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COMPETITION BETWEEN COMPLETE FUSION AND QUASI-FISSION IN REACTIONS BETWEEN MASSIVE NUCLEI. THE FUSION BARRIER

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1. Introduction

Experimental data [1] obtained by measuring cross sections for the formation of evaporation residues, $\sigma_{ER}(E)$, in the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd are analyzed. The $\sigma_{ER}(E)$ values calculated within the framework of the existing models of complete fusion are at strong variance with the experimental data. In our point of view, this disagreement is due to quasi–fission which dominates in the decay of massive dinuclear systems formed in these reactions after the full dissipation of the kinetic energy of collision. In the existing models of complete fusion the quasi–fission channel leading to the decay of the initial dinuclear systems is not taken into account. In this paper a model is proposed for calculation of the competition between complete fusion and quasi–fission in massive symmetric dinuclear systems. The $\sigma_{ER}(E)$ values calculated for the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd by using this model are close to the experimental data.

2. Model of the competition between complete fusion and quasi–fission

In the common case the compound nucleus production cross section can be written in the following form:

$$\sigma_{CN}(E_{cm}) = \pi \lambda\!\!\!^{-}_0{}^2 \sum_{\ell=0}^{\ell_f} (2\ell+1) T(\ell, E_{cm}) W_{fus}(\ell, E_{cm}) \tag{1}$$

where ℓ_f is the angular momentum corresponding to the vanishing fission barrier, $\lambda\!\!\!^{-}_0$ is the de Broglie wave length, E_{cm} is the bombarding energy in the CMS, T is the penetration coefficient of the ℓ-th partial wave, W_{fus} is the compound nucleus production probability after the capture. The last multiplier takes into account the competition between the complete fusion and quasi–fission.

In developing the model we have used the interpretation of the mechanism of compound –nucleus formation suggested in ref. [2]. The dissipation of the kinetic energy of collision is followed by the formation of a dinuclear system (DNS). The fusion of the nuclei constitutes DNS evolution during which nucleons, shell by shell, are transferred from one nucleus to the other. The individuality of each nucleus incorporated in the DNS is conserved during the whole process leading to compound nucleus formation. In reactions between massive nuclei the initial DNS, as a result of strong Coulomb forces, can decay to two fragments with close masses, i.e. quasi-fission will occur. In the present paper the relationship between the compound-nucleus formation channel and quasi-fission channel in a massive DNS is considered.

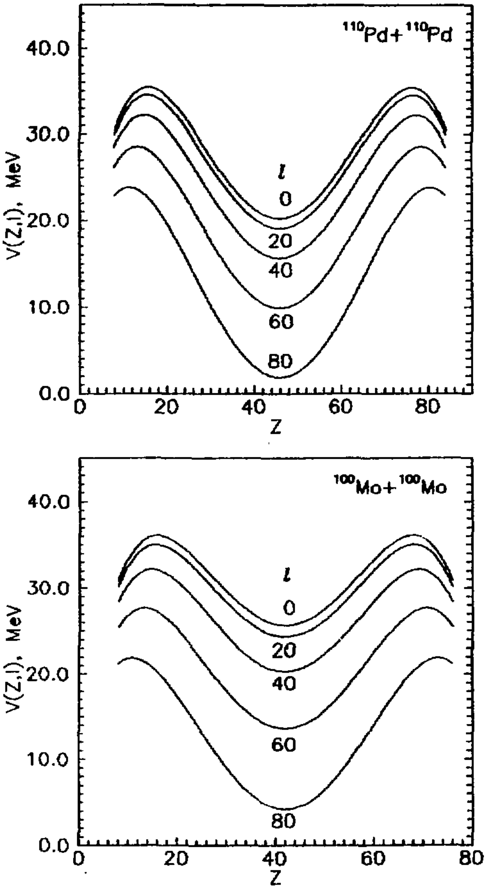

Fig.1. Potential energy of the dinuclear system as a function of its charge asymmetry at different angular momenta l.

The evolution of the DNS is determined by the potential energy of the system, which is considered as a function of its charge asymmetry and the angular momentum of the collision, $V(Z,l)$. The potential energy of the DNS formed in the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd is presented fig. 1. The $V(Z,l)$ values have been calculated using the liquid-drop masses of nuclei and the nucleus-nucleus potential $V(R)$ including the nuclear, Coulomb and centrifugal potentials, i.e.

$$V(R) = V_N(R) + V_C(R) + V_\ell(R), \tag{2}$$

where R is the distance between the nuclear centres. The DNS is taken to have the form of two spherical nuclei whose surfaces overlap. R in $V(Z,l)$ corresponds to the bottom of a pocket in the $V(R)$ potential. The nuclear interaction potential $V_N(R)$ is assumed to have the form of the folding potential [3]. In the Coulomb potential $V_C(R)$ a partial overlapping of nuclear volumes has been taken into account [4]. The centrifugal potential $V_\ell(R)$ has been calculated for two sticking nuclei and for the rigid-body moment of inertia.

As one can see in fig. 1, in both reactions the initial DNS lies in the potential energy minimum, thus forming a kind of a giant nuclear molecule. In order that fusion could occur, the DNS, while evolving towards a compound nucleus, should cross the potential energy maximum (the Businaro-Gallone point), i.e. it should overcome the potential barrier. This barrier can naturally be termed as the fusion barrier B^*_{fus}.

Now we turn to the quasi-fission channel. Usually quasi-fission in asymmetric nuclear systems is considered [5]. These systems evolve towards a symmetric shape with the subsequent decay into two nuclear fragments with close masses. In the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd the initial DNS has a symmetric shape already at the moment of formation, this shape being a favourable one for decay because of the maximum value of the Coulomb repulsion. Therefore, in the analysis of the decay of a massive symmetric DNS it is possible to use a sudden approximation. This assumption corresponds to the retaining individuality of the DNS nuclei [2] and its small overlapping. Thus, in the process of quasi-fission the DNS should overcome the potential barrier (B_{qf}) which coincides with the depth of the pocket of interaction potential $V(R)$ (see fig. 2).

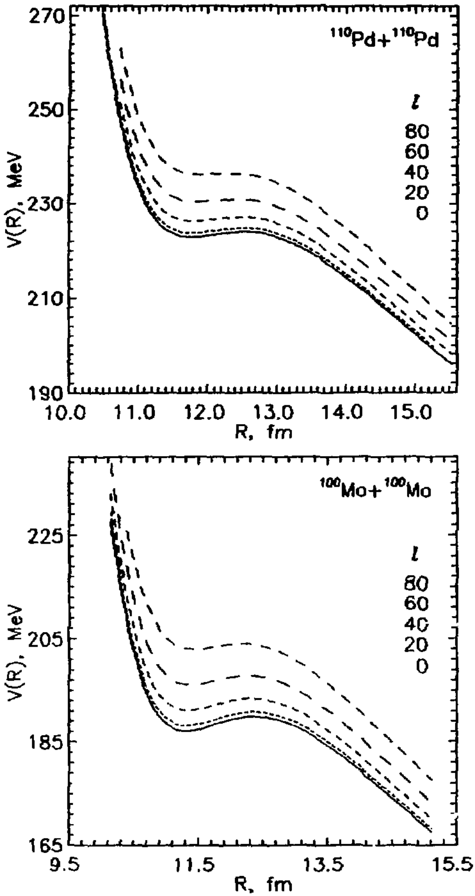

Fig.2. Nucleus-nucleus potential at different angular momenta l.

Thermal equilibrium is established in the DNS rather fast, for few units of 10^{-22} s. The time of the quasifission is one order of magnitude more than this time. Therefore, a statistical approach can be used to calculate the competition between complete fusion and quasi-fission. The possibility of using a statistical approach to the DNS decay is indicated by the Q_{gg}-systematics cross sections of deep inelastic transfer reactions products [6]. The probability for the DNS to evolve via complete fusion or quasi-fission is determined by the level densities at the maxima of the fusion and quasi-fission barriers. To describe the DNS level density one has used the expression proposed in ref. [7]:

$$\rho_i(E^*) = \left[\frac{g^2}{g_1 g_2}\right]^{1/2} \frac{g}{6^{3/4}(2gE^*)^{5/4}} \exp[2(aE^*)^{1/2}], \tag{3}$$

where i is B^*_{fus} or B_{qf}, g_1 and g_2 are the densities of single-particle states near the Fermi surface for the two nuclei incorporated in the DNS, $2g = g_1 + g_2$ and $a = \pi^2 g/3$. The values of g_1 and g_2 are taken according to the systematics [8]. Taking into account the above assumption we can use for W_{fus} in (1) the following ratio

$$W_{fus} = \frac{\rho_{B^*_{fus}}}{\rho_{B^*_{fus}} + \rho_{B_{qf}}} . \tag{4}$$

The ratio $\rho_{B_{qf}}/(\rho_{B^*_{fus}} + \rho_{B_{qf}})$ determines the quasi-fission probability. The DNS excitation energy E^* has been estimated using the data of ref. [9] which have shown that, in contrast to fission, in the process of quasi-fission light particles do not carry off a considerable portion of the excitation energy of the system.

3. Calculation of $\sigma_{ER}(E)$ for the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd

The factors taken into account in calculating the $\sigma_{ER}(E)$ values for the reactions ^{100}Mo + ^{100}Mo and ^{110}Pd + ^{110}Pd are as follows: (i) the competition between complete fusion and quasi-fission in the initial DNS, and (ii) the competition between fission and the emission of light particles and γ-rays in compound-nucleus de-excitation. The calculation of the competition between complete fusion and quasi-fission has been done in the framework of a model proposed by us. Compound-nucleus de-excitation has been analyzed in the framework of a statistical model by using the Monte-Carlo method [10]. The nucleon capture cross section $\sigma_C(E)$ has been calculated using an optical model [11] for both reactions. As is shown in refs. [9,12], a considerable part of the excitation energy of the massive compound nucleus is carried off by neutrons before the nucleus reaches the saddle point, at which excitation energy is about 30–40 MeV. Taking into account the fission of compound nucleus only at $E^* \leq 35$ MeV we obtained a better agreement between the calculated and experimental data. The fact that in the reaction $^{110}Pd + ^{110}Pd$ the intermediate system, on route to a compound nucleus, emits an α-particle [1] has also been taken into account.

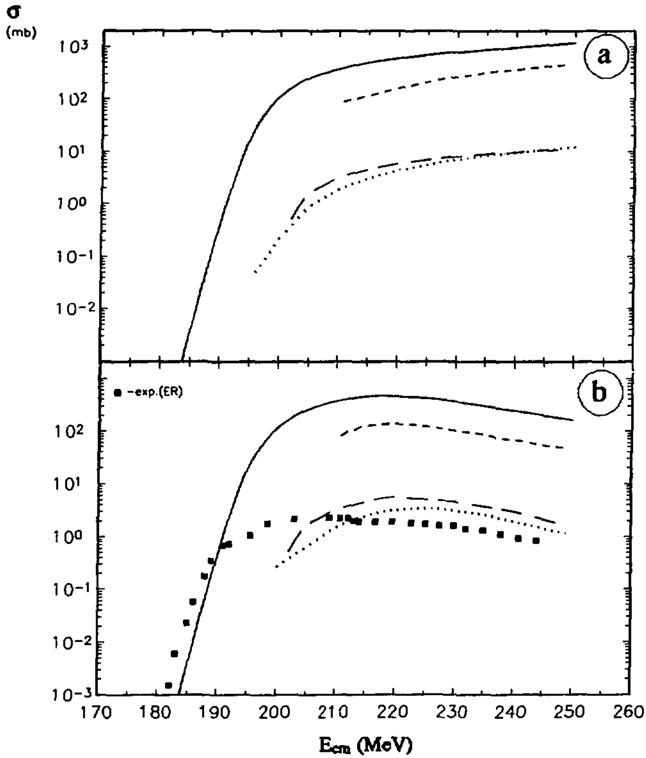

Fig.3. Compound nucleus formation cross sections (a) and evaporation residue cross sections (b) for the reaction $^{100}Mo+^{100}Mo$, as a functions of E_{cm}. The results of calculation in the framework of the optical model, surface friction model, macroscopic dynamic model and our model are presented by solid line, short dashed line, long dashed line and dotted line, respectively. The experimental data are presented by solid squares.

The results of the $\sigma_{CN}(E)$ and $\sigma_{ER}(E)$ calculations using the model developed here are presented in figs. 3 and 4. Our calculated data for the same reaction characteristics by using the traditional complete-fusion models, namely the optical [11], surface-friction [13] and macroscopic dynamical [14] ones, are also given in these figures for comparison. The drastic disagreement between the experimental data and the results of calculations using the optical model and the surface-friction one is due to the fact that these models neglect the quasi-fission process following DNS formation.

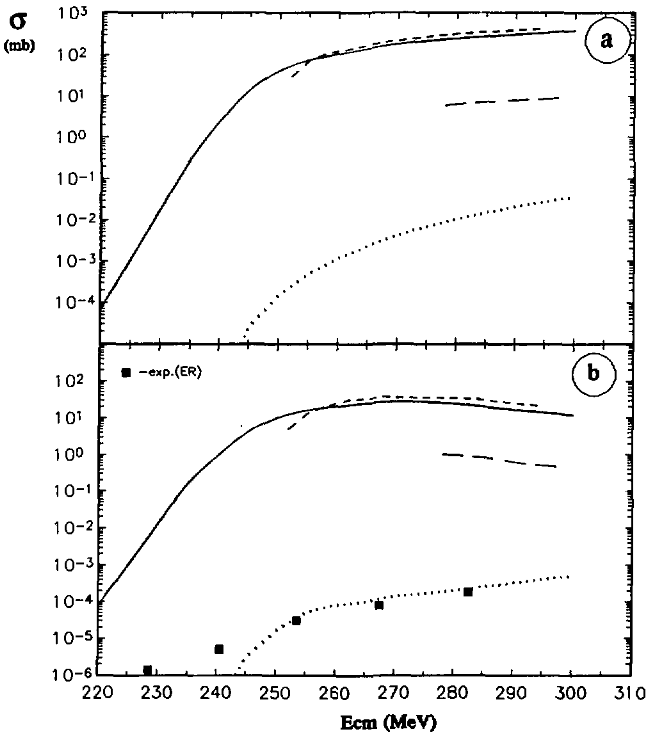

Fig.4. The same as in fig.3 but for the reaction $^{110}Pd+^{110}Pd$.

The macroscopic dynamical model [14] takes into account the competition between different nuclear processes that occur in the entrance channel of the reaction. The result of collision depends on a relationship between the kinetic energy of the collision E_{cm}, the Coulomb barrier B_C and the extra-extra push energy E_{xx}. If $E_{cm} > B_C + E_{xx}$ during collision the nuclear system takes a more compact shape than the saddle-point one of the compound nucleus, thus complete fusion occurs. In the case of $E_{cm} < B_C + E_{xx}$, the nuclei cannot fuse and the system decays via quasi-fission or deep inelastic transfer reactions. In the reaction ^{110}Pd + ^{110}Pd the E_{xx} value is equal to 60 MeV. At $E_{cm} > B_C + E_{xx}$ the macroscopic dynamical model is expected to be capable of describing $\sigma_{CN}(E)$. However the $\sigma_{ER}(E)$ value calculated using this model is about three orders of magnitude larger than the experimental one. According to ref. [14], at energies below $B_C + E_{xx}$ no compound nucleus can be formed at all. As one can see from the experimental data presented in fig. 4, $\sigma_{ER}(E)$ goes smoothly to energies several tens of MeV below $B_C + E_{xx}$. Apparently the reason for the discrepancy lies in the macroscopic approach itself, in which the real nuclei consisting of nucleons and possessing shell structure are replaced by drops of a homogeneous nuclear liquid.

4. Summary

A satisfactory description of $\sigma_{ER}(E)$ using our model of competition between complete fusion and quasi-fission can be considered as indicative of the realistic interpretation of the mechanism of compound-nucleus formation proposed in ref. [2]. The analysis carried out has made it possible to reveal an important feature of the fusion of massive nuclei such as the existence of the fusion barrier B^*_{fus}. It should be emphasized that the fusion barrier B^*_{fus} that occurs in a massive DNS as it evolves in the direction of compound nucleus formation differs radically from the extra-extra push concept used in the macroscopic dynamical model [14]. The extra-extra push energy is an additional kinetic energy exceeding the entrance potential barrier, which should be imparted to the projectile. As a result, the fusing nuclei take a more compact shape compared to that of a fissioning nucleus at the saddle point. In contrast to the extra-extra push energy, the energy required to overcome the fusion barrier

B^*_{fus} comes from the DNS excitation energy. The presence of excitation energy just provides the possibility of such an endoenergetic redistribution of nucleons between the DNS nuclei, which brings the system to the fusion barrier. After reaching the fusion barrier the DNS decreases its potential energy with increasing charge asymmetry while the driving forces lead the DNS to compound nucleus formation.

Deformation of the nuclei incorporated in the DNS and an exchange of valent nucleons between them lead to some changes in the potentials of the nucleus–nucleus interaction, $V(R)$. However, the main features of the potential $V(Z,l)$ for massive DNS and, first of all, the occurrence of the fusion barrier B^*_{fus} remain unchanged.

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