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Multipolarities of nuclear transitions involved in the one neutron disintegration of ^{238}U[†]

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Measurements of the electrodisintegration cross section $^{238}U(e,e',n)^{237}U$ in the energy region 6–25 MeV are presented. A virtual photon analysis of experimental data shows that neutron emission occurs only through $E1$ absorption. Our data establish an upper limit to the strength of $E2$ transitions, which is only 0.25% of the $E1$ transitions. Existing data on the decay channels of the isoscalar giant quadrupole resonance in ^{238}U are compared with available data on $E2$ absorption by this nucleus. A discussion of available experimental data indicating a selectivity of decay modes on the spin and parity of the excited resonance is presented. The sensitivity of electrodisintegration cross sections to the existence of quadrupole components is assessed.

[NUCLEAR REACTIONS $^{238}U(e,e',n)$; $E = 6–25$ MeV; measured $\sigma_{e,n}(E)$; DWBA virtual photon analysis, deduced photoabsorption λL.]

I. INTRODUCTION

It has been shown, by the branching between (γ,n), $(\gamma,2n)$, and $(\gamma,3n)$ cross sections, that once the photonuclear giant resonance (PGR) has been excited, its decay mode is predominantly statistical.[1] In heavy nuclei, in the energy region below the threshold for $2n$ disintegration, the decay is dominated by one neutron emission, as Coulomb barrier inhibits charged particle emission.

The PGR is actually composed of an isovector giant dipole resonance (GDR) plus an isoscalar giant quadrupole resonance (GQR) and possibly other multipole modes.[2] The GQR and GDR, located at $63/A^{1/3}$ MeV and $80/A^{1/3}$ MeV, respectively, are in the energy region where neutron emission is the dominant decay mode of the PGR. As there is no known selection rule which forbids a dipole or quadrupole resonance to decay by neutron emission, one would expect that the decay of both the GDR and GQR are similarly dominated by neutron emission.

It is difficult, however, owing to their relative strength, to obtain the dipole and quadrupole components from measurements of (γ,n) cross sections.

In this paper we present measurements of the absolute electrodisintegration cross section $^{238}U(e,e',n)^{237}U$. These measurements have been performed in order to study the strength of $E1$ and $E2$ contributions to this reaction.

As it is well known,[3,4] the $E2$ virtual photon spectra are one order of magnitude bigger than the corresponding $E1$ spectra for high-Z nuclei (see Fig. 1). Consequently, measurements of the electrodisintegration cross section are a sensitive tool for the study of $E1$ and $E2$ contributions in a particular decay channel of the PGR. We discuss below the sensitivity of this method.

II. VIRTUAL PHOTON METHOD

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

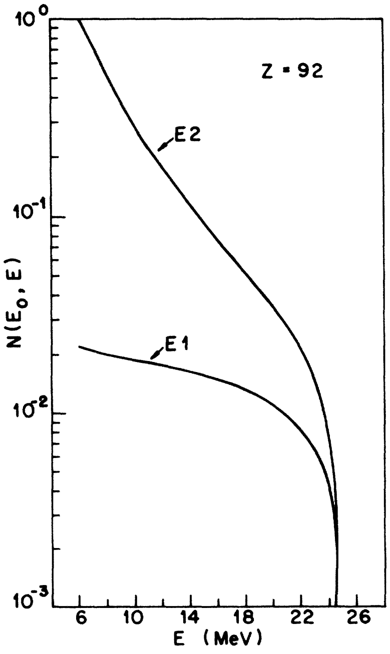

FIG. 1. Electric dipole and quadrupole virtual photon spectra for electrons of kinetic energy 24.5 MeV, scattered by a uranium nucleus.

photodisintegration process through

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

where E_0 is the electron incident energy, E is the photon energy, $N^{\lambda L}$ is the virtual photon spectrum, and $\sigma_{\gamma,x}^{\lambda L}(E)$ is the photodisintegration cross section through a nuclear transition of multipolarity λL. Computable expressions for $N^{\lambda L}$ have been obtained by Gargaro and Onley[4] using distorted wave approximation.

It is convenient to study how the existence of a quadrupole component in the one neutron photodisintegration of ^{238}U would show up in the electrodisintegration cross section. Let us then assume that the measured (γ,n) cross section $(\sigma_{\gamma,n})$ is composed by a dipole $(\sigma_{\gamma,n}^{E1})$ plus a quadrupole $(\sigma_{\gamma,n}^{E2})$ component. Using expression (1), the electrodisintegration cross section can be evaluated by:

$$\sigma_{e,n}^{E1+E2}(E_0)=\int_0^{E_0}\{\sigma_{\gamma,n}(E)N^{E1}(E_0,E)+\sigma_{\gamma,n}^{E2}(E)[N^{E2}(E_0,E)-N^{E1}(E_0,E)]\}E^{-1}dE\,, \tag{2}$$

where we have assumed

$$\sigma_{\gamma,n}^{E2}=\sigma_{\gamma,n}-\sigma_{\gamma,n}^{E1}. \tag{3}$$

In this paper we will use for $\sigma_{\gamma,n}$ the available experimental data of Veyssière *et al.*[5] and Dickey and Axel.[6]

To assess the sensitivity of the electrodisintegration cross section to the quadrupole strength we have evaluated expression (2) representing $\sigma_{\gamma,n}^{E2}$ with a Breit-Wigner formula of area S, peak position E_p, and width Γ. We have used $S=35$ MeV mb, which corresponds to 50% of the energy-weighted sum rule (EWSR),[7] $\Gamma=3$ MeV, a typical width for high-Z nuclei[8] and $E_p=10$ MeV, in accordance with the observed $63/A^{1/3}$ dependence for the excitation energy of the GQR.[9]

We then compare the evaluated $\sigma_{e,n}^{E1+E2}$ with the expected electrodisintegration cross section in the case of a pure E_1 process $(\sigma_{e,n}^{E1})$, which is evaluated setting $\sigma_{\gamma,n}^{E2}=0$ in expressions (2) and (3). In Fig. 2 the ratio of the calculated cross sections $\sigma_{e,n}^{E1+E2}$ and $\sigma_{e,n}^{E1}$ is shown.

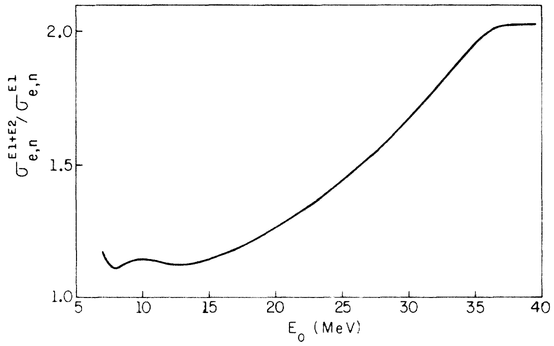

FIG. 2. Ratio of the calculated cross sections $\sigma_{e,n}^{E1+E2}/\sigma_{e,n}^{E1}$ versus electron kinetic energy. $\sigma_{e,n}^{E1+E2}$ is obtained by assuming that the measured (γ,n) is composed by a GDR plus a GQR which exhausts 50% of the EWSR. $\sigma_{e,n}^{E1}$ is obtained by assuming the measured (γ,n) to be a pure $E1$ process.

The assumed $\sigma_{\gamma,n}^{E2}$ has a small peak cross section of 7.4 mb as compared with the measured $\sigma_{\gamma,n}$ which is 192.0 ± 7.1 mb[5] at 9.95 MeV of excitation energy and has an integrated strength of only 3% of the measured $\sigma_{\gamma,n}$ integrated strength.[10] As can be seen from Fig. 2, this $\sigma_{\gamma,n}^{E2}$ that would be very difficult to identify in (γ,n) measurements has a considerable contribution in $\sigma_{e,n}$. At 25 MeV it contributes 50% to the electrodisintegration cross section.

While the GQR has been extensively studied by inelastic scattering, which measures the quadrupole absorption by the nucleus, the study of its decay modes has been restricted to measurements of inverse capture reactions.[11] This technique limits the experimental information to the cases where the residual nucleus is stable and to those decays that lead directly to the ground state of the residual nucleus. Measurements of the angular distribution of the emitted particle in photonuclear reactions are limited to the region near the threshold of the decay channel, since it depends on the spin state of the residual nucleus, which can be left in an excited state. Coincidence measurements between the emitted particle and the cascade γ rays, or between the emitted particle and the scattered projectile, are very difficult with presently available techniques.

The high sensitivity of the electrodisintegration cross section to quadrupole absorption offers the possibility of studying the decay channels of the GQR through feasible experiments. The multipolarity assignment from such measurements depends on the reliability of the virtual photon method, which derives from quantum electrodynamics. The best test of this method is to compare its theoretical predictions with experimental measurements of σ^-/σ^+, the ratio of the cross sections for nuclear excitations by electrons and positrons. Apart from the fact that electrons are attracted by the nucleus while positrons are repelled, all other electromagnetic interactions are identical and the differences in the cross sections have little to do with the physics of the nucleus, being purely consequences of electrodynamics. It has been shown[12] that the distorted-wave Born approximation (DWBA) calculations of Gargaro and Onley are in good agreement with experimental data on σ^-/σ^+ as a function of the nuclear atomic number and electron incident energy. Similarly, these calculations are in good agreement with available measurements on the ratio of photo-to electro-disintegration.[13,14]

III. MEASUREMENTS AND ANALYSIS

Very thin uranium targets (thickness of the order of 10^{-5} radiation lengths), placed in a vacuum chamber, were bombarded in the electron linear accelerator of Universidade de São Paulo. The electron flux was measured in a Faraday cup. The amount of ^{238}U in the targets was determined by α spectroscopy. The cross section was obtained by measuring the activity of the 59.5 KeV γ-ray line from the 6.75 day decay of ^{237}U using a Ge-Li low energy photon spectrometer system. A typical pulse height spectrum is shown in Fig. 3.

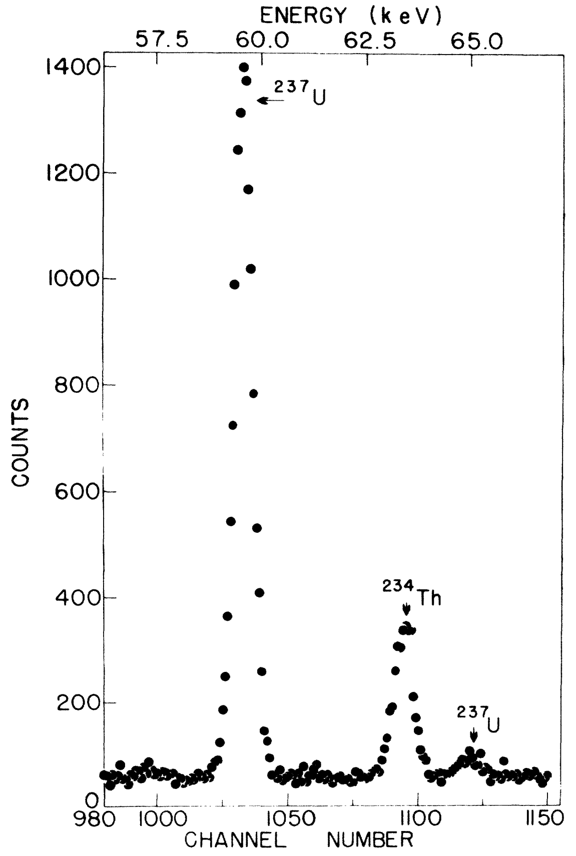

FIG. 3. Typical pulse height spectrum showing the 59.5 KeV γ-ray line from the 6.75 day decay of ^{237}U.

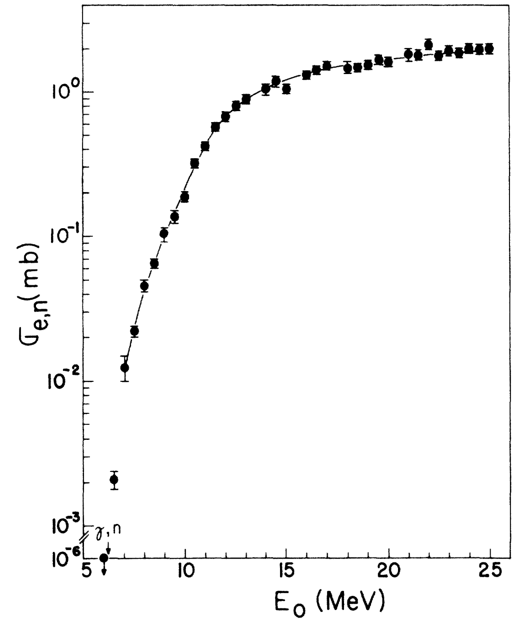

FIG. 4. Experimental cross section for the reaction ^{238}U$(e,e',n)^{237}$U versus electron kinetic energy. The point at 6.0 MeV is an upper limit to the cross section. The full curve is the predicted electrodisintegration cross section for a pure $E1$ process. No free parameters adjusted.

In Fig. 4 the experimental cross section for the reaction $^{238}(e,e',n)^{237}$U, as a function of the electron incident energy, is shown as full circles. The errors indicated include the statistical uncertainties of the measured quantities and the estimated contributions arising from electron flux measurements, target nonuniformity, and target positioning relative to the electron beam and detector. The point at 6.0 MeV is an upper limit. The full curve is the predicted electrodisintegration cross section for a pure $E1$ process $(\sigma^{E1}_{e,n})$ obtained using $\sigma_{\gamma,n}=\sigma^{E1}_{\gamma,n}$ in expressions (2) and (3). In Fig. 5 the ratio of our experimental data to the predicted $\sigma^{E1}_{e,n}$ is shown by the points. The errors refer only to the uncertainty of our experimental points. This ratio shows no evidence of an increase with the electron incident energy that is expected in the case of significant $E2$ contribution. Actually, the best straight line fit to the points, shown by the full curve, yields a negligible slope, leading to a constant ratio with value 1.038 ± 0.009. Our results are 4% higher than those obtained from the $\sigma_{\gamma,n}$ data and can be interpreted as a very good

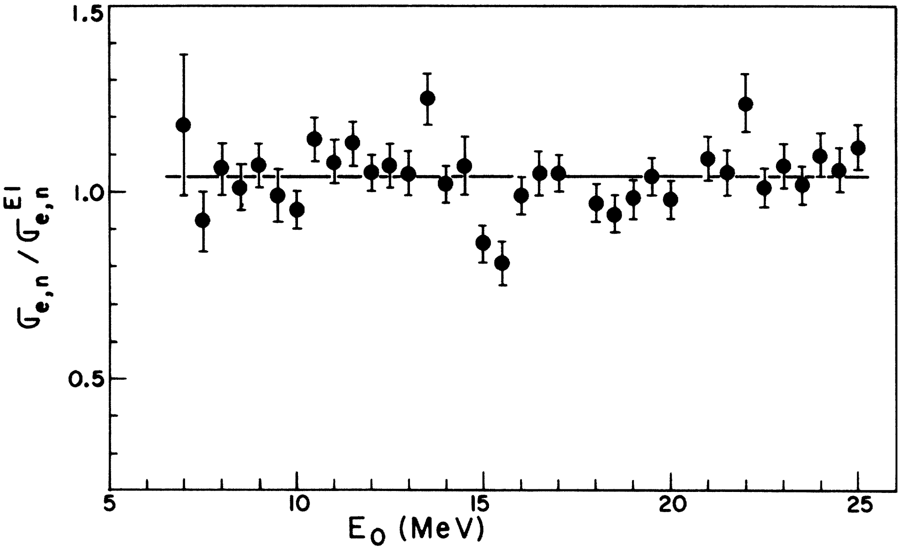

FIG. 5. The ratio of our experimental cross section to the predicted cross section for a pure $E1$ process is shown by the points. The full curve shows the best straight line fit to the points.

agreement between two absolute values of the same physical quantity measured by different methods. The difference is well within quoted errors. Hereafter we have divided our experimental values by 1.038 to merge both absolute measurements.

In order to establish an upper limit to the $E2$ contribution allowed by our data, we carried out a least squares fit to the experimental data, using expression (2) and representing $\sigma_{\gamma,n}^{E2}$ by a Breit-Wigner formula with $E_p = 10$ MeV, $\Gamma = 3$ MeV, and variable S. The best fit is obtained for $S = 0$ corresponding to $\sigma_{\gamma,n}^{E2} = 0$. At the 95% confidence level the integrated $\sigma_{\gamma,n}^{E2}$ exhausts 8% of the EWSR. This upper limit corresponds to only 0.25% of the $\sigma_{\gamma,n}$ integrated cross section.[10]

IV. DISCUSSION

Our results show that no neutron emission from 2^+ states is observed, setting a small upper limit for this decay. This is a rather unforeseen result, since, at 9.95 MeV excitation energy, the measured[5] $\sigma_{\gamma,n}$ is 192.0 ∓ 7.1 mb, $\sigma_{\gamma,\mathrm{Total}}$ is 252.0 ∓ 5.0 mb, and, from statistical considerations, the same dominance of the neutron channel in the GQR would be expected.

Evidence of the selectivity of the decay mode on the multipolarity of the excited resonance is already contained in some available experimental data as presented below.

According to Hanna,[11] (γ, α_0) cross sections, measured through the inverse capture reaction (α, γ_0), show that α emission is 10 times more probable by $E2$ than by $E1$ absorption. Recently, Wolynec, Martins, and Moscati[3] have shown, by measuring the cross section for $^{238}\mathrm{U}(e, e', \alpha)^{234}\mathrm{Th}$, that the (γ, α) reaction proceeds dominantly through $E2$ transitions. Using a virtual photon analysis, it was shown that the amount of absorbed $E2$ strength used for the (γ, α) reaction exhausts 50% of the EWSR. These data locate $\sigma_{\gamma,\alpha}^{E2}$ at the excitation energy of 9 MeV, with a width of 3.7 MeV full width at half maximum (FWHM).

Preliminary data on the absolute electrofission cross section and the angular distribution of fission fragments in $^{238}\mathrm{U}$ indicate that a significant fraction of the EWSR is exhausted by this channel, the quadrupole component being concentrated around 10 MeV. The (e, e', α) and (e, e', f) results indicate that for $^{238}\mathrm{U}$ the dominant modes of decay of the GQR are the α and fission channels. These results associated with the $E1$ character of $^{238}\mathrm{U}(e, e', n)^{237}\mathrm{U}$ indicate that we are in the presence of some previously unknown selection rule. We would like to comment on how such selection rule could be compatible with established statistical behavior of nuclear decay channels.

In the framework of the hydrodynamical model, which describes so well the general features of the GDR, isovector dipole oscillations are described as oscillations of protons against neutrons, while isoscalar $E2$ oscillations are described as mass density oscillations.[15] It could be that, once the $E1$ oscillations are excited, the nucleus would deexcite dominantly through evaporation of neutrons or protons, the relative strength of these channels being statistical in nature, as is revealed by the branching between

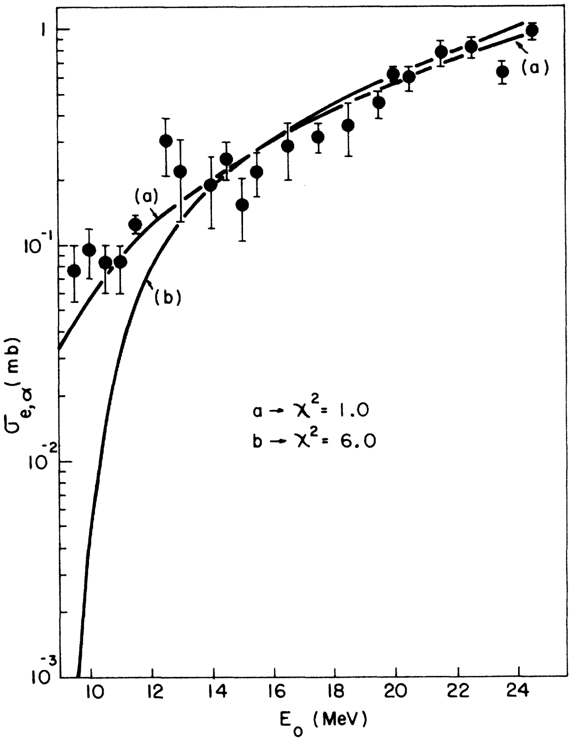

FIG. 6. Experimental cross section for the reaction ^{238}U(e,e',α)^{234}Th from Ref. 3. Curve (a) shows the predicted electrodisintegration cross section for $\sigma_{\gamma,\alpha}$ being a pure $E2$ process and represented by a Breit-Wigner with $S = 28$ MeV mb, $E_p = 8.9$ MeV, and $\Gamma = 3.7$ MeV (see Ref. 3). Curve (b) shows the predicted electrodisintegration cross section using for $\sigma_{\gamma,\alpha}$ the $E2$ resonance from Ref. 16 with a strength of 90% of the EWSR, which leads to the lowest reduced χ^2. The reduced χ^2 of both curves to the experimental data are indicated.

(γ,n), ($\gamma,2n$), and ($\gamma,3n$). When the isoscalar oscillations are excited, as they do not separate neutrons from protons, the nucleus would deexcite dominantly by emission of deuterons, α particles, etc., the relative strengths of these channels being statistical in nature.

We would like to discuss the compatibility of the ^{238}U(e,e',α)^{234}Th measurements with the only available data on electric quadrupole absorption by ^{238}U.

Lewis and Horen[16] observed a resonance in (p,p') inelastic scattering from ^{238}U, in the energy region 10–14 MeV, tentatively assigned as $E2$, exhausting (85 ± 50)% of the EWSR. No structure was seen below 10 MeV.

In Fig. 6 we reproduce the experimental data on the ^{238}U(e,e',α)^{234}Th cross section. Curve (a) shows the predicted electrodisintegration cross section for $\sigma^{E2}_{\gamma,\alpha}$ represented by a Breit-Wigner formula of $S = 28$ MeV mb, $\Gamma = 3.7$ MeV, and $E_p = 8.9$ MeV. These parameters yield the best fit to the points.[3]

Curve (b) shows the predicted electrodisintegration cross section, using for $\sigma^{E2}_{\gamma,\alpha}$ the resonance observed by Lewis and Horen with a strength which exhausts 90% of the EWSR. We have computed the reduced χ^2 value for different strengths of this resonance. In the region from 80% to 100% of the EWSR the obtained values are around 6. Outside this region we obtain significantly higher values. As can be seen, the resonance observed by Lewis and Horen is incompatible with the (e,e',α) data. The impossibility of improving the fit by changing the strength is related to the sensitivity of the fit on the peak position of the $E2$ resonance. It is impossible to fit the electrodisintegration results with a resonance that has negligible strength below 10 MeV.

V. CONCLUSIONS

The electrodisintegration absolute cross section measurements ^{238}U(e,e',n)^{237}U performed in this work show that the one neutron emission proceeds exclusively through $E1$ absorption. We have set an upper limit to $E2$ transitions of only 0.25% of the $E1$ transitions in this channel. This result indicates that we are in the presence of some previously unknown selection rule.

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