, in order to study evaporative and pre-equilibrium reaction mechanisms, influence of alpha clusterization in the projectile nucleus on the initial exciton configuration of the non-equilibrium particles and alpha-particle preformation probability in compound nucleus.

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