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Spin and excitation energy dependence of fission survival for the $^{19}F+^{175}Lu$ system

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Evaporation residue (ER) excitation function and γ-ray multiplicity in coincidence with ER's have been measured for the $^{19}F+^{175}Lu$ system for studying the spin dependence of dissipation effects in fission. A combined analysis of total ER cross section and the spin distribution data confirms that there is no onset of dissipation in the presaddle region of the fission process.

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New features indicating deviations from the standard statistical model have emerged over the decade from studies in heavy-ion-induced formation and consequent decay of hot and rotating fissile compound nuclei. One normally identifies certain milestones in the evolution dynamics of such heavy nuclear systems, viz., complete equilibration stage or the compound nucleus formation, saddle state and nuclear scission. It is generally understood that the observed deviations relate to the effect of dynamical delays associated with the attainment of these milestones due to the large scale rearrangement of nucleons that accompanies such an evolution process. Light particle and photon emissions indicate enhanced yields before the scission stage. Evaporation residue formation cross sections are larger than the statistical model predictions. These features point out that the progress towards fission is hindered and efforts are made to identify a threshold behavior in terms of excitation energy and fissility [1]. Dynamical delays affect the multiplicity of emissions and fission survival and can divulge crucial information about the nature of nuclear viscosity.

If emitted before the saddle, excess neutrons make it (the saddle nucleus) colder. This, besides improving the chances for fission survival in conformity with experiments, is seen to be crucial for interpretation of fission fragment anisotropy data [2]. Calculations by Fröbrich *et al.* [3] revealed that emission is initially presaddle but with higher excitation energy a gradual preponderance occurs for the post-saddle emissions which do not alter the fission survival chances nor influence the saddle temperature.

Available fission evaporation competition data correspond to a range of parameter space of the model calculations. This may be attributed to the lack of exclusive and comprehensive data along with the ambiguity of model calculations for want of desirable precision in nuclear parameters. On the experimental side, data collected so far are integrated over the entire spin range. Heavy ions bring in a large amount of spin. Relevant parameters regulating the evolution of the compound nucleus are spin dependent and comprehensive tests with spin-gated data provide for a critical testing of models and concepts involved in understanding the fusion-fission dynamics. This helps in answering crucial questions in other branches of heavy ion physics relating to fission survival at high spin for heavy nuclei. For example, calculations by Thoennessen [4] were concerned with the possible interpretation of feeding of the superdeformation band if the nuclear viscosity is large. It was found that for the same evaporation residue cross section, the spin distribution could be altered by a varying amount of nuclear friction. Similarly, attempts to extract the fission lifetime from the excitation energy dependence of fission probability suffered due to nonavailability of fission probability data as a function of spin [5].

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Here we report on our measurements for a heavy compound nucleus (^{194}Hg*) over a range of excitation energies and spins where both of them effectively influence the fission evaporation competition. Also the dissipation effects [1] are expected to be already set in for the fissility and excitation energy range chosen. To the best of our knowledge, no such studies have been reported so far as the experiments on fission hindrance effects on ER formation hitherto only considered the total cross sections. The present measurements have been performed over a range of energies around the Coulomb barrier using the ^{19}F beam where the quasifission channel is expected to be absent [6].

The experiment was performed in two runs using the 15UD Pelletron at the Nuclear Science Center with ^{19}F beam energies between 90 and 139 MeV on 200 μg/cm^2 natLu target on 250 μg/cm^2 Al backing. The spin distribution measurements were carried out using dc beams of energies up to 125 MeV. A pulsed beam was used for the ER cross section measurements which could be extended up to 139 MeV of beam energy, and also to a few other systems, viz., the ^{19}F $+^{181}$Ta and the ^{19}F$+^{197}$Au where previous measurements were available. Our measurements gave results in agreement with previous studies. All these measurements utilized the sliding seal target chamber of the recoil mass separator HIRA [7] with the chamber modified with special bucket structures from top and bottom plates to accommodate γ detectors in close geometry. HIRA was employed with full acceptance corresponding to a solid angle of slightly more than 10 msr in order to transport the evaporation residues (ER's) to its focal plane where they were detected by a large 5 cm $\times$ 5 cm two dimensionally position-sensitive double-sided Si strip detector. A thin carbon foil was used for charge-state reequilibration before the recoiling ER's enter HIRA. The pulsed beam with 4 μs pulse separation was used to record the time of flight of the slow moving recoils over the flight path of HIRA ($\approx$9 m). The ER's were clearly isolated in a 2D plot of time of flight vs energy from the low-energy scattered beam components. This approach of residual low-energy beam background separation has been quite successful even when very low-energy recoils are involved as there is no need of an intermediate Parallel Plate Avalanche Counter which was required in an earlier measurement using the Fragment Mass Analyzer at Argonne [8]. Detailed measurements of the charge, energy, and angular distributions of ER's were carried out. These measurements were employed to extract the HIRA transport/detection efficiencies along with estimates for their beam energy and ER channel dependence. The γ-ray ER coincidences were measured using first a high resolution HPGe detector and subsequently with an array of 14 BGO detectors. The HPGe data were used to determine the absolute ER detection efficiencies of HIRA which were in agreement with those extracted from the measured charge, energy, and angular distributions of ER's. The BGO array was used to measure γ-ray fold distribution in coincidence with the ER's at the focal plane. High singles count rate seen by the BGO array could be handled as detector signals were processed individually and time recorded using a multichannel TDC. The γ-ray fold distributions were used to extract the spin distributions of ER's following the method explained in Refs. [9–11].

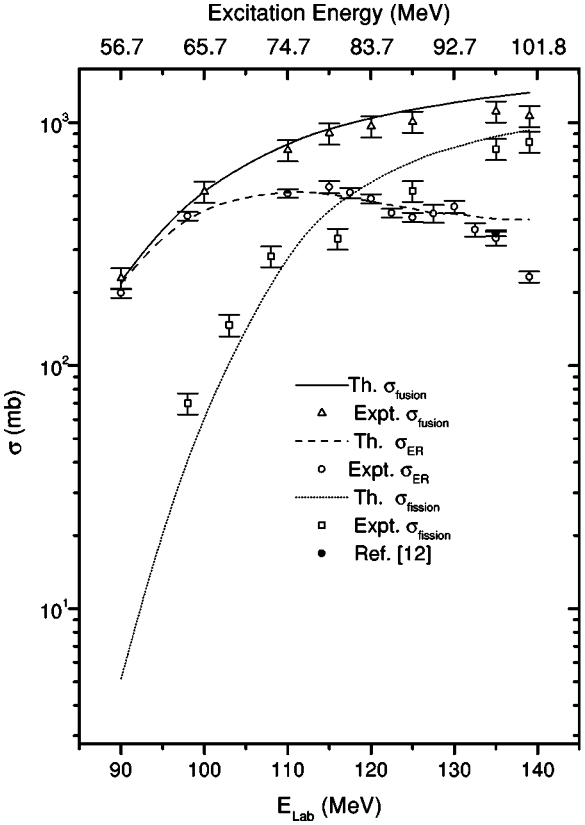

FIG. 1. The ER excitation function for the ^{19}F$+^{175}$Lu reaction. Open circles are present measurements and a solid point at 135 MeV is the measurement of Ref. [12] and the continuous curve is the PACE prediction. Fission data are from Ref. [14].

The measured ER excitation function is shown in Fig. 1. The figure also includes the previous fission data and the theoretical estimates. Fusion cross sections are obtained by adding the fission and ER cross sections. The ER cross section measured by Rajagopalan [12] is also shown by a solid point which is in very good agreement with our measurement. The standard statistical model code PACE2 [13] is used to get the statistical prediction of the fission survival probability. The Sierk barriers used in the code were scaled by a factor of 0.9 to obtain good overall agreement with the ER cross sections measured by us in the lower energy region. The level density parameter a_n was taken equal to $A/9$, while parameter ratio a_f/a_n was taken equal to 1. They were kept constant over the energy range. The ER cross sections measured by us and fission cross sections reported earlier [14] are used to obtain the experimental fusion excitation function. Available fission cross sections were extrapolated/interpolated as required for the energies where ER cross sections were measured. The extrapolation was required only in the lower energy region where fission is not the dominant term of the total fusion cross section. Simplified coupled channels calculations were done using the code CCDEF [15] to fit the experimental fusion excitation function, and the obtained parameters were used for the theoretical calculations based on PACE2 code as shown in Fig. 1. At higher

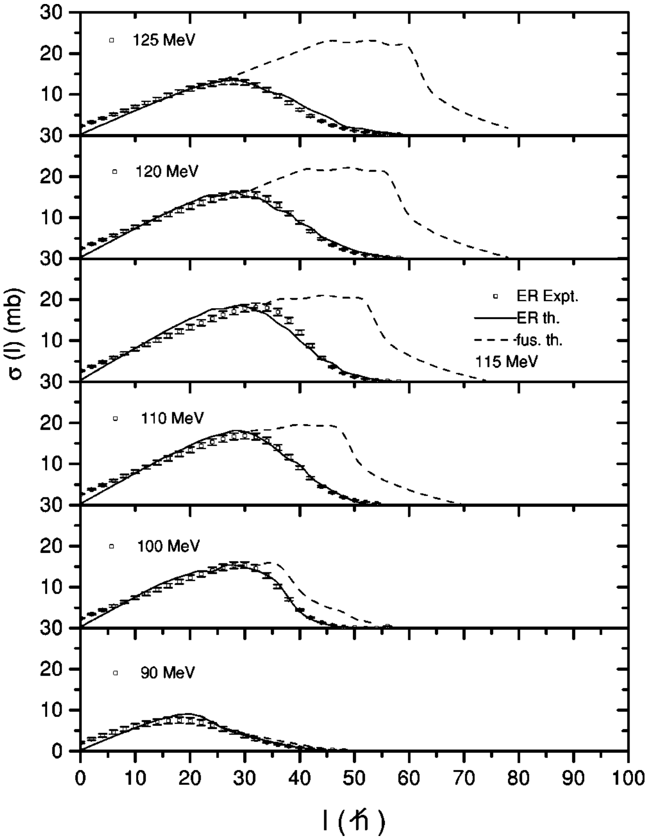

FIG. 2. The spin distribution for different excitation energies. The experimental ER spin distributions [$\sigma_{\mathrm{ER}}(l)_{\mathrm{expt}}$] are shown by open circles with error bars. The theoretical ER spin distributions [$\sigma_{\mathrm{ER}}(l)_{\mathrm{th}}$] are shown using continuous lines while the dotted line shows the fusion spin distributions.

energies, the experimental excitation function shows some indication of a shallow well above around 120 MeV and then eventually a gradual decrease. The experimental ER cross sections are found to be lower than the theoretical estimates for energies above 130 MeV. While an interpretation of this fall of experimental cross section with respect to statistical model calculations using a temperature-dependent fission barrier is unphysical [16], an explanation could be sought in terms of an increase in the level density parameter ratio a_f/a_n with excitation energy. It may not be possible to come to a conclusion about the mechanism in the absence of spin distribution data for these higher energies. We, however, note that there is no enhancement of the ER cross section as compared to that predicted by statistical model calculation which indicates that there may not be any manifestation of fission hindrance.

As pointed out earlier, the situation *vis-à-vis* ER cross sections entails an ambiguity with respect to the fission barrier scaling, etc. The ER spin distribution can be used here beneficially as they should provide far more stringent tests in discerning the reaction dynamics in the context of the hypothesis of fission hindrance [3]. Although the ER excitation function is successfully used as a probe for the search of existence of the fission hindrance phenomena, detailed ER spin distribution or the survival probability of the hot nucleus of each specific spin (along with the ER excitation function and other particle and fission data) provides sensitive information about the evolution of the fusion-fission and evaporation process.

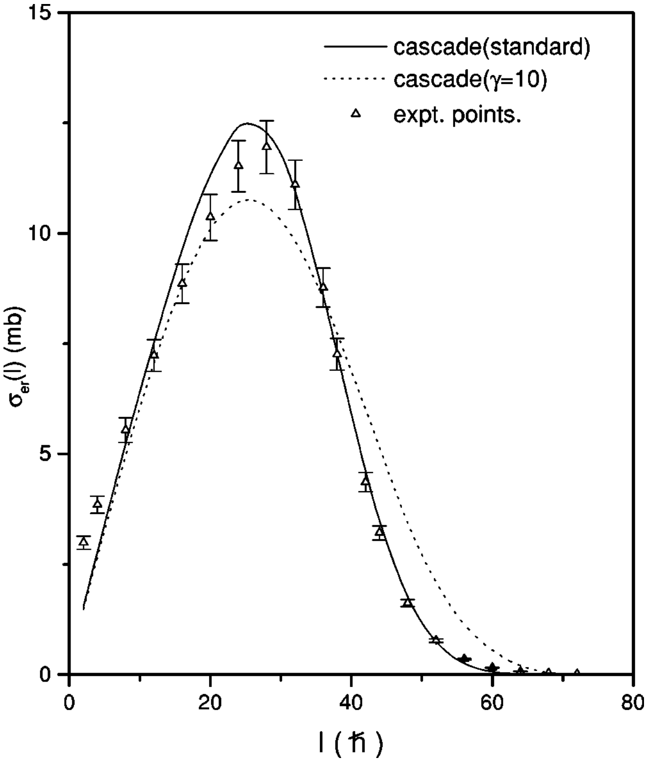

FIG. 3. The ER spin distribution at 125 MeV with and without the hindrance factor. Note that the experimental points fit the standard CASCADE predictions for the whole range of l (3 to 72 $\hbar$) (continuous curve) while the inclusion of a viscosity coefficient $\gamma=10$ in the code CASCADE (dotted curve) tends to worsen the fit.

Experimentally, the spin distribution has been extracted in a two-step process. Starting with multiplicity distribution $P(M)$ defined by a set of three parameters describing a Fermi function [5], fold distribution $Q(p)$ is generated following the relation used in Ref. [17]:

$$Q(p)=\binom{N}{p}\sum_{l=0}^{p}(-1)^{p-l}\binom{p}{l}[1-(N-l)\Omega]P(M), \quad (1)$$

where $\binom{N}{p}$ denotes the number of ways p combinations are possible out of N numbers; Ω is the γ-detector efficiency.

Transformation of the multiplicity to the spin distribution is made assuming ER's to be good rotors with two units of angular momentum carried away by each nonstatistical γ-ray emission [10]. Fold distributions are derived from the spin distribution for comparison with experimental data. The χ^2 fit to the experimental fold distribution gives the optimized spin distribution and is compared directly with the theoretical predictions. The ER spin population for different energies is shown in Fig. 2.

The theoretical spin distribution for fusion σ_{fus-l} was obtained using the code CCDEF as explained earlier. The fission survival probability calculated using the code PACE2 (with the Sierk barrier scaled by a fixed factor as mentioned earlier) as a function of spin for each excitation energy is then used to obtain the theoretical ER cross section for a given spin (σ_{ER-l}). It turns out that fission strongly depletes the cross section at higher spins due to lowering of the fission barrier with spin. The standard statistical model calculations seem to reproduce the shape of the experimental data quite well up to the highest energy at which the spin distribution measurement was made in this experiment (the total areas of the theoretical and experimental spin distributions differ in accordance with ER-excitation function comparison as discussed in Fig. 1). The experimental mean and second moments of the spin distributions match very well with those obtained from the CCDEF calculations. However, we undertook a detailed analysis for the case of highest beam energy of 125 MeV for the spin distribution data. The calculations were done using the modified CASCADE code [18]. The fission barriers were varied so as to reproduce the ER cross sections and calculations were done with and without the viscosity effects. The standard CASCADE calculations with Sierk barriers scaled by a factor of 0.87 reproduce the measured ER cross section and result in a spin distribution as shown by the solid line in Fig. 3. The dotted line corresponds to the inclusion of fission hindrance corresponding to a dissipation strength parameter of $\gamma = 10$. The Sierk barriers in this case reduced by a scale factor of 0.69 reproduce the experimental ER cross section. Thus the two calculations lead to same ER cross section but result in quite different spin distributions. The shape of the distribution deviates from the standard CASCADE calculations, giving an enhanced ER cross section at higher spin values. The predictions of the standard model fit our data well without any hindrance being considered.

Thus we find that spin dependence of the fission survival and dissipation effects provides a new and unique way of differentiating between model calculations. It is seen that the new data support the standard statistical model calculations for the system studied. There is no indication of dissipation effects in the presaddle regime. Effectively this also implies that the excess prefission emissions may come mostly from the postsaddle stage and that an alternative mechanism for the enhanced fission fragment anisotropies seen in the barrier region should be sought in terms of dynamical effects [19,20].

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