To be presented at the International Symposium on Weak and Electromagnetic Interactions in Nuclei, Heidelberg, W. Germany, July 1-5, 1986

CONF-860741--5

Photon Decay of Giant Resonances

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We have determined the total gamma-decay probability, the ground-state gamma branching ratio, and the branching ratios to a number of low-lying states as a function of excitation energy in ^{208}Pb to ~ 15 MeV. The total yield of ground-state E2 gamma radiation in ^{208}Pb can only be understood if decay of compound states is considered. Other observations in ^{208}Pb include the absence of a significant branch from the giant quadrupole resonance (GQR) to the low-lying collective states at 2.6 MeV and 4.08 MeV, and a strong branch to a 3^- state at 4.97 MeV.

CONF-860741--5

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Over the past decade several new giant resonances (GR) have been observed and classified [1]. Most of the observation of these new resonances has been accomplished through the use of light mass hadronic probes (protons, alphas, etc.), utilizing either inelastic scattering or charge exchange reactions. Recently, some advantages to excitation of isoscalar giant resonances using inelastic scattering of medium energy heavy ions have been investigated [2].

While some selectivity in GR excitation is obtained in inelastic scattering by selection of the incident particle in general inelastic scattering is not selective among the various multipoles. It is of considerable importance to find a method to study the complicated GR structure that would provide multipole selectivity and would at the same time provide a model independent measure of the transition strength in the resonance. A measurement of the photon decay of the giant resonances can provide such information and we report here the results from such measurements.

The giant electric multipole resonances in heavy nuclei are simple nuclear states embedded in a dense spectrum of more complex states, with which they mix. The consequent damping of the giant resonances offers an excellent test of our understanding of many-body physics in atomic nuclei. The questions now being asked [3,4] concerning the microscopic structure and the damping of these resonances require more detailed experiments than those which have served to build up the systematic catalog of gross properties of the resonances over the last decade [1]. The data required are coincidence data on the particle and gamma decay of the resonances, which can probe aspects of the resonance structure not addressed by the existing systematics.

The GR are described microscopically as a coherent superposition of one-particle, one-hole excitations relative to the ground state [1,5,6]. This coherent state is connected — by definition — to the ground state by a strong electromagnetic matrix element. Observation of the corresponding electromagetic decay deexciting the GR is of great importance, because of its direct relationship to the concept of a GR, since it offers the possibility of a determination of the

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*Operated by Martin Marietta Energy Systems, Inc. under contract DE-AC05-840R21400 with the U.S. Department of Energy.

resonance strength independent of that provided by analysis of inelastic scattering data with reaction models. Unfortunately, the electric GR lies above particle emission thresholds, with the consequence that the γ decay, in heavy nuclei, occurs for only about one in 10^4 decays.

The particle-hole states that make up the resonance can decay directly into the continuum, producing a free particle and the A-1 nucleus in the corresponding hole state. This is considered a direct decay process, and the corresponding width $\Gamma^{\uparrow}$ is called the escape width. Observation of the distribution of hole states left behind after such decays would provide detailed information about the microscopic structure of the resonances. Unfortunately, in a heavy nucleus such direct particle decays are also rare and difficult to isolate from more common processes [7,8]. The resonances in a heavy nucleus typically lie in a region of very high level density. The simple 1p-1h states of the resonance are consequently mixed or damped into the more complex np-nh states which exist at the same excitaiton energy.

This mixing or damping can be thought of as an alternative decay process for the coherent state [3,7,8]. From this point of view, the GR is excited as a primary doorway state in the inelastic scattering process. This state decays directly via $\Gamma^{\uparrow}$ or by gamma emission, or it "decays" into the continuum of more complex (compound) states. These states then decay statistically, usually by particle emission. A width $\Gamma^{\downarrow}$, the spreading width, is associated with this decay into the continuum. The observed width of the GR state is thus $\Gamma_T = \Gamma^{\uparrow} + \Gamma^{\downarrow}$ (we can safely neglect Γ_γ). For heavy nuclei, $\Gamma_T \sim \Gamma^{\downarrow}$ [7,8]. A microscopic understanding of this damping process is the focus of current theoretical work on giant resonances. Decay studies can provide insight into this process too, if, as has been suggested, the most important states involved in the mixing process are the 2p-2h states formed by coupling the 1p-1h states of the resonance to low-lying surface vibrations [4]. Evidence for the importance of such couplings should appear in the particle or gamma decay to the low-lying collective states.

The measurements were carried out by exciting the giant resonances using 380 MeV ^{17}O inelastic scattering and detecting the γ-decay (in coincidence with the inelastically scattered ^{17}O) in a 4π, γ-ray spectrometer. The use of ~ 22 MeV/nucleon ^{17}O inelastic scattering provides very large cross sections and excellent peak-to-continuum ratios for the GQR. This is pointed out in Fig. 1 where we show a comparison between the giant resonance structure observed in ^{208}Pb as excited by 376-MeV ^{17}O ions [2b] and 334-MeV protons [9]. The large peak located at 10.6 MeV in the ^{17}O spectrum is from excitation of the isoscalar giant quadrupole resonance. The ^{17}O spectrum which was obtained with ~ 200-keV energy resolution shows the existence of fine structure at excitation energies between ~ 7 MeV and the GQR. These peaks are observed also in the (p,p') spectrum [Fig. 1(b)] which was obtained with about 70-keV resolution. The most pronounced difference between the ^{17}O and proton spectra is near 14 MeV, in the region of the giant dipole and giant monopole resonances. This is expected because at the incident energies utilized, proton scattering provides stronger excitation of these resonances. The considerable similarity between the spectra from proton and ^{17}O inelastic scattering is surprising since different types of states could be excited by the two different probes. The ^{17}O probe excites predominantly isoscalar, non spin-flip, states whereas in medium-energy proton scattering contributions from spin-flip excitations should be present. The similarity of the fine structure peaks in the ^{17}O and proton spectra strongly suggests that the peaks arise mainly from excitation of isoscalar states.

There are primarily two experimental capabilities available at ORNL that contributed to our successful γ-decay measurements. The first, discussed above, is the use of ~ 25 MeV/nucleon heavy ions that excite the giant resonances with large cross sections and yield large resonance peak-to-continuum ratios. We chose ^{17}O because the particle thresholds are very low and thus the projectile excitation cross section near the GR region in ^{208}Pb in coincidence with outgoing ^{17}O is negligible. The second feature is the existence at ORNL of the Spin Spectrometer

[10], a crystal ball device, which is a 4π, segmented NaI gamma ray spectrometer consisting of 72 NaI detectors (see Fig. 2). Each detector is 17.8 cm thick and ~ 7.6 cm in diameter at the front and 15.2 cm diameter at the back. In the present experiment, the NaI elements at 0° and 180° (relative to the beam direction) were removed for the beam entrance and exit pipes. The Spin Spectrometer with its nearly 4π geometry provides high efficiency detection [10] for both gamma radiation and neutrons. Neutrons and gamma rays were distinguished by time of flight. The flight path is too short to permit resolution of neutron decay to individual levels in ^{207}Pb. However, the residual excitation energy in ^{207}Pb following neutron emission is accurately determined from the total gamma-ray energy in the Spin Spectrometer.

Charged reaction products were detected in six Si surface barrier detector telescopes each consisting of a 500 μm thick ΔE and a 1500 μm thick E detector. These detector telescopes provided excellent mass separation. Each telescope was covered with a trapezoidal collimator having an opening angle of $\Delta\theta = 3°$ and $\Delta\phi = 9°$, yielding a total solid angle for the array of 22.6 msr.

Events which involved pure γ decays were isolated by specifying two criteria. (a) No neutron pulse was seen by the spectrometer, and (b) the total energy carried away by gamma radiation accounted, within the resolution of the detectors

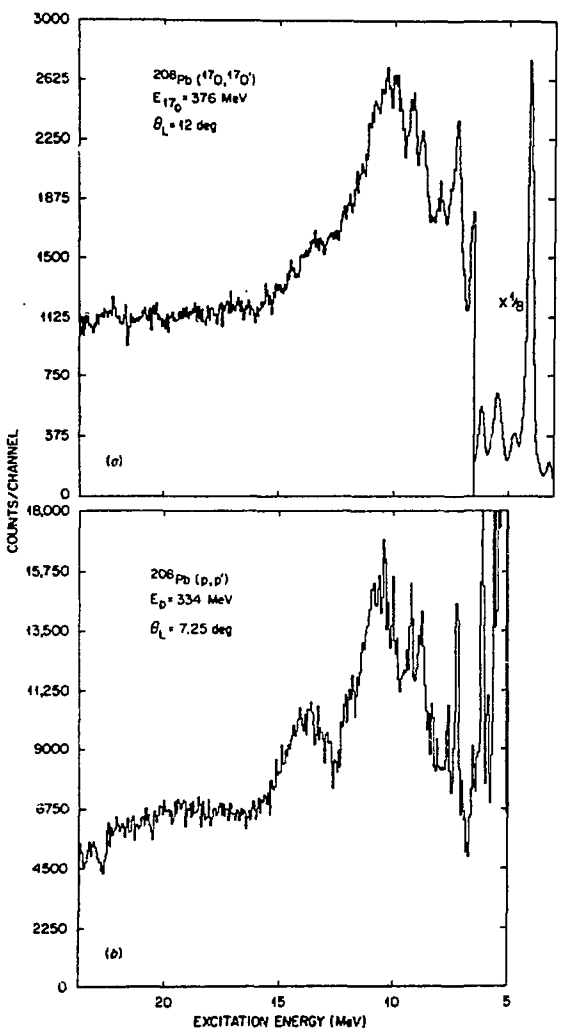

Fig. 1. Inelastic scattering spectra for excitation energies between ~ 3 MeV and ~ 24 MeV. (a) (^{17}O, ^{17}O'), 12 degrees [Ref. 2b] and (b) (p,p'), 7.25 degrees [Ref. 9].

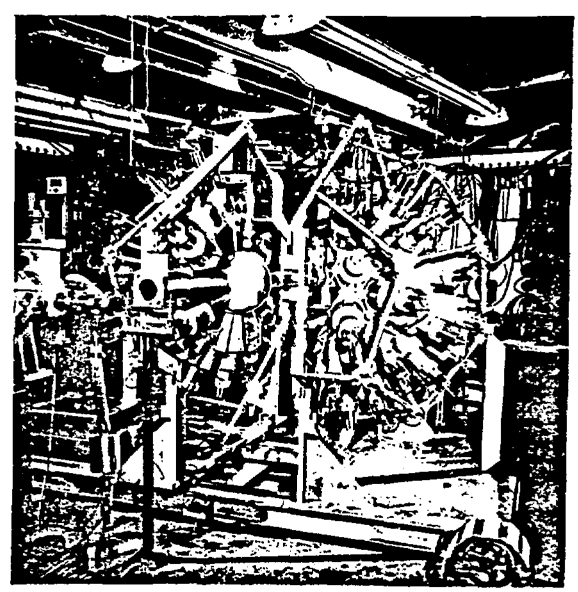

Fig. 2. ORNL Spin Spectrometer. The spectrometer is shown with one half pulled back to expose the spherical scattering chamber.

involved, for the total excitation energy of ^{208}Pb in the event, as determined by the energy of the inelastically scattered ^{17}O.

This isolation of gamma decay events is illustrated in Fig. 3 which shows a two-parameter histogram of events in which NaI pulses were detected in coincidence with a charged particle identified as ^{17}O in one of the telescopes. The abscissa is the excitation energy in the initial ^{208}Pb nucleus derived from the energy of the ^{17}O. The ordinate is the sum of the gamma ray energies detected in the spectrometer. These should be events in which no neutron pulse was detected, but since virtually all the GR decay is via neutrons [above $E^*(^{208}Pb) \sim 8$ MeV], and since the neutron detection efficiency is less than 100%, the requirement of the absence of a neutron pulse still leaves a substantial background of n-decay events. However, these background events are well separated from pure γ-decay events because of the neutron separation energy, S_n. The pure gamma-decay events should be found in the region outlined on Fig. 3, for which the sum E_γ is approximately equal to $E^*(^{208}Pb)$. In order to avoid confusion from the detection of high energy particles from the sequential decay of ^{18}O and ^{18}F back to ^{17}O following transfer reactions, an event was considered for further analysis only if the largest pulse height occurred in a NaI element at $\theta_{lab} > 66°$. Figure 3a shows all γ rays that fulfill the above requirements. The yield of these events is found to fall off approximately exponentially above S_n. The total gamma branching ratio at 11 MeV is $\sim 2 \times 10^{-3}$.

It is important to select those gamma events which decay directly to the ground state. Unfortunately the number (k) of gamma detectors which are triggered in an event is not useful for this selection. Calibration experiments with 25-MeV protons on ^{12}C show that a single 15.1 MeV gamma ray triggers, on the average, about three detectors and has a significant probability to trigger as many as five. We have used the parameter

$$V = \left| \sum_{i=1}^{k} \vec{h}_i \right| / \sum_{i=1}^{k} \left| h_i \right|$$

to identify ground state gamma decays. The h_i are the individual gamma ray pulse heights recorded in an event. These pulse heights can be assigned a direction as well as a magnitude by noting the position in the Spin Spectrometer array of the detector which produced them; hence, a "vector pulse height," $\vec{h}$, (or apparent photon momentum vector) is obtained for each triggered detector. V is the ratio of the magnitude of the vector sum of pulse heights to the scaler sum. For an event resulting from a single gamma ray this quantity should be near one since only adjacent detectors are triggered. For a cascade decay involving multiple gamma rays V should approach zero as the number of gamma-rays increases. Figure 3b is the same plot as 3a, subject to the additional requirement that $V > 0.95$. It is clear that the rarity of the ground state, GR γ-branch among the large "background" of high-multiplicity cascade γ-ray events requires a device having many γ detectors and 4π geometry like the Spin Spectrometer.

Figure 4 shows the sum gamma-ray spectra obtained from the two-dimensional plots such as Fig. 3. The results shown in Fig. 4 are from those events located between the masks (diagonal lines) on Fig. 3. The solid curve on Fig. 4 is the γ-ray spectrum for all values of V, i.e. all gammas, and corresponds to the data on Fig. 3a. The dashed curve corresponds to γ-events for which $V > 0.98$ (Fig. 3b) and consists only of gamma rays from ground state transitions. The peak at 2.61 MeV from the 3^- state decay has the same number of counts in both spectra. This is of course expected since the state decays 100% to the ground state. On the other hand, in the region above ~ 10 MeV the total γ-branch exceeds the ground state γ-branch by factors of 5-10.

Figure 5 shows the ratio of the solid and dashed gamma-ray spectra in Fig. 4, which is equal to the ground state gamma ray branching ratio, $\Gamma\gamma_0/\Gamma\gamma_{Total}$. Figure

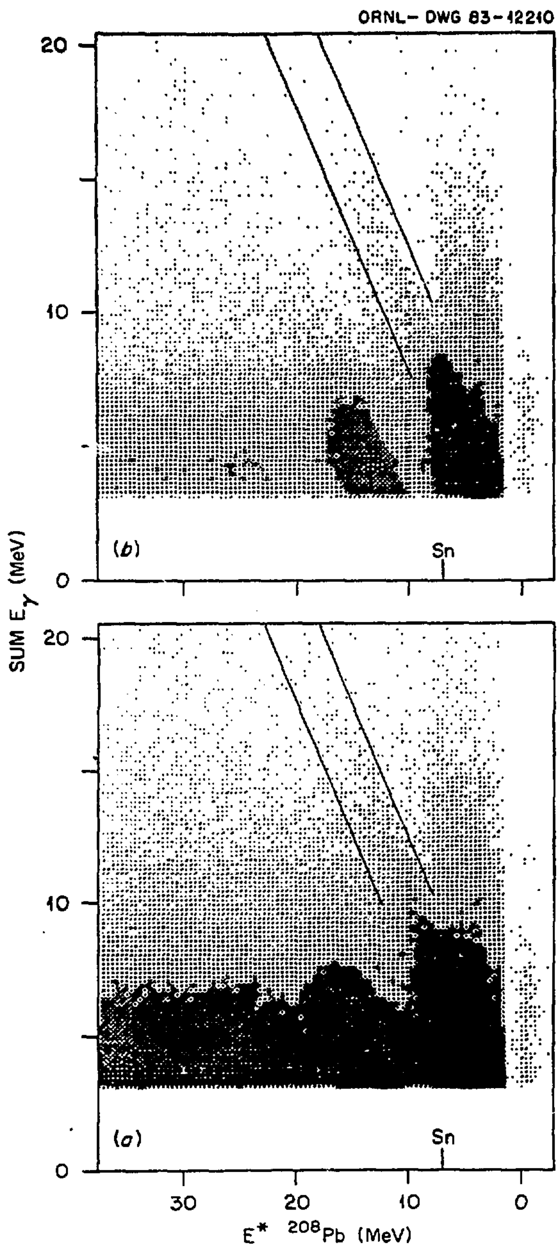

Fig. 3. (a) Is a plot of all events in which no delayed pulse (neutron) was observed. The solid lines indicate the boundaries of the region for which sum $E_\gamma \sim E^*$ ^{208}Pb (they should extend to sum $E_\gamma = 0$). In (b) the additional constraint $V > 0.95$ has been applied.

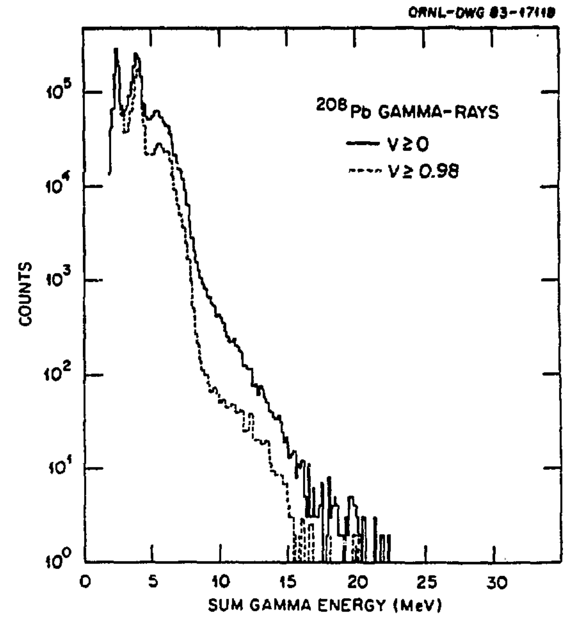

Fig. 4. Gamma-ray spectra from ^{208}Pb for $V > 0$ (all gamma rays) and $V > 0.98$ (only ground state gamma rays.)

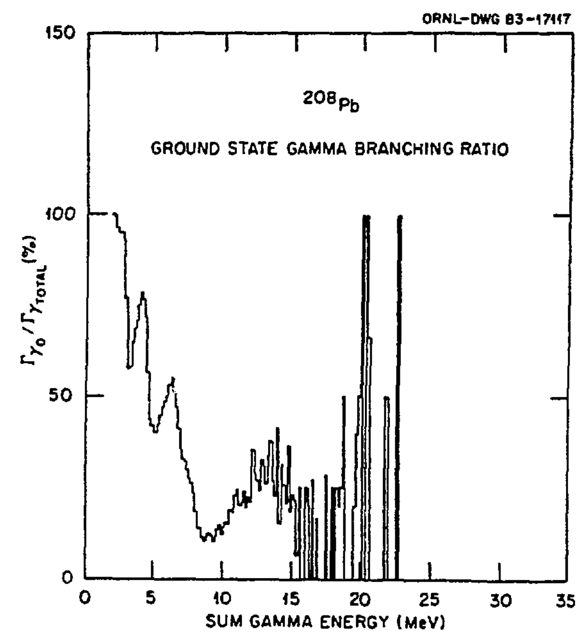

Fig. 5. Ground state gamma-ray branching ratio (%) as a function of sum gamma-ray energy (or excitation energy in ^{208}Pb).

5 shows the regions of excitation in ^{208}Pb which have strong electromagnetic matrix elements to the ground state, i.e. very collective states. In the high excitation energy region such states are defined as giant resonances. The spectrum shows the 2.61 MeV, 3^-, state which has a branching to the ground state of 100%. The peak at ~ 4 MeV arises from excitation of the 2^+ and 4^+ states in ^{208}Pb. It is not completely clear what provides the strong ground state enhancements in the 6 MeV region other than a group of 1^- states in that energy region. The ground state branching ratio then falls rapidly at the neutron separation energy but begins to rise again near 10 MeV. An obvious broad structure is observed in the 10-17 MeV energy region. Two peaks are found in this region, one at ~ 11 MeV, the other at ~ 13.5 MeV. These energies correspond with the known energies of the giant quadrupole and giant dipole resonances, respectively. It is to be noted that any L = 4 or 6 strength in the GQR region would not have an observable ground state decay. Furthermore, the giant monopole resonance would not have a ground state gamma branch. Thus, the peaks at 11 and 13.5 MeV are from "clean" excitations of the GQR and GDR.

Using angular distributions of the ground state gamma rays we can establish that the region of 9.5 to 11.5 MeV consists of (70 ± 10)% quadrupole radiation. The spectrum of ground-state gamma rays and the singles spectrum were fit using resonance parameters from Ref. 9. By dividing the ground-state gamma-ray yield by the singles yield of scattered particles populating the GQR, we obtain an experimental ground-state branch

$$R_{\gamma 0} = (3.2 \pm 0.4) \times 10^{-4} \qquad (^{208}\mathrm{Pb}, \mathrm{GQR}) .$$

This value has been corrected for instrumental efficiency and for the fraction of quadrupole radiation in the region obtained from fits to the photon angular distribution.

The results for $\Gamma_{\gamma 0}$ can be compared to expectation based on the energy-weighted sum rule (EWSR). If we consider the ground-state gamma decay to occur directly from the GR doorway state, then it should be considered as occurring in competition with the damping process, characterized by $\Gamma^{\downarrow}$, which we identify with the experimentally observed resonance width Γ_{exp}. The ground-state gamma width for a state exhausting 100% of the isoscalar L = 2 EWSR is [1,11,12]

$$\Gamma_{\gamma 0}(\mathrm{EWSR}) = 8.07 \times 10^{-7}\, E_{\gamma 0}^{5}\, B(E2\downarrow)_{\mathrm{EWSR}} \;\; \mathrm{MeV} ;$$

$$B(E2\uparrow)_{\mathrm{EWSR}} = 5B(E2\downarrow)_{\mathrm{EWSR}} = \frac{49.88\, Z^2R^2}{A\, E_{GQR}} \;\; e^2\mathrm{fm}^4 .$$

Using these expressions we find that for 100% of the EWSR the expected branch is

$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma^{\downarrow}}\right)_{\mathrm{DIRECT}} = 8.62 \times 10^{-5} .$$

This accounts for only about 25% of the observed branch. In ^{208}Pb the compound 2^+ states into which the GQR is damped decay almost exclusively by neutron emission. It has been pointed out [13] that the neutron widths of the compound states in ^{208}Pb are unusually small, leading to a large contribution to the ground-state gamma decay from the compound states. In order to relate the observed ground-state branch to the sum rule strength in the GQR region, a quantitative estimate of this effect is required. The desired quantity is $\langle \sigma_{\gamma 0}^{CN}(E)/\sigma(E)\rangle$, where the denominator is the total cross section for excitation of the GQR and $\sigma_{\gamma 0}^{CN}(E)$ is the cross section for ground-state gamma production in the reaction. This ratio can be expressed [14-16] as

$$R^{CN}_{\gamma 0} = \frac{\sigma^{CN}_{\gamma 0}(E)}{\sigma(E)} \approx S\,\frac{\langle\Gamma_{\gamma 0}(E)\rangle_{CN}}{\langle\Gamma_n(E)\rangle_{CN}}\ .$$

The quantity $\langle\Gamma_N(E)\rangle_{CN}$ is the average neutron (≈ total) width of the compound states; $\langle\Gamma_{\gamma 0}(E)\rangle$ is calculated as in Ref. [13] and is proportional to $\Gamma_{\gamma 0}$ (EWSR). The ratio of compound widths can be calculated with reasonable confidence [13], employing experimental neutron strength functions [13,17,18] for ℓ = 0, 1, and 2 neutron emission up to ~ 3 MeV above threshold, and the Hauser-Feshbach formula with optical model transmission coefficients for larger ℓ and excitation energies. We find the ratio of average widths in the above expression averaged over the GQR between 9.5 and 11.5 MeV to be between 8.0×10^{-5} and 1.1×10^{-4}, depending on the optical potential employed. The enhancement factor [14-16] (S) in the expression for the compound branch arises because of the properties of the Porter-Thomas distributions which the individual $\Gamma_{\gamma 0}$ are assumed to follow [15,16], and because of the strong correlation between the excitation and ground-state gamma-decay process [16]. In the usual model of the inelastic excitation process, the excitation matrix elements are proportional to the ground-state decay matrix elements. Hence, the treatment of compound decay following inelastic excitation is very similar to compound-elastic gamma-ray scattering. Assuming that the total neutron width $\langle\Gamma_n\rangle_{CN}$ does not fluctuate rapidly and using the fact that $\langle\Gamma_n\rangle \gg \langle\Gamma_\gamma\rangle$, we obtain S ≈ 3.0 [Refs. 15,16]. Thus, the theoretical ground-state branch, assuming 100% of the EWSR strength is in the range

$$R_{\gamma 0\ \text{Theory}} = 3.1 - 4.2 \times 10^{-4}\ ,$$

so that the experimental branch corresponds to between 79% and 105% of the EWSR. This value is in excellent agreement with the value from inelastic scattering [1,9].

It is also of great interest to see if gamma-decay branches other than the ground-state decay can be identified. In particular, direct decays to the low-lying collective states, the 3^- state at 2.61 MeV and the 2^+ state at 4.085 are of interest. Figure 6 shows the relative strength of gamma-ray branches to a number of low-lying states. Figures 6b and 6c are for direct decays to the 3^-, 2.61 and 2^+, 4.08 states, respectively. Figure 6d is the relative strengths for decays populating the 4.97-MeV, 3^- state. The yield distributions in Fig. 6, other than the ground-state yield, must be considered semiquantitative, especially where they indicate very small strengths, since adequate background subtraction has not been done. Nevertheless, they are valuable to indicate general features. A few of the more striking aspects include the marked absence of strength to the 2.61 and 4.08 MeV states across the resonance region. A strong yield of decays to the 3^- state at 4.97 MeV (thought to be a noncollective state dominated by a single 1p-1h configuration) is seen to appear at ~ 9 MeV and remains significant across the GQR region. A very similar, though weaker, strength distribution to that shown in Fig. 6d is seen for decays to a 5^- state at 3.9 MeV. This indicates the existence of high-spin strength underlying the GQR. A more quantitative treatment of decay branches from the GQR region (i.e., a bin from 9.5 to 11.5 MeV) is shown in Table I. It should be noted that the absence of decay to the 2.6-MeV, 3^- state, which appears remarkable at first sight, agrees with recent calculations [19,20].

The observed ground-state E2 gamma decay strength from the 9.5- to 11.5-MeV region in ^{208}Pb can be accounted for quantitatively using the properties of the GQR obtained from hadron scattering experiments, provided both compound and direct decays are considered. Compound decays dominate in ^{208}Pb, but the relative importance of compound and direct decays can vary widely, even for neighboring nuclei. While the direct decay branch varies slowly from nucleus to nucleus, the average compound neutron widths, which determine the compound gamma contribution, vary greatly. For example, calculations predict that the compound contribution of E2 gamma emission from the GQR in ^{209}Bi should be almost an order of magnitude smaller than in ^{208}Pb.

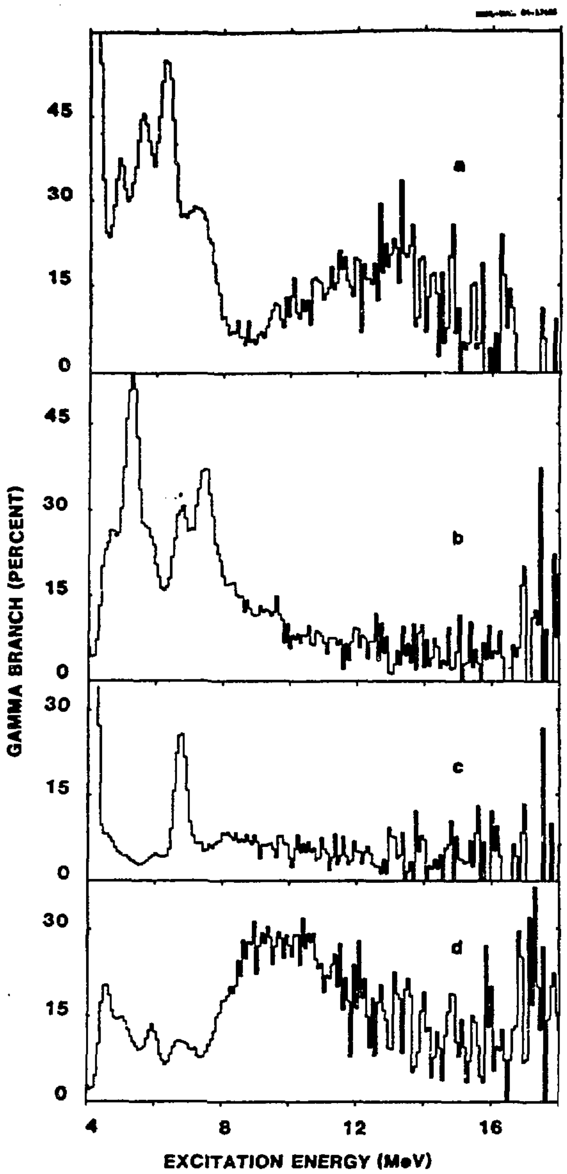

Fig. 6. Relative gamma-decay strengths for transitions to a number of low-lying levels in ^{207}Pb: (a) for ground-state decays; for transitions to the 2.61-MeV, 3^- state; (c) the 4.08-MeV, 2^+ state; (d) the 4.97-MeV, 3^- state.

TABLE I. Relative gamma branching to low-lying states in ^{208}Pb from an excitation energy region 9.5-11.5 MeV [E(GQR) ± Γ(GQR)/2]. The 5-7 MeV, 1^- states refers to a group of 1^- states in that region known from (γ,γ') experiments.

Final state energy	Final state spin	Decay branch relative to g.s.		
		Experiment	Ref. 19	Ref. 20
0.0	0^+	1.0	1.0	1.0
2.61	3^-	0.04 ± 0.04	0.027	0.035
4.085	2^+	$0.02^{+0.05}_{-0.02}$		9×10^{-3}
5-7	1^-	1.80 ± 0.04		0.53
4.97	3^-	1.80 ± 0.04		0.53 (~ 4.7) 1.6 (~ 5.5) 0.2 (~ 6.3)

The very small branch observed to the 2.61-MeV, 3^- state from the GQR region is also worthy of note. Statistical estimates give a 30-40% E1 branch to this state from a 2^+ state at 10.7 MeV. As mentioned earlier, this suppression appears to be well understood [19,20]. However, neither of these calculations considers damping beyond 2p-2h states. The data show that the mechanisms responsible for the suppression of this decay survive to the compound states.

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