Angular anisotropy of the fusion-fission and quasifission fragments

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Abstract. The anisotropy in the angular distribution of the fusion-fission and quasifission fragments for the $^{16}\text{O} + ^{238}\text{U}$, $^{19}\text{F} + ^{208}\text{Pb}$ and $^{32}\text{S} + ^{208}\text{Pb}$ reactions is studied by analyzing the angular-momentum distributions of the dinuclear system and compound nucleus which are formed after capture and complete fusion, respectively. The orientation angles of the axial symmetry axes of the colliding nuclei relative to the beam direction are taken into account for the calculation of the variance of the projection of the total spin onto the fission axis. It is shown that there is a large contribution of the quasifission fragments in the $^{32}\text{S} + ^{208}\text{Pb}$ reaction to the deviation of the experimental angular anisotropy from the statistical model results. Enhancement of anisotropy at low energies in the $^{16}\text{O} + ^{238}\text{U}$ reaction is connected with the quasifission of the dinuclear system having low temperature and relatively small effective moment of inertia.

PACS. 25.70.Jj Fusion and fusion-fission reactions – 25.70.Lm Strongly damped collisions – 25.85.Ge Charged-particle-induced fission

1 Introduction

The study of the mechanism of the fusion-fission process in the reactions with massive nuclei is of interest for both experimentalists and theorists to obtain a favorable way for the synthesis of superheavy elements or exotic nuclei far from the stability line. The last experiments on the synthesis of superheavy elements $Z = 114, 115, 116$ and 118 were successful at beam energies corresponding to 35–40 MeV excitation energies of the compound nucleus which is higher enough than the Bass barrier. The deformed actinide nuclei were used as targets in the synthesis of new superheavy nuclei in the $^{48}\text{Ca} + ^{238}\text{U}, ^{244}\text{Pu}, ^{248}\text{Cm}$ reactions [1]. This means that the orientation angle of the symmetry axis of the target nucleus relative to the beam direction affects the fusion-fission mechanism. The cross-sections of events corresponding to the synthesis of superheavy elements are not higher than few picobarns [1] and the width of the evaporation residues excitation function is very narrow. At the same time the measured cross-sections of the fission fragments are several tens of millibarn [2] and the excitation function of fission fragments yields is very wide. This means that only a very small part of collisions in the narrow range of the beam energy leads to the formation of the evaporation residues considered as superheavy elements. The problem is to establish this small range of the beam energy as the optimal condition for the synthesis of superheavies. The main reason leading to the small values of the evaporation residue cross-sections seems to be connected with the small survival probability $W_{\text{sur}}$ of the heated compound nucleus against fission by evaporating neutrons. It is well known that the $W_{\text{sur}}$ decreases by an increase of the excitation energy $E_{\text{CN}}$ and angular momentum $\ell_{\text{CN}}$ of the compound nucleus [3].

But the formation of the compound nucleus in reactions with massive nuclei has a hindrance: not all of the dinuclear systems formed at capture of the projectile by the target nucleus can be transformed into compound nuclei. We should stress that the estimation of the formation
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probability is difficult by both experimental and theoretical methods. The determination of the fusion probability from the experimental data is ambiguous due to the difficulties to identify pure fission fragments of the splitting compound nucleus from the fragments which are formed in other processes of heavy-ion collisions like fast-fission, quasifission and deep inelastic collisions. By the way, the restoration of its value from the cross-sections of evaporation residues is model dependent. As a result there is a field for speculations which can be clarified indirectly by the analysis of the physical results connected with the formation of the compound nucleus. The angular distribution of reaction fragments is one of the informative quantity allowing us to study the fusion-fission mechanism of heavy-ion collisions. The study of correlations between mass and angular distribution of fragments of full momentum transfer reactions allows us to separate the pure fission fragments of the compound nucleus with a compact shape [4]. The mass and angular-momentum distributions of the reaction fragments are determined by the dynamics of collision. The complete kinetic energy relaxation (capture stage) is a main characteristic of the quasifission reactions. This means that quasifission takes place only after the capture of the projectile by the target nucleus. The mass equilibrium can be reached or not in dependence on the masses and mass asymmetry of the reactants [5], as well as on the dynamics of collision.

The goal of the present paper is to show the ability of the method based on the dinuclear-system (DNS) concept to calculate the angular-momentum distribution for the fusion-fission and quasifission fragments by analyzing the anisotropy of the angular distribution of both fusion-fission and quasifission fragments in reactions with deformed and nearly spherical target nuclei. Quasifission produces fragments like the fission fragments thus confusing the estimation of the fusion cross-section. In the quasifission process, the compound-nucleus stage is not reached.

In our model we calculate dynamically only the capture stage of the reaction. The second stage is the competition between complete fusion and quasifission in the evolution of the dinuclear system. We consider this stage by the statistical method based on the assumptions that in the relatively long-lived dinuclear system the thermal equilibrium is reached after the complete transformation of the relative kinetic energy into the excitation energy of the intrinsic and surface vibration degrees of freedom. It is assumed that the equilibrium of mass asymmetry degrees of freedom is reached. The mass distribution strongly depends on the potential energy surface. From the theoretical analysis of the fusion-fission and quasifission reactions it is known that the reaction time of the fusion-fission process is sufficiently longer than the one of quasifission. The competition between these processes takes place after the capture of nuclei has occurred. The capture stage can be analyzed with the diabatic potential because its time is about $5\cdot7\cdot10^{-22} \text{s}$. But the competition between fusion-fission and quasifission processes can take place during short or longer times in dependence on the beam energy and orbital angular momentum, as well as on how massive are the colliding nuclei. The short-time competitions between quasifission and fusion can be investigated by the diabatic potential. For the long-time competitions we deal with a potential which is intermediate between the diabatic and the adiabatic one. The reactions considered in our paper have large mass asymmetry. Therefore, in the analysis of these reactions we deal with the short-time competitions between quasifission and complete fusion. So, the use of the diabatic potential in our analysis is not in contradiction with the physical picture of the process. For example, this kind of conclusions was made in ref. [6] where the author discussed the use of the diabatic and adiabatic potentials in the study of quasifission in a heavy fusing system.

The partial capture, fusion and quasifission excitation functions, as well as the corresponding mean square values of the angular momentum calculated in this work were used to determine the anisotropy $A$ of the fragment angular distribution by formula (1) as a function of the spin distribution of the fissioning systems: compound nucleus and dinuclear system. The results were compared with the experimental data for the observed anisotropy $A$ of the angular distributions of fragments of the $^{16}\text{O} + ^{238}\text{U}$ [7], $^{19}\text{F} + ^{208}\text{Pb}$ [8] and $^{32}\text{S} + ^{208}\text{Pb}$ [5,9] reactions. It was shown that the large anisotropy of in the angular distribution of fragments of the full momentum transfer events in the $^{16}\text{O} + ^{238}\text{U}$ [7] reaction at the lowest beam energies is connected to the contribution of the quasifission products. The contribution of the latter process is dominant in the $^{32}\text{S} + ^{208}\text{Pb}$ [5,9] reaction for all the beam energy range and this causes the large anisotropy in the measured angular distribution of the fragments.

We present also the results obtained by an alternative way of estimation of the angular anisotropy of the quasifission products $A_{qf}$. $A_{qf}$ is estimated from the angular distribution of the quasifission products. The rotation angle of the dinuclear system is found as the sum of the rotation angles during capture and before its break-up for the given initial values of the beam energy and orbital angular momentum $\ell_0$. The former angle is found by solving the equation of motions for capture and the latter angle is estimated by the product of the angular velocity and decay time of the dinuclear system.

The paper is organized in the following way. In sect. 2, we discuss the possibility to use the anisotropy of the angular distribution of fragments to establish their origination. In sect. 3 we present the method to calculate the orbital angular-momentum distribution, mean square values $(\ell^2)$, and anisotropy $A$ of the angular distribution of the fission and quasifission fragments. A short presentation about how we calculate capture, fusion, and quasifission excitation functions is given in sect. 4. The results of the anisotropy of the fragment angular distribution of the fission and quasifission fragments are presented and discussed in sect. 5. In sect. 6, we present an alternative way to calculate the angular anisotropy making use of the rotational angle and partial quasifission cross-sections. Conclusions are given in sect. 7.