Inhibition of the Fission Decay Channel of the Isoscalar Giant Quadrupole Resonance in the Actinide Region

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A measurement of the fission probability of the isoscalar giant quadrupole resonance, excited by inelastic scattering of 120-MeV α particles, yields an upper limit of 0.01 for the fission probability of the isoscalar giant quadrupole resonance in ^{232}Th, compared to 0.055 ± 0.015 for the underlying continuum.

The study of isoscalar giant resonances in heavy nuclei has been mainly concentrated[1-3] on systematics of excitation energies, widths, and percentages of energy-weighted sum rules (EWSR) exhausted by the giant resonances of various multipolarities. Except for the total width, very little is known experimentally about the partial decay modes of the giant quadrupole resonance (GQR) in heavy nuclei. It is usually assumed that of the two components $\Gamma^{\uparrow}$ and $\Gamma^{\downarrow}$ contributing to the total damping width Γ, the direct component $\Gamma^{\uparrow}$ due to the coupling of the resonant mode to the continuum is small. The dominant mode $\Gamma^{\downarrow}$ is due to coupling of the resonance to more complicated degrees of freedom in the nucleus. This coupling will eventually lead to very complicated states of motion which will decay in a way which is characteristic for a compound nucleus at the relevant excitation energy. For the giant dipole resonance (GDR) the energy distribution of the decay neutrons is in agreement with this model.[4] For nuclei in the actinide region where fission can compete with neutron decay, the GDR is already known[5] to have a fission probability that is similar to the one of the compound nucleus, as expected.[6]

Contrary to this picture, two recent electrodisintegration studies[7,8] of ^{238}U seemed to indicate that the GQR decays predominantly through the α channel. However, in later experiments[9,10] these results have been refuted. Also, in an electrofission experiment on ^{238}U, Arruda Neto *et al.*[11] claim to have found an $E2$ giant resonance located at 9.9 MeV, with a width of 6.8 MeV and exhausting 70% of the EWSR. This result suggests that the fission probability P_f of the GQR is much larger than that of the compound nucleus at the same excitation energy.[6]

In this Letter, we report on a measurement of the fission decay in coincidence with α particles scattered from the GQR region of ^{232}Th and ^{238}U. This is the first time that the decay of the GQR in a heavy nucleus has been studied using a coincidence technique. In this way the value of P_f for the GQR can be determined by comparing the single, inelastic α spectrum (which clearly shows the excitation of the GQR) with the fission-coincident α spectrum. Our measured P_f value for the GQR of ^{232}Th is much lower than the corresponding value for the giant dipole resonance (GDR) and for the compound nucleus. This is not only in disagreement with the experimental results of Ref. 11, but it also implies that the damping model, as briefly outlined above, does not hold for the isoscalar GQR.

The experiment was performed in two stages. In both cases, an analyzed beam of 120-MeV α particles from the Kernfysisch Versneller Instituut (KVI) cyclotron was used. In the first stage, the α particles scattered from a rolled ^{232}Th target were detected in a telescope consisting of a 2-mm ΔE and a 5-mm E solid-state detector. Fission fragments in coincidence with inelastically scattered α particles were detected in two 60-μm surface-barrier detectors, situated opposite to each other and along the recoil axis of the ^{232}Th nuclei. A single spectrum at $\theta_{\rm lab} = 14°$ is shown in the top of Fig. 1. The bump characteristic for the isoscalar giant resonance[1-3] is located at around 11 MeV excitation. In contrast to what has been found in the lead region, the GR peak can be fitted with one Gaussian peak, centered at $E_x = 11.0 \pm 0.3$ MeV and with a width of 4.0 ± 0.5 MeV full width at half maximum. These numbers agree with inelastic proton scattering data[12] obtained for ^{238}U and are in clear disagreement with the results from Ref. 11. Coincidence $(\alpha, \alpha' f)$ measurements were performed for laboratory angles of the inelastically scattered α particles from 10° to 18.5°. The spectrum of α par-

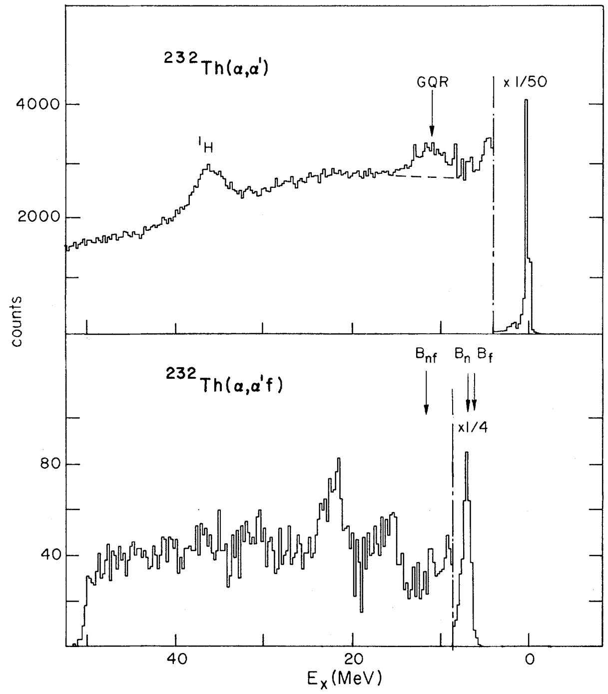

FIG. 1. Spectra of inelastically scattered α particles from ^{232}Th, singles at $\theta_{\rm lab}=14°$, and in coincidence with the fission fragments at $\theta_{\rm lab}=10°-18.5°$ (summed).

ticles coincident with the fission fragments, integrated over all angles, is shown in the bottom of Fig. 1. Although the statistics is rather poor, a few features of the spectrum can be recognized. The peak around $E_x=6$ MeV results from the fact that the fission threshold[13] ($B_f=6.15$ MeV) is lower than the neutron binding energy ($B_n=6.4$ MeV). Beyond this, the spectrum is flat and decreases slightly up to the second-chance fission threshold ($B_{nf}=12.6$ MeV), after which it rises to about double its value. It then decreases slightly till the threshold for third-chance fission ($B_{2nf}=18.1$ MeV) where it rises once more. The bump at around $E_x=22$ MeV is presumably due to the deexcitation of ^{232}Th by two successive neutron emissions, where the remaining ^{230}Th nucleus is excited above its fission threshold but below the neutron binding energy. α particles resulting from ^{5}Li and ^{5}He breakup due to proton- and neutron-pickup reactions ending in states above the fission barrier in the residual nuclei come at apparent excitation energies of 25 MeV and higher. No bump due to the decay of the GQR was observed but this α-fission coincidence spectrum lacks the proper statistics to make a definite statement about the fission probability of the GQR.

Later, we used the quadrupole-triple-dipole magnetic spectrograph[14,15] to detect inelastically scattered α particles corresponding to excitation energies between 4 and 14 MeV. The spectrograph was set[16] at $\theta_{\rm lab}=18°$ with a full opening of 6°, corresponding to a solid angle of 10.3 msr. The energy resolution was about 75 keV. For the fission detectors we used the same setup as described above. A single spectrum for α particles scattered from ^{232}Th is shown in the top of Fig. 2. The bump corresponding to the GQR excitation is clearly visible. Contaminant peaks due to ^{12}C and ^{16}O are indicated. The background is drawn corresponding to the way this was done in the spectrum shown in the inset, which was taken with a ΔE-E counter telescope system.[2]

The α spectra of ^{232}Th and ^{238}U in coincidence with fission are shown in the middle and bottom of Fig. 2, respectively. Again we readily observe the peak around $E_x=6$ MeV and the flat and structureless spectra beyond this. Quite obvious is the absence of a bump corresponding to the decay of the GQR into fission, in contrast with the singles spectra for ^{232}Th where the GQR is clearly observed.

For ^{232}Th, α-fission angular correlation data were measured. Fission fragments were detected at 0°, 10°, 20°, 30°, 40°, 50°, 75°, and 90° with respect to the recoil axis. The angular correlations are strongly forward peaked[16] for $E_x \sim 6$ MeV and become less so with increasing excitation energy. These data were used for obtaining fission probabilities, where we assumed that the α-fission angular correlation pattern is cylindrical symmetric around the recoil axis. Coincident α-fission absolute cross sections were obtained by integrating over target thickness, dead-time-corrected charge, and solid angles of fission detectors and spectrograph, after correction for angular correlation factors. The singles α absolute cross section was calculated from target thickness, dead-time-corrected charge, and solid angle. This resulted in a fission probability for ^{232}Th of $P_f=0.27\pm0.05$ for the interval $6.0\leq E_x\leq 6.4$ MeV, and $P_f=0.055\pm0.015$ for the continuum between 9 and 13 MeV. The former value agrees with the fission probability found by Back *et al.*[13]; the latter value agrees with data obtained from photofission and fast-neutron-induced fission.[6]

An upper limit for the fission-decay probability of the GQR in ^{232}Th can be obtained by drawing a smooth line through the continuum in the coincident α-fission spectra, and estimating an upper

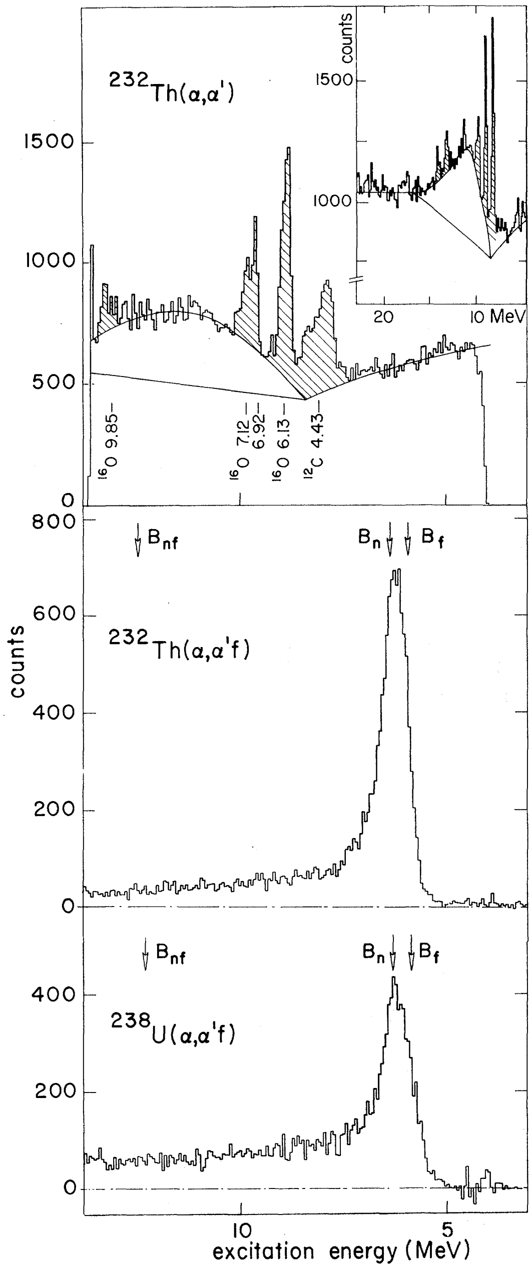

FIG. 2. Spectra of inelastically scattered α particles at $\theta_{lab}=18°$, singles (top) and in coincidence with fission for ^{232}Th (middle) and ^{238}U (bottom). Inset on the right-hand side of the top spectrum: singles spectrum of ^{232}Th at $\theta_{lab}=17°$, measured with a ΔE-E counter telescope.

limit for the number of counts above this line in the region between 9 and 13 MeV. This gives an upper limit of 0.01 for the fission probability of the GQR in ^{232}Th. Although at this stage we cannot give any absolute fission probabilities for ^{238}U, the results as shown in Fig. 2 (bottom) indicate that also for this nucleus the fission probability of the GQR is at most 20% of that of the underlying continuum. This contradicts clearly the results of Ref. 11.

Our experimental results suggest that in the decay of the GQR a statistical equilibrium is never reached. This might indicate that the GQR is strongly coupled to the continuum, so that it mainly decays by direct neutron emission. Alternatively, pre-equilibrium neutron emission might be so large that a full statistical equilibrium is never obtained. Whatever the reason, the difference between the (isoscalar) GQR and (isovector) GDR is surprising. It is just possible, of course, that the similar fission probability of the GDR and the compound nucleus is accidental and that GDR fission occurs through a special mechanism. In this connection it is interesting to note that the excitation energy of the $K=0^-$ part of the GDR strongly decreases with increasing deformation. In fact it turns out that the total excitation energy of the $K=0^-$ part of the GDR, E_x+E_{def}, is about constant as a function of deformation so that direct fission of this component might have an enhanced probability.

Summarizing, we have found that the decay of the isoscalar giant quadrupole resonance into the fission channel in ^{232}Th and ^{238}U is much smaller than one would predict from systematics and than what is observed for the underlying continuum. This is difficult to understand on the basis of the usual models for giant-resonance decay in heavy nuclei.

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Test of the Time-Dependent Hartree-Fock Theory in the ^{208}Pb+^{208}Pb Reaction

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Time-dependent Hartree-Fock calculations using Coulomb interaction and modified Skyrme force have been performed for the ^{208}Pb + ^{208}Pb reaction at laboratory bombarding energy per nucleon of 7.4 MeV/amu. The energy loss, scattering angles, and charge widths are in good agreement with experiment.

A variety of models, mostly phenomenological, have been proposed for the understanding of deep-inelastic collisional phenomena. In marked contrast to these is the time-dependent Hartree-Fock (TDHF) approximation, which provides a microscopic description of nuclear dynamics and is both intuitively appealing and aesthetically pleasing in its formulation. For computational ease and economy the TDHF calculations have so far essentially been performed for systems involving light nuclei.[1-6] A first application to very heavy systems was for the head-on ^{208}Pb + ^{208}Pb collision[7] and more recently to Kr-induced reactions.[8] The agreement with experiment of some of these calculations[3,4,8] have indicated the usefulness of the TDHF description to large-amplitude dynamical processes. However, the reproduction of experimentally observed energy loss, scattering angles, charge and mass widths, etc., accompanying a deep-inelastic process provides us with a very severe and crucial test of a parameter-free, microscopic TDHF theory. In this Letter, I wish to make such a test of the TDHF theory in its application to the ^{208}Pb + ^{208}Pb reaction. The experimental data for this reaction at laboratory bombarding energy per nucleon of 7.5 MeV/amu have been obtained at Gesellschaft für Schwerionenforschung.[9,10]

I have performed an axially symmetric THDF calculation for the study of the ^{208}Pb + ^{208}Pb reaction at laboratory bombarding energy per nucleon $E/A = 7.4$ MeV/amu. The effective interaction used in the calculations consists[5] of the direct Coulomb interaction and modified Skyrme force II with no spin-orbit interaction. The absence of spin-orbit interaction leads to an open-shell nature of the ^{208}Pb nucleus. We have therefore considered a dynamical generalization of the filling approximation according to which the density matrix of a ^{208}Pb ion can be expressed as[7]

$$\rho(\vec{r}, \vec{r}\,', t) = \sum_i \{n_i\} \varphi_i(\vec{r}, t) \varphi_i^*(\vec{r}\,', t), \tag{1}$$

where $\varphi_i(\vec{r}, t)$ are the complex single-particle wave functions of the Slater determinant and satisfy the TDHF equations

$$i\hbar(\partial/\partial t)\varphi_j(\vec{r}, t) = h(\vec{r}, t)\varphi_j(\vec{r}, t), \quad j = 1, 2, \ldots, A, \tag{2}$$

where A is the total mass number of the two ions and $h(\vec{r}, t)$ is the TDHF one-body Hamiltonian. The occupation numbers $\{n_i\}$ in Eq. (1) are taken to be time independent and are chosen to have the following values:

$$\{n_i\}_{\text{protons}} = \begin{cases} 1 \text{ for orbitals up to the } (3s\,2d\,1h) \text{ shell filled by 70 protons,} \\ \frac{6}{11} \text{ for the } 1h \text{ orbit which is uniformly filled by the remaining protons;} \end{cases}$$
$$\{n_i\}_{\text{neutrons}} = \begin{cases} 1 \text{ for orbitals up to the } (3p\,2f\,1h) \text{ shell filled by 112 neutrons,} \\ \frac{7}{13} \text{ for the } 1i \text{ orbit for the remaining 14 neutrons.} \end{cases} \tag{3}$$