Decay of the Isoscalar Giant Resonances in ^{208}Pb

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The decay of the giant-resonance region in ^{208}Pb has been studied in a α'-γ angular correlation experiment via the reaction chain $^{208}\mathrm{Pb}(\alpha,\alpha')^{208}\mathrm{Pb}^{\mathrm{GR}}(n)^{207}\mathrm{Pb}^*(\gamma)^{207}\mathrm{Pb}$. The correlation functions are in agreement with the assumption of predominant $E2$ strength for the resonance around $E_x = 10.9$ MeV, but require considerable strengths of excitation modes higher than $E0$ for the resonance around $E_x = 13.7$ MeV. The coincident α-particle spectra show significant fine structure in the giant-resonance region.

A sensitive method to obtain information about structure and multipolarity of giant resonances (GR) is the study of their decay by angular-correlation measurements. There are two main advantages of angular-correlation experiments: The background can be reduced drastically and additional information can be obtained from the angular correlation functions. Especially for a giant monopole resonance the angular correlation function must be isotropic in all decay channels.

We studied the decay of the isoscalar resonances in ^{208}Pb via α'-γ correlations of the reaction $^{208}\mathrm{Pb}(\alpha,\alpha')^{208}\mathrm{Pb}^{\mathrm{GR}}(n)^{207}\mathrm{Pb}^*(\gamma)^{207}\mathrm{Pb}$. In ^{208}Pb in hadron scattering[1,2] as well as in electron scattering[3] two overlapping resonances with widths of about 2–3 MeV were found around 10.9 MeV (GR1) and 13.7 MeV (GR2). From the analysis of these experiments the lower resonance has been assigned to be the giant quadrupole resonance, whereas for the upper resonance from hadron scattering evidence has been found for a "breathing mode" exhausting $\gtrsim 100\%$ of the $E0$ energy-weighted sum rule.[1,2]

It was the purpose of our experiment to get more detailed information about the excitation region of these resonances. Therefore we measured α'-γ angular correlations at two fixed α-scattering angles of 16° and 24° (corresponding to maxima in the α-angular distribution of the two resonances) for eight positions of the γ detectors in the reaction plane. The inelastically scattered α particles were detected by four Si(Li) detectors arranged symmetrically with respect to the beam axis. The γ quanta leaving the active target volume were detected by two Ge(Li) detectors. Quantities measured were (1) the energy of the scattered α particles, (2) the energy of the γ quanta, and (3) the time-of-flight difference between α' and γ. The peak of true coincidences in the time-of-flight spectrum had a width (full width at half maximum) of 10 ns. Particle identification was not necessary because the excitation region of interest is free of reaction products other than α particles.

In the upper part of Fig. 1 a γ spectrum coincident with the scattered α particles from the GR region is displayed. Compared with the singles γ spectrum shown in the lower part, only the γ quanta from two transitions are significantly enhanced. They belong to the n decay into the first ($J=\frac{5}{2}^-$) and the second ($J=\frac{3}{2}^-$) excited state of ^{207}Pb, respectively, which subsequently decay

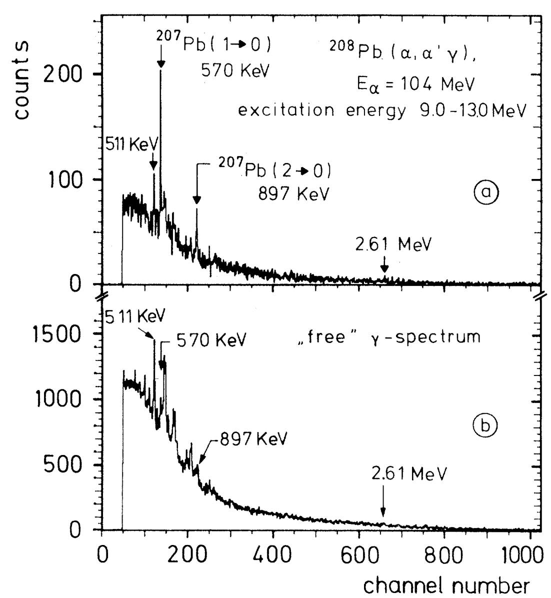

FIG. 1. (a) γ spectrum coincident with α particles scattered from the giant-resonance region; (b) γ spectrum without coincidence requirement.

into the ground state. Considering the fact that γ quanta from other decay channels were not found it seems very unlikely that only ground-state transitions occur in these decay channels. Therefore we conclude that the GR's of interest decay predominantly through neutron emission into the lowest states of ^{207}Pb, where the decays into the ground state and the third excited state ($\tau \sim 1$ s) can in principle not be observed in our experiment.

In Fig. 2 particle spectra coincident with the photopeaks of the γ quanta of the two observed transitions in ^{207}Pb are shown. The spectra of Figs. 2(a) and 2(b) correspond to the n decay into the first and the second excited state, respectively. In Fig. 2(c) the sum of both spectra is shown. Random coincidences which are accumulated simultaneously in our experiment are subtracted. The spectra are integrated over all γ angles. In order to get the values for the α-γ angular correlation functions (cf. Fig. 3), which were extracted from the coincident γ spectra after subtraction of random coincidences and the Compton coincidence background, GR1 was limited between 9.0 and 12.3 MeV and GR2 between 12.5 and 15.1 MeV, respectively. There are striking differences between these coincident spectra and the corresponding singles spectrum. In contrast to the singles spectra the GR bump appears practically free of background. It is framed by deep minima showing that most of the large background in the singles spectra is due to processes which have nothing to do with the GR phenomenon. The events on the left- and right-hand side of the GR region are due to the fact that in the γ spectrum the photopeaks of interest sit on a background composed of Compton edges which correspond to γ decays of states other than the GR's of interest. The events on the right-hand side (lower excitation energies) are associated with the γ decay of low-lying states in ^{208}Pb. The events on the left-hand side (higher excitation energies) mainly belong to ^{3}He-γ coincidences from the reaction ^{208}Pd$(\alpha, {}^3\mathrm{He})^{209}Pb^*(\gamma)$-^{209}Pb. The fine structure observed in the GR region proved to be significant. It occurs in all coincident spectra as a distinctly correlated pattern with "peaks" at about 8.3, 8.8, 9.4–9.7, 10.25, 10.7, 11.25, 12.0–12.3, 12.7, and 13.7–14.2 MeV. In the reaction ^{208}Pb(γ, n) fine-structure peaks at about the same energies have been observed.[4] Fine structure in the GR region of ^{208}Pb was also seen in electron scattering[3] and attributed to isovector modes. These modes, however, cannot be excited by α scattering. Finally, it should be mentioned that in comparison with the singles spectra in the coincident spectra the region of GR2 is enhanced relative to the region of GR1, probably a result of the larger width of the decay of GR1 into the ground-state of ^{207}Pb.

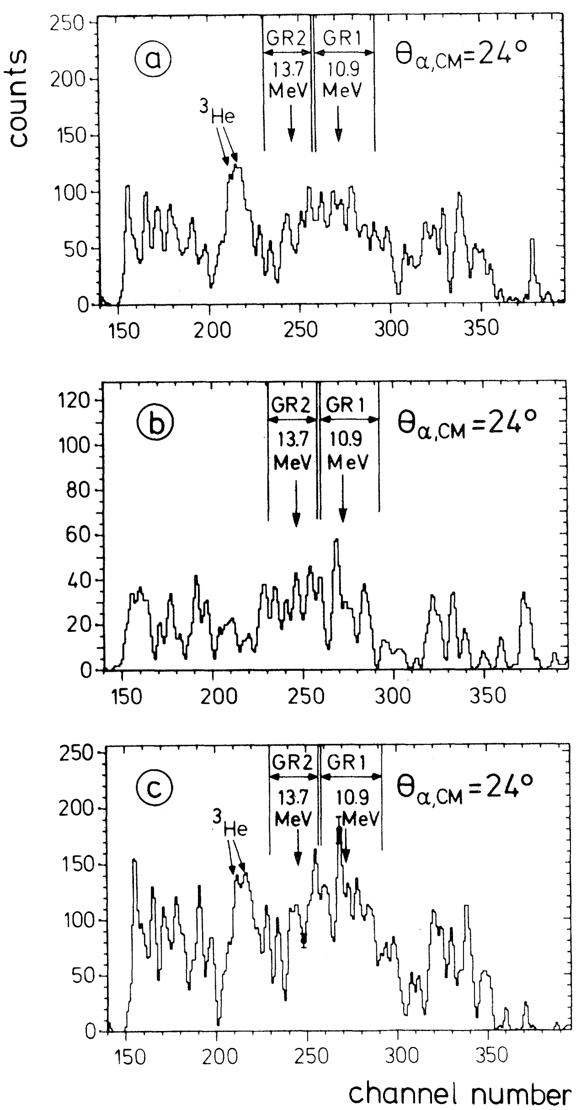

FIG. 2. Particle spectra coincident with the γ quanta corresponding to the n decay (a) into the first excited, (b) into the second excited state of ^{207}Pb, and (c) sum of both.

In the following we discuss what additional information about the GR region can be obtained from the angular correlation functions. In Fig. 3(a) the experimental angular correlation functions corresponding to the α-scattering angle of

16° are shown for the decay of GR1 into the first (upper diagram) and second (lower diagram) excited state of ^{207}Pb, respectively. The dashed lines represent best fits according to the most general form of the in-plane correlation function for the spins of $\frac{5}{2}$ and $\frac{3}{2}$ of the corresponding states in ^{207}Pb under the assumption of an $E2$ mode for GR1. It can be written as (cf. Rybicki, Tamura, and Satchler[5])

$$W(\varphi_\gamma) = A + B\sin^2(\varphi_\gamma - \varphi_1) + C\sin^2 2(\varphi_\gamma - \varphi_2) \qquad (1a)$$

and

$$W(\varphi_\gamma) = A + B\sin^2(\varphi_\gamma - \varphi_1), \qquad (1b)$$

respectively. Obviously the experimental correlation functions are in agreement with the quadrupole assignment to this resonance. We further calculated the angular correlation functions using different microscopic 1p-1h wave functions for the strongest $E2$ states in the giant-resonance region obtained from random-phase approximation calculations. For the calculation of the parameters in Eq. (1), the statistical tensor of the GR state populated by the (α, α') reaction, the statistical tensor of the n decay into the excited state of ^{207}Pb, and the properties of the subsequent γ decay, which are well known in our case, are needed. We calculated the statistical tensors describing the (α, α') reaction in the framework of the distorted-wave Born approximation using the optical potential of Gils *et al.*[6] The statistical tensors of the unobserved intermediate n emission depend strongly on the partial widths corresponding to the different possible angular momenta of the n decay. These widths were calculated as the products of the n transmission coefficients for the different angular momenta and the corresponding overlap of the 1p-1h wave functions of the GR with the n-hole states in ^{207}Pb to which the GR decays. In these calculations we used the wave functions of Rinker and Speth.[7] In Fig. 3(a) one can see a good agreement with this calculation (calc. 1) for the decay of GR1 into the second excited state (lower diagram), but it cannot describe the data of the decay to the first excited state. The result obtained for the α-scattering

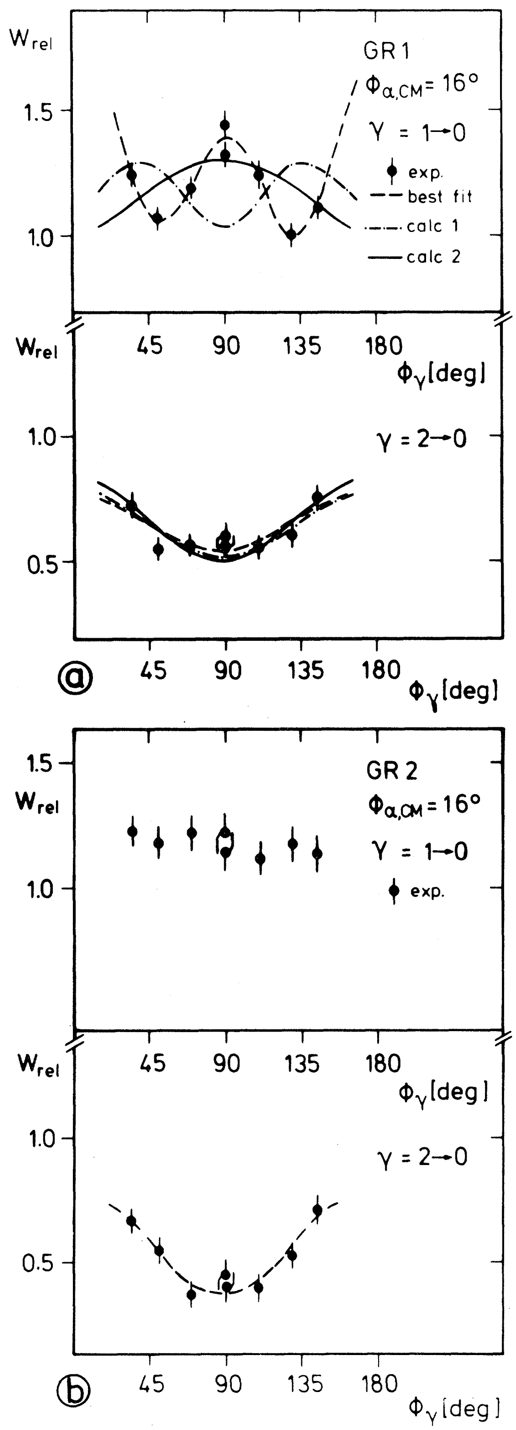

FIG. 3. Experimental angular correlation functions of the decay of (a) GR1 and (b) GR2 into the first (upper diagram) and second (lower diagram) excited state of ^{207}Pb, respectively. The vertical lines on the data points represent experimental uncertainties. The dashed curves are best fits corresponding to the assumption of an $E2$ mode of GR1 and an excitation mode higher than $E0$ of GR2, respectively. The full curves represent statistical calculations, the dashed-dotted curves calculations including 1p-1h wave functions.

angle of 24° is quite similar. To demonstrate the sensitivity of the angular correlation functions we calculated "statistical" decay widths from the transmission coefficients alone (calc. 2). The drastic difference between both calculations is obvious.[8] Also, calc. 2 can only reproduce the data of the decay into the second excited state. It should be mentioned, however, that modifying single components of the wave functions of calc. 1, one can reproduce the correlation data of the first excited state, too. This procedure, however, is ambiguous.

In Fig. 3(b) the experimental correlation functions of GR2 are shown for the α-scattering angle of 16°. The correlation function of the decay into the first excited state of ^{207}Pb (upper diagram) is nearly isotropic in agreement with the assumption that GR2 contains predominantly $E0$ strength. The correlation function of the decay into the second excited state (lower diagram), however, shows a significant anisotropic pattern in contradiction to the assumption of pure $E0$ strength. Again the result for the α-scattering angle of 24° is quite similar. Consequently there must be considerable strength of higher multipolarities. The dashed curve represents a best fit, which principally holds for all multipolarities higher than zero, because in this case the expansion of the angular-correlation function is limited by the spin $\frac{3}{2}$ of the residual nucleus.[5] From the fact that anisotropy appears at least in one decay channel and from the degree of this anisotropy compared to the correlation function of GR1 we roughly estimate a strength of higher multipolarities of about 30–40% in the region of GR2. Recently from the analysis of an electron-scattering experiment the question arose whether the argument that α particles will not excite the $\Delta T = 1$ giant dipole resonance should not be questioned.[9] The assumption of an excitation of the giant dipole resonance, which is concentrated in the region of GR2, is not in contradiction to the pattern of the anisotropic correlation function of GR2. Taking into account experimental data for the corresponding α angular distribution of GR2, however, suggests that this strength predominantly belongs to even multipolarities—probably to $E2$ or $E4$. This would be in agreement with the result of a (γ, n) experiment,[10] in which evidence for $E2$ strength in ^{208}Pb was obtained in the region of energy of GR2.

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