Theory of the compactness of the hot fusion reaction $^{48}Ca + ^{244}Pu \rightarrow ^{292}114^*$

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Within the fragmentation theory, extended to include the orientations degrees of freedom and hexadecupole deformations, for optimized orientations, the $^{48}Ca + ^{244}Pu \rightarrow ^{292}114^*$ reaction is shown to be a "compact" hot fusion reaction. The barrier is highest (hot fusion) and interaction radius smallest (compact), which occur for the collisions in the direction of the minor axis of the deformed reaction partner (i.e. for 90° orientation of ^{244}Pu). In addition to the $^{48}Ca + ^{244}Pu$ reaction valley, a number of other new reaction valleys (target-projectile combinations) are shown to arise for the "optimally oriented hot" fusion process, the $^{48}Ca + ^{244}Pu$ being the best (lowest barrier) and $^{54}Ti + ^{238}U$ as the next possible best reaction for forming the cold compound nucleus $^{292}114^*$. A similar reaction valley for $^{48}Ca + ^{244}Pu$ is found absent in the "optimally oriented cold" fusion process.

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I. INTRODUCTION

Recently, for the first time, Oganessian *et al.* [1] have measured the excitation functions of the $4n$ channel in the hot fusion reaction $^{48}Ca + ^{244}Pu \rightarrow ^{292}114^*$. It is found that, compared to the well-studied $^{206,208}Pb$-based cold fusion (excitation energy $E^* \sim 10$–20 MeV) reactions [2], here the peak of the excitation functions is broader as well as shifted to an higher excitation energy (peaked at $E^* \sim 41$ MeV). These authors suggested that this increased number of emitted neutrons or the increased fusion threshold could arise if the major contribution to the formation of compound nucleus comes from a "compact" configuration in the entrance channel, associated with the orientation of the deformed reaction partner during its interaction with the spherical ^{48}Ca beam (i.e., the collisions taking place at the minimum interaction radius). In this article, based on the fragmentation theory extended to include the orientations degrees of freedom and hexadecupole deformations [3,4], we show that the above suggestion of Ref. [1] is borne out and this reaction is infact a "compact hot fusion" reaction. For the barrier to be the highest (hot fusion), the interaction radius is found to be the smallest (compact) and occurs for the collisions in the direction of the minor axis of the deformed nucleus (i.e., for 90° orientation of the deformed nucleus). Furthermore, we find that this reaction appears as a "cold reaction valley" (one of the minima) in only the "optimally oriented hot" fusion potential energy surface (PES) of the compound nucleus $^{292}114^*$ and that, compared to other reaction valleys, the barrier is lowest for this reaction. Interestingly, such a reaction valley is found absent for $^{48}Ca + ^{244}Pu$ in a similar PES calculated for the "optimally oriented cold" fusion process. The optimum orientation for cold fusion (lowest barrier) of $^{244}Pu + ^{48}Ca$ occurs for 0° orientation of ^{244}Pu.

The fragmentation theory, recently extended to include the higher multipole deformations and orientations degrees of freedom, is very briefly described in Sec. II. We present the results of our calculation in Sec. III, and a summary and discussion in Sec. IV. Calculations are made only for the coplanar ($\phi = 0°$) case.

II. THE FRAGMENTATION THEORY

According to this theory [3,4], worked out in terms of the mass and charge asymmetries $\eta = (A_1 - A_2)/(A_1 + A_2)$ and $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$, the relative separation $\vec{R}$, the deformations $\beta_{\lambda i}$, $\lambda = 2$, 3, and 4, the quadrupole, octupole, and hexadecupole deformations of two nuclei ($i = 1$, 2), the two orientation angles θ_i and the azimuthal angle ϕ ($= 0°$ for coplanar nuclei) between the principal planes of two nuclei, and the fragmentation potential as follows:

$$V(\eta, \eta_Z, R) = -\sum_{i=1}^{2} B_i(A_i, Z_i, \beta_{\lambda i}) + V_C(R, Z_i, \beta_{\lambda i}, \theta_i, \phi) + V_P(R, A_i, \beta_{\lambda i}, \theta_i, \phi). \quad (1)$$

Here, B_i are the binding energies, taken from the calculations of Möller *et al.* [5] or from experiments [6], and V_C and V_P are, respectively, the Coulomb and nuclear proximity potentials, given (for $\phi = 0°$ case) by the following:

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

and

$$V_P = 4\pi \bar{R}\gamma b \Phi(s_0), \quad (3)$$

where, for the axially symmetric shapes,

$$R_i(\alpha_i) = R_{0i}\left[1 + \sum_{\lambda} \beta_{\lambda i} Y_{\lambda}^{(0)}(\alpha_i)\right], \quad (4)$$

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with $R_{0i} = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}$, the specific surface energy constant $\gamma = 0.9517[1 - 1.7826\{(N-Z)/A\}^2]$ (in MeV fm^{-2}), and the nuclear surface thickness $b = 0.99$ fm, and the universal function $\Phi(s_0)$, which depends on the minimum separation distance s_0, is

$$\Phi(s_0) = \begin{cases} -\frac{1}{2}(s_0 - 2.54)^2 - 0.0852(s_0 - 2.54)^3 \\ -3.437 \exp\left(-\frac{s_0}{0.75}\right) \end{cases} \qquad (5)$$

respectively, for $s_0 \leqslant 1.2511$ and $\geqslant 1.2511$. The minimized (in α_i) separation distance s_0, in units of b, is defined [7] for coplanar nuclei (see inset in Fig. 4) as

$$\begin{aligned} s_0 &= R - X_1 - X_2 \\ &= R - R_1(\alpha_1)\cos(\theta_1 - \alpha_1) - R_2(\alpha_2)\cos(180 + \theta_2 - \alpha_2), \end{aligned} \qquad (6)$$

and the mean curvature radius $\bar{R}$, characterizing s_0, is as follows:

$$\frac{1}{\bar{R}^2} = \frac{1}{R_{11}R_{12}} + \frac{1}{R_{21}R_{22}} + \frac{1}{R_{11}R_{22}} + \frac{1}{R_{21}R_{12}}, \qquad (7)$$

where R_{i1} and R_{i2} are the principal radii of curvatures at the two points of closest approach of nuclei. For explicit expressions of R_{i1} and R_{i2} and other details, see Ref. [7].

Finally, for noncoplanar nuclei ($\phi \neq 0^\circ$) we use the same formalism as for $\phi = 0^\circ$ above, but by replacing for the out-of-plane nucleus ($i = 1$ or 2) the corresponding radius parameter $R_i(\alpha_i)$ with the projected radius parameter $R_i^P(\alpha_i)$ in both the Coulomb and proximity potentials. For details, see Refs. [4,8].

For fixed orientations, the charges Z_i in (1) are fixed by minimizing the potential in η_Z coordinate, which fixes the deformations $\beta_{\lambda i}$ also. Then, Eq. (1) gives the fragmentation potential $V(\eta)$ for fixed R and, normalized to the binding energies, the scattering potential $V(R)$ for fixed η. In fragmentation theory [9–14] the *cold* compound system is considered to be formed for *all* those target-projectile (t-p) combinations that lie at the *minima* of $V(\eta)$ of a given compound nucleus, calculated for all possible t-p combinations. In this theory, the above information on potential energy minima (*the cold reaction valleys*) is further optimized [15] by the requirements of smallest interaction barrier, largest interaction radius and nonnecked (no saddle) nuclear shapes. For coplanar ($\phi = 0^\circ$) *optimally* oriented nuclei, we find that the same result is manifested in the form of the following two criteria [3,4]: (i) the interaction radius is smallest, but the barrier is highest, which means a (most) compact hot nuclear shape, called the optimum oriented hot fusion configuration and (ii) the barrier is lowest, but the interaction radius is largest, which means an elongated (noncompact) cold nuclear shape, called the optimum oriented cold fusion configuration. These criteria are found to remain fixed for the fixed signs of quadrupole deformations (prolate, oblate, or spherical) of two interacting nuclei, not influenced by the (+/−) signs of their hexadecupole deformations [3,4]. Finally, it may be stressed here that the above-mentioned criterion for *cold reaction valleys* is still satisfied, respectively, for each of the optimally oriented hot and optimally oriented cold fusion processes.

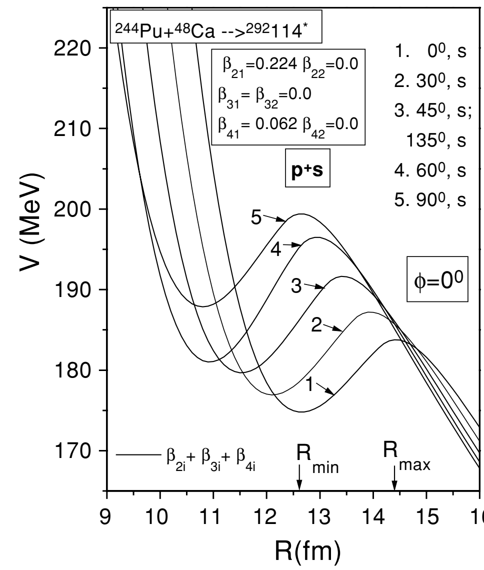

FIG. 1. Scattering potentials for ^{244}Pu + ^{48}Ca → ^{292}114* reaction at various orientations. R_{min} and R_{max} refer, respectively, to the highest (hot) and lowest (cold) barrier positions.

III. CALCULATIONS AND RESULTS

Figure 1 gives the scattering potentials for the in-plane ($\phi = 0^\circ$) prolate-spherical (p$^+$s) ^{244}Pu + ^{48}Ca → ^{292}114* reaction, calculated at illustrative different orientations of ^{244}Pu. The superscript (+) on p represents the positive sign of hexadecupole deformation β_{41} for ^{244}Pu. Figure 2 shows the variations of the barrier heights V_B and barrier positions R_B (from Fig. 1) as a function of the orientation angle θ_1 of ^{244}Pu. Evidently, the barrier is highest (hot) and its position

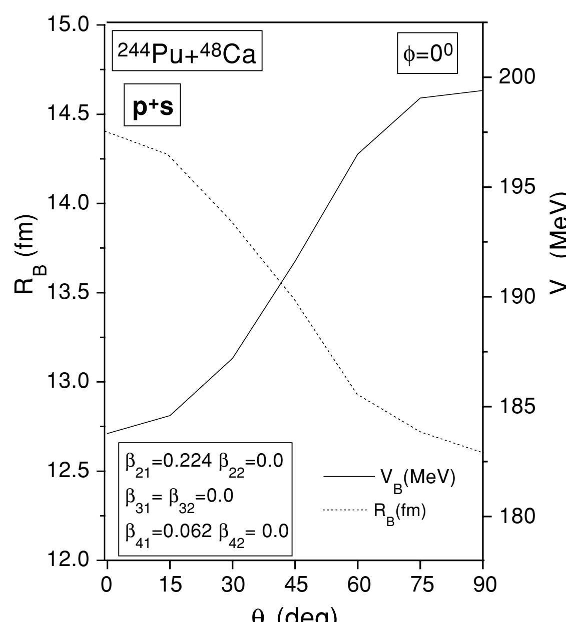

FIG. 2. The barrier heights V_B (solid line) and barrier positions R_B (dashed line) plotted as a function of the orientation angle θ_1 of the deformed nucleus in ^{244}Pu + ^{48}Ca reaction.

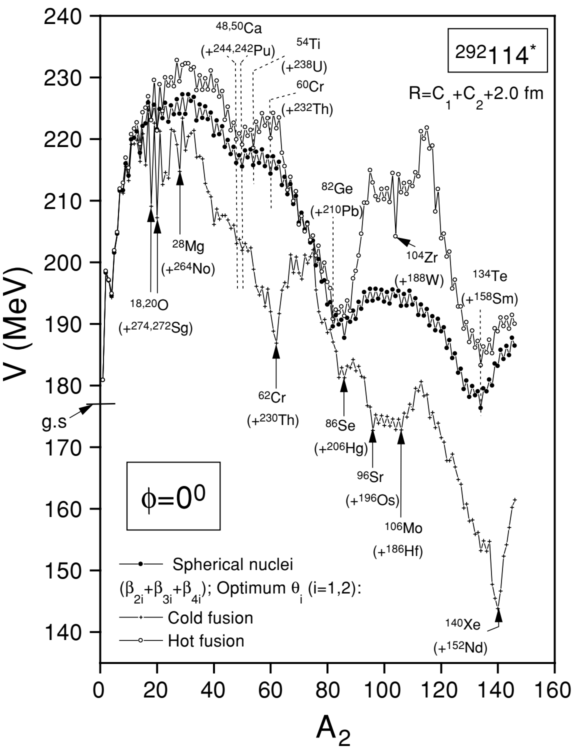

FIG. 3. Fragmentation potentials for the optimally oriented hot and cold fusion of the different t-p combinations with $\lambda = 2$, 3, and 4 and for spherical nuclei, leading to $^{292}114^*$. The ground-state energy is denoted by g.s.

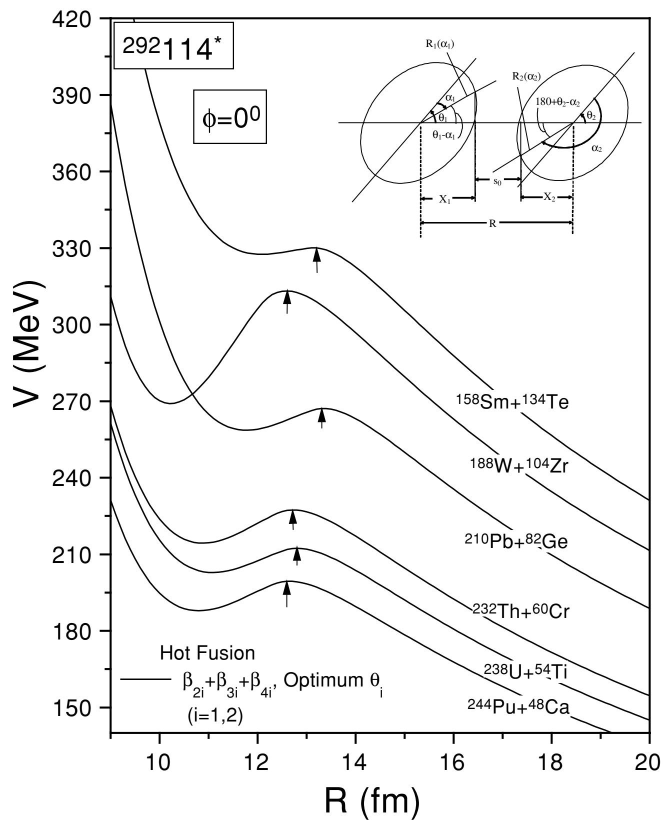

FIG. 4. Same as for Fig. 1, but because of different t-p combinations referring to minima in the optimally oriented hot fusion PES of Fig. 3. The arrows indicate the barrier positions. The inset shows schematically the two colliding, axially symmetric deformed, oriented nuclei, lying in the same plane.

minimum (compact) for $\theta_1 = 90^\circ$ (see Fig. 2, or curve 5 in Fig. 1), representing the optimum oriented, compact hot fusion configuration. Similarly, the barrier is lowest (cold) and its position maximum (elongated) for $\theta_1 = 0^\circ$ (see Fig. 2, or curve 1 in Fig. 1), representing the optimum oriented, elongated cold fusion configuration. Note that in Fig. 1, $R_{\min} = R_{01} + b_1$ and $R_{\max} = R_{01} + a_1$, where a_1 and b_1 are the semimajor and semiminor- axes of the deformed nucleus, R_{01} being the radius of its spherical reaction partner. Thus, the 90° orientation of ^{244}Pu result in a compact hot fusion process, whereas its 0° orientation gives rise to an elongated cold fusion process.

Figure 3 shows the fragmentation potentials for optimum hot and optimum cold orientations of the different t-p combinations (for optimum orientations, see Table 1 of Ref. [4]), forming the compound nucleus $^{292}114^*$ at a fixed $R = C_1 + C_2 + 2.0$ fm, C_i being the Süssmann central radii ($C_i = R_i - b^2/R_i$, $i = 1$, 2). The case of spherical nuclei is also plotted for comparisons. First of all, we notice that $^{244}\text{Pu} + {}^{48}\text{Ca}$ (more so its neighbor $^{242}\text{Pu} + {}^{50}\text{Ca}$, but ^{50}Ca is radioactive) is a reaction valley (a minimum) *only* in the optimally oriented hot fusion PES and the same is absent in optimally oriented cold fusion PES. (Note that for this asymmetric region of mass asymmetry, the PES for hot fusion of deformed, oriented nuclei is nearly the same as for spherical nuclei.) This suggests that the optimally oriented $^{244}\text{Pu} + {}^{48}\text{Ca}$ is a hot fusion reaction. However, Fig. 4 shows that, relatively speaking, it is actually a cold fusion reaction with optimum orientations of the hot fusion process (i.e., of a compact configuration).

Figure 4 gives the scattering potentials for all the t-p combinations referring to minima in the optimally oriented hot fusion PES of Fig. 3. Apparently, the barrier is lowest for the $^{244}\text{Pu} + {}^{48}\text{Ca}$ reaction and interaction radius nearly the same for all cases. This kind of criterion was laid down long time back [15] for cold fusion reaction valleys. Another interesting result from Fig. 4 is that the neighboring reaction $^{238}\text{U} + {}^{54}\text{Ti}$, involving another actinide, also presents itself as the next best possible candidate for a cold fusion reaction leading to $^{292}114^*$. For use of rare earths, the deep potential pocket in $^{188}\text{W} + {}^{104}\text{Zr}$ could offer an added advantage for a possible good fusion reaction. Note that here we have not considered the t-p combinations of very light nuclear masses, referring to the region of cluster radioacticity and/or to the known very hot fusion reactions studied at Berkeley.

IV. SUMMARY AND DISCUSSION

We have shown that, within the extended fragmentation theory, the calculated orientations-dependent scattering potentials, and hence the barrier heights and positions, allow us to obtain the optimum orientation of the deformed reaction partner in a hot fusion reaction such as $^{244}Pu + ^{48}Ca \rightarrow ^{292}114^*$. For the optimally oriented hot fusion process, the interaction radius is smallest and the barrier highest, which means a most compact hot configuration. For the $^{244}Pu + ^{48}Ca \rightarrow ^{292}114^*$ reaction, it is shown that the compact hot configuration occurs at 90^0 orientation and hence in the direction of minor axis of ^{244}Pu. The result that this reaction is an optimally oriented hot fusion reaction, and not an optimally oriented cold fusion reaction, follows from the fact that $^{244}Pu + ^{48}Ca$ combination is a reaction valley (minimum) only in the PES calculated for hot optimally oriented collisions and that such a minimum is not present in the similar PES of $^{292}114^*$ for cold optimally oriented collisions.

In addition to the $^{244}Pu + ^{48}Ca$ minimum, a number of other potential energy minima (t-p combinations) are also predicted to be present whose compact configurations (orientations) could be determined by using Table 1 in Ref. [4], as per the signs of their quadrupole moments. This is not done here in this article (note that, for the optimally oriented hot fusion, all configurations are compact). However, a relative comparison of the barrier heights (and positions) for all of these t-p combinations, referring to potential energy minima, further shows that the combination $^{244}Pu + ^{48}Ca$ is the coldest fusion reaction for forming the compound nucleus $^{292}114^*$ because it lies the lowest. The interaction radii are nearly the same for all the t-p combinations. In other words, the $^{244}Pu + ^{48}Ca \rightarrow ^{292}114^*$ reaction is in fact a cold fusion reaction, as was defined by some of us (RKG and WG) and collaborators in early 1970s for the spherical nuclei [15]. The fact that the inclusion of orientation effects does not change the result is a manifestation of the result of Fig. 3 that for asymmetric combinations, such as $^{244}Pu + ^{48}Ca$, the optimally oriented hot collisions give nearly the same PES as for spherical nuclei. The notation of warm or hot fusion for Ca-based fusion reactions, without the orientation effects, is only a relative term, because the excitation energies involved in the Pb-based fusion reactions are only about half of the ones in ^{48}Ca-based reactions.

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[1] Yu. Ts. Oganessian *et al*., Phys. Rev. C **69**, 054607 (2004).
[2] S. Hofmann, G. Münzenberg, and M. Schädel, Nucl. Phys. News (NUPECC) **72**, 733 (2004).
[3] R. K. Gupta, *et al*., *Proceedings DAE Nucl. Phys. Symp.*, Mumbai (India) **46**B, 194 (2003); nucl-th/0307055.
[4] R. K. Gupta, M. Balasubramaniam, R. Kumar, N. Singh, M. Manhas, and W. Greiner, J. Phys. G: Nucl. Part. Phys. **31**, 631 (2005).
[5] P. Möller *et al*., At. Data Nucl. Data Tables **59**, 185 (1995).
[6] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 4 (1995).
[7] R. K. Gupta, N. Singh, and M. Manhas, Phys. Rev. C **70**, 034608 (2004).
[8] M. Manhas and R. K. Gupta, Phys. Rev. C (2005) accepted for publication.
[9] H. J. Fink *et al*., *Proceedings of the International Conference on Reactions between Complex Nuclei* (North-Holland, Nashville, TN, 1974), Vol. 2, p. 21.
[10] J. Maruhn and W. Greiner, Phys. Rev. Lett. **32**, 548 (1974).
[11] R. K. Gupta, W. Scheid, and W. Greiner, Phys. Rev. Lett. **35**, 353 (1975).
[12] A. Sandulescu *et al*., Phys. Lett. **B60**, 225 (1976).
[13] R. K. Gupta, Sov. J. Part. Nucl. **8**, 289 (1977).
[14] R. K. Gupta *et al*., *Heavy Elements and Related New Phenomena*, edited by W. Greiner and R. K. Gupta (World Scientific, Singapore, 1999), Vols. I and II.
[15] R. K. Gupta, A. Sandulescu, and W. Greiner, Phys. Lett. **B67**, 257 (1977).