ISOTOPIC DEPENDANCE OF NEUTRON EMISSION FROM DINUCLEAR SYSTEM*

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Using the statistical approach, we study the isotopic dependence of the de-excitation of dinuclear systems formed in the entrance channel of heavy ion reactions. The probabilities of neutron emission from the dinuclear systems $^{62-73}$Ni+^{208}Pb are estimated and a possible experiment for the observation of this emission is discussed.

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1. Introduction

The experimental study of neutron emission in heavy ion reactions has been very useful for the study of the fusion–fission and quasifission dynamics [1,2] in reactions in which the compound nuclei, if produced, have excitation energies larger than 70 MeV. For smaller energies, the neutron emission accompanying the quasifission from nearly symmetrical configurations has been studied both experimentally [3] and theoretically [4]. The possibility to distinguish the pre-scission and post-scission neutrons emitted in these reactions is very promising for the analysis of the mechanism of heavy ion interaction. In order to increase the number of pre-scission neutrons, one can lower the neutron binding energy in the nuclear system by taking neutron-rich isotopes as projectiles. In this paper we consider the neutron emission from the dinuclear systems (DNS) formed in the reactions $^{62-73}$Ni+^{208}Pb and estimate the probability of this process using the statistical approach.

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2. Probability of neutron emission from DNS

The DNS model [5], which seems to be successful in describing fusion and quasifission processes, is used in our treatment. This model assumes that the DNS is formed after the colliding nuclei pass over the Coulomb barrier and come to the touching configuration. The DNS evolves by diffusion in the relative distance R between the centers of nuclei and in the mass (charge) asymmetry coordinate $\eta = (A_1 - A_2)/(A_1 + A_2)$ ($\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$) ($A_1$, Z_1 and A_2, Z_2 are the mass and charge numbers of the DNS nuclei, $A_{\mathrm{DNS}} = A_1 + A_2$ is the mass number of the DNS). Since the nuclei in the DNS are excited because of the dissipation of the incident kinetic energy, the neutron emission is possible during the DNS evolution. The diffusion over the small potential barrier [5] to larger R leads to the decay of the DNS which we call quasifission. The diffusion to smaller η_Z with the consecutive decay in R because the increasing Coulomb repulsion leads to the quasifission as well.

Under the assumption of a small overlap of the nuclei in the DNS we calculate the potential energy as follows [5]:

$$U(R, \eta, \eta_Z, \beta_1, \beta_2, J) = B_1 + B_2 + V(R, \eta, \eta_Z, \beta_1, \beta_2, J)\,, \tag{1}$$

where B_1 and B_2 are the mass excesses of the fragments at their ground states, β_1 and β_2 are their parameters of quadrupole deformations. The nucleus–nucleus potential $V(R, \eta, \eta_Z, \beta_1, \beta_2, J)$ is the sum of the Coulomb potential, the nuclear potential and the centrifugal potential [4, 5]. Due to the decrease of the stability of the DNS with respect to the decay in R and the decrease of the DNS excitation energy with increasing J at a fixed value of the incident energy $E_{\mathrm{c.m.}}$, only partial waves with small angular momentum contribute to the probabilities of neutron emission from DNS. Therefore we perform our calculations at $J = 0$.

In the statistical approach the evolution of the excited DNS is prescribed by the competition between the neutron emission and the DNS transition over the barrier B^R_{qf} in R in the entrance channel at $\eta_Z = \eta_{Z_0} = 0.49$ or over the barrier B^{η}_{qf} in η_Z, in the direction to smaller η_Z. We find the values of these barriers by the analysis of potential energy surface obtained with (1).

The probability of neutron emission is be defined as follows

$$P_n = \sum_i w(\eta_i) \frac{\Gamma_n(E^*_{\mathrm{DNS}_i}, \eta_{Z_0}, \eta_i)}{\Gamma_n(E^*_{\mathrm{DNS}_i}, \eta_{Z_0}, \eta_i) + \Gamma^R_{qf}(E^*_{\mathrm{DNS}_i}, \eta_{Z_0}, \eta_i) + \Gamma^{\eta}_{qf}(E^*_{\mathrm{DNS}_i}, \eta_{Z_0}, \eta_i)}\,, \tag{2}$$

where Γ_n is the width of the neutron emission channel, and Γ^R_{qf} and Γ^{η}_{qf} are the widths of transitions over the barriers B^R_{qf} and B^{η}_{qf}, respectively. To take into account the distribution of the DNS in η in the vicinity of η_0 where the DNS potential energy is minimal at given η_{Z_0}, one can introduce the statistical weights $w(\eta_i)$ of the states η_i with the excitation energies E_{DNS_i}. In our calculations this distribution is given by Boltzmann formula [6]. If the distribution of the DNS in η at given η_{Z_0} is strongly peaked at η_0, one can set $w(\eta_i) = \delta_{\eta_i,\eta_0}$. Analogously (2), one can define the probabilities of quasifission of the DNS P^R_{qf} and P^η_{qf} in R and η.

The probabilities of neutron emission, quasifission at η_{Z_0} and at smaller η_Z for dinuclear systems formed in the reactions $^{62-73}$Ni+^{208}Pb at the excitation energy $E^*_{\mathrm{DNS}} = 30\,\mathrm{MeV}$ are shown in Fig. 1. The calculations are performed assuming the DNS configuration close to the thermodynamic equilibrium. Taking into account the fluctuations in η, we get a smoother dependence of P_n on A_{DNS}. As seen, the direct quasifission in R is the dominant process in the reactions ^{A_1}Ni+^{208}Pb at $A_1 < 72$. With increasing neutron number the diffusion to smaller charge asymmetries rapidly grows. For the DNS with $A_{\mathrm{DNS}} > 280$, we have $P^\eta_{qf} > P^R_{qf}$ and the DNS mostly evolves to more symmetrical configurations from which it decays. At the fixed DNS excitation energy in the interval between 15 and 30 MeV the value P_n increases by a factor 3 with increasing A_{DNS} from 270 till 281. This is about 6 times smaller than the increase of the neutron emission from the compound nucleus with the same total mass number. With increasing

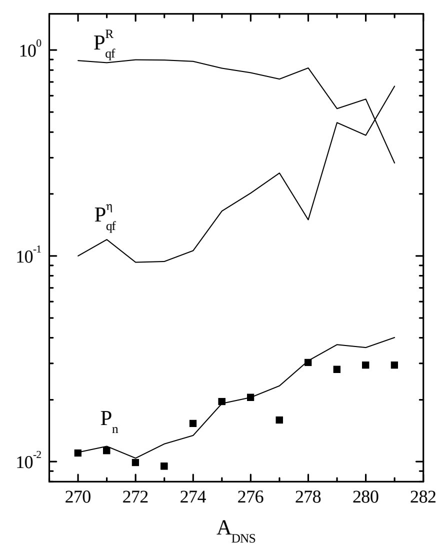

Fig. 1. The probabilities of neutron emission and quasifissions in R and in η_Z for the DNS formed in the reactions $^{62-73}$Ni+^{208}Pb at excitation energy of the DNS in the entrance channel $E^*_{\mathrm{DNS}} = 30\,\mathrm{MeV}$. The values of P_n calculated with $w(\eta_i) = \delta_{\eta_i,\eta_0}$ are presented by closed points.

mass the neutron binding energy decreases and the fission barrier usually increases in the compound nucleus. Although the neutron binding energy decreases in the DNS the quasifission probability remains at the same level.

Since the characteristic time of neutron evaporation ($\tau_n \sim 10^{-19}$ s) is much larger than the time ($\tau_{qf} \sim 10^{-21}$ s) of the DNS decay and the formation of free fragments, the neutrons emitted from free fragments have larger projections of momenta on the axis of the reaction in the c.m. system. Therefore, there is a chance to distinguish the pre-scission neutrons from those emitted from free fragments (see Ref. [1, 2]).

3. Summary

Using the statistical approach, we studied the isotopic dependence of neutron emission from the DNS being in the local potential minimum and formed in the entrance channel of the reactions $^{62-73}$Ni+^{208}Pb. The detailed description of our calculations, the analysis of dependence of P_n on the excitation energy of the DNS and the consideration of the case when the DNS fragments have different temperatures are presented in Ref. [6].

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