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DEPENDENCE OF FUSION BARRIER HEIGHTS ON THE DIFFERENCE OF PROTON AND NEUTRON RADII* **

A. Dobrowolski, K. Pomorski

Theoretical Physics Department, M. Curie-Skłodowska University
pl. M. Curie-Sklodowskiej 1, 20-031 Lublin, Poland

and J. Bartel

Institute of Subatomic Research, Louis-Pasteur University
Strasbourg, France

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Using the Skyrme effective nucleon–nucleon interaction together with the semiclassical Extended Thomas–Fermi approach (ETF) we investigate the relative change of the fusion barrier heights for the reaction $^{16}\mathrm{O} + ^{208}\mathrm{Pb}$ as function of the nuclear proton or neutron radii of the colliding nuclei.

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Over the last decade an intense experimental activity leading to the synthesis of superheavy elements and nuclei far from β-stability is observed in laboratories such as GANIL, GSI, JINR, LBL or RIKEN. Heavy-ion collisions are the main tool to obtain such a synthesis. It has been shown that theoretical models based on the macroscopic approach, like the liquid drop model or the Extended Thomas–Fermi (ETF) method are able to reproduce fusion barriers quite accurately.

The analysis of experimental data on electron and α-particle scattering, pionic atoms, and annihilation of antiprotons shows that in most nuclei the neutrons and protons have slightly different r.m.s. radii which is mainly due to the Coulomb repulsion and an unequal number of both types of nucleons.

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Since only the radii and tails of the density distributions of the colliding ions decide about the shape and the height of fusion barriers, we have chosen the semiclassical ETF model [1] to determine in a self-consistent way the density profiles of target and projectile. This approach allows to describe, for any effective nucleon–nucleon interactions of the Skyrme type [2], the macroscopic part of the nuclear energy as function of the local densities $\rho_n(\vec{r})$ and $\rho_p(\vec{r})$ and their derivatives (see Ref. [1] for a review). The profiles of the proton and neutron densities can be obtained through a density-variational calculation with the constraint of preserving Z and N.

$$\frac{\delta}{\delta\rho_q} \int d^3r \left\{\mathcal{E}[\rho_n,\rho_p] - \lambda_n\,\rho_n(\vec{r}) - \lambda_p\,\rho_p(\vec{r})\right\} = 0, \qquad q = \{p,n\}\,. \tag{1}$$

Such an approach yields excellent estimates for the semiclassical (liquid-drop type) energies and density profiles [1,3]. It has in particular been shown [1,4] that modified Fermi functions of the form

$$\rho_q(r) = \rho_0^{(q)} \left(1 + \exp\frac{r - R_q}{a_q}\right)^{-\gamma_q} \tag{2}$$

which are used in our calculations, are an excellent approximation to the full variational solution of Eq. (1).

Using the "*sudden approximation*" (as described *e.g.* in Ref. [5]), *i.e.* keeping the nuclear densities *frozen* and neglecting all possible rearrangement effects during the collision (see Fig. 1), we introduce the potential

$$V(d\,) = \int d^3r\,\{\mathcal{E}\,[\rho_1+\rho_2] - (\mathcal{E}\,[\rho_1] + \mathcal{E}\,[\rho_2])\}\,, \tag{3}$$

where $\mathcal{E}[\rho]$ is the Skyrme ETF energy–density functional [1,6].

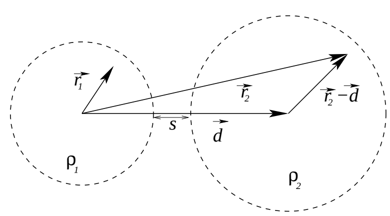

Fig. 1. Geometry of the collision. s and d denote respectively the distance between the equivalent sharp surfaces and the centers of mass of the colliding nuclei.

The Coulomb interaction between the two nuclei is evaluated in the classical approximation as

$$V_{\rm Coul}(d\,) = \int \frac{\rho_{ch}^{(1)}(r_1)\,\rho_{ch}^{(2)}(r_2)}{|\vec{r}_1 - \vec{r}_2|}\, d^3r_1\, d^3r_2\,. \tag{4}$$

We have shown in Ref. [7] through an analysis of 291 different reactions leading to different superheavy nuclei that a simple parameterisation of the ion–ion potential $V(d)$ based on the above ETF approach is able to describe the fusion barriers quite accurately.

The main purpose of the present study is to investigate the sensitivity of the fusion barrier heights on the relative variation of neutron and proton radius and on the diffuseness of the nuclear surface.

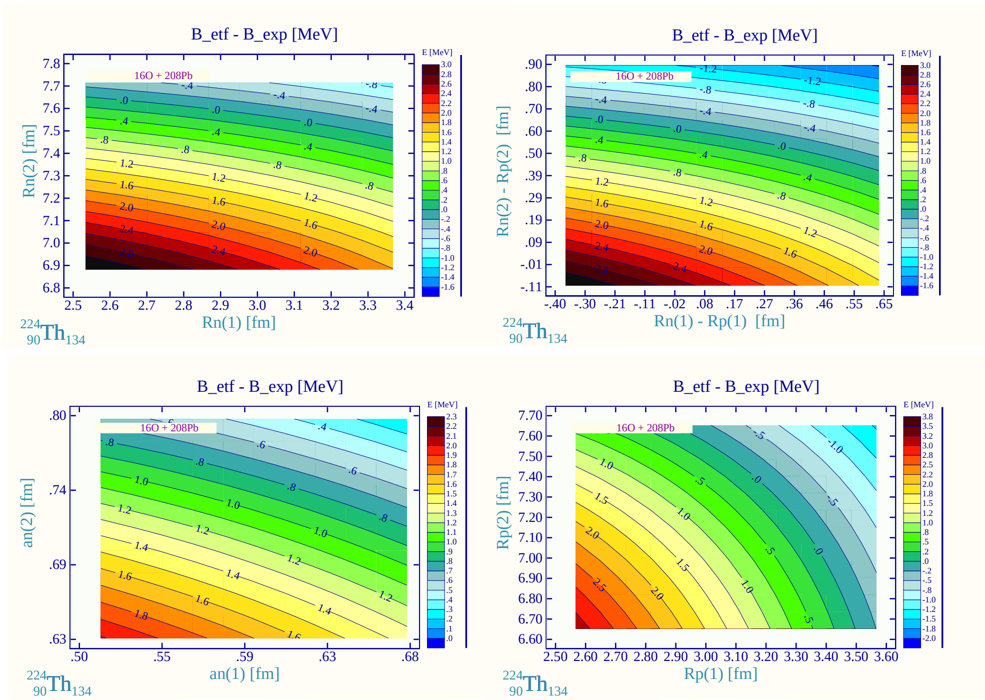

Fig. 2. Difference of experimental and theoretical fusion barrier heights for the reaction $^{16}O+^{208}Pb$ as function of neutron radius R_n (upper-left), width of neutron skin, defined $R_n - R_p$ (upper-right), neutron surface width parameter a_n (lower-left) and proton radius R_p (lower-right). The ETF variational values of radii and surface diffuseness parameters are situated in the middle of the axes. The experimental value of the barrier height is taken from Ref. [8].

It is commonly known that neutron contrary to proton r.m.s. radii are determined experimentally with relatively poor accuracy but nevertheless some data exist for nuclei situated in different mass regions. On the other hand, one can easily show in a simple and straightforward way that the r.m.s. radius is determined by all four density parameters entering Eq. (2). Since neither the nuclear radius R_q, nor the diffuseness parameter a_q, which determines essentially the nuclear surface, are observables, we are allowed to vary their values to some extent, provided the nuclear volume is conserved. Fig. 2 shows that by a change of the neutron radius of one of the colliding ion by 1 fm we are able to change the fusion barrier height by 2–3 MeV.

When instead of the neutron we vary the proton radius, we observe that the change in the fusion barrier becomes even more dramatic as we act simultaneously on the effective nuclear and Coulomb potential. A similar effect, though somewhat less pronounced, can be achieved by varying the surface width parameter of target or projectile. One should be aware in this context that the range of variation of the density parameters obtained with different Skyrme forces can reach several percent.

One should also mention here that our semiclassical approach, even though giving a quite reasonable description of fusion barriers, can only be considered as a guideline (or a first step) on the way to a more microscopic approach which takes also quantum corrections into account. These corrections will somewhat change the details of the landscapes shown in Fig. 2 (as shown for the case of fission barriers in Ref. [9]) even if such a change will not exceed a few MeV.

The effect of a difference of proton discussed here *versus* neutron density radii gives some orientation on how much the fusion barrier height, which is the central quantity for heavy-ion collisions, can depend on the macroscopic features of the involved nuclear densities. It should finally be emphasized that the mutual orientation in space of the colliding ions plays an even more essential role for fusion barriers as compared to differences in proton–neutron density distributions as discussed in this paper (for comparison see Ref. [10]).

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