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Absence of anomalous entrance channel effects in sub-barrier heavy ion fusion

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Fusion cross sections and gamma ray multiplicities have been measured for the ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn entrance channels leading to the ^{170}Hf compound nucleus. The mean spins deduced from the gamma multiplicities do not show any anomalous behavior as observed in some other measurements.

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Sub-barrier fusion reactions play an important role in a number of physical processes. Elemental nucleosynthesis in a stellar environment is dependent on very sub-barrier fusion reactions such as the ^{12}C$(\alpha,\gamma)^{16}$O reaction [1]. For light systems such as this the reaction rate is often determined by specific resonances. For heavier systems where the compound nuclear level density is higher the dependence of the cross section on bombarding energy is smooth and the interest centers more on the cross section enhancement associated with coupling other degrees of freedom to the relative motion coordinate. Barrier penetration on multidimensional potential energy surfaces is of considerable interest in chemical reactions [2] as well as in nuclear reactions.

It is now well-known that sub-barrier heavy ion fusion can be enhanced by many orders of magnitude over that expected from one-dimensional barrier penetration [3]. A number of suggestions have been made for the origin of this enhancement, including collective shape effects, and the role of nucleon transfer channels. The importance of static deformations is well established [4]. Less clear is the role of particle transfer and particularly of neutron transfer as a doorway to neck formation.

The early studies of sub-barrier fusion focused on measuring the fusion excitation function: the dependence of fusion cross section on bombarding energy. This may be thought of as the zeroth moment of the partial wave (spin) distribution, $\sigma(l)$. More stringent tests of reaction models can be obtained by measuring the higher moments of the spin distribution, such as the mean spin and the mean square spin. This is because one can have different spin distributions which integrate to the same fusion cross section. Qualitatively, in most models the effect of coupling other channels to the entrance channel is to enhance the cross section at all sub-barrier energies, whereas the effect on the mean spin appears as an enhancement near the barrier which disappears at both lower and higher energies [5]. The results of mean spin measurements to date have not led to a clear picture. Although many systems exhibit an increase of the mean spin near the barrier of the magnitude expected, several systems exhibit a larger than expected increase. There are some hints that these deviations occur primarily for more symmetric entrance channels, although contrary examples can be cited [5]. The purpose of the present study was to explore several reactions differing in their entrance channel mass asymmetry which lead to the same compound nucleus. By choosing reactions that lead to the same compound nucleus one is assured that there is the same rotational energy cost in finally reaching the compound nucleus for a given partial wave in each system. More importantly, by making the same compound nucleus, certain systematic uncertainties in determining the cross section and particularly in the deduction of the mean spin will be common to all systems. This enables a more stringent comparison between the results for the different systems. The three systems studied are the ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn systems leading to ^{170}Hf is formed at excitation energies near 50 MeV for all three reactions at near-barrier energies.

The results presented in this report are the product of a collaboration between groups working at the University of Washington and at the TANDAR Laboratory in Buenos Aires. The study involves the measurement of the fusion evaporation residue cross sections, the fusion fission cross sections, and the gamma ray multiplicities. The details of the three experiments will be reported elsewhere [6,7].

The evaporation residue cross sections were measured at the TANDAR laboratory using the x-ray activation technique. Evaporation residues were collected on catcher foils and analyzed off-line for x rays resulting from radioactive decay of the various residues. The characteristic x rays of the different elements were followed as a function of time and the resulting decay curves were decomposed into the contributions from individual nuclides. Decay scheme information was used to deduce the number of x rays per decay for each product. The channel yields were summed to give the total evaporation residue yield at each energy. The uncertainties in the absolute cross section due to uncertainties in detector efficiency and decay scheme information is about 15%, while the relative comparisons for the cross sections for different systems have a smaller uncertainty.

For the more symmetric entrance channel at higher energy fission competes with particle evaporation, and one must include the fission cross section to get the total fusion cross section. We have measured the fission cross section for the two more symmetric entrance channels. A kinematic coincidence technique was used to uniquely identify the fission fragments. The differential fission cross sections were measured near 55° in the c.m., an angle from which the total fission cross section can be deduced with little uncertainty due to angular distribution effects. The fission cross section comprises about 30% of the fusion cross section at the highest energy for the ^{48}Ti+^{122}Sn system and about 10% for the ^{32}S+^{138}Ba system. The fission cross section is predicted to be small for the ^{28}Si+^{142}Ce system and was not measured. We have added the small amount predicted by a statistical model

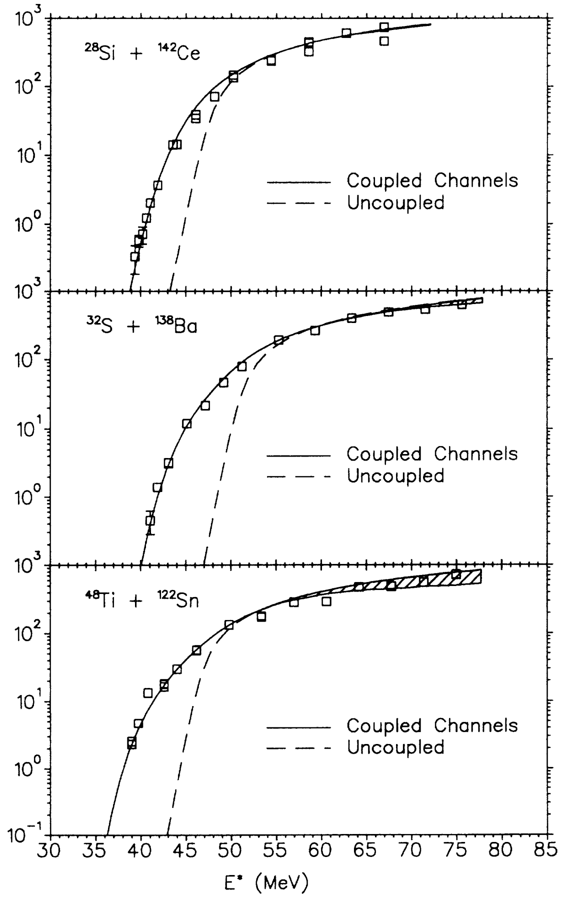

FIG. 1. Fusion excitation functions for ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn as a function of excitation energy in the compound nucleus. The shaded area represents the contribution of fission to the total fusion cross section. The solid curves are from coupled channels fits to the data. The dashed curves are from a one-dimensional barrier penetration model calculation.

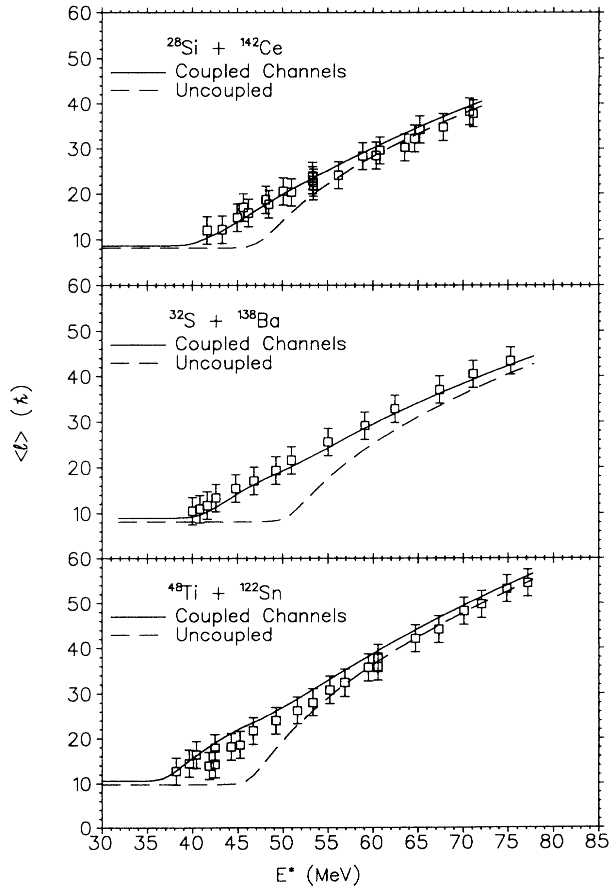

FIG. 2. Mean spins for ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn as a function of excitation energy in the compound nucleus. The solid curves are the predictions of our CCDEF calculations that fit the fusion excitation function for each system respectively.

calculation (4% at the highest energy) for this system. The total fusion excitation functions for the three systems are shown in Fig. 1. Since the evaporation residue and fission cross sections were determined at different energies, we have interpolated the fission cross section to add to the evaporation residue cross section to get the total fusion cross section points shown. The cross hatched area representing fission is also obtained by smooth curves through the fusion and fission data.

We have performed coupled channels calculations using the CCDEF code for the three systems studied [8]. We included the lowest-lying 2^+ and 3^- states for both target and projectile, using literature values of deformation parameters. We also included the one-neutron pickup channel. We have found that including additional transfer channels has little effect [7]. The only adjustable parameter in these calculations is the strength of the nuclear potential determining the spherical nucleus barrier height. This parameter is fine tuned about a global parametrization to reproduce the high energy cross section. The results of these calculations are compared with the data in Fig. 1. A very satisfactory representation of the data is achieved.

We have also measured gamma-ray multiplicities in order to extract the mean spin of the compound nuclear spin distribution. The gamma rays were detected by 7.6 cm by 7.6 cm NaI detectors covered by graded absorbers so as to achieve a flat total efficiency as a function of gamma-ray energy. Three detectors were placed at angles close to the zero of $P_2(\cos\theta)$ so as to minimize angular distribution effects. Fusion events were tagged by measuring gamma rays in coincidence with evaporation residues. The evaporation residues were separated from the beam by an electrostatic deflector. Further discrimination against projectilelike fragments was achieved by time-of-flight. The raw gamma-ray multiplicities were corrected for gammas below the threshold of our detectors and for converted transitions.

The conversion of gamma-ray multiplicities to mean spin was performed using a procedure similar to that of Halbert *et al.* [9]. This procedure has been checked for a nearby compound nucleus using above-barrier light ion induced reactions [10]. The contribution to the mean spin from compound nuclei which fission has been deter-

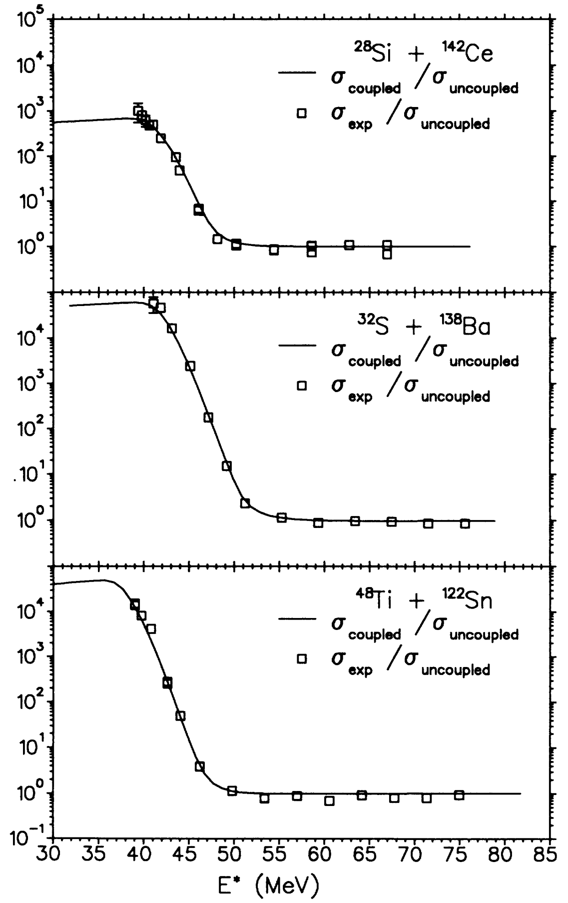

FIG. 3. Ratio of experimental fusion cross sections (squares) to cross sections from an uncoupled (one-dimensional) barrier penetration model for ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn as a function of the excitation energy in the compound nucleus. The solid curve in each panel is the ratio of the results of a coupled channels calculation relative to the results of the uncoupled calculation.

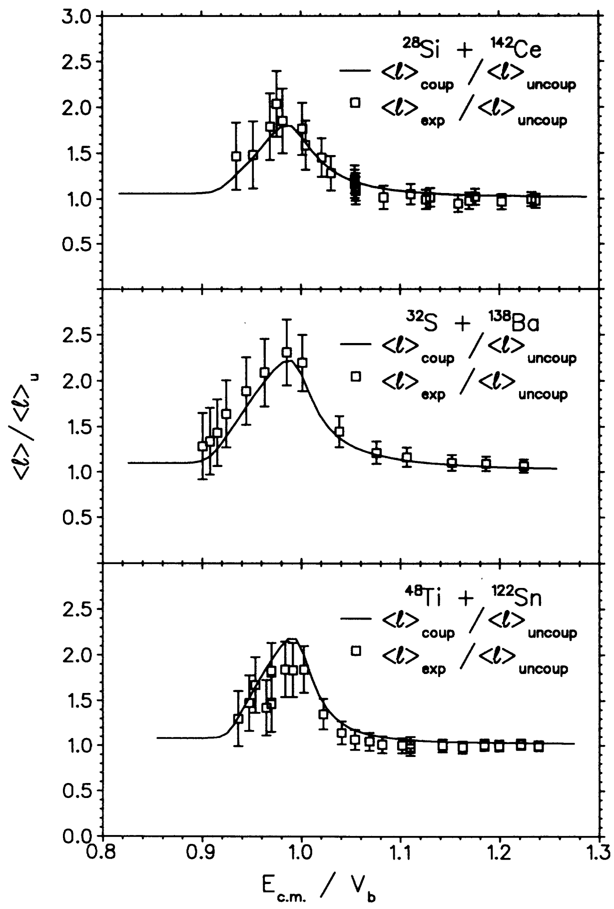

FIG. 4. Ratio of experimental ⟨l⟩'s (squares) to the ⟨l⟩'s from uncoupled (one-dimensional) barrier penetration model calculations for ^{28}Si+^{142}Ce, ^{32}S+^{138}Ba, and ^{48}Ti+^{122}Sn as a function of the energy in the center of mass relative to the fusion barrier in the uncoupled case. The solid curve in each panel is the ratio of coupled channels calculated ⟨l⟩'s with all couplings included relative to the same uncoupled ⟨l⟩'s.

mined by application of a sharp-cutoff model to the evaporation residue and fission cross sections. The mean spins obtained in this way are shown for the three systems in Fig. 2. Also shown in this figure are the coupled channels model predictions based on the fit to the fusion cross sections discussed previously. No new parameters are involved in this calculation. The model is able to reproduce the mean spins quite well for all systems, although there is some indication of a slight overestimation for the ^{44}Ti+^{122}Sn system near the barrier.

The success of a coupled channels calculation employing known quadrupole and octupole coupling strengths is in contrast to some earlier studies. Unexpected entrance channel effects have been reported by Halbert *et al.* [9], who concluded that the coupling strengths had to be increased by 50% to account for their mean spin and cross section data for the ^{64}Ni+^{100}Mo system. This conclusion is somewhat sensitive to the emphasis placed on reproducing their highest-energy cross-section datum [5]. A very recent experiment [11] reports cross sections for this system in agreement with coupled channels calculations. In a comparison of two entrance channels leading to the same ^{132}Ce compound nucleus, Hennrich *et al.* [12] found that the mean spin for the ^{32}S+^{100}Mo was consistent with expectations whereas the mean spin for the ^{36}S+^{96}Mo system was appreciably larger than expected. In order to exhibit the rather different way in which coupling to other degrees of freedom affects the fusion cross sections and the mean spins, it is instructive to plot both the ratio of the experimental data to an uncoupled calculation, and the ratio of the coupled channels calculations to the uncoupled calculations. This is done in Figs. 3 and 4. One sees that the fusion cross section gets increasingly enhanced with decreasing energy, until at very sub-barrier energies the model predicts a saturation at enhancements of about 10^3 to 10^4 for these systems. This saturation occurs when the bombarding energy drops below the lowest barrier resulting from the coupling. In contrast to this behavior for the cross section, the mean spin ratio exhibits a peak just below the barrier. This is the energy where the contributions from different $l=0$ barriers allow the largest change in the highest partial wave which can be transmitted easily. The decrease of the ratio with decreasing energy to a saturation value occurs at energies below the lowest barrier where the *relative* penetration of different partial waves no longer changes significantly with energy.

In summary, we have measured the fusion cross sections and mean spins for three entrance channels with differing mass asymmetry leading to the same compound nucleus. Contrary to some previous observations, we do not find any anomalous behavior as the mass asymmetry changes. The observations are well reproduced by coupled channels calculations with coupling strengths taken from known collectivities.

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