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CRYSTAL BALL STUDIES OF GIANT RESONANCE GAMMA DECAY

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ABSTRACT

We have carried out coincidence experiments to investigate the photon and neutron emission from the giant resonance region in ^{208}Pb and ^{90}Zr using the ORNL Spin Spectrometer, a 72-segment NaI detector system. States in ^{208}Pb and ^{90}Zr were excited by inelastic scattering of 380-MeV ^{17}O . 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. Especially interesting observations include the absence of a significant branch from the giant quadrupole resonance to the 3^- state at 2.6 MeV, a strong branch from this resonance to a 3^- state at 4.9 MeV, and the dominance of decays to various 1^- states at 5-7 MeV from the region around 14 MeV of excitation (EO resonance). Comparable but less complete data were also obtained on ^{90}Zr .

INTRODUCTION

A large amount of systematic data on the average properties of isoscalar giant electric multipole resonances has been obtained over the last decade, primarily from inelastic scattering experiments using a variety of probes.¹⁻³ Many of the questions now being asked about the giant resonances (GR) will require more detailed experimental data, which can only be obtained from coincidence (i.e., decay) experiments.^{1,4,5} Such experiments offer the possibility of probing details of the structure of the GR not addressed by existing systematics.

The GR are described microscopically as a coherent superposition of one-particle one-hole excitations relative to the ground state.^{1,6,7} 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

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inelastic scattering data with reaction models. Unfortunately, the electric GR lie 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 Γ^\dagger 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.^{8,9} The resonances in a heavy nucleus typically lie in a region of very high level density. The simple lp-lh 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.^{5,8,9} From this point of view, the GR is excited as a primary doorway state in the inelastic scattering process. This state decays directly via Γ^\dagger 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 Γ^\ddagger , the spreading width, is associated with this decay into the continuum. The observed width of the GR state is thus $\Gamma_T = \Gamma^\dagger + \Gamma^\ddagger$ (we can safely neglect Γ_γ). For heavy nuclei, $\Gamma_T \sim \Gamma^\ddagger$ (Refs. 8,9). A microscopic understanding of this damping process is the focus of current theoretical work on giant resonances.⁵ 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 lp-lh 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.

EXPERIMENT

We have recently carried out an experiment at the HHIRF at ORNL, designed to study both the γ decay and particle decay of the giant resonance region (~ 9 to 20 MeV of excitation) in ^{208}Pb .

The resonance region of ^{208}Pb was excited by inelastic scattering of 381-MeV ^{17}O from ^{208}Pb . Oxygen-17 was chosen as a projectile because the low neutron binding energy (4.1 MeV) minimizes interference from gamma rays from projectile excitation. The inelastically scattered ^{17}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 ~ 500 μm and ~ 1000 μm , respectively. The energy resolution was ~ 800 keV, and the mass resolution was sufficient to separate ^{17}O from adjacent oxygen isotopes. A singles spectrum of inelastically scattered ^{17}O is shown

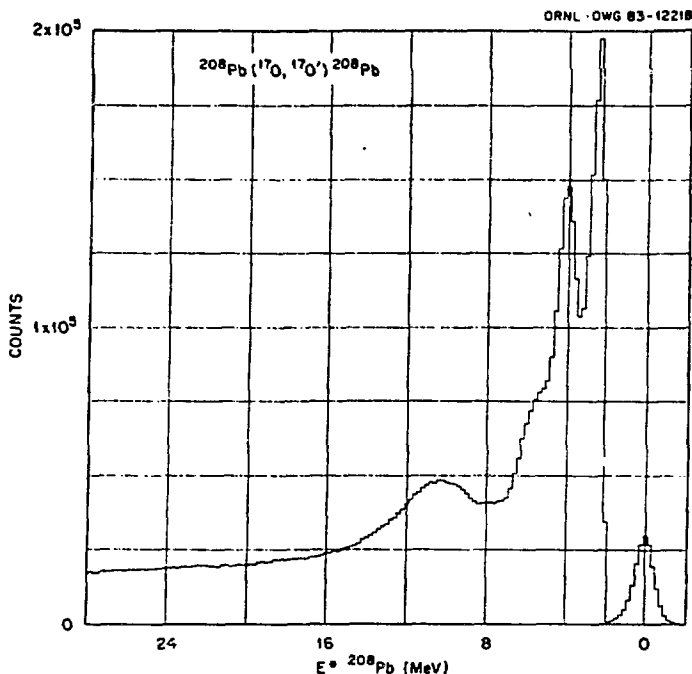


Fig. 1. Spectrum of 380-MeV ^{17}O scattered by ^{208}Pb . The elastic peak has been prescaled by a factor 512. The large bump between 9 and 15 MeV results from excitation of giant resonances.

in Fig. 1. Strong excitation of the giant resonance region, centered at ~ 11 MeV, is evident. Decay products were detected in 70 elements of the ORNL Spin Spectrometer. The spectrometer, which has been described in detail elsewhere,¹⁰ 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° and 180° 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 $^{12}\text{C}(p,p')^{12}\text{C}$ 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.

Figure 3 shows some of the levels of ^{207}Pb and ^{208}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}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.

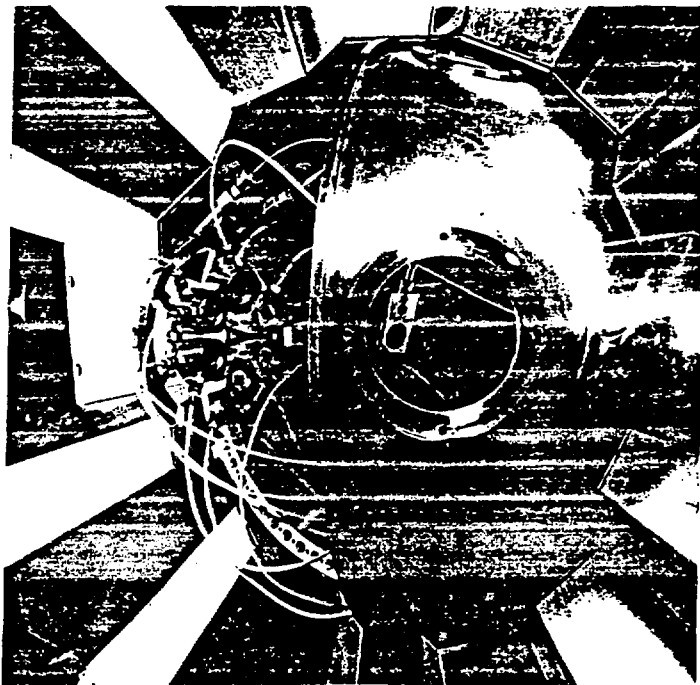


Fig. 2. Six-telescope array in the Spin Spectrometer. The exit hemisphere and one part of the spherical reaction chamber were removed for the photograph. The beam enters from the right, and the target is at the center.

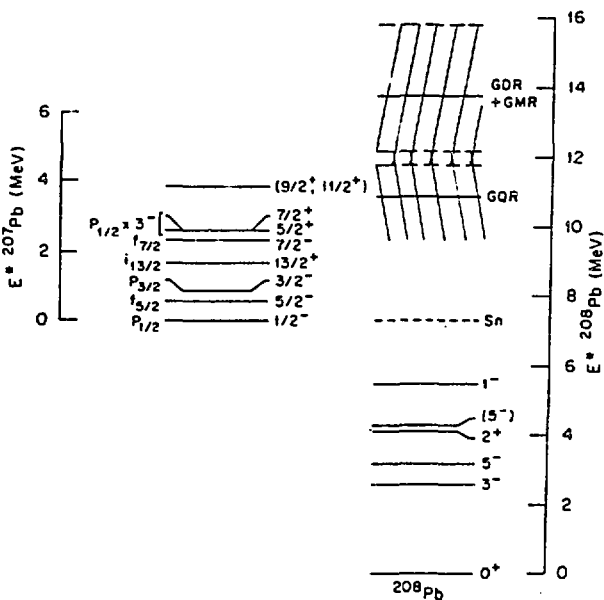


Fig. 3. Selected levels in ^{208}Pb and ^{207}Pb . The configuration labels on the ^{207}Pb states refer to neutron hole states.

ANALYSIS AND DISCUSSION

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.

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 ^{17}O 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 ~ 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 $V = |\sum \vec{h}_i|/H$ 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}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.

The separation of neutron decays from purely gamma decays is illustrated in Fig. 4. The horizontal axis measures excitation energy in ^{208}Pb obtained from the kinetic energy of the inelastically scattered ^{17}O 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}Pb) below this line in Fig. 4. Events in which a neutron was emitted should lie below this line in the figure.

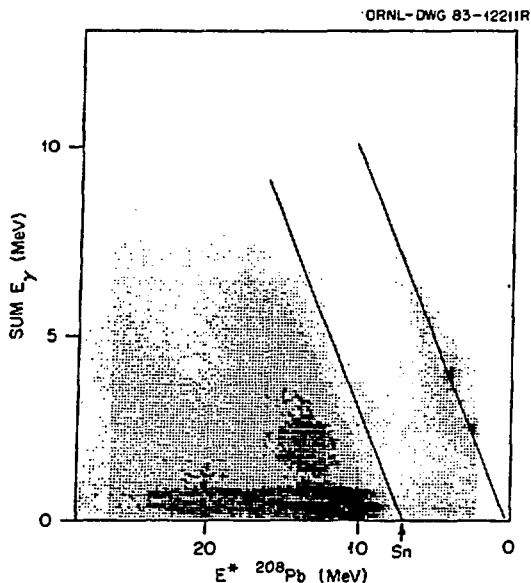


Fig. 4. Two-parameter density plot of events from $^{208}\text{Pb}(^{17}\text{O}, ^{17}\text{O}')$ in which one or more NaI detectors registered a delayed pulse. These should be due to neutron decays. The abscissa is derived from the energy lost by the inelastic ^{17}O . The ordinate is the sum of the γ -ray energies seen in the NaI detectors and is equal to the excitation energy in the residual nucleus.

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}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}Pb known 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 ~ 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

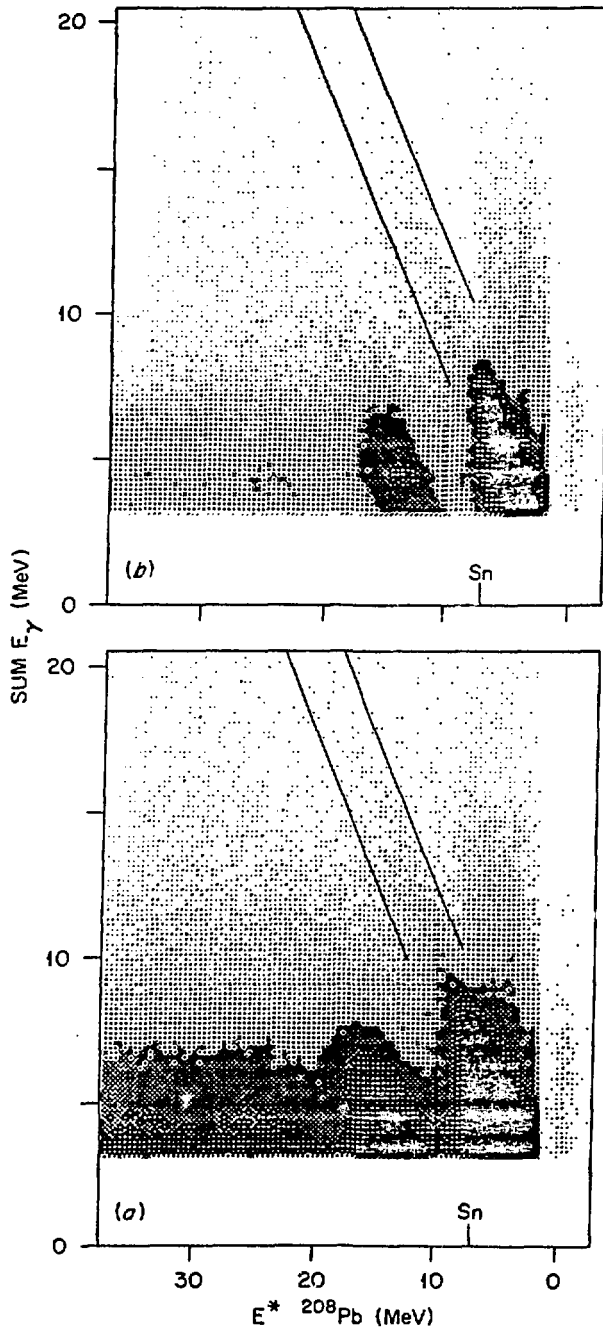


Fig. 5. Two-parameter density plot of events from $^{208}\text{Pb}(^{17}\text{O},^{17}\text{O}')$ in which no NaI detector registered a delayed pulse. The axes are the same as for Fig. 4. Events falling between the pairs of lines are due to γ -decay events: (a) all events; (b) events satisfying the additional requirement $V > 0.95$ to select ground-state transitions.

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

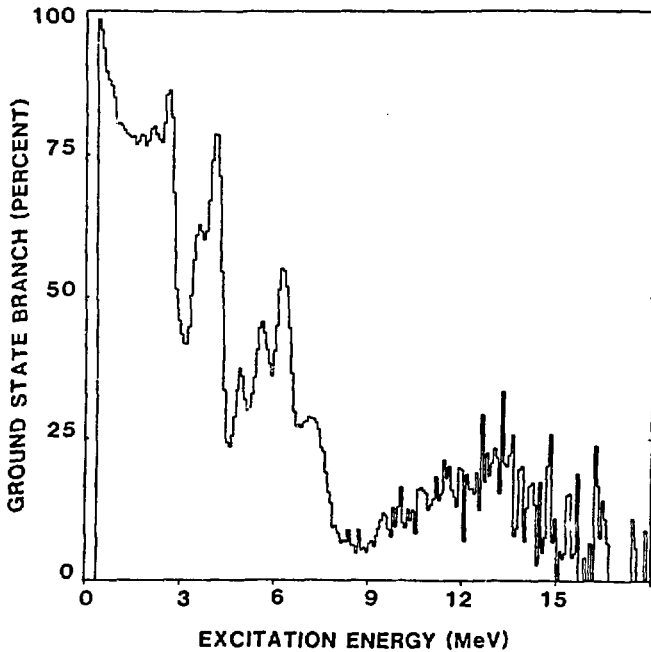
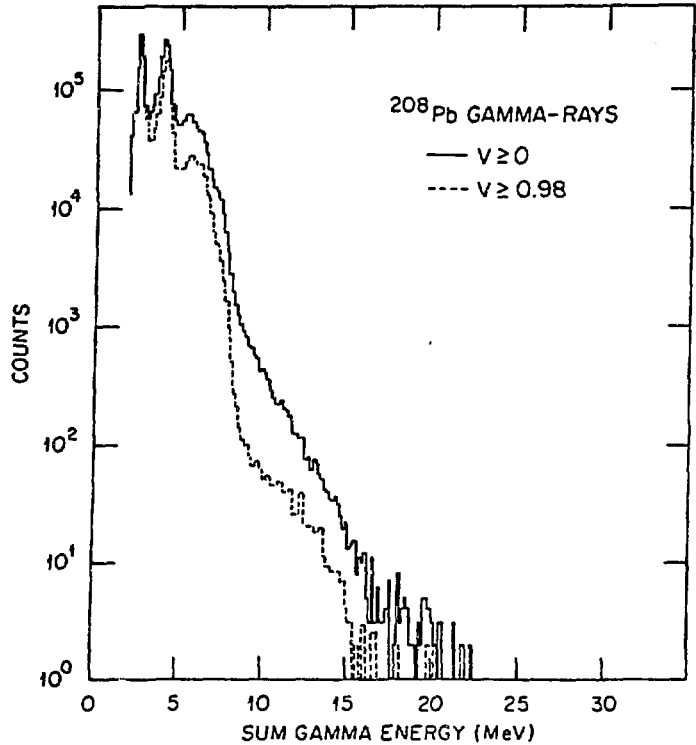


Fig. 7. Ratio of ground-state γ -decay events to total gamma yield as a function of ^{208}Pb excitation energy.

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 ^{17}O singles spectrum, we obtain

$$\frac{\Gamma_{\gamma 0}}{\Gamma_T} = (3.27 \pm 0.45) \times 10^{-4} .$$

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. This result can be used to obtain an absolute value for $\Gamma_{\gamma 0}$ if we identify the Γ_T with the spreading width of the GQR, which, in turn, is identified with the experimental width of the resonance from Table I.

TABLE I. Properties of states above 8 MeV in ^{208}Pb observed in $^{208}\text{Pb}(p,p')$, from Ref. 14. The last two columns refer to the present $^{208}({}^{17}\text{O}, {}^{17}\text{O}')$ experiment. Expected σ is the cross section expected for ^{17}O scattering based on the proton results. Observed σ is the cross section which we observe. Uncertainties of about 15% apply to both the observed and expected cross sections.

Excitation energy (MeV)	L	Γ (MeV)	EWSR fraction (%)	For (${}^{17}\text{O}, {}^{17}\text{O}'$)	
				Expected σ (mb/sr)	Observed σ (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	

$$\Gamma_{\gamma 0} = \frac{\Gamma_{\gamma 0}}{\Gamma_T} \times \Gamma_{\text{EXP}} = 654 \pm 91 \text{ eV} \quad (\text{GQR}) .$$

This implies, taking $E_{\gamma 0} = 10.6 \text{ MeV}$,¹¹

$$B(E2+) = (5.81 \pm 0.81) \times 10^3 \text{ e}^2\text{fm}^4 .$$

This should correspond with the energy-weighted sum-rule value,^{12,1}

$$\int EB(E2+) = 49.9 \text{ A}^{5/3} \text{ e}^2\text{fm}^4$$

or

$$B(E2+)_{\text{EWSR}} = 49.9 \text{ A}^{5/3} / 5E_{\gamma 0} = 6.86 \times 10^3 \text{ e}^2\text{fm}^4 .$$

Therefore,

$$\frac{B(E2+)}{B(E2+)_{\text{EWSR}}} = 0.85 \pm 0.12$$

for the GQR.

A significant yield of dipole ground-state gamma transitions is observed above 12 MeV. It is not possible to establish the excitation cross section for the GDR from the spectrum of inelastically scattered ¹⁷⁰ since the GDR is so weakly excited and so broad. Calculations assuming the GDR is exclusively Coulomb excited predict a cross section of ~4 mb. Taking this value and assuming a ground-state decay width exhausting the E1 sum rule, we find the observed yield of dipole transitions to be ~60% of the predicted value, with an uncertainty of ~30%.

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 lp-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

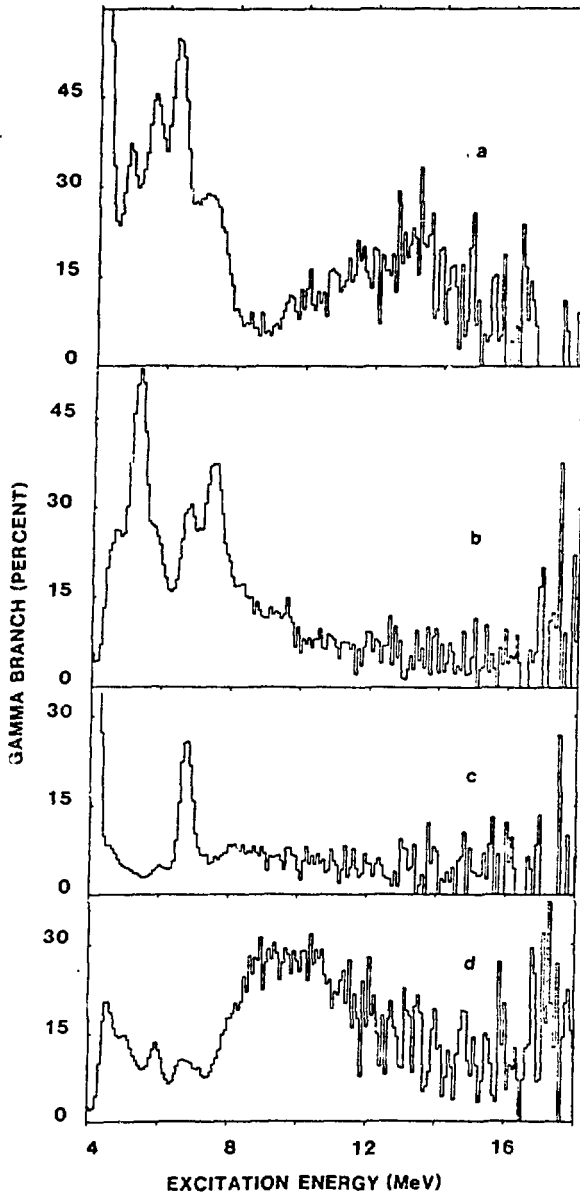


Fig. 8. Relative gamma-decay strengths for transitions to a number of low-lying levels in ^{207}Pb : (a) for ground-state decays; (b) for transitions to the 2.61-MeV, 3^- state; (c) the 4.08-MeV, 2^+ state; (d) the 4.97-MeV, 3^- state.

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. It should be noted that the absence of decay to the 2.6-MeV, 3^- state, which appears remarkable at first sight, agrees with a recent calculation by Bortignon, Broglia, and Bertsch.¹³

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

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

We hope we have been able to give an indication of the richness of detailed data which these experiments have opened up. We have not even mentioned the neutron decay information. We believe that as the results are refined and more and improved data are obtained, we will make a significant contribution to the understanding of the microscopic properties of the giant resonances.

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