# EXCITATION AND PHOTON DECAY OF GIANT RESONANCES EXCITED BY INTERMEDIATE ENERGY HEAVY IONS

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## ABSTRACT

Inelastic scattering of medium energy heavy ions provides very large cross sections and peak-to-continuum ratios for excitation of giant resonances. For energies above about 50 MeV/nucleon, giant resonances are excited primarily through Coulomb excitation, which is indifferent to isospin, thus providing a good probe for the study of isovector giant resonances. The extremely large cross sections available from heavy ion excitation permit the study of rare decay modes of the giant resonances. In particular, recent measurements have been made of the photon decay of giant resonances following excitation by 22 and 84 MeV/nucleon $^{17}$O projectiles. The singles results at 84 MeV/nucleon yield peak cross sections for the isoscalar giant quadrupole resonance and the isovector giant dipole resonance of approximately 0.8 and 3 barns/sr, respectively. Data on the ground state decay of the isoscalar giant quadrupole and isovector giant dipole resonances are presented and compared with calculations. Decays to low-lying excited states are also discussed. Preliminary results from an experiment to isolate the $^{208}$Pb isovector quadrupole resonance using its gamma decay are presented.

# MASTER

Coincidence experiments designed to investigate decay properties now make up a significant part of the experimental study of giant resonances. Since most giant resonances (GR) lie above the particle emission threshold the dominant decay mode is usually nucleon or alpha emission (neutron emission in heavy nuclei) with gamma decay having a small ($\lesssim 10^{-3}$) probability. Nucleon emission can in principle carry important information about the microscopic structure of resonances, damping mechanisms and damping rates. Photon decay studies face difficulties resulting from the small probability of such events, yet they too can provide significant information, often illuminating aspects of the GR different from those probed by nucleon decays. As will be seen, the low probability of photon decay can be mitigated by the large GR cross sections and resonance to continuum ratios which can be achieved with inelastic scattering of selected heavy ions at energies above ~20 MeV/nucleon and both the cross section and resonance to continuum ratio rapidly increase with increasing bombarding energy.

Photon decay data can be extremely sensitive to GR multipolarity—thus compensating for a principal weakness in heavy ion scattering. For example, gamma decay back to the ground state following heavy ion scattering is certain to be dominated by E1 decay, therefore by the isovector giant dipole resonance (IVGDR). Under very favorable conditions ground state decay of the giant quadrupole resonance (GQR) can also be observed — but higher multipolarities in the 10 to 25 MeV excitation energy region are extremely unlikely to contribute to the g.s. decay. This is illustrated in figure 1, which shows the ground state gamma width ($\Gamma_{\gamma 0}$) expected for a sharp state exhausting 100% of the relevant isoscalar (IS) or isovector (IV) energy weighted sum rule (EWSR) as a function of multipolarity and energy, relative to that for the IVGDR. Ground state gamma decay can also yield data on the electromagnetic strength of resonances, and provide simple, well-defined conditions under which we can investigate the multistep theory of nuclear reactions in terms of which GR decay is conventionally discussed.

Photon decays from the GR to low lying excited states are also potential sources of significant information. These data, like ground state decays, provide significant multipole selectivity — but are not limited to L = 1 and 2 resonances. Decays to excited states, like ground state decay, are dominated by E1 transitions. Thus, for example, transitions from the GR region to a low lying 5$^-$ state in an even-even nucleus is clear evidence for high spin (4$^+$ or 6$^+$) strength. Decays to low lying collective states can provide important information about the coupling of (isovector) GR modes to these low frequency collective modes. Recent calculations[1,2] have shown that E1 transitions between isoscalar GR and low lying collective states (also isoscalar) can be strongly suppressed. Thus, study of such transitions can provide important data on the isospin character of resonances.

There have been several ways suggested that heavy ions might enhance the study of giant resonances: by providing larger cross sections, larger peak-to-continuum ratios due to a decrease of knock-out reactions, and the possibility to selectively excite resonances of high angular momentum. Early results obtained with heavy ions of energy $\lesssim$ 15 MeV/nucleon realized none of these hoped for advantages. More recently, accelerators have been able to provide heavy ions in the energy range of 20-30 MeV/nucleon and experiments have been performed to excite giant resonances with those higher energy beams. It had been anticipated that the cross section for heavy-ion excitation of giant resonances should increase rapidly with increasing beam energy. In figure 2 we show spectra from the ($^{16}$O, $^{16}$O')[3] and ($\alpha,\alpha'$)[4] reactions on $^{208}$Pb at 400 MeV and 152 MeV respectively. At 25 MeV/nucleon the giant resonance spectrum is much more prominent than it is at the lower heavy-ion energies. The cross section at the grazing angle is ~40 mb/sr, comparable to the ($\alpha,\alpha'$) cross section but the peak-to-continuum ratio is much larger for the heavy-ion reaction than for the alpha particle reaction. However, note in the oxygen spectrum the large rise in cross section at excitation energies just below that of the quadrupole resonance. This large peak arises from excitation of states in the $^{16}$O projectile and points out one of the serious problems with heavy-ion

inelastic excitation of giant resonances; excitation of the projectile.
It is possible to eliminate or at least substantially reduce con-
tamination of the heavy ion inelastic spectra from projectile excita-
tion by choosing a projectile that is unbound to neutron emission at
very low energy, projectiles such as $^{13}$C or $^{17}$O. The spectrum in
figure 3a is from inelastic scattering[5] of 376 MeV $^{17}$O and does not
show the large peak at about 6-8 MeV from projectile excitation seen
with $^{16}$O since $^{17}$O is neutron unstable at about 4 MeV. It is
interesting to compare the $^{17}$O spectrum with that shown in figure 3b
from the $^{208}$Pb(p,p') reaction[6] for 334 MeV protons. Within the
respective energy resolutions (~200 keV for $^{17}$O, ~70 keV for (p,p')),
the proton and $^{17}$O spectra are almost identical except for the region
of the IVGDR. These spectra clearly demonstrate that care must be
exercised in the choice of the heavy ion projectile used, and the
energy of the heavy ion should also be considered to ensure that the
excitation energy region of interest is not compromised by projectile
effects. These problems with heavy ion scattering are often difficult
to detect and can lead to incorrect conclusions concerning the excita-
tion of new states in nuclei.

While use of heavy ion inelastic scattering in the energy range
of 20-30 MeV/nucleon clearly offers large cross sections and enhanced
peak-to-continuum ratios, and proper choice of projectile can eliminate
many of the effects of projectile excitation, it is still a fair
assessment that all of the heavy-ion measurements to date show a selec-
tivity similar to that observed with lighter probes. This is to say
that the spectra are dominated by excitation of the ISGQR and the
ISGMR. Furthermore, identification of the multipolarity of the giant
resonance is difficult because the angular distributions for different
angular momentum transfers in inelastic heavy-ion scattering are so
similar.

Can we then expect any future for heavy-ion excitation of giant
resonances? We strongly suggest that the answer is yes. The answer
lies in the use of still higher energy heavy ions where the effects

of Coulomb excitation become dominant over the nuclear interaction. Coulomb excitation by high-energy heavy ions will provide, as we shall see below, very large differential cross sections for inelastic excitation of the low multipolarity resonances. Furthermore, Coulomb excitation operates equally well on isoscalar and isovector states providing the possibility that for the first time, hadron scattering can provide strong excitation of isovector giant resonances.

If we consider the Coulomb excitation process in terms of the rapidly changing Coulomb field created at the target by a projectile passing at high velocity in terms of the equivalent virtual photon field, then the Coulomb excitation process is equivalent to the absorption of the virtual photons by the nucleus. In figure 4 we show intensity spectra for electric dipole virtual photons as seen by a $^{208}$Pb target for a range of $^{16}$O incident energies between 50 and 1500 MeV/nucleon. At the lowest incident energies the virtual photon spectrum drops rapidly with increasing excitation energy and clearly shows why Coulomb excitation with low-energy projectiles is limited to the study of low-lying states. On the other hand, the spectrum at 1500 MeV/nucleon is almost flat in the excitation energy range of 10-50 MeV/nucleon.

To make these calculations more relevant to experimental observation we show in figure 5 differential cross sections for excitation of the ISGQR in $^{208}$Pb for several incident energies of $^{17}$O. At the lower energies, 25 and 50 MeV/nucleon, the cross section is mainly from the nuclear interaction, while at the higher energies Coulomb excitation dominates. The effect of the increasing importance of Coulomb excitation with increasing incident energy is dramatic. The peak cross section for excitation of the ISGQR increases by over two orders of magnitude between 25 MeV/nucleon and 500 MeV/nucleon, and would continue to increase at even higher energies.

Perhaps even more dramatic is the effect of the Coulomb excitation on the excitation of the IVGQR at 22 MeV in $^{208}$Pb by $^{17}$O projectiles as shown in the calculated differential cross sections on figure 6. The nuclear excitation of the isovector states proceeds through the isospin

part of the nucleon-nucleus interaction which is quite weak in comparison with the strength of the non-spin and non-isospin parts. On the other hand, the Coulomb excitation is as strong for isovector states as it is for isoscalar states, all other things being equal. At 25 MeV/nucleon the maximum cross section expected for the IVGQR is ~0.5 mb/sr, compared to a measured cross section of about 60 mb/sr for the ISGQR. On the other hand, at 500 MeV/nucleon where the Coulomb excitation is dominant, the cross section for the IVGQR is calculated to be 10,000 mb/sr!

We have been involved in a research program at GANIL with collaborators from GANIL, Saclay, and Strasbourg in measurements of the excitation and photon decay of giant resonances excited by 84 MeV/nucleon $^{17}$O beams. Measurements[7] were made using the 84 MeV/nucleon $^{17}$O beam (full energy for $^{17}$O) from the GANIL facility. Inelastically scattered $^{17}$O ions were detected and identified in the energy loss magnetic spectrometer SPEG. The overall energy resolution was about 800 keV due in large part to the use of a 5.1 mg/cm² $^{208}$Pb target. The spectrograph was set to accept events in the angular range from 1.5 degrees to 5.0 degrees. Figure 7 shows a spectrum from the GANIL measurements (solid line) compared to a spectrum, already shown in figure 3a, from 22 MeV/nucleon measurements at ORNL. The lower energy data is normalized to the GANIL data in the unstructured nuclear continuum (about 40 MeV). There are several obviously outstanding features in the GANIL data. First the giant resonance peak is huge, rising almost a factor of 10 above the continuum. Reference to figure 3a shows that the 22 MeV/nucleon spectrum rises over a factor of two above the continuum as does the proton spectrum shown in figure 3b. Clearly, one of the objectives of the use of heavy ions for giant resonance studies, the possibility of enhancing the peak-to-continuum ratio, has been realized. It is also apparent from figure 7 that the excitation energy of the centroid of the giant resonance peak in the GANIL data is higher than in the lower energy data. As will be shown below this is due to the fact that the Coulomb excitation of the IVGDR dominates the ISGQR at the higher energy while the quadrupole resonance

is the strongest excitation in the lower energy data. Note that the GANIL data shown in figure 7, the giant resonance peak and the peaks from excitation of low-lying states are on the same arbitrary cross section scale. The peak height of the giant resonance structure is as large as that for the 4.08 MeV, $2^+$ level and larger than that for the 2.6 MeV, $3^-$ level.

At incident heavy ion energies of 50-100 MeV/nucleon the Coulomb excitation probability drops very rapidly with increasing excitation energy, changing by over a factor of two across a peak as broad as the IVGDR. Thus, the shape of the IVGDR peak is considerably altered by the excitation mechanism from that observed in photonuclear work. Figure 8 shows the effect of the reaction mechanism on the shape of the IVGDR for excitation by 84 MeV/nucleon (dotted line) and 22 MeV/nucleon (dash-dot line) $^{17}O$ incident ions. The solid curve shows the shape of the IVGDR as taken from photonuclear measurements.[8] As expected the effect is more dramatic at the lower energy. We have used the shape as shown in figure 8 in the analysis of the data from GANIL and from ORNL. The shape of the IVGDR as altered by the Coulomb interaction changes slightly with angle.

Figure 9 shows spectra from the GANIL measurements at three angles decomposed into peaks from the ISGQR, IVGDR, and ISGMR with centroids and widths taken from previous measurements and for the IVGDR, from the shape shown on figure 8. The areas of the peaks were allowed to vary and the shape of the underlying continuum was taken as generally flat under the peak. It is comforting to be able to say, for perhaps the first time, that, at least at most angles, the assumptions made about the shape and magnitude of the continuum underlying the giant resonances do not dominate the uncertainty in the data. The cross sections for the ISGMR and the IS giant hexadecapole resonance are quite small relative to the cross section for the dipole and quadrupole resonances and for that reason are quite uncertain and will not be dwelled upon in this discussion except to note that the cross sections are consistent with previous measurements.

As seen from the angular distributions for the IVGDR and the ISGQR shown on figure 10, at most angles, excitation of the IVGDR dominates the spectrum. The cross section for the IVGDR reaches a magnitude of nearly 3 barns/sr which is about four times the peak cross section of about 800 mb/sr for the ISGQR. These huge cross sections show that we have realized another hoped for attribute of heavy-ion excitation of giant resonances--very large cross sections. The calculation shown as the solid line on the dipole data was generated assuming only Coulomb excitation of the IVGDR and the magnitude corresponds to 110% of the EWSR between 7 and 18.9 MeV. In the same energy range, the photonuclear reaction yields about 103% of the EWSR. We thus, account very well for the dipole excitation with the Coulomb interaction and resonance parameters from photonuclear data.[8] The calculation for the ISGQR assumes both Coulomb and nuclear excitation as shown by the separate curves plotted on figure 10. The angular distribution is well described by the L = 2 calculation with a deformation length of 0.49 fm corresponding to exhaustion of 60% of the EWSR, in good agreement with previous data. The combination of excitation of the ISGQR via both Coulomb and nuclear interactions provides for a broader angular distribution than is observed for the dipole where only Coulomb excitation is indicated.

The study of the photon decay from the giant resonances was carried out at GANIL by detecting the gamma rays in $BaF_2$ detectors clustered in groups of 7 or 19, in coincidence with the inelastically scattered $^{17}O$ ions detected in the magnetic spectrograph, SPEG. For the data reported here only 4, "7-packs" were used consisting of right hexagonal crystals with face-to-face dimension of 8.7 cm and length 14 cm. The 7-packs were positioned at angles $(\theta,\phi)$ of $(95°,0°)$, $(70°,180°)$, $(134°,180°)$, and $(90°,270')$. For the measurement[9,10] of the photon decay carried out at Oak Ridge using 22 MeV/nucleon $^{17}O$ ions, the gammas were detected in the 70 element NaI ball, the Spin Spectrometer, and the $^{17}O$ ions in a ring of silicon surface barrier detectors. Figure 11 shows an inelastic scattering spectrum at 84 MeV/nucleon 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). Figure 11 corresponds to a broad 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⁺ states, and the 5.512 MeV 1⁻ states. Gamma 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 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 GR region. The comments made earlier, together with the large cross sections for the IVGDR, would lead us to expect the 9 to 20 MeV region of the gamma coincidence spectrum to be dominated by the IVGDR. This is illustrated qualitatively in figure 12. The heavy solid line is the GR peak from the singles data. The short dashed curve is the distribution of IVGDR cross section calculated assuming pure Coulomb excitation, and utilizing the strength distribution for the IVGDR from photonuclear experiments. The histogram is the gamma coincidence spectrum, arbitrarily normalized. Clearly, the ground state gamma coincidence effectively selects the IVGDR from the complex multipole distribution present in the singles spectrum. This fact is illustrated more quantitatively in figures 13 and 14 which show $^{17}O$ -$\gamma_0$ angular correlations. In figure 13 the correlation is displayed as a function of $^{17}O$ angle, for ground state gammas at $\theta = 90°$, $\phi = 270°$, while in figure 14 the data are displayed as a function of $\gamma$ angle for the $^{17}O$ ions detected in the range $\theta(^{17}O) = 2°$ to 3.5°. In this case the angle $\theta_\gamma$ is referred to the direction of the $^{208}Pb$ recoil rather than the beam axis. The lines on figures 13 and 14 are calculations carried out with the code ECIS,[11] assuming pure Coulomb excitation of the IVGDR with its total strength and distribution taken from Ref. 8. The calculation of the absolute theoretical cross sections in figure 13 involve an average ground state gamma branching ratio, which is, of course, not provided by the ECIS calculation. For now this branching ratio can be regarded

as determined by fitting the overall normalization in figure 13 to be
0.017 ± 0.002, however, we will see later that this quantity is in
excellent agreement with a calculation containing no free parameters.

All IVGDR calculations shown assume pure Coulomb excitation.
Nuclear excitation of the IVGDR can play a role primarily through terms
arising from the fact that both projectile and target have a neutron
excess.  Calculations employing a nuclear transition density calculated
following the methods of Satchler,[12] demonstrate that the nuclear
contribution to the cross section of the IVGDR is about $10^3$ times
smaller than the Coulomb, and has no significant effect on any of the
calculations presented here.

The absolute yield of ground state gamma rays can be calculated
from the properties of the IVGDR by applying the ideas of the multistep
theory of nuclear reactions.[13,14]  The collective 1p-1h GR state is
considered as a doorway state which couples strongly to the inelastic
scattering process.  This state damps into the more complex 2p-2h,
3p-3h, etc. states eventually reaching the fully damped compound
states.  The cross section for emission of ground-state gamma rays
following inelastic scattering can be expressed as:

$$\sigma_{x,x'\gamma_0}(E) = \sigma_{x,x'}(E) \left( \sum_{i=1}^{r} \frac{\Gamma_{\gamma 0,i}}{\Gamma_i} \left[ \prod_{j=1}^{i-1} \frac{\Gamma_j^{\downarrow}}{\Gamma_j} \right] \right). \tag{1}$$

$\sigma_{x,x'}(E)$ is the distribution of excitation cross section obtained from
a DWBA calculation, the sum in parentheses runs over the hierarchy of
levels of complexity from the doorway stage (i = 1) to the compound
($r^{th}$) stage.  The quantity $\Gamma_i^{\downarrow}$ represents the damping width of the $i^{th}$
stage while $\Gamma_i$ is the total width.  Application of this general
expression requires a great deal of knowledge concerning the various
widths associated with each stage.  For simplicity and without much
justification, we will use a two stage approximation, considering only

the GR doorway and the compound states, as:

$$\sigma_{x,x'\gamma_0}(E) = \sigma_{x,x'\gamma_0}(E) \left( \frac{\Gamma_{\gamma 0}}{\Gamma} + \left[ \frac{\Gamma^{\downarrow}}{\Gamma} \right] B_{CN}(E) \right), \tag{2}$$

where the index 1 for the doorway state has been dropped. $\Gamma_{\gamma 0}$ can be calculated directly from the GR strength, $\Gamma$ is identified with the experimental width of the resonance, and $B_{CN}(E)$ is the compound nucleus branching ratio. The quantity in square brackets assures that only that fraction of systems which survive the damping process ($\Gamma^{\downarrow}$ is the damping width) is included in the compound term. Theoretical and experimental results for $^{208}$Pb indicate the $\Gamma^{\downarrow} \gtrsim 0.9 \, \Gamma$, so that this factor can be considered as introducing an uncertainty of up to 10% in the compound contribution (we will set it to unity). The compound branching ratio can be calculated from mean $\gamma_0$ and total widths obtained from Hauser-Feshbach calculations,[15,16] but including a correction for effects due to the distribution of partial widths which have been discussed extensively in the literature:[17] i.e.,

$$B_{CN} = C \frac{\langle \Gamma_{\gamma 0,CN} \rangle}{\langle \Gamma_{CN} \rangle} \tag{3}$$

where C is calculable in a straight forward way[17] if we assume the partial widths have a Porter-Thomas distribution. The results of a calculation using Eq. (2), and the properties of the IVGDR ($\Gamma = 4.0$ MeV and $E_0 = 13.5$ MeV and strength = 100% of classical EWSR between 8 and 25 MeV) from Ref. 8 are compared with $\gamma$-angle-averaged experimental data in figure 15. The contribution of the first and second terms of Eq. (2) are shown separately as dashed and dash-dotted curves respectively, and the sum as a solid line. The branching ratio, integrated over excitation energy from 9.5 to 25 MeV, is found to be 0.016, in excellent agreement with the value 0.017 ± 0.02 found earlier in connection with the data in figure 13. Furthermore the distribution of $\gamma_0$ yield as a function of excitation energy is reproduced very well.

Inelastic scattering of heavy ions at lower energies generally excites isovector resonance states very weakly. We have studied the ground state gamma decay of the giant resonance region following the $^{208}Pb(^{17}O,^{17}O')$ reaction at 22 MeV/nucleon. Experimental details can be found elsewhere.[9,10] At this energy the inelastic singles spectrum ($\theta(^{17}O) = 13°$) is dominated by the isoscalar giant quadrupole resonance (ISGQR), with a cross section of about 40 mb/sr while the IVGDR is calculated to have a cross section < 3 mb/sr. In figure 16 the total ground state gamma coincidence spectrum is shown. Comparison with figure 11 shows the much smaller yield of high energy gamma radiation in this case. Figure 17 shows the GR region of figure 16, compared with a calculation identical to that discussed above in connection with figure 15. In figure 17a the total experimental spectrum is shown compared to a calculation including only the IVGDR, which, in spite of its weak excitation is clearly dominant. In figure 17b data obtained by subtracting the calculated IVGDR contribution from the experimental spectrum is compared with a calculation for the ISGQR gamma decay. The ISGQR resonance parameters are taken from high resolution (p,p') data.[18] In both figure 17a and 17b the doorway and compound terms are shown separately as dash-dot and short-dashed curves respectively, while the heavy solid lines are the sum. The light solid line in figure 17a represents the tail of the yield from around the neutron separation energy, while in figure 17b the light solid line represents the contribution of narrow $2^+$ states found at 8 and 9.3 MeV in (p,p').[18] The gamma ray angular correlation data shown in figure 17c confirms the presence of E2 gamma radiation in the 9 to 11 MeV region and agrees very well with the relative E2 and E1 contribution predicted by the calculations. From the data in figure 17b we obtain a total E2 ground state cross section of 17 ± 4 μb/sr, corresponding to a total branching ratio for the ISGQR of $(4.1 \pm 1.0) \times 10^{-4}$ or an electromagnetic reduced matrix element of $B(E2\uparrow) = (6.2 \pm 1.2) \times 10^3$ $e^2fm^4$ for the 10.6 MeV ISGQR. This corresponds to 87 ± 20% of the strength expected for a state exhausting the full E2 EWSR, assuming the ratio of neutron to proton matrix elements in the ISGQR is

$M_n/M_p \approx N/Z = 1.5$. An experimental value for the ratio $M_n/M_p$ can be deduced from our B(E2↑) if the cross section for alpha-particle ine-lastic scattering[19] is used as a measure of $(M_n + M_p)^2$. We obtain $M_n/M_p = 1.35 \pm 0.33$ in good agreement with the value N/Z expected for an approximately isoscalar GR having equal neutron and proton defor-mation. Electron scattering results[20] can be combined with (α,α') results in a similar way to obtain $M_n/M_p \sim 1.75 \pm 0.4$, again in good agreement with N/Z. These results disagree with the small value of B(E2↑) = $(1.01 \pm 0.6) \times 10^3$ $e^2fm^4$ and $M_n/M_p = 3.8$ deduced from recent $\pi^+$ and $\pi^-$ scattering data.[21] These quantities would require that the 10.6 MeV GQR in $^{208}$Pb have a strongly mixed isospin character.

It has been realized for some time that gamma decay of GR to low lying collective states should carry important information about the coupling of low frequency surface vibrations to the GR. Such experi-ments on the IVGDR are an important part of the research program at tagged photon facilities. We have studied the branching to low-lying excited states in $^{208}$Pb as a function of excitation energy between ~8.5 and 16 MeV in our 22 MeV/nucleon $^{17}$O scattering experiments at Oak Ridge. The results have been discussed extensively elsewhere.[9,10] Table I summarizes the data obtained for a 2 MeV wide bin centered on the ISGQR. A particularly interesting feature is the absence of any significant decay directly 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. Clearly it is strongly suppressed. The only decays from the ISGQR region strong enough to be clearly identified are a branch to the 4.9 MeV, 3⁻ state and a decay to the 5.512 MeV, 1⁻ state. The latter is grouped in Table I with decays to a number of other states tentatively identified with known 1⁻ levels between 5 and 7 MeV. The 5.5 MeV state accounts for about 60% of this yield. Decay to the 5⁻ state at 3.2 MeV was seen in the 8.5-9.5 MeV excitation energy bin and weaker evidence for decay to the 5⁻ state at 3.9 MeV in the 9.5-10.5 MeV bin was found, confirming the presence of 4⁺ or 6⁺ strength in these regions. In the decay of the 12.5-15.5 MeV excitation region, the only lines identified

TABLE I. Relative photon branching to low-lying states in $^{208}$Pb from the excitation energy region of 9.5-11.5 MeV.

| Final state | | Decay branch relative to g.s. | | |
| --- | --- | --- | --- | --- |
| $E_x$ (MeV) | $J^\pi$ | Experiment | Calculations | |
| | | | Ref. 1 | Ref. 2 |
| 0.0 | $0^+$ | 1.0 | 1.0 | 1.0 |
| 2.61 | $3^-$ | 0.04 ± 0.04 | 0.027 | 0.035 |
| 4.085 | $2^+$ | $0.02 \begin{smallmatrix} + 0.05 \\ - 0.02 \end{smallmatrix}$ | | $9 \times 10^{-3}$ |
| 4.97 | $3^-$ | 1.80 ± 0.50 | | 2.3[a] |
| 5-7 | $1^-$ | 1.50 ± 0.50 | | 0.34 |

[a]Sum for three states at 4.7, 5.5, and 6.3 MeV.

correspond to $1^-$ states at 5.51, 7.06, and/or 7.08 MeV. This would be consistent with the photon decay mode expected from the giant monopole resonance which dominates the excitation cross section in this region.

The strong suppression relative to statistical estimates of decays from the GQR region to the 2.6 MeV, $3^-$ state is very interesting. Two recent calculations[1,2] (Table I) 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. A significant isovector admixture in the GQR would lead to a strong enhancement of this transition.[2] Our data rule out such an admixture. It should be noted that our results on the ground state decay show that compound decay is important for the ISGQR (resulting primarily from unusually small compound neutron widths in $^{208}$Pb). It would be reasonable to assume that fully damped states

are also important in decays to excited states. The suppression of E1 transitions to the 3⁻, 2.6 MeV state must therefore survive the damping process, indicating that the compound states into which the GQR mixes retain the isoscalar character of the GQR doorway.

The calculations[1,2] illustrating the sensitivity of the gamma branch from GQR states in $^{208}$Pb to the 2.6 MeV, 3⁻ state to the isospin character of the GQR state was a major motivation for the 84 MeV/nucleon $^{17}$O scattering experiments discussed earlier. These calculations suggested that the strong branch to the 3⁻ state might be an effective way to isolate the IVGQR in $^{208}$Pb. Our initial GANIL experiments were a preliminary test. A longer run to study the IVGQR in this way has just been completed. The comparative shortage of information concerning the isovector GR is largely because of the weakness of isovector excitation in hadron inelastic scattering. The results of the preliminary 84 MeV/nucleon run clearly show how the increasing importance of Coulomb excitation (which is indifferent to isospin) for higher energy heavy-ion scattering changes this situation. There is at least some hope for sensitivity to the IVGQR at GANIL energies, though higher energies would be preferable.

Figure 18 shows the strength distribution for the IVGQR in $^{208}$Pb calculated by Bortignon et al.[22] The dashed line in the same figure shows the expected distribution of IVGQR cross section for the $^{208}$Pb($^{17}$O,$^{17}$O') reaction at 84 MeV/nucleon, resulting from the strong energy dependence of the Coulomb excitation process. The yield of γ-γ coincidences involving transitions through the 2.6 MeV, 3⁻ state should be roughly proportional to the product of these two curves. Shown in figure 19 is the corresponding γ-γ coincidence yield as a function of excitation energy ($E^*$) in $^{208}$Pb, where $E_{\gamma_1} + E_{\gamma_2} \approx E^*$ and $E_{\gamma_1} = 2.6$ MeV. In spite of the very poor statistics this result is at least tantalizing.

In conclusion we believe that gamma decay studies can make a significant contribution to our knowledge of the structure of giant resonances. Heavy ion inelastic scattering followed by gamma decay will become an increasingly important tool at higher bombarding

energies. Even for the IVGDR the very large cross sections which can be obtained, and the well understood properties of the dominant Coulomb excitation process should soon supplement or perhaps even improve upon results obtained from photon scattering experiments.

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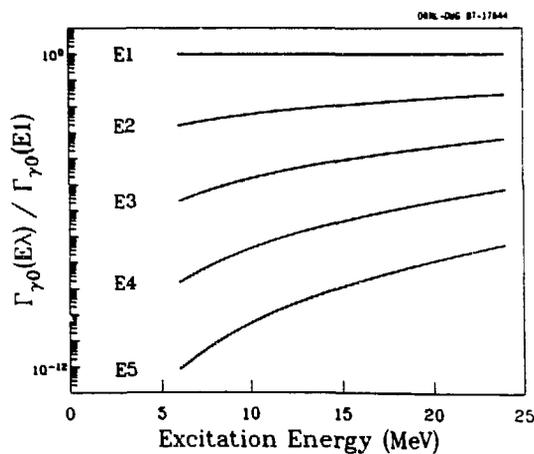
Fig. 1. Ground-state gamma widths of hypothetical sharp states fully exhausting the appropriate isovector or iso-scalar energy weighted sum rule as a function of the excitation energy of the state, relative to the E1 width.
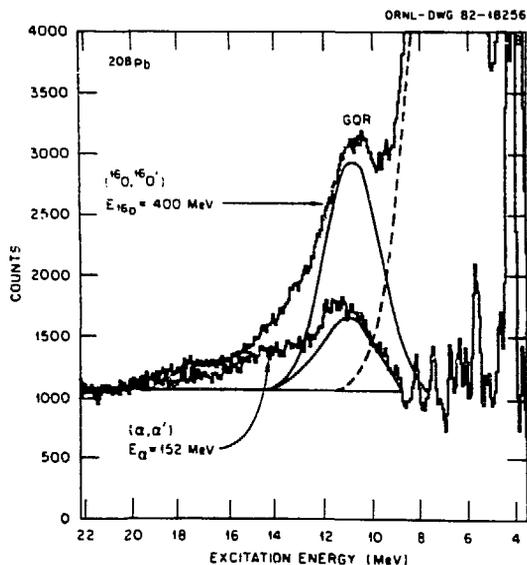


Fig. 2. Comparison of $^{208}$Pb giant resonance spectra as obtained from the ($^{16}$O,$^{15}$O') reaction at 400 MeV and the ($\alpha,\alpha'$) reaction at 152 MeV. The spectra are normalized at 22 MeV (Ref. 3).
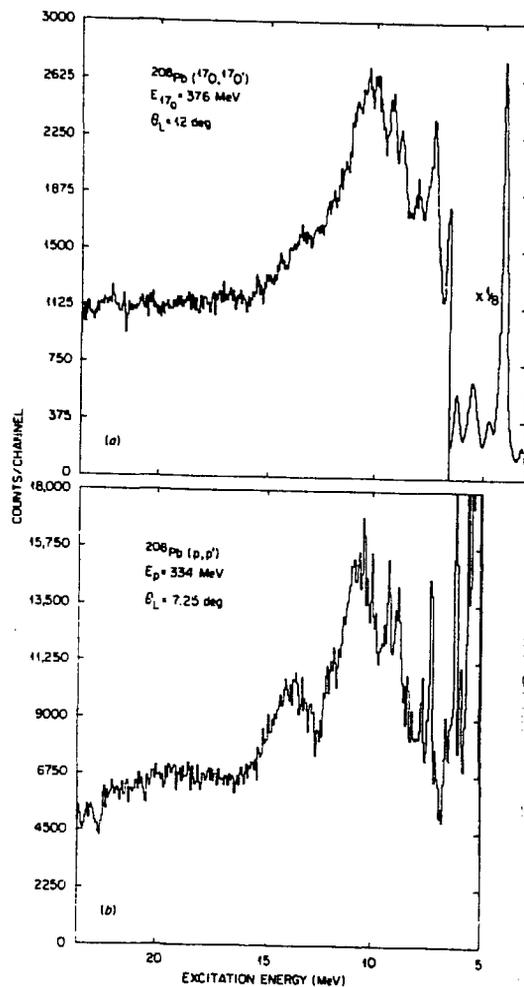


Fig. 3. Inelastic scattering spectra for excitation energies between ~3 and ~24 MeV. (a) ($^{17}$O,$^{17}$O'), 12° (Ref. 5), (b) (p,p'), 7.25° (Ref. 6).

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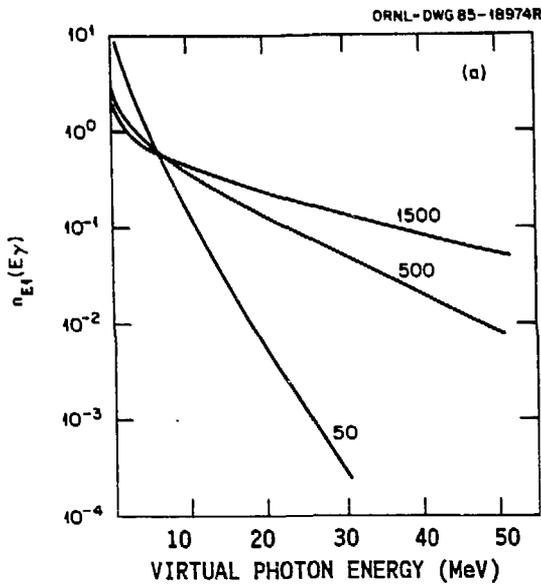
**Fig. 4.** E1 virtual photon intensity spectrum seem by a $^{208}$Pb target due to 50, 500, and 1500 MeV/nucleon $^{16}$O beams.



$^{17}$O + $^{208}$Pb
T = 0 GQR  E = 11MeV
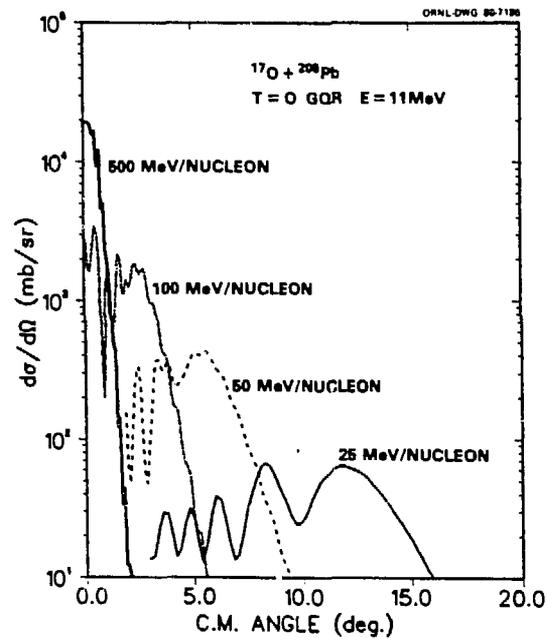
**Fig. 5.** Calculated angular distributions for the isoscalar giant quadrupole resonance excited by inelastic scattering of various energy $^{17}$O ions.



$^{17}$O + $^{208}$Pb
T = 1 GQR  E* = 22 MeV
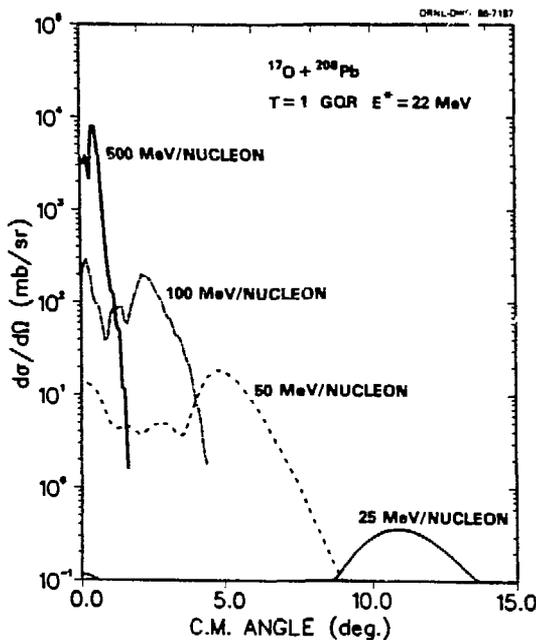
**Fig. 6.** Calculated angular distributions for excitation of the isovector giant quadrupole resonance in $^{208}$Pb by inelastic scattering of $^{17}$O ions of several different energies.



Comparison of relative giant resonance excitation

$^{208}$Pb($^{17}$O,$^{17}$O')$^{208}$Pb

------- 22 MeV/A. 12 deg.

———— 84 MeV/A. 2.60 deg.
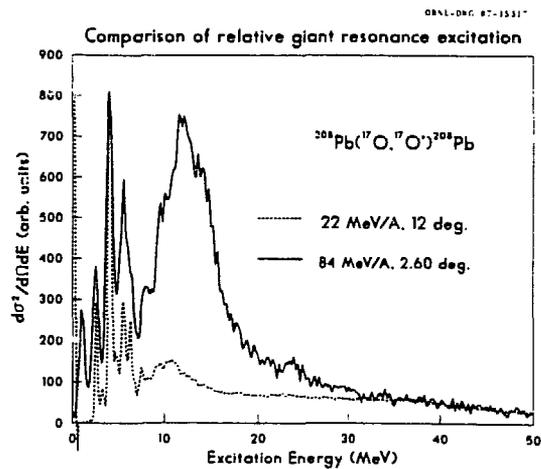
**Fig. 7.** Spectra from inelastic scattering of 84 (Ref. 7) and 22 (Ref. 5) MeV/nucleon $^{17}$O from $^{208}$Pb. The two spectra are normalized in the unstructured continuum near 40 MeV.
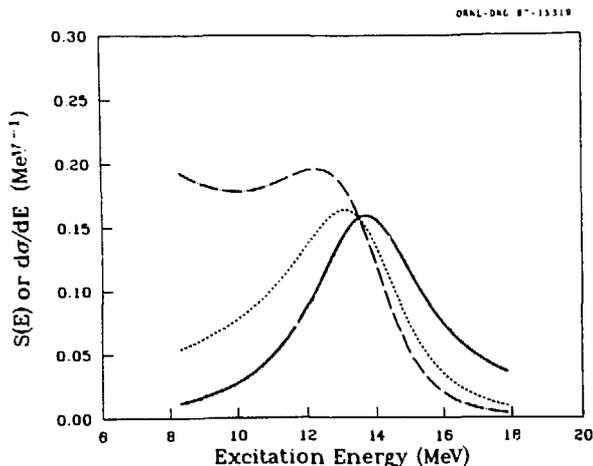
Fig. 8. This figure shows the effect the rapidly changing Coulomb excitation probability as a function of excitation energy has upon the shape of the $^{208}$Pb IVGDR. The solid curve is the dipole shape from photonuclear reactions. The dotted curve is the shape expected from excitation by 84 MeV/nucleon $^{17}$O ions and the dash-dotted curve is the shape expected for excitation by 22 MeV/nucleon $^{17}$O ions.
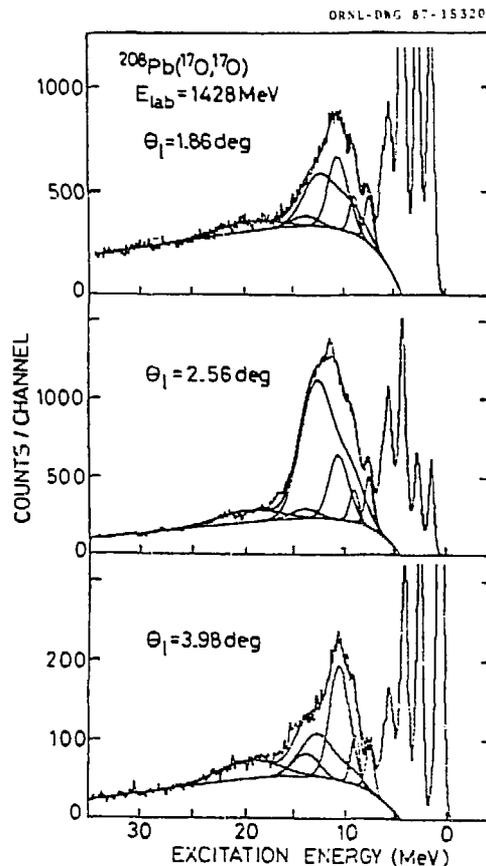
Fig. 9. Inelastic scattering spectra at $\theta_{lab}$ = 1.86°, 2.56°, and 3.98° from the $^{208}$Pb($^{17}$O,$^{17}$O') reaction at 1428 MeV. The solid curves show a decomposition of the spectra into resonance peaks at ~10.6 MeV (ISGQR), ~13.6 MeV (IVGDR), 14 MeV (ISGMR), 7.5 MeV, 9.1 MeV and a broad, undefined, peak centered at ~20 MeV and an underlying continuum (Ref. 7).
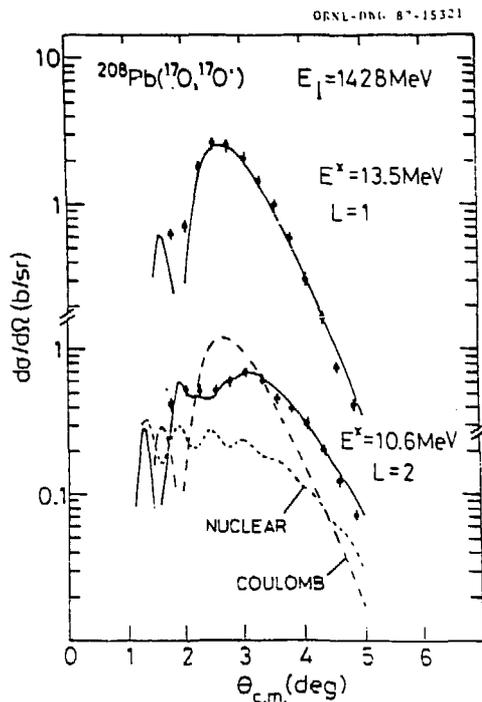
Fig. 10. Experimental and calculated angular distributions for the isovector giant dipole resonance (upper part) and the isoscalar giant quadrupole resonance (lower part) in $^{208}$Pb. For the ISGQR, the calculated Coulomb and nuclear contributions to the cross section are shown (dashed lines) (Ref. 7).
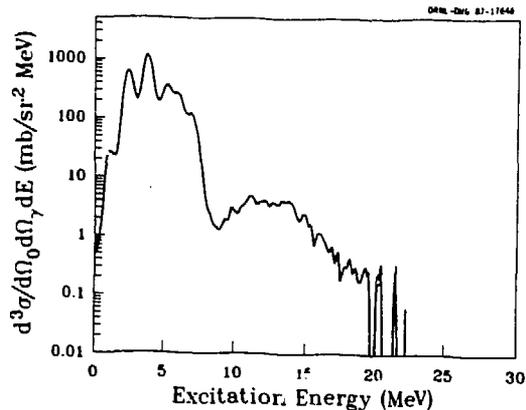


Fig. 11. Inelastic spectrum in coincidence with gamma rays to the ground state. (The $^{17}$O angles are $\theta = 2.0°-3.5°$ in this case, the gamma detector angles are given in the text.)
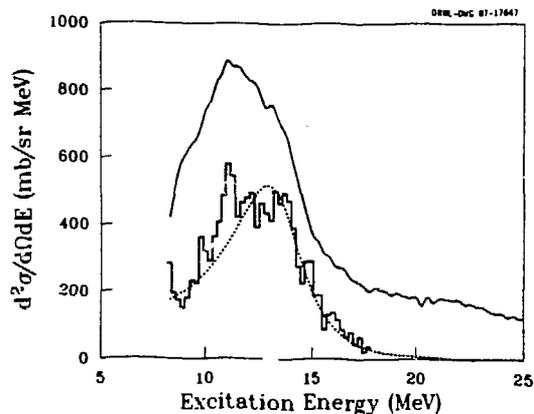


Fig. 12. Multipole selectivity by gamma coincidence. The heavy solid line is the giant resonance region of the 84 MeV/nucleon data in figure 7. The dashed line is the theoretical contribution of the giant dipole resonance to the experimental spectrum. The histogram is the $^{17}$O-$\gamma_0$ coincidence data of figure 11.
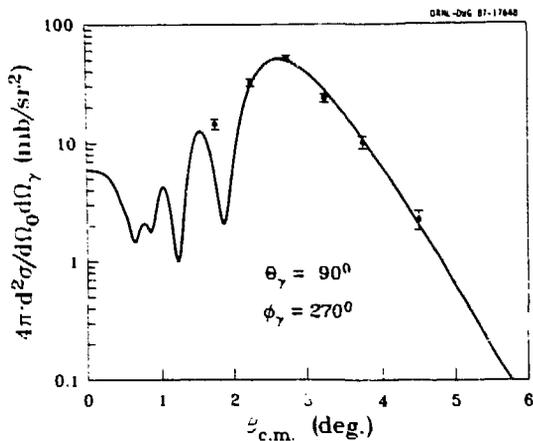
Fig. 13. $^{17}O-\gamma_0$ angular correlation for the $^{208}Pb(^{17}O,^{17}O')$ reaction at 84 MeV/nucleon, for fixed $\gamma$ angle $\theta_\gamma = 90°$, $\phi_\gamma = 270°$.
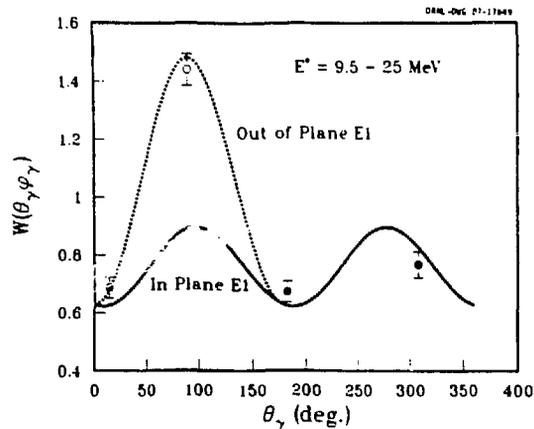


Fig. 14. The same correlation as figure 13., but for fixed $^{17}O$ angle ($\theta = 2°-3°$) and varying $\gamma$ angle. The lines are from theoretical calculations assuming pure Coulomb excitation of the GDR. Filled data points and the solid curve lie in the reaction plane ($\phi = 0°$ and $180°$). (For convenience the $\phi = 180°$ half plane is labeled by $\theta + 180°$.) The open point and dashed line refer to the $\phi = 270°$ half plane.
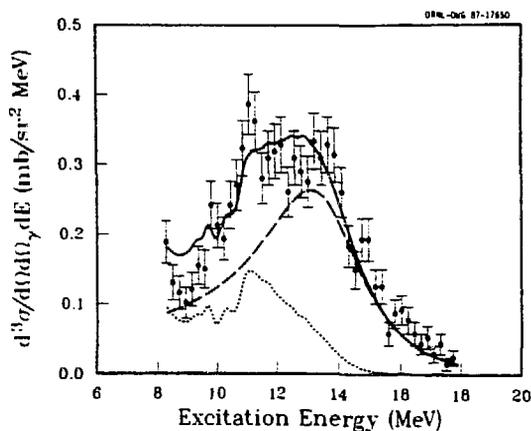


Fig. 15. The ground state gamma coincidence yield for 84 MeV/nucleon $^{17}O$ scattering on $^{208}Pb$, compared with calculations as discussed in the text.
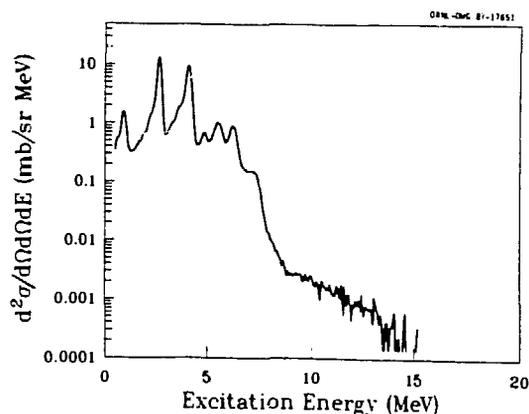


Fig. 16. The angle-integrated ground-state gamma ray cross section in coincidence with inelastically scattered $^{17}O$ ions at $\theta = 13°$, for $^{208}Pb(^{17}O,^{17}O')$ at 22 MeV/nucleon.

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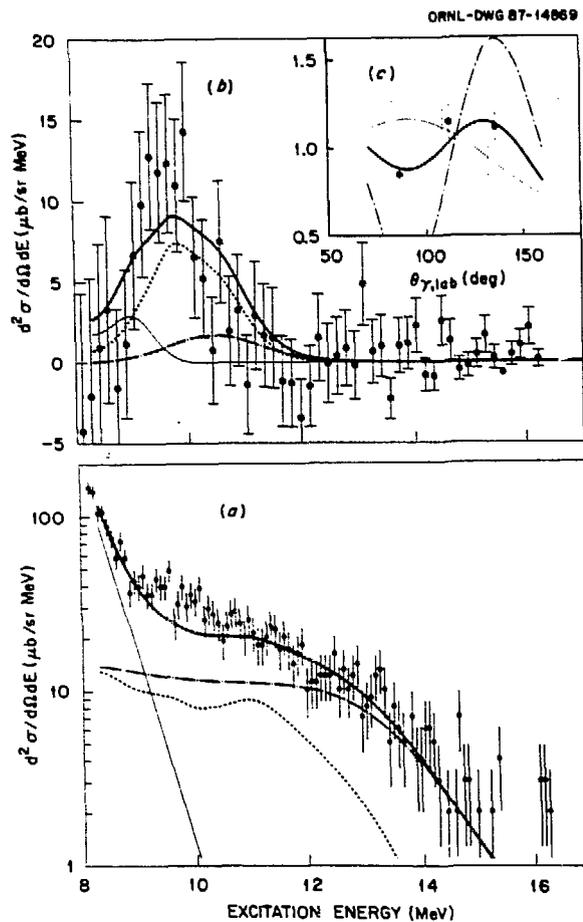


Fig. 17. Ground state gamma ray coincidence data compared with calculations using Eq. (2). This is a subset of the data of figure 16. The data and calculations shown in figure 17a and 17b are discussed in the text. Figure 17c shows experimental $\gamma_0$ angular correlations for energy bins from 9-11 MeV (solid points) and 12-15 MeV (open points). The dashed curve 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.
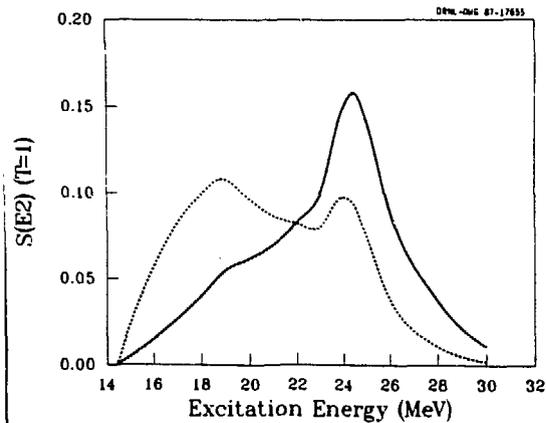


Fig. 18. The calculated iso-vector quadrupole strength function in $^{208}Pb$ (Ref. 22). The dashed curve is the corresponding distribution of inelastic cross section for 84 MeV/nucleon $^{17}O$ scattering on $^{208}Pb$.
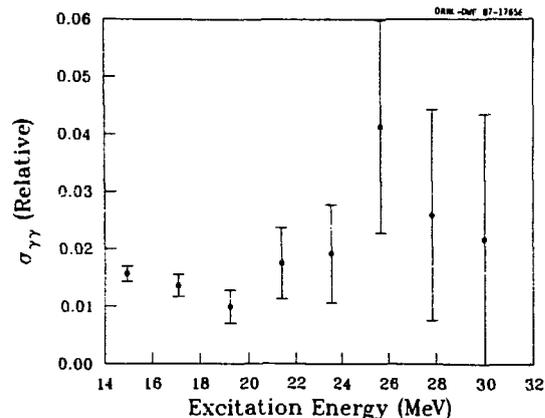


Fig. 19. The relative distribution of $\gamma\gamma$ coincidence yield as a function of excitation energy, subject to the conditions discussed in the text.

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