OBJECTIVE

The research outlined in this proposal is directed toward obtaining a better determination of time scales involved in fission and fission-like processes. This work could provide new insights into fission dynamics and nuclear viscosity and may even aid in creating new strategies for heavy element synthesis. In an excited fissioning system, neutron emission, charged particle emission, and giant dipole resonance (GDR) γ-ray emission occur on time scales that are comparable with fission. Studies of the competition between these decay modes can thus yield information on the fission lifetime [1, 2, 3]. In the case of GDR γ-ray emission, the photon energy spectra are mass- and shape-dependent [4], so it may be possible to gain insight into some shape parameters of the fissioning system by separating the contributions of the compound system and the fission fragments.

In the proposed studies, fission time scales will be probed by measuring both pre- and post-scission neutrons and GDR γ rays for several systems. These measurements will be made simultaneously, in an effort to avoid experimental biases in the neutron and the GDR γ-ray "clocks." At the same time, this approach should allow for a more consistent theoretical analysis, and thus place further restrictions on the fission time scale. The proposed experiments will focus on the following reactions: 133 MeV ^{16}O + ^{208}Pb, 133 MeV ^{16}O + ^{176}Yb, 104 MeV ^{4}He + ^{209}Bi, and 104 MeV ^{4}He + ^{188}Os. The use of both light and heavy projectiles may also provide insights into the influence of angular momentum on the fission time scale.

This proposal follows the style and format of Physical Review C.

BACKGROUND

Over the years, the fission time scale determined from neutron emission accompanying fission has been extensively studied [5–12]. There have also been numerous studies involving light charged particle emission [13–20]. A number of experiments involving GDR γ-ray emission have been carried out as well [21–29]. Use of these decay modes to measure fission time scales has met with limited success. In particular, time scales obtained by the first and last methods, with which the proposed research is concerned, can differ by an order of magnitude or more [3, 12]. This is quite interesting and would seem to indicate the need for further work to reconcile the cause(s) of these differences. The research proposed here should help to distinguish differences attributable to the underlying physics from those due to to systematic errors and the model analyses. This will then shed some light on what might be necessary to gain a better understanding of the physics involved. The two methodologies for determining the time scale for the fission process differ somewhat in the basic assumptions and analytical techniques, though they are founded on similar principles.

An excited compound nucleus can decay through a variety of decay channels, given adequate excitation energy. It frequently decays through γ-ray emission, neutron emission, charged particle emission, or fission. At any given time in the decay process, each of these will compete with each other according to their decay widths, Γ_x. In the case of fission, the daughter nuclei are also excited and also decay by these methods, although a second fission is very unlikely at modest excitation energies ($\approx$100-200 MeV).

Pre- and post-scission neutrons can be separated via the kinematic focussing of the post-scission neutrons in the direction of the emitting fragment. Similarly, GDR γ rays emitted from the compound system and the daughter fragments can be recognized by their different energies. For a GDR built on the nuclear ground state, the energy spectrum is expected to peak at

$$E = \frac{79}{A^{1/3}}, \tag{1}$$

where A is the mass number [4]. For a nucleus with mass around 220, this corresponds to about 13 MeV. In contrast, the peak energies for symmetric fission fragments should be about 3.5 MeV higher. A fit to the overall energy spectrum provides the relative number of each, from which an estimate of the time scales for fission can be made.

In the case of neutron measurements, the fission time can be thought of as a sum of times for several different processes. This can be written approximately as [1]

$$\tau = \tau_{form} + \tau_{sadd} + \tau_{scis} + \tau_{acc}, \tag{2}$$

where τ_{form} is the time associated with the formation of the compound nucleus, τ_{sadd} is the time required to achieve quasi-static equilibrium at the saddle point, τ_{scis} is the time for the system to evolve to scission, and τ_{acc} is the time for the fragments to gain most of their acceleration due to Coulomb repulsion. The last term is technically not part of the fission time scale, but is present in the neutron time scale simply because neutrons emitted by the fragments before they have attained enough of their final velocity will be indistinguishable from neutrons emitted by the compound nucleus. Analogously, for GDR γ-ray measurements, the form would be

$$\tau = \tau_{form} + \tau_{sadd} + \tau_{scis}. \tag{3}$$

Note that τ_{acc} is not present in the time scale given by analysis of GDR γ-ray data simply because the energies of the GDR γ rays are dependent upon the shape and size of the nucleus, so that once fission has occurred, any GDR γ rays observed will already be at the higher energies expected of fission fragments. The quantity τ_{sadd} is of special interest, as it is identified with the fission time delay or transient time [30]. In all cases, it would be very useful to determine each of these terms separately. Determination of all these quantities is expected to provide the value of the nuclear viscosity.

To this end, one might be able to set some limits on τ_{form} by forming the same compound nucleus through different entrance channels, as in the cases proposed here; 133 MeV ^{16}O + ^{176}Yb and the 104 MeV ^{4}He + ^{188}Os. For a lighter projectile, τ_{form} should be shorter simply due to the lessened importance of dynamical complications in the entrance channel, *e.g.* neck formation, diffusion, and viscosity. This would be reflected in the measurements as smaller values of the pre-scission neutron multiplicity (ν_{pre}) and a reduced yield of pre-fission GDR γ rays.

Similarly, it might be possible to gain a handle on τ_{acc} by comparing the τ's from the two techniques. A complication with this approach is that the nascent fragments in the vicinity of scission can be quite deformed. Some additional time is required for the fragments to shape equilibrate.

The separation of τ_{sadd} and τ_{scis} has proven to be a tricky business. In some early works, deviations in the yield of pre-fission neutrons and γ rays from statistical model predictions provided a measure of τ_{sadd} [31, 32]. However, it is now clear that failure of statistical models to reproduce ν_{pre} does not necessarily mean that there is a significant time delay since neutrons can be emitted throughout the descent from saddle to scission. Furthermore, conventional statistical model codes do not account for neutron evaporation during fission. Neutrons emitted during both time intervals cannot be separated kinematically. This has prompted the use of other approaches, such as studies of the mass distributions [19, 33, 34], fission excitation functions [35–39], and evaporation residue cross sections [40]. There is still no consensus on τ_{sadd}.

Possibly more constrained measurements and analyses, such as those proposed here, will offer some new insight into the fission time delay. Even if they do not, they should yield a better determination of the fission time.

PROCEDURE

These experiments will be carried out at the TAMU Cyclotron Institute, using beams supplied by the K500 superconducting cyclotron. The experiment will be performed by an international collaboration representing the United States, Russia, France, and Belgium. The National Barium Fluoride Collaboration (NBFC) will provide the acquisition system as well as 144 hexagonal BaF_2 crystal scintillator detectors used for γ-ray detection [41]. Eight large neutron detectors and associated electronics will be provided by the DEMON collaboration (Belgium and France) [42]. The Dubna group will provide a special thin-walled reaction chamber, osmium targets, and some custom electronics. Finally, the TAMU group, a member of the NBFC, will provide 50 of the BaF_2 detectors, the start detector, and the position sensitive parallel plate avalanche counters (PPAC's).

The fission fragments will be detected by two position sensitive PPACs, each with an active area of 225 cm^2. These will be mounted on either side of the target, one perpendicular to the beam axis, and the other at angles of 80° and 60°, for the systems using 104 MeV ^{4}He and 133 MeV ^{16}O beams, respectively. For the maximum geometric efficiency, the center of the detector will be only 10 cm away from the center of the target, giving a solid angle of some 2.25 steradians (18% of 4π) per PPAC. Detection of fission fragments together with either neutrons or γ rays will trigger the experiment.

The experiment will be triggered by detection of fission fragments in a start detector (small, transmission, non-position sensitive PPAC), which will be placed in front of the large PPAC at 90°. The large PPAC's will provide the high geometrical efficiency necessary to help overcome the small branching ratio for GDR γ-ray emission: 10^{-3}–10^{-4} per fission. They will also provide the x- and y-resolution necessary to reconstruct the fission fragment folding angle, giving a position resolution of less than 1 mm and a time resolution of approximately 250 ps. Such PPAC information will allow the masses and energies of the fission fragments to be reconstructed [43].

The pre- and post-scission neutrons will be detected by the DEMON liquid scintillator detectors, which are 16 cm in diameter and 20 cm in length. They will be placed both in and out of the reaction plane (see Figure 1), as defined by the fragments detected in the large PPAC's. Each detector will be placed at a nominal distance of 1.2 m from the target center. The solid angle for each detector will be approximately 0.0014 steradians (0.11% of 4π). The ratio of in-plane to out-of-plane

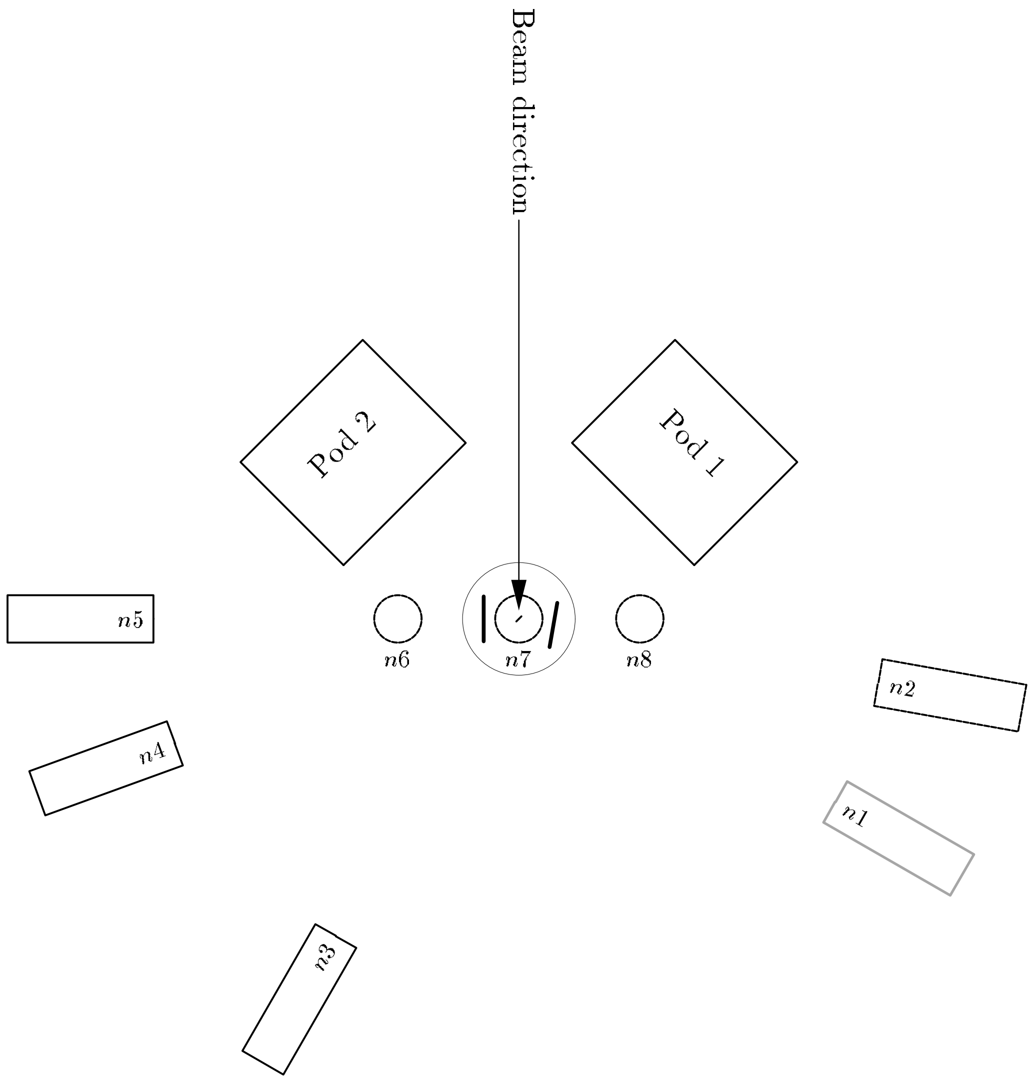

FIG. 1. A schematic of the layout of the various detectors around the target. The DEMON detectors are indicated by $n1$–$n8$. The $n1$ detector is below the reaction plane defined by the fission fragment detectors, while $n2$ and $n6$–$n8$ are above. The two pods of BaF_2 detectors are also shown. The two PPACs are indicated by the thicker straight lines between $n6$, $n7$, and $n8$. The reaction chamber is indicated by the thin-lined circle surrounding the target and PPAC's.

neutrons will give the relative contributions due to pre- and post-scission neutron emission. Both the time-of-flight separation given by the long flight path as well as the pulse shape discrimination of the NE213 scintillator will be used to separate neutrons from gamma rays in the off-line analysis. Post-scission neutrons will be separable from pre-scission neutrons by virtue of the kinematical focussing of the former due to their emission from the quickly-moving fission fragments.

The GDR γ rays will be detected by two pods of 72 hexagonal BaF_2 crystals. These pods will consist of a rough rectangle of nine layers of eight crystals in a hexagonal close-packed arrangement to facilitate the detection of high energy γ-rays. Each individual BaF_2 crystal will be 6.5 cm face to face and 20 cm in length. The two pods will be placed $\approx$55 cm from the center of the target, each at an angle of 135° with respect to the beam axis, giving a solid angle of 0.83 steradians (6.6% of 4π). Again, the time-of-flight and the inherent pulse shape discrimination properties of the BaF_2 crystals will be used to separate photons from neutrons off-line, as in the case of the DEMON detectors.

ANALYSIS

Data analysis will be approached in a multi-stage manner. First, the data from the PPAC's must be analyzed to reconstruct the fission fragment masses and energies in addition to giving a reliable start time determination. This part of the analysis will be carried out using custom software designed by the Dubna group. The software utilizes an iterative procedure starting with the time-of-flight and x-y position information to reconstruct an accurate start time (t_0) and physically meaningful fission fragment information, *e.g.* the fission fragment masses and energies. After these values converge, the data files will be rewritten to include them on an event by event basis.

Concurrently with the PPAC analysis, preliminary γ-ray analysis will begin. This will provide the calibrations and the important γ-ray gates for cleaning up the data. Algorithms for reconstructing electromagnetic showers produced in the crystals by the incident γ rays will also be implemented and tested. Additional algorithms for the analysis will be constructed when needed. Once the PPAC analysis is complete, the γ-ray data will then be re-analyzed, taking into account the corrected t_0. The added data from the PPAC's will be used to set gates on fission events, as well as to examine the effects of mass asymmetry and differing total kinetic energy (TKE) ranges upon the γ-ray spectrum. The final γ-ray spectra will be fit to statistical model calculations using a modified form of the code CASCADE [44]. The parameters resulting in the best fits will provide enough information to determine pre- and post-scission γ-ray multiplicities and energies as a function of mass asymmetry and TKE, as well as information on the fission time scales.

Neutron analysis will also begin after the PPAC data are analyzed and rewritten, since accurate knowledge of t_0 is very important in determining neutron energies. Pre- and post-scission neutron multiplicities will be determined by kinematic analysis. These multiplicities will be also examined for mass asymmetry and TKE effects. The resultant values will be compared to statistical model calculations to give the neutron-analysis values for the fission time scales.

CONCLUSIONS

In summary, it is proposed to study time scales for fission using both neutron and GDR γ ray measurements. Comparison of the time scales yielded by the GDR γ-ray measurements to those obtained from the neutron measurements improve our understandings of the two techniques and allow for a much more constrained extraction of fission times.

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