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Isoscalar giant resonances in ^{232}Th

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The giant resonance region in ^{232}Th has been studied with inelastic α scattering at $E_\alpha = 120$ MeV. The observed resonance peak can be fitted with one Gaussian peak centered at 11.0 ± 0.3 MeV with full width at half maximum equal to 4.0 ± 0.3 MeV. If pure $L = 2$, this peak would exhaust $(130 \pm 25)\%$ of the $E2$ energy-weighted sum rule. Considerable admixture of $L = 0$ and/or higher multipole strength could be accommodated, if only 60–80% of the $E2$ energy-weighted sum rule is assumed to be exhausted.

[NUCLEAR REACTIONS ^{232}Th(α, α'), $E_\alpha = 120$ MeV, measured $d\sigma/d\Omega$; isoscalar giant resonances, DWBA, deduced L, β.]

The study of the effect of deformation on the width and excitation energy of the giant quadrupole resonance (GQR) in deformed nuclei has aroused considerable interest in recent years. The splitting of the giant dipole resonance (GDR) into $K^\pi = 0^-, 1^-$ components in well deformed nuclei has already been well known both theoretically[1] and experimentally.[2] Both in the rare earth and the actinide nuclei, the splitting of the GDR could be well described[2] by simple relations of energy, width, and percentage of $E1$, energy-weighted sum rule (EWSR), exhausted in the two parts of the GDR to the deformation of the nuclear ground state. After the discovery of the GQR, one expected similarly to observe the splitting of the GQR in well deformed nuclei into its three components $K^\pi = 0^+, 1^+, 2^+$. However, experimentally this expectation did not materialize. What one did observe[3] was a broadening on the low excitation energy side of the GQR rather than a splitting of the GQR in these deformed nuclei. The observation of a possible effect due to deformation on the higher energy tail of the GQR is hampered by the presence of the giant monopole resonance, which is reportedly located[4] at $E_x = 80A^{-1/3}$ MeV. Many theoretical papers[5] have since appeared which in fact show that the splitting of the GQR in well deformed nuclei is smaller than the width of the resonance. This should lead in the case of the GQR to a broadening rather than a splitting of the resonance.

Recently an (e,f) experiment[6] was performed on ^{238}U. While in an earlier publication Lewis and Horen[7] found a rather narrow GQR (3–4 MeV) in ^{238}U in inelastic (p,p') at $E_p = 61$ MeV, in the more recent (e,f) work it is claimed that the GQR decays by about 100% by fission and has a width [full width at half maximum (FWHM)] of 6.9 MeV and $E_x = 9.9$ MeV and, moreover, exhausts ~70% of the $E2$, EWSR. Both width and excitation energy obtained for the GQR in ^{238}U in the (e,f) experiment are in direct conflict with the values obtained by Lewis and Horen.[7] Moreover, the result of the (e,f) experiment[6] that the GQR decays 100% by fission is in contradiction with a recent $(\alpha, \alpha' f)$ experiment[8] performed at this lab where the GQR in both ^{232}Th and ^{238}U was found to be inhibited to fission decay. Also in a $(^6\text{Li}, ^6\text{Li}'f)$ experiment[9] a small fission probability for the decay of the GQR was found.

In view of the recent revived interest in the excitation and decay of isoscalar giant resonances in the actinide region we present in this communication of our data an analysis of the ^{232}Th(α, α') reaction performed at $E_\alpha = 120$ MeV. Only analysis pertaining to the giant resonance region will be presented, since our resolution was not good enough to deal with the low-lying states. However, the reader is referred to a recent high resolution (p,p') experiment performed[10] on various deformed nuclei including ^{232}Th.

A 120 MeV energy analyzed beam of alpha particles from the KVI AVF cyclotron was used to bombard a 1.8 mg/cm^2 thick, self-supporting ^{232}Th target. The elastically and inelastically scattered alpha particles were detected in a ΔE-E detector telescope system. The ΔE and E were solid state detectors of 0.7 and 5 mm thickness, respectively. The overall energy resolution obtained with this system was around 150 keV. For more details of the experimental setup see Ref. 11.

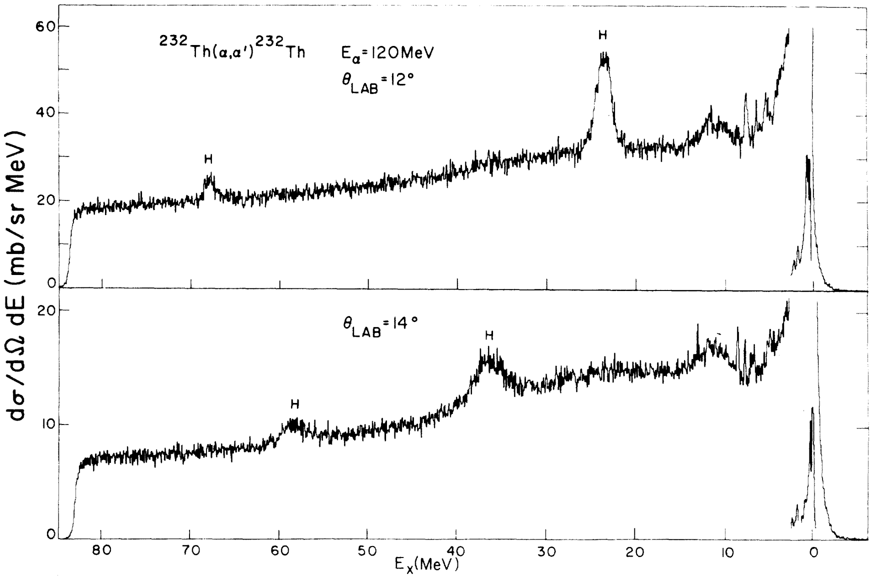

FIG. 1. Spectra of the ^{232}Th(α, α′) reaction at $E_\alpha = 120$ MeV taken at $\theta_{lab} = 12°$ and 14°. The sharp peaks in the giant resonance (GR) region (~11 MeV) are due to scattering from ^{12}C and ^{16}O contaminants. Broad peaks due to scattering from hydrogen are labeled.

Differential cross sections were measured in 1° steps from 12° to 20° in the lab system. In Fig. 1, two ^{232}Th spectra taken at 12° and 14° are shown. These spectra extend to high excitation energies ($E_x = 85$ MeV) in ^{232}Th. In addition to the giant resonance peak around $E_x = 11$ MeV, two peaks corresponding to α scattering from hydrogen contaminant in the target are apparent in both spectra. Moreover, a broad bump starting around $E_x = 20$ MeV and extending to $E_x = 45$ MeV is recognizable. This corresponds to α particles resulting from ^{5}Li and ^{5}He breakup obtained in the (α, ^{5}He) and (α, ^{5}Li) reactions on ^{232}Th. Composite structures were observed at $E_x \sim 0.8$ and 1.1 MeV. Our resolution is not good enough to make definite statements about various contributions to these structures. Further sharp structure observed in the region of the giant resonance region is due to oxygen and carbon contaminants.

Absolute cross sections were calculated using target thickness measurements, integrated collected charge, and measured solid angle. The elastic cross section so obtained was found to agree with the prediction of an optical model calculation.

The data were analyzed in a straightforward manner. A background was assumed to run smoothly from higher to lower excitation energies and was subtracted. In Fig. 2, where an inelastic α spectrum taken at $\theta_{lab} = 15°$ is shown with an emphasis on the region of the GR, a possible way to subtract the background is demonstrated. Here, in contrast to the lead data obtained[11] at 120 MeV, only one Gaussian peak was found necessary to fit the GR structure. One can, of course, fit the structure for the sake of consistency with two peaks as was found[4,11] necessary for the lead region. However, in the ^{232}Th case one can choose the peak position of GR2 at liberty, and hence

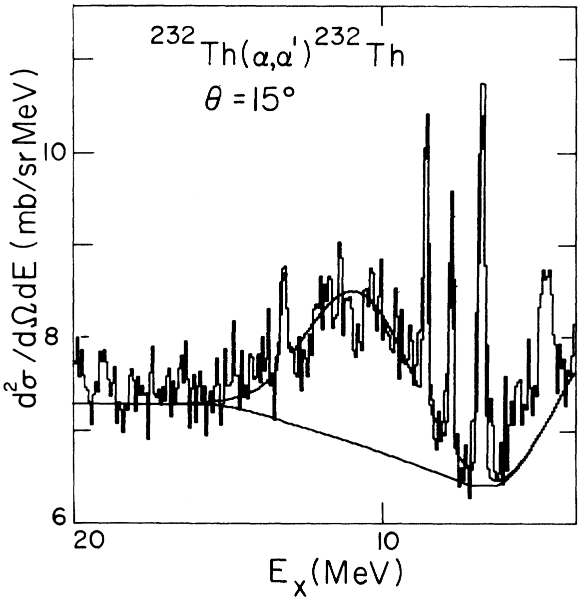

FIG. 2. A ^{232}Th(α, α′) spectrum emphasizing the region of the GR taken at $\theta_{lab} = 15°$. Sharp peaks are due to ^{12}C and ^{16}O contaminants. The curve through the data is a result of a fit to the GR with a Gaussian peak and a background as is also shown in the figure.

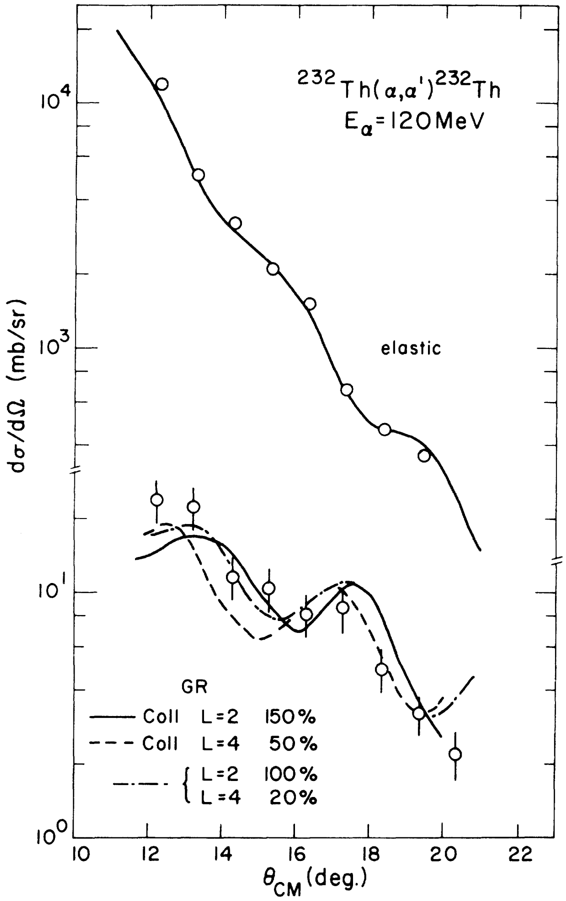

FIG. 3. Differential cross sections of elastic scattering and of the GR structure. The curve through the elastic scattering data is a result of an optical model calculation. The curves shown for the GR are results of collective model DWBA calculations as described in the text.

there is large uncertainty as to the position and width of GR2 in contrast to the lead region. For instance, if we assume that GR2 was located at $E_x = 13.7$ MeV, we would find a good fit to the observed spectra by the combination $E_x = 11.0 \pm 0.3$ MeV, Γ(FWHM) $= 3.4 \pm 0.3$ MeV for GR1 and $E_x = 13.7$ MeV and $\Gamma = 2.7 \pm 0.4$ MeV for GR2. This would result in cross sections for two GR peaks GR1 and GR2 which in general look like the data of GR1 and GR2 in the lead region.[11] But the quality of the present data is not good enough to justify such a decomposition. For this reason, we were content to fit the data with one Gaussian peak. The excitation energy and width of the GR structure are $E_x = 11.0 \pm 0.3$ MeV and $\Gamma_{\mathrm{FWHM}} = 4.0 \pm 0.3$ MeV, respectively.

Distorted-wave Born approximation (DWBA) calculations with collective form factors were performed to fit the differential cross section of the giant resonance. The optical model potential used was obtained[12] from an analysis of elastic scattering on ^{208}Pb at $E_\alpha = 135$ MeV and has the parameters

$$V = 155 \text{ MeV} \quad r_R = 1.282 \text{ fm} \quad a_R = 0.677$$

$$W = 23.26 \text{ MeV} \quad r_I = 1.478 \text{ fm} \quad a_I = 0.733 \quad R_c = 1.4 \text{ fm}$$

with a Woods-Saxon shape.

The differential cross section for elastic scattering calculated with the above potential is seen to fit (Fig. 3) the data in the measured angular range rather well. In Fig. 3, we also show the extracted data for the GR peak. Three lines are shown which are predictions of DWBA calculations[13] with collective form factors. The solid line is for $L = 2$ transfer and 150% of the $E2$, EWSR. It is seen to give an acceptable fit to the data, except for the two most forward angles. The dashed line is for $L = 4$ transfer and is drawn to show that the two most forward points could be reproduced by $L = 4$ admixture. The best overall fit is obtained with a calculation where a mixture of 100% $E2$, EWSR and 20% $E4$, EWSR is assumed; this is the dashed-dotted line in Fig. 3, which is seen to reproduce the forward points reasonably. If the percentage of $E2$, EWSR is reduced to 70%, then up to 70% of the $E0$, EWSR could be accommodated without any deterioration of the fit.

The percentages of the EWSR quoted have been

TABLE I. Excitation energy, width, deformation length and percentages of EWSR's for a few possible decompositions of the GR peak in ^{232}Th.

E_x (MeV)	Γ_{FWHM} (MeV)	J	βR	% EWSR[a]
11.0 ± 0.3	4.0 ± 0.3	2	0.59	130 ± 25
		2+4		85% $E2$ + 17% $E4$
		0+2+4		60% $E0$ + 60% $E2$ + 17% $E4$

[a] The percentages of the EWSR for $E2$ and $E4$ are obtained by normalizing to the percentages of EWSR for the low-lying 2^+ and 4^+ states in ^{208}Pb obtained from electromagnetic measurements by a factor as described in the text.

obtained in the following manner. First deformation parameters have been obtained by comparing experimental cross sections to DWBA cross sections. From the βR values isoscalar transition rates $B(IS,\ 0\to L)$ for uniform density were calculated. The percentages of the EWSR, $S(IS)$, were then obtained by comparing to the isoscalar EWSR $\tilde{S}_L$ of the various multipolarities:

$$S(IS)=E_x B(IS,0\to L)/\tilde{S}_L\,.$$

For $E2$ and $E4$ these were further renormalized by factors of 1.25 and 1.48. Such factors are needed for comparison of isoscalar transition rates obtained from inelastic α scattering with electromagnetic transition rates obtained from inelastic electron scattering. The above factors 1.25 and 1.48 were obtained from a similar analysis of the 2^+ and 4^+ states of ^{208}Pb at $E_x = 4.085$ and 4.324 MeV, respectively (see Ref. 11 for more details).

In Table I, we summarize the results of our analysis. The excitation energy and width of the GR peak we observe for ^{232}Th are in agreement with those obtained[7] for ^{238}U from inelastic proton scattering. The percentage of the EWSR obtained in this analysis depends on the choice made for the background. The background used in the analysis to obtain the cross section shown in Fig. 3 could be considered as a lower limit. If an upper limit background were drawn (not shown in Fig. 2) around 110% of the $E2$, EWSR would fit the data. The values listed in Table I constitute averages between the upper and lower limit backgrounds with an estimated error of ~20%. The value of $130\pm25\%$ $E2$, EWSR is consistent with the value of $85\pm20\%$ obtained from ^{238}U (p,p') if no normalization factor of 1.25 is applied.

Our data are in conflict with the data obtained from (e,f) measurements,[6] where an excitation energy and a width of 9.9 and 6.9 MeV, respectively, were found for the GQR. At best we observe a broadening of about 0.4 MeV of the GQR as compared to the ^{208}Pb data $[\Gamma_{\mathrm{FWHM}}(^{208}\mathrm{Pb})\approx 3.0$ MeV], if we assume that the GR peak observed in ^{232}Th can be decomposed in two peaks GR1 and GR2 as discussed above. Furthermore, it should be noted that the percentages of the EWSR's obtained for ^{232}Th are similar to those obtained for the nuclei ^{206,208}Pb and ^{209}Bi (Ref. 11) and that all of the results for ^{232}Th as presented here are consistent with the systematics observed for the giant resonances in heavy nuclei.[14]

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