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Isovector Giant Quadrupole Resonance in ^{63}Cu

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Abstract The decay of the isovector E2 giant resonance in ^{63}Cu has been studied by measuring the $(e,2n)$ cross section, in the incident electron energy range 22-45 MeV. The photodisintegration induced by bremsstrahlung was also measured. The electrodisintegration results have been analyzed using the distorted wave Born approximation $E1$ and E2 virtual photon spectra to obtain these multipole components in the corresponding $(\gamma,2n)$ cross section. It is found that the isovector E2 giant resonance decays dominantly by two-neutron emission in ^{63}Cu. This decay channel exhausts 65 percent of the energy weighted E2 sum.

1. INTRODUCTION

The possible existence of a giant quadrupolr resonance was discussed soon after the explanation of the nuclear photoeffect[1]. The latter was explained as a dipole oscilation of the nucleus[2]. Using the excitation energy $E_x(E1)$ of the giant dipole resonance (GDR) as normalization, the excitation energy of the corresponding quadrupole mode, $E_x(E2)$, was calculated based on hydrodynamical analogies and found to be 1.6 times $E_x(E1)$ [3]. Microscopic models for the $E1$ were developed later', but since the dipole resonance has no experimentally identifiable isoscalar part, there was no immediate need to consider separately isoscalar and isovector interactions. The attempt to unify the macroscopic and microscopic treatment of the giant dipole resonance[5] led to the incorporation of isospin-dependent particle-hole interactions into the microscopic model[4]. The unified description leads to the prediction of a splitting of all giant modes into isovector and isoscalar parts. The isoscalar parts are always lower in energy than the unperturbed state because of the attractive nature of the isoscalar particle-hole force, while the isovector parts are higher in energy. For the case of quadrupole excitations the unperturbed energy of $2\hbar\omega_0 = 80A^{-1/3}$ MeV changes into $\sim 60A^{-1/3}$ MeV for $\Delta T = 0$ and $\sim 130A^{-1/3}$ MeV for $\Delta T = 1$ [6].

For the isoscalar giant quadrupole resonance there is already a good systematics in the literature[7,8]. Most of the data about this collective mode come from hadron inelastic scattering, which selectively excites isoscalar modes. For the isovector quadrupole mode there is comparatively little experimental evidence. Since isovector excitations are suppressed in hadronic interactions, the evidence comes from electromagnetic experiments: capture reactions and electron scattering. Capture reaction measurements can give direct indication of the isoscalar and isovector nature of excitations by comparing magnitude and sign of the appropriate Legendre coefficients in, e.g., (γ,p_0) and (γ,n_0) angular distributions. However they observe only that part of the isovector quadrupole mode that decays to the ground state of the residual nucleus, which is usually only a few percent of the total strength. Inclusive electron scattering excites all modes and it is very difficult to separate them. As an example, fig. 1 shows the decomposition of the electron scattering cross section in ^{63}Cu into isovector $E1$ and E2 and isoscalar E2 resonances[2]. From this decomposition the isovector quadrupole is located around 32 MeV excitation energy and exhausts 82% of the corresponding sum rule.

It has to be pointed out that inclusive electron scattering has to take recourse to general theoretical expectations and to comparison with hadron inelastic scattering, which suppresses isovector excitations, in order to establish evidence for the isonature of a certain excitation. Furthermore, since the isovector E2 resonance appears in the tail region of the E1, the strength is very dependent on the radiative tail subtraction, as can be seen in fig. 1, Apart from that, there is an increased model dependence of these results as compared to those for the isoscalar resonance. While for the latter it is generally accepted that it can be represented accurately enough by a surface oscillation (Tassie model, Goldhaber-Teller model), this may no longer be true for isovector oscillations, as has been shown for the dipole case[10]. Another point is that isovector sum rules are not as model independent as isoscalar sums, because of the effects of exchange contributions. The the isovector energy weighted sum rule, which is obtained from the isoscalar one replacing Z^2 by NZ, has to be regarded as a lower limit for the isovector strength.

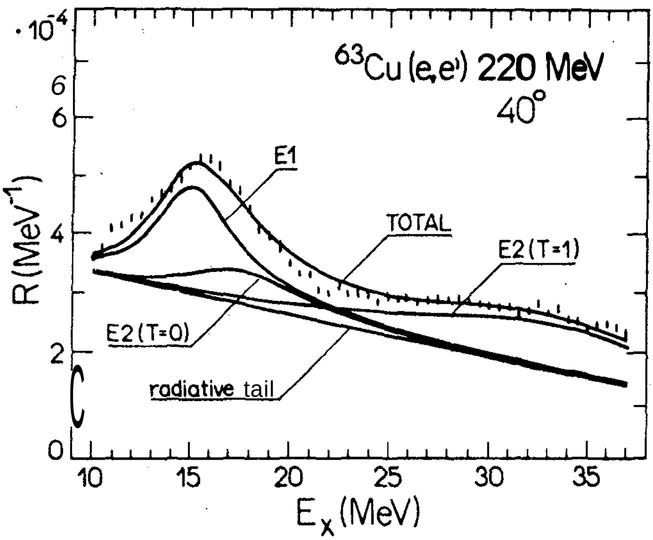

Fig.1 - isovector E1 and E2 and isoscalar E2 giant resonances observed in electron scattering in ^{63}Cu[9].

Fig. 2 shows the location of the isovector *E2* resonance in several nuclei. The data are from electron scattering and capture reactions and were obtained from the compilations of Bertrand[7] and Pitthan[11] plus the recent data of ref. 9. As fig. 2 shows, the isovector E2 is located at $120\text{-}130A^{-1/3}$ MeV for most nuclei. According to ref. 11 the isovector *E2* mode exhausts ~100% of the energy weighted sum in most nuclei.

Since we have poor information on the isovector *E2* mode as yet, a better knowledge of this mode is of great interest. The reason is that we can learn about features that are not present inthe isoscalar mode. The main properties which influence the isovector strengths, which play little or no role for the isoscalar case, are velocity-dependent and exchange effects in nuclear interactions[6]. Once we have learned to measure the isovector resonances accurately and to evaluate results independent of model, we will have more stringent tests of nuclear models.

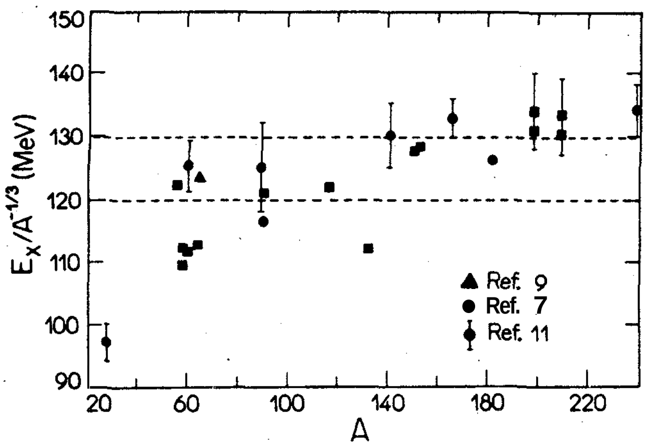

Fig.2 - Systematics for the excitation energy of the isovector E2 qiant resonance versus the atomic mass A.

Apart from the lack of accurate data on the isovector quadrupole mode, there is no data about its decay properties. There is recent evidente that the decay of giant resonances is dominantly statistical[12]. If this is also the behaviour of the isovector quadrupole mode, we would expect that in ^{63}Cu it would decay dominantly by emission of two neutrons, since this is the dominant decay mode of photoabsorption arqund 32 MeV excitation energy. The (γ,n) decay channel becomes vanishingly small above 27 MeV [13]. This has motivated us to search for the isovector $E2$ in the $(\gamma,2n)$ decay channel.

In this paper we report measurements of the $(\gamma,2n)$ electrodisintegration cross section in ^{63}Cu. In order to perform the multipole decornposition, the virtual photon method is used.

2. THE VIRTUAL PHOTON METHOD

During the last decade the study of the giant multipole resonances, together with the emergence of virtual photon calculations using the distorted-wave Born approximation (DWBA) of Onley and collaborators[14-17], have Jointly stimulated a renaissance of interest in electrodisintegration experiments.

The basic premise of the virtual photon technique is that the electrodisintegration cross section, $\sigma_{e,x}(E_0)$, for incident electrons of energy E_0, can be expressed in terms of the photonuclear cross section, $\sigma^{\lambda L}_{\gamma,x}(E)$ associated with the absorption of real photons of energy E and multipolarity λL through the virtual photon spectrum, $N^{\lambda L}(E_0,E,Z)$

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

In fig. 3 the $E1$ and E2 DWBA virtual photon spectra for electrons of incident energy 45 MeV are shown for Cu. The advantage of an electrodisintegration experiment is that it enhances E2 absorption, because the E2 spectrum is bigger than E1. Even though virtual photon spectra for finite nuclei are already available[17], throughout this work we will use DWBA spectra for a point nucleus, because for the energy range considered here in ^{63}Cu size corrections are negligible.

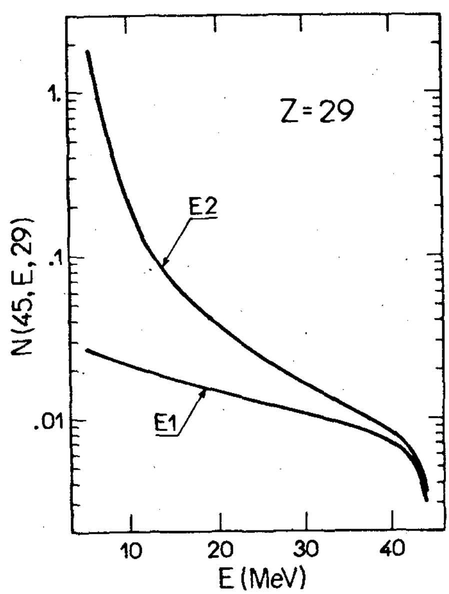

Fig.3 - $E1$ and E2 virtual photon spectra for 45 MeV electrons inelastically scattered from a copper nucleus.

The enhancement of the E2 relative to the $E1$ virtual photon spectra has already been exploited in several experiments to study E2 absorption by nuclei, e.g. references 18-21. In these experiments the photodisintegration cross section induced by bremsstrahlung, $\sigma_{br,x}(E_0)$, is also measured by interposing a radiator ahead of the target:

$$\sigma_{br,x}(E_0) = N_r \int_0^{E_0-m} \sum_{\lambda L} \sigma_{\gamma,x}^{\lambda L}(E) K(E_0,E,Z) \frac{dE}{E} \qquad (2)$$

where N_r is the number of nuclei/cm^2 in the radiator and $K(E_0, E,Z)$ is the bremsstrahlung cross section. By using the radiator the multipole composition of the photons seen by the target is changed. For ^{63}Cu and the energies involved here the virtual spectrum contains about twice as many E2 photons as $E1$ photons, but the bremsstrahlung spectrum has no preferred multipoles.

Several experimental checks of the DWBA virtual photon spectra have been made[21-25], but the most accurate of these tests was an experiment where an isochromat of the $E1$ virtual photon spectrum was measured by counting the number of ground-state protons emitted by the 16.28 MeV isobaric analogue state in ^{90}Zr as a function of incident electron energy[25]. The experimental results agree with those predicted by the virtual photon calculation within the experimental error of one percent.

The bremsstrahlung cross section which enters in eq.(2) has also been subjected to experimental tests[26]. It was shown that the Davies-Bethe-Maximon bremsstrahlung cross section, which will be used in this work, is in excellent agreement with photodisintegration experimental results above 28 MeV.

3. THE EXPERIMENT

The ^{63}Cu$(e,2n)$ cross section was measured by residual activity. The residual nucleus ^{63}Cu decays by β^+ (62%) and electron capture (38%) to ^{61}Ni [27]. We have followed the decay by detecting the 67.4 keV γ-ray line that results from the decay to ^{61}Ni, using a Ge-Li detector system.

The targets (five) used are 99.89 enriched ^{63}Cu with a thickness of 10.16 ± 0.10 mg/cm^2 measured by weighing. The targets were activated in the electron beam of the São Paulo Linear Electron Accelerator. The LINAC current was measured by a Faraday Cup.

We have also measured the photodisintegration induced by bremsstrahlung using a 0.358 g/cm^2 copper radiator, placed in the electron beam just ahead of the target. The LINAC current wasmeasuredusing a secondary emission monitor calibrated relative to a Faraday, Cup. The measured yields were corrected for energy loss of electrons in the radiator and the electrodisintegration produced in the targets was subtracted.

The results obtained for the electrodisintegration cross section and the bremsstrahlung induced photodisintegration are shown in fig. 4 by the open and full circles respectively.

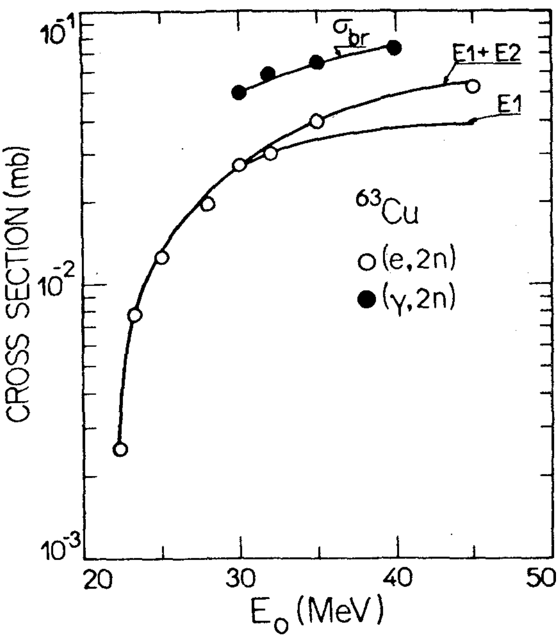

Fig.4 - $\sigma_{e,2n}(E_0)$ for ^{63}Cu (open circles) and the photodisintegration induced by bremsstrahlung (full circles). The statistical errors are of the size of the points or smaller. The smooth curves (E1+E2) and σ_{br} are the best fit to the data (see text).

4. DIXUSSION

In order to decompose our experimental electrodisintegration cross section in terms of *E*1 and *E2* contributions we write eq.(1) as:

$$\sigma_{e,2n}(E_0) = \int_0^{E_0-m_e} \sigma_{\gamma,2n}(E) N^{E1}(E_0,E,z)\frac{dE}{E} + \int_0^{E_0-m_e} \sigma^{E2}_{\gamma,2n}(E)\left[N^{E2}(E_0,E,Z) - N^{E1}(E_0,E,Z)\right]\frac{dE}{E} \quad (3)$$

Since the $(\gamma,2n)$ threshold is at 19.7 MeV, in the energy range covered by our experiment the multipoles that are expected to contribute are the isovector $E1$ and isovector $E2$. Around 30 MeV there should also be the isoscalar E3 mode, but it gives negligible contribution to the electrodisintegration cross section (see ref.21). In eq. (3) we use for $\sigma_{\gamma,2}(E)$ available photonuclear data[2']. Since the photonuclear data do not distinguish different multipoles we are assurning:

$$\sigma_{\gamma,2n} = \sigma^{E1}_{\gamma,2n} + \sigma^{E2}_{\gamma,2n}$$

or $\quad (4)$

$$\sigma^{E1}_{\gamma,2n} = \sigma_{\gamma,2n} - \sigma^{E2}_{\gamma,2n}$$

For $\sigma^{E2}_{\gamma,2n}$(E) we will use a Lorentzian shape with peak at $120A^{-1/3}$ (E_p = = 30 MeV) and a width of 8 MeV. The systematics for the isovector $E2$ indicates that it is a broad resonance as illustrated in fig. 1.

The curves labelled $(E1+E2)$ and σ_{br} shown in fig.4 are the best fits to our data using eq. (3) for the electrodisintegration cross section and eq. (2) for the brernsstrahlung yield simultaneously. Fig.5 shows the photonuclear data from ref. 28 decornposed into $E1$ and E2, as obtained from the fit to our data. Just to illustrate the effect, curve labelled $E1$ in fig. 4 is the result of integrating the cross section of fig. 5 assuming it is all $E1$. The difference between curves $(E1+E2)$ and $E1$ is 40% at 45 MeV. The calculated photodisintegration yield, of course, remains unchanged if we assume that the photonuclear cross section is all $E1$. The difference between curves $(E1+E2)$ and $E1$ shows the sensitivity of electrodisintegration cross section to the multipole cornposition of the photonuclear process. The isovector E2 cornponent obtained from the fit exhausts 65 percent of the energy weighted sum. This result

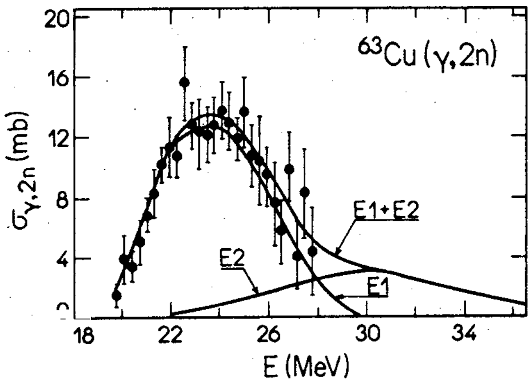

Fig. 5 - The data points show the photonuclear cross section (γ,2n) from ref.28. The curves show the decornposition into E1 and E2 components.

is consistent with the electron scattering result of ref. 9, which finds that the isovector E2 exhausts 82 percent of the corresponding sum. Since we observed only the dominant decay channel, the remaining strength can be in other channels $(\gamma,pn;\gamma,2p;\ldots)$.

5. CONCLUSIONS

We have measured the $(e,2n)$ cross section for ^{63}Cu. Combining this measurement with photodisintegration induced by bremsstrahlung we have shown that the $(e,2n)$ cross section is the dominant decay channel for the isovector E2 resonance in this nucleus, exhausting 65 percent of the energy weighted sum.

The electrodisintegration cross section can be used as an important tool to measure the decay of E2 strength in nuclei.

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Resumo

O decaimento da ressonância gigante isovetorial de quadrupolo elétrico no ^{63}Cu foi estudado através da medida da secção de choque $(\gamma,2n)$, usando-se elétrons de energia 22-45 MeV. A fotodesintegração induzida por bremsstrahlung foi também medida. Os resultados da eletrodesintegração foram analisados usando-se os espectros de fótons virtuais $E1$ e E2 calculados na aproximação de Born de ondas distorcidas, a fim de se obter a composição multipolar de processo $(\gamma,2n)$ correspondente. Obtemos que a ressonância gigante isovetorial *E2* decai dominantemente pela emissão de dois nêutrons. Esse canal de decaimento esgota 65 por cento da correspondente regra da soma ponderada em energia.