FUSION AND FISSION IN HEAVY SYSTEMS NEAR THE BARRIER

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W. Henning
Physics Division
Argonne National Laboratory
Argonne, IL 60439

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Fusion and fission reactions have been studied near the barrier for $^{58,64}\text{Ni}$ beams incident on all even Sn targets. Excitation functions have been measured over an energy range from well below to ~ 1.4 times the fusion barrier. We discuss the sub-barrier fusion yields, the observed fission behavior in comparison to theoretical model predictions and the possible influences of compound-nucleus structure effects at these energies near the barrier.

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I. INTRODUCTION

Heavy-ion fusion near the barrier provides an opportunity to study the interaction potential between two nuclei, both experimentally and theoretically, in a situation where only a tractable number of degrees of freedom seem of importance. The transition from a composite nuclear system to two separated heavy fragments is familiar from the well-known process of nuclear fission. There are similarities and differences between the two processes. Fission is considered to be a slow, adiabatic transition where there is sufficient time to allow all degrees of freedom to equilibrate. Fusion is thought to be fast with, near the barrier, possibly only quasi-elastic processes competing and influencing the interaction potential. Conventional fission studies near the barrier generally consider low angular momenta. In fusion between two heavy nuclei large angular momenta are involved even at barrier energies. This will also be true for heavy-ion fission at the barrier.

We have studied fusion¹ and fusion-fission² for the systems $^{58,64}\text{Ni} + ^{112-124}\text{Sn}$, with Ni beams from the Argonne Superconducting Linac incident on all even Sn targets. In addition to fusion products remaining after particle evaporation ("evaporation residues") we have measured fission cross sections, first of all with the intention of establishing the total fusion cross section. There are additional aspects of interest for these systems: i) The ratio of Coulomb to nuclear (surface) force spans the region where some dynamical models predict the onset of fusion inhibition at the barrier; ii) the barrier heights of the entrance (fusion) and exit (fission) channel 2-body interaction potentials are nearly identical when the ground-state mass differences are taken into account; iii) in terms of compound nucleus excitation, the classically calculated curve for the grazing angular momentum approaches the yrast line much more closely than for more asymmetric

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entrance channels leading to the same compound nucleus (Figure 1). As a consequence structure effects at high angular momentum may become more pronounced in the decay of the relatively cold compound nuclei produced in the $^{58,64}\text{Ni} + ^A\text{Sn}$ reactions.

Figure 1. Schematic figure illustrating, for classically calculated grazing collisions, the excitation-energy vs. angular momentum population of a Pt compound nucleus near $A = 188$ when populated by various target-projectile combinations. Also indicated are fission barrier and yrast line as a function of angular momentum. The insert shows theoretical predictions for the yrast line of ^{188}Pt from a microscopic-model calculation, as discussed later in the text.

II. EVAPORATION RESIDUE CROSS SECTIONS

Cross sections were measured at and near 0° utilizing an electrostatic deflector which removed most of the beam-like flux. Most of the experimental details and results have been published previously.^{1,2} Here we just want to emphasize the fact that the electric field deflects in one direction and consequently the full angular distribution for the evaporation residues can be measured in the direction perpendicular to this deflection. This is illustrated in Figure 2 and an example of a typical angular distribution is given in Figure 3.

Figure 2. Electrostatic-deflector and detector set-up to measure yields of fusion residues after particle evaporation.

Figure 3. Angular distributions of evaporation residues measured with the electrostatic deflector for three deflector-voltage settings.

Uncertainties in detection efficiency, and consequently in the cross section measurements, are therefore strongly reduced by this technique.

The results for the evaporation residue cross sections are shown in Figure 4. In the lower part we have plotted the maxima in cross section for each excitation function. There are substantial differences in the maximum cross sections between systems, close to an order of magnitude, most likely originating from different fission competition as suggested by the results of statistical model calculations which are also indicated in the figure.

Figure 4. Top: Excitation functions for $^{58,64}\text{Ni}$ -induced fusion on the even Sn targets followed by particle evaporation. Left: Cross section values at $E_{c.m.} = 180$ MeV as a function of compound nucleus mass. The solid- and dashed-line histograms are results of statistical model predictions.¹

III. FISSION CROSS SECTIONS

Fission fragments were measured with two kinematically coincident detectors:
i) a small ΔE -gas, E-silicon surface barrier detector telescope defining the solid angle and yielding ΔE , E , θ , and time-of-flight signals and ii) a large area gas detector providing information on ΔE , E , θ and the azimuthal angle ϕ . Angular distributions in the forward angle-range revealed a $1/\sin \theta$ dependence; small corrections to the distributions calculated from the statistical fission model using rotating liquid drop model saddle-point shapes³ were included. The angle and mass integrated fission cross-section is plotted in Figure 5 for the various Ni + Sn systems.

FISSION EXCITATION FUNCTION $^{56}\text{Ni} + {}^A\text{Sn}$

FISSION EXCITATION FUNCTION $^{64}\text{Ni} + {}^A\text{Sn}$

Figure 5. Excitation functions of fission after fusion for $^{58,64}\text{Ni} + {}^A\text{Sn}$.

IV. TOTAL FUSION CROSS SECTIONS

The sums of the evaporation-residue and fission cross sections yield the total fusion cross sections, as plotted for example for $^{64}\text{Ni} + {}^A\text{Sn}$ in Figure 6. The data show the following features: i) There is no or very little difference between the maxima in cross section reached in the various systems. The large differences previously observed in the evaporation residue yields arise from changing fission competition in the decay process. However, as discussed below in detail, the fission to light-particle-evaporation competition is not easily reproduced by statistical model calculations of the relative decay widths. ii) Except for the energy region below the barrier, the fusion cross sections are well represented by dynamical fusion model calculations employing the equations given by Björnholm and Swiatecki.⁴ This is illustrated by the solid line drawn in Figure 6. In particular, when taking into account the $(N-Z)/A$ dependence of this later model, the data are well described for the whole range of neutron number. This is in contrast to the earlier model⁵ which predicted the onset of fusion inhibition near the barrier when spanning a change in neutron number of 18 for a constant compound nucleus charge $Z = 78$. iii) At energies below the classical barrier, which corresponds to the energy where the dynamical-model cross section is predicted to go to zero, there is considerable fusion cross section indicating quantum-mechanical tunneling through the interaction barrier.

Figure 6. Total fusion cross sections for $^{64}\text{Ni} + {}^A\text{Sn}$. Absolute errors, including systematic uncertainties, are approximately 20%.

V. SUB-BARRIER FUSION

It is well established by now that the sub-barrier cross section for heavy-ion fusion is strongly affected by the quasielastic degrees of freedom, inelastic scattering and few-nucleon transfer. Quite generally, coupling of these channels to elastic scattering modifies the interaction potential in such a way that enhanced tunneling occurs at sub-barrier energies compared to a situation where the interaction potential is solely represented by the elastic-scattering real potential say from a folding model approach.⁶ This is clearly observed in our Ni + Sn data (Figure 6) and explicitly demonstrated for two of the systems leading to the same compound nucleus (Figure 7).

Figure 7. Values of the subbarrier evaporation-residue cross section for $^{58}\text{Ni} + ^{124}\text{Sn}$ (filled circles) and $^{64}\text{Ni} + ^{118}\text{Sn}$ (open circles), compared with optical-model reaction cross sections (solid line), the extra-push model (long-dashed line), and a Hill-Wheeler barrier-penetration calculation (short-dashed line). Error bars denote statistical uncertainties only.

The importance of these other degrees of freedom can be indirectly demonstrated by the elastic scattering analyses and calculations represented in Figure 8 for $^{58}\text{Ni} + ^{124}\text{Sn}$. In the lower part we have plotted the quality of a modified optical-model calculation in comparison to elastic scattering data measured near the barrier ($E_{\text{cm}} = 176.5$ MeV) in terms of a ratio of χ^2 relative to χ_0^2 , the latter being the optimum χ^2 obtained from a six-parameter optical-model fit to the data. The χ^2 values are obtained in modified optical model calculations where a distorting potential of the type sketched in Figure 8 (dashed curve) was added at various radii. The χ^2 values indicate the extent to which this distortion is felt in the elastic scattering calculation; an effect is only observed where the distortion is moved to radii $R > 14$ fm. Clearly the imaginary potential and thus absorption dominate the scattering matrix up to this distance, which extends well out to and beyond the barrier region. It is obvious then, that the barrier penetration must be strongly effected by additional degrees of freedom other than real-potential elastic scattering only.

A study to determine which channels are most important is presently underway at Argonne. In a first measurement of $^{58,64}\text{Ni} + \text{Sn}$ at energies somewhat above the barrier⁷ we have found that the quasielastic processes contribute up to 600 mb, i.e. $\approx 30\%$, of the total reaction cross section. This ratio might be expected to increase when approaching the barrier.

Figure 8. Results of optical-model calculations for $^{58}\text{Ni} + ^{124}\text{Sn}$ at $E_{\text{c.m.}} = 176.5$ MeV (see text).

As already mentioned, statistical model calculations for the compound-nucleus decay using the code CASCADE⁸ do not represent the fission decay widths when standard model parameters are used. We are presently involved in a systematic study as to which physical parameters are most sensitive for an adequate description of the data. This parameter search is not yet completed and we therefore restrict our discussion at this point to a more qualitative description of the observed discrepancies as illustrated in Figure 9 for one system. The calculated curve for fission overpredicts magnitude and overall slope observed in the data. The trend, in addition, is opposite to what is generally observed in heavy-ion fission with

Figure 9. Evaporation-residue, fission, and total fusion cross sections for $^{64}\text{Ni} + ^{124}\text{Sn}$. The curves labeled B_{RLDM} and B_{SIERK} are statistical model calculations for fission as discussed in the text.

more asymmetric entrance channels (typically ^{28}Si , ^{32}S etc. projectiles), and consequently higher compound nucleus excitation energy (see Figure 1). In those systems a reduction in fission barrier relative to the standard liquid-drop model predictions has been observed, typically to $\sim 85\%$, which recently has been quite convincingly demonstrated to be accounted for by finite-range effects in the fission-barrier calculations.⁹ Here, however, such a calculation (performed by

implementing Sierk's formalism¹⁰ into CASCADE) increases the discrepancy (Figure 9). For a more systematic discussion we extract, both from the data and the calculation, the energy value at which the fission width Γ_f and particle-decay width Γ_x are of equal magnitude, i.e. at the crossover of fission and evaporation-residue excitation functions.

The results are plotted in Figures 10, both in terms of C.M. energy and compound-nucleus excitation energy. The discrepancies between data and calculations are substantial and become largest for systems with lowest compound nucleus excitation energy, i.e. closest vicinity to the fission-barrier and compound nucleus yrast line. (In the calculated curves small irregularities due to ground-state mass

Figure 10. Left-hand side: C.M. energies for the cross-over of evaporation-residue and fission excitation functions, i.e. C.M. energies at which fission width Γ_f and particle-decay width Γ are of equal magnitude. Right-hand side: Same cross-over energy, but now in terms of compound nucleus excitation energy.

differences have been smoothed out to emphasize the overall trend.)

It is worth while mentioning that the calculations were performed using the experimentally observed total fusion cross section for compound nucleus formation. The low-energy enhancement in the observed fission yield over the calculated one thus does not reflect the enhanced fusion cross section, since this has been factored out, but rather a "sub-barrier fission enhancement". This is emphasized in Figure 11, where the $^{58}\text{Ni} + \text{Sn}$ fission data are plotted together with a standard CASCADE calculation with parameters chosen such that at energies above the barrier the overall trend of the data is reproduced.

FISSION EXCITATION FUNCTION $^{58}\text{Ni} + {}^A\text{Sn}$

Figure 11. Illustration of the "sub-barrier fission enhancement" as discussed in the text.

At the fusion-barrier energies, both the entrance and exit-channel two-body potential barrier heights are very close in value when ground-state mass differences are correctly accounted for. It is possible that the vicinity of compound nucleus yrast line and saddle point barrier-height (Figure 1; see also reference 11) make the present fission data sensitive to structure effects (see also the indications of irregularities in the fission excitation function behavior which, however, need to be more firmly established experimentally). It seems also possible that selected degrees of freedom couple to the fission exit channel below and near the barrier similar to the sub-barrier situation for the fusion entrance channel.

VII. SUMMARY AND CONCLUSIONS

Fusion and fission cross sections have been measured below and near the entrance channel barrier for $^{58,64}\text{Ni}$ beams incident on all even-even Sn isotopes. For these heavy systems again a substantial fusion yield at sub-barrier energies is observed, reflecting the importance of coupling between elastic and most likely inelastic scattering and neutron-transfer channels at these energies. Fission

yields appear substantially suppressed as compared to statistical model predictions except for the sub-barrier regime. This behavior might be influenced by the closeness in these systems of the compound nucleus excitation energy to the yrast line and to the fission barrier, noticeably for high angular momenta.

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