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GAMMA DECAY OF GIANT RESONANCES EXCITED BY HEAVY IONS

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ABSTRACT

Experiments on ^{208}Pb bombarded by ^{17}O at 22 MeV/nucleon (ORNL) and 84 MeV/nucleon (GANIL) are reviewed. Inelastically scattered projectiles were detected at forward angles in coincidence with gamma rays seen in NaI (ORNL) or in BaF_2 (GANIL). The ^{17}O were identified by 6 Si telescopes covering $\theta = 11.5°-14.5°$ (ORNL) or by the focal-plane detector system of the energy-loss spectrometer SPEG, set to accept $\theta = 1.5°-5.0°$ (GANIL). The γ-ray data provide information on (1) the multipole character of various parts of the giant resonance region, (2) matrix elements between the GR region and low-lying states in ^{208}Pb, and (3) the relative contribution of direct and compound processes to γ_0 decay. At the higher energy the 9-15 MeV GR region is excited very strongly. The isovector giant dipole is dominant over most of the angles studied. Significant contributions from the isoscalar giant quadrupole and monopole resonances are also present. Decomposition of the GR into L = 1, 2, and 0 components was based on coincidences with the overwhelmingly dipole γ_0 transitions. The magnitude (1.7 ± 0.2%) and energy distribution of the γ_0 branch can be reproduced well by a parameter-free calculation. The γ_0 decay of the isoscalar giant quadrupole resonance is more easily observed at the lower energy. The γ_0 angular correlations confirm the presence of E2 radiation from states in the 9-11 MeV region. The B(E2) implies that the ratio of neutron to proton matrix elements is consistent with the expected value of N/Z. This conclusion is confirmed by evidence from Coulomb-nuclear interference in the singles data at 84 MeV/nucleon. Photon decays to excited states indicate that 4^+ and/or 6^+ strength is present around 9-10 MeV, and are consistent with a monopole contribution from 12.5-15.5 MeV. Decays to the 3^- level at 2.6 MeV are absent, which can be explained as a cancellation of matrix elements due to the isoscalar nature of the 10.6 MeV GQR and the 2.6 MeV state. The γ-γ coincidence yield at 84 MeV/nucleon for cascades passing through the 2.6 MeV level shows a peak near 23 MeV, consistent with a prediction for the isovector giant quadrupole resonance and with data from (γ,n) and (e,e').

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This paper is an informal review of work by our group on gamma decay of the giant resonance excited by inelastic scattering of ^{17}O by ^{208}Pb and ^{209}Bi. The initial work at Oak Ridge National Laboratory was done with a beam of 22 MeV/nucleon; at GANIL the beam energy was 84 MeV/nucleon. Our collaborators are listed at the end of this paper.

A few points about the excitation of giant resonances (GR) should be mentioned before discussing their decay. *(1)* The excitation probability increases rapidly with bombarding energy. This is evident in Fig. 1 which compares inelastic spectra for ^{17}O on ^{208}Pb at 22 MeV/nucleon (data taken at ORNL) with 84 MeV/nucleon (data taken at GANIL). *(2)* As the bombarding energy increases, Coulomb excitation plays an increasingly important role. At 84 MeV/nucleon over half the total GR excitation is due to the isovector giant dipole resonance (IV GDR). Nuclear excitation contributes a negligible amount to excitation of the IV GDR.[1] *(3)* The dipole excitation is dominated by the Coulomb interaction. Unlike nuclear excitation, Coulomb excitation excites isovector and isoscalar states equally well. This makes it feasible to study isovector resonances with particle beams. Some of these points are illustrated in Fig. 2 by the GR excitation cross sections calculated for 100% of the respective energy-weighted sum rule (EWSR).

We chose ^{17}O as our probe because it has only three particle-stable excited states. This simplifies the inelastic spectra, since if the ^{17}O projectile is excited to any state above 3.8 MeV, it breaks up and is not detected as ^{17}O.

We now consider the γ decay of giant resonances. It is a rare decay mode, typically less than one in a thousand of all decays. Nevertheless, it can provide much useful information. Figure 3 shows the relative ground-state gamma decay widths for states exhausting the appropriate EWSR. Gamma decay to low-lying states is strongly dominated by E1 transitions. By selecting decays to the 0^+ ground state, we can isolate the dipole strength in the GR region. Decays to known excited states can also provide useful information because of the E1 dominance. For example, we have observed γ decays from about 9 or 10 MeV excitation in the GR region to low-lying 5^- states; this is clear evidence for 4^+ or 6^+ strength in the giant resonance.[1]

In our first experiment at GANIL, we used four arrays of seven BaF_2 scintillation crystals to detect γ rays. In our second run we used 3 arrays of 19 crystals each and 6 arrays of 7 crystals each.[2] These were operated in coincidence with inelastic ^{17}O registered by the focal-plane detector system of the magnetic energy-loss spectrograph known as SPEG. The spectrograph accepted ^{17}O scattered between 1.5° and 5°. The upper spectrum in Fig. 1 shows the inelastic ^{17}O singles for the range 2.0 to 3.0°. Excitation of low-lying states is evident, at 2.6, 4.1, and 5.5 MeV, but the major part of the yield belongs to the giant resonance.

We have determined the cross section for inelastic ^{17}O in coincidence with γ_0, the gamma transition to the ground state of ^{208}Pb. To identify the γ_0 transitions, we required that *(a)* only one BaF_2 cluster had fired, *(b)* one detector in that cluster must have had at least half of the total γ energy, and *(c)* the total γ energy was equal to the energy lost by the inelastic ^{17}O. Figure 4 compares the shape of the GR region seen in the singles data (full line) with the γ_0 coincidence data. The histogram is the coincidence spectrum, normalized for comparison with the singles data. The dashed curve is the normalized IV GDR cross section calculated on the assumption of pure Coulomb excitation and using the GDR strength distribution measured in ^{208}Pb (γ,n) experiments.[3] Clearly the γ_0 coincidence effectively selects the IV GDR from the many multipoles expected in this region of excitation energies.

In Fig. 5, we show the angular correlation of the γ_0 transition, in plane and out of plane, as a function of the γ-ray angle with respect to the ^{208}Pb recoil direction. The points are from experiment. The curves are coupled-channels calculations (ECIS)[4] for pure E1 Coulomb excitation. The data confirm that γ_0 decay selects the dipole component of the GR. Figure 6 shows the differential cross section for fixed γ-ray angle. The magnitude of the calculated curve was adjusted to fit the experimental points by adopting a ground-state branching ratio of (1.7 ± 0.2)%.

We will now see that this result can be predicted by a parameter-free calculation based on the multistep theory of nuclear reactions.[5] The collective 1p-1h GR state is considered as a doorway state that may damp into the more complex 2p-2h, 3p-3h, etc. states, eventually reaching the fully damped compound states. Since little is known about the intermediate states, we have tried a simple approximation in which there are only two stages, the GR doorway and the compound states; this leads to the equation:

$$\sigma_{^{17}O,^{17}O'\ \gamma_0}(E) = \sigma_{^{17}O,^{17}O'}(E)\ [\ \frac{\Gamma_{\gamma_0}}{\Gamma} + \frac{\Gamma\downarrow}{\Gamma}\ B^{CN}_{\gamma_0}(E)\ ]$$

Everything in the square brackets is known from other experiments or reliable theories. The first term in the brackets is the branching ratio for the direct decay of the doorway state back to the ground state. The Γ_{γ_0} can be calculated from the GR strength and the total width Γ is known from many experiments. The second term is the compound-nucleus contribution, which is significant for ^{208}Pb. The first factor (the damping width $\Gamma\downarrow$ divided by the total width Γ) gives the probability that the doorway state damps into the compound-nuclear states. For ^{208}Pb, theoretical and experimental results indicate that $\Gamma\downarrow$ is 90% or more of the total width. We take $\Gamma\downarrow/\Gamma$ as unity, thereby introducing an uncertainty of no more than 10% into the compound-nucleus term. The B_{CN} factor is the ground-state branching ratio of the compound states, which we obtain from Hauser-Feshbach calculations;[6,7] we include the Moldauer-Axel correction[8] for a Porter-Thomas distribution of partial widths. Figure 7 shows the results for the two terms. Their sum reproduces the experimental data very well both in shape and magnitude. The ground-state branching ratio integrated over excitation energy from 9.5 to 25 MeV is 1.6%, in excellent agreement with the 1.7 ± 0.2% deduced earlier by fitting the experimental data to a calculation for the excitation step only.

At lower energies, Coulomb excitation is less important and isovector resonances are only weakly excited (see Fig. 2). We have studied the ground-state γ decay of the GR region following inelastic excitation of ^{208}Pb by ^{17}O at 22 MeV/nucleon. This experiment was done at Oak Ridge and the γ rays were detected in the Spin Spectrometer, a 72-segment NaI crystal ball. The inelastic ^{17}O was detected by six cooled Si surface-barrier ΔE, E telescopes at a scattering angle of 13°, where the calculated cross section for the IS GQR has its peak. At this angle the calculated cross section for the IV GDR is about 15 times smaller. Nevertheless, in the ^{17}O spectrum coincident with ground-state γ rays, the GDR is dominant because the chance of an E2 decay to the ground state is 2 or 3 orders of magnitude less than for an E1 decay. In Fig. 8(a) we show calculations similar to those shown in Fig. 7. We first calculate the IV GDR part. The predicted contribution of the doorway (direct) term is given by the dash-dot curve. The dotted curve is the compound nucleus term. It includes contributions from the g.s. decay of known 1^- states near the neutron threshold ($E_x = 7.4$ MeV). The tail is mainly due to the experimental resolution. Adding up the calculated components gives the full line in Fig. 8(a) which accounts for most of the yield except around 10 MeV excitation. We now subtract the full line from the data. The difference spectrum is plotted as the histogram in Fig. 8(b). The dash-dot and dotted curves shown here are the doorway and compound-nucleus contributions calculated for the IS GQR; the resonance parameters and strength were taken from high resolution (p,p') data.[9] There are additional small contributions from 2^+ states at 8 and 9.3 MeV, also known from the (p,p') data.[9] The sum of these three quadrupole components matches the difference spectrum quite well. The γ-ray angular correlations are shown in Fig. 8(c). For the 12-16 MeV region, no quadrupole component is expected and the data (open points) agree well with the pure E1 prediction (dotted curve). The heavy line shows the angular correlation predicted for the relative strengths of the E1 + E2 mixture deduced for the 9.5-11 MeV region. It is in excellent agreement with the data (full points). It should be mentioned again that there is no fitting here – everything is predicted from other experimental results or theory.

From the data in Fig. 8(b), we obtain a total g.s. branching ratio for the IS GQR of $(4.1 \pm 1.0) \times 10^{-4}$, or a $B(E2)\uparrow = (6.2 \pm 1.2) \times 10^3 e^2 fm^4$. This corresponds to (87 ± 20)% of the full E2 EWSR, assuming the ratio of neutron to proton matrix elements in the IS GQR is $M_n/M_p \approx N/Z = 1.54$. Alternately, we can deduce an experimental value for M_n/M_p from our $B(E2\uparrow)$ if we use the (α,α') cross section[10] as a measure of $(M_n + M_p)^2$. This gives us $M_n/M_p = 1.33 \pm 0.33$, in good agreement with the value N/Z expected for an approximately isoscalar GR having equal neutron and proton deformation. In Fig. 9 we show this result as the right-most point. The point second from the left, $M_n/M_p \approx 1.75 \pm 0.4$, is from inelastic electron scattering data[11] combined with the (α,α') results. We can also use the (p,p') data together with (e,e'n) data[12] to provide $M_n/M_p = 1.6$, plotted at the extreme left. These results are all consistent with N/Z. The result $M_n/M_p = 3.8$ comes from π^+ and π^- scattering data,[13] and would require that the 10.6-MeV GQR in ^{208}Pb have a strongly mixed isospin character.

We have made similar decompositions of the 84 MeV/nucleon inelastic singles spectra to obtain the IS GQR cross section for ^{208}Pb as a function of ^{17}O angle. The points in Fig. 10 show the resulting differential cross section[14] of the GQR. The full curves are calculated for GQR strength based on M_n/M_p = N/Z while the dashed curves are for $M_n/M_p = 3.8$. The N/Z curves reproduce both the magnitude and the angular distribution of the experimental data very well. There is some sensitivity to the choice of the GQR strength, but this is small compared to the order-of-magnitude dip at 2.5° shown by the dashed curves but not by our data. We conclude that the ratio of the neutron to proton matrix elements for the GQR at 10.6 MeV is close to N/Z, consistent with it being a pure isoscalar resonance.

The collective properties of the GDR should be almost identical for ^{208}Pb and ^{209}Bi. This is confirmed by comparing the inelastic ^{17}O singles spectra at 84 MeV/nucleon for ^{209}Bi (Fig. 11) and ^{208}Pb (Fig. 12): their giant resonance regions are indistinguishable. However, the decay properties of the GR do show important differences. In Bi, the compound-nuclear γ decay competes much less successfully with neutron decay than in Pb because of level-density considerations; the calculated compound-nucleus contribution to the γ_0 decay in Bi is negligible compared with the direct γ_0 decay. In Fig. 13 the points show the ratio of the measured ^{208}Pb γ_0 decay to the ^{209}Bi γ_0 decay. Where the direct contribution is calculated to be important (see Fig. 7) the γ_0 cross section is the same for Pb and Bi. But near 10 MeV, where the compound-nuclear contribution is significant for Pb and negligible for Bi, we see a 60% excess experimental yield for Pb. This is predicted very well (dashed curve in Fig. 13) by the parameter-free calculations.

We conclude with a few remarks about gamma decay from the GR to low-lying collective states of ^{208}Pb. Table 1 shows results[1] for the GQR centered at 10.6 MeV. We see decay to the 1^- states at 5.5 and 7.1 MeV, as expected for E1 decay of a quadrupole resonance. The most remarkable feature is that decay to the first 3^- state is strongly suppressed although decay to the 3^- state at 4.97 MeV is quite strong. Two calculations have successfully predicted this suppression.[15,16] It arises from a combination of factors, among which is cancellation between neutron and proton matrix elements because both the 10.6-MeV GQR and the 2.61-MeV state are isoscalar. A significant isovector admixture in the GQR would lead to a strong enhancement of the 2.61-MeV transition. The data show also that this suppression must be occurring for the compound as well as the direct decays. That is, the suppression survives the damping process: the compound states into which the GQR mixes must retain the isoscalar character of the GQR doorway.

The sensitivity of the calculations to the isospin character of the GQR suggested to us that a search in the GR region for a strong decay branch to the 2.61-MeV 3^- state might be an effective way to isolate the IV GQR. We need Coulomb excitation to populate this resonance, which is why we did the experiment with the 84-MeV/nucleon ^{17}O beam available at GANIL. We looked for inelastically scattered ^{17}O in coincidence with the 2.61-MeV γ ray and another single γ ray of at least 10 MeV. About 110 events met this triple-coincidence criterion. They are shown by the histogram in Fig. 14. For comparison, a recent prediction by Bortignon et al.,[17] convoluted with the energy dependence of the excitation cross section, is shown by the curve in Fig. 14. The good agreement with the prediction supports our belief that we are observing the γ decay of the IV GQR. Our preliminary results for the resonance parameters are given in Table 2 in comparison with the theoretical predictions and other experimental results.

We are excited by the possibilities of this new kind of spectroscopy and hope that you feel the same way.

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REFERENCES

1. J. R. Beene, R. L. Varner, and F. E. Bertrand, Nucl. Phys. A482 (1988) 407c.
2. F. E. Bertrand, J. R. Beene, and D. J. Horen, proceedings of Third International Conference on Nucleus-Nucleus Collisions, Saint-Malo, France, June 6-11, 1988 (to be published).
3. B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47 (1975) 713.
4. J. Raynal, Phys. Rev. C 23 (1981) 2571.
5. H. Feshbach, A. Kerman, and S. Koonin, Annals of Physics 125 (1980) 429; M. Hussein and K. McVoy, Phys. Rev. Lett. 43 (1979) 1645; H. Dias, M. S. Hussein, and S. K. Adhikari, Phys. Rev. Lett. 57 (1986) 1998.
6. J. R. Beene et al., Phys. Lett. 164B (1985) 19.
7. H. Dias et al., Phys. Lett. 173B (1986) 335.
8. P. A. Moldauer, Phys. Rev. C 11 (1974) 426; P. Axel et al., Phys. Rev. C 2 (1970) 689.
9. F. E. Bertrand et al., Phys. Rev. C 34 (1986) 45.
10. H. P. Morsch et al., Phys. Rev. C 28 (1983) 1947.
11. G. Kilgus et al., Z. Phys. A326 (1987) 41.
12. G. O. Bolme et al., preprint; L. S. Cardman, in Proceedings of the International School of Intermediate Energy Physics, ed. R. Bergere, S. Costa, and C. Shaerf (World Scientific, Singapore, 1986), p. 163.
13. S. J. Seestrom-Morris et al., Phys. Rev. C 33 (1986) 847.
14. D. J. Horen, J. R. Beene, and F. E. Bertrand, Phys. Rev. C 37 (1988) 888.
15. P. F. Bortignon, R. A. Broglia, and G. F. Bertsch, Phys. Lett. 148B (1984) 20.
16. J. Speth, D. Cha, and V. Klemt, Phys. Rev. C 31 (1985) 2310.
17. P. F. Bortignon (private communication).
18. T. Murakami et al., Phys. Rev. C 35 (1987) 479.
19. M. Nagao and Y. Torizuka, Phys. Rev. Lett. 302 (1973) 1068.
20. R. Pitthan et al., Phys. Rev. Lett. 33 (1974) 849; 34 (1975) 848.

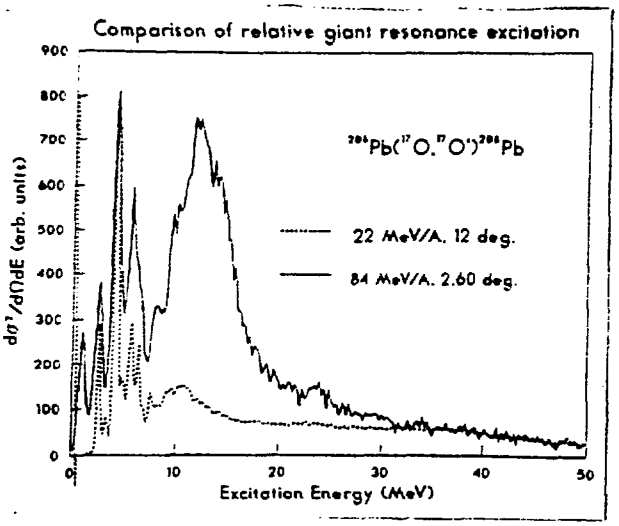

FIG. 1. Comparison of spectra for 84 and 22 MeV/nucleon ^{17}O scattered by ^{208}Pb. The spectra are normalized near 40 MeV.

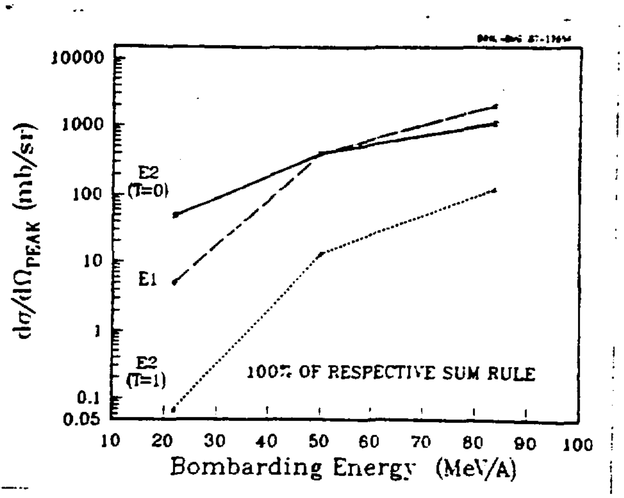

FIG. 2. Calculated peak differential cross sections for excitation of various giant resonances by ^{208}Pb(^{17}O,^{17}O').

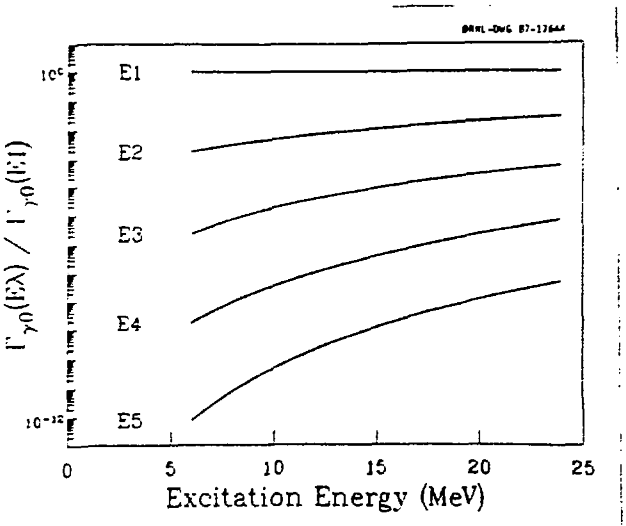

FIG. 3. Ground-state decay widths of hypothetical sharp states exhausting the EWSR for various multipoles, relative to the E1 width, as a function of excitation energy.

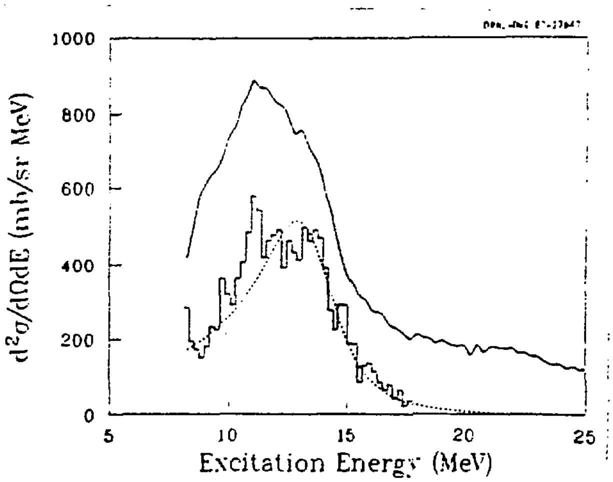

FIG. 4. Comparison of singles and γ_0 coincidence spectra in the GR region for ^{208}Pb(^{17}O,^{17}O') at 84 MeV/nucleon. The full curve represents the singles. The histogram is the experimental coincidence spectrum. The dashed curve is a prediction of the ^{17}O-γ_0 spectrum based on data for ^{208}Pb(γ,n). The histogram and the dashed curve have been normalized to permit them to be shown on the same scale.

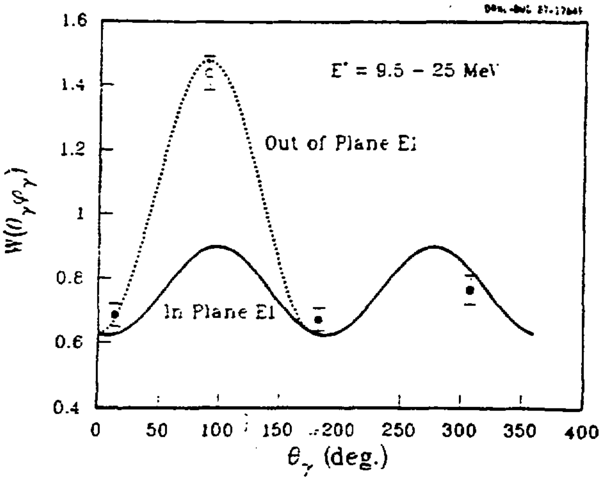

FIG. 5. Angular correlation for ^{208}Pb(^{17}O,^{17}O'γ_0) at 84 MeV/nucleon for ^{17}O' angles of 2.0° to 3.0°. The points are from experiment while the curves are coupled-channels calculations for E1 decay.

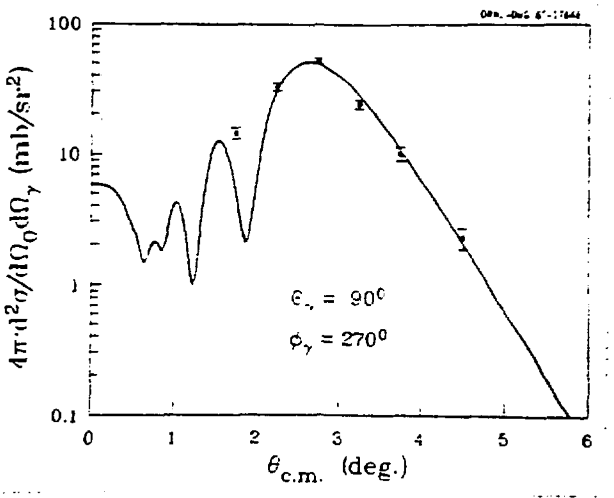

FIG. 6. Differential cross section for ^{17}O-γ_0 coincidences for 84 MeV/nucleon ^{17}O on ^{208}Pb. The points are from experiment; the curve is the coupled-channels E1 calculation.

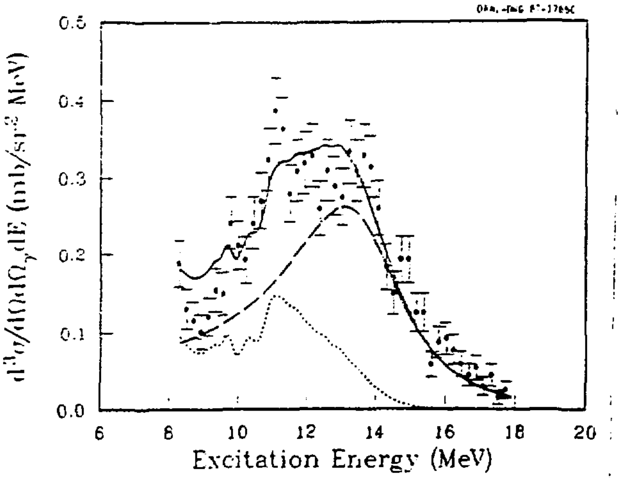

FIG. 7. Differential cross section for γ_0-coincident ^{17}O from 84 MeV/nucleon ^{17}O inelastically scattered by ^{208}Pb. The points are from experiment. The curves are theoretical predictions from the multistep theory of nuclear reactions. The dashed curve is the direct component, the dotted curve is the fully damped (compound-nucleus) term, and the full line is the sum of the two.

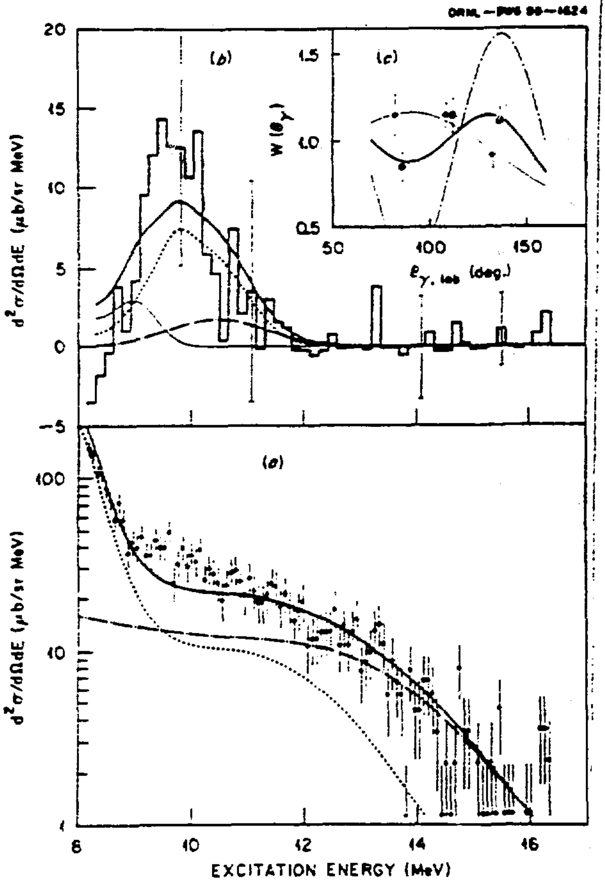

FIG. 8. Cross sections for ^{208}Pb(^{17}O,^{17}O'γ_0) at 22 MeV/nucleon. The curves are predictions based on the multistep theory of nuclear reactions. *(a)* Experimental data (points) in comparison with E1 predictions for the direct term (dash-dot), the compound nucleus term (dotted), and their sum (full line). *(b)* Quadrupole component. The histogram shows the experimental data of *(a)* after subtraction of the full line of *(a)*. The curves are E2 predictions for the direct term (dash-dot), compound term (dotted), and their sum (full line). *(c)* Ground-state γ-ray angular correlations. The full circles are experimental results for excitation energy 9.5 to 11 MeV and the diamonds are for 12 to 16 MeV. The dotted curve is for E1 decay of the IV GDR while the dash-dot curve is for E2 decay of the IS GQR. The full curve represents the E1 + E2 mixture predicted for 9.5-11 MeV by the results of *(a)* and *(b)*.

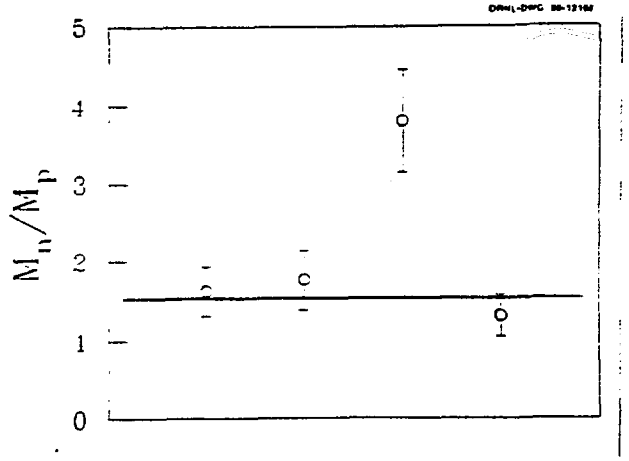

FIG. 9. Ratio of neutron to proton matrix elements deduced from various experiments as described in the text. The line shows N/Z = 1.54.

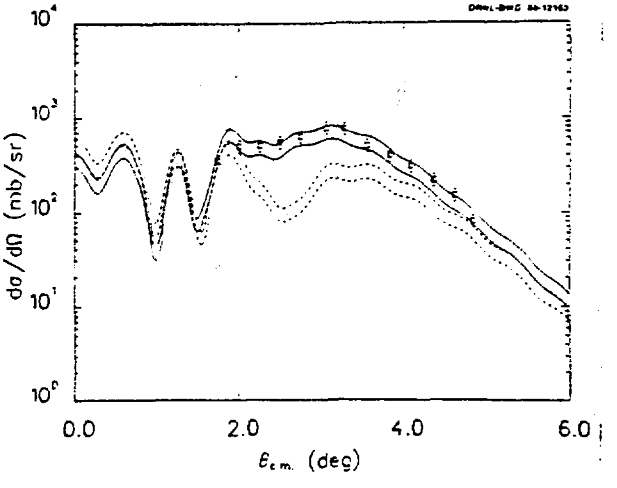

FIG. 10. Differential cross section for the GQR peak as a function of angle. The points are experimental results. The two solid curves are calculated for M_n/M_p = N/Z while the dashed curves are for M_n/M_p = 3.8. In each pair of curves, the upper curve is the prediction for a GQR strength of 80% EWSR and the lower for 50% EWSR.

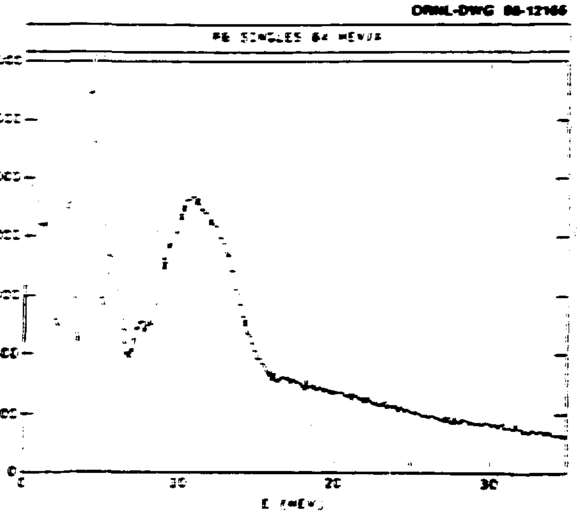

FIG. 11. Singles spectrum for 84 MeV/nucleon ^{17}O inelastically scattered by ^{208}Pb.

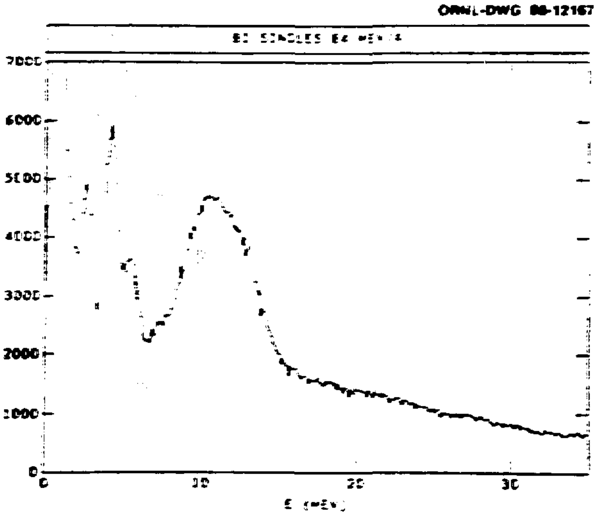

FIG. 12. Singles spectrum for 84 MeV/nucleon ^{17}O inelastically scattered by ^{209}Bi. The ordinate is adjusted to match that of Fig. 11.

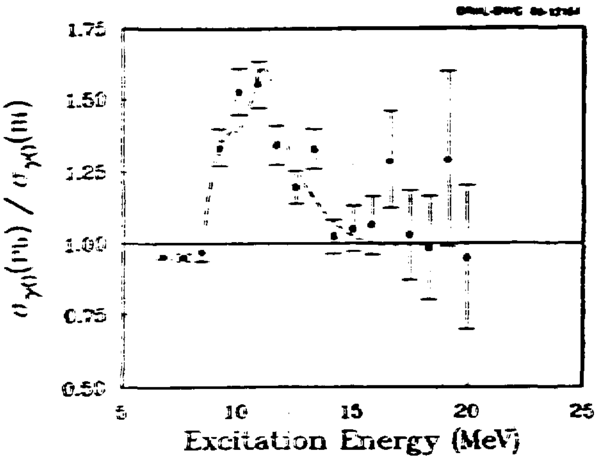

FIG. 13. Ratio of γ_0-coincident spectra for 84 MeV/nucleon ^{17}O scattered by ^{208}Pb and ^{209}Bi (points). The curve is the predicted ratio.

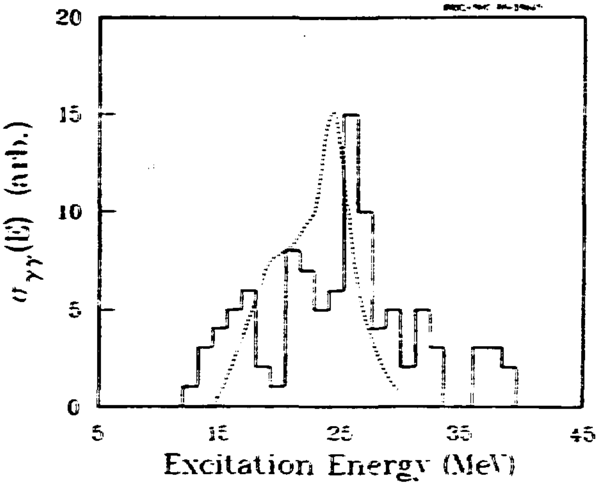

FIG. 14. The histogram is the triple coincidence data, $\gamma_1\gamma_2{}^{17}O'$, ($\gamma_1 > 10$ MeV, $\gamma_2 = 2.6$ MeV). The curve is the predicted (Ref. 17) distribution of IV GQR strength convoluted with the energy dependence of the probability of excitation by 84 MeV/nucleon ^{17}O on ^{208}Pb.