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Probing Reaction Dynamics with GDR Decay

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The giant dipole resonance (GDR) has been a prolific source of information on the physics of the nucleus. Mostly it has taught us about nuclear structure, but recently experiments have utilized the GDR as a probe of nuclear reaction dynamics. In this report two examples of such investigations are discussed involving very different reactions and probing time scales that differ by a factor of ~10^3.

1. INTRODUCTION

The giant dipole resonance (GDR) was first identified almost fifty years ago, and soon recognized as a collective excitation, involving essentially all the nucleons in the nucleus. Since this time the GDR has had a profound influence on the development of an understanding of nuclear structure physics. About fifteen years ago, effects of the GDR were clearly identified in the decay of highly excited nuclei produced in compound nucleus reactions [1]; the quantitative study of nuclear structure effects at finite nuclear temperature, probed by the GDR, began. More recently the GDR decay has been used as a tool to explore the dynamics of nuclear reactions – in particular the "hindrance" of fission due to dissipative effects (see ref. 2 and references therein). GDR decay studies have also been used to probe the range of validity of preequilibrium decay models [3,4]. In this brief report, we discuss two new applications of the decay of the GDR to nuclear reaction dynamics. In both cases the time scale of the reaction is investigated. However, the reactions studied are dramatically different, and the time scales probed differ by several orders of magnitude.

2. THE TIME SCALE OF FUSION REACTIONS

It was predicted in the pioneering work of Swiatecki [5] that under certain conditions fusion reactions involving mass symmetric entrance channels could take appreciably longer to produce an equilibrated compound nucleus than reactions producing the same nucleus by a more mass asymmetric entrance channel.

We have made a quantitative investigation of this effect using two pairs of reactions producing ^{164}Yb at $E^* = 49$ MeV and ^{110}Sn at $E^* = 56$ MeV. The reactants employed were ^{16}O + ^{148}Sm and ^{64}Ni + ^{100}Mo for ^{164}Yb, and ^{18}O + ^{92}Mo and ^{50}Ti + ^{60}Ni for ^{110}Sn.

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Theoretical predictions obtained from the dissipative reaction dynamics code HICOL [6] are shown in Fig. 1 for time evolution of two degrees of freedom in fusion– thermal (i.e., nuclear excitation) energy and shape (quadrupole moment). A dramatic difference in the time scales over which these degrees of freedom reach steady state (equilibrium) values is obvious for the ^{164}Yb systems in Fig. 1 – but much less dramatic for the ^{110}Sn systems. This different behavior is expected on the basis of the semiquantitative arguments of Swiatecki [5] who pointed out that both the entrance channel asymmetry and the effective fissility of the composite system (roughly Z^2/A) are crucial parameters in determining the delay imposed on the reaction by dissipative effects. The larger effective fissility of the ^{164}Yb system results in greater sensitivity to entrance channel asymmetry.

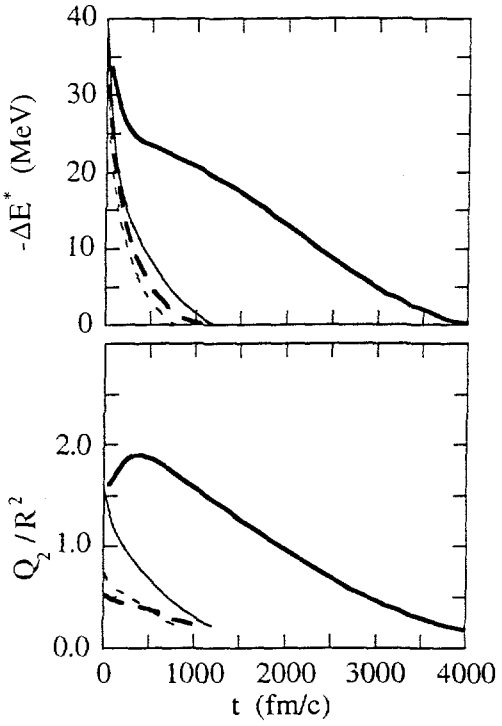

Figure 1. HICOL calculations for the time evolution of excitation energy and quadrupole moment in four heavy ion fusion reactions producing the fused systems ^{164}Yb and ^{110}Sn. The systems are ^{64}Ni + ^{100}Mo (heavy solid line), ^{16}O + ^{148}Sm (heavy long-dash), ^{50}Ti+^{60}Ni (light solid) and ^{18}O+^{92}Mo (light short-dash). The quantities plotted are (upper panel) the excitation-energy deficit $\Delta E^*(t) = E^*(t)-E^*(\infty)$, and (lower panel) the quadrupole moment divided by $R^2 = 1.2\ A^{1/3}$.

How can the effects shown in Fig. 1 be probed experimentally? Among the desirable characteristics of an experimental probe are: (1) that it is primarily sensitive to the earliest stages of the reaction, (2) that its emission probability depend strongly on excitation energy, and, (3) that it have a well defined sensitivity to the nuclear shape. The emission of photons from the decay of the GDR meets all these criteria admirably. Let us focus initially on the decay of the ^{164}Yb system excited to ~50 MeV. Aside from the very rapid initial change in ΔE^* (Fig. 1) the HICOL code predicts, for the ^{64}Ni + ^{100}Mo system, a slow almost linear approach to the equilibrium value of excitation energy with a total amplitude ΔE^*~25 MeV. Statistical model calculations predict that ~50% of GDR decay photons (defined as photons with $E_\gamma > 11$ MeV) come from the initial excited system (i.e., from $E^* = 50$ MeV). Thus the requirement of sensitivity to the earliest reaction stage is met. The same statistical calculations predict that in the GDR photon yield is a very steep function of increasing excitation energy near 50 MeV, therefore, the sensitivity to excitation energy is also met. The dependence of the GDR strength distribution on the shape of the nucleus is well known [7].

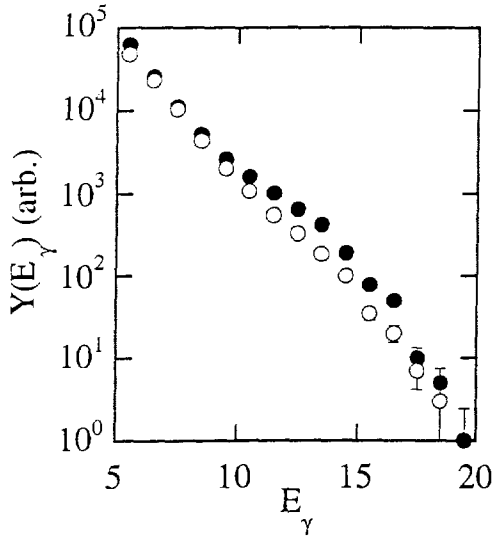

Figure 2. Statistical model calculation of the γ-ray decay spectrum for E^*=50 MeV ^{164}Yb. The solid points are for a conventional calculation with standard GDR parameters, the open points are for a time-dependent calculation employing the time dependence of excitation energy and shape obtained from the HICOL code for ^{64}Ni+^{100}Mo.

Thus, qualitatively, we expect the yield of GDR photons emitted in the reaction (and the shape of the spectrum) to reflect the predicted difference in time scales between the ^{16}O + ^{148}Sm reaction and the ^{64}Ni + ^{100}Mo reaction. Is, however, this difference large enough to be observed? To investigate this we have carried out statistical model calculations based on the Monte Carlo statistical model code evapOR [8], in which the time dependent variation in excitation energy and shape are explicitly included. A preliminary version of this analysis based on a cruder implementation of the time dependence has been reported elsewhere [9]. In the present calculations the time dependence of excitation energy and shape are introduced by polynomial approximations to the curves in Fig. 1. These time depended parameters are sampled at each decay step by each event in the Monte Carlo simulation, according to the total elapsed time. Sample calculated γ-ray decay spectra are shown in Fig. 2. The two curves represent calculations with and without the time dependent ΔE^* and quadrupole moment effects. For simplicity in comparing with experimental data the spectra are normalized to have the same integrated yield in the 6-8 MeV range. The relative suppression of γ-ray yield above ~10 MeV is evident for the delayed fusion calculation.

Experimental data (see ref. 9 for experimental details) for the two pairs of entrance channels are shown in Fig. 3 for ^{164}Yb and ^{110}Sn. A large difference in the γ-ray spectra produced by ^{16}O + ^{148}Sm and ^{64}Ni + ^{100}Mo is evident, while the spectra for the two entrance channels populating ^{110}Sn are identical within experimental uncertainties. These data, therefore, clearly support the qualitative predictions of the HICOL code, as shown in Fig. 1.

We next undertake a quantitative investigation of the effect seen in ^{164}Yb decay in Fig. 3. The time-dependent statistical model we have built depends explicitly on the time dependence in excitation energy and shape obtained from HICOL. We have not yet developed a method of analysis which would allow us to extract the time scale of fusion in a general way. Instead, we take the *form* of the time dependence predicted by HICOL and apply a scaling factor f_t to the time scale. Rather than attempt to fit the γ-ray spectral shapes as a function of f_t, we will instead work with the yield ratio $R = Y_2(E\gamma)/Y_1(E\gamma)$ with, where the Y_i are integrals of the γ-ray spectra between two energy limits. The energy limits employed are above11 for Y_2 and 7 to 10 MeV for Y_1. Results of this analysis are shown in Fig. 4. The results of statistical model calculations for the decay of ^{164}Yb are shown, as a function of the scale factor f_t , for two different level density parameters a = A/8.5 and A = A/10. We can see that the ^{16}O + ^{148}Sm data is consistent with $f_t = 0$, as expected, while the ^{64}Ni + ^{100}Mo reaction requires $1.6 < f_t < 2.9$. We can convert this to an absolute "fusion time" if we use a value of τ_{hicol} = 4000 fm/c for the HICOL calculation (read off Fig. 1); the

resulting experimental fusion time is $6500 < \tau_{exp} < 11500$. From what is known about the effects of dissipation or other reactions (deep inelastic scattering, fission) it is surprising that the data require a significantly longer fusion time than predicted by HICOL.

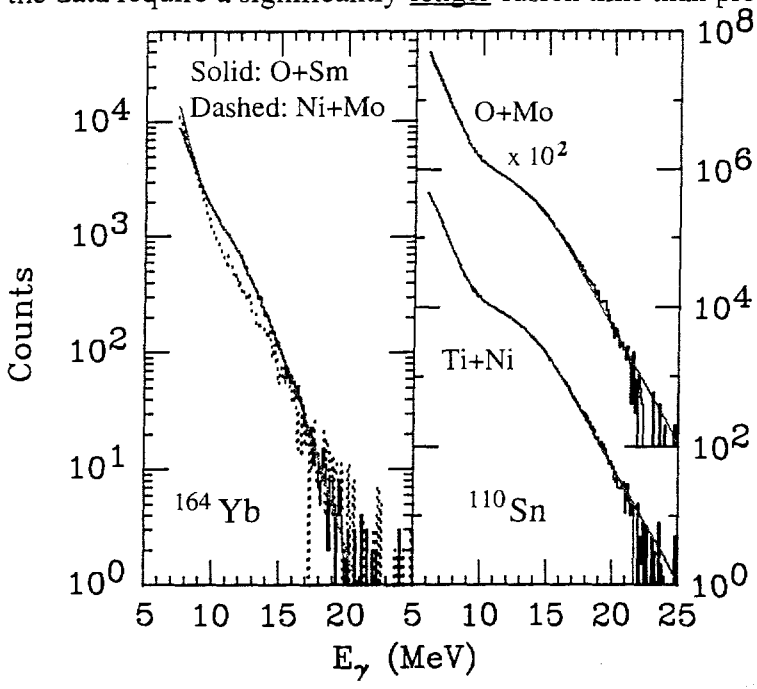

Figure 3. Gamma-ray spectra for decay of ^{164}Yb (50 MeV) on the left-hand side and ^{110}Sn (56 MeV) on the right hand side. In the ^{164}Yb spectra the Ni+Mo data is shown as a dashed histogram, and the O+Sm data as a solid histogram. A statistical model calculation with conventional parameters is shown as a solid line. For the ^{110}Sn data both entrance channels are shown as solid histograms, with the O+Mo channel offset by a factor of 100. The solid lines superimposed on the histograms represent the same conventional statistical model calculation.

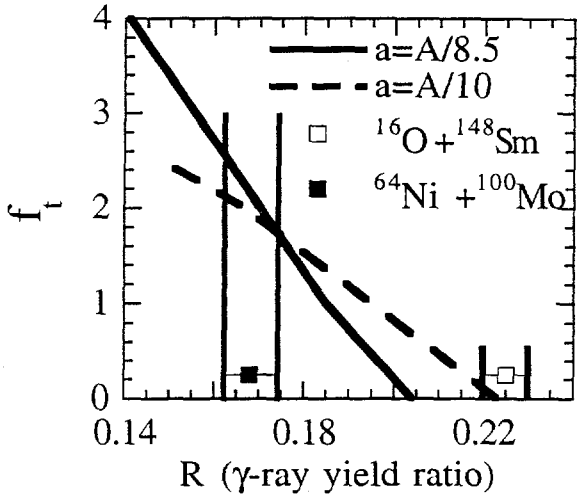

Figure 4. Comparison of the experimental ratio R (the high energy , E_γ>11 MeV, γ-ray yield divided yield in the interval 7 MeV < E_γ < 10 MeV), to values calculated with the time dependent statistical model code as a function of the time scale factor f_t defined in the text, for two different level density parameters.. The data points are experimental values for Ni+Mo (filled) and O+Sm (open).. Only the horizontal (R) position of the data points is significant. The 1σ limits (error bars are arbitrarily extended vertically to ease comparison with the calculations.

2.1. Relationship to other entrance channel effects

We have presented our data as a measurement of the time scale of fusion. This is somewhat at variance with the point of view adopted in similar studies of decay of excited nuclei produced by different entrance channels. If the effects of reaction dynamics (including

trivial effects like differences in angular momentum) can be ruled out, differences in the decay of nuclei produced at the same excitation energy by different reactions reflect failures of the independence hypothesis upon which the notion of an equilibrated compound nucleus is based. Several such "entrance channel effects" have been reported in recent years, on systems very similar to the ^{164}Yb system reported here. An example is the ^{156}Er system, which has been investigated with the ^{12}C + ^{144}Sm and ^{64}Ni + ^{96}Zr reactions. Two entrance channel effects have been reported, both related to cross sections for specific neutron evaporation channels (the xn channels account for most of the evaporation cross section. Initial studies carried out by the Argonne group [10,11] reported anomalous suppression of n emission in the symmetric entrance channel, such that the average number of emitted neutrons $\bar{x} = \sum x\sigma_{xn}$ (where σ_{xn} is the cross section for emission of x neutrons) was smaller than could be accounted for by statistical model calculations – while the result from the asymmetric entrance channel agreed with predictions. A more sensitive experiment was performed at the Heidelberg Crystal Ball in which the entrance channel angular momentum was measured directly by γ-ray multiplicity technique [12]. This experiment showed a large difference between the two entrance channels in the ratios of partial xn cross sections as a function of angular momentum [$\sigma_{2n}(L)/\sigma_{3n}(L)$], which could not be accounted for by the author's statistical model calculations.

Are these effects on xn cross sections a result of the fusion time effect to which we ascribe our observation of differences in the γ-ray spectra? According to our time dependent statistical model calculations on the ^{164}Yb system, the answer is no. The value of $\bar{x}$ changes by only a few percent up to $f_t \sim 5$ (the largest we have investigated), though there is some broadening of the distribution of x. Likewise the effect of the time dependent excitation energy and shape produce on the $\sigma_{2n}(L)/\sigma_{3n}(L)$ ratio is almost an order of magnitude smaller than the difference between the entrance channels observed experimentally. The delay time predicted by HICOL is simply too short to have a significant impact on observables related to neutron emission cross section, which integrate over time scales orders of magnitudes greater than the upper limit to fusion time (11500 fm/c) deduced from our γ-ray measurements.

These results imply some other reaction dynamic effect related to entrance channel asymmetry or even a failure of the independence hypothesis might occur for reactions like the one we have studied. Either eventuality would complicate the interpretation of our results. Consequently we have made a careful study of the decay of the ^{164}Yb system populated by ^{16}O + ^{148}Sm and ^{64}Ni + ^{100}Mo over an excitation energy range form 40 to 53 MeV. Data for this analysis was available from earlier studies of sub- and near-barrier fusion in these systems in the ORNL Spin Spectrometer [13,14]. The results of this analysis are interesting in themselves [15], but space is too limited for an adequate discussion. Our findings are that there is no systematic suppression of $\bar{x}$ in symmetric entrance channel; experimental values of $\bar{x}$ for both entrance channels are equally well accounted for by the statistical model at all energies. We do observe an effect on the σ_{2n}/σ_{3n} ratio similar to that reported in [12], however in our case the observations can be entirely accounted for in terms of statistical model calculations including the effects of the relationship of observed γ-ray multiplicity to entrance channel angular momentum predicted by the statistical model and the response of the Spin Spectrometer. [We have not reanalyzed the results of ref. 12 and cannot claim that our analysis applies to that data.] Our conclusion is that for the observables related to neutron emission cross sections, the ^{164}Yb decay data from our two entrance channels is entirely consistent with statistical model [15].

3. GR DAMPING: A TIME DEPENDENT STUDY

We turn now to the decay of the GDR excited under very different circumstances, namely Coulomb excitation of ^{208}Pb by 80 MeV/nucleon ^{64}Zn. In this reaction the GDR couples strongly to the entrance channel; it is excited with a cross section of >10b/sr (the Zn scattering angle is 3° in the lab), with well over 99% of the cross section accounted for by virtual photon absorption (Coulex). The experiment was carried out at GANIL, using SPEG to detect and identify scattered ^{64}Zn ions, and the TAPS [17] array to detect decay photons.

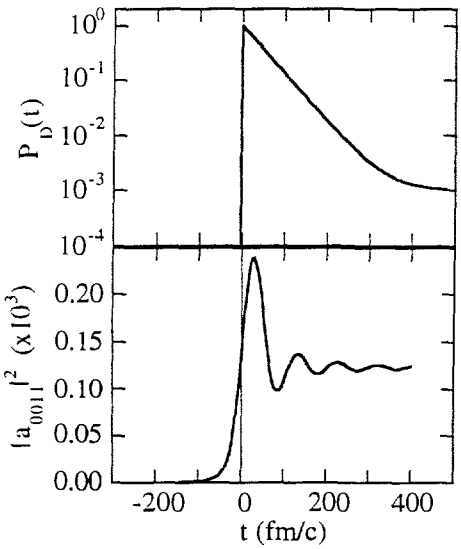

Figure 5. The lower panel shows the time dependence of one of the semiclassical Coulomb excitation amplitudes (J,m=1,1) of the GDR for the reaction ^{208}Pb(^{64}Zn,^{64}Zn') at 80 MeV/nucleon and a scattering angle of 3°. The position of t=0 is defined by the point of closest approach on this trajectory. The upper panel shows the time dependence of the occupation probability of the class D states (Equation 1), assuming instantaneous excitation at t=0, as discussed in the text. Note that the upper panel is a log plot while the lower panel is linear.

It is convenient to frame our discussion in terms of a picture of the development of preequilibrium and equilibrium processes due to Brink [18]. We divide the total space of ^{208}Pb excited states available to the reaction into two classes. One class, D, corresponds to states containing a GDR phonon, while the other class C consists of compound states in which the GDR phonon is not excited. In principle we should consider multiple excitations of the GDR phonon but we measure the excitation energy in ^{208}Pb directly, and limit our observation to energies where multiple phonon excitation is negligible. (In fact in the same experiment we measured the cross section for two phonon excitation [19], which is very small relative to the one phonon cross section and concentrated at higher energy than that considered here.) Following Brink we can write down a set of rate equations relating the population probability of the two classes:

$$\frac{dP_D(t)}{dt} = -\Gamma_D\, P_D(t) + \Gamma_C^{\downarrow}\, P_C(t)$$

$$\frac{dP_C(t)}{dt} = -\Gamma_C\, P_C(t) + \Gamma_D^{\downarrow}\, P_D(t) \qquad (1)$$

The excitation is assumed to occur instantaneously at t = 0. Our reaction couples exclusively to the D class, providing the initial conditions $P_D(0) = 1$. The Γ_i in Eq. 1 are total depopulation rates for the two classes, and include transitions to the other class (mixing or damping) as well as true decay. We can write $\Gamma_i = \Gamma_i^{\downarrow} + \Gamma_i^{\uparrow}$ where $\Gamma_i^{\downarrow}$ is the mixing rate out

of the class i and the $\Gamma_i^{\uparrow}$ is the total decay rate summed over all channels. For the C class $\Gamma_i^{\uparrow}$ should be identified with the normal statistical decay (evaporation) and is hence a departure from conventional notation. Fig. 5 (upper part) illustrates the behavior of $P_D(t)$ predicted by Eq. 1 for GDR decay in ^{208}Pb following coherent excitation of the D class states. The plot reflects a typical assumption for heavy nuclei that $\Gamma_D^{\uparrow} \approx \Gamma_D^{\downarrow}/10$, and identifies Γ_D with the experimental width of the GDR in ^{208}Pb (4 MeV) corresponding to Γ_D^{-1} = 49 fm/c. There is a rapid decay of $P_D(t)$ (governed by $\Gamma_D^{\downarrow}$ from 1 at t = 0 to an equilibrium value $\sim\rho_D/\rho_C$, where the ρ are densities of the two classes of 1^- states ($\rho_D \sim 1$ MeV^{-1}, $\rho_C \sim 1000$ MeV^{-1} at the GDR). The total excited population $P_D + P_C$ eventually decays away to zero at a rate determined by $\Gamma_C^{\uparrow}$, but this time scale is orders of magnitude longer than that associated with the rate Γ_D, and is essentially infinite on the scale of Fig. 5. Gamma decay of the GDR occurs only from the D states with a partial width γ^D, so that the rate of GDR γ-decay $\gamma^D P_D(t)$. Precompound γ decay is therefore emission prior to the time P_D has fallen to its equilibrium value while compound emission corresponds to decay after the equilibrium value is reached. Total γ-ray yields are time integrals of $\gamma^D P_D(t)$.

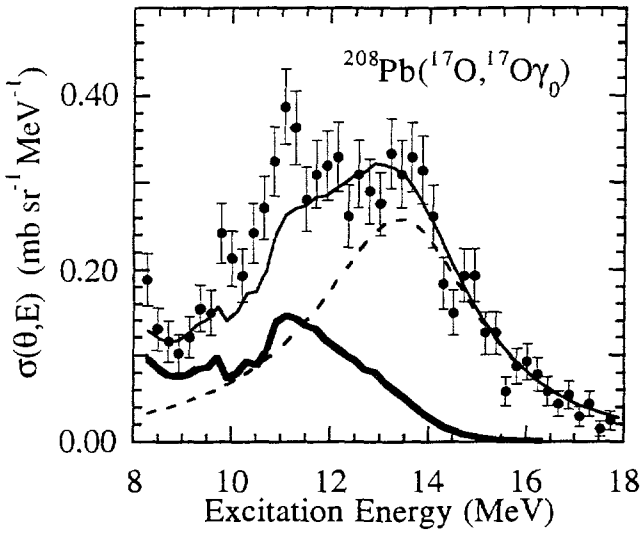

Figure 6. Experimental ground state γ-decay coincidence spectrum for the GDR in ^{208}Pb from inelastic scattering of ^{17}O at 84 MeV/nucleon. The heavy solid line is a statistical model calculation, including width fluctuation effects, and consequently reflects the expected decay from the fully damped states. The dashed line is a calculated precompound contribution.

Of course the excitation process is not infinitely fast, as implied by the $P_D(t)$ curve on Fig. 5. At 80 MeV/nucleon, the projectile velocity is ~0.4c, implying a reaction time $2(R_{Pb}+R_{Zn})/v \sim 60$ fm/c. This is illustrated pictorially in Fig. 5 (lower panel) which shows the square of the excitation amplitude for one particular m-substate of the 1^- GDR, as a function of time with t = 0 defined at the point of closest approach. The calculation is done in the semiclassical approximation [20] at an impact parameter corresponding to the peak of the GDR excitation cross section. It is clear that the precompound GDR photon decays should occur over the same time scale as the excitation process. It turns out that the time dependent Coulomb excitation calculations predict that the relative population of m substates (more properly the alignment tensors) are not constant during the excitation process and in fact reach their asymptotic value over times on the order of 100-200 fm/c (as you would infer from Fig. 5). Consequently the angular distribution of GDR decay photons is, in principle, different during the early precompound stage from that during the equilibrated compound stage.

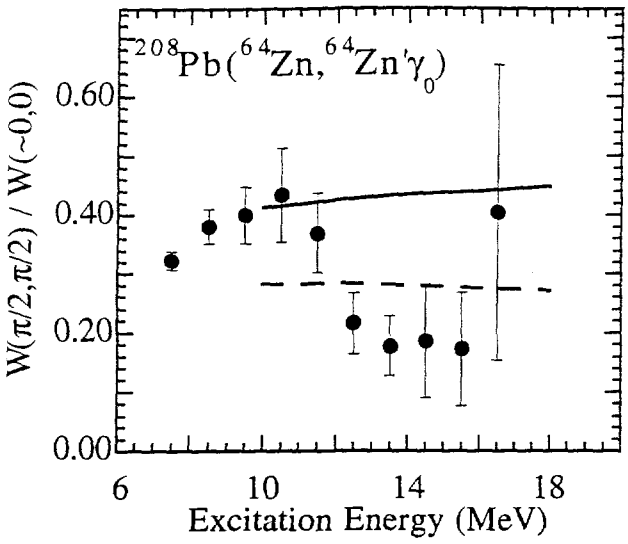

Figure 7. Experimental ratios of ground state γ-decay yield at two angles from the decay of the GDR in ^{208}Pb excited by inelastic scattering of 80 MeV/nucleon ^{64}Zn. The lines are discussed in the text.

The decay of the GDR in ^{208}Pb offers an opportunity to observe this time dependent effect experimentally, for reasons illustrated by the ground-state γ-ray decay spectrum shown in Fig. 6 [3,4]. The heavy solid line is a Hauser-Feshbach calculation of the yield of GDR γ-decay from the fully damped system (including width fluctuation effects); ^{208}Pb is unusual in that this fully-damped component is a significant fraction of the yield up to an energy (~11 MeV) not far below the middle of the resonance. This yield is suppressed with increasing energy due to rapidly increasing competition from neutron evaporation, so that above 12 MeV excitation energy, pre-compound decay evidently dominates. We have searched for the explicit effect of the time dependence of these decay components in the angular distribution of γ-rays from GDR decay in ^{208}Pb. The results are shown in Fig. 7. The quantity plotted is the ratio of γ-ray decay yield along a direction perpendicular to the reaction plane to the yield along the linear momentum transfer direction. The solid curve gives the prediction of a calculation ignoring the time dependent effects discussed above and therefore appropriate to decays on the time scale after equilibrium between P_D and P_C is reached (compound decays). Since the time scale of the precompound decay is almost the same as the excitation time, it is necessary to explicitly include the effects of decay in the Coulomb excitation calculations, in order to make a quantitative prediction for the precompound angular distribution. The dashed line in Fig. 7 is from such a semiclassical calculation including an explicit decay term [20](represented by a constant width of 4 MeV). The resulting prediction is shown as the dashed line in Fig. 7. If we interpret the experimental data using these calculations, they clearly imply that at excitation energies greater than 12 MeV, fast (precompound) decay predominates, while below 11 MeV the angular distribution is consistent with a fully equilibrated (slow time scale) decay. This result is in qualitative agreement with the earlier analysis of the ground state γ-decay yield from the GDR, illustrated in Fig. 6 [4]. We have not yet completed a quantitative enough analysis of the data in Fig. 7 to extract a damping time directly from the data, however, it is clear that the data imply that γ-decay from energies above 12 MeV occurs over a time scale comparable to that expected if we associate the entire experimental width with Γ_D (i.e., ~49 fm/c), while the γ-rays emitted at the low excitation energy end of the GDR can be associated with times >> 49 fm/c.

4. SUMMARY

In this report two experiments have been described which utilize GDR decay to investigate the time scale of two collective processes of considerable physical interest. In

Section 2 we have described a measurement sensitive to the time scale of fusion of heavy nuclei in mass-symmetric entrance channels. The motion involved here is a large amplitude, very low frequency collective phenomenon. We establish that the time scale for the particular system studied is up to ~ three times slower than predicted by a conventional dissipative dynamics calculation.

In Section 3 we turned our attention to the time scale associated with the damping of a strong small-amplitude high frequency collective mode, the GDR. This time scale was found to agree with the commonly held notion that $\Gamma^{\downarrow}$ for the GDR in heavy nuclei makes up essentially all of the observed experimental width of the GDR. Our results also confirm the physical reality of multistep reaction models applied to giant resonance decay.

ACKNOWLEDGMENTS

The experiments described in this report are the work of many people. Michael Thoennessen of Michigan State University has been intimately involved in every phase of the work in Section 2, while Paul Mueller of ORNL is responsible for much of the work reported in Section 3. All the work reported here was done in close collaboration with my ORNL colleagues F. E. Bertrand, D. J. Horen, P. E. Mueller, R. L. Varner, M. L. Halbert, and D. H. Olive. The work in Section 2 was done in collaboration with M. Thoennessen, E. Ramakrishnan, and R. Kryger of Michigan State University, D. G. Sarantites and D. W. Stracener of Washington University, and W. Spang of Julich. The work reported in Section 3 is one aspect of an experiment done in collaboration with Y. Schutz, W. Mittig, P. Roussel-Chomaz, P. Latridou, F. Lefevre, M. Marqués, T. Matulewicz, and R. Ostendorf of GANIL; J. van Pol, and H. W. Wilschut of KVI; J. L. Ferrero and A. Marín of Valencia; R. Holtzmann of GSI; and M. Thoennessen and B. Sherrill of MSU. This experiment benefited from the work of the entire TAPS collaboration, including members from GSI and Giessen not directly involved as collaborators.

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