Target Deformation Effects at Large Angular Momenta in Heavy-Ion Fusion Reactions

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Excitation functions for fission following fusion of ^{32}S and ^{144,154}Sm exhibit a strong dependence on the deformation of the target nucleus, although the fission decay selects large ($l \geq 37\hbar$) angular momenta.

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The extent to which the fusion of heavy ions is influenced by the nuclear structure of the target and projectile nucleus is currently of great interest although unambiguous examples of such effects are very few. One such example is the effect of target or projectile deformation, which is expected to play a significant role[1-4] in the determination of fusion cross sections. In the case of the fusion of ^{16}O with Sm near the Coulomb barrier,[5] the cross section for the deformed ^{154}Sm was found to be considerably larger than for the spherical ^{148}Sm, a difference which can be accounted for by the lowering of the interaction barrier at the poles of the deformed nucleus for low-angular-momentum partial waves.

The question of whether or not such a effect will persist at energies well above the threshold region is an open one. At higher incident energy, any influence of nuclear structure will be even less visible in the total fusion cross section because of the contribution of many partial waves. Nuclear structure effects, in particular the effects of deformation discussed above, are expected to be most prominent for grazing partial waves which are most sensitive to features of the interaction barrier. However, the bulk of the total fusion cross section arises from the more central collisions which will tend to mask such effects. It is therefore necessary in some way to select the large-partial-wave contributions to the fusion cross section in order to isolate, for example, the effects of deformation. In the present Letter we report the results of measurements of fission following the fusion of ^{32}S with ^{144,154}Sm. As the fission decay results from a lowering of the fission barrier with respect to the yrast line with increasing angular momentum,[6] the measured cross sections represent the contributions of the highest partial waves to the total fusion cross section,[7] and might therefore be expected to display the effects of deformation.

A beam of ^{32}S ions from the Argonne National Laboratory superconducting linac was used to bombard targets of ^{144,154}Sm. The fission fragments were detected in coincidence with use of Si surface-barrier detectors placed approximately symmetrically on either side of the beam axis. The defining detector subtended a solid angle of 22 msr, the other 64 msr. A coincidence efficiency of 82% was measured. The absolute cross-section scale was obtained by normalizing the fission yields to the elastic scattering yield in a monitor detector placed at $\theta_{lab}=21°$ to the beam. Data were taken over the energy range $E_{lab}=138$ to 231 MeV in steps ranging from 1 MeV at the lower energies to 10 MeV at the highest energies. The beam energy was easily changed in small steps by adjusting the amplitude of the last active resonator of the linac. Energy changes in larger steps are equally easy by turning on or off the appropriate number of independently phased resonators. Total fusion-fission cross sections were obtained from the measured differential cross sections at $\theta_{c.m.}=90°$ by assuming a $1/\sin\theta$ angular distribution. This assumption is consistent with the results of a subsequent measurement[8] of the fission-fragment angular distribution for 200-MeV ^{32}S + ^{144,154}Sm, and is also in agreement with the findings of Bisplinghoff *et al.*[9] for the similar ^{35}Cl + ^{141}Pr system.

The measured total fission cross sections for ^{32}S + ^{144}Sm and ^{32}S + ^{154}Sm are shown plotted versus

$E_{c.m.}$ in Fig. 1. We see that although the cross sections for both systems are essentially identical at the higher energies, they have quite different slopes in the threshold region. This effect is accentuated in Fig. 2 where the ratio $\sigma(^{154}Sm)/\sigma(^{144}Sm)$ is plotted as a function of E_{lab}, this ratio reaching a value of almost 6 at the lowest energy measured. These results are qualitatively similar to those of Stokstad *et al.*,[5] who measured larger fusion cross sections for the deformed target than for the spherical one at subthreshold energies.

In order to obtain a more quantitative understanding of these observations we have performed a simple model calculation of the fusion-fission cross sections, which incorporates in an approximate way the effects of target deformation. The quantity calculated is the angle-averaged cross section $\langle\sigma(\theta)\rangle$, where θ is the angle between the symmetry axis of the deformed nucleus and the beam direction. The angle-dependent cross section $\sigma(\theta)$ is given by

$$\sigma(\theta) = \pi\lambda\!\!\!^{-}{}^2 \sum_{l=4}^{\infty} (2l+1)T_l(\theta)P_l^f. \quad (1)$$

The $T_l(\theta)$ are the angle- and angular-momentum-dependent barrier transmission coefficients, which were calculated according to the method given by Wong.[3] This method assumes an inverted parabolic interaction barrier specified by an angular-momentum-independent curvature $\hbar\omega_0$ and a height $V_l(\theta)$ given by

$$V_l(\theta) = V_0(\theta) + (\hbar^2/2\mu R_0^2)l(l+1), \quad (2)$$

where V_0 and R_0 are the height and position of the s-wave barrier. The fission probability P_l^f was calculated using the standard Fermi-gas expression[10] for the competition between neutron evaporation and fission. The angular momentum dependence of this quantity was taken into account by the introduction of angular-momentum-dependent neutron binding energies B_l^n and fission barriers B_l^f, which are given by

$$B_l^n = B_0^n + \hbar^2 l(l+1)/2\mathscr{I}_0 \quad (3)$$

and

$$B_l^f = B_0^f + \hbar^2 l(l+1)/2\mathscr{I}_s. \quad (4)$$

Here $\mathscr{I}_0$ and $\mathscr{I}_s$ are moments of inertia characterizing the yrast and saddle-point shapes[6] of the rotating compound nucleus.

The parameters used in the calculations are listed in Table I. The interaction barriers were obtained by scaling those for $^{16}O + Sm$ complete fusion[5] according to the size of the participating nuclei. The level-density parameter for neutron decay was taken to be $a_n = A/8.5$ and that for fission $a_f = 1.1\, a_n$, both of which are standard. The ^{144}Sm data were then fit by varying B_0^f and $\hbar\omega_0$. The value of $\hbar\omega_0$ was then fixed and the ^{154}Sm data fit by varying only B_0^f and β_2. The results of these calculations are shown as solid lines in Figs. 1 and 2. For comparison, a calculation which assumes $\beta_2 = 0.0$ for ^{154}Sm is shown as a dashed line in both figures. We take the results as strong qualitative evidence for the existence of an entrance-channel deformation effect in the

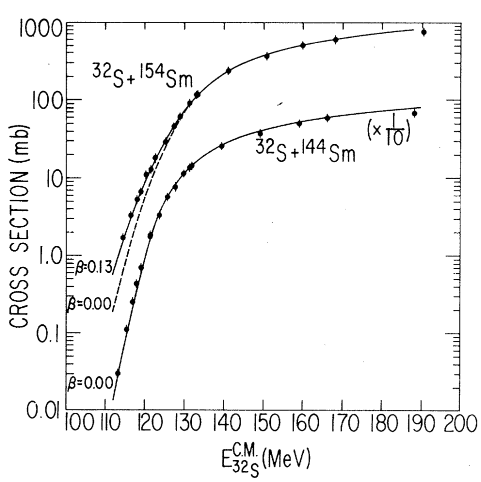

FIG. 1. Fission excitation function for $^{32}S + ^{144,154}Sm$ as a function of center-of-mass energy. The solid and dashed curves represent model calculations as described in the text. The error bars reflect the relative errors; the uncertainty in the overall normalization is believed to be less than 25%.

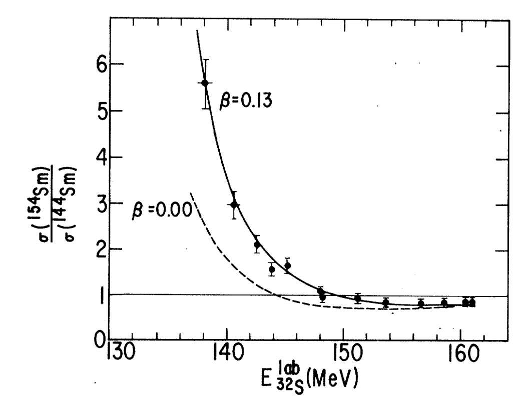

FIG. 2. The ratio of fusion-fission cross section for ^{154}Sm and ^{144}Sm target nuclei as a function of E_{lab}. The solid and dashed curves represent model calculations as described in the text.

TABLE I. Parameters used in the calculation of fusion-fission cross sections.

	β_2	V_0 (MeV)	R_B (fm)	$\hbar\omega_0$ (MeV)	Q (MeV)	B_0^n (MeV)	B_0^f (MeV)	$\hbar^2/2\mathscr{I}_0$ (MeV)	$\hbar^2/2\mathscr{I}_s$ (MeV)
^{144}Sm	0.0	112.0	10.5	10.0	−80.0	11.0	17.0	0.0066	0.0031
^{154}Sm	0.13	108.0	10.7	10.0	−61.0	9.10	18.7	0.0060	0.0031

fusion-fission process.

Before discussing the quantitative significance of these calculations, however, several remarks are in order. It was found necessary to introduce a constant normalization factor 0.6 for both systems to reproduce the overall magnitude of the measured cross sections. This may reflect an incorrect choice for the ratio a_n/a_f, the interaction barrier V_0 or possibly indicate the importance of decay modes other than neutron evaporation or fission, alpha-particle emission for example.[11] Secondly, the procedure of fitting the $\hbar\omega_0$ for ^{144}Sm, and keeping it constant and only changing β_2 to fit the ^{154}Sm data may mask any interdependence of the various parameters. Lastly, the neglect of the azimuthal angle needed to completely specify the orientation of the target for noncentral collisions is perhaps a significant omission. The consequence of this omission is that the calculations tend to overestimate the effect of deformation and correct averaging over the azimuthal orientation angle will result in a larger value of β_2 needed to fit the data.

With these points in mind, we note that the value of $\beta_2 = 0.13$ from the present calculations is smaller than both the accepted value of $\beta_2 = 0.27$ for the ^{154}Sm ground-state deformation[12] and the value of $\beta_2 = 0.20$ obtained from ^{16}O + ^{154}Sm fusion measurements.[5] Inclusion of azimuthal averaging may bring the present value into agreement with that of Ref. 5, but it seems likely that other deficiencies of the calculations are equally important. Of particular interest in this respect is the importance of dynamical effects as opposed to the purely static effects considered here.

In conclusion, fusion-fission cross sections for spherical and deformed target nuclei have been measured in the fission threshold region to selectively study the high-angular-momentum contributions to the total fusion cross sections and their dependence on nuclear deformation. The results are qualitatively similar to those previously observed for low angular momenta near the fusion threshold. The data can be accounted for by static deformations in a simple model, although the inadequacies of the model preclude a quantitative discussion of the significance of the deformation parameter β_2 extracted from the data. Clearly further work is needed in order to better answer questions such as of the importance of dynamical versus static effects, which are central to our understanding of heavy-ion interactions.

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