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Effect of Proximity Force on Potential Barrier in Fusion Reaction *

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Abstract The macroscopic deformed potential energies for fusion reactions are determined within a generalized liquid drop model (GLDM) which includes the volume—, surface-, and Coulomb-energies, the proximity effects, the mass asymmetry, and an accurate nuclear radius. In ordinary fission studies, it is assumed that the surface and Coulomb-energies control the hight and width of the barrier. The surface energy E_S takes into account only the effect of the surface tension force and does not include the contribution of the attractive nuclear forces between surfaces in regard to the neck or the gap between the nascent fragments. The nuclear proximity energy is adopted to take into account these additional surface effects in general liquid drop model. At the contact point, the proximity energy reaches maximum while it decreases both sides till to zero. The proximity energy decreases the barrier height by several MeV and moves the position of the barrier top forward, which corresponds to two separated fragments in unstable equilibrium by the balance between the attractive nuclear proximity force and the repulsive Coulomb force in the GDLM. It turns out that a wide macroscopic potential pocket in fusion process is formed due to proximity energy and appears at large deformation. This behavior does not appear at the barrier for the fusion reaction of light nucleus-nucleus collision.

Key words effect of proximity force, macroscopic deformed potential, fusion reaction

The synthesis of super heavy elements has been apparently strongly advanced in recent years for both theoretical studies [1—5] and experiments using both cold (Zn on Pb)[6] and warm (Ca on U, Pu and Cm)[7] fusion reactions at GSI, Dubna and Berkeley. The experimental data analysis is also discussed[8].

In the cold fusion, the synthesis of the SHE are produced by reaction of type the X + (Pb, Bi) → SHE + 1n at sub barrier energies. In order to calculate the formation cross section of deformed SHE in the cold fusion, several models have been proposed. Adamian etal[9]. assumed that after the full dissipation of the collision kinetic energy, a dinuclear system is formed. After that such a system evolves to the compound nucleus by the nucleon transfer from one nucleus to another one. Denisov etal[10]. developed a dinuclear system model in which Low energy surface vibrations and a transfer of few nucleons are taken into account. They found that the contribution of the surface vibrations to the fusion cross section is larger than that of the nucleon transfer. The best fits are obtained by considering both transfer and vibrations simultaneously. Smolanczuk[11] proposes a simple model to describe the formation of super heavy elements in the cold fusion reaction in which the compound nucleus is formed by quantum tunnelling through pure Coulomb barrier or the phenomenological fusion barrier. It is worth noting that Smolanczuk's model can describe the process of the fusion reaction, however, the fusion barrier used in the model is either the pure Coulomb barrier or the phenomenological fusion barrier.

The recent investigation pointed out that the height, position and width of the potential barrier are the main ingredients to fission and fusion reactions[12]. Very recently, Sahu et al[13]. constructed a fusion barrier which is an analytically

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solvable, smooth, short-ranged, realistic and composite barrier potential with parameters controlling the flatness at the top, the range and asymmetry of the barrier. They found asymmetry of the barrier provides the correct explanation of the sub-barrier enhancement of the experimental data of fusion cross section and the oscillatory structure in barrier distribution function can been described by the flatness of the barrier near the top. Therefore, in order to provide reasonable predicts, it is important to derive the potential barrier by the model instead of an input or adjustable parameters. The generalized liquid drop model (GLDM)[12] is one of the most successful macroscopic models. The model is able to describe process of both fusion and fission reactions through quasi-molecular deformation mechanism.

The main formalism of the GDLM can be described as follows. For a deformed nucleus, the macroscopic total energy is defined as[8]

$$E_{\rm GLDM} = E_{\rm LDM} + E_{\rm N}, \tag{1}$$

where $E_{\rm LDM}$ and $E_{\rm N}$ are the liquid drop model energy and the nuclear proximity energy, respectively. The energy of the liquid drop model includes the volume, surface and Coulomb energies,

$$E_{\rm LDM} = E_{\rm V} + E_{\rm S} + E_{\rm C}. \tag{2}$$

For the one-body shape, the volume energy $E_{\rm V}$, surface energy $E_{\rm S}$ and Coulomb energy $E_{\rm C}$ read

$$E_{\rm V} = - a_{\rm V}(1 - k_{\rm V}I^2)A, \tag{3}$$

$$E_{\rm S} = a_{\rm S}(1 - k_{\rm S}I^2)A^{2/3}(S/4\pi R_0^2), \tag{4}$$

$$E_{\rm C} = \frac{3}{5}e^2(Z^2/R_0)\,\frac{1}{2}\int(V(\theta)/V_0) \times (R(\theta)/R_0(\theta))^3\sin\theta{\rm d}\theta, \tag{5}$$

where A, Z and $I = (N - Z)/A$ are the mass, charge and relative neutron excess of the compound nucleus, respectively; $V(\theta)$ is the electrostatic potential at the surface of the shape and V_0 is the surface potential of the sphere. After the separation, the volume- and Coulomb-energies of the GLDM read

$$E_{\rm V} = - a_{\rm V}[(1 - 1.8I_1^2A_1 + A_2], \tag{6}$$

$$E_{\rm S} = a_{\rm S}[(1 - 2.6I_1^2)A_1^{2/3} + A_2^{2/3}], \tag{7}$$

$$E_{\rm C} = 3/5e^2Z_1^2/R_1 + 3/5e^2Z_2^2/R_2 + Z_1Z_2/r. \tag{8}$$

The volume- and surface-coefficients have been chosen to be $a_{\rm V} = 15.494$ and $a_{\rm S} = 17.9439$, respectively. In order to reproduce the increase of the ratio $r_0 = R_0/A^{1/3}$, effective sharp radius of the radioactive emitter is defined by $R_0 = (1.28A^{1/3} - 0.76 + 0.8A^{-1/3})$. To ensure volume conservation, the radii R_1 and R_2 of the daughter and alpha nuclei are given by $R_1 = R_0(1 + \beta^3)^{-1/3}$, $R_2 = R_0\beta(1 + \beta^3)^{-1/3}$, where $\beta = (1.28A_2^{1/3} - 0.76 + 0.8A_2^{-1/3})/(1.28A_1^{1/3} - 0.76 + 0.8A_1^{-1/3})$.

The nuclear proximity energy can be written as

$$E_{\rm N} = 2\gamma\int_{h_{\min}}^{h_{\max}}\Phi(D/{\rm b})2\pi h{\rm d}h, \tag{9}$$

where h is the ring radius in the plane perpendicular to the longitudinal deformed axis and D is the distance between the opposite infinitesimal surface[12]; b is the surface width, Φ is called the Feldmeier function[14]. The surface parameter $\gamma = 0.9517\sqrt{(1 - 2.6I_1^2)(1 - 2.6I_2^2)}\ {\rm MeV\cdot fm^{-2}}$.

It is well known that in the early fission studies, researchers assumed that the repulsive Coulomb force and attractive surface tension force control the evolution of nuclear shapes. In order to describe the evolution process of nuclear shapes, the radius of nuclear shape expanded by Legendre polynomials led to elongated one body configuration which was able to explain the bulk properties of the nuclear fission. However, this description of a deformed radius fails to reproduce the deep and narrow necks of nuclear deformed shape in the fusion reaction. It turns out that[12] the quasi-molecular mechanism can provides the deep and narrow necks of nuclear deformed shape in the fusion path. A two-parameter shape sequence has been defined[12] to describe the continuous transition from one initial spherical nucleus to two tangent spherical fragments.

$$R(\theta) = \begin{cases} a^2\sin^2\theta + c_1^2\cos^2\theta, & 0 \leqslant \theta \leqslant \dfrac{\pi}{2} \\ a^2\sin^2\theta + c_2^2\cos^2\theta, & \dfrac{\pi}{2} \leqslant \theta \leqslant \pi \end{cases}, \tag{10}$$

where c_1 and c_2 are the elongations of two interacting nuclei and a is the neck radius. Assuming the volume conservation, we can completely define the shape by the two parameters $s_1 = a/c_1$ and $s_2 = a/c_2$. For a given decay channel, the radio $\eta = R_2/R_1$ between radii of the future fragments allows to connect s_1 and s_2:

$$s_2^2 = \frac{s_1^2}{s_1^2 + (1 - s_1^2)\eta^2} \qquad (0 \leqslant s_1, s_2, \eta \leqslant 1), \tag{11}$$

where s_1 decreases from 1 to 0, the shape evolves continuously from one sphere to two touching spheres with the formation of a neck while keeping spherical ends.

The macroscopic deformed potential energy ($E_{\rm def}$) of a nucleus is calculated within the generalized liquid drop model (GLDM). Very recently, Royer et al[15]. applied GLDM theory to predict the potential barriers of cold fusion reactions. In this report, we will investigate the effect of the proximity energy on the macroscopic deformed potential energy in fusion reaction. In order to illustrate the influence of the proximity energy on the macroscopic potential energy, we choose two very different systems: one is heavy-ion system ^{64}Ni + ^{208}Pb→^{272}110*, another is light nucleus-nucleus system such as ^{16}O + ^{16}O→^{32}S. The macroscopic deformed potential energies of ^{64}Ni + ^{208}Pb→^{272}110* and ^{16}O + ^{16}O→^{32}S reactions versus the mass-center distant R for the fusion reaction are displayed in Fig. 1 and Fig. 2, respectively. The dashed curve denotes the pure macroscopic potential energy given by the GLDM and solid line represents that the proximity energy is not included. In ordinary fusion studies, it is often only that barrier is taken into account. One can see from Fig. 1 the dashed curve shows that a wide macroscopic potential pocket due to proximity energy appears at large deformations and the energy is almost constant till the spherical compound nucleus. In general liquid drop model, the surface energy E_S takes into account only the effect of the surface tension force and does not include the contribution of the attractive nuclear forces between surfaces in regard to the neck or the gap between the nascent fragments. The nuclear proximity energy is adopted to take into account these additional surface effects in the deformation path. At the contact point, the proximity energy reaches maximum while it decreases both sides till to zero. For ^{64}Ni + ^{208}Pb→^{272}110* reaction, the proximity energy decreases the barrier height by 42MeV and moves the position of the barrier top forward about 1fm, which corresponds to two separated fragments in unstable equilibrium by the balance between the attractive nuclear proximity force and the repulsive Coulomb force in the GDLM. For ^{16}O + ^{16}O→^{32}S reaction, the situation is quite different from heavy ion system. One can see from Fig. 2 that the dashed line has the same behaviors like heavy ion system. After contact point (R = 5.57fm), the potential is balance between the attractive nuclear proximity force and the repulsive Coulomb force and reaches maximum (R = 8.1fm), then the curve rapidly drop down. The solid line due to proximity energy becomes smoothly drop down and the height of the barrier decreases by 6MeV and the position of the barrier top moves forward about 2.5fm. The proximity energy does not produce a wide macroscopic potential pocket for light nucleus-nucleus reaction. This means that the compound nucleus is completely formed by quantum tunnelling through the barrier for light nucleus-nucleus system. Very recently, Sahu et al[13]. also show the properties, they constructed a phenomenological fusion barrier which is an analytically solvable, smooth, short-ranged, realistic and composite barrier potential with parameters controlling the flatness at the top, the range and asymmetry of the barrier. They found asymmetry of the barrier provides the correct explanation of the sub-barrier enhancement of the experimental data of fusion cross section and the oscillatory structure in barrier distribution function can been described by the flatness of the barrier near the top. Therefore, the potential barrier derived by the GLDM has the properties of phenomenological one. The compound nucleus is formed by a quantum tunnelling through the barrier and a spherical nucleus is located at the minimal valley.

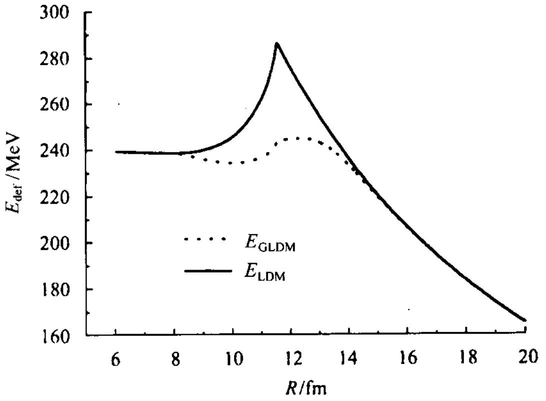

Fig. 1. The macroscopic deformed potential energies of ^{64}Ni + ^{208}Pb→^{272}110* reaction versus the mass-center distant R.

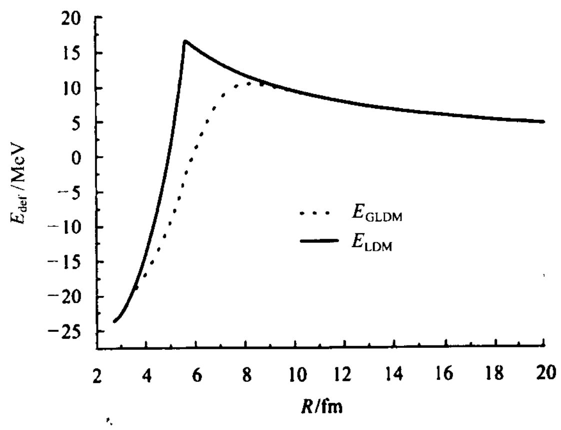

Fig. 2. The macroscopic deformed potential energies of ^{16}O + ^{16}O→^{32}S reaction versus the mass-center distant R.

In summary, the generalized liquid drop model with a quasi molecular shape is able to predict the potential energy of fusion reactions, which includes an accurate radius, a proximity and the mass asymmetry. The quasi-molecular shape

can describe nuclear deformations with deep and narrow necks which specially plays an important role in the formation of super-heavy elements. The influence of the proximity energy on the macroscopic deformed potential energy is quite different for heavy ion and light nucleus-nucleus systems. Although the macroscopic deformed potential energies have similar behaviors for two systems such as reduce of the barrier height and move the position of the barrier top forward, but the proximity energy doe not produce a wide macroscopic potential pocket for light nuclei system.

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亲和力对熔合反应位垒的影响*

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摘要　熔合反应的宏观形变位能由推广的液滴模型来确定,它包括体积能、表面能、库容能、亲和力效应、质量的不对称性和精确的核半径.在过去裂变研究中,人们假定表面能和库仑能控制着位垒的高度和宽度.表面能也只考虑表面张量力效应,并不包括颈部或刚形成的碎片的表面之间吸引核力的贡献.在推广的液滴模型中,亲和力考虑了这些附加的表面效应.在两个核的接触点,亲和能达到最大值,它的两边逐渐减少直到零.亲和能减少位垒的高度并移动位垒峰的位置,它对应于吸引的亲和力和排斥的库仑力之间平衡的两个分开碎片的位置.研究表明:对于超重核熔合过程,亲和能使得宏观形变位能有一个宽的坑(pocket),它对应于核的大形变.对于轻的核-核系统,这种现象不出现.

关键词　亲和力效应　宏观形变位能　熔合反应

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