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Alpha Decay of the Giant Quadrupole Resonance in ^{238}U†

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Evidence for the α decay of the giant quadrupole resonance is reported. Measurements of the reaction ^{238}U$(e,e',\alpha)^{234}$Th in the region 9-24 MeV are presented. The results imply that the reaction goes dominantly through $E2$ absorption. The amount of $E2$ strength used by the α emission channel exhausts 50% of the isoscalar energy-weighted sum rule.

It has recently been suggested that the study of (γ,α) and (α,γ) reactions could reveal interesting features of the giant quadrupole resonance (GQR) since in these reactions the effects of the isovector giant dipole resonance (GDR) are supressed.[1] In this Letter, evidence that the GQR decays strongly by α emission is presented.

The GQR has been extensively studied by electron and hadron scattering. From these measurements it is possible to observe the strength of quadrupole absorption by the nucleus. While for the dipole absorption the dominant mode of decay of the GDR is by neutron emission and fission, no measurements have been reported on the decay modes of the GQR.

The electrodisintegration cross section by emission of a particle x (integrated over all scattering angles), $\sigma_{e,x}(E_0)$, is related to the corresponding photodisintegration cross section, $\sigma_{\gamma,x}{}^{\lambda L}(E)$, through

$$\sigma_{e,x}(E_0)=\int_0^{E_0}\sum_{\lambda L}\sigma_{\gamma,x}{}^{\lambda L}(E)N^{\lambda L}(E_0,E)E^{-1}dE, \qquad (1)$$

where E_0 is the electron bombarding energy, E is the photon energy, $N^{\lambda L}$ is the virtual photon spectrum, and $\sigma_{\gamma,x}{}^{\lambda L}$ is the cross section for photodisintegration through a nuclear transition of multipolarity λL. Gargaro and Onley[2] have obtained computable expressions for $N^{\lambda L}$ using the distorted-wave approximation and agreement with experimental results has been shown by Nascimento, Wolynec, and Onley[3] and Wolynec and co-workers.[4,5]

If we know that in the energy range under study there are one or two dominant multipoles in the absorption, then the sum in expression (1) reduces to one or two terms. It is possible in this case to obtain the multipolarity of the transitions involved in the photodisintegration by measuring the electrodisintegration cross positions.

Since the quadrupole component of virtual photons is one order of magnitude larger than the dipole for high Z (see Fig. 1), while real plane-wave photons have all multipole components in equal amounts, the relative magnitude of the cross section for the quadrupole to the dipole

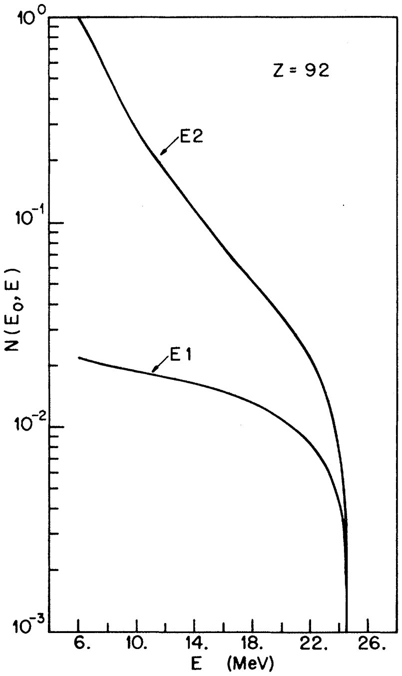

FIG. 1. Electric dipole and quadrupole virtual photon spectra for electrons of kinetic energy 24.5 MeV, scattered by a uranium nucleus.

mode is greatly enhanced for electrons as compared to photons, the enhancement being greater the higher the Z of the target nucleus.[3] The above considerations led us to choose (e, e', α) reactions and ^{238}U as our first candidate for the study of the decay of the GQR through α emission.

Very-thin uranium targets (thickness of the order of 10^{-5} radiation lengths) were bombarded in the electron linear accelerator of Universidade de São Paulo. The amount of ^{238}U in the targets was determined by α spectroscopy. Prior to bombardment the natural activity of the 63-keV γ-ray line, from the decay of ^{234}Th to ^{234}Pa, was counted in a Ge-Li low-energy photon spectrometer. As the half-life of this decay is 24.1 days, ^{234}Th is in radioactive equilibrium with ^{238}U and the activity of that γ-ray line is proportional to the ^{238}U α activity. After irradiation the 63-keV line activity was measured in the same counter and geometry. The previously determined contribution associated with spontaneous α emission was subtracted as background. In Fig. 2 a typical pulse-height spectrum is shown. We measured the cross section through the activity of the 63-keV line and checked that the ratio of the activities of the 63- and 92.5-keV lines, both from ^{234}Th, remained constant through all spectra, prior to and after bombardment.

In Fig. 3 the experimental cross section for the reaction ^{238}U$(e,e',\alpha)^{234}$Th, as a function of electron incident energy, is shown as full circles. Below 9 MeV the cross section was too small to be measured. The main contribution to the er-

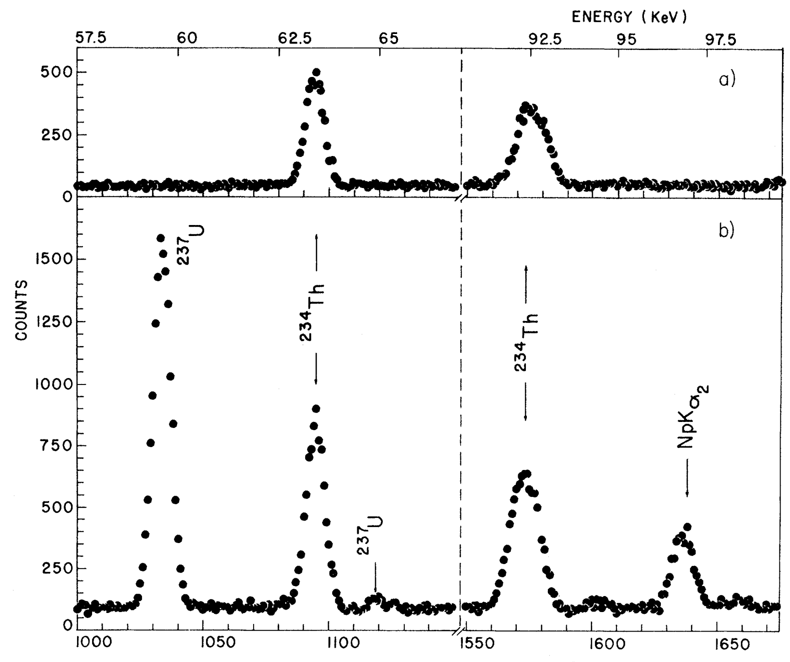

FIG. 2. Typical pulse-height spectrum: (a) prior to bombardment; (b) after bombardment.

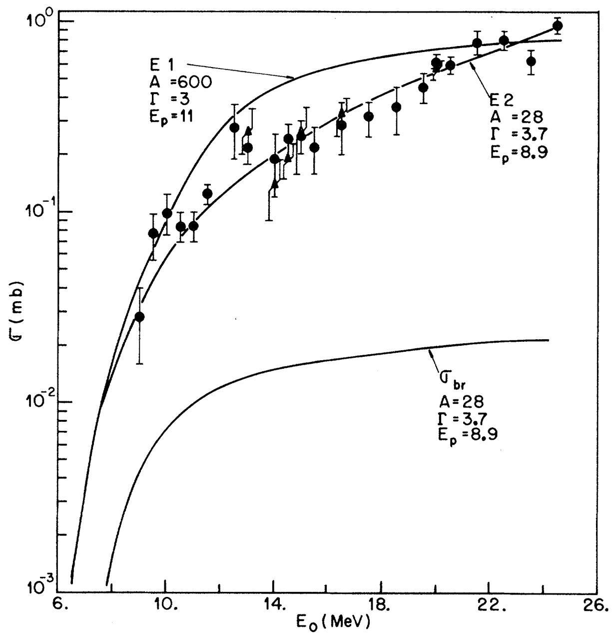

FIG. 3. Experimental cross section for the reaction $^{238}U(e,e',\alpha)^{234}Th$ (circles), versus electron kinetic energy. The triangles refer to the experimental yield for the same reaction induced by electron plus bremsstrahlung. The labeled curves are the calculated values (Breit-Wigner parameters indicated) for the bremsstrahlung yield (curve σ_{br}) and the cross section for (e,e',α) in the cases of a pure $E2$ process (curve $E2$) and a pure $E1$ process (curve $E1$).

rors indicated comes from the subtraction of the natural activity that typically amounted to 70% of the activity after irradiation.

We have also measured the yield for electron-plus-bremsstrahlung-induced α emission, $\sigma_{e,\alpha} + \sigma_{br,\alpha}$. For these measurements a 0.01-radiation-length aluminum radiator was placed in front of the targets. As shown in Fig. 3, within experimental errors, there is no difference between the values obtained for $\sigma_{e,\alpha}$ (full circles) and $\sigma_{e,\alpha}+\sigma_{br,\alpha}$ (triangles). This behavior is typical of an $E2$ process. If α emission occurred dominantly through $E1$ absorption, the expected values for $\sigma_{br,\alpha}$ would be of the same magnitude as $\sigma_{e,\alpha}$ and consequently $\sigma_{e,\alpha}+\sigma_{br,\alpha}$ would be about twice the value for $\sigma_{e,\alpha}$.[4,5]

The amount of quadrupole strength absorbed by the nucleus and used for α emission can be estimated by evaluating the integral of expression (1) with only the $E2$ virtual-photon kernel and an assumed cross section for $\sigma_{\lambda,\alpha}{}^{E2}(E)$.

As an approximation we represented $\sigma_{\lambda,\alpha}$ with a Breit-Wigner formula of area A, width Γ, and peak position E_p. In Fig. 3 the best fit to experimental data, obtained for $A = 28$ MeV mb, $\Gamma = 3.7$ MeV, and $E_p = 8.9$ MeV, is shown as the curve labeled $E2$. The cross section was supposed to vanish below 6 MeV since only above this value does α emission compete favorably against γ deexcitation.[6] The strong dependence of the χ^2 of the fit on the values of A, E_p, and Γ indicates the sensitivity of the method. At the 95% confidence level our results can be stated as $A = 28 \pm 3$ MeV mb, $\Gamma = 3.7 \pm 1.2$ MeV, and $E_p = 8.9 \pm 0.3$ MeV.

From the above results we conclude that the amount of absorbed $E2$ strength used for the (γ,α) reaction exhausts (50 ± 5)% of the isoscalar energy-weighted sum rule.[7] The (γ,α) cross section is concentrated around 9 MeV, which is compatible with the location at $58/A^{1/3}$ MeV predicted by Bohr and Mottelson[8] for the isoscalar giant quadrupole resonance.

The curve labeled σ_{br} in Fig. 3 is the predicted bremsstrahlung yield with our radiator inserted, assuming a quadrupole resonance with the parameters given above. The small magnitude of this result explains why we were unable to detect any difference in the yields with and without the radiator.

The curve labeled $E1$ in Fig. 3 is the predicted yield curve for a pure $E1$ process. In order to obtain a yield curve of the same magnitude as the experimental results, it would be necessary to assume a Breit-Wigner shape with $A = 600$ MeV mb (more than half the integrated cross section for $\sigma_{\gamma,n}$) which is unrealistic and incompatible with our experimental results taken with a radiator.

The emission of α's from ^{238}U excited at around 9 MeV might appear puzzling. Even though the reaction is exothermic and the emitted α's have kinetic energies up to 15 MeV, this is still below the Coulomb barrier. We have then evaluated the transition rate, T_0, using the Geiger-Nuttal relation with empirical coefficients, as given in Ref. 8. For 15-MeV α's $T_0 = 5\times10^{15}$ sec^{-1}, resulting in a half-life of about 10^{-16} sec.

In summary, we have measured the cross section for the reaction $^{238}U(e,e',\alpha)^{234}Th$ and shown that our results can be explained on the basis of a pure $E2$ process, exhausting 50% of the isoscalar energy-weighted sum rule. We have corroborated the suppression of α emission through excitation of the GDR. These results, associated with the strong enhancement of $E2$ excitation by electrons, establishes (e,e',α) reactions as a sensitive detector for the experimental study of the GQR.

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Time Reversal Test in ^{57}Fe†

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The linear polarization of the $E2$-$M1$ 122-keV γ ray of ^{57}Fe following the electron capture decay of polarized ^{57}Co was measured with a Compton polarimeter. An average time-reversal–noninvariant counting asymmetry of $(-0.4\pm 0.8)\times 10^{-5}$ was obtained. This corresponds to a phase angle between the $E2$ and $M1$ matrix elements of $\sin\eta = (-3.1 \pm 6.5)\times 10^{-4}$, consistent with time-reversal invariance.

The phenomenon of CP nonconservation has so far been observed only in the neutral K meson system. A compilation of the CP-nonconserving parameters furthermore reveals that the observed CP-nonconservation is mainly due to a CPT-conserving, T-nonconserving interaction.[1] This raises the question of whether one expects to observe T nonconservation in other systems, especially in the broad class of nuclear phenomena.

In the particular case of electromagnetic transitions, time-reversal noninvariance will manifest itself by the presence of a relative phase η other than 0 or π between reduced matrix elements of interfering multipoles in a mixed transition. Experimental limits on $\sin\eta$ so far are a few parts in 10^3, and are close to the limits of P-even, T-odd observables predicted by the classes of $\Delta Y = 0$ millistrong and electromagnetic theories proposed to account for the observed CP nonconservation.[2,3] It is thus of interest to push down the experimental limit by an order of magnitude to clarify this situation. The purpose of this Letter is to describe the results of a new experiment which provides a considerably lower limit on T nonconservation in nuclear physics.

Experimental measurements of η must involve at least three vectors, such as the nuclear polarization $\vec{J}$, the γ-ray momentum $\vec{k}$, and the γ-ray linear or circular polarization $(\vec{E}, \vec{P}_\gamma)$. Recent experiments using angular correlation techniques measured T-odd quantities of the form $(\vec{J}\cdot\vec{k}_1\times\vec{k}_2)\times(\vec{k}_1\cdot\vec{k}_2)$,[4-6] $\vec{k}_1$ and $\vec{k}_2$ being γ-ray momenta in a cascade. Polarization of the initial state was achieved by either capture of polarized thermal neutrons or low-temperature nuclear orientation. The precision obtainable by this method was limited by the inherent low count rate in a coincidence experiment. If, however, the linear polarization $\vec{E}$ is determined in addition to the direction of a γ ray, terms of the form $(\vec{J}\cdot\vec{k}\times\vec{E})(\vec{J}\cdot\vec{k})\times(\vec{J}\cdot\vec{E})$ can be measured. By measuring the absorption of linearly polarized recoiless γ rays in a magnetic medium, several authors[7-9] have established good limits on $\sin\eta$. This method is unfortunately hampered by multiple scattering, Faraday rotations, and large final-state effects.

We report here a new approach to the measurement of the quantity $(\vec{J}\cdot\vec{k}\times\vec{E})(\vec{J}\cdot\vec{k})(\vec{J}\cdot\vec{E})$ based on nuclear polarization by means of low temperature and strong magnetic field. The case chosen is