Neutron decay of the isoscalar giant resonance region in ^{90}Zr

K. Fuchs, W. Eyrich, A. Hofmann, B. Mühldorfer, U. Scheib, and H. Schlösser
Physikalisches Institut der Universität Erlangen-Nürnberg, D-8520 Erlangen, Federal Republic of Germany

H. Rebel
Kernforschungszentrum Karlsruhe, Institut für Kernphysik, D-7500 Karlsruhe, Federal Republic of Germany
(Received 13 August 1984; revised manuscript received 4 April 1985)

The neutron decay of the giant resonance region between 13.0 and 18.0 MeV in ^{90}Zr has been studied in an $(\alpha,\alpha'\mathrm{n})$ coincidence experiment at $E_\alpha = 104$ MeV. In the region of the giant quadrupole resonance between 13 and 16 MeV, additional strength with multipolarity $L \geq 4$ was identified. For the resonant strength in the region of the giant monopole resonance, a direct decay component of about 12% can be estimated. In addition, evidence for a preequilibrium decay was found.

I. INTRODUCTION

A powerful method for getting detailed information about the giant multipole resonances is the coincident observation of the decay particles after excitation through inelastic scattering. Because of excitation energies lying mostly above particle emission thresholds, the isoscalar electric giant resonances usually decay by emission of neutrons, protons, and α particles. In light nuclei, where a large fraction of the decay of the giant resonances (GR's) takes place by emission of charged particles, a series of coincidence experiments (compare, e.g., Ref. 1 and references given therein) has been performed showing a large direct decay component for the lightest nuclei, whereas with increasing mass ($A \gtrsim 28$) the statistical decay becomes dominating.

Because of the experimental difficulties connected with the spectroscopy of neutrons, only few experimental data on GR's are available for heavy nuclei where the neutron decay is the dominant decay mode. In previous coincidence experiments on ^{208}Pb, we studied the neutron decay of the region of the isoscalar electric GR's in a first step indirectly in (α,α',γ) measurements[2] via the observation of the γ quanta of the subsequent transitions in the residual nucleus ^{207}Pb in coincidence with the scattered α particles. Continuing these experiments, we investigated the n decay of the region of the $E2$ GR in ^{208}Pb into the individual low lying states of ^{207}Pb directly in $(\alpha,\alpha'\mathrm{n})$ coincidence measurements[3] and beyond that the n decay of the $E0$ GR region also in an $(\alpha,\alpha'\mathrm{n})$ coincidence experiment.[4] In this experiment, where the decay into the individual states of ^{207}Pb could not be resolved completely, information about the decay of the excited strength was obtained mainly from the shape of the n spectra. To get independent information about the resonating strength and the underlying "physical" background, we measured in the $(\alpha,\alpha'\mathrm{n})$ experiments in a maximum and a minimum of the $E2$ ($E0$) (α,α') angular distribution.

In the following, we report on an $(\alpha,\alpha'\mathrm{n})$ coincidence experiment to study excitation and n decay of the isoscalar, electric giant resonances in the giant quadrapole resonance (GQR) and giant monopole resonance (GMR) region in ^{90}Zr. For a later comparision with the results of the present experiment on ^{90}Zr we briefly summarize the main results of the ^{208}Pb measurements:

The resonant strength decays, predominantly following statistical rules. For the $E0$ region a direct decay component of about 15% of the total width could be identified. Moreover, there is evidence for a preequilibrium decay component of about 5% of the total width into special one-phonon—one-hole states of ^{207}Pb. The decay of the underlying observed background can be described totally within the statistical model.

In the $E2$ region, significant strength of higher multipolarities ($E4$ and $E6$) could be identified. The observed $E2$ strength shows fine structure similar to that reported in electron scattering experiments. For the $E0$ region we found strong evidence for additional strength with multipolarity $L \geq 2$.

To get more systematic information on strength with higher multipolarities, as it was identified in the ^{208}Pb case and on the contribution of a direct decay component, we extended our investigations to ^{90}Zr. A medium heavy nucleus was chosen in order to investigate a nucleus between ^{208}Pb and the light nuclei which have been studied rather extensively in coincidence experiments by observation of the charged particle decay.[1] Moreover, ^{90}Zr is a suitable system for model calculations due to its closed shell structure. For ^{90}Zr the decay situation, which is shown in Fig. 1, is as favorable as for ^{208}Pb. Similarly to ^{207}Pb, the spins of the low lying states in ^{89}Zr act as a "filter" which allows a separation of strengths with multipolarities $L \geq 4$ from $E2$ and $E0$ strengths for the GQR region. Due to their low energy, the decay neutrons can only transfer small angular momenta. Therefore, $E2$ and $E0$ strengths excited in the GQR region predominantly decay into the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ "low spin" states, whereas a strong feeding of the $\frac{9}{2}^+$ "high spin" state clearly indicates the decay of strength with multipolarities $L \geq 4$.

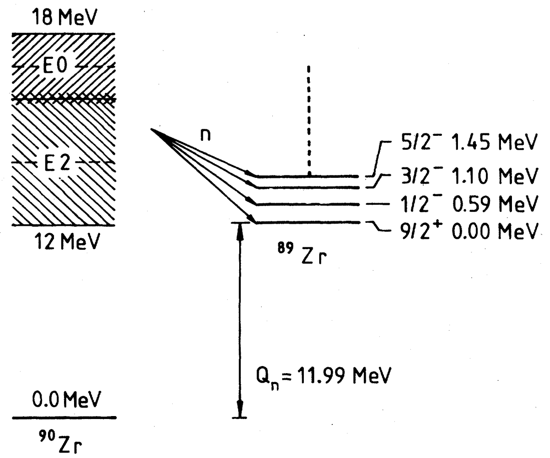

FIG. 1. Scheme of the neutron decay of the $E0$- and $E2$-GR regions in ^{90}Zr.

II. EXPERIMENT

The experiment was performed at the energy-analyzed 104 MeV α beam of the Karlsruhe cyclotron. The experimental setup was similar to that of the ^{208}Pb n decay measurements which is described in detail in Ref. 4. Again, the beam preparation and the careful shielding of the n detectors against background radiation was one of the most important points for the feasibility of the experiment. We used the same special scattering chamber with thin walls (2 mm thick) of aluminum in the direction of the n detectors as in the ^{208}Pb experiments. The target consisted of a self-supporting enriched ^{90}Zr foil ($>98\%$) with a thickness of 20 and 10 mg/cm^2. The α particles were measured by four detector telescopes consisting of 500 μm ΔE Si surface barrier detectors and 5000 μm E Si(Li) detectors. In contrast to the ^{208}Pb experiments in the ^{90}Zr case, particle identification proved to be necessary due to the Q value of the (α,^{3}He) reaction on ^{90}Zr of $Q=-13.4$ MeV. To get independent information about the decay of the resonating strength and the underlying background, the α detectors were arranged symmetrically with respect to the beam axis in a maximum ($\phi_{\alpha,\mathrm{lab}}=17.0°$) and a minimum ($\phi_{\alpha,\mathrm{lab}}=25.5°$) of the (α,α') angular distribution of the $E2$ ($E0$) strength. As in the ^{208}Pb experiments, we measured the time of flight of the decay neutrons with two large plastic scintillators at the eight positions $(\theta_n,\phi_n)=(101°\pm112.5°)$, $(101°\pm157.5°)$, $(143°\pm112.5°)$, and $(143°\pm157.5°)$ [z axis perpendicular to the (α,α') reaction plane, x axis in beam direction]. This gives an exact average of the angular correlation function for multipolarities up to two and a still satisfactory average for higher multipolarities as described in Ref. 4. Thus, by summing over the different measured angles of the decay neutrons we get model independent branching ratios of the decay into the individual states of ^{89}Zr for the region of the $E2$ GR and the model independent strength distribution of the decay neutrons for the $E0$ region, where the decay into the individual states can no longer be resolved.

The energy threshold of the n detectors was about 0.7

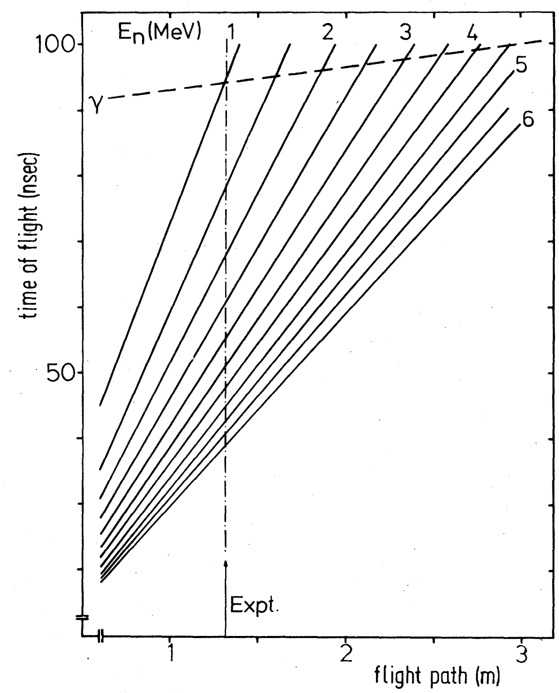

FIG. 2. Relation between flight path and time of flight for the interesting region of neutron energies.

MeV; the lowest energy evaluated was about 1.0 MeV. The photomultiplier tubes were cooled to 0 °C to reduce their noise. The time resolution against the high frequency of the cyclotron, which was operated in the 11 MHz mode, was about 1.5 nsec. For the used flight distance of 1.32 m, this corresponds to an energy resolution between about 50 and 350 keV for the neutrons with energies between 1 and 4 MeV from the region of the $E2$ GR (13 MeV $\leq E_x \leq$ 16 MeV), and $\lesssim 500$ keV for the fastest neutrons from the $E0$ region ($E_x \lesssim 18$ MeV). The underlying relation between flight path and time of flight for the interesting energy region is shown in Fig. 2. The efficiency of the n detectors was constant within 20% for the neutrons of interest (1 MeV $\lesssim E_n \lesssim$ 6 MeV) slowly decreasing to higher energies as shown in Ref. 4. Together with the energy resolution of the α detectors of $\lesssim 250$ keV, an overall resolution of $\lesssim 300$ keV for the $E2$ region and of $\lesssim 550$ keV for the $E0$ region was achieved. This is sufficient to observe the n decay of the GQR region into the individual low lying states of ^{89}Zr separately, as can be seen from Fig. 1. The setup of the used electronics was based on fast slow circuits similar to those described in Ref. 4. The α particle identification was obtained from the ΔE and E signals of the coincident events by applying conventional hardware procedures. The events recorded in list mode on magnetic tapes were defined to consist of the energy of the scattered α particles, the time of flight of the neutrons, and the time of flight difference between α particles and neutrons. Before the coincidence experiment we measured singles (α,α') scattering spectra in the angular region between $\phi_{\mathrm{c.m.}}=14°$ and $\phi_{\mathrm{c.m.}}=27°$ in steps of 0.5° in order to also get angular distributions of the

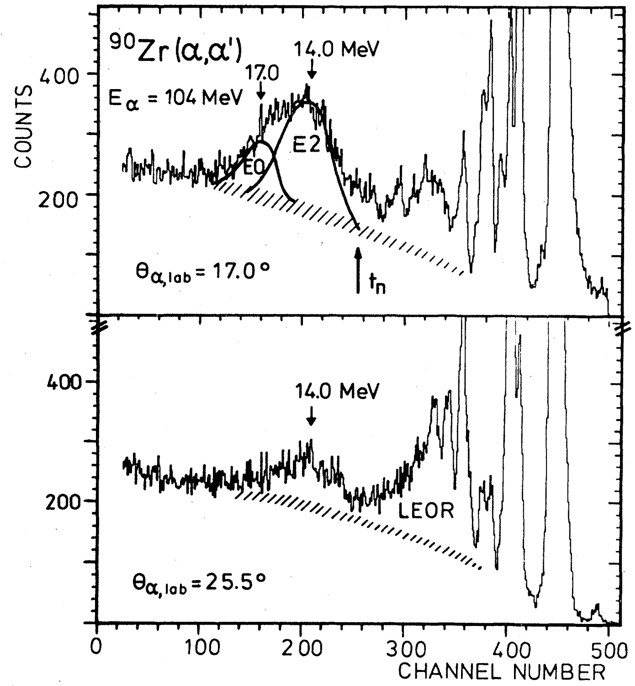

FIG. 3. ^{90}Zr(α,α') spectra at $E_\alpha=104$ MeV for a maximum (upper part) and a minimum (lower part) of the $E2$-angular distribution.

GR's of interest and especially to fix the angles for the coincidence experiment.

III. ANALYSIS AND DISCUSSION

A. Singles scattering spectra

As a first step, we analyzed the singles scattering spectra. In Fig. 3 are shown the spectra taken at the maximum of the $E2$ distribution at $\phi_{\alpha,\mathrm{lab}}=17°$ (upper part) and at the minimum at $\phi_{\alpha,\mathrm{lab}}=25.5°$ (lower part) with the setup of the coincidence experiment. The relative normalization factor between the two spectra is 3.0 corresponding to the different solid angles chosen to equalize the counting rates in the coincidence experiment. In the spectra, the center of the $E2$ GR at about 14 MeV and of the $E0$ GR at about 17 MeV and the low lying octopole resonance (LEOR) not discussed in this paper are indicated. Moreover, the threshold for n emission at $E_x=-12.0$ MeV is labeled, and a smooth background line is drawn which, as usual, is not free of arbitrariness. Subtracting this background and taking Gaussian shapes for the GQR and GMR with parameters extracted from small angle scattering[5] as displayed in Fig. 3 for the maximum spectrum, from distorted-wave Born approximation (DWBA) analyses on the base of the extended optical model we get a value of about $60\%\pm20\%$ $E2$ and about $80\%\pm20\%$ $E0$ (energy weighted sum rule) EWSR which agrees fairly well with the results of other single scattering experiments.[5,6] The large errors reflect mainly the uncertainty of the assumed background. Moreover, it should be pointed out that the assumed Gaussian shape of the strength distribution can only be a rough estimate as shown in the ^{208}Pb coincidence experiment.[3,4]

B. Neutron spectra from the decay of the $E0$ GR region

To get information about the decay modes of the observed GR's in ^{90}Zr, we first discuss the region of the $E0$ GR. As shown in detail in Ref. 4, for the ^{208}Pb experiment, a largely model independent extraction of the direct decay component is possible from the shape of the spectrum of the decay neutrons. In the case of a pure statistical decay, this spectrum should have an evaporation shape approximately described by the well-known formula

$$N(E_\mathrm{n})=E_\mathrm{n}\exp(-E_\mathrm{n}/T)\ ,$$

where E_n is the energy of the decay neutrons and T describes the nuclear temperature. An experimental excess of fast neutrons compared to this curve corresponding to the decay into the low lying hole states of the residual nucleus yields an estimate of the direct decay component. The discrimination between direct and statistical decay by this method presumes, however, that the number of states available in the residual nucleus is large enough so that, besides the low lying one-hole states, a sufficient number of states with more complicated structure can be populated in the decay. As we have pointed out in Refs. 3 and 4, and as it will be discussed in Sec. III C, this is not the case for the $E2$ GR region in ^{90}Zr and ^{208}Pb and is also not strictly fulfilled for the $E0$ GR region in ^{90}Zr. Therefore, it is important to get additional experimental information which allows a model independent extraction of a direct decay component after separation of the decay of the resonant strength from the decay of the underlying background. To obtain this information we measured not only the decay in a maximum of the $E0$ GR angular distribution, but also in a minimum. As the underlying background shows a very smooth angular distribution, which we checked in our singles measurements and which is known also from experiments on other nuclei (cf., e.g., Ref. 7), this procedure is useful to disentangle the decay of the investigated resonant strength and the underlying physical background.

In Fig. 4 the coincident spectra of the decay neutrons from the center of the $E0$ GR (17 MeV $\leq E_x \leq$ 18 MeV) are shown. The lower part shows the spectrum for the measured maximum of the $E0$ angular distribution ($\phi_\alpha=17°$) and the upper part the corresponding spectrum for the measured minimum ($\phi_\alpha=25.5°$). To obtain these spectra, event by event was calculated from the time of flight of each neutron and the energy of the corresponding scattered α particle. To get an average over the angular correlation function, which is necessary for the extraction of model independent decay quantities,[4] both spectra are summed over the different measured angles of the decay neutrons and normalized to the same total strength excited in ^{90}Zr. The dashed line represents the curve of a pure statistical decay $[N=E_\mathrm{n}\exp(-E_\mathrm{n}/T)]$ which is adjusted simultaneously to the two experimental spectra at low neutron energies ($E_\mathrm{n}<2.5$ MeV in the maximum spectrum and $E_\mathrm{n}<3.5$ MeV in the minimum spectrum); the

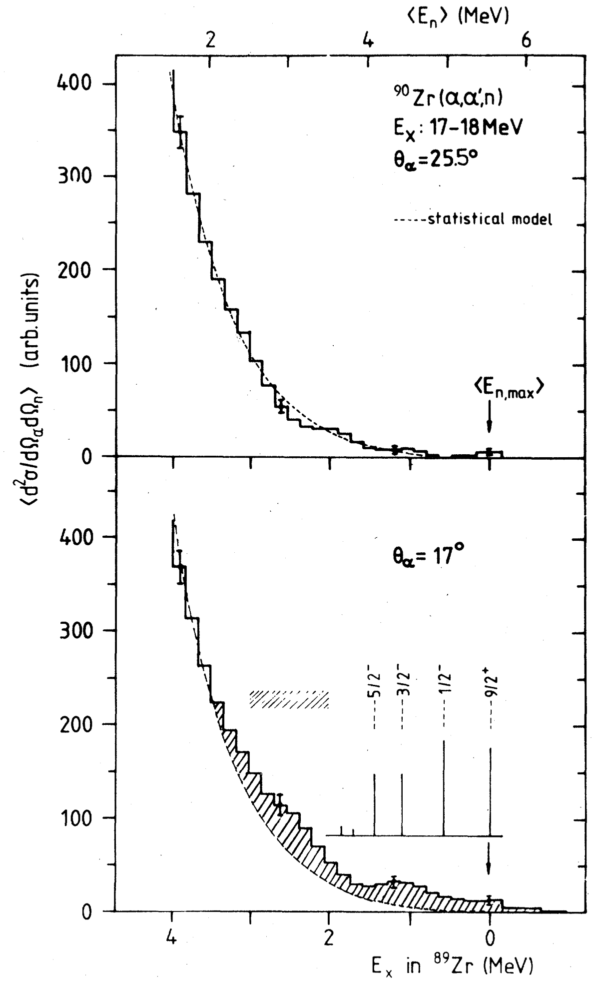

FIG. 4. Neutron decay spectra of the reaction ^{90}Zr(α,α'n) between 17 and 18 MeV excitation energy in ^{90}Zr for an excitation maximum (lower part) and minimum (upper part) of the GMR. The error bars represent statistical errors. (The enhancement in the maximum spectrum in comparison to the minimum spectrum and the evaporation curve is statistically signficant by more than seven standard deviations in the excitation energy region $0 \leq E_x \leq 1.5$ MeV and by about five standard deviations in the region between 2 and 3 MeV.)

fitted nuclear temperature is $T=0.6$ MeV in agreement with an estimate within the statistical model (compare, e.g., Ref. 8). The spectrum for the measured minimum can be described well by the evaporation curve and shows at the high energy tail only a very small excess of fast neutrons, whereas the spectrum of the maximum strongly exceeds the statistical model curve at the high energy end corresponding to a nonstatistical decay.

From the difference in both spectra we conclude that the excess of fast neutrons predominantly belongs to the decay of the resonant strength, the portion of which is much larger in the maximum of the $E0$ angular distribution, as is obvious from Fig. 3. The evaporation shape of the upper spectrum in Fig. 4 shows that the background below the resonant strength, which to a large extent is excited in complicated multistep processes, has only a very small nonstatistical decay component. These qualitative results agree with those of the decay of the $E0$ GR region in ^{208}Pb (Ref. 4). To get more quantitative results one can perform similar estimates as in the ^{208}Pb case. In the decay spectrum of the maximum, the excess over the evaporation spectrum has a value of $(5\pm1)\%$ of the total decaying strength, where, for neutron energies below 1.5 MeV, the spectrum is extrapolated by the statistical curve. Taking only this information into account, this value gives the nonstatistical decay component of the total excited strength including the background. From the resonance to background ratio of about 1:3 in the center of the $E0$ region, which can be taken from the maximum α spectrum shown in Fig. 3, and assuming a pure statistical decay of the background which should be a reasonable estimate as can be seen from the minimum decay spectrum, one gets a value of about $(15\pm3)\%$ for the nonstatistical decay component of the resonant strength in the $E0$ region. It is interesting to notice that this value is rather similar to that of the nonstatistical decay component of the $E1$ GR in the neighboring nucleus ^{89}Yr known from (γ,n) measurements.[9]

The main part of the nonstatistical decay of the resonant strength in the $E0$ region of ^{90}Zr has to be connected with a direct decay of the 1p-1h doorway state of the resonating strength into the low lying one-hole states of the residual nucleus ^{89}Zr. There are, however, other decay modes which can contribute to the excess of fast neutrons. In the lower part of Fig. 4 the low lying states of ^{89}Zr with their relative hole strengths which are known from pickup reactions[10] are indicated. Obviously the excess of the fastest neutrons corresponding to excitation energies $E_x \lesssim 1.5$ MeV in ^{89}Zr is connected with the decay into these one-hole states. Similarly to the ^{208}Pb$\rightarrow$^{207}Pb case, the experimental excess of fast neutrons, however, ranges to excitation energies in ^{89}Zr (2.0 MeV $\lesssim E_x \lesssim 3.5$ MeV) where no states with large hole strengths are known but where 1p-2h phonon hole states are situated[11] which arise from the coupling of the lowest one-hole states in ^{89}Zr to the low lying collective phonon states ($2^+,3^-$) in ^{90}Zr. These phonon hole states should be populated preferably from such 2p-2h configurations in ^{90}Zr, in which the 1p-1h doorway state of the GR is coupled to the low lying phonon states in ^{90}Zr. From this it is very likely that at least part of the enhancement of the decay yield in this energy region has to be added to the spreading width of the decay as a "preequilibrium component." In this respect the $(15\pm3)\%$ nonstatistical decay is an upper limit for the direct decay width; a more probable value for this component is 10—12 %.

The percentages we quote for the nonstatistical decay of the $E0$ GR are obtained under the assumption that a pure statistical decay of $E0$ strength at an excitation energy of $\langle E_x \rangle = 17.5$ MeV (17—18 MeV) in ^{90}Zr leads to an evaporation shaped n spectrum. The experimental decay spectrum of the measured minimum of the $E0$ GR (upper part of Fig. 4) shows obviously that the decay of the background, which should consist of a distribution of different multipolarities, is well described by an evaporation shape. To check the shape of the spectrum for the statistical decay of individual multipolarities especially of $E0$ strength precisely, it would be necessary to calculate the branching ratios for the decay into the individual levels of the residual nucleus ^{89}Zr within the statistical model and to compare the result with the evaporation curve and the experiment. This is not strictly feasible in the present situation since levels and spins in ^{89}Zr are completely known only for excitation energies up to 2 MeV and since the total experimental resolution of our experiment of about 500 keV (FWHM) for the $E0$ GR region is not sufficient to separate the decay into the individual states. However, the information from the limited excitation energy region $0 \le E_x \le 2$ MeV in ^{89}Zr obtained with our experimental resolution should be sufficient to check the agreement between experiment, evaporation shape, and explicit statistical calculation in this excitation energy region, which is the most interesting one for the extraction of a nonstatistical decay branch. For this purpose we divide the region $0 \le E_x \le 2$ MeV into a region I (0 MeV $\le E_x \le 1.5$ MeV) which contains the four low lying hole states $\frac{9}{2}^+$ (0.0 MeV), $\frac{1}{2}^-$ (0.59 MeV), $\frac{3}{2}^-$ (1.10 MeV), and $\frac{5}{2}^-$ (1.45 MeV) and a region II (1.5 MeV $\le E_x \le 2.0$ MeV) with six levels[12] ($\frac{9}{2}^+$, $\frac{5}{2}^+$, $\frac{3}{2}^-$, $\frac{5}{2}^+$, $\frac{3}{2}^-$, and $\frac{13}{2}^+$) which contain only very little hole strength as known from pickup measurements.[10] In the upper part of Table I is shown the ratio $\Gamma_{\rm I}/\Gamma_{\rm II}$ for the population of the levels in regions I and II from the decay of strength in the interesting energy region 17 MeV $\le E_x \le 18$ MeV in ^{90}Zr for different multipolarities (0^+, 2^+, 4^+, and 6^+) calculated explicitly within a simple statistical model. Thereby the branching ratios are obtained as a sum over the various contributing transmission coefficients of the decay into the individual states of regions I and II using standard optical potentials. Obviously the ratio $\Gamma_{\rm I}/\Gamma_{\rm II}$ shows only a small variation (0.8—1.0) for the different multipolarities. The value of 0.9 extracted from the evaporation curve adapted to the experiment as shown in Fig. 4 lies just in the middle of this small interval. From the stability of this value we conclude that strong deviations of the experimental ratio from the statistical value of ≈ 0.9, especially to higher values, are a clear indication for a nonstatistical decay component. In the lower part of Table I the experimental ratios $\Gamma_{\rm I}/\Gamma_{\rm II}$ are given for the measured minimum and maximum of the $E0$ angular distribution. The value of the minimum of 0.9 ± 0.2 is well reproduced by the statistical model, whereas the maximum spectrum gives a distinctly higher value of $\Gamma_{\rm I}/\Gamma_{\rm II} = 2.7 \pm 0.3$. These results confirm that the experimental enhancement of fast neutrons in the decay spectrum of the measured maximum of the $E0$ GR has to be attributed to a nonstatistical decay component of the $E0$ GR in ^{90}Zr. Moreover, they support the procedure discussed which leads to the value of about 10—12% for the direct decay component. This value is somewhat smaller than the value of 15—20% of the resonant strengths in the $E0$ GR region in ^{208}Pb extracted from our measurements of Ref. 4. One reason for a larger direct decay component for the case of ^{208}Pb can be the double closed shell structure of this nucleus in comparison to ^{90}Zr where only the neutron shell is closed.

TABLE I. Ratio $\Gamma_{\rm I}/\Gamma_{\rm II}$ of the population of region I (0 MeV $\le E_x \le 1.5$ MeV) in ^{89}Zr and region II (1.5 MeV $\le E_x \le 2.0$ MeV) from the decay of the center of the $E0$ GR region (17—18 MeV) in ^{90}Zr calculated within the statistical model and from the experiment. The theoretical values include a folding of 500 keV corresponding to the experimental energy resolution.

	$\Gamma_{\rm I}/\Gamma_{\rm II}$
Statistical model	
Calculation taking into account the decay into the individual states of ^{89}Zr explicitly	
Mode excited in ^{90}Zr	
0^+	1.0
2^+	0.8
4^+	0.9
6^+	0.8
Evaporation curve (adapted to the experiment, see Fig. 4)	0.9
Experiment	
Minimum of $E0$ angular distribution	0.9 ± 0.2
Maximum of $E0$ angular distribution	2.7 ± 0.3

C. Neutron spectra from the decay of the $E2$ region

In the following, the decay of the strength in the $E2$ GR region between about 13 and 16 MeV is discussed. As can be seen from the decay scheme in Fig. 1, for this energy region the number of the available states in ^{89}Zr is very small. Therefore, also in the case of a pure statistical decay, the low lying one-hole states will be populated strongly, and the decay spectrum is very different from an evaporation shape. This situation is qualitatively the same as in the ^{208}Pb case.[3] Detailed information about the excited strength and its decay can be obtained, however, if the branching ratios of the decay into the individual low lying states of ^{89}Zr are measured separately. From these data it is especially possible to look for strength with multipolarity $L \ge 4$ in the $E2$ GR region, because this strength can be identified by its dominant decay into the $\frac{9}{2}^+$ ground state.

This "spin filter" effect, which was already applied successfully in the ^{208}Pb decay experiment,[3,4] can be seen more quantitatively from statistical model calculations as described before. In Fig. 5 the result of such a calculation is shown for the relative branching ratios for the decay of strengths with different multipolarities into the four lowest states of ^{89}Zr as a function of the excitation energy in ^{90}Zr. For the region of the $E2$ GR between 13 and 16 MeV the low spin states with $J^\pi = \frac{1}{2}^-$ and $\frac{3}{2}^-$ are populated strongly from the decay of $E0$ and $E2$ strength, whereas the $\frac{9}{2}^+$ state has only a small branch for these multipolarities. The situation is vice versa for the decay of $E4$ and $E6$ strength. Below 13 MeV excitation energy this scheme of course is disturbed by threshold effects.

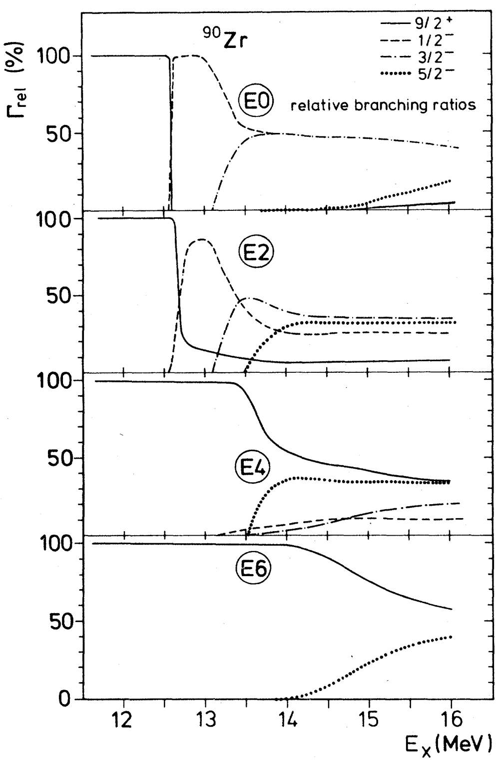

FIG. 5. Relative branching ratios for the decay of $E0$, $E2$, $E4$, and $E6$ strengths from the GQR region in ^{90}Zr into the four lowest states in ^{89}Zr (calculated from the statistical model).

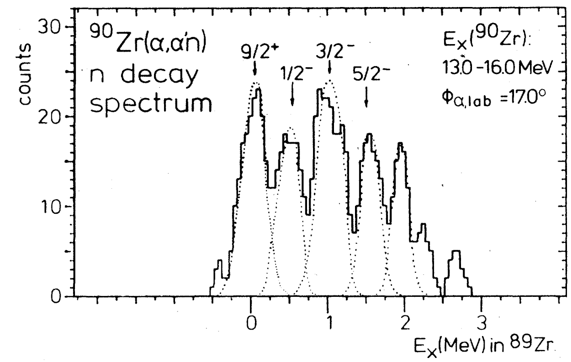

FIG. 6. Spectrum of the n decay of the GQR region in ^{90}Zr into the individual states of ^{89}Zr.

These calculations within the statistical model should be suitable for a comparison with the experimental results since the statistical decay is the dominant mode, as it is known, from the decay of the $E0$ region. Similarly to the ^{208}Pb case, the value of about 85% statistical decay should be valid also for the $E2$ GR. Moreover, the spin filter arguments qualitatively hold also for a direct decay. This was tested using 1p-1h random-phase approximation (RPA) wave functions[13] for the $E2$ GR in ^{90}Zr.

In Fig. 6 a typical experimental decay spectrum of the $E2$ GR region (13 MeV $\leq E_x \leq$ 16 MeV) evaluated from the (α,α'n) data corresponding to one position of the n detectors and to the maximum of the $E2$ (α,α') angular distribution is shown. The indicated energies of the low lying levels in ^{89}Zr agree well with the position of the peaks of the experimental spectrum. By folding Gaussians into the spectra with half-widths known from the experimental energy resolution as shown by the dotted curves in Fig. 6, the population of the individual states in ^{89}Zr from the $E2$ GR region can be gathered. One of the most interesting results, which is conspicuous in all spectra, is the strong population of the $\frac{9}{2}^+$ state. From this we claim that in the region of the $E2$ GR in ^{90}Zr considerable strength with multipolarity $L \geq 4$ is excited in the (α,α') reaction. In Fig. 7 the corresponding energy distribution of the strength decaying into the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ state (upper part) and the $\frac{9}{2}^+$ state (lower part) indicated in Fig. 6 is compared. The strength decaying into the low spin states with predominant multipolarity $L=2(0)$ is concentrated around the known maximum ($E_x \approx 14.3$ MeV) of the $E2$ GR in ^{90}Zr, whereas the strength decaying into the $\frac{9}{2}^+$ state, having mainly multipolarity $L \geq 4$, shows a relative flat distribution. Another interesting point is that significant fine structure as seen in the corresponding spectra of ^{208}Pb (Refs. 3 and 4) does not appear in these spectra. For a model independent extraction of the identified strength with higher multipolarity, the present experimental information is not sufficient. One can, however, estimate this strength assuming a pure statistical decay using the branching ratios calculated within

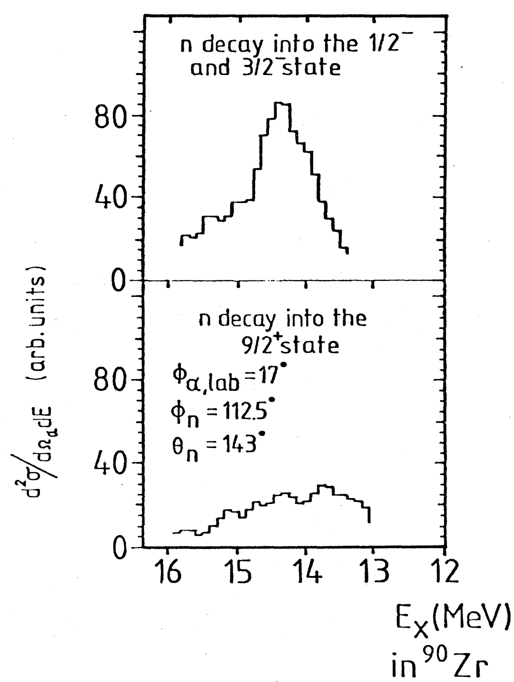

FIG. 7. Strength distribution in the giant quadrupole resonance region of ^{90}Zr from the neutron decay into the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states (upper part) and into the $\frac{9}{2}^+$ state (lower part) of ^{89}Zr.

TABLE II. Experimental branching ratios of the decay of the $E2$ GR region in ^{90}Zr (13 MeV $\leq E_x \leq$ 16 MeV) into the four lowest states of ^{89}Zr and the results of a statistical model fit.

States in $^{89}Zr(J^\pi)$	$\frac{9}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
Relative branching ratios experimental (%)	14±2	23±2	34±2	29±2
Relative branching ratios statistical model (%)	16	23	35	26
GR mode	$E2$	$E4$	$E0$	
Relative strength (%)	66±5	23±5	11±5[a]	

[a]From singles spectrum.

the statistical model shown in Fig. 5. For simplification, the additional assumption is made that the strength with higher multipolarity has $L=4$. The strength of the tail of the $E0$ distribution reaching into the discussed region of the $E2$ GR was extracted from the singles scattering spectrum (compare Fig. 3). Adjusting the branching ratios calculated within the statistical model to the experimental values, one gets the relative contribution of the strength with $L=4$ in the $E2$ GR region. The results are shown in Table II. The fit of the branching ratios, which agrees well with the experimental values of the decay into the four lowest states discussed, gives for the $E4$ strength a contribution of $(23\pm5)\%$ to the total strength. From this, one can roughly estimate a sum rule value of 5–10% $E4$ EWSR. Up to about $\frac{1}{3}$ of the $E4$ strength can be replaced by strength with multipolarity $L=6$ without getting significantly worse results for the fit to the data. The existence of considerable $E4$ strength in the $E2$ GR region of ^{90}Zr agrees with RPA calculations.[13,14] Moreover, the estimated EWSR value and the flat strength distribution agree fairly well with the calculations of Ref. 14, where a continuous distribution of the strength with different multipolarities is obtained within a so-called surface excitation model of the spreading width by coupling the GR modes to the nuclear surface vibrations.

In summary, the $(\alpha,\alpha'n)$ data show that in the $E2$ GR region in ^{90}Zr considerable strength of higher multipolarities (mainly $L=4$) is excited. This result is qualitatively the same as for the ^{208}Pb nucleus. In contrast to the ^{208}Pb case, this strength shows a flat distribution without significant fine structure. From the decay of the $E0$ GR region it is obvious that besides the dominating statistical decay width there exists a direct decay width of 10–12%, a value which is somewhat smaller than the direct decay component in the case of ^{208}Pb. Moreover, as in the ^{208}Pb decay, we found evidence for a preequilibrium decay into one-phonon–one-hole states.

ACKNOWLEDGMENTS

We would like to thank the staff of the Karlsruhe Cyclotron for their cooperation. This work was supported by the Bundesministerium für Forschung und Technologie and by the Kernforschungszentrum Karlsruhe.

[1]J. Speth and A. van der Woude, Rep. Prog. Phys. **44**, 719 (1981).
[2]W. Eyrich, A. Hofmann, U. Scheib, S. Schneider, F. Vogler, and H. Rebel, Phys. Rev. Lett. **43**, 1369 (1979).
[3]H. Steuer, W. Eyrich, A. Hofmann, H. Ortner, U. Scheib, R. Stamminger, D. Steuer, and H. Rebel, Phys. Rev. Lett. **47**, 1702 (1981).
[4]W. Eyrich, K. Fuchs, A. Hofmann, U. Scheib, H. Steuer, and H. Rebel, Phys. Rev. C **29**, 418 (1984).
[5]C. M. Rosza, D. H. Youngblood, J. D. Bronson, Y. W. Lui, and U. Garg, Phys. Rev. C **21**, 1252 (1980).
[6]F. E. Bertrand, G. R. Satchler, D. J. Horen, J. R. Wu, A. D. Bacher, T. G. Emery, W. P. Jones, and D. W. Miller, Phys. Rev. C **22**, 1832 (1980).
[7]M. N. Harakeh, K. van der Borg, T. Ishimatsu, H. P. Morsch, and A. van der Woude, Phys. Rev. Lett. **38**, 676 (1977).
[8]E. Vogt, Adv. Nucl. Phys. **1**, 261 (1968).
[9]L. M. Young, Ph.D. thesis, University of Illinois, 1972.
[10]H. Taketani, M. Adachi, M. Ogawa, and K. Ashibe, Nucl. Phys. **A212**, 448 (1973).
[11]A. Nilsson and M. Grecescu, Nucl. Phys. **A212**, 448 (1973).
[12]*Table of Isotopes*, 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).
[13]W. Knüpfer (private communication).
[14]F. E. Serr, P. F. Bortignon, and R. A. Broglia, Nucl. Phys. **A393**, 109 (1983).