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## ELECTROMAGNETIC DECAY OF GIANT RESONANCES\*

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We have carried out coincidence experiments to investigate the photon and neutron emission from the giant resonance regions of  $^{208}\text{Pb}$  and  $^{90}\text{Zr}$  using the ORNL Spin Spectrometer, a 72-segment NaI detector system. 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  $^{208}\text{Pb}$  to  $\sim 15$  MeV. Similar data were also obtained on  $^{90}\text{Zr}$ . The total yield of ground-state E2 gamma radiation in  $^{208}\text{Pb}$  and the comparative absence of such radiation in  $^{90}\text{Zr}$  can only be understood if decay of compound (damped) states is considered. Other observations in  $^{208}\text{Pb}$  include the absence of a significant branch from the giant quadrupole resonance (GQR) to the  $3^-$  state at 2.6 MeV, a strong branch to a  $3^-$  state at 4.97 MeV from the same region, and transitions to various  $1^-$  states between 5-7 MeV from the  $E^* \sim 14$  MeV region (E0 resonance).

### 1. INTRODUCTION

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 (GR) offers an excellent test of our understanding of many-body physics in atomic nuclei. The questions now being asked<sup>1,2</sup> 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.<sup>3-5</sup> 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.<sup>3-5</sup>

The GR are described microscopically as a coherent superposition of one-particle one-hole excitations relative to the ground state.<sup>3-6,7</sup> This coherent state is connected — by definition — to the ground state by a strong electromagnetic matrix element. Observation of the corresponding electromagnetic 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 resonance strength independent of that provided by analysis of inelastic

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scattering data with reaction models. Unfortunately, the electric GR lie above particle emission thresholds, with the consequence that the  $\gamma$  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  $\Gamma^+$  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.<sup>8,9</sup> 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 excitation energy.

This mixing or damping can be thought of as an alternative decay process for the coherent state.<sup>1,8,9</sup> From this point of view, the GR is excited as a primary doorway state in the inelastic scattering process. This state decays directly via  $\Gamma^+$  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  $\Gamma^+$ , the spreading width, is associated with this decay into the continuum. The observed width of the GR state is thus  $\Gamma_T = \Gamma^+ + \Gamma^+$  (we can safely neglect  $\Gamma_\gamma$ ). For heavy nuclei,  $\Gamma_T \sim \Gamma^+$  (Refs. 8,9). A microscopic understanding of this damping process is the focus of current theoretical work on giant resonances.<sup>5</sup> 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.<sup>2</sup> Evidence for the importance of such couplings should appear in the particle or gamma decay to the low-lying collective states.

## 2. EXPERIMENT

We have recently carried out experiments at the HHIRF at ORNL, designed to study both the  $\gamma$  decay and particle decay of the giant resonance region ( $\sim 9$  to 20 MeV of excitation) in  $^{208}\text{Pb}$  and  $^{90}\text{Zr}$ . The  $^{208}\text{Pb}$  experiment has been discussed elsewhere,<sup>10-12</sup> and a reasonably detailed description of the analysis is given in Ref. 8. Nevertheless, a brief recounting of the experiment and analysis techniques will be included here.

The resonances were excited by inelastic scattering of 381-MeV  $^{170}\text{O}$ . Oxygen-17 was chosen as a projectile because the low neutron binding energy (4.1 MeV) minimizes interference from gamma rays from projectile excitation. For  $^{90}\text{Zr}$ ,

four telescopes at  $\theta = 8.9^\circ$  and  $\Delta\theta = 1.5^\circ$  were used. For  $^{208}\text{Pb}$  the inelastically scattered  $^{17}\text{O}$  was detected in six cooled Si surface-barrier telescopes arranged symmetrically around the beam at an angle  $\theta = 13^\circ$  subtending  $\Delta\theta = 3^\circ$  and  $\Delta\phi = 9^\circ$  each and a total solid angle of 22.6 msr. The telescopes consisted of two elements of thickness  $\sim 500 \mu\text{m}$  and  $\sim 1000 \mu\text{m}$ , respectively. The energy resolution was  $\sim 800 \text{ keV}$ , and the mass resolution was sufficient to separate  $^{17}\text{O}$  from adjacent oxygen isotopes. A singles spectrum of inelastically scattered  $^{17}\text{O}$  is shown in Fig. 1. Strong excitation of the giant resonance region, centered at  $\sim 11 \text{ MeV}$ , is evident. Decay products were detected in 70 elements of

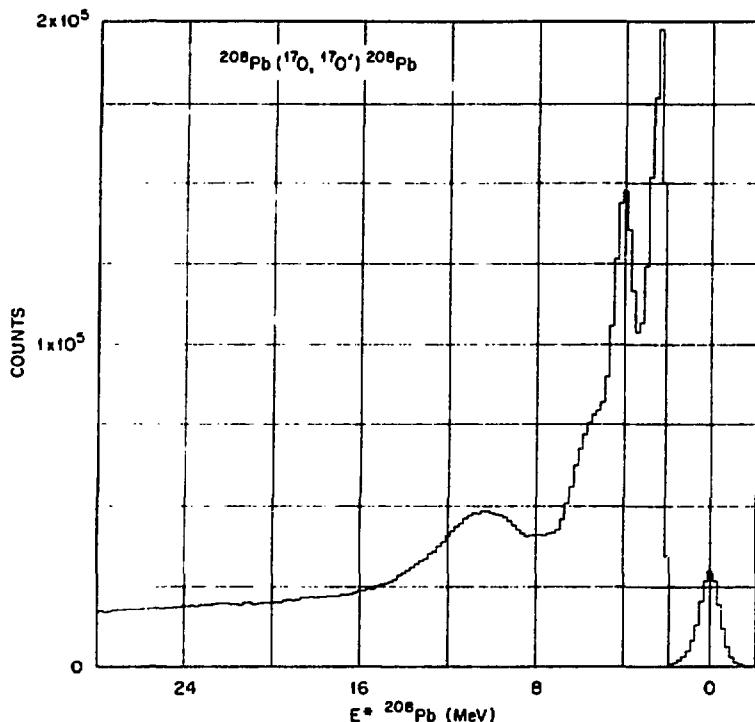


Fig. 1. Spectrum of 380-MeV  $^{17}\text{O}$  scattered by  $^{208}\text{Pb}$ . The elastic peak has been prescaled by a factor 512. The large bump between 9 and 15 MeV results from excitation of giant resonances.

the ORNL Spin Spectrometer. The spectrometer, which has been described in detail elsewhere,<sup>13</sup> consists of a spherical shell of NaI 17.8-cm thick, divided into 72 independent modules surrounding the target chamber. For the present experiment, two modules at  $0^\circ$  and  $180^\circ$  were removed to allow the beam to enter and leave the chamber. A photograph showing the experimental setup, including

a portion of the Spin Spectrometer, is shown in Fig. 2. The response of the spectrometer to high-energy photons was determined by using the  $^{12}\text{C}(\text{p},\text{p}')^{12}\text{C}$  reaction with 24-MeV protons, which produces 4.43-, 12.71-, and 15.11-MeV gamma radiation. The response at lower energies was obtained from a variety of radioactive sources.



Fig. 2. Six-telescope array in the Spin Spectrometer. The exit hemisphere and one part of the spherical reaction chamber were removed for the photograph. The beam enters from the right, and the target is at the center.

Figure 3 shows some of the levels of  $^{207}\text{Pb}$  and  $^{208}\text{Pb}$  relevant to the present experiment. The goal of the experiment is to study, as completely as possible, the decay of states in the 9- to 16-MeV region of  $^{208}\text{Pb}$ . Only two decay modes are important. Neutron emission accounts for >99% of decays, while gamma rays are emitted with a probability of  $\sim 10^{-3}$  to  $10^{-4}$ . This report focuses on the gamma decay. Copious information on  $n$  decay was also obtained and will be reported elsewhere.

### 3. ANALYSIS

The experiment posed a number of difficulties for which the Spin Spectrometer, with its very large efficiency and multiple segments, proved almost ideal.

The chief experimental problems were, first, isolating gamma decays from the  $>10^3$  times more frequent  $n$  decays in the GR region; second, distinguishing direct gamma transitions to the ground state from multiple or cascade decays; and, third, isolating decays which directly populated low-lying states of interest (e.g., the  $3^-$ , 2.61-MeV state) by a single gamma ray from the GR region.

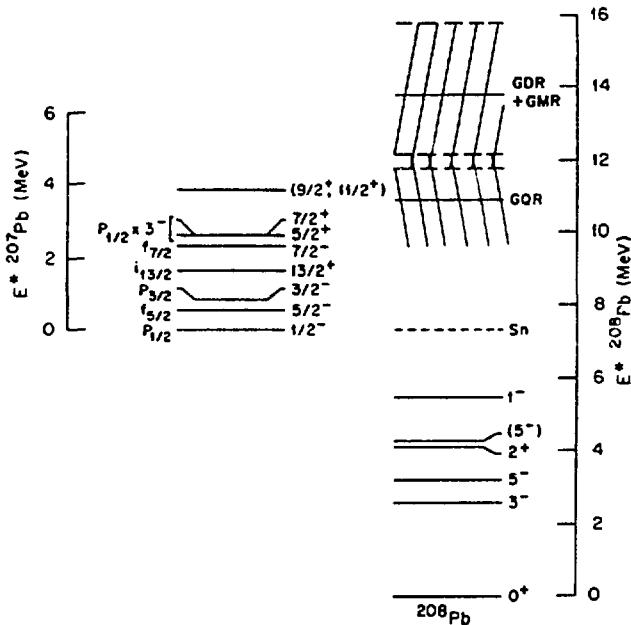


Fig. 3. Selected levels in  $^{208}\text{Pb}$  and  $^{207}\text{Pb}$ . The configuration labels on the  $^{207}\text{Pb}$  states refer to neutron hole states.

The raw data obtained from the spectrometer consisted of pulse heights from the individual NaI elements and times of these pulses relative to the inelastically scattered  $^{170}$  with which they were in coincidence. A number of derived parameters were obtained which were used to address the questions raised earlier. The total gamma-ray pulse height,  $H = \sum h_i$ , was constructed by summing all those pulses which occurred within a prompt time window. This window (which was a function of pulse height) was narrow enough to eliminate pulses resulting from detection of neutrons with energies less than  $\sim 5$  MeV, due to their longer flight time to the NaI. Single high-energy gamma rays are extremely unlikely to trigger a single NaI detector. Consequently, the number of detectors triggered is not very useful for isolating single gammas. A more useful quantity can be constructed by considering each pulse height observed in an element of the spectrometer as a vector quantity,  $\vec{h}_i$ , with direction

determined by the location of the element, from which the quantity  $V = |\Sigma \vec{h}_j|/H$  is formed. For a single high-energy gamma ray,  $V \sim 1$ , while for multiple gamma rays a smaller value of  $V$  is much more likely. Other useful quantities are the cluster sum pulse height and the cluster multiplicity. They are constructed for each event as follows. First, the largest pulse height is found, and a cluster sum is created by adding to it all the pulse heights in the five or six nearest neighboring detectors. Then the next largest pulse height not yet included in a sum is found, and a cluster sum is calculated from its nearest neighbors (not including those already used). This process continues until all the NaI pulses which satisfy the time gate are used. The number of clusters found is called the cluster multiplicity. For events such as those encountered in  $^{208}\text{Pb}$  decay, in which a small number of gamma rays (usually fewer than four) are emitted, the cluster sums are a much better reflection of individual gamma-ray energies than the separate NaI pulse heights.

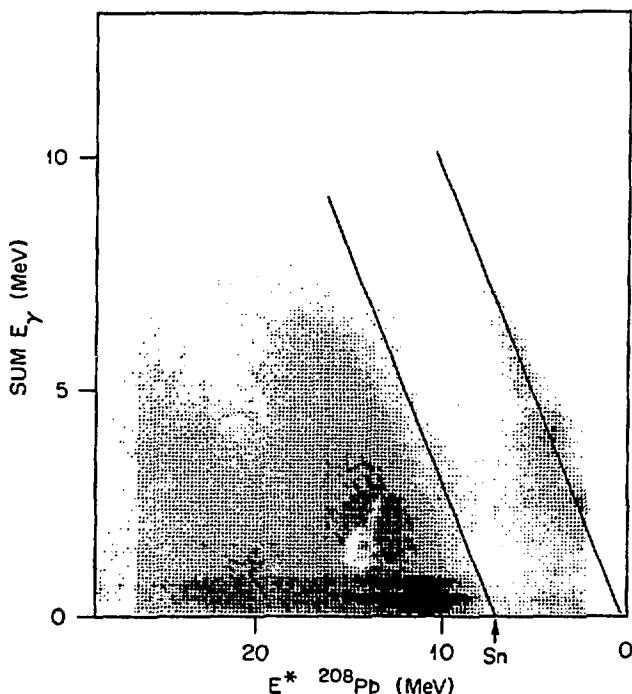


Fig. 4. Two-parameter density plot of events from  $^{208}\text{Pb}(170,170')$  in which one or more NaI detectors registered a delayed pulse. These should be due to neutron decays. The abscissa is derived from the energy lost by the inelastic  $^{170}$ . The ordinate is the sum of the  $\gamma$ -ray energies seen in the NaI detectors and is equal to the excitation energy in the residual nucleus.

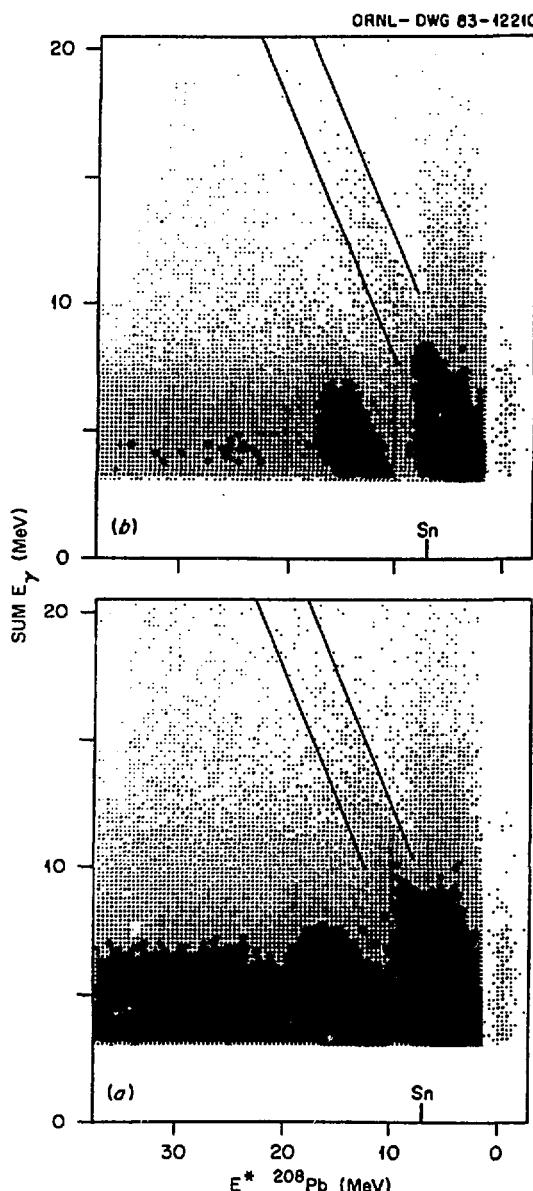


Fig. 5. Two-parameter density plot of events from  $^{208}\text{Pb}(^{170},^{170'})$  in which no NaI detector registered a delayed pulse. The axes are the same as for Fig. 4. Events falling between the pairs of lines are due to  $\gamma$ -decay events: (a) all events; (b) events satisfying the additional requirement  $V > 0.95$  to select ground-state transitions.

The separation of neutron decays from purely gamma decays is illustrated in Fig. 4. The horizontal axis measures excitation energy in  $^{208}\text{Pb}$  obtained from the kinetic energy of the inelastically scattered  $^{170}$  ions. The vertical axis is the sum gamma-ray energy. The upper solid line in the figure is the line which would be occupied by events for which these two quantities are equal. Purely gamma decays were isolated by placing a gate around this line, as in Fig. 5a (the width of the gate in each direction reflecting instrumental resolution). Another line is drawn 7.4 MeV (the  $n$  binding energy in  $^{208}\text{Pb}$ ) below this line in Fig. 4. Events in which a neutron was emitted should lie below this line in the figure.

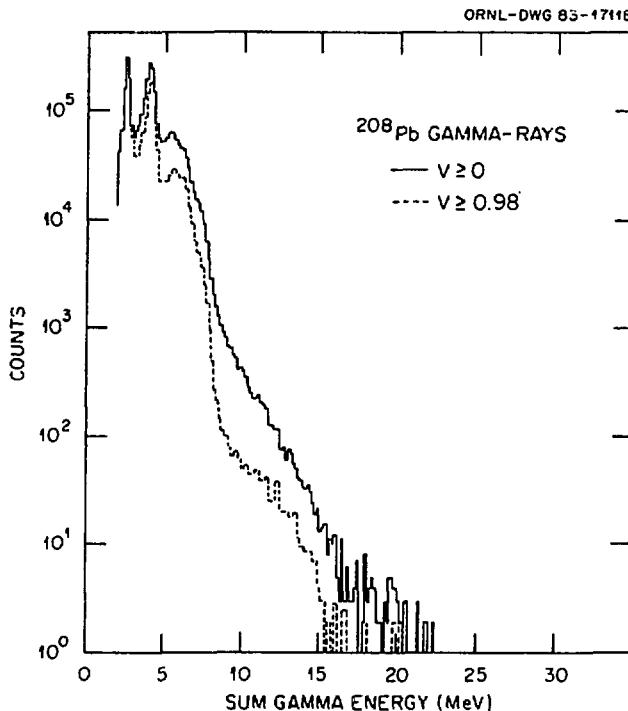


Fig. 6. Gamma-ray spectra from  $^{208}\text{Pb}$  for  $V > 0.98$  (only ground-state gamma rays).

Direct single-step transitions to the ground state were isolated by requiring that the cluster multiplicity be one and the parameter  $V > 0.98$ . (This value was arrived at experimentally using the 15.1-MeV  $^{12}\text{C}$  calibration data.) Figure 5b shows the result of imposing this requirement. Figure 6 shows spectra obtained by projecting the gates in Figs. 5a and 5b onto the sum

gamma-energy axis. Taking the ratio of spectra such as these produces the ground-state branching spectrum shown in Fig. 7. The peaks in this spectrum below the neutron binding energy are at the position of states in  $^{208}\text{Pb}$  known

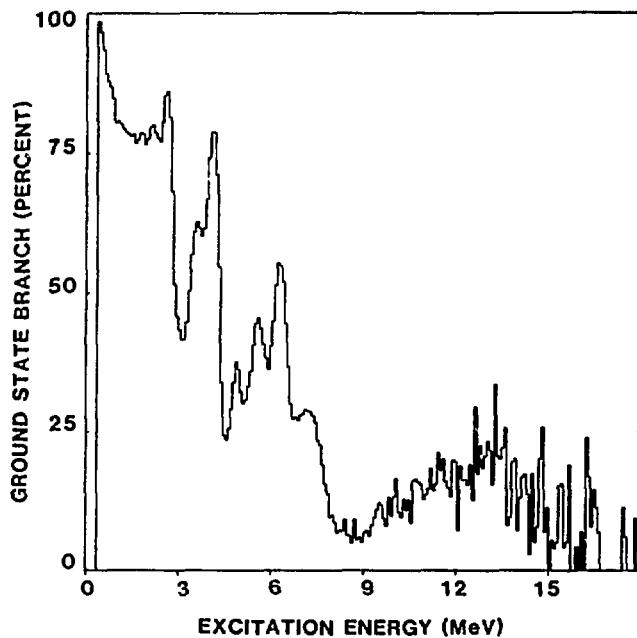


Fig. 7. Ratio of ground-state  $\gamma$ -decay events to total gamma yield as a function of  $^{208}\text{Pb}$  excitation energy.

to have large ground-state branches. Above the neutron binding energy, the ground-state branching falls off rapidly until the vicinity of the giant quadrupole resonance (GQR) is reached. The large peak in the branching spectrum between  $\sim 9$  and  $15$  MeV nicely illustrates the strong localization of electromagnetic strength to the ground state in this region. The bump contains contributions from both the GQR at  $10.6$  MeV and the giant dipole resonance (GDR) at  $13.4$  MeV, which is very weakly excited in the reaction. We have not been able to decompose the ground-state gamma spectrum into quadrupole and dipole components as a function of energy; however, we can establish that the region of  $9.5$  to  $11.5$  MeV consists of  $(70 \pm 10)\%$  quadrupole radiation. Contribution of multipolarities, other than  $L = 1$  and  $2$ , to the ground-state decay is extremely unlikely. The spectrum of ground-state gamma rays was fit using the resonance parameters in Table I. By dividing the ground-state gamma-ray yield

by the singles yield of scattered particles populating the GQR, obtained from a fit to the  $^{170}$  singles spectrum, we obtain

$$\frac{\Gamma_{\gamma 0}}{\Gamma_T} = (3.27 \pm 0.45) \times 10^{-4} \quad (^{208}\text{Pb}, \text{GQR}) .$$

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.

TABLE I. Properties of states above 8 MeV in  $^{208}\text{Pb}$  observed in  $^{208}\text{Pb}(p, p')$ , from Ref. 22. The last two columns refer to the present  $^{208}(^{170}, ^{170}')$  experiment. Expected  $\sigma$  is the cross section expected for  $^{170}$  scattering based on the proton results. Observed  $\sigma$  is the cross section which we observe. Uncertainties of about 15% apply to both the observed and expected cross sections.

Excitation energy (MeV)	L	$\Gamma$ (MeV)	EWSR fraction (%)	For $(^{170}, ^{170}')$	
				Expected $\sigma$ (mb/sr)	Observed $\sigma$ (mb/sr)
8.11	4	0.4	3	9	13
8.35	3	0.4	4	5	
8.86	2	0.4	7	8	6
9.34	2	0.4	5	5	13
10.6	2	2	70	50	60
12.0	4	2.4	10	17	18
13.6	1	4.0	100	~4	20
13.9	0	2.9	100	10	

A similar analysis can be applied to our  $^{90}\text{Zr}$  data [ $E^*(\text{GQR}) = 14$  MeV,  $\Gamma = 3.4$  MeV]. We find

$$\frac{\Gamma_{\gamma 0}}{\Gamma_T} = (6 \pm 3) \times 10^{-5} \quad (^{90}\text{Zr}, \text{GQR}) .$$

The Zr result suffers from very poor statistics. This will be much improved when the analysis of a new experiment on Zr is completed. We estimate that we have increased the amount of data available by a factor of 20-50.

These 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  $\Gamma^+$ , which we identify with the experimentally observed resonance widths  $\Gamma_{\text{exp}}$  (20 MeV in  $^{208}\text{Pb}$  and 3.4 MeV in  $^{90}\text{Zr}$ ). The ground-state gamma widths for a state exhausting 100% of the isoscalar  $L = 2$  EWSR is<sup>1,14-16</sup>

$$\Gamma_{\gamma 0}(\text{EWSR}) = 8.07 \times 10^{-7} \left[ \frac{5}{E_{\gamma 0}} B(E2+)_{\text{EWSR}} \right] \text{ MeV} ;$$

$$B(E2+)_{\text{EWSR}} = \frac{49.88}{A} \frac{Z^2 R^2}{E_{\text{GQR}}} e^2 f_{\text{im}}^4 .$$

Using these expressions we find for the direct ground-state branch

$$\left[ \frac{\Gamma_{\gamma 0}(\text{D})}{\Gamma^+} \right]_{100\% \text{ EWSR}} = 8.62 \times 10^{-5} \quad (^{208}\text{Pb}) ;$$

$$\left[ \frac{\Gamma_{\gamma 0}(\text{D})}{\Gamma^+} \right]_{100\% \text{ EWSR}} = 4.6 \times 10^{-5} \quad (^{90}\text{Zr}) .$$

Taken at face value, this implies the  $\Gamma_{\gamma 0}$  strength in  $^{208}\text{Pb}$  corresponds to 379% of the EWSR and that in  $^{90}\text{Zr}$  to  $\sim 130\%$ ! Apparently, we should look either for some process associated with the reaction mechanism which might enhance the ground-state decay, or some process other than the direct process which might contribute to it. The simplest explanation is decay of the compound states into which the GQR is damped. We can estimate this effect:

$$\frac{\Gamma_{\gamma 0}}{\Gamma} (\text{CN}) \sim \frac{\langle \Gamma_{\gamma 0} \rangle_{2+}}{\langle \Gamma_n \rangle_{2+}} \Big|_{E_{\text{GQR}}}$$

where  $\langle \Gamma_{\gamma 0} \rangle$  is the average ground-state branch of the individual compound states and  $\langle \Gamma_n \rangle$  is the corresponding average neutron width.<sup>17</sup>

$$\langle \Gamma_{\gamma 0}(E_{\gamma}) \rangle = \frac{E_{\gamma 0}^5 f_{E2}(E_{\gamma 0})}{\rho(J = 2, E_{\text{GQR}})}$$

where  $f_{E2}(E_{\gamma})$  is the E2 gamma strength function and  $\rho$  is the density of states.

Similar expressions can be given for the average neutron width,<sup>18</sup>

$$\langle \Gamma_n \rangle = \frac{\sum_f \left( \frac{(2\ell + 1)}{g} S_{\ell} v_{\ell} \sqrt{E_n} \times 10^3 \text{ MeV} \right)}{\rho(J = 2, E_{\text{GQR}})} ,$$

where the sum is over final states (spin  $I$ ) in the  $A - 1$  nucleus,  $v_{\ell}$  is the

penetrability factor,<sup>18,19</sup>  $E_n$  is the neutron kinetic energy (MeV), and  $S_\lambda$  is the neutron strength function<sup>18-20</sup> for orbital angular momentum  $\lambda$ ,

$$\left\langle \frac{\Gamma_{\gamma 0}}{\Gamma} \right\rangle (\text{CN}) \approx 1.3 \times 10^{-4} \quad ({}^{208}\text{Pb}) ;$$

$$\left\langle \frac{\Gamma_{\gamma 0}}{\Gamma} \right\rangle (\text{CN}) \approx 7 \times 10^{-6} \quad ({}^{90}\text{Zr}) .$$

Since both the CN and direct calculations assumed 100% of EWSR, our data, if we allow ~50% uncertainty in the CN estimate, implies

$${}^{208}\text{Pb E2 } \gamma 0 \text{ strength } \sim (145 \pm 50)\% \text{ EWSR,}$$

and

$${}^{90}\text{Zr E2 } \gamma 0 \text{ strength } \sim (113 \pm 60)\% \text{ EWSR.}$$

Note that in earlier reports,<sup>10,12</sup> due to an error in our expression for the direct  $\Gamma_{\gamma 0}$  sum rule of a factor of  $(A/Z)^2$ , we quoted values of ~85% of the EWSR for the EWSR for the direct component alone in  ${}^{208}\text{Pb}$ .

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 8 shows the relative strength of gamma-ray branches to a number of low-lying states. Figure 8a is for ground-state transitions, and Figs. 8b and 8c are for direct decays to the  $3^-$ , 2.61 and  $2^+$ , 4.08 states, respectively. Multistep cascades are ruled out in these cases by requiring that the cluster multiplicity discussed earlier be precisely two. Figure 8d is the relative strengths for decays populating the 4.97-MeV,  $3^-$  state. The yield distributions in Fig. 8, 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. Another interesting feature is the strong yield of decays to the 2.61-MeV state at ~5.2 MeV of excitation energy. This might be an indication of the long sought two-phonon octupole vibrational states. 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. This is in marked contrast to the absence of decays to the lower lying collective  $3^-$  state. A very similar, though weaker, strength distribution to that shown in Fig. 8d 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 II.

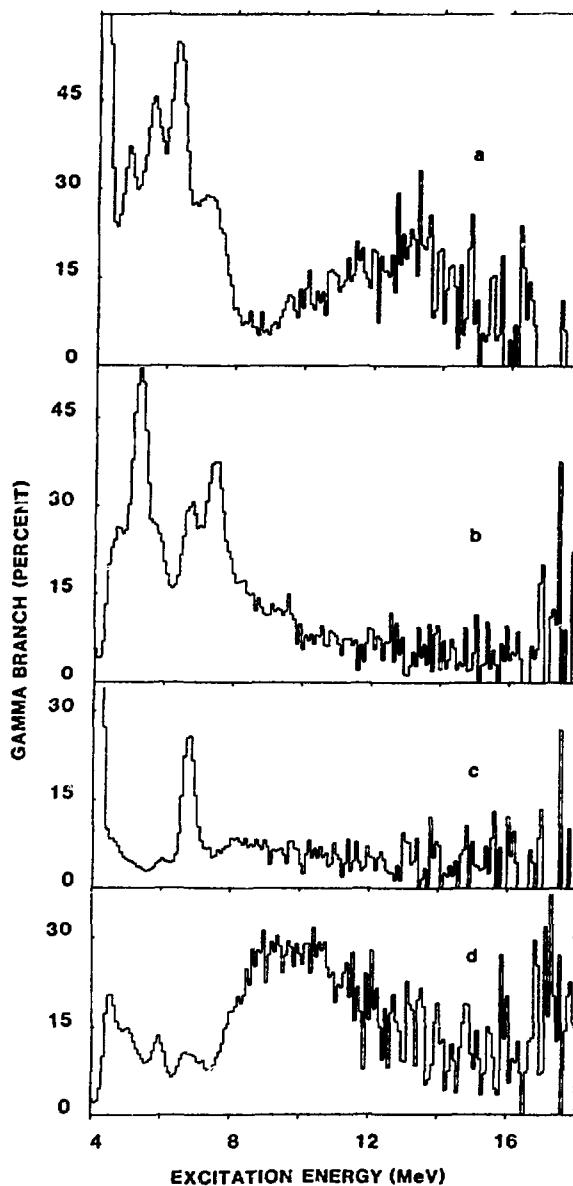


Fig. 8. Relative gamma-decay strengths for transitions to a number of low-lying levels in  $^{207}\text{Pb}$ : (a) for ground-state decays; (b) for transitions to the 2.61-MeV,  $3^-$  state; (c) the 4.08-MeV,  $2^+$  state; (d) the 4.97-MeV,  $3^-$  state.

It should be noted that the absence of decay to the 2.6-MeV, 3<sup>-</sup> state, which appears remarkable at first sight, agrees with a recent calculation by Bortignon, Broglia, and Bertsch.<sup>21</sup>

TABLE II. Relative gamma branching to low-lying states in  $^{208}\text{Pb}$  from an excitation energy region 9.5-11.5 MeV [ $E(\text{GQR}) \pm \Gamma(\text{GQR})/2$ ]. The 5-7 MeV, 1<sup>-</sup> states refers to a group of 1<sup>-</sup> states in that region known from  $(\gamma, \gamma')$  experiments.

Energy	$J^\pi$	Relative gamma branch (%)
0	0 <sup>+</sup>	$20 \pm 2$
2.61	3 <sup>-</sup>	$0.8 \pm 0.8$
3.97	5 <sup>-</sup>	$\sim 5-10$
4.08	2 <sup>+</sup>	$0.3^{+1.0}_{-0.3}$
4.97	3 <sup>-</sup>	$36 \pm 5$
5-7	1 <sup>-</sup>	$23 \pm 9$

#### 4. DISCUSSION

The strength of the ground-state E2 gamma branch from the GQR of both  $^{208}\text{Pb}$  and  $^{90}\text{Zr}$  seems to be accounted for reasonably well if effects of compound decay are included. Quantitative conclusions are hampered by the limitations of our crude estimate of the compound-state  $\langle \Gamma_n \rangle$ , but this estimate seems at least to offer an explanation of the much greater importance of compound decays in  $^{208}\text{Pb}$  than in  $^{90}\text{Zr}$ . However, some inconsistencies remain. The absence of a direct E1 branch from the GQR to the 2.61-MeV, 3<sup>-</sup> state in  $^{208}\text{Pb}$  is well accounted for by the calculations of Ref. 21; however, we must also consider the compound decay, and in a strongly statistical decay this branch should be about 1.4 times larger than the E2 ground-state branch. The compound decay to this state is apparently also greatly suppressed.

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