Observation of Mean-Spin Barrier Bump in Sub-barrier Fusion of ^{28}Si with ^{154}Sm

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Abstract

We have measured the fusion excitation function and gamma-ray multiplicities, M_γ , for the $^{28}\text{Si} + ^{154}\text{Sm}$ system. We have also measured M_γ for the $^{16}\text{O} + ^{166}\text{Er}$ system that leads to the same compound nucleus, ^{182}Os . This is used to calibrate the connection between M_γ and the first moment of the spin distribution of the compound nucleus, $\langle \ell \rangle$. We find that the deduced $\langle \ell \rangle$ in $^{28}\text{Si} + ^{154}\text{Sm}$ agrees reasonably well with theoretical expectations, and in particular exhibits the barrier bump expected when another degree of freedom is strongly coupled to the relative motion.

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The fusion between heavy ions at low bombarding energies are governed largely by the quantum mechanical penetration through the Coulomb plus

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centrifugal barrier. Fusion cross section excitation functions have been measured for many heavy ion systems, and are observed to become orders-of-magnitude larger than one-dimensional barrier penetration calculations at the lowest observable energies. These enhancements are understood in terms of theoretical models which explicitly consider the coupling of the relative-motion coordinate in the entrance channel to other degrees of freedom (deformation, vibration, and transfer)[1, 2]. Thus sub-barrier fusion is an interesting process for probing the role of several degrees of freedom in quantum mechanical tunneling processes. However, a more stringent test can be obtained by comparing not only the fusion cross section but also the shape of the spin distribution which comprises the fusion cross section.

Information on the first moment of the spin distribution, $\langle \ell \rangle$, can be obtained from measurement of average gamma ray multiplicities, M_γ [3]–[5]. Higher moments can in principle be deduced by measuring full multiplicity distributions with large-array gamma detectors[6, 7]. Recently, $\langle \ell \rangle$ has been determined from measurements of the ratio of the population of a high spin isomer state to that of a low spin ground state[8, 9]. The second order moment of the spin distributions can be obtained from measurements of alpha or fission fragment angular anisotropies[10, 11].

One-dimensional barrier penetration models predict that the first moment of the spin distribution should decrease more slowly with decreasing bombarding energy as one approaches the barrier, and eventually become an approximately constant but non-zero value at sub-barrier energies[12]. This saturation effect of $\langle \ell \rangle$ at energies below the Coulomb barrier has been observed recently for $^{12}\text{C} + ^{128}\text{Te}$, $^7\text{Li} + ^{133}\text{Cs}$, and $^3\text{He} + ^{136}\text{Ba}$ [8, 9], where the coupling to the shape degrees of freedom is relatively weak. If the coupling to other degrees of freedom, such as shape degrees of freedom, is strong, then

$\langle \ell \rangle$ increases in the vicinity of the barrier. This gives rise to a bump in the energy dependence of $\langle \ell \rangle$ relative to the no-coupling case[12]. Although increases in $\langle \ell \rangle$ have been observed at low bombarding energies[5, 6, 12], the predicted energy dependence has not been clearly established experimentally, largely because of the difficulties in obtaining information at sub-barrier energies where the cross section is small.

In the present work we have exploited the sensitivity of an electrostatic deflector to measure gamma ray multiplicities as a probe of the spin distribution in the $^{28}\text{Si} + ^{154}\text{Sm}$ system. Traditionally the connection between the measured gamma ray multiplicities and $\langle \ell \rangle$ has been made through the systematic relation between these quantities in neighboring regions of the periodic table[3] or through *a priori* expectations for this relation[6]. In the present study we decided to calibrate this connection experimentally by using the reaction $^{16}\text{O} + ^{166}\text{Er}$ that leads to the same compound nucleus ^{182}Os . At bombarding energies between 75 and 100 MeV this reaction spans the same range of excitation energies and multiplicities as the reaction $^{28}\text{Si} + ^{154}\text{Sm}$ at bombarding energies between 107 and 144 MeV, as can be seen by comparing Fig. 1b and Fig. 2b. The relevant energy range spanned by the $^{16}\text{O} + ^{166}\text{Er}$ reaction lies above the Coulomb barrier for this system, where the spin distribution becomes relatively model independent once the fusion cross section is reproduced.

Measurements were made using both the tandem accelerator at the Tandem Laboratory and the tandem-booster accelerator at the University of Washington. The measurement of the $^{28}\text{Si} + ^{154}\text{Sm}$ fusion cross sections were performed at the Tandem Laboratory using the delayed x-ray activity technique discussed in Ref. 13. The known half-lives and the number of x-rays produced per decay are the same as those used in the $^{16}\text{O} + ^{166}\text{Er}$ reaction,

which leads to the same residual nuclei[14]. The experimental fusion cross sections for $^{28}\text{Si} + ^{154}\text{Sm}$ are presented in Fig. 2a (open squares) as a function of laboratory bombarding energy. We have also made an independent measurement of the fusion cross section at several energies by measuring the absolute intensities of the rotational de-excitations in the 4n channel product ^{178}Os . When these intensities are extrapolated to $J=0$ and corrected for the fraction of the fusion cross section leading to the 4n channel, they give rise to cross sections in good agreement with those obtained by the delayed x-ray activity method (see plus symbols in Fig. 2a).

The gamma multiplicities were obtained using the electrostatic deflector at the University of Washington Nuclear Physics Laboratory[5]. This electrostatic deflector was used in combination with two $7.6\text{cm} \times 7.6\text{cm}$ NaI detectors and a low pressure multi-wire proportional counter (Breskin detector)[17]. The Breskin counter, in conjunction with the time signal from the pulsed beam, provided the time of flight of the particles. This information enabled us to separate the evaporation residue fusion products from the quasi-elastic events. The ratio of these residues in coincidence with the NaI detectors to the residues singles yields M_γ , independent of the efficiency of the Breskin detector. Since the fusion products are strongly peaked at zero degrees, high efficiency can be achieved with this device. The results of our multiplicity measurements for $^{16}\text{O} + ^{166}\text{Er}$ and $^{28}\text{Si} + ^{154}\text{Sm}$ are shown in the Figs.1b and 2b. The values of M_γ reported here have not been corrected for internal conversion. This correction is included however in the determination of $\langle \ell \rangle$ and is the same for both of the systems studied here.

The fusion cross section excitation function for the $^{16}\text{O} + ^{166}\text{Er}$ system has been measured recently[14], and is shown in Fig. 1a. The fusion excitation function has been fit by the Wong model[15] which takes into account the

quadrupole deformation of the target, and by a coupled channels model[16] where we have included both the projectile and target quadrupole deformations and also the target hexadecapole deformation and octupole vibration. We show the expectation of these two models for $\langle \ell \rangle$ in Fig. 1c. Above the barrier, V_b , both models agree fairly well, with the difference among them giving an estimate of the uncertainty in the value of $\langle \ell \rangle$ at each energy. The connection between the measured M_γ and $\langle \ell \rangle$ was made using a modified version of the procedure used by Halbert *et al.*[6]. The results for the $^{16}\text{O} + ^{166}\text{Er}$ system in Fig. 1c thus serve as a calibration of this procedure. Then we use this procedure for obtaining $\langle \ell \rangle$ from M_γ for the $^{28}\text{Si} + ^{154}\text{Sm}$ system at excitation energies between 42 and 74 MeV. The results are shown in Fig. 2c.

As in the case of the $^{16}\text{O} + ^{166}\text{Er}$ calibration reaction, we have fit the fusion excitation function for $^{28}\text{Si} + ^{154}\text{Sm}$ with the same models as mentioned above. The parameters used are given in the figure caption. We then show in Fig. 2c the expected $\langle \ell \rangle$ from these models. It can be seen that the coupling effects are very strong, leading to a large increase in the $\langle \ell \rangle$ values near the barrier. It is also seen that our measurements are in accord with this expectation, demonstrating clearly the expected effect. The quadrupole deformation of ^{154}Sm is the dominant contributor to the coupling effects.

It is perhaps useful at this point to recall the physical origin of the increase in $\langle \ell \rangle$ at near-barrier energies. Depending on the relative orientation of the deformed reaction partners, the $\ell=0$ barrier is either raised or lowered compared to that for spherical reaction partners. At bombarding energies near the $\ell=0$ barrier a lowering of the barrier allows many more partial waves to contribute than would otherwise be possible, increasing the $\langle \ell \rangle$ dramatically. At very sub-barrier energies one is below the barrier for

all orientations, and the ℓ distribution is determined by the relative penetrabilities of the different ℓ -dependent barriers which for parabolic barriers is independent of energy when $E \ll V_b$. At energies well above the barrier many ℓ values are already above-barrier, and fluctuations in the $\ell=0$ barrier affects a smaller fraction of the contributing partial waves and $\langle \ell \rangle$ approaches the no-coupling limit at high E .

In summary, we have measured the average gamma ray multiplicities for the $^{16}\text{O} + ^{166}\text{Er}$ and $^{28}\text{Si} + ^{154}\text{Sm}$ systems which lead to the same compound nucleus ^{182}Os . The former reaction serves as a calibration reaction for obtaining the connection between M_γ and $\langle \ell \rangle$ in the compound nucleus of interest. An electrostatic deflector provided sufficient sensitivity to make measurements well below the barrier for the latter reaction. The energy dependence of $\langle \ell \rangle$ shown in Fig. 2c for the $^{28}\text{Si} + ^{154}\text{Sm}$ system at near-barrier energies demonstrates clearly for the first time the large increase in $\langle \ell \rangle$ expected for systems where the shape degrees of freedom are strongly coupled to the relative motion degree of freedom.

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Figure Captions

Figure 1: $^{16}\text{O} + ^{166}\text{Er}$ a) Fusion excitation function (ref.14). The solid curve is the Wong model fit ($V_b=64.5$ MeV c.m. $R_b=11.06$ fm, $\hbar\omega=3.40$, $\beta_2R=0.23 \times 6.58=1.5$ fm). The dashed curve is the same fit with the coupling turned off. The dotted curve is from a coupled channels calculation ($V_B = 65.3$ MeV c.m. $R_b = 11.27$, $\hbar\omega = 9.61$) including the static deformation ($\beta_2R=0.342 \times 6.60=2.26$ fm) and the octupole vibration ($\beta_3R=0.053 \times 6.60=0.35$ fm) b) Experimental γ -ray multiplicities as a function of laboratory energy. Excitation energies E^* of the compound nucleus ^{182}Os are also shown. c) Experimental $\langle \ell \rangle$ obtained from multiplicities. The solid and dotted curves are $\langle \ell \rangle$ from the Wong model and coupled-channels fits above. The dashed curve is from the Wong model without coupling.

Figure 2: $^{28}\text{Si} + ^{154}\text{Sm}$ a) Fusion excitation functions from x-ray activities and rotational band de-excitation of ^{154}Sm (^{28}Si , 4n) ^{178}Os . The solid curve is Wong model fit to the ($V_b=101.5$ MeV c.m. $R_b=10.91$ fm, $\hbar\omega=4.55$, $\beta_2R=0.24 \times 6.43=1.54$ fm). The dashed curve is the same fit with the coupling turned off. The dotted curve is a coupled channels calculation ($V_B = 102.2$ MeV c.m. $R_b = 11.48$, $\hbar\omega = 4.3$) including the deformation effect of ^{154}Sm ($\beta_2R=0.341 \times 6.43=2.19$ fm, $\beta_4R=0.07 \times 6.43=0.45$ fm) the octupole vibration of ^{154}Sm ($\beta_3R=0.1 \times 6.43=0.64$ fm) and the quadrupole vibration of ^{28}Si ($\beta_2R=-0.41 \times 3.42=-1.37$ fm). b) Experimental γ -multiplicities. Excitation energies of the compound nucleus ^{182}Os are also shown. c) Experimental $\langle \ell \rangle$ from multiplicities. The solid and dotted curves are $\langle \ell \rangle$ from the Wong model and coupled-channels fits above. The dashed curve is the Wong model without coupling.

Fig. 1

Fig. 2

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