Neutron Decay of the Giant Quadrupole Resonance Region in ^{208}Pb

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The n decay of the giant resonance region between 8.5 and 12.5 MeV in ^{208}Pb has been studied in an $(\alpha,\alpha'n)$ coincidence experiment at $E_x = 104$ MeV. The energy resolution was sufficient to observe the decay into the different states of ^{207}Pb separately. The strong population of the $\frac{13}{2}^+$ state shows that large contributions of the total strength excited in the giant quadrupole resonance region have multipolarities $\geqslant 4$. The α spectra coincident with the decay neutrons show fine structures in the giant quadrupole resonance region of ^{208}Pb.

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In heavy nuclei the decay of the giant resonances (GR's) takes place predominantly by emission of neutrons because of the high Coulomb barriers for the emission of charged particles. Therefore the investigation of the decay of the GR's becomes very difficult for those nuclei, and up to now only few experimental data have been available.

In a previous experiment[1] performed on ^{208}Pb, we demonstrated that it is possible to get important information about the neutron decay channel by measuring the γ quanta from the deexcitation of the residual nucleus ^{207}Pb in coincidence with the scattered particles instead of the neutrons themselves. To obtain complete information, however, the direct measurement of the neutrons in coincidence with the scattered particles seems to be indispensable. Compared to the α'-γ experiment the obvious advantage of the α'-n experiment is that it is possible to observe the decay into all states populated in the residual nucleus (especially into the ground state and the isomeric $\frac{13}{2}^+$ state at 1.63 MeV in ^{207}Pb), and that there are no side-feeding problems. The energy resolution, however, is limited not only by the energy resolution of the measured neutrons but also by the resolution of the scattered α particles, and there is an experimental threshold which limits the lowest n energy observable. Although the information which can be obtained from both types of experiments is overlapping to some extent, important aspects exist where they are complementary.

In this Letter we mainly report the results of an $(\alpha, \alpha'n)$ coincidence experiment on ^{208}Pb about the decay of the giant quadrupole resonance (GQR) which is located around 10.9 MeV. The experiment was performed on the energy-analyzed 104-MeV α beam of the Karlsruhe cyclotron. The aim of this experiment was to study the decay of the GR region between 8.5 and 12.5 MeV into the individual states of ^{207}Pb for small energy intervals corresponding to the fine structure observed in the α'-γ experiment.[1] In order to avoid model-dependent assumptions a sufficient average over the angular correlation function is necessary. Therefore we measured absolute angular correlations at eight special positions of the neutron detectors out of the reaction plane. This gives an exact average of the angular correlation function for multipolarities up to two and a still satisfactory average for higher multipolarities. To separate the GR strengths from the physical background four Si(Li) α detectors arranged symmetrically with respect to the beam axis were placed at maxima ($\varphi_{\alpha'\,\mathrm{lab}} = 23.5°$) and minima ($\varphi_{\alpha'\,\mathrm{lab}} = 17°$) of the α angular distribution of the GQR. The energy resolution for the α particles was about 220 keV. To obtain a sufficient energy resolution of the decay neutrons we applied a time-of-flight technique using two plastic detectors with an area of 25×25 cm^2 at a flight distance of about 1.50 m. The n detectors were shielded against background radiation by lead, cadmium, and paraffin enriched with boron. The time resolution against the high frequency of the cyclotron was about 1.4 nsec. This corresponds to an energy resolution between about 40 and 300 keV for the neutrons of interest. The energy threshold of the n detectors was about 1 MeV; the lowest energy evaluated was about 1.3 MeV. Above this energy the efficiency of the n detectors is nearly constant

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over the interesting energy region of the neutrons. In addition to the neutrons we measured the γ quanta in coincidence with the scattered α particles at eight equivalent positions by two Ge(Li) detectors, in a way similar to that in Ref. 1. The setup of the electronics was based on fast-slow-circuit technique. The interesting events were stored in list mode on magnetic tapes. The information recorded was the energy of the scattered α particles, the time of flight of the neutrons, the energy of the γ quanta, and the time-of-flight differences between α particles and neutrons and between α particles and γ quanta.

In order to obtain the spectra of the decay neutrons from the GR region into the various states of ^{207}Pb kinematical plots were made event by event. Two representative spectra[2] summed over two positions of the n detectors are shown in Fig. 1. They correspond to a minimum (17°) and a maximum (23.5°) of the α angular distribution of the GQR, respectively. The indicated energies of the low-lying levels in ^{207}Pb agree with the peaks of the experimental spectra. By folding the spectra with Gaussians of half widths known from the experimental energy resolution as shown by the dotted curves in Fig. 1, the population of the individual states in ^{207}Pb from the decay of the region of the GQR in ^{208}Pb can be gathered. The most surprising result which is conspicuous in all spectra is the strong appearance of the isomeric $\frac{13}{2}^+$ state.

The experimental results can be compared with the predictions of a simple statistical-model calculation where the decay probability of a certain multipolarity is given by the sum over the contributing transmission coefficients. In Fig. 2 relative branching ratios are calculated as a function of energy for the five lowest states in ^{207}Pb. The higher states, which can be populated for $E_x(^{208}\mathrm{Pb}) \gtrsim 10$ MeV, contribute with less than about 30% to the strength of the whole energy region between 8.5 and 12.5 MeV. The relative intensities for the population of the lowest three states in ^{207}Pb obtained from this calculation under the assumption of only $E2$ strength in the GR region of ^{208}Pb agree qualitatively with the experimental data. Obviously the $\frac{13}{2}^+$ state, however, is practically not populated from the decay of $E2$ strength in the interesting energy region. The population from $E4$ strength is still relatively small whereas it is strong from $E6$ strength; the $\frac{1}{2}^-$ state behaves vice versa. Therefore we claim that the states with the lower spins in ^{207}Pb are populated mainly from $E2$ strength; the $\frac{13}{2}^+$ state, however, is populated from higher multipolarities. Because the minima are more pronounced in the α angular distribution for $E2$ strength than for higher multipolarities, moreover, one should expect that the $\frac{13}{2}^+$ state is relatively more strongly populated for the position

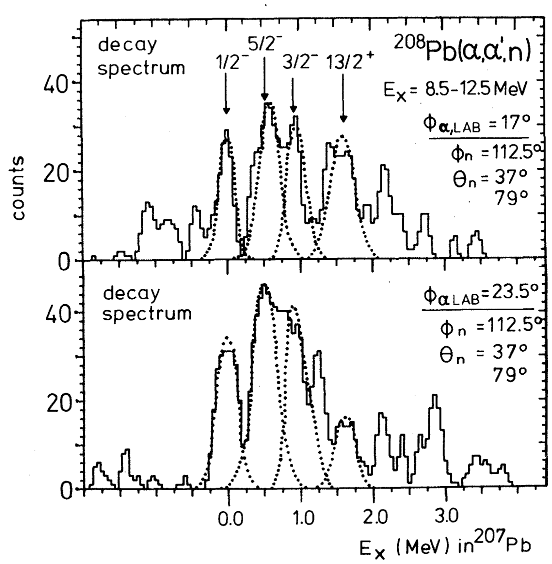

FIG. 1. Neutron spectra of the decay of the GQR region in ^{208}Pb into ^{207}Pb for the two α-scattering angles observed. The dotted curves represent Gaussians fitted to the experimental data.

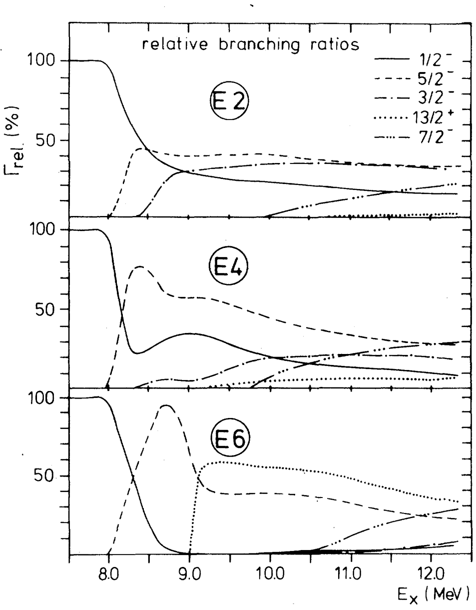

FIG. 2. Relative branching ratios as a function of energy, calculated for different multipolarities by use of a statistical model for the decay of the GQR region into the lowest five states of ^{207}Pb.

of the α detector in a minimum of the angular distribution of the GQR than in a maximum. This trend is confirmed by the experiment as can be seen by comparing the upper and lower parts of Fig. 1. Thus the decay of the quadrupole strength and the physical background, especially the contribution of higher multipolarities, can be roughly separated. In general in this way model-independent information about the strengths of different multipolarities in the GR region can be obtained provided that it decays with sufficiently small n energies to states of sufficiently different spins.

In Figs. 3(a)–3(c) the strength distributions in ^{208}Pb corresponding to the decay into the ground state ($\frac{1}{2}^-$), the first and second excited state ($\frac{5}{2}^-$, $\frac{3}{2}^-$), and the third excited state ($\frac{13}{2}^+$) of ^{207}Pb are shown for the energy region between 8.5 and 12.5 MeV. The energy thresholds of the α'-n experiment lie about 1.3 MeV above the physical thresholds. The results of the α'-n experiment are represented by the drawn curves in Figs. 3(a)–3(c). The strength distribution for the decay into the first and second excited states extracted from the α'-n experiment is completed below the experimental threshold by the data of the α'-γ experiment [dotted curve in Fig. 3(b)], where no experimental threshold occurs. For the $\frac{13}{2}^+$ state the strength between the physical and experimental thresholds [dotted curve in Fig. 3(c)] was obtained[3] by comparison of the spectra of the decay experiment with the respective singles spectrum, which is shown in Fig. 3(d) for the α-scattering angle of 23.5°. The strength distributions thus available in the energy region between 8.5 and 12.5 MeV for the decay into the lowest four states of ^{207}Pb show fine structures. In spite of the relatively large experimental errors the pattern of the spectra of Figs. 3(a) and 3(b) seems to be roughly correlated, whereas there is practically no correlation with the strength distribution corresponding to the $\frac{13}{2}^+$ state. This confirms the statement that the $\frac{13}{2}^+$ state and the other states in ^{207}Pb are mainly fed from strengths of different multipolarities. Fine structure in the $E2$ distribution in the energy region discussed was also observed in a recent (e,e') scattering experiment.[4]

Summing up the strengths decaying into the lowest four states of ^{207}Pb one gets $(76 \pm 5)\%$ of the total strength excited in the energy interval between 8.5 and 12.5 MeV. Up to about 11 MeV nearly the whole strength decays into these states. At higher energies the decay into higher

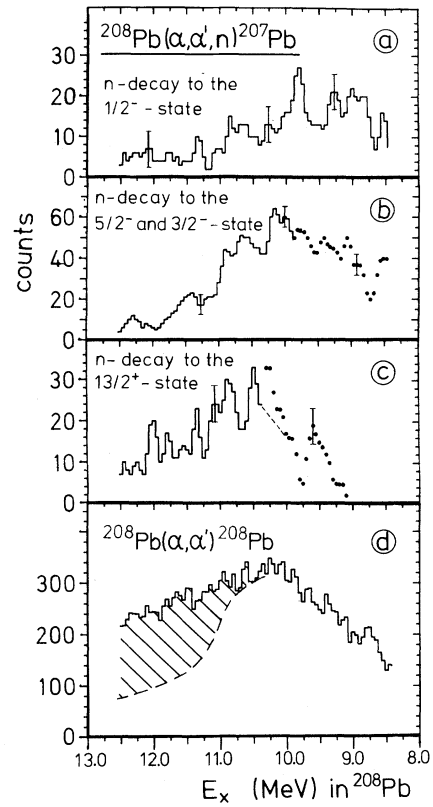

FIG. 3. Strength distributions in ^{208}Pb corresponding to the decay into (a) the ground state, (b) the first and second excited states, and (c) the third excited state in ^{207}Pb, and (d) the corresponding singles spectrum.

states of ^{207}Pb becomes important [hatched area in Fig. 3(d)], but the fraction decaying into the lowest four states is still large.

From Fig. 3(c) it can be seen that the strength distribution of the decay into the $\frac{13}{2}^+$ state increases with a steep slope immediately above the physical threshold at 9.0 MeV. It exhausts about 20% of the total strength in the region between $E_x = 8.5$ and 12.5 MeV. From this it must be concluded that a considerable part of the strength excited in α scattering in the GQR region of ^{208}Pb has multipolarities higher than or equal to 4. This is in agreement with random-phase approximation calculations,[5,6] which predict considerable $E4$ and $E6$ strength in this energy region. The fraction of higher multipolarities can be estimated by comparing the experimental strengths with the model calculations of Fig. 2. Under the assumption that the strength feeding the $\frac{13}{2}^+$ state has a pure multipolarity higher than 6 one gets a lower limit for this fraction of about 20%; a pure multipolarity of 4 is not sufficient to reproduce the strong experimental population of the $\frac{13}{2}^+$ state. The more realistic assumption of a distribution around a multipolarity of 6 leads to a fraction of about 40% of the total strength.

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[2]The spectra in Figs. 1 and 3 are smoothed corresponding to average intervals of about 100 keV.

[3]In the energy interval between about 9.7 and 10.3 MeV this strength gives only an upper limit for the strength decaying into the $\frac{13}{2}^+$ state because of the contribution of the unobserved decay into higher states of ^{207}Pb. Including the information about the decay into these higher states from the α'-γ experiment one gets the dotted curve in Fig. 3(c) as a lower limit.

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^{12}C + ^{12}C Reaction Cross Section between 70 and 290 MeV Obtained from Elastic Scattering

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Measurements of the elastic scattering of ^{12}C on ^{12}C at ten laboratory energies between 120 and 290 MeV were made to determine the reaction cross section σ_R and the total nuclear cross section σ_T. Analysis of these data and existing data at lower energies shows that σ_R reaches a maximum at around 200 MeV in the laboratory whereas σ_T shows little variation with bombarding energy.

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The variation of the nuclear reaction cross section $\sigma_R(E)$ has been investigated recently by DeVries and collaborators.[1,2] They have focused attention on the fact that values of σ_R for light-ion projectiles (up to helium) cannot be parametrized by the usual geometric form

$$\sigma_R(E) = \pi(R+\lambda\!\!\!^{-})^2\left[1 - \frac{Z_1 Z_2 e^2}{(R+\lambda\!\!\!^{-})E_{\mathrm{c.m.}}}\right] \tag{1}$$

over the entire energy range. For example, if R is adjusted to reproduce σ_R at low energies, Eq. (1) overestimates σ_R at high energies. The difference between this geometric limit and the measured values has been parametrized by multiplying the right-hand side of Eq. (1) by a factor $1 - T(E)$ where $T(E)$, the transparency, reflects a finite mean free path for the interacting ions. The authors of Ref. 1 emphasize that values of T increase quite rapidly at energies above 10 MeV/A even for strongly absorbed projectiles such as α particles and that this increase seems to correlate with the known falloff of the nucleon-nucleon cross section[1,3] suggesting the dominance of the latter in determining σ_R.

Calculations of the energy variation of σ_R (Refs. 1 and 2) and σ_T, the total nuclear cross section,[4] based on the Glauber model give quite a good account of the available data and in this sense support the above conclusion. In particular the calculations predict that for ^{12}C + ^{12}C scattering σ_R and σ_T reach a maximum at $E_{\mathrm{c.m.}} \sim 100$ MeV.

Although some data for ^{12}C + ^{12}C exist at high-

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