Rapid Increase in Prescission GDR γ-ray Emission with Energy

D. J. Hofman[a*], B. B. Back[a*], and P. Paul[b†]

[a]Argonne National Laboratory, Argonne, IL 60439, USA
[b]Department of Physics, SUNY Stony Brook, Stony Brook, New York 11794, USA

A rapid increase in the emission of prescission giant dipole resonance (GDR) γ-rays with bombarding energy is observed in excited Th and Cf nuclei formed in the reactions $^{16}O+^{208}Pb$ and $^{32}S+^{nat}W,^{208}Pb$. This increase begins around $E_{exc} = 40$ MeV for the $^{16}O+^{208}Pb$ reaction and $E_{exc} = 70$ MeV for the ^{32}S-induced reactions. The excess γ-ray yield above these thresholds cannot be described within the standard statistical model. Statistical model calculations which include a temperature dependent nuclear dissipation are able to reproduce simultaneously the observed GDR γ-ray spectra and recently measured evaporation residue cross sections.

1. INTRODUCTION

This report focuses on our analysis of experimentally measured giant dipole resonance (GDR) γ-rays and evaporation residue cross sections resulting from two fusion-fission reactions forming Th compound nuclei.

It is by now a well established experimental fact that fission is slower than expected when the energy and average angular momentum of a compound nucleus is increased. The available experimental data on prescission neutron [1] and GDR γ-ray [2] emission (e.g. see Fig. 1) consistently show excess yields over standard expectation when the compound nucleus is heated to a temperature above 25% of the fission barrier [3]. These observations have generally been understood within the framework of a dissipative fission model. However, it is not yet clear as to how strongly the various stages of the fission process are being affected by the dissipation.

Two (of many) possible explanations for the fission retardation are either an increasing nuclear viscosity or a minimum dynamical fission time scale. Both approaches have been successful, the first primarily in the analysis of GDR γ-rays and the second initially in the analysis of prescission neutron multiplicities.

The possible existence of nuclear viscosity in the fission motion has its roots in the work of Kramers [5], who calculated the diffusion rate across a barrier in a dissipative medium. His model, when applied to the fission process, shows a reduction of the fission rate as nuclear viscosity is increased. In addition, there is a transient build-up time of the fission flux before it reaches a stationary flow across the barrier and a slowing of the descent

*Supported by the U.S. Department of Energy, Nuclear Physics Division, under contract No. W-31-109-ENG-38
†Partially supported by the U.S. National Science Foundation

from saddle to scission. Within our analysis, these three effects are governed by a dimensionless linear friction parameter γ, where $\gamma > 1$ corresponds to an over-damped fission motion, $\gamma < 1$ to an under-damped motion, and $\gamma = 0$ to no damping.

The alternate explanation concerns the possible existence of a dynamical fission time scale. In this view there exists a minimum fission time scale which becomes evident only when the statistical fission rate increases to a point where the dynamical time scale becomes experimentally measurable [6,7]. This effect is implemented in the same statistical model code by simply inhibiting fission for a fixed amount of time before restoring the normal non-dissipative (Bohr-Wheeler) fission rate.

Recent measurements of evaporation residue cross sections in the actinide region have provided an additional experimental constraint to the calculations by being sensitive only to the dissipation inside the saddle point during the full evaporation cascade. The high-energy prescission GDR γ-rays, on the other hand, are mainly emitted in the early decay stages of the compound nucleus, where the excitation energy is high. We thus wish to explore whether the evaporation residue cross section data, in conjunction with the GDR γ-ray results, can aid in differentiating between various scenarios.

2. RESULTS

Fig. 1 shows the excess yield of GDR γ-rays over standard statistical model predictions for three reactions at several bombarding energies. This trend mirrors that seen in prescission neutron multiplicities and provides our motivation and starting point.

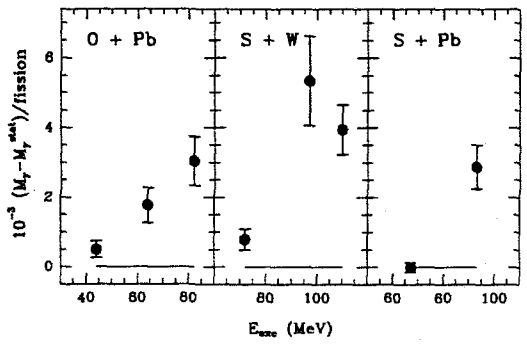

Figure 1: The excess γ-ray multiplicity (E_γ = 7–15 MeV) is shown as a function of initial excitation energy in the compound system (taken from Ref. [4]).

Our calculations are carried out within the Hauser-Feshbach formalism as implemented in a modified version of the statistical model code CASCADE[8]. The main ingredients of this code are the level density parameters, fission barrier heights, and particle transmission coefficients. For the level density parameters, we use a=A/9.0 at high excitation energies and the Dilg [9] parameterization at low energies. Fission barriers are from Sierk's finite range liquid drop model [10], and we have included a T^2 fission barrier temperature dependence as parameterized by Newton *et al.* [11]. Transmission coefficients were calculated by a version of Wilmore and Hodgson's optical model code [12] modified to include the work of Rapaport *et al.* [13]. The GDR emission strength was fixed at the classical sum rule.

The dotted lines of Fig. 2 correspond to standard statistical model predictions (i.e. γ=0) which are compared to data for the GDR γ-ray spectra (upper right panel), γ-fission angular correlations W(0°)/W(90°) (upper left panels), and evaporation residue cross sections (lower left panel) in the ^{16}O+^{208}Pb reaction. The excess yield in the γ-ray energy spectra and the positive anisotropy in the γ-fission angular correlation around E_γ=10 MeV is a result of GDR γ-ray emission from an aligned deformed compound

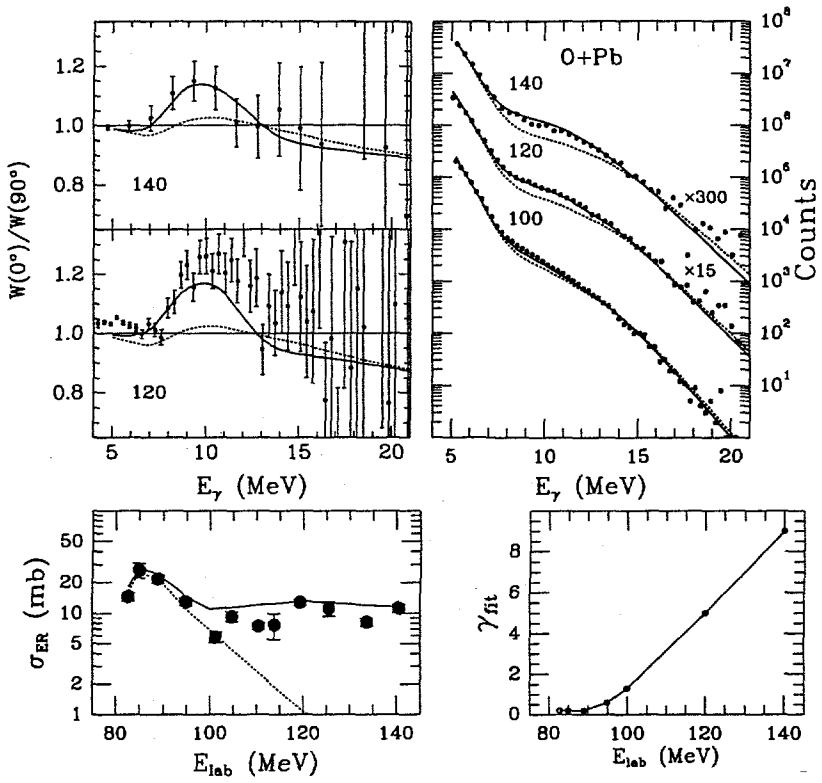

Figure 2. Calculations without nuclear viscosity (dotted lines) and including nuclear viscosity γ_{fit} (solid lines) for GDR γ-ray spectra, γ-fission angular correlation and evaporation residue cross sections in the reaction $^{16}O+^{208}Pb$. The experimental data are taken from Refs. [14–17].

nucleus, and represents a direct signature of prescission GDR emission. The standard statistical model fails to describe all results above a bombarding energy $E_{lab} \sim 100$ MeV.

The experimental data can be simultaneously described by increasing the nuclear friction parameter at the higher energies. The solid lines of Fig. 2 correspond to the results of this procedure for different values of the friction parameter γ (γ_{fit} in lower right panel). We find that a nuclear viscosity which increases as a function of energy simultaneously describes the GDR γ-ray results and evaporation residue cross sections.

In the $^{32}S + ^{184}W$ reaction we find much the same situation. Fig. 3 contains calculations both without (dotted lines) and with (solid lines) nuclear viscosity. The standard statistical model calculations fails to describe the measured GDR results and evaporation residue cross sections. Including a viscosity which increases for increasing bombarding energy (γ_{fit}) simultaneously gives a better description of the data.

Next we explore the idea that the fission retardation is caused by a dynamical fission time scale during which fission cannot occur. For the $^{16}O+^{208}Pb$ reaction a fission delay time of 70×10^{-21}s is able to describe the GDR γ-ray spectra and γ-fission angular correlations quite well (see Fig. 4). This value also describes the evaporation residue cross section reasonably well below $E_{lab} \sim 115$ MeV. However this delay time underpredicts both the magnitude and slope of the evaporation residue cross sections at the

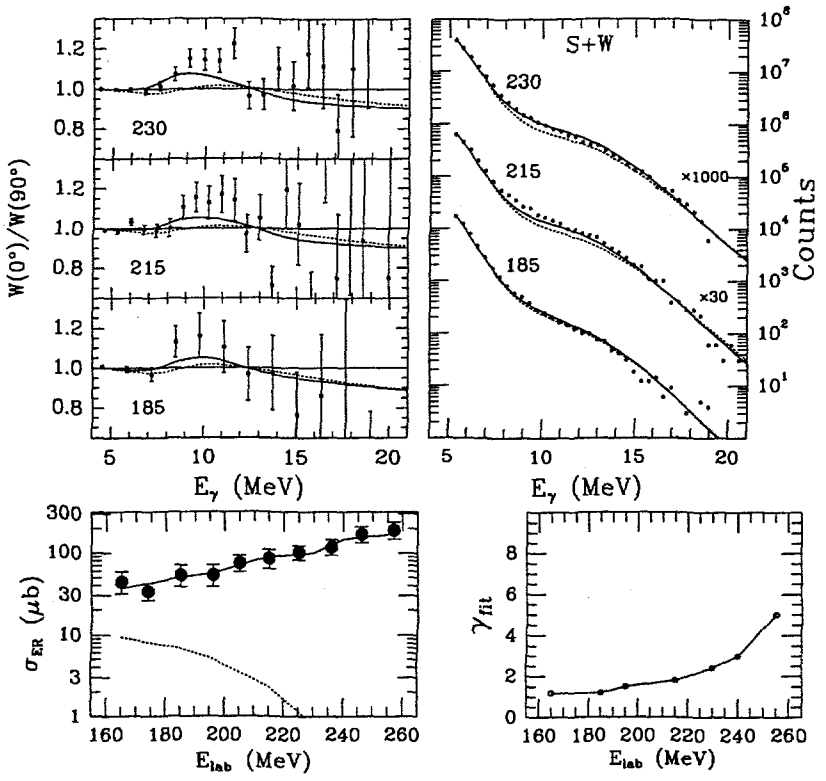

Figure 3. Calculations without nuclear viscosity (dotted lines) and including nuclear viscosity $\gamma_{\rm fit}$ (solid lines) for GDR γ-ray spectra, γ-fission angular correlations and evaporation residue cross sections in the reaction ^{32}S+^{184}W. Experimental data are from [15,18].

higher bombarding energies. This is because the higher bombarding energy translates into an increased initial excitation energy and spin, and for this delay time the compound nucleus is unable to cool down enough behind the fission barrier to increase the predicted evaporation residue yields to their experimental values.

The discrepancy with the evaporation residue cross sections can be removed by increasing the delay times at the higher bombarding energies as shown by dashed lines in Fig. 4. The fission delay time is varied from 60×10^{-21}s at $E_{lab} = 83$ MeV to 500×10^{-21}s at $E_{lab} = 140$ MeV. This procedure is able to describe the measured evaporation residue cross sections, but slightly under-predicts the GDR γ-ray energy spectrum at $E_{lab} = 100$ MeV and over-predicts the spectrum at $E_{lab} = 140$ MeV (see upper right panel of Fig. 4).

The same procedure applied to the ^{32}S + ^{184}W reaction yields similar results. A constant fission delay time of 30×10^{-21}s describes the GDR γ-ray energy spectra and γ-fission anisotropy to the same level as the viscous fission fits of Fig. 3. However this result under-predicts the measured evaporation residue cross section at the highest measured bombarding energy ($E_{lab} = 257$ MeV) by a factor of 6. Increasing the time delay as a function of energy to a value 100×10^{-21}s at $E_{lab} = 257$ MeV describes the evaporation residue yields, but over-predicts the γ-ray energy spectrum at the highest energy measured ($E_{lab} = 230$ MeV). Thus it appears that a dynamical fission time delay is not sufficient to

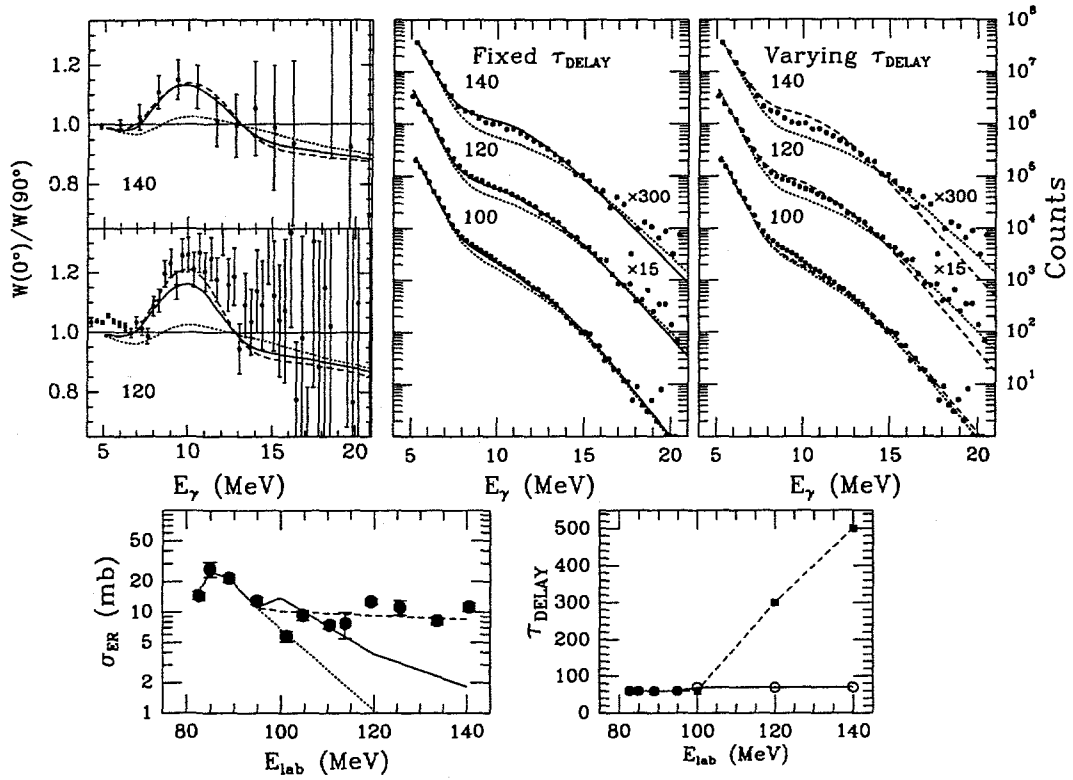

Figure 4. Calculations without a fission delay time (dotted lines), a fixed fission delay time τ_{DELAY} (solid lines) and a varying fission delay time τ_{DELAY} (dashed lines) for data from the ^{16}O+^{208}Pb reaction.

describe both the GDR γ-ray results and the evaporation residue cross sections for both reactions, and it is necessary to also reduce the fission rate itself (as occurs in the viscous fission fits).

3. CONCLUSIONS

A simultaneous description of GDR γ-ray data and evaporation residue cross sections is possible within the framework of a dissipative fission process where the nuclear viscosity increases as a function of bombarding energy.

Fig. 5 gives a summary of the values of the linear friction coefficient obtained from our analysis for two reactions leading to thorium compound nuclei, namely ^{16}O+^{208}Pb and ^{32}S + ^{184}W. In both cases the friction is seen to rise quite strongly with increasing initial excitation energy or temperature. The fact that the two results do not fall on the same curve raises many questions. It might be reasonable to expect a changing nuclear viscosity to be a universal feature of nuclear matter independent of the reaction involved. In this context we note two special features of the ^{32}S+^{184}W reaction which may be playing a role. First, it is known that at least 40% of the total fission cross section is coming from quasi-fission (quasi-fission plays a negligible role in the ^{16}O + ^{208}Pb reaction). Secondly,

the $^{32}S+^{184}W$ reaction produces a shell-stabilized initial compound system with N=126, whereas the $^{16}O+^{208}Pb$ reaction does not (N=134).

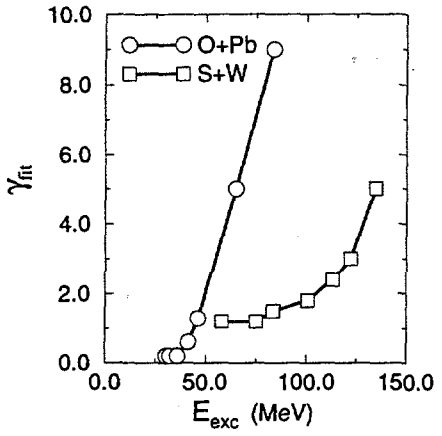

Figure 5: Extracted values of the linear friction coefficient (γ_{fit}) plotted versus initial excitation energy.

It would be of interest to extend the measurements of both GDR γ-rays and evaporation residue cross sections to still higher energies in order to map out the behavior of the nuclear friction parameter. It seems unlikely it will continue to rise indefinitely, and may flatten out or even turn over and decrease. Such a behavior would be similar to that found in the propagation of zero sound in liquid He^3 at low temperatures [19]. The reaction ^{16}O + ^{208}Pb may provide the best hope for such a measurement since the contribution from quasi-fission is small and the γ-rays from the fission fragments still do not overwhelm the prescission yields.

We would like to thank M.N. Harakeh, I. Diószegi and H. van der Ploeg for sending us their version of their optical model code. One of us (D.J.H.) also thanks the conference sponsors for providing additional financial support.

REFERENCES

1. D. Hilscher and H. Rossner, Ann. Phys. Fr. **17**, 471 (1992).
2. P. Paul and M. Thoennessen, Ann. Rev. Nucl. Part. Sci. **44**, 65 (1994).
3. M. Thoennessen and G. F. Bertsch, Phys. Rev. Lett. **71**, 4303 (1993).
4. D. J. Hofman, B. B. Back, and P. Paul, Phys. Rev. C **51**, 2597 (1995).
5. H. A. Kramers, Physica **7**, 284 (1940).
6. H. van der Ploeg, *et al.*, Phys. Rev. Lett. **75**, 970 (1995).
7. R. Vandenbosch, Phys. Rev. C **50**, 2618 (1994).
8. R. Butsch, *et al.*, Phys. Rev. C **44**, 1515 (1991).
9. W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. A **217**, 269 (1973).
10. A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
11. J. O. Newton, D. G. Popescu, J. R. Leigh, Phys. Rev. C **42**, 1772 (1990).
12. Wilmore and Hodgson, Nucl. Phys. A **55**, 673 (1964).
13. J. Rapaport, *et al.*, Nucl. Phys. A **330**, 15 (1979).
14. M. Thoennesen, *et al.*, Phys. Rev. Lett. **59**, 2860 (1987).
15. I. Diószegi, *et al.*, Phys. Rev. C **46**, 627 (1992).
16. D. J. Hofman, *et al.*, Phys. Rev. Lett., **72**, 470 (1994).
17. K.-T. Brinkmann, *et al.*, Phys. Rev. C **50**, 309 (1994).
18. B. B. Back, *et al*, to be published.
19. W. R. Abel, A. C. Anderson, and J. C. Wheatley, Phys. Rev. Lett. **17**, 74 (1966).