Orientations for hot compact and cold elongated fusion

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Introduction

In low energy heavy-ion fusion reactions the colliding nuclei overcome the fusion/interaction barrier and form the compound nucleus. This means for the fusion reactions the barrier height as well as barrier position plays a key role. For deformed nuclei, both of these quantities depend on the orientation of the symmetry axis with respect to the collision axis. The orientation for which barrier height is maximum and interaction radius is minimum is known as *hot compact* and the orientation, which corresponds to minimum barrier height and maximum interaction radius is known as *cold elongated* [1]. Thus the probability of formation of a compound nucleus is highly influenced by the orientations of the colliding nuclei.

In this work, the hot compact and cold elongated orientations have been obtained for the fusion of the isotopes of Titanium (Ti) and Neodymium (Nd). Now, with respect to the shapes of the colliding nuclei, there are following eight possible combinations: oblate-oblate, oblate-prolate, oblate-spherical, prolate-oblate, prolate-prolate, prolate-spherical, spherical-oblate, spherical-prolate. The isotopes of Ti and Nd taken for these combinations along with their shapes and deformation values, respectively, are: ^{44}Ti (spherical, β_2=0), ^{43}Ti (oblate, β_2=-0.042), ^{48}Ti (prolate, β_2=0.011) and ^{142}Nd (spherical, β_2=0, ^{181}Nd (oblate, β_2=-0.125) and ^{150}Nd (prolate, β_2=0.237). The deformation values of target and projectile has been taken from the recent data of [2].

The hot compact and cold elongated orientations have been obtained by varying the orientation of either target or projectile for a fixed orientation of the other in steps of 30°, first the deformations have been considered up to quadrupole (β_2) order and then same procedure has been repeated by considering the deformation up to hexadecupole (i.e. $\beta_2+\beta_3+\beta_4$) order.

Formalism

The interaction potential between two deformed and oriented nuclei in a collision plane as a function of relative separation R is,

$$V(R) = V_P(R, A_i, \beta_{\lambda_i}, \theta_i) + V_c(R, Z_i, \beta_{\lambda_i}, \theta_i) \quad (1)$$

where, β_{λ_i}, λ = 2, 3 and 4 corresponds to quadrupole, octupole, hexadecupole deformations of colliding nuclei (i=1, 2) and θ_i are the orientation angles. The nuclear proximity potential [3] is,

$$V_P(R) = 4\pi\gamma\bar{R}b\phi(s_0) \quad (2)$$

where $\bar{R}$ is the mean curvature radius, $\gamma = 0.9517\left[1-1.75826(\frac{N-Z}{A})^2\right]$ MeV fm^{-2} is the surface energy constant, b (=0.99 fm) the nuclear surface thickness and $\phi(s_0)$ is the universal function and depends on the minimum separation between the surfaces of colliding nuclei, given as

$$\phi(s_0) = \begin{cases} -\frac{1}{2}(s_0-2.54)^2 - 0.0852(s_0-2.54)^3 \\ -3.437\exp(-\frac{s_0}{0.75}), \end{cases} \quad (3)$$

respectively for $s_0 \leq 1.2511$ and $s_0 > 1.2511$. The condition of $s_0 = R - R_1(\alpha_1)cos(\theta_1-\alpha_1) - R_2(\alpha_2)cos(180+\theta_2-\alpha_2)$ being at minimum distance is obtained from $\frac{ds_0}{d\alpha_1} = \frac{ds_0}{d\alpha_2} = 0$, R_i are the principle radii of curvature (for detail see [1] and references there in). The Coulomb

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potential [4] for the two deformed and oriented nuclei in a plane is,

$$V_C(R) = \frac{Z_1 Z_2 e^2}{R} + \sum_{\lambda,i=1,2} \frac{3Z_1 Z_2 e^2}{2\lambda+1} \frac{R_i^\lambda(\alpha_i)}{R^{\lambda+1}} \times Y_\lambda^{(0)}(\theta_i)\left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2 Y_\lambda^{(0)}(\theta_i)\right] \quad (4)$$

Calculations and results

First of all the variation of the interaction potential as a function of relative separation between the colliding nuclei has been studied by fixing the orientation of either and varying that of the other in steps of 30° at different fixed orientations from 0-180° for all the eight combinations (as mentioned in the introduction). The barrier positions and heights have been compared for different orientations for a given combination and the orientations of hot compact and cold elongated is selected for each of the combination. The same procedure has been repeated by taking deformations up to hexadecupole order.

TABLE I: Orientations angles (θ_1, θ_2) for hot compact configurations of different shaped (oblate, prolate and spherical) T-P combinations.

S.No.	T-P combination	Shapes of T-P	Orientations θ_1, θ_2 (in degrees)
1.	^{43}Ti+^{181}Nd	o - o	0, 0
2.	^{43}Ti+^{150}Nd	o - p	0, 90
3.	^{43}Ti+^{142}Nd	o - s	0, 0
4.	^{48}Ti+^{181}Nd	p - o	90, 0
5.	^{48}Ti+^{150}Nd	p - p	90, 90
6.	^{48}Ti+^{142}Nd	p - s	90, 0
7.	^{44}Ti+^{181}Nd	s - o	0, 0
8.	^{44}Ti+^{150}Nd	s - p	0, 90

Table I shows the orientations for hot compact configurations for the systems under consideration and it is found that if either of the colliding nucleus is prolate then whatsoever be the shape of the other nucleus, the interaction barrier is maximum when the prolate nucleus is oriented at 90° and another one is at 0°. Further, if the target is prolate then the addition of higher deformations (up to β_4 = +ve) gives rise to a small decrease in the height of interaction barrier and there is no change in the orientation angles for the hot compact configuration (not shown in Table I).

Similarly, Table II is for the cold elongated configurations and it is clear from the table that if either of the colliding nucleus is oblate then whatsoever be the shape of other nucleus the cold elongated configurations is obtained when the oblate shaped nucleus is oriented at 90° and another is at 0°. The addition of higher deformations (up to β_4 = +ve) gives rise to a small decrease in the height of the interaction barrier if target is prolate and there is no change in the orientation angles for the cold elongated configuration.

Finally, we conclude that the hot compact configuration is obtained when prolate partner is oriented at 90° and other at 0°. Similarly, cold elongated is obtained when oblate partner is oriented at 90° and other at 0°.

TABLE II: Same as Table. I, but for cold elongated configurations.

S.No.	T-P combination	Shapes of T-P	Orientations θ_1, θ_2 (in degrees)
1.	^{43}Ti+^{181}Nd	o - o	90, 90
2.	^{43}Ti+^{150}Nd	o - p	90, 0
3.	^{43}Ti+^{142}Nd	o - s	90, 0
4.	^{48}Ti+^{181}Nd	p - o	0, 90
5.	^{48}Ti+^{150}Nd	p - p	0, 0
6.	^{48}Ti+^{142}Nd	p - s	0, 0
7.	^{44}Ti+^{181}Nd	s - o	0, 90
8.	^{44}Ti+^{150}Nd	s - p	0, 0

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