INTERACTION BETWEEN TWO AXIALLY SYMMETRIC NUCLEI

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A simple expression for the Coulomb interaction potential between two deformed, arbitrarily oriented, and axially symmetric nuclei has been obtained. An accurate approximation for the nuclear contribution to the interaction between those nuclei has been proposed. The complete interaction potential between nuclei with prolate-prolate, prolate-oblate, and oblate-oblate deformations and various orientations has been studied.

1. Introduction

Nuclei can be both spherical and deformed in their ground state. The shape of both nuclei participating in a reaction affects the barrier height and the potential of their interaction. The barrier height is of great importance for the reactions of subbarrier fusion and synthesis of superheavy elements. Nuclear reactions, where deformed nuclei are engaged, are widely applied to the synthesis of superheavy elements in many laboratories around the world [1–6]. The reactions of subbarrier fusion of strongly deformed F, Ne, and Mg isotopes play a very important role in the burning of stars [7–9] and govern their evolution. Therefore, it is important to study the properties of the interaction potential between two deformed nuclei arbitrarily oriented with respect to each other.

The interaction potential between two nuclei is composed of the potentials of the nucleus-nucleus and Coulomb interactions and the centrifugal potential. The determination of the Coulomb part of a nuclear interaction potential is reduced to the calculation of a sixfold integral [10–17]. The nuclear component of the potential can be presented as either a sixfold or a triple multiple integral, depending on the model used [10, 12–14, 16–20]. The calculation of these integrals is a challenging problem for the numerical methods, especially in the case where nuclei, being in their ground state, are strongly deformed. Bearing this circumstance in mind, it is important to possess a simple and rather accurate method for the calculation of the interaction potential between two deformed and arbitrarily oriented nuclei.

2. Coulomb Interaction Between Two Axially Symmetric Nuclei

The calculation of Coulomb interaction between two nuclei, whose centers of mass are located at a distance R from each other, requires evaluating the sixfold integral

$$V_{\mathrm{C}}(R) = e^2 \int \frac{\rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)}{|\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|} d\mathbf{r}_1 d\mathbf{r}_2, \tag{1}$$

where e is the proton charge, and $\rho_i(\mathbf{r}_i)$ is the proton density distribution over the i-th nucleus ($i = 1, 2$). The vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ are determined in the coordinate systems O_1 and O_2, respectively, as is illustrated by Fig. 1. The origin of each coordinate system is fixed at the center-of-mass of the corresponding nucleus.

Various expressions are used to present the denominator in Eq. (1) [21, 22]; however, most convenient for us is the following expression proposed in work [22]:

$$\frac{1}{|\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|} = \sum_{\ell_1,\ell_2=0}^{\infty} \frac{r_1^{\ell_1} r_2^{\ell_2}}{R^{\ell_1+\ell_2+1}} \frac{4\pi(-1)^{\ell_2}(\ell_1+\ell_2)!}{\sqrt{(2\ell_1+1)(2\ell_2+1)}} \times$$

$$\times \sum_m \frac{Y_{\ell_1 m}(\vartheta_1,\varphi_1) Y_{\ell_2 -m}(\vartheta_2,\varphi_2)}{\sqrt{(\ell_1+m)!(\ell_1-m)!(\ell_2+m)!(\ell_2-m)!}}, \tag{2}$$

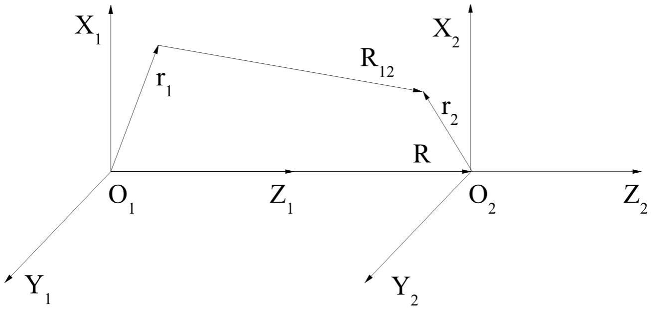

Fig. 1. Coordinate systems fixed at the center of mass of the corresponding nucleus

where $Y_{\ell m}(\vartheta,\varphi)$ are the spherical harmonics [21], and $(r_i,\vartheta_i,\varphi_i)$ are the spherical coordinates in the laboratory coordinate system O_i.

In order that the relative position of two axially symmetric nuclei be fixed unambiguously in space, it is enough to define three Euler angles: Θ_1, Θ_2, and Φ. The angle Θ_i determines the angle of rotation of the i-th nucleus around the axis O_iY_i, and the angle Φ is an angle between the projections of nuclei's symmetry axes onto an arbitrary plane OXY (see Fig. 1). For the description of a rotation transformation of the spherical functions $Y_{\ell m}(\vartheta,\varphi)$, the Wigner D-functions were used [21].

The distributions of proton density in both nuclei were approximated as

$$\rho_i(\mathbf{r})=\rho_{i0}\theta(R_i(\vartheta_i')-r)$$

making use of the unity-step function $\theta(x)$. Then, the nuclear surface can be described by the expression

$$R_i(\vartheta_i')=R_{i0}\left[1+\sum_{\ell\geq 2}\beta_{i\ell}Y_{\ell 0}(\vartheta_i')\right], \tag{3}$$

where R_{i0} and $\beta_{i\ell}$ are the radius of the spherical nucleus and the deformation parameters, respectively. Proceeding from Eq. (3) and applying the Wigner D-functions to the description of a rotation of nuclei, the following expressions were obtained for the shapes of a deformed nucleus in the laboratory coordinate system O_i:

$$R_1(\vartheta_1,\varphi_1,\Theta_1)=R_{10}\Bigg[1+\sum_{\ell\geq 2}\beta_{1\ell}\times$$

$$\times\sum_{m=-\ell}^{\ell}Y_{\ell m}(\vartheta_1',\varphi_1')D^{\ell}_{m0}(0,\Theta_1,0)\Bigg], \tag{4}$$

$$R_2(\vartheta_2,\varphi_2,\Theta_2,\Phi)=R_{20}\Bigg[1+\sum_{\ell\geq 2}\beta_{2\ell}\times$$

$$\times\sum_{m=-\ell}^{\ell}Y_{\ell m}(\vartheta_2',\varphi_2')D^{\ell}_{m0}(\Phi,\Theta_2,0)\Bigg], \tag{5}$$

where ϑ_i' and φ_i' are the angles in the own coordinate system O_i', whereas ϑ_i and φ_i are the angles in the laboratory coordinate system O_i.

Making use of the formulas obtained, taking into account that the value of the quadrupole deformation parameter for stable nuclei in the ground state is much larger, as a rule [23–26], than the value of any other parameter of a high-multipole deformation ($\beta_{i2}^2\approx\beta_{i\ell}|_{\ell\geq 3}$), and confining the consideration to the summands of the β_{i2}^2-order, we obtained the Coulomb potential for two deformed, axially symmetric, and arbitrarily oriented nuclei in the following form:

$$V_{\rm C}(R,\Theta_1,\Theta_2,\Phi)=\frac{Z_1Z_2e^2}{R}\Bigg\{1+$$

$$+\sum_{\ell\geq 2}[f_{1\ell}(R,\Theta_1,R_{10})\beta_{1\ell}+f_{1\ell}(R,\Theta_2,R_{20})\beta_{2\ell}]+$$

$$+f_2(R,\Theta_1,R_{10})\beta_{12}^2+f_2(R,\Theta_2,R_{20})\beta_{22}^2+$$

$$+f_3(R,\Theta_1,\Theta_2,R_{10},R_{20})\beta_{12}\beta_{22}+$$

$$+f_4(R,\Theta_1,\Theta_2,\Phi,R_{10},R_{20})\beta_{12}\beta_{22}\Bigg\}, \tag{6}$$

where Z_1 and Z_2 are the numbers of protons in nuclei 1 and 2, respectively;

$$f_{1\ell}(R,\Theta_i,R_{i0})=\frac{3R_{i0}^{\ell}}{(2\ell+1)R^{\ell}}Y_{\ell 0}(\Theta_i), \tag{7}$$

$$f_2(R,\Theta_i,R_{i0})=\frac{6\sqrt{5}R_{i0}^2}{35\sqrt{\pi}R^2}Y_{20}(\Theta_i)+\frac{3R_{i0}^4}{7\sqrt{\pi}R^4}Y_{40}(\Theta_i), \tag{8}$$

$$f_3(R,\Theta_1,\Theta_2,R_{10},R_{20})=\frac{R_{10}^2R_{20}^2}{R^4}\Bigg[-\frac{3}{20\pi}+$$

$$+\frac{3}{10\sqrt{5\pi}}\left(Y_{20}(\Theta_1)+Y_{20}(\Theta_2)\right)+\frac{51}{25}Y_{20}(\Theta_1)Y_{20}(\Theta_2)\Bigg]=$$

$$= \frac{27R_{10}^2R_{20}^2}{80\pi R^4}\Big[17\cos^2(\Theta_1)\cos^2(\Theta_2)$$

$$-5\cos^2(\Theta_1) - 5\cos^2(\Theta_2) + 1\Big], \tag{9}$$

$$f_4(R,\Theta_1,\Theta_2,\Phi,R_{10},R_{20}) = \frac{R_{10}^2R_{20}^2}{R^4}\Big\{\cos^2(\Phi)\Big[\frac{3}{10\pi}-$$

$$-\frac{3}{5\sqrt{5\pi}}\left(Y_{20}(\Theta_1)+Y_{20}(\Theta_2)\right)+\frac{6}{25}Y_{20}(\Theta_1)Y_{20}(\Theta_2)\Big]-$$

$$-\frac{27}{20\pi}\cos(\Phi)\sin(2\Theta_1)\sin(2\Theta_2)\Big\} =$$

$$= \frac{27R_{10}^2R_{20}^2}{40\pi R^4}\Big[\cos^2(\Phi)\sin^2(\Theta_1)\sin^2(\Theta_2)-$$

$$-2\cos(\Phi)\sin(2\Theta_1)\sin(2\Theta_2)\Big]. \tag{10}$$

From Eqs. (6)–(10), it follows that the Coulomb potential between two deformed axially symmetric nuclei depends on the angles Θ_1, Θ_2, and Φ which define the orientation of nuclei in space. In addition, this potential consists of summands that are proportional to $\beta_{1\ell}$, β_{12}^2, $\beta_{2\ell}$, β_{22}^2, and $\beta_{12}\beta_{22}$.

Earlier, the dependences of the Coulomb interaction potential between two deformed axially symmetric nuclei on the parameters Θ_1, Θ_2, β_{12}, β_{12}^2, β_{22}, and β_{22}^2 were calculated numerically in work [2] for some nuclear orientations. The dependence of the total interaction potential between two nuclei on the rotation angle Φ was considered in works [14, 17], also by numerical calculations.

3. Nuclear Interaction Between Two Axially Symmetric Nuclei

The nuclear potential between two spherical nuclei has been studied in the semimicroscopic approximation in work [12]. The nuclear part of interaction is defined as a difference between the energies of two interacting nuclei calculated in the cases of finite and infinite distances between them. In so doing, the Coulomb interaction is neglected. The energy of the nuclear system is defined as a sum of the kinetic and the potential energy of nucleons.

The kinetic energy was calculated in the modified Thomas–Fermi approximation. The potential energy was determined by the Skyrme energy-density functional with the SkM* parametrization. The kinetic and potential energies depend on the proton and neutron densities in both nuclei. The distribution of nucleon density was studied in the Hartree–Fock approximation for the Skyrme forces SkM*.

The nuclear part of the interaction potential between spherical nuclei depends on the average curvature of nuclei's surfaces at their nearest points and on the distance between them [12]. Taking advantage of the proximity theorem [27], the nuclear part of the interaction potential between two deformed nuclei can be written down in the form

$$V_{\rm n}(R,\Theta_1,\Theta_2,\Phi) \approx \frac{C_{10}+C_{20}}{C_{\rm def}}V_{\rm n}^0(d^0(R_{\rm sph},R_{10},R_{20})), \tag{11}$$

where

$$C_{\rm def} = \Big[(C_1^{\|}+C_2^{\|})(C_1^{\perp}+C_2^{\perp})\Big]^{1/2} \tag{12}$$

is the generalized inverse curvature,

$$d^0(R_{\rm sph},R_{10},R_{20}) = d(R,\Theta_1,\Theta_2,\Phi,R_{10},R_{20},\beta_1,\beta_2), \tag{13}$$

$V_{\rm n}^0(d^0(R_{\rm sph},R_{10},R_{20}))$ is the nuclear part of the interaction potential between two spherical nuclei with radii R_{10} and R_{20} [12],

$$d^0(R_{\rm sph},R_{10},R_{20}) = R_{\rm sph} - R_{10} - R_{20}$$

is the shortest distance between the surfaces of two spherical nuclei, the centers of mass of which are separated by the distance $R_{\rm sph}$, $C_{i0} = 1/R_{i0}$ is the surface curvature of the i-th spherical nucleus, and $C_i^{\|}$ and $C_i^{\perp}$ are the principal curvatures of the surfaces of corresponding deformed nuclei at their nearest points. The expressions for the quantities $V_n^0(d^0(R_{\rm sph},R_{10},R_{20}))$ and $C_{\rm def}$ were taken from works [12] and [28], respectively.

The surface curvatures $C_i^{\|(\perp)}$ depend on relevant angles which determine the relative position of two nuclei, as well as on the nuclear deformation parameters. The coordinates of surface contact points, the surface curvatures at those points, and the distance between surfaces were found numerically. In so doing, we used expressions obtained for the principal curvatures of the surfaces in the second-order approximation:

$$C_1^{\|} = \kappa_1 + \kappa_1', \tag{14}$$

$$C_1^{\perp} = \kappa_1 - \kappa_1', \tag{15}$$

$$C_2^{\|} = \kappa_2 + \kappa_2'\cos(2\Phi), \tag{16}$$

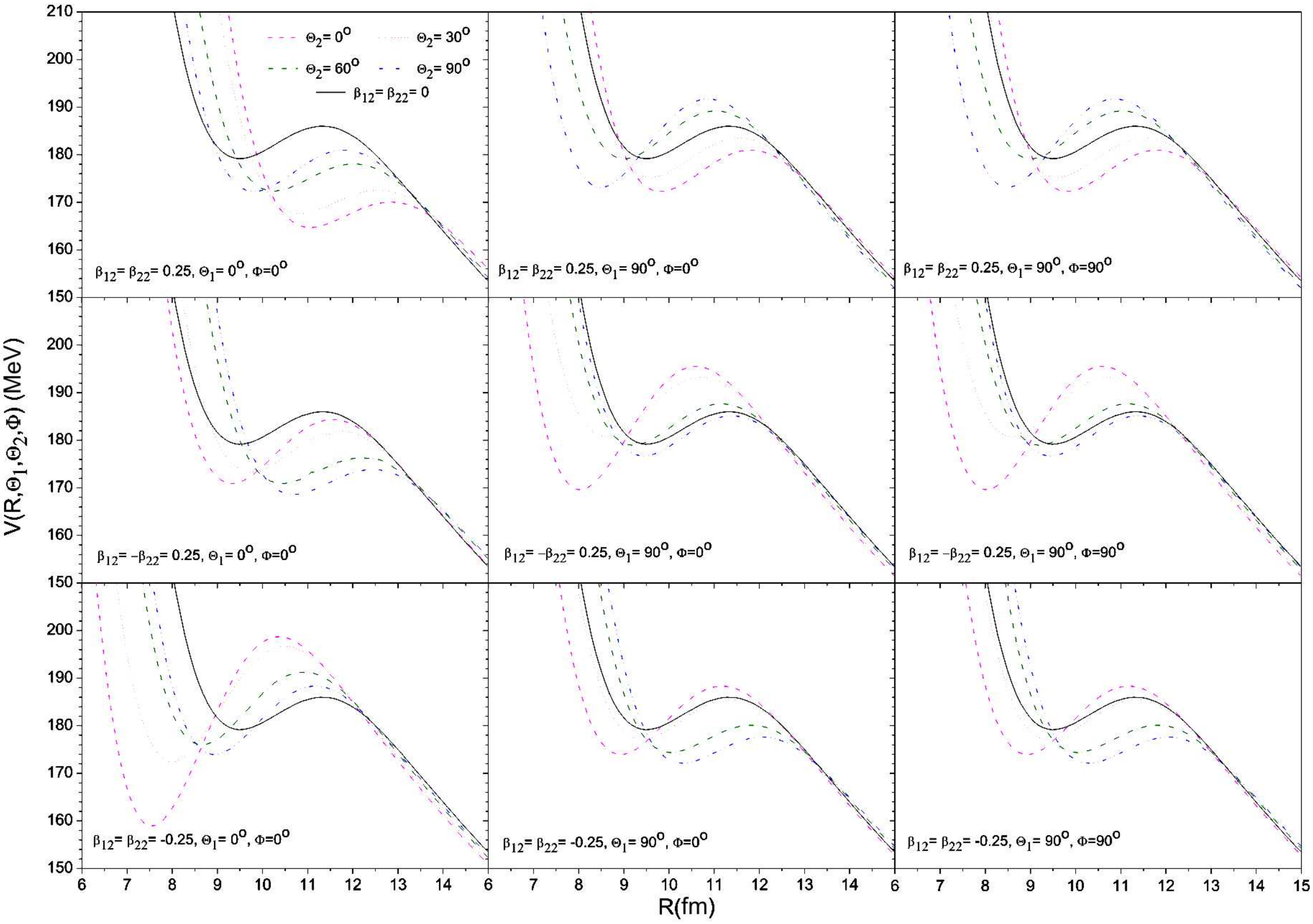

Fig. 2. Nucleus-nucleus potential for systems ^{90}Zr($\beta_{12} = 0.25$) + ^{90}Zr($\beta_{22} = 0.25$) (the upper row), ^{90}Zr($\beta_{12} = 0.25$) + ^{90}Zr($\beta_{22} = -0.25$) (the middle row), and ^{90}Zr($\beta_{12} = -0.25$) + ^{90}Zr($\beta_{22} = -0.25$) (the lower row) at various relative orientations of the nuclei. For the sake of comparison, each panel includes the plot of the interaction potential between non-deformed (spherical) nuclei

$$C_2^{\perp} = \kappa_2 - \kappa_2' \cos(2\Phi), \quad (17)$$

$$\kappa_i(R_{i0}, \beta_{i\ell}, \vartheta') \approx C_{i0}\left[1 + \sum_{\ell \geq 2} \frac{\ell(\ell+1) - 2}{2} \beta_{i\ell} Y_{\ell 0}(\vartheta') - \right.$$

$$\left. -5\beta_{i2}^2 (Y_{20}(\vartheta'))^2 + \frac{\beta_{i2}^2}{4\pi}\right], \quad (18)$$

$$\kappa_i'(R_{i0}, \beta_{i\ell}, \vartheta') \approx -C_{i0} \frac{3}{8\pi} \sin^2(\vartheta') \left[2\sqrt{5\pi}\beta_{20} + 5\beta_{20}^2 - \right.$$

$$\left. -30\cos^2(\vartheta')\beta_{20}^2 + 15\sqrt{\pi}\beta_{40}(7\cos^2(\vartheta') - 1)\right], \quad (19)$$

where ϑ' is the angle in the own coordinate system of the nucleus that corresponds to a point on the nuclear surface, which is nearest to the surface of the other nucleus. In Eqs. (16) and (17), the Euler theorem [29] was used for the transformation of the nucleus surface curvature at a rotation. We note that the contribution of the summands $\beta_{i\ell}$ with $\ell > 2$ to expression (19) is insignificant, owing to the assumption that $\beta_{i2}^2 \approx \beta_{i\ell}$ provided that $\ell \geq 3$ (see Section 2.).

4. Interaction Between Axially Symmetric Nuclei With Different Relative Orientations

If the orbital moment of two nuclei is equal to zero, the total potential of interaction between them is defined as a sum

$$V(R,\Theta_1,\Theta_2,\Phi) = V_{\mathrm{C}}(R,\Theta_1,\Theta_2,\Phi) + V_{\mathrm{n}}(R,\Theta_1,\Theta_2,\Phi). \tag{20}$$

The depth and the width of the capture well in the nucleus-nucleus interaction potential, as well as the barrier height, are known to play a dominant role in the formation of a compound nucleus in fusion reactions [13]. This circumstance is associated with the necessity to overcome the barrier that exists between two separated nuclei and with a formation of a scission neck between contacting nuclei in the capture well, as well as with the following evolution of a shape of the nuclear system. Therefore, it is very important to study the influence of a deformation and an orientation of nuclei on the nucleus-nucleus interaction potential.

Taking advantage of Eqs. (6)–(13), we studied the potential of interaction between two deformed nuclei characterized by different deformation parameters and different relative orientations. The fusion reaction ^{90}Zr+ ^{90}Zr was taken as an example. In the ground state, the ^{90}Zr nucleus is a sphere; however, by changing the shapes of nuclei, we studied the nucleus-nucleus interaction potential and its dependence on the relative orientation of nuclei. In Fig. 2, the radial dependences of the interaction potential in the ^{90}Zr + ^{90}Zr system calculated for various values of deformation parameters and various relative orientations of the nuclei are depicted. For the sake of comparison, each panel also includes the plot of the interaction potential in the system consisting of two spherical ^{90}Zr nuclei.

By comparing the potential dependences presented in Fig. 2, we have drawn the following conclusions:

– The width of the capture well and the barrier height strongly depend on the relative orientation of deformed nuclei and on the deformation type.

– The barrier height and the capture well depth are minimal in the case of a prolate-prolate system at the angles $\Theta_1 = \Theta_2 = 0$. Moreover, the interaction potential is most flat and the barrier radius is largest in this case.

– The barrier is highest and the capture well is deepest in the case of an oblate-oblate system at the tilt angles $\Theta_1 = \Theta_2 = 0$. In this case, the barrier radius is minimal.

– The influence of a nuclear rotation around the OZ axis that passes through the center of mass of each nucleus is insignificant.

In Fig. 3, the dependences of the nucleus-nucleus potential in the vicinity of the barrier on the rotation

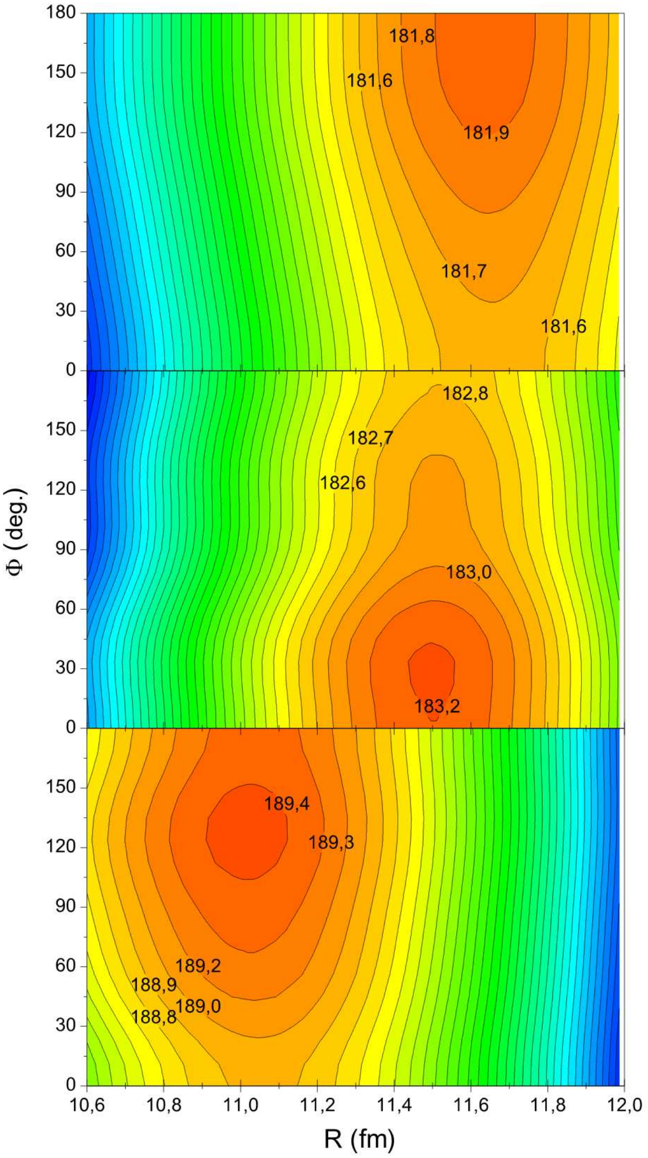

Fig. 3. Nucleus-nucleus potential versus the rotation angle Φ for various types of systems (prolate-prolate, prolate-oblate, and oblate-oblate ones) at the angles $\Theta_1 = \Theta_2 = 45°$

angle Φ are exhibited for various system types (prolate-prolate, prolate-oblate, and oblate-oblate ones) and for the case $\Theta_1 = \Theta_2 = 45°$. Since the nuclei are axially symmetric, the interaction potential is also symmetric with respect to the turnover of nuclei around the OZ axis. Taking this fact into account, the coordinate along the Φ axis varies from 0 to 180°. The analysis of those plots brought us to a conclusion that the effect is most pronounced in the case of a prolate-oblate system, and, for the given nuclei, it amounts to about 0.5 MeV, whereas the effect produced by Θ_2-rotation at fixed Θ_1 is equal to about 10 MeV.

The actual values for the barrier height and position result from an interplay between the repulsive Coulomb potential and the attractive nuclear one occurring between the nuclei. The nuclear interaction is short-range, being substantial only at very short distances between nuclear surfaces. Unlike the nuclear interaction, the Coulomb one is long-range, and its dependence on the distance between the surfaces of interacting nuclei is weaker. Owing to all that, the height and the position of the barrier strongly depend on the relative orientation of deformed nuclei, and, as a consequence, the barrier is higher for compact systems. For heavy strongly deformed nuclei, the barrier height changes by approximately 25 MeV, depending on their relative orientation. The Φ-rotation does not change the distance between nuclear surfaces substantially and, hence, affects insignificantly the barrier height and position.

5. Conclusions

The main results of our researches can be formulated as follows:

– An expression for the calculation of the Coulomb potential between two deformed, axially symmetric, and arbitrarily oriented nuclei has been obtained.

– The nuclear part of the interaction potential has been studied numerically, making use of the proximity theorem.

– The interaction potential has been demonstrated to depend strongly on the deformation parameters and a relative orientation of nuclei. The deformation of both nuclei and their relative orientation considerably influence the barrier height and position. For instance, the barrier height for heavy strongly deformed nuclei changes by approximately 25 MeV, depending on their relative orientation. Therefore, the account of a nuclear deformation is very important while studying the process of fusion of two nuclei at energies close to the barrier energy.

– More compact systems are characterized by higher barriers and deeper potential wells.

– The difference between the highest and the lowest barrier values, which are attained at different relative orientations of the nuclei, is larger in the case of a prolate-prolate nuclear system, as compared with an oblate-oblate one. In contrast to that, the difference between the depths of the deepest and the shallowest potential wells is larger in the case of an oblate-oblate nuclear system.

– The influence of a nuclear rotation around the axis that connects the centers of mass of the nuclei (the angle Φ) on the potential of their interaction is insignificant and, against the background of the effect produced by the rotation of nuclei at the angles Θ_1 and Θ_2, comprises no more than 5%.

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ВЗАЄМОДІЯ ДВОХ АКСІАЛЬНО-СИМЕТРИЧНИХ ЯДЕР

В.Ю. Денисов, М.О. Пилипенко

Р е з ю м е

Отримано простий вираз для кулонівської взаємодії двох деформованих довільно орієнтованих аксіально-симетричних ядер. Запропоновано апроксимаційний вираз для ядерної частини взаємодії деформованих ядер. Досліджено повний потенціал взаємодії двох ядер з різними орієнтаціями для витягнуто-витягнутої, витягнуто-сплюснутої та сплюснуто-сплюснутої систем.