Strong Enhancement of Subbarrier Fusion due to Negative Hexadecapole Deformation

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Within a modified barrier penetration model the fusion cross section for ${}^{16}_{8}O + {}^{184}_{74}W$ is calculated at subbarrier energies. It is shown that nuclei with positive quadrupole moments and large negative hexadecapole moments have enhanced fusion cross sections over elongated systems only. Fusion measurements with such systems will provide a definitive answer to the question of deformation effects on subbarrier fusion.

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The relative importance of both static and dynamic deformation effects on subbarrier fusion of heavy systems is still not understood in detail. Vaz, Alexander, and Satchler[1] suggest that dynamical effects such as neck formation may be important precursors to fusion. Esbensen[2] has suggested that zero-point motion of collective surface vibrations should also be included. Recently, Reisdorf *et al.*[3] showed strong evidence for the argument that there is no need to invoke degrees of freedom such as neck formation, and that deformation lengths deduced from collective-model analyses are sufficient to explain fusion data. Many other authors[4-6] have shown strong correlation between enhanced fusion cross sections and static quadrupole deformation of frozen-shape nucleus-nucleus potentials.

In this paper we present theoretical calculations for fusion reactions which clearly show a new mechanism that will help quantify the role of static deformed potentials at these subbarrier energies. Our calculations are based on a modified barrier penetration model in which the nucleus-nucleus potential is constructed from a semimicroscopic double-folding prescription.[7] This potential is quite general and applies to any local, central N-N interaction and two arbitrary noncentral density distributions.

These calculations clearly show that fusion reactions involving spherical projectiles and deformed targets with positive quadrupole moments and large negative hexadecapole moments will have an enhanced fusion cross section over deformed isotopes with quadrupole deformation only. The results add evidence to the suggestion that the deformed potential energy itself can result in enhanced fusion cross sections.[3-6] To date, such evidence results from fusion measurements between spherical and deformed nuclei with quadrupole deformation only. We conclude that reactions with isotopes that have large negative hexadecapole moments will result in even larger fusion yields. Other calculations[7] prove that nuclei with large positive hexadecapole moments will not show this effect.

Very few nuclei in the periodic table are known to have quadrupole deformation plus large negative hexadecapole moments. Coulomb excitation[8] experiments and recent electron scattering measurements[9] suggest that ${}^{184}_{74}W$ and ${}^{180}_{72}Hf$ are suitable candidates. Although the experimental hexadecapole deformation parameter[8] for ${}^{184}_{74}W$ may not be known accurately enough[10] the fusion results presented here are for ${}^{16}_{8}O + {}^{184}_{74}W$ at subbarrier energies and clearly show the effect described. No experimental fusion measurements with these nuclei have been carried out to date, although measurements are planned on the more suitable ${}_{72}Hf$ isotopes[10] where accurate electron scattering data will soon become available.[9]

The subbarrier fusion cross section was calculated with the standard barrier penetration model,[1-6]

$$\sigma_F(E_{\text{c.m.}}) = \pi\lambda^2 \sum_{L=0}^{\infty} (2L+1) T_L(E_{\text{c.m.}}) P_L(E_{\text{c.m.}}), \tag{1}$$

where $P_L(E_{\text{c.m.}})$ is the fusion probability for the penetrating wave, normally taken to be unity. The transmission coefficient $T_L(E_{\text{c.m.}})$ was taken from the usual WKB form[1-6] but we average T_L over the orientation angle β_2 of the deformed target relative to the nuclear symmetry axis (see Fig. 1) i.e.,

$$T_L(E_{\text{c.m.}}) = \langle T_L(E_{\text{c.m.}}, \beta_2)\rangle_{\beta_2}, \tag{2}$$

where

$$T_L(E_{\text{c.m.}}, \beta_2) = \exp\left(\frac{-2}{\hbar}\int_{a(\beta_2)}^{b(\beta_2)} \{2\mu[V_L(r, \beta_2) - E_{\text{c.m.}}]\}^{1/2} dr\right). \tag{3}$$

In Eq. (3) $a(\beta_2)$ and $b(\beta_2)$ are the inner and outer turning points, respectively, calculated for every orientation-dependent total potential $V_L(r, \beta_2)$. This potential is a sum of an orientation-dependent nuclear and Coulomb term plus the usual angular momentum barrier,

$$V_L(r, \beta_2) = U_N(r, \beta_2) + U_C(r, \beta_2) + L(L+1)\hbar^2/2\mu r^2. \tag{4}$$

The nuclear and Coulomb potentials in (4) were calculated with use of the microscropic double-folding model in momentum space.[7] A less general expression for this potential between a spherical and deformed nucleus is given by

$$U_N(r, \beta_2) = \sum_{l=0,2,4} (2/\pi)(2l+1)^{1/2}P_l(\cos\beta_2)\int_0^\infty dk\, k^2 j_l(kr)\bar{v}(k)A_{00}{}^{(1)}(k)A_{l0}{}^{(2)}(k). \tag{5}$$

The symbols in this formula are discussed in Ref. 7. The nuclear interaction $U_N(r, \beta_2)$ was derived from G-matrix elements based on the Reid soft-core potential,[7] and the multipole components of the densities in momentum space $A_{ln}{}^{(2)}(k)$ were calculated from experimental deformed Fermi distributions.[7,8] The ^{16}O experimental density was taken from the work of Sick and McCarthy.[11] There are no adjustable parameters in our theory.

In Fig. 1 three sets of the total potential $V_L(r, \beta_2)$ for $^{16}_{8}O + ^{184}_{74}W$ are shown for $L = 0$ and $\beta_2 = 0°$, 45°, and 90°, respectively. For each value of β_2 three curves are plotted, labeled A, B, and C. Curve A represents the total potential for $^{16}_{8}O + ^{184}_{74}W$ with the experimental deformation parameters $\delta_2 = 0.262$ and $\delta_4 = -0.189$ for $^{184}_{74}W$ deduced from Coulomb excitation.[8] Curve B corresponds to this potential when the hexadecapole deformation parameter is set equal to zero; that is, quadrupole deformation only. Curve C corresponds to the interaction between the two equivalent spherical systems when both quadrupole and hexadecapole moments are set equal to zero.

If one assumes that the height and width of the potential barrier are important variables in subbarrier fusion, it can be seen from Fig. 1 that only for angles β_2 near 90° is the interaction barrier for the spherical system lower than for deformed nuclei. At $\beta_2 = 0°$ curve B has the lowest interaction barrier. For this elongated-shaped nucleus, the barrier increases as β_2 increases,[4,7] only becoming larger than the spherical system for $\beta_2 \sim 80°$. When used in barrier penetration models such as Eqs. (1)–(5), this effective lowering of the interaction barrier for elongated systems results in enhanced fusion cross sections[2-6] over those for spherical systems.

Our calculations show that fusion measurements involving nuclei with quadrupole moments and large *negative* hexadecapole moments will have enhanced cross sections over elongated isotopes. Such measurements would provide additional evidence and tests for correlation between potential-energy surfaces and fusion cross sections.

The mechanism for this enhancement is shown in Fig. 1. Unlike elongated nuclei, as β_2 is increased from 0°, the potential barrier decreases quickly, becoming lower than the elongated system and reaching a minimum around 45°. Beyond 45°, the barrier slowly increases, only becoming larger than the elongated system around $\beta_2 \sim 75°$. The insets in Fig. 1 accurately reproduce the nuclear shapes and clarify the lowering of the potential barrier for $\beta_2 = 45°$ over $\beta_2 = 0°$. When $\beta_2 = 45°$, the distance between the centers of the two nuclei is greatest with large nuclear-matter overlap. Hence the dominant long-ranged monopole-monopole Coulomb force takes its smallest value in the presence of a relatively strong short-ranged nuclear force. When $\beta_2 = 0°$, the distance between the centers is smaller for large nuclear-matter overlap. Hence the dominant long-ranged Coulomb force takes a larger value than for $\beta_2 = 45°$. For $\beta_2 = 90°$, the Coulomb force obviously dominates the reaction mechanism.

In Fig. 2 we show subbarrier fusion cross sections calculated with Eqs. (1)–(5) for the potentials labeled A, B, and C in Fig. 1. It can be seen that the largest cross section occurs for the system with both quadrupole moments and large nega-

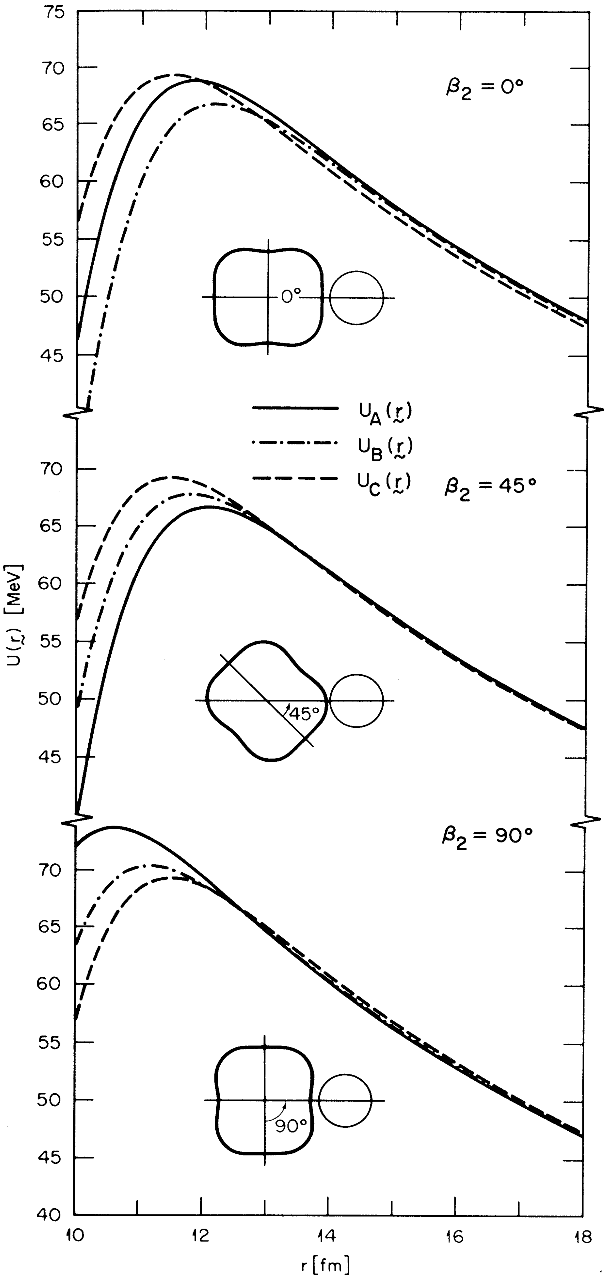

FIG. 1. Total nuclear plus Coulomb potential for $^{16}_{8}O + ^{184}_{74}W$, calculated for three values of the orientation angle β_2. The meaning of potentials $U_A(r)$, $U_B(r)$, and $U_C(r)$, as well as the parameters used, is described in the text. The insets show an accurate representation of the shape of $^{184}_{74}W$ with the deformation parameters of Ref. 8.

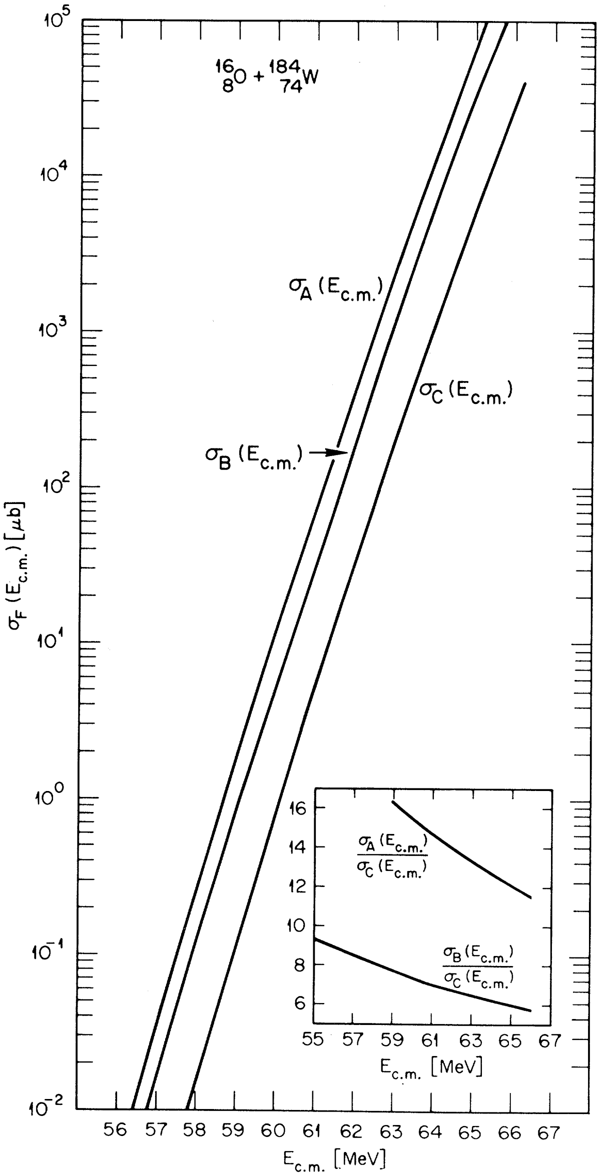

FIG. 2. Total fusion cross section calculated with use of formulas (1)–(5). The cross sections labeled σ_A, σ_B, and σ_C correspond to the fully deformed system, zero hexadecapole moment, and spherical, respectively. The inset shows the ratio of these quantities.

tive hexadecapole moments. Although the greatest enhancement occurs for the transition from spherical to elongated isotopes, the inset in Fig. 2 shows at least an additional factor of 2 increase in going to the fully deformed isotope.

To conclude, such enhancements of the fusion cross section, due to large negative hexadecapole deformations, are measurable and should quantify our understanding of collective degrees of freedom in subbarrier fusion reactions.

Finally, exploratory calculations with heavier systems suggest that reaction partners like $^{184}_{74}W$ or $^{180}_{72}Hf$ result in an enhanced fusion probability and should be considered as new candidates in the search for superheavy nuclei via the cold-fusion idea.

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