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STUDIES OF FISSION HINDRANCE IN HOT NUCLEI

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Abstract

The study of dissipation in hot nuclear systems is a subject of great current interest. Different experimental techniques and observables have recently been utilized which are sensitive to the dissipation in large-scale shape rearrangements, such as those encountered in heavy-ion fusion, fission and quasifission reactions. To study the dynamical shape evolution of hot nuclear systems it is necessary to measure properties (or processes) that are sensitive to the time-scale on which these shape changes occur. Several methods, such as the emission of pre-scission particles (n , p and α) and γ -rays, have been used to study the fission time-scale in relation to these (well known) decay processes. Recently it has also been pointed out that measurements of the evaporation residue cross section, which are very sensitive to the competition between particle emission and fission, probe the fission time-scale. This paper will present recent studies of the evaporation residue cross section in the $^{32}\text{S}+^{184}\text{W}$ system carried out at the ATLAS Fragment Mass Analyzer, including the methods for obtaining absolute cross sections.

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1. INTRODUCTION

Experimental studies of the time-scale of fission of hot nuclei has recently been carried out using the emission rates of neutrons [1], γ -rays [2], and charged particles [3] as "clocks" for the fission process. These experiments have shown that the fission process is strongly retarded (or hindered) relative to expectation based on the statistical model description of the process well beyond any uncertainties in the model parameters. It therefore appears that a dynamical description of the fission process at these energies is more relevant [4] and that the experimental data are able to shed light on the dissipation in the shape degree of freedom. However, these experiments are not very sensitive to whether the emission occurs mainly before or after the traversal of the saddle point as the system proceeds toward scission. Various dissipation models are, however, strongly dependent on the deformation and shape symmetry of the system. As an alternative to these methods we therefore measure the evaporation probability for hot nuclei formed in heavy ion fusion reactions. As the hot system cools down by the emission of neutrons and charged particles there is a finite chance to undergo fission after each evaporation step. If the fission branch is suppressed due to dissipation there is therefore a strongly enhanced probability for survival which manifests itself as an evaporation residue cross section which is larger than expected from statistical model predictions. This effect depends, however, only on the dissipation strength inside the saddle point and may therefore provide the desired separation between pre-saddle and post-saddle dissipation.

In this paper, we report on recent measurements of evaporation residue cross sections for the $^{32}\text{S}+^{184}\text{W}$ system over a range of beam energies using the Argonne Fragment Mass Analyzer (FMA). In order to obtain absolute cross sections, it is, however, also necessary to determine the transmission probability through the FMA of heavy, slow moving reaction products as encountered in these processes. Such measurements have been made using elastically scattered target recoil nuclei and the results are also discussed in this work.

2. EXPERIMENTAL ARRANGEMENT

The measurements were carried out using ^{32}S -beams from the ATLAS superconducting linac at Argonne. Beam energies of 50, 80, and 110 MeV were used for the measurements of the transport efficiency through the Fragment Mass Analyzer. The cross sections for evaporation residues produced in the $^{32}\text{S}+^{184}\text{W}$ reaction were measured at beam energies of 165, 174, 185, 195, 205, 215, 225, 236, 246, and 257 MeV. The Argonne Fragment Mass Analyzer [5] was used for identification of reaction products, either elastic recoils or evaporation residues. A schematic illustration of this instrument is shown in Fig. 1.

Figure 1: Schematic illustration of the Argonne Fragment Mass Analyzer. The beam enters from the left.

In these experiments a sliding seal target chamber is used to allow for measurements at finite angles. This is required in order to obtain the angular distributions for integration of the total evaporation residue cross section. Elastically scattered S-ions were registered in a Si detector placed at 30° relative to the beam axis. These data were used for normalization purposes. A $40\ \mu\text{g}/\text{cm}^2$ carbon foil was placed 10 cm downstream from the target to properly simulate the conditions of the subsequent evaporation residue measurements. Here such a foil is used to reset the charge state of reaction products, which may be abnormally highly charged as a result of Auger electron emission following the γ decay of short-lived isomers.

Several different entrance apertures for the FMA were used as detailed

below. Reaction products transmitted through the FMA are dispersed in M/q (mass/charge) at the focal plane, where the spatial distribution is measured by a thin x-y position sensitive avalanche detector. When the FMA is placed at 0° some settings of the electrostatic and magnetic fields of the instrument allows beam particles scattered off the anode of the first electrostatic dipole, ED1, to be transported to the focal plane (presumably after a subsequent forward scattering ion the vacuum chamber of the magnetic dipole MD1). When measuring small cross sections, as in the present study, it is therefore mandatory to achieve a clean separation between evaporation residues and beam particles. This is achieved by measuring their flight-time over the 40 cm distance to a double sided Si strip detector placed behind the focal plane. The information on the particle mass obtained from the time-of-flight and energy measurement provided by this Si-detector gives a clean discrimination against the scattered beam. The efficiency for transporting evaporation residues from the focal plane to the Si-detector is measured by looking at the spatial distribution over the face of the detector. It is typically around 87%.

3. TRANSPORT EFFICIENCY MEASUREMENTS

Extensive calculations of the transport of reaction products were carried out during the design phase of the instrument using the computer code GIOS [6, 5]. These show that the energy acceptance depends strongly on the angular deviation from the optical axis of the instrument. This is illustrated in Fig. 2 where a schematic representation of the transport probabilities is shown as a contour diagram with respect to the horizontal angular deviation $\Delta\theta$ and the particle energy. In order to reliably measure cross sections using this instrument it is therefore necessary to verify these calculations empirically.

This has been done using the following approach. Different entrance apertures were used for these measurements. One is the so-called "full" aperture, which subtends entrance angles of $\pm 2\frac{1}{4}^\circ$ in both the horizontal and vertical directions resulting in a $\Omega_{full} = 6.24$ msr solid angle. This solid angle was subdivided into nine equal sections, and the transmission probability was measured for four of these using smaller apertures as illustrated in Fig. 2.

Figure 2: Schematic illustration of the FMA acceptance as a function of energy and horizontal entrance angle of the incident ions (right) and the coverage of entrance apertures (left).

The three apertures centered in the horizontal plane containing the beam axis denoted the "left", "center" and "right" apertures served to probe the dependence of the transmission probability on the horizontal entrance angle, θ_x into the instrument. The "top" aperture is expected to yield results very similar to those obtained for the "center" aperture since the transmission probability is very weakly dependent on the vertical entrance angle, θ_y .

In order to avoid many beam energy changes to map out the energy dependence we change instead the field settings for the FMA to correspond to a number of different particle energies. This is possible since the theoretical transmission probability depends only on the ratio of the particle energy to the energy setting of the FMA.

Finally, in order to derive a transmission probability, we measure the complete distribution of charge-states. This is important in order to accurately estimate the population of the charge-state used in the measurement. As an example we show the measured charge state distribution for elastic recoils from the $^{32}\text{S} + ^{184}\text{W}$ reaction measured at 80 MeV beam energy as open circles in the upper panel of Fig. 3.

Figure 3: The charge-state distribution for 80 MeV $^{32}\text{S}+^{184}\text{W}$ elastic recoils (upper panel) and the measured absolute efficiency for transmission through the FMA (lower panel).

The solid curve represents a gaussian fit to the distribution which is used to derive the charge state fraction in $q=19$ (indicated by the arrow) for which the dependence of the FMA energy setting was measured. The charge state distribution was carried out with the FMA set for an energy of 38 MeV for the ^{184}W recoils using the full entrance aperture. As will be shown below, for this aperture less than 100% of the recoils are transported to the focal plane of the FMA, hence the integrated charge distribution falls below the theoretical prediction of Shima *et al.* [7] (dashed curve). We also note that the Shima formula slightly underpredicts the mean charge state at this energy.

The transmission probability is then derived from the following expression

$$P_{trans} = \frac{1}{p(q)} \frac{N_{fma} \sigma_{mon} \Omega_{mon}}{N_{mon} \sigma_{fma} \Omega_{fma}}, \quad (1)$$

where $p(q)$ is the charge state fraction, N_{fma} and N_{mon} are the number of counts detected in the FMA and monitor, respectively, σ_{mon} and σ_{fma} are

the differential Rutherford cross sections for beam particles scattered into the monitor detector and target recoils incident into the FMA, respectively, and Ω_{mon} and Ω_{fma} are the their solid angles.

The measurements of elastic recoils were performed with the different entrance apertures in place while scanning over the energy setting of the FMA. The resulting transport efficiencies through the FMA are displayed in the lower panel of Fig. 3. We observe the expected result that the acceptance for the smaller apertures (left, center, right) reach 100% over a relatively extended range of energy settings, ca. $\pm 15\%$ around a central value. As expected, lower energy settings are required for recoils entering through the right aperture to be transmitted to the focal plane in order to avoid striking the cathode of ED1. On the contrary, higher than average energy settings are required for transmitting recoils entering the left aperture, to avoid striking the anode of ED1. Not shown is the transmission curve for the top aperture, which essentially coincide with the one shown for the center aperture.

We also observe that the transmission through the full entrance aperture only reaches a maximum of about 80%. That 100% efficiency is not reached with this aperture arises from the fact that there is no energy setting for which there is full transmission for all three partial apertures.

The fact that 100% transmission through the FMA is observed on an absolute scale over the theoretically expected range of energy settings reinforces the confidence in the theoretical calculations for the instrument. We are therefore confident that absolute cross sections can be made with the instrument using these measurements and theoretical simulations for the transmission efficiency of the instrument. In the following we will therefore describe such a measurement, namely the evaporation residue measurement for the $^{32}\text{S} + ^{184}\text{W}$ reaction.

4. CROSS SECTION MEASUREMENTS

The evaporation residue cross section for the $^{32}\text{S} + ^{184}\text{W}$ reaction was measured for beam energies in the range $E_{beam} = 165\text{--}257$ MeV. Evaporation residues were identified by time-of-flight and energy measurement using the focal plane PPAC detector and the Si-strip detector placed ca. 40 cm behind the fo-

Figure 4: Charge-state distribution of evaporation residues from the $^{32}\text{S} + ^{184}\text{W}$ reaction measured at three beam energies.

cal plane. As for the transmission measurements discussed in Sect. 3, a $40 \mu\text{g}/\text{cm}^2$ carbon foil was placed in front of the FMA ca. 10 cm from the target in order to reset anomalous charge-state distributions arising from the decay of short-lived isomers. The charge state distributions, which were measured at three beam energies, are shown in Fig. 4. The dashed curves represent the the formula of Shima *et al.* [7], whereas a somewhat better fit to the data is given by the gaussian fit (solid curves) with a fixed standard deviation of $\sigma=3$. The arrows indicate the charge state setting of the FMA used for the cross section measurement. The derivation of the evaporation residue cross section at intermediate beam energies is based on an interpolation between these measured charge state distributions.

Since the FMA disperses in M/q at the focal plane there will be cases

Figure 5: Angular distribution of evaporation residues from the $^{32}\text{S} + ^{184}\text{W}$ reaction measured at three beam energies.

of ambiguities in the mass identification, since overlaps between light mass products from one charge state, q , will invariably overlap with heavy products from the neighbouring charge state, $q + 1$, when compound nuclei with high excitation energy are studied. We are not able to resolve this ambiguity with the present setup, and have therefore obtained the cross sections by integrating all counts that fall between the positions for $M/q - \frac{1}{2}$ and $M/q + \frac{1}{2}$ along the focal plane. Since the FMA is set up for the most abundant charge state, q and mass, M , we argue that the loss of residues with charge state, q , and masses that fall outside this window is compensated by the acceptance of residues with charge states, $q + 1$ and $q - 1$ that fall inside this window.

The angular distributions of evaporation residues were measured at three beam energies utilizing the sliding-seal target chamber for the FMA. Differ-

Figure 6: Transport efficiency dependence on energy setting of the FMA.

ential cross sections as a function of the mean angle, $\langle \theta_{lab} \rangle$, relative to the beam axis are shown in the left side panel of Fig. 5. The right side panel shows the cross sections converted to $d\sigma/d\theta$, which is relevant for the angular integration of the total evaporation residue cross section. The angle integrated cross sections are thus derived from a fit to the data expressed in terms of $d\sigma/d\theta$ using the function $2\pi \sin \theta \exp(\theta^2/2\sigma_\theta^2)$. The curves shown in the left side panel of Fig. 5 are computed by removing the $2\pi \sin \theta$ term. We observe that these latter curves underrepresent the differential cross section at small angles indicating that the angular distribution really has two components. However, we do not feel that the data are of sufficient quality to allow for a reliable separation of two components and by observing the fits to the $d\sigma/d\theta$ data it is clear that only a very small error could arise from this simplification.

Finally, the data are corrected for the efficiency for transporting evaporation residues through the FMA. We estimate this transport efficiency on the basis of the *relative* transport efficiency measured at 245 MeV beam energy as a function of the energy setting of the FMA, E_{FMA} , see Fig. 6. We observe that this efficiency function closely matches the *absolute* efficiency function measured for elastic recoils from the reaction 80 MeV $^{32}\text{S}+^{184}\text{W}$ (after appro-

Figure 7: Comparison of cross sections for the S+W reactions.

appropriate scaling of the x-axis). We therefore assume that the transport efficiency for the evaporation residues from the 245 MeV $^{32}\text{S}+^{184}\text{W}$ reaction is given by the measured transport efficiency for the elastic recoils at 80 MeV, which in this case is 80% at the energy setting used in the measurement (indicated by the arrow).

5. DISCUSSION

The resulting evaporation residue cross sections for the $^{32}\text{S}+^{184}\text{W}$ reaction are shown as filled circles in Fig. 7. Fission-like cross sections and a derived estimate of the complete fusion cross sections for the $^{32}\text{S}+^{182}\text{W}$ reaction are shown as open circles [8, 9] and open squares [9], respectively, along with theoretical calculations using a modified Extra Push model [10].

The evaporation residue data are compared with a statistical model calculation (solid curve) using Sierk fission barriers [11] scaled by a factor of 0.9 to approximately account for the cross section at low beam energies. We observe that the measured cross section increases with beam energy, whereas the statistical model predicts a decreasing cross section because of an increased probability for fission during the longer evaporation cascades. Because the evaporation residue cross section is such a small fraction of the complete fusion cross section we find, however, that it is very sensitive to the nuclear viscosity of the system inside the barrier. The dashed curve represent a statistical model calculation where the effects of viscosity are included using a linear normalized dissipation coefficient of $\gamma=5$, corresponding to a strongly overdamped motion in the fission degree of freedom. We see that this leads to an increase of about a factor 10 in the evaporation residue cross section, but the overall shape of the excitation function is virtually unchanged. Within this framework it therefore appears that the viscosity (or dissipation) increases rather rapidly over this range of beam energies i.e. from 200 to 260 MeV, which corresponds to an excitation energy range of $E_{exc}=85\text{-}136$ MeV. Similar effects have been observed in studies of pre-scission γ -rays [2] albeit in that case it appears to take place over an even smaller excitation energy interval.

6. SUMMARY

Measurements of evaporation residue cross sections for heavy fissile systems are shown to provide rather direct evidence for the fission hindrance (or retardation) which is caused by strong nuclear dissipation in the fission

degree of freedom for hot nuclei. The data obtained for the $^{32}\text{S}+^{184}\text{W}$ system show an increasing evaporation cross section with excitation energy, whereas a decrease is expected on the basis of statistical model considerations and calculations. The data indicate an increase in the linear normalized dissipation coefficient γ from $\gamma=0$ at $E_{\text{exc}}=85$ MeV to $\gamma=5$ at $E_{\text{exc}}=135$ MeV. This increase is not predicted nor understood within existing theoretical dissipation models and warrants further study, both experimentally and theoretically.

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