THE INFLUENCE OF ^{35}Cl DEFORMATION ON THE FUSION REACTION WITH ^{92}Zr

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In this research we have studied the effect of ground state quadrupole and hexadecapole deformation of ^{35}Cl on the calculation of the interacting potential and the heavy ion fusion cross-section of ^{35}Cl+^{92}Zr system. The results that are obtained based on the Double Folding method show that the height of fusion barrier strongly depends on the orientation between two interacting nuclei. Also the calculated cross-sections are in a better agreement with the experimental data in comparison to those calculated assuming that the interacting nuclei are spherical in their ground state.

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1. Introduction

The interaction potential between two interacting nuclei is one of the most important ingredients in the description of the nuclear reactions. This potential consists of two parts, short-range nuclear attraction and long-range Coulomb repulsion. The combination of these two potentials causes the formation of Coulomb barrier in total potential. It is well known that if we neglect the effect of the rotational and vibrational modes of the interacting nuclei on the calculation of total potential, then the calculation of the total potential between two spherical nuclei leads to a single barrier and in the case that, at least one of the nuclei to be considerably deformed in it's ground state, the total potential will depend on the orientation between the symmetry axes of two colliding nuclei [1–3].

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Recently, the ^{35}Cl+^{92}Zr system is analyzed by using the Double-Folding (DF) and proxy methods [4, 5]. In both of these studies the interacting nuclei are taken to be spherical in their ground states. One can see that the fusion cross-sections calculated by using the single barrier penetration model do appear in better agreement with the corresponding experimental data. Since the obtained results from the Hartree–Fock–Bogoliubov (HFB) method reveal a considerable quadrupole deformation for the ^{35}Cl in its ground state [6], it seems that taking the spherical shape for ^{35}Cl could not be an appropriate assumption in the study of the interactions in which this nucleus is involved. This motivates us to study this effect on the calculation of total potential, and the complete fusion cross-section of ^{35}Cl+^{92}Zr system.

The system was also analyzed by Hagino *et al.* using the couple-channel formalism [7]. In this work the nuclear part of the total potential is taken to be in the Woods–Saxon form and the parameters of this potential are chosen to obtain the best agreement between analytic calculation of the fusion cross-section and experimental data. Nevertheless, a better agreement to the scattering data is obtained when the nuclear potential with larger diffuseness is applied. Since we are going to study the effect of deformation of ^{35}Cl on the total potential of the ^{35}Cl+^{92}Zr reaction, regardless of choosing the Woods–Saxon form for the nuclear potential, we employ the DF model to calculate this part of the total potential.

In Sec. 2 we discuss DF model and its basic inputs. The effect of ^{35}Cl quadrupole and hexadecapole deformation on the cross-section of ^{35}Cl+^{92}Zr is made in Sec. 3 and Sec. 4 is devoted to some concluding remarks.

2. Theory

Double-folding model [8] is one of the most common methods to calculate the internuclear potential in the heavy ion reactions. One of the basic inputs in the calculation of this model is the nuclear matter density of colliding nuclei. In order to calculate the total potential of the deformed nuclei one has to use the density function. This function is taken to be the two parameter Fermi (2PF) distribution,

$$\rho(R,\theta) = \frac{\rho_\circ}{1+\exp[r-R(\theta)/a]}\,, \tag{1}$$

where

$$R(\theta) = R_\circ \left[1+\sum_l \beta_l Y_{l,0}(\theta)\right] \tag{2}$$

the β_l coefficients are the deformation parameters of the nucleus. For spherical nuclei, these parameters are equal to zero. In the case when one of the participant nuclei in the reaction is spherical in its ground state, the nuclear potential can be calculated by

$$U(\boldsymbol{R},\phi) = \int d\boldsymbol{r}_1 d\boldsymbol{r}_2\, \rho(\boldsymbol{r}_1)V(\boldsymbol{s})\rho(\boldsymbol{r}_2)\,, \tag{3}$$

where $\rho(\boldsymbol{r}_1)$ and $\rho(\boldsymbol{r}_2)$ are the density of the projectile and the target nucleus, respectively, $\boldsymbol{R}$ is the distance between their centers, $\boldsymbol{S} = \boldsymbol{R} + \boldsymbol{r}_1 - \boldsymbol{r}_2$, and ϕ is the orientation angle of deformed nucleus with respect to R, see Fig. 1. $V(\boldsymbol{s})$ is the nucleon–nucleon (NN) interaction. In the present calculations, we used the M3Y-Reid effective NN [9] in its form

$$V(s) = \left[7999.0\,\frac{e^{(-4s)}}{4s} + 2134.25\,\frac{e^{(-2.5s)}}{2.5s}\right] - 276.0\left(1 - 0.005\,\frac{E_{\mathrm{L}}}{A_{\mathrm{P}}}\right)\delta(s) \tag{4}$$

the first and second major terms are the direct and exchange contributions to the NN forces. E_{L} and A_{P} are the incident energy in laboratory frame and the mass number of the projectile nucleus, respectively. One can reduce the six-dimensional integration of the DF model to the sum of the products of three one dimensional integrals using the multipole expansion of nuclear matter distribution of deformed nuclei (see for more details Ref. [1]).

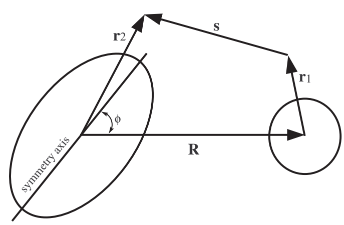

Fig. 1. The coordinate system used in the Double Folding model.

3. Calculations

In the calculations of the nucleus–nucleus potential for ^{35}Cl+^{92}Zr reaction using the DF model, the nuclear matter densities of the target and the projectile nuclei for simplicity are assumed to be proportional to the charge densities in these nuclei (*i.e.*, $\rho_A = \rho_Z A/Z$). In these calculations we have used the two parameter Fermi distribution (2PF) for proton densities. The density parameters for the participant nuclei that are obtained from HFB calculations [6] are given in Table I.

The nuclear potential is of prime importance in the fusion cross-section calculations. We have calculated the total potential of this system considering different orientations in the reaction of ^{35}Cl with ^{92}Zr. The obtained results for the height and position of the fusion barrier corresponding to the

TABLE I

The values of the quadrupole (β_2), hexadecapole (β_4) deformation parameters and R_0, a_0 for the charge distribution. Values of these parameters are determined by HFB calculation [6].

Nuclei	β_2	β_4	R_0	a_0
^{35}Cl	-0.11	-0.02	3.4175	0.5268
^{92}Zr	0.0	0.0	4.9725	0.4991

different orientation angles are indicated in Fig. 2. Obviously, with increasing the orientation angle ϕ the height of the fusion barrier decreases, also the value of the fusion barrier height for $\phi = 0°$ is about 1.75 MeV greater than corresponding value to $\phi = 90°$. It reveals that when $\phi = 90°$ the nuclear potential is more attractive than at $\phi = 0°$. It is due to the greater overlap of colliding nuclei when $\phi = 90°$.

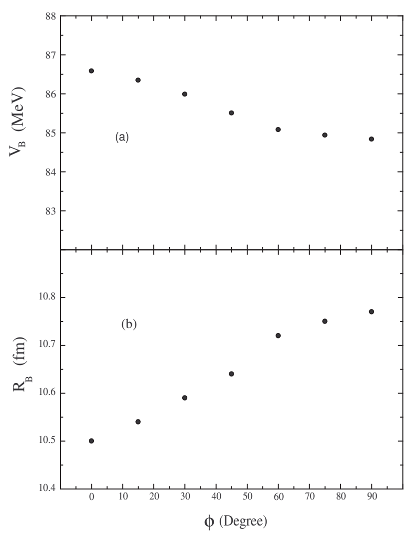

Fig. 2. (a) The height and (b) the position of the fusion barrier of the ^{35}Cl+^{92}Zr system for different orientations.

To illustrate in a very simple way the influence of the orientation in this reaction, the one-dimensional penetrability is calculated as a function of the bombarding energy for different orientation angles. The obtained results are indicated in Fig. 3. The one-dimensional penetrability is calculated using:

$$P(E,\phi) = \exp\left(-\frac{2}{\hbar}\int\limits_{b_1(\phi)}^{b_2(\phi)}\sqrt{2\mu(V(R,\phi)-E)}dR\right), \tag{5}$$

where $b_1(\phi)$ and $b_2(\phi)$ are the turning points and μ is the reduced mass. The total complete fusion cross-section is calculated by,

$$\sigma_{\text{fus}}(E) = \frac{1}{4\pi} \int \sigma_{\text{fus}}(\phi) d\Omega \,. \tag{6}$$

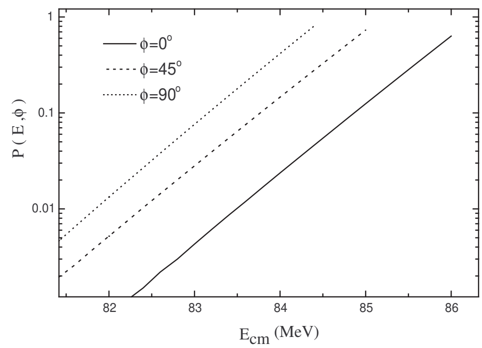

Fig. 3. Dependence of the one-dimensional barrier penetrability on the bombarding energy in the center-of-mass frame for the ^{35}Cl+^{92}Zr system for different orientations.

The results are shown in Fig. 4. The solid line corresponds to the calculated fusion cross-section when deformation parameter of ^{35}Cl is not equal to zero (spherical-deformed) and the dash line to the case that the deformation parameters are taken equal to zero (spherical–spherical). The experimental data of the fusion cross-sections come from [7].

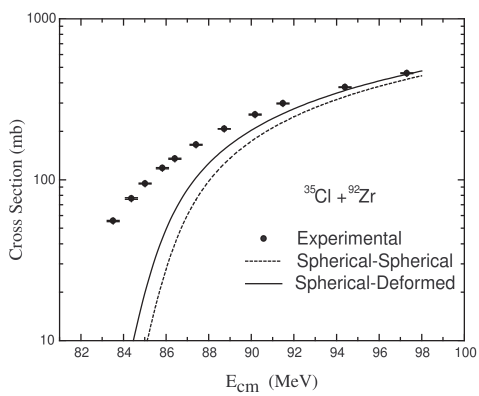

Fig. 4. Calculated fusion cross-sections and experimental data of the ^{35}Cl+^{92}Zr. The solid line shows the calculated fusion cross-section (spherical-deformed) and dash line is correspondent to the case when the taken deformation parameters of ^{35}Cl equal zero (spherical–spherical).

4. Conclusion

In this paper we have studied the ^{35}Cl+^{92}Zr system using the DF model. The obtained results reveal that the quadrupole and hexadecapole deformation of the ^{35}Cl is a physically important quantity in the calculation of the nucleus–nucleus potential of this interacting system. This effect changes the height of the fusion barrier by about 1.75 MeV and its position by about 0.25 fm (Fig. 2). Also this variation of the total potential is important in the calculation of the fusion cross-section (Fig. 4). Therefore, one can conclude that taking the spherical shapes for ^{35}Cl could not be an appropriate assumption in studying some reactions in which this nucleus is involved.

Comparison between the analytically calculated fusion cross-sections and the experimental data on the ^{35}Cl+^{92}Zr system is shown in Fig. 4. It can be seen that our results are in slightly better agreement with the experimental data particularly in higher energies. At low energies the calculated cross-sections are lower than corresponding experimental data, what might be due to the channel coupling effects such as phonon excitations in ^{35}Cl and ^{92}Zr which have been ignored in the present calculations. One may expect an additional improvement due to the decrease of fusion barrier [10], when those coupling effects are taken into account.

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