Probing Fission Dynamics With Neutrons and GDR Gamma Rays

T. Botting, G.G. Chubarian, R.P. Schmitt, K.L. Wolf, M.J. Murray, B.J. Hurst, H. Jabs, M. Hamelin,
A. Bacak, Yu.Ts. Oganessian‡, M.G. Itkis‡, E.M. Kozulin‡, N.A. Kondratiev‡, V.S. Salamatin‡,
I. Pokrovski‡, F. Hanappe†, E. de Goes Brennand†, A. Huck*, L. Stuttge*, E. Liatard**, J. Beene***,
R. Varner***, M. Halbert***, N. Gan***
‡ *Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia*
† *Universite Libre de Bruxelles, Brussels, Belgium*
* *Centre de Recherches Nucleaires, Strasbourg, Cronenbourg, France*
** *Institut des Sciences Nucleaires, Grenoble, France*
*** *ORNL, Oak Ridge, TN, U.S.A.*

As described previously [1], the fission dynamics of four reactions (133MeV ^{16}O on ^{208}Pb and ^{176}Yb and 104MeV ^{4}He on ^{209}Bi and ^{188}Os) have been studied using both neutrons and GDR γ rays. Whereas previous studies have used a single method, such as the so-called neutron clock [2,3] or giant dipole resonance (GDR) γ rays [4], here it was undertaken to use both of these methodologies simultaneously to examine a variety of fissioning systems.

The experiment made use of the National Barium Fluoride Array (NBFA) in two pods of 72 crystals each, two large parallel plate avalanche counters (PPACs) and one small PPAC start detector constructed at TAMU, eight liquid scintillator neutron detectors from the DEMON array [5], and a reaction chamber from the Dubna collaborators. The detailed experimental setup has been described previously [6].

The analysis was approached in a multifold fashion. The PPAC data were painstakingly analyzed using software developed in Dubna which uses an iterative process to account for slight drifts in the beam position. The fission mass and energy distributions were then generated from kinematics. Events in which both fission fragments were observed along with their angles, velocities and accurate start time are rewritten to tape for later use in the GDR and neutron clock analyses.

Following the PPAC analysis, the neutron data were analyzed in Belgium to extract pre- and post-scission neutron multiplicities. These were evaluated for each system as a whole and for each of the mass cuts used in the γ-ray analysis. This was accomplished via moving-source fits to the observed neutron energy spectra as a function of angle after calibrating and folding in the detector responses.

The BaF_2 calibrations and cleanup of the γ-ray data were performed while the PPAC analysis was being carried out. In addition, algorithms were constructed and tested to reconstruct the γ-ray showers in the central areas of each pod. In reconstructing the showers, the crystal with the highest energy was identified and its energy was summed with those of the surrounding crystals on an event by event basis. Cosmic rays were also rejected by use of the so-called "bullseye" method of Jabs [7].

The raw data have been analyzed for all systems. Table 1 summarizes the various fission results of the four systems. Errors given correspond to a standard deviation of one sigma. Figure 1 shows the total fission-associated γ-ray yield for all systems but ^{4}He+^{188}Os, which yielded

Table 1. Fission fragment characteristics for each reaction studied.

Reaction	Events	⟨Mass⟩ (amu)	⟨TKE⟩ (MeV)	$\langle\Theta_{fold}\rangle$ (degrees)	$\langle t_0\rangle$ Offset (ns)
$^{16}O + ^{208}Pb$	10.867 M	112 ±17	163.2±25.0	180.4±4.6	2.80±0.73
$^{4}He + ^{209}Bi$	7.411 M	106.5±14	140.7±16.9	180.2±3.7	2.72±0.57
$^{16}O + ^{176}Yb$	2.300 M	96 ±14	133.0±22.0	180.4±4.1	2.73±0.65
$^{4}He + ^{188}Os$	0.047 M	96 ±15	133.7±19.5	180.1±3.4	2.80±0.63

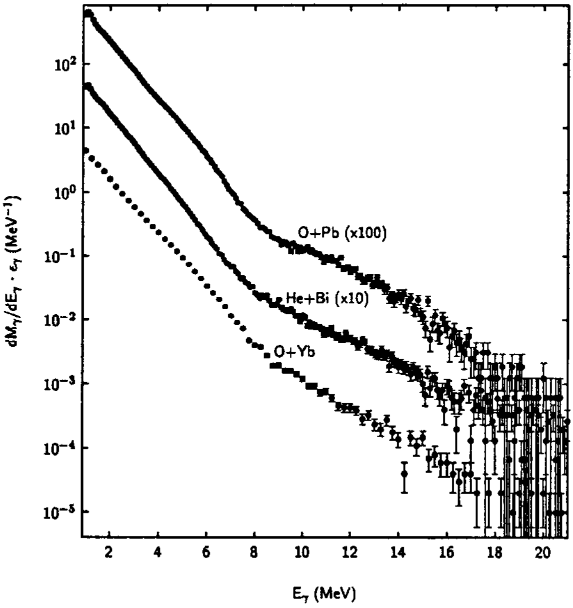

Figure 1. Total absolute fission γ yield $<M_\gamma>$ for the three reactions with adequate statistics. The topmost spectrum correspond to ^{16}O+^{208}Pb, increased by a factor of 100. The central spectrum represents ^{4}He + ^{209}Bi, times 10. The bottom is the $<M_\gamma>$ spectrum for ^{16}O + ^{176}Yb.

Table 2. Extracted neutron multiplicities for the various reactions. Uncertainties are +/- 0.5 neutrons in all cases.

System	ν_{pre}	ν_{post}	ν_{tot}
^{16}O+^{208}Pb	4.2	2.5	6.7
^{4}He+^{209}Bi	4.8	2.4	7.2
^{16}O+^{176}Yb	4.8	2.2	7.0
^{4}He+^{188}Os	4.4	2.6	7.0

insufficient statistics for GDR γ-ray analysis. The GDR contributions are clearly visible as large enhancements centered around approximately 12MeV. There is also a slight enhancement in the region 3-8MeV. While the origin of the latter enhancement is unknown, it is not due to neutrons. It is assumed that the enhancement in this region is associated with the double shell closure, which while not well-understood, agrees with previous observations [8]. Effects of fragment mass asymmetry and various TKE cuts were also investigated in the γ-ray spectra, with no fragment mass or TKE dependence observed in the GDR region. The only mass-dependent effect was present in the high-energy statistical decay region, as in the observations of Fitzgerald *et al.*[8].

The neutron results from the moving-source fits are given in Table 2. Note that the pre-scission multiplicities are similar, which is as expected from the similar excitation energies produced in these reactions. Post-scission multiplicities reflect the amount of excitation remaining in the fragments after separation.

Model calculations using CASCADE [9] have been applied to data from each of the reactions shown in Figure 1. In each case, there is a significant enhancement in the GDR region above and beyond what can be accounted for by any reasonable set of input parameters.

In an effort to understand this enhancement in terms of the nuclear viscosity, the code TIMCASC [10] was used to fit the data. This code is a modification of the original CASCADE wherein the nuclear viscosity has been introduced in the form of a friction constant, γ. Using this code linked to MINUIT, a set of GDR parameters is determined which give the best fit to the spectra at a variety of different values for the friction coefficient, γ. Since the experimental γ-ray spectra also include contributions from the fragments, the code had to be provided with a library of fission fragment data to allow spectra for the whole decay cascade to be constructed. This library was not extant and had to be created. Three months of computing time on muon.tamu.edu (a quad-processor HP-9000) and ccomp.tamu.edu (a dual-processor Pentium II-450) were required to accomplish this task, in addition to numerous code adaptations and debugging. Once these were in place, the fitting procedures were undertaken, using reasonable ranges for the GDR centroid, width, and strength, and the deformation of the compound nucleus as the only free parameters. These fits are currently nearing convergence. A total of seven separate computers (the two above, and five 533Mhz Alpha-based machines) are being used to maximize computing power for this task.

All that remains is to extract time scales for both clocks from the model fits with the lowest chi-square values. Since TIMCASC already includes the concept of a time for each step in the decay cascade, this is trivial. From these time scales, the neutron and GDR γ-ray clocks can be directly compared, perhaps yielding a better understanding of past discrepancies between them.

References

[1] T. Botting, *et al.*, *Progress in Research*, 1997-1998, Cyclotron Institute, Texas A&M University, p. II-10.

[2] A. Gavron, *et al.*, Phys. Rev. C **35**, 579 (1987) and references therein.

[3] D. J. Hinde *et al.*, Phys. Rev. C **45**, 1229 (1992).

[4] M. Thoennessen *et al.*, Phys. Rev. Lett. **59**, 2860 (1987).

[5] D. Durand, *et al.*, *Proceedings of the International Conference on New Nuclear Physics with Advanced Techniques*, Ed. F. A. Beck, S. Kossionides and C. A. Kalfas, World Scientific: Singapore, 173 (1992).

[6] T. Botting, *et al.*, *Progress in Research*, 1996-1997, Cyclotron Institute, Texas A&M University, p. II-26.

[7] H. Jabs, Masters Thesis, TAMU, 1997.

[8] J. B. Fitzgerald, *et al.*, *Proceedings of the Second International Conference on Dynamical Aspects of Nuclear Fission*, Eds. J. Kristiak and B.I. Pustylnik, JINR Press, Dubna, pp.68-87 (1994), and references therein.

[9] F. Puelhofer, Nucl. Phys. **A280**, 276 (1977).

[10] G. van 't Hof, *et al.*, Nucl. Phys. **A638**, 613 (1998).