EXCITATION AND PHOTON DECAY OF GIANT MULTIPOLE RESONANCES

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Fred E. BERTRAND and James R. BEENE

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6368, U.S.A.*

A brief review of the excitation of giant multipole resonances via Coulomb excitation is given which emphasizes the very large cross sections that can be realized through this reaction for both isoscalar and isovector resonances. Discussion and results where available, are provided for the measurement of the photon decay of one and two phonon giant resonances. It is pointed out throughout the presentation that the use of E1 photons as a "tag" provides a means to observe weakly excited resonances that cannot be observed in the singles spectra.

1. INTRODUCTION

Throughout this conference we have heard about exciting new measurements that have been made possible through the revolution in high-resolution gamma-ray detection using large arrays of Compton suppressed Ge detectors. We are also reminded that even larger arrays of this type are now funded in the U.S. and Europe and will be in use within the next few years. Throughout this period of time a smaller but no less significant "revolution" has also been occurring in the means for detection of high-energy photons. This revolution is based on the use of scintillators that can provide very fast timing along with energy resolution that is still in the same range as that achieved with NaI(Tl) detectors that have heretofore been the scintillator of choice for high-energy photon detection. The most often used of the new scintillators is BaF₂ which is now commonly available in lengths up to 25 cm. Large arrays of these detectors in lengths greater than 15 cm have now been built at a few laboratories including ORNL. These large detector arrays make possible the study of the emission of high energy photons from medium- and high-energy heavy-ion reactions where the separation of the photons from the copious flux of neutrons can be achieved because of the fast timing characteristics of the BaF₂ detectors.

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One of the areas of study that has been made possible because of the existence of these new detectors is that of the decay of giant multipole resonances via photons. Giant resonances are located at excitation energies that are above the particle separation threshold and thus, the resonances decay preferentially by particle emission. Indeed, for heavy nuclei, giant resonances decay almost entirely by neutron emission. For example, the photon decay branch from the isovector giant quadrupole resonance (IVGQR) to the ground state in ^{208}Pb is expected to be around 10^{-4} . Such a small branch obviously requires a detection system that is large and that can provide clear neutron/gamma-ray separation. Furthermore, such measurements require a reaction that provides large cross sections for excitation of the giant resonances under study.

While large arrays of BaF_2 detectors provide the means to detect the photons from giant resonance decay, the Coulomb excitation reaction using medium-energy heavy ions provides the needed large excitation cross section. For heavy ions above about 50 MeV/nucleon Coulomb excitation begins to dominate the excitation of giant resonances^{1,2}. This fact leads to extremely large cross sections and to the important fact that both isoscalar and isovector resonances are excited with equal probability via Coulomb excitation. This latter fact provides, for the first time, large cross sections for the excitation of isovector resonances in hadronic scattering. Figure 1 shows angular distributions for the excitation of the ISGQR in ^{208}Pb by inelastic scattering of various energy ^{17}O ions. While the cross sections at the peak of the angular distribution for 25 MeV/nucleon are as large or larger than those attained in light-ion excitation of the resonances, for energies above 50 MeV/nucleon the cross sections become extremely large, reaching several barns/sr at 100 MeV/nucleon and tens of barns/sr at higher energies. Such large cross sections make possible the study of rare decay processes such as photon decay in spite of the very small branching ratios. Figure 2 shows that the cross section for the excitation of the IVGQR in ^{208}Pb increases very rapidly with increasing bombardment energy approaching the same cross section as that for the ISGQR for energies above 200 MeV/nucleon.

In this presentation we show a summary of some of the types of studies that are made possible using the photon decay from giant resonances. We have carried out measurements on all of the areas discussed and we show representative data where it is already available. However, before proceeding two more points should be made by way of introduction. First, does the Coulomb excitation really provide such large cross sections as predicted? Figure 3 shows a spectrum from 84 MeV/nucleon¹ (solid) and 22 MeV/nucleon³ (dashed) ^{17}O ions inelastically scattered from ^{208}Pb . The two spectra are normalized to one another at 40 MeV of excitation energy. It is clear that the cross section for giant resonances in the 11-MeV region of the spectrum is several times larger at 84

FIGURE 1

Calculated angular distributions for the isoscalar giant quadrupole resonance excited by inelastic scattering of various energy ^{17}O ions.

FIGURE 2

Ratio of calculated cross sections for excitation of the IVGQR (22 MeV) and ISGQR (10.6 MeV) by inelastic scattering of various energy ^{17}O ions.

MeV/nucleon than at the lower energy, in agreement with the calculations shown in figure 1. It is also clear that the peak-to-continuum ratio is greatly enhanced at the higher energy. This we attribute to the fact that Coulomb excitation, which provides the large enhancement of the resonance cross section over the lower energy data, primarily provides single step excitation of low multipolarity states. Thus, high multiplicities and multistep excitations that may make up much of the continuum will not increase in magnitude nearly as rapidly with increasing bombardment energy as the giant resonances thus leading to the outstanding peak-to-continuum ratio seen in figure 3. Another interesting point in figure 3 is that the energy of the resonance peak is apparently shifted to higher excitation energy in the 84 MeV/nucleon data. We can understand this with reference to figure 4 which shows the peak cross section for three resonances in the energy range we have studied. At the lowest energy, 25 MeV/nucleon, the ISGQR is the strongest excitation while the isovector giant dipole resonance (IVGDR) cross section is lower by about a factor of about ten. The cross section for the isovector giant quadrupole resonance (IVGQR) is too small to be considered at this energy. At 84 MeV/nucleon, the situation changes dramatically due to Coulomb excitation. The IVGDR cross section is now about three times larger than that for the ISGQR and since in ^{208}Pb the excitation energy of the dipole resonance is

FIGURE 3

Spectra from inelastic scattering of 84 (reference 1) and 22 (reference 3) MeV/nucleon ^{17}O from ^{208}Pb . The two spectra are normalized in the unstructured continuum near 40 MeV.

FIGURE 4

The peak differential cross section for inelastic scattering of ^{17}O from ^{208}Pb to the resonance states indicated as a function of beam energy.

higher than that of the quadrupole, the peak should have shifted to a higher excitation energy. The cross section for the IVGQR shows a very large increase at 84 MeV/nucleon reaching a cross section as large as that of the ISGQR at 25 MeV/nucleon.

Finally, what should we expect to see in the photon decay? Figure 5 shows calculated gamma-ray decay widths for various multipolarity photons plotted relative to the E1 width and as a function of photon decay energy (excitation energy). It is clear that E1 photon decay will dominate by at least an order of magnitude over any other multipolarity. When this is considered with the cross sections plotted on figure 4 we expect that when photons to the 0^+ ground state, of for example ^{208}Pb , are observed, the decay coincidence spectrum should be dominated by the giant dipole resonance. Only at the lower energy of about 25 MeV/nucleon will there be any chance of observing the photon decay to the ground state from the ISGQR. For this reason we talk in terms of using the E1 photons as "tags" for the observation of giant resonances. This means that if one of the photons in the decay pattern of a giant resonance is an E1 photon, then that branch may be strong enough to be observed in coincidence with the inelastically scattered particle and through such techniques it may be possible to observe resonances that are not excited strongly enough to be observed directly in the singles spectrum.

Measurements⁴ using 22 MeV/nucleon ^{17}O ions were carried out using the coupled accelerators of the ORNL HHIRF. The inelastically scattered ^{17}O ions were detected in an array of six silicon detector telescopes placed at about 13

degrees. The photons were detected in the 70 element NaI ball, the Spin Spectrometer.

Measurements¹ using 84 MeV/nucleon ^{17}O , 95 MeV/nucleon ^{36}Ar , and 60 MeV/nucleon ^{86}Kr were carried out at the GANIL facility in Caen, France. In those measurements the inelastically scattered heavy ions were detected in the magnetic spectrograph, SPEG, and the photons were detected in coincidence in an array of BaF₂ detectors. Our most recent experiment at GANIL used 228 BaF₂ detectors arranged in packs of 19 detectors. The detectors are provided from ORNL, GSI, and the TAPS collaboration.

In all of the experiments coincidences were measured between the inelastically scattered heavy ions and photons to the ground state or photons from the resonance to an excited state which then decays by photon emission to the ground state.

2. IVGDR MEASUREMENTS AT 84 MeV/NUCLEON

Figure 6 shows an inelastic scattering spectrum¹ produced with 84 MeV/nucleon ^{17}O ions with the requirement of a coincidence with a single gamma ray to the ground state (i.e., with $E_\gamma = E^*$, where E^* is the excitation energy). The spectrum in figure 6 corresponds to a range of ^{17}O angles from 2° to 3.5°. The gamma coincidence spectrum shows prominent structures corresponding to well known low-lying states which have strong ground-state gamma branches, notably the 2.6 MeV 3-, 4.08 MeV 2+, and the 5.512 MeV 1- state. Gamma-ray angular distributions demonstrate that most of the yield between the 5.5-MeV state and the neutron separation energy (7.4 MeV) corresponds to 1- states (probably the 5.5, 7.06 and 7.08 MeV 1- states), but a 2+ state, at ~6.2 MeV is also present. Above the neutron separation energy the coincident yield falls rapidly, but rises again to a strong broad peak in the giant resonance region. The comments made earlier lead us to expect the 9 to 20 MeV region of the gamma coincidence spectrum to be dominated by the IVGDR. That this is the case is shown on figure 7 which shows the 84 MeV/nucleon ^{17}O - γ angular correlation

FIGURE 5

Ground-state gamma widths of hypothetical sharp states fully exhausting the appropriate isovector or isoscalar energy weighted sum rule as a function of the excitation energy of the state, relative to the E1 width.

FIGURE 6

Inelastic spectrum in coincidence with gamma rays to the ground state. The ^{17}O angles are $\theta = 2.0^\circ$ - 3.5° in this case, the gamma detector angles are given in the text.

FIGURE 7

^{17}O - γ_0 angular correlation for $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}')$ reaction at 84 MeV/nucleon for fixed γ angle $\theta_\gamma = 90^\circ$, $\phi_\gamma = 270^\circ$.

for ground state gammas at $\theta_\gamma = 90^\circ$ and $\phi_\gamma = 270^\circ$. The solid line is calculated assuming pure Coulomb excitation of the GDR. As expected, the data indicate that the ground state photon decay at 84 MeV/nucleon is completely dominated by the excitation and decay of the IVGDR.

It is to be noted that the model used for the collective excitation of the IVGDR is the "standard" model set forth by Satchler⁵ that has been used for giant resonance calculations since the earliest days of giant multipole resonance studies via direct reactions.

The point we make here is that our results at 84 MeV/nucleon indicate that the excitation and the photon decay of the giant dipole and quadrupole resonances is completely understood both qualitatively and quantitatively in terms of the standard reaction codes. At 84 MeV/nucleon where the excitation of the IVGDR is completely accounted for via Coulomb excitation, the IVGQR can be subtracted from the inelastic scattering spectrum with an accuracy limited only by the uncertainty in the photonuclear measurements. The agreement with the decay results which isolated the GDR shows this to be the case. Furthermore, as shown on figure 3, at many angles the continuum is so small relative to the resonance peaks that the continuum can be removed without introducing large uncertainties.

3. IVGDR AT LOWER ENERGIES

As is suggested on figure 4 and demonstrated in figures 3 and 6 from the GANIL measurements, the IVGDR dominates not only the photon coincidence

spectrum but also the singles spectrum at the higher bombarding energies. However, as we have pointed out (figure 4), this will not be the case with lower-energy heavy-ion excitation. Figure 8 shows a singles spectrum taken from the HHIRF measurements⁴ using 22 MeV/nucleon ¹⁷O. We show the spectrum decomposed into resonance peaks found⁶ in 334 MeV proton inelastic scattering using cross sections calculated for 22 MeV/nucleon ¹⁷O ions. As is expected from our earlier discussions, the spectrum is dominated by excitation of the ISGQR. The IVGDR is negligible in the singles. However, as is shown on the lower part of figure 9, the giant resonance photon coincidence spectrum is dominated by the decay of the giant dipole resonance⁴. We reach this conclusion by comparison of the data with calculations described in reference 4. It is to be noted that the calculations account extremely well

FIGURE 8

Analysis of inelastic singles spectrum from the reaction ²⁰⁸Pb(¹⁷O,¹⁷O') using 22 MeV/nucleon ¹⁷O. Figure 8 shows the singles spectrum together with two possible estimates of the continuum underlying the GR region as discussed in the text. The figure shows the spectrum in the GR region after subtraction of an assumed continuum (reference 4), together with fits to the data employing the set of peaks and peak properties given in reference 6.

FIGURE 9

Ground state gamma ray coincidence data compared with calculations (reference 4). The data and calculations shown in figure 9a and 9b are discussed in the text. Figure 9c shows experimental γ_0 angular correlations for energy bins from 9-11 MeV (solid points) and 12-15 (open points). The dashed curve in figure 9a is for pure E1 decay of the IVGDR. The dash-dot curve is for pure E2 decay of the ISGQR while the solid curve represents the E1 + E2 mixture predicted at 9-11 MeV by the calculations shown in a and b.

for the spectrum at excitation energies as high as 16 MeV above which we no longer observe the photon coincidences because of the low yield. There is, however, some excess yield of coincidence photons near 10 MeV, the energy of the ISGQR. In figure 9b we compare this excess yield to the same type of calculation as we showed in the lower part of the figure for the dipole resonance, and find excellent agreement⁴. The insert in the upper right hand corner of the figure shows the angular correlation of the decay photons taken at energies near the peak of the dipole resonance and near the peak of the quadrupole resonance. It is clear that near the peak of the dipole the data are reproduced by a dipole calculation only while at the peak of the quadrupole resonance a mixture of dipole and quadrupole strength is needed as we would expect.

These results again indicate again that use of the ground state photon decay can provide a means to isolate resonances that have an E1 photon decay branch even when the strength of the resonance is so small that it is unobservable in the singles spectrum. This fact opens the possibility for investigation of the mechanism for excitation of the isovector dipole resonance using both heavy- and light-ion excitation. For example: How important is nuclear excitation of the IVGDR in heavy ion scattering as a function of incident beam energy? What is the effect on the IVGDR excitation of adding one or two neutrons to the projectile? What is the magnitude of the asymmetry term in the proton-nucleus optical which excites the IVGDR in light ion inelastic scattering? All of these questions on the reaction mechanism can be answered if the giant dipole resonance is cleanly excited in the spectrum; this can be accomplished through ground state photon coincidences.

4. ISOLATION OF THE ISOVECTOR GIANT QUADRUPOLE RESONANCE

While a large number of isoscalar giant resonances have been identified over the past 15 years the same cannot be said for the electric isovector giant resonances⁷ except for the long established isovector giant dipole resonance. This dearth of information for isovector giant resonances is due primarily to the fact that inelastic hadron scattering does not excite isovector resonances via nuclear excitation very strongly relative to isoscalar states. However, as we have pointed out earlier in this paper this is not the case for Coulomb excitation via heavy ions. Some data have been reported on isovector giant quadrupole resonances from inelastic electron scattering but these results are in general somewhat uncertain and no appropriate electron experiments have been carried out in many years⁷.

Along with the measurement of the ground-state photon decay from the ISGQR region, we have also studied the branching to low-lying excited states in ²⁰⁸Pb by measuring γ - γ coincidences as a function of excitation energy between ²8.5 and 16 MeV in our 22 MeV/nucleon ¹⁷O scattering experiments⁴. A

particularly interesting feature of those results is the absence of any significant direct decay to the 3^- state at 2.6 MeV. Purely statistical arguments suggest that this branch from the region of the ISGQR should be approximately equal to the ground-state branch. The suppression relative to statistical estimates of decays from the GQR region to the 2.6 MeV, 3^- state is very interesting. Two recent calculations^{8,9} predict this suppression. In both calculations the suppression arises from a combination of factors, among which is cancellation between neutron and proton matrix elements because of the isoscalar nature of both the 10.6 MeV quadrupole resonance and the 2.6 MeV, 3^- state.

The same calculations by Speth *et al.*⁹ that indicate the suppression of the decay branch between the isoscalar GQR and the 3^- state in ^{208}Pb predict an enhancement of the decay branch between the isovector GQR and the 3^- state. Thus, it may be possible to isolate the IVGQR by "tagging" the resonance via its decay branch through the low-lying 3^- state.

We have carried out such an experiment using the 84 MeV/nucleon ^{17}O beam at GANIL to excite the isovector resonance and then to measure the triple coincidences between inelastically scattered ^{17}O ions and 2.61-MeV photons and photons having energy greater than 10 MeV. Figure 10 shows the results of those measurements by a histogram.

Although there are not many counts in the triple coincidence data, they are uniquely determined and we believe represent the distribution of IVGQR strength decaying through the 3^- state. We have also measured the branch to the ground state and find the ratio between that branch and the branch to the 3^- state to be approximately one. Table 1 gives the parameters of the IVGQR as deduced from our measurements and those from calculations¹⁰ and other measurements^{11,12,13}. The dashed curve on figure 10 is from an RPA calculation by Bortignon *et al.*¹⁰ and is in excellent agreement with the data.

FIGURE 10

The histogram shows the measured relative distribution of $\gamma\gamma$ coincidence yield ($E_\gamma > 10$ MeV, $E_\gamma = 2.6$ MeV) as a function of excitation energy, subject to the conditions discussed in the text. The dashed curve is from the calculation of the IVGQR strength distribution by Bortignon (reference 10).

TABLE 1
Isovector Giant Quadrupole Resonance ^{208}Pb

	Present Experiment ($^{17}\text{O}, ^{17}\text{O}'\gamma\gamma$)	Bortignon ¹⁰ Calculation	(γ, n) ¹¹ Forward/ Backward Asy.	(e, e') ¹²	(e, e') ¹³
Centroid (MeV)	22.6 ± 0.4	22.4	23.5 ± 1.5	~ 22	22.5
Width (MeV)	6 ± 2	3.6			5 ± 1
EWSR (%)	~ 50	61		60 ± 25	85 ± 28

5. MULTIPHONON GIANT RESONANCES

One of the most interesting of the many unanswered questions concerning giant resonances is the existence of the expected spectrum of multiphonon giant resonance states. For example, while the IVGDR in ^{208}Pb is a one-dipole phonon excitation, there should be a two-phonon giant dipole resonance located at approximately twice the energy of the single-phonon state, ~ 27 MeV. Likewise, there should be three-phonon and four-phonon giant dipole states and multiphonon states for other resonances as well. Multiphonon states built on giant resonances are, of course, not the only type of multiphonon states that should exist. For example, another class of such states is the giant resonance built on top of a low-lying collective state. Again, taking ^{208}Pb as an example, one expects a giant dipole resonance state built on top of the low-lying 4.08 MeV, 2^+ state that would have an excitation energy of ~ 17 MeV. This state would be composed of one quadrupole phonon and one dipole phonon while the two-phonon giant dipole resonance would be formed from two dipole phonons.

The idea of multiphonon states is simple and has been proposed for many years. The difficulty is to observe and uniquely identify these states in an experimental spectrum. The probability for exciting the multiphonon states is orders of magnitude smaller than that for exciting the single-phonon states and methods must be found to excite such states with cross sections large enough to deal with experimentally. The excitation of multiphonon states has been the topic of several recent theoretical papers. In particular, Baur and his coworkers have extensively discussed the possibility for observation of multiphonon states via their excitation in medium-energy heavy-ion reactions¹⁴. We briefly address the prospects for direct observation of two-phonon states in which at least one of the phonons is a GDR phonon.

As we have shown in this presentation, heavy-ion Coulomb excitation provides very large cross sections for giant dipole states. Figure 11 shows cross sections (at the peak of the differential cross section) for excitation of the GDR $\otimes$ 2^+ state and the GDR $\otimes$ GDR in ^{208}Pb by 60 MeV/nucleon projectiles as a function of projectile charge. It is to be noted that the cross section for excitation of a two-phonon state scales as Z^4 for fixed projectile velocity while that for a one-phonon state scales as Z^2 . The curves at the top of the figure are for excitation of the one-phonon ($n = 1$) GDR (solid) and 4.08 MeV, 2^+ (dashed) states while the lower curves are for excitation of two-phonon states ($n = 2$). While the cross sections for $n = 1$ states are very large, for Kr beams ~ 5 -8 barns/sr, the $n = 2$ cross sections are two orders of magnitude smaller. On figure 12 we show why higher beam energy is important for the observation of multiphonon giant resonances. We show calculated cross sections for excitation of $n = 1$, $n = 2$ and $n = 3$ giant dipole resonance states excited via the inelastic scattering of Kr ions as a function of incident Kr energy. New accelerators under construction can deliver high-energy beams of heavier Z ions thus being able to take advantage of the Z^4 increase, for example, for $n = 2$ states.

We feel that with the beam energies currently available at GANIL the cross section for excitation of even the simplest $n = 2$ state may be too small to directly

FIGURE 11

Cross sections for excitation of one-phonon ($n = 1$) and two-phonon ($n = 2$) states of different types in ^{208}Pb via inelastic scattering of particles with charge Z at 60 MeV/nucleon. The heavy solid and dashed lines are for the 2^+ or $2^+ \otimes \text{GDR}$ and GDR or GDR $\otimes \text{GDR}$, respectively. The thin dashed and solid curves are for excitation of the same states via ^{16}O inelastic scattering and scaled by Z^2 or Z^4 for $n = 1$ and $n = 2$, respectively.

FIGURE 12

Total cross sections for single, double, and triple phonon GDR states in ^{208}Pb excited by inelastic scattering of ^{86}Kr ions as a function of incident ion energy.

observe in the inelastic scattering spectrum. However, we point out that we have shown that the photon decay at high excitation energies is totally dominated by E1 photons. Thus, if the $n = 2$ state is built up of at least one dipole phonon then observation of the photon decay from that state becomes a viable means for isolation of the state from the multitude of states in the inelastic scattering spectrum. The photon decay branch for the $n = 1$ GDR is $\sim 1.7\%$ which we believe is large enough to be observed even in coincidence with photons from a second GDR built on top of the first. It is the strong Coulomb excitation and photon decay branch of the GDR that makes these experiments feasible even at the relative low energies of the GANIL accelerator. Recently, we have carried out an experiment at GANIL to search for the types of two-phonon states discussed here. The data from that experiment are currently under analysis. Certainly, a great deal more could be done with the higher energy heavy-ion beams to be available from SIS and COSY but as we have noted before, those facilities must have available a high resolution spectrograph that can be used at very small angles before spectroscopic investigation of these states can be undertaken.

6. SUMMARY

For energies above about 50 MeV/nucleon, the excitation of giant multipole resonances via inelastic scattering proceeds mostly via Coulomb excitation. Such excitation leads to very large cross sections for the low multipolarity resonances ($L = 1, 2$) and to extraordinarily large peak-to-continuum ratios. The large cross sections permit measurements to be made of low-yield decay products from the resonances such as photon decay. We have shown that the dominant yield of decay photons is from E1 photons and that using the E1 photons can provide a means to isolate and identify one- and multiphonon isovector and isoscalar giant resonances.

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