Giant Resonances and Intermediate Energy Heavy Ions: Electromagnetic Decay Experiments

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Abstract

We briefly explore how large cross sections for excitation of both isoscalar and isovector giant multipole resonances which can be obtained using intermediate energy heavy-ion reactions can be utilized in photon-decay coincidence experiments to provide new information on subjects ranging from basic nuclear structure properties to resonance damping and pre-compound decay. We also discuss experiments in which photon-decay techniques are used as a tag to isolate and identify very weakly excited modes, enabling us to explore such diverse subjects as hadronic excitation of the giant dipole resonance, the distribution of isovector quadrupole strength in ^{208}Pb , and the excitation of two-phonon giant resonance strength.

1. INTRODUCTION

The study of the wide variety of collective modes that exist in the continuum region of the nuclear spectrum continues to be one of the most interesting, and productive areas of nuclear physics. Even the isovector giant dipole resonance (GDR), the first collective mode identified in the nucleus, remains an object of intense study. This is reflected both in the work on dipole modes in neutron halo nuclei reported earlier in this conference, and by the talks on the GDR in excited nuclear systems presented later in this session. My talk concerns recent experiments on giant vibrational modes studied with electromagnetic decay. Much of the work we will describe is made possible, or at least much simpler, by a few well understood characteristics of electromagnetic decay intermediate-energy heavy-ion reactions.

The strength of electromagnetic transitions generally decreases rapidly with increasing multipolarity. Low energy E1 transitions between bound states are usually strongly suppressed compared to single-particle estimates because most E1 strength is concentrated in the GDR; nevertheless, these E1's generally compete favorably with higher multipoles. For higher transition energies, near the peak of the E1 strength distribution, E1 transitions overwhelm even strongly enhanced decays by other electromagnetic multipoles. E1 transitions, especially near the peak of the GDR, are even strong enough to compete to an easily observable extent with particle emission from states in the continuum. These features make electromagnetic decay studies of

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continuum states practical, and, in particular cases, a highly selective tool for isolating resonance strength.

More than a decade ago, when use of heavy-ion scattering as a quantitative tool for study of giant resonances was first being contemplated, it was already realized that such reactions suffered from a number of disadvantages compared to lighter hadronic probes [1]. The characteristic dependence of light-ion scattering angular distributions on angular momentum transfer is almost model-independent, and is qualitatively reproduced by models which take into account strong absorption. This feature of light-ion scattering was the primary reason these reactions proved to be such a useful tool for giant resonance studies. For heavier probes, the increasing importance of the Coulomb potential results in angular distributions for inelastic scattering which exhibit almost no sensitivity to multipolarity. Consequently, reactions with these probes have not proved useful for the almost model-independent multipolarity determinations familiar from light-ion studies.

We now know that there are some compensating advantages of heavy-ion reactions. Early work confirmed [2,3,4] the expectation that heavy ions might provide an improvement in the ratio of excitation cross section for resonances to that of the underlying nuclear continuum. It was found, for example, that the ($^{17}\text{O}, ^{17}\text{O}'$) reaction at 22 MeV/nucleon produced a peak-to-continuum ratio comparable to the best available from light probes (300 MeV protons) [5,6]. This fact, together with the much larger absolute excitation cross sections provided by heavy ions, made such probes especially promising for coincidence experiments [6]. It was not clear how this peak-to-continuum ratio might evolve with increasing bombarding energy, but it was obvious (if sometimes overlooked) that absolute cross sections for low multipoles, should increase rapidly above about 50 MeV/nucleon, as Coulomb excitation of giant resonances became increasingly important. Since Coulomb excitation excites isoscalar and isovector states equally well, heavy-ions also promised to be an important tool for study of isovector strength, which had been very difficult to study with light-ion scattering, because of the relative weakness of the isovector nucleon-nucleus interaction.

In section 2, we will briefly summarize the results of our first series of giant resonance excitation and decay experiments, in the energy range where Coulomb excitation dominates. In section 3, we will explore some of the results and techniques from these experiments that might be applied to study the excitation of the GDR by hadronic probes via the nuclear interaction. In section 4, we explore experiments utilizing heavier intermediate-energy probes (Ar and Kr) and what can be learned by applying gamma-coincidence techniques in these experiments.

2. DECAY EXPERIMENTS WITH 84 MeV/NUCLEON ^{17}O

Our investigation of the electromagnetic decay of giant resonances began with studies of ^{208}Pb using 22 MeV/nucleon beams and the ($^{17}\text{O}, ^{17}\text{O}'\gamma$) reaction at the HHIRF in Oak Ridge. At this energy, Coulomb excitation of giant resonances plays almost no role. The dominance of the isoscalar part of the nucleus-nucleus interaction, lead to a corresponding dominance of isoscalar

strength in the excitation spectrum. This enabled us, using the ORNL Spin Spectrometer, to carry out a detailed investigation of various γ (and neutron) decay branches of these isoscalar states. Results of this study have been published [6,7,8] and will not be discussed in any detail here; however, one result, the observation of the strong suppression of the E1 decay from the isoscalar giant quadrupole resonance (ISGQR) in ^{208}Pb to the collective 3 ν vibration at 2.6 MeV [6], and the explanation of that result [9,10], led to the suggestion [8] that this decay mode would be enhanced for the IVGQR, and might be used to isolate it experimentally. This suggestion was the motivation for moving up to 84 MeV/nucleon, where Coulomb effects enhance the excitation of the isovector strength.

Figure 1. Comparison of the excitation of ^{208}Pb by the inelastic scattering of ^{17}O at 22 (dotted curve) and 84 (solid curve) MeV/nucleon.

Experiments to investigate giant resonance excitation and decay, with the $(^{17}\text{O}, ^{17}\text{O}'\gamma)$ reaction at 84 MeV/nucleon were carried out at GANIL, using the SPEG facility to detect and identify inelastically scattered ^{17}O ions, and arrays of multiple BaF_2 crystals to detect γ -rays. (Experimental details are given elsewhere [11]). Figure 1 shows the resulting inelastic singles spectrum on a ^{208}Pb target, compared to a corresponding spectrum taken at 22 MeV/nucleon. The resonance bump centered at an excitation energy of ~ 12 MeV, dominates the spectrum almost as dramatically as the GDR dominates a photonuclear spectrum. The total cross section

in this bump at a scattering angle of $\sim 2.5^\circ$ is more than 3 b/sr, of which the GDR accounts for ~ 2 b/sr and the ISGQR ~ 0.7 b/sr. The remaining cross section is mostly accounted for by the giant monopole resonance and the small amount of $L=4$ strength found in this region [11]. But more impressive than the absolute cross section, and largely unanticipated, is the large relative decrease in the underlying nuclear continuum cross section at the higher energy. The continuum cross section above the resonance cross section ($E^* \sim 30$ MeV) amounts to only about 60 mb/sr/MeV, or only about twice that at 22 MeV/nucleon, compared to a sixty fold increase in resonance cross section. This, even more than the large resonance cross section, illustrates the potential value of heavy-ion reactions for study of exotic high-lying strength, and low yield decays.

Figure 2. The ground state γ -decay coincidence spectrum corresponding to the 84 MeV/nucleon singles spectrum in Figure 1.

Figure 3. $^{17}\text{O}'$ - γ_0 angular correlation for fixed γ detection angle, and an excitation energy range from 9 to 12 MeV. The solid curve is a pure E1 Coulomb excitation calculation.

The spectrum corresponding to the 84 MeV/nucleon data in Figure 1 in coincidence with single photon decays to the ground state is shown in Figure 2. Various ^{17}O - γ angular correlations demonstrated that, as would be expected from general considerations alluded to in the introduction, the ground state γ -coincidence spectrum above $E^* \sim 9$ MeV can be accounted for entirely in terms of decay of the GDR, within the limits of experimental accuracy. Furthermore, the excitation of the GDR can be accounted for very accurately in terms of pure Coulomb excitation. An example of one such correlation is shown in Figure 3. The solid line is a pure Coulomb excitation calculation. From these data it was determined that the integrated ground-state γ -decay branching ratio of the ^{208}Pb GDR is a rather large 0.019 ± 0.002 . It turns out that this value and, in fact, the energy dependence of the ground-state coincidence spectrum are well accounted for by parameter-free calculations, based on pure Coulomb excitation, the GDR strength distribution from photonuclear data, and the ideas of the multistep compound emission (MSCE) model [11-13]. The usefulness of the MSCE approach was further explored in reference [14] with a comparison of the GDR decay in ^{208}Pb to that in ^{209}Bi .

These are the aspects of the 84 MeV/nucleon data which I wanted to emphasize, because they illustrate some of the points on which experiments in the next three sections are based. A wide variety of other results were obtained from the analysis of these data, ranging from an experimental verification of the isoscalar character of the 10.6 MeV GQR in ^{208}Pb , to information on the IVGQR strength distribution. These results have been discussed in detail elsewhere [11,14,15].

3. HADRONIC EXCITATION OF THE IVGDR

Even though the existence of the GDR has been known almost since the quantitative study of nuclear physics began, there is still more to be learned about it. Two extreme macroscopic pictures of the GDR have been available for many years (the Goldhaber-Teller (GT) and Steinwedel-Jensen (SJ) pictures [17,18]) which make distinctly different predictions about the form of the GDR transition density [19]. Microscopic (RPA) calculations are found [20] to generate states with transition densities similar to the macroscopic models, though the GDR strength is generally spread over two or more RPA states, some with GT-like and others with SJ-like transition densities. In spite of the vast amount of systematic information on the GDR which is available, there is still no experimental data with good sensitivity to the form of the transition density.

Figure 5. The inelastic singles spectrum from the $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}')$ reaction at 22 MeV/nucleon, showing a multipole decomposition of the data, together with the contribution of the IVGQR calculated from the photonuclear strength function.

Figure 6. The ground state γ -ray coincidence spectrum corresponding to Figure 5. The histogram is data, the heavy solid curve is the contribution of the GDR alone, calculated with the same strength distribution as the cross section in Figure 5. For details see [6].

There is also almost no reliable information on the excitation of the GDR by the nuclear interaction, because the isovector parts of the nucleus-nucleus and the nucleon-nucleus interactions are weak compared to the isoscalar parts. The resulting strong excitation of concentrated isoscalar strength near the GDR has made reliable study of hadronic excitation of the GDR impossible. The E1 dominance of the ground-state γ -decay discussed in Section 2 offers the possibility of isolating the GDR, even in a large background of non-dipole isoscalar strength. How effectively this can be done is illustrated even better by the inelastic singles and ground-state γ -decay coincidence spectra from the $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}'\gamma)$ reaction at 22 MeV/nucleon shown in Figures 5 and 6 [6].

Figure 5 shows the singles spectrum, indicating the very small calculated contribution of the IVGDR. Figure 6 shows the corresponding ground-state γ -decay coincidence spectrum. The dark solid line is the expected contribution of GDR decay to the ground-state γ -decay spectrum. In spite of the negligible contribution of the GDR to the singles spectrum, the GDR clearly dominates the γ -decay coincidence spectrum.

The radial form of the nuclear part of the transition potential for the excitation of the GDR is given by [19]

$$\delta U(r) = -\alpha_1 \left\{ \left[\frac{2Z}{A} f_0^n(r) - \frac{2N}{A} f_0^p(r) \right] - \left[\frac{2Z}{A} f_1^n(r) + \frac{2N}{A} f_1^p(r) \right] \right\} \quad (1)$$

where $f_j^i(r)$ for $i=n,p$ and $j=1,0$ refer to neutron, proton and isoscalar, isovector pieces respectively. The form of $f(r)$ depends on the model one chooses to represent the dipole oscillation. For the GT and SJ models, $f(r)$ is given by equations 2 and 3 respectively:

$$f_j^i(r) = \frac{dU_j^i(r)}{dr_i} \quad (\text{GT}) \quad (2)$$

$$f_j^i(r) = CU_j^i(r)j_i(kR) \quad (\text{SJ}) \quad (3)$$

where $|U_j^i(r)|$ represents the neutron and proton parts ($i=n,p$) of the isoscalar or isovector ($j=0,1$) pieces of the optical potential [19], k is determined from the boundary conditions of the SJ model [17], and the constant C is adjusted to generate the same dipole moment as the GT expression.

In general, the GDR excitation depends on both the isovector and isoscalar parts of the projectile-nucleus interaction: Equation 1 is split into two pieces in square brackets, one for each of these contributions. The isoscalar part (first bracket) depends on the difference between the neutron and proton parts of the optical potential, which in turn can be related via models (e.g. the folding model [19]) to the differences in neutron and proton densities of the target. For isoscalar projectiles, like alpha particles, this is the only part of the interaction that survives. Thus GDR excitation by isoscalar probes can be used to obtain information about the so-called neutron skin of a heavy nucleus [19]. Experiments based on this notion, and utilizing the ground-state γ -decay coincidence method to isolate a very small GDR cross section have recently been reported by the KVI group [21]. For an experiment on an $N=Z$ target like ^{40}Ca only the isovector (second) piece in Equation 1 survives, provided the projectile-nucleus interaction has a non-zero isovector piece. Thus, a study of GDR excitation with the $^{40}\text{Ca}(p,p'\gamma)$ reaction can provide direct information about the rather poorly known isovector part of the nucleon-nucleus interaction, U_1 . This is illustrated by Figure 7 which shows the sensitivity of the GDR excitation cross section to $|U_1|$. If the analyzing power is measured this experiment can also provide information about the radial form of the

transition potential. This sensitivity is illustrated in Figure 8 by showing expected results for the two extreme macroscopic models.

Figure 7. The "sensitivity" of the cross section for excitation of the GDR by $^{40}\text{Ca}(p,p')$ to the modulus of the isovector central (symmetry) potential. The quantity plotted is the relative change in cross section for a 1 MeV change in $|U_1|$.

Figure 8. The analyzing power (asymmetry) for GDR excitation by $^{40}\text{Ca}(p,p')$ at 140 MeV.

4. EXPERIMENTS WITH AR AND KR BEAMS

Cross sections for Coulomb excitation of giant resonances increase rapidly with both the velocity and nuclear charge of the projectile (we will, for simplicity consider only target excitation). At high enough energies, the excitation probabilities, particularly for the GDR, become large enough that multiple excitation of the giant modes might be expected. This possibility has been explored extensively in recent papers by Baur and his collaborators [21] (see also references therein). Experiments to investigate these states have been carried out at the AGS [22] and at GSI [23]. In this section we explore the question of whether much lower energy experiments ($E/A \sim 100$ MeV/nucleon) might be able to make some contribution to this investigation.

Figure 9 shows the total (angle integrated) cross section as a function of bombarding energy for Coulomb excitation of a selection of one-, two-, and three-phonon states in ^{208}Pb with ^{86}Kr beams. All the multiple excitations shown involve the GDR, but the mixed two phonon $2^+ \otimes \text{GDR}$ state is included along with multiple GDR excitations. The $3^- \otimes \text{GDR}$ state involving the low lying (2.61 MeV) octupole state has a similar energy dependence, with a slightly smaller cross section. It is clear that large bombarding energies, much exceeding 1 GeV/nucleon, are needed for study of multiple ($n \geq 3$) GDR excitation. However, it is also clear that, provided sensitive and definitive enough detection and identification methods are available, the mixed two-phonon states and even the two-phonon GDR $\otimes$ GDR state, might be profitably

studied with comparatively low-energy beams, where high resolution spectroscopic studies can be done using the magnetic spectrometers available at facilities like GANIL. Data on the excitation strength, width, and decay properties of such states are of great interest, as they carry potentially new information about resonance damping, anharmonicities, and phonon-phonon interactions.

Figure 9. Total cross section for Coulomb excitation of some one-, two-, and three-phonon states in ^{208}Pb by ^{86}Kr scattering. The excitations involving only the GDR (solid lines) are labeled by the phonon number, n .

mb/sr (^{86}Kr). The other identification tool is the electromagnetic de-excitation of the GDR phonon, which has already been discussed extensively in the preceding sections.

Figure 10. Singles inelastic scattering spectra for ^{36}Ar and ^{86}Kr on ^{208}Pb at 95 and 60 MeV per nucleon respectively.

Our intermediate-energy experiments on two-phonon states rely on two tools for identification of the states. One is the expected Z of the projectile dependence of the excitation cross section. Two-phonon excitation cross sections at a given projectile velocity scale as Z^4 , while one-phonon excitations scale as Z^2 [21]. Consequently we acquired data with the highest energy ^{36}Ar and ^{86}Kr beams available at the GANIL facility (95 and 60 MeV/nucleon, respectively). Our existing ^{17}O data provides a third Z point. To illustrate this point, the calculated peak differential cross sections for these three projectile combinations for excitation of the GDR @ GDR state are ~ 1 mb/sr (^{17}O), ~ 50 mb/sr (^{36}Ar) and ~ 120

Singles spectra for the inelastic scattering of ^{36}Ar and ^{86}Kr on ^{208}Pb , detected and identified in SPEG at GANIL are shown in Figure 10. If we consider first the spectrum for 95 MeV/nucleon ^{36}Ar at a scattering angle of 2.5° , we find that the trend observed in going from 22 to 84 MeV/nucleon ^{17}O scattering illustrated in figure 1 has continued with the further increase in projectile velocity and, in this case, charge. The total cross section in the broad resonance region bump centered at 12 MeV is ~ 15 b/sr; the GDR

should account for about 10 b/sr. The continuum cross section is ~ 120 mb/sr/MeV at an excitation energy of 30 MeV. Referring back to Figure 1 we see that in going from excitation by 22 MeV/nucleon ^{17}O to 95 MeV/nucleon ^{36}Ar the cross section in the resonance region has increased by more than a factor of 250 (60 mb/sr to 15 b/sr) while the continuum cross section, taking 30 MeV as a reference point, has increased only a factor of ~ 4 !

The spectrum acquired with the 60 MeV/nucleon ^{86}Kr beam is also shown in Figure 10, normalized to match at 30 MeV. The cross section in the resonance region is similar to the ^{36}Ar case, about 17 b/sr, but the GDR accounts for only a little more than half of this (~ 9 b/sr). The spectrum certainly looks less favorable than the ^{36}Ar spectrum. This is largely due to poorer energy resolution due to target inhomogeneity, however the much stronger (~ 3 times) excitation of 2^+ and 1^- strength below 8 MeV plays a role. Elastic scattering data indicates that the energy resolution was ~ 2.2 MeV FWHM for the ^{86}Kr data, which is still adequate for the two-phonon investigation. Note that the ^{36}Ar data should also provide much improved data on the IVGQR compared to our earlier ^{17}O results. The peak differential cross section for excitation of the IVGDR by 95 MeV/nucleon ^{36}Ar is expected to be ~ 450 mb/sr which is five times as large as the 84 MeV/nucleon ^{17}O cross section.

The γ -ray coincidence data corresponding to Figure 10 is still being analyzed. Figure 11 illustrates schematically how we hope to use the electromagnetic decay of the GDR phonon to isolate and identify two-phonon strength. The horizontal scale (excitation energy) is obtained from the energy of the inelastically scattered ion. The coincident total γ -ray energy (ΣE_γ) measured in BaF_2 arrays is plotted on the vertical axis. The locus along which all the excitation energy is accounted for by detected γ -radiation is the 45° dash-dotted line. The region expected to be occupied by events corresponding to decay of the various one- and two-phonon states involving the GDR are indicated on the figure along with numbers which are relative yields in our experimental geometry (including γ -detection efficiency) for ^{208}Pb (^{86}Kr , $^{86}\text{Kr}'$) at 60 MeV/nucleon, normalized to the Kr- $\gamma\gamma$ triple coincidence yield for the decay of the $n=2$ GDR in Pb.

Figure 11. A schematic illustration of the experimental method employed to isolate two phonon strength in a heavy-ion scattering spectrum by γ -decay coincidence. The shaded region at the bottom of the plot represents a region of intense γ background from decays following emission of one or more neutrons.

Figure 12 Time dependent effects on the reaction-plane angular correlation of ground state γ -decays of the GDR in ^{208}Pb , as a function of damping width. The calculation is for 95 MeV/nucleon Ar bombardment, and a scattering angle of 2.5° .

ground-state γ decay of the GDR in ^{208}Pb . It is straightforward to introduce the effect of a state decaying at a rate comparable to the excitation time in a semi-classical Coulomb excitation reaction [21,25,26]. In this way we find that time dependent effects in the resonance damping and decay can be observed and investigated through the angular distribution of decay photons. This is illustrated in Figure 12, which shows the effect of the existence of a finite damping time on the the GDR ground state γ -decay angular correlation.

5. SUMMARY

For heavy-ion bombarding energies above about 50 MeV/nucleon the excitation of low-multipolarity giant resonances proceeds mostly by Coulomb excitation. This leads to very large differential cross sections near the grazing angle, and to very large peak-to-continuum ratios. The available data are consistent with a steady and continuing improvement in this ratio both with increasing projectile velocity and Z . This observation has important implications for searches for exotic high-lying strength and for study of low-probability decay modes. We have discussed the importance of E1 dominance in the electromagnetic decay of giant resonance and illustrated a number of ways in which photon decay can be utilized in the isolation and identification of resonances. We have emphasized in particular how the strong E1 de-excitation of the GDR phonon can be used as a tool for getting at a variety of interesting physics.

There are many other interesting aspects of the Coulomb excitation of giant resonances by intermediate energy heavy ions. One that has received comparatively little attention concerns the time scale of the excitation. If we consider $^{208}\text{Pb} + ^{36}\text{Ar}$ at 95 MeV per nucleon and estimate the reaction time by the diameter of a Pb nucleus divided by the projectile velocity we find an interaction time of ~ 30 fm/c, which is comparable to the "damping time" of the GDR in Pb $\tau_\downarrow \sim 50$ fm/c ($\tau_\downarrow = \hbar/\Gamma_\downarrow$). If the ideas developed in the MSCE theory [12,14] mentioned briefly in section 2, and the application of it to GDR γ -decay [6,14,16] are correct, then emission with a time scale characteristic of $\Gamma_\downarrow$ contributes significantly to the

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