Fission and Particle Decay of Cold Compound Nuclei with High Angular Momentum

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We have measured fission and particle-evaporation cross sections for the nuclei $^{170-188}$Pt formed with the reactions ^{58,64}Ni + $^{112-124}$Sn. This represents the first systematic study of the decay of compound nuclei formed with heavy projectiles ($A_{proj} \gtrsim \frac{1}{2} A_{target}$), and thus endowed with large angular momenta at relatively low excitation energies. Using a statistical model and a single set of input parameters, we have reproduced all the data.

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Heavy-ion fusion reactions have been extremely useful in probing the nature of nuclei at high angular momentum and the compound nucleus has been investigated by observation of the two competing dominant decay modes: light-particle evaporation and fission. These investigations have raised questions in recent years concerning the energy dependence of the cross sections near and below the Coulomb barrier,[1] the modeling of the competition between particle evaporation and fission,[2-7] and the necessity for an "extra-push" energy.[8,9] Much of this work has proceeded with use of asymmetric entrance channels, where the mass of the projectile was significantly different from that of the target nuclei. While these reactions do lead to population of compound nuclei with high angular momenta, these angular momenta are accompanied by large excitation energies (50–100 MeV). Investigations of the systems $^{170-188}$Pt formed by the fusion of ^{58,64}Ni with the even tin isotopes ($^{112-124}$Sn) were reported in an earlier Letter.[10] That work is distinguished by the use of an entrance channel more symmetric in mass, still high in compound angular momenta, but at much lower excitation energy, typically 10–15 MeV closer to the yrast line than previous studies.

In our earlier work, with the fused systems within 10–30 MeV of the yrast line, the possibility of observing nuclear-structure effects at large spin and low temperature was noted. An order-of-magnitude variation in the maximum cross sections for leaving an evaporation residue was observed in going from the most neutron-poor to the most neutron-rich nuclei formed. This variation could be due to differences either in compound-nucleus–formation cross sections or in the fission competition. In order to investigate this further we have undertaken a separate measurement of the complementary piece of the decay spectrum, the fission process.

With Ni beams between 200 and 380 MeV from the Argonne superconducting linac, fission fragments were detected in coincidence between a detector telescope (gas ΔE, Si E, with time of flight) and a large-area, position-sensitive (in two dimensions) gas detector. The charge and energy information for both fragments when coupled to the position and time-of-flight data presented an overdetermination of binary reactions and permitted a unique identification of fission-like processes. Angular distributions of the fission fragments were taken for all systems at several energies and were consistent with statistical-model predictions.[11] More complete details of this experiment will be published in a later paper.[12]

The sum of the cross sections for leaving evaporation residues and for fission is assumed to be the total compound-nucleus, or fusion, cross section. Consequently, the fission cross section divided by this sum represents the probability that the compound system, once formed, decays by fission. In order to form this sum the cross sections for evaporation residues, Ref. 10, were interpolated to the energies at which the fission cross sections were measured. This is the first experiment in which both the total fusion cross section and the fission probability were measured over such a wide range of neutron excess. Typical data are shown in Fig. 1. The large span in neutron excess covers a substantial range in fissility ($\sim Z^2/A$) and allows an exploration of fission over a range of center-of-mass energies, corresponding to different angular momentum distributions. In several cases the same compound nucleus may be reached with both ^{58}Ni and ^{64}Ni beams, where nearly the same excitation energy can be produced with different angular momentum distributions.

The present measurement then allows a substantive test of the statistical-model analysis of compound-nucleus decay and the investigation of several parameters to these models at low excitation energies above the yrast line. It is not our goal to define all the parameters of such models. Wherever possible, we have drawn upon the literature to provide reasonable

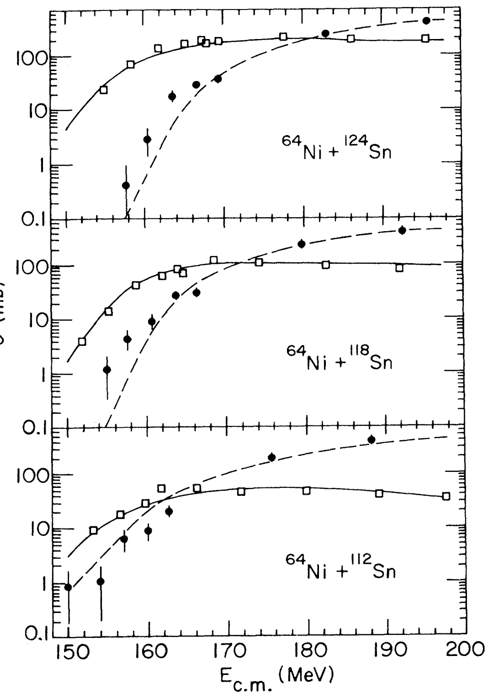

FIG. 1. Experimental cross sections for fission (solid dots) and for leaving evaporation residues (squares) for the systems of ^{64}Ni + ^{112,118,124}Sn. The curves are predicted cross sections obtained from a statistical-model calculation discussed in the text. The uncertainties in the energies are ~ 1 MeV in the laboratory.

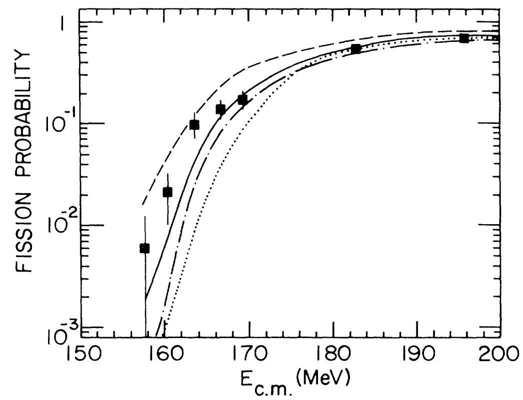

FIG. 2. The fission probability for the system ^{64}Ni + ^{124}Sn. The different curves refer to model calculations with different input parameters. The dotted, solid, and dashed curves refer to the fission barrier from Ref. 17 with $\sigma = 4\hbar$, $15\hbar$, and $30\hbar$. The dot-dashed curve is calculated with the same parameters as the solid curve except for use of the unreduced fission-barrier in the standard RLDM.

choices of the parameters that could not be determined from our data. We shall briefly discuss the choice of the four parameters of the statistical model that are correlated, strongly affect the fission probability, and lack definitive experimental determination: the level densities for particle emission and for fission, the fission-barrier height, and the angular momentum distribution in the compound nucleus.

In recent years an increasing body of data has lead to the conclusion that the fission-barrier heights predicted by the rotating–liquid-drop model (RLDM)[13] are consistently too large.[5,14–16] Several schemes have been used to reduce the barrier, and most recent among these is one which is consistent with our knowledge of nuclei and the framework of the RLDM.[17] In this approach the sharp surface of the nucleus is smeared out in a prescribed manner, and there are no remaining free parameters in the description of the fission-barrier height. The method has been applied successfully to some recent fission data.[14] To model our data we have used this prescription within a modified version of the statistical-model code CASCADE.[18]

The parameters a_n and a_f used to calculate the level densities at the ground state and saddle point determine the decay probabilities for particle evaporation and fission. In our calculations we have fixed $a_n = A/8$ and $a_f/a_n = 1.00$ and then explored the errors introduced by this simplification. We find that the effects of deformation on the level-density ratio, such as had been suggested,[19] would affect the fission probability by at most 10% and thus are comparable to experimental errors.

With these parameters of the statistical model fixed, the large body of data obtained in the present work allows a systematic study of the partial-wave distribution of the compound nucleus, which directly and strongly affects the competition between fission and evaporation. Recent work has shown problems with the sharp-cutoff model of the partial-wave distribution, especially at near-barrier energies.[20] For a diffuse cutoff in the partial-wave distribution of the entrance-channel transmission coefficients one takes $T_l = 1/\{1+\exp[2(l-l_0)/\sigma]\}$. We investigated the fission competition as a function of the diffuseness parameter, σ. With all other parameters for the statistical model fixed, we attempted to achieve an overall fit to our data with a single value of σ, although there is no *a priori* reason to expect σ to remain constant.

Both the optimization of the parameter σ and the treatment of the fission barrier according to Sierk[17] are required for a reasonable fit. Without the modified barrier, calculated fission excitation functions were shifted to higher energies, in obvious disagreement with the data. The sensitivity to the choice of the parameter σ was also established by a more detailed comparison between calculations and the data. The value of the χ^2 obtained with measured fission probabilities for all fourteen systems is at a sharp minimum

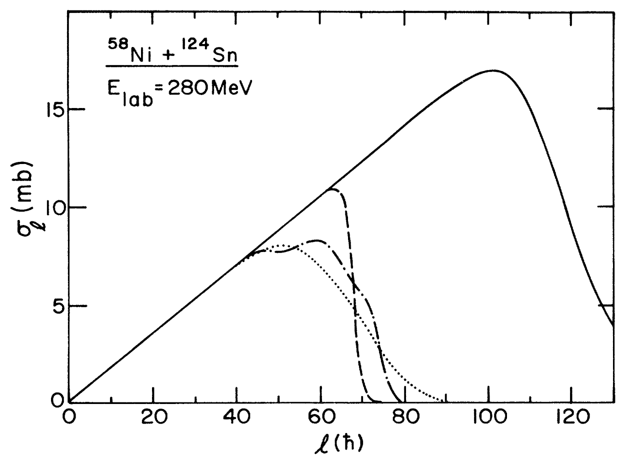

FIG. 3. Calculated angular momentum distributions of cross sections. The solid curve is an optical-model prediction of the total-reaction cross section calculated with parameters fitted to elastic scattering; the dashed curve is the fusion cross section calculated with the incoming-wave boundary condition; the dot-dashed curve shows the additional effect of coupling to inelastic states; and the dotted curve represents the partial-wave distribution deduced from the present data with the statistical model as discussed in the text.

when a value of $\sigma = 15\hbar$ is used. The sensitivity of the calculations to the choice of σ and to the Sierk treatment of the fission barrier is illustrated in Fig 2.

The diffuseness of the partial-wave distribution in the entrance channel may also be estimated from reaction dynamics. In Fig. 3 we show the partial-wave distribution calculated with an optical-model potential that fits the elastic scattering[21] of ^{58}Ni from ^{116}Sn and use it as the basis of such an estimate. The fit and all subsequent reaction calculations were performed with the code PTOLEMY.[22] Using the incoming-wave boundary condition as a measure of the partial waves that penetrate to sufficiently small radii to permit fusion, we obtain the dashed curve in Fig. 3 for the partial-wave distribution for fusion, indicating a considerably sharper cutoff in l than we obtained above from the analysis of the fission data. However, if one now includes the coupling of quasielastic channels [represented by the first 2^+ and 3^- states in both Ni and Sn, with their observed $B(E\lambda)$'s and form factors taken as the derivative of the real potential] the result is the dot-dashed curve in Fig. 3, in qualitative agreement with the partial-wave distribution determined from the fission data (the dotted curve). There are undoubtedly other quasielastic channels to be included, neutron transfer in particular, whose importance may even change with neutron excess, but the qualitative effect of the coupling of the quasielastic channels on the partial-wave distribution for fusion is of the right magnitude to be consistent with the fission data.

Such an effect, induced by the coupling of quasielastic channels, is also consistent with that required to explain the subbarrier enhancement of compound-nucleus–formation cross sections.[1] Indeed, the analysis of our measured excitation functions for the total fusion cross section for subbarrier energies, yields partial-wave distributions consistent with the ones deduced from the present fission-decay studies.[12]

We have found that the competition between fission and light-particle emission can be well represented by existing statistical models, using "accepted" parameters. The need to use fission-barrier heights which are reduced from the simple RLDM values is clear, and a partial-wave distribution which is quite diffuse and which is consistent with coupled-channel calculations using measured 2^+ and 3^- coupling strengths is found to be necessary to reproduce the fission data. We conclude from the successful reproduction of all the fission-probability data that the tremendous variation of the cross sections for evaporation residues was in fact a reflection of the changing fission competition and not of compound-nucleus–formation effects. We have shown for the first time that at high spin and low excitation energy above the yrast line the competition between fission and particle evaporation can be reasonably represented by the statistical model with standard parameters. This competition was investigated in a systematic manner spanning a large variation of neutron excess.

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