UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01000 - SÃO PAULO - SP
BRASIL

publicações

IFUSP/P-382

HYDRODYNAMIC MODELS FOR THE GIANT DIPOLE RESONANCES

by

J.D.T. Arruda-Neto

Instituto de Física, Universidade de São Paulo

janeiro/1983

HYDRODYNAMIC MODELS FOR THE GIANT DIPOLE RESONANCE

J.D.T. Arruda-Neto

Instituto de Física, Universidade de São Paulo, Brazil

ABSTRACT

The interplay between the experimental photonuclear E1-form factors and the theoretical predictions of the Goldhaber-Teller, Steinwedel-Jensen, and Droplet models was investigated. It was found that the Goldhaber-Teller displacement mode alone describes the main trend of the experimental form factors, as a function of the mass number. Also, it was verified that the Droplet model, while describring well the centroid energy of the E1- resonances, does not describe the form factors in terms of a mixture of the Goldhaber-Teller and Steinwedel-Jensen modes.

INTRODUCTION

The Giant Dipole Resonances (GDR) of the photo-induced reactions have been found to be a general feature of all nuclei since their first observation by Baldwin and Klaiber in 1947; they show almost the same behavior and the properties change only smoothly with the particle number A[1].

The explanation of the GDR in terms of a collective motion goes back to a suggestion by Goldhaber and Teller[2] (GT) on the basis of a few early experiments. According to the displacement mode picture of the GDR proposed by GT, this resonance is explained in terms of a vibration of a proton sphere against a neutron sphere; the restoring potential against the separation of protons and neutrons is the symmetry energy. This model gives an A-dependence of the centroid energy as $A^{-1/6}$. They have also proposed the more sophisticated two-fluid model, later worked out by Steinwedel and Jensen[3] (SJ), where the GDR might consist of density vibrations of the neutron and proton fluids against each other with the surfaces fixed; this corresponds to the lowest acoustic mode in a spherical cavity and gives the correct A-dependence of the centroid energy, $A^{-1/3}$. However, the SJ model is restricted to spherical nuclei; the extension to statically deformed nuclei was carried out by Danos and Okamoto[4] and , then, Danos and Greiner[5] coupled the giant resonances to the vibrations and rotations of strongly deformed nuclei. The coupling of the giant resonances to the low-energy spectrum of spherical nuclei has been investigated in the framework of a harmonic vibrator model[6,7].

In an atempt to explain more accurately the energy A-dependence for the excitation of the GDR, Myers et al.[8] suggested a new macroscopic description; they considered the GDR as a superposition of GT and SJ modes. As a consequence, the GDR was found to contain a large component of the GT-type of motion, with the SJ mode becoming comparable for heavy nuclei. The restoring forces were all calculated using the Droplet Model[8], and the actual magnitude of the energies serves to fix the value of the effective mass m* used in the theory.

However, the form factor of the GDR (and ony other giant resonance), evaluated at the photon point ($q=\omega$), is a rich source of information about the nuclear structure. The form factor, which can be deduced from the strength (represented by the integrated cross section), is proportional to the total reduced transition probability. This latter quantity is a property of the nuclear levels involved in the transition. Therefore, in this sense, it is more difficult to draw general conclusions in terms of the relative amounts of the SJ and GT modes as a function of A, as is not the case for the centroid energy of the GDR (after Myers *et al.*[8]).

In this paper we plan to analyse the behavior of the GDR--form factor, as a function of A, by comparing experimental results and the predictions of the GT and SJ models.

HYDRODYNAMIC FORM FACTORS

For a complete discussion of the hydrodynamic models, including several refinements to the classical descriptions we refer the reader to the book of H. Überall[9] and ref. 8.

In their simplest forms (spherical nuclei and no mesonic effects included) the tranverse E1 form factors obtained from the GT and SJ models are[9,10]:

A) Goldhaber-Teller

$$\left|\langle 1^- \| \hat{T}_1^{el}(q) \| 0\rangle\right|^2 = \frac{NZ}{A}\,\frac{\omega_1 F^2(q)}{4\pi m_p} \qquad (1)$$

where ω_1 is the excitation energy of the GDR, m_p the proton mass, $F(q)$ is the ground state form factor normalized such that $F(0) = 1$ and expandend as

$$F(q) = 1 - \frac{1}{6} q^2 \langle R^2\rangle + \frac{1}{120} q^4 \langle R^4\rangle - \cdots ,$$

q is the momentum transferred to the nucleus, and R is the nuclear radius. The GT model (in its original form) does not provide any of the level energies, and thus these have to be taken from experiment, or from particle-hole calculations. Also, it can be shown that the matrix elements of the GT model exhaust the classical sum rule (TRK).

B) Steinwedel-Jensen

$$\left|\langle 1^- \| \hat{T}_1^{el}(q) \| 0\rangle\right|^2 = 24\left[\frac{\rho_0 R_0^2 K}{m_p^2\,\omega_1}\right]\left(\frac{ZN}{A^2}\right)^2\left[\frac{A_{100}}{q}\, j_1(qR_0)\, j_1(k_{10}R_0)\right]^2 \qquad (2)$$

where ρ_0 is the constant total density, K the nuclear symmetry energy, R_0 the nuclear radius assuming the nucleus as a rigid sphere, k_{10} is determined from the boundary condition $\left[\frac{d}{dr}\, j_\ell(k_{\ell n} r)\right]_{r=R_0} = 0$ for the giant dipole state ($\ell=1$) in the lowest state of excitation (n=0) and the amplitude A_{100} (ℓ=1, m=0, n=0) is given by

$$A_{\ell mn} = \left\{ j_\ell(k_{\ell n}R_0)\left[\frac{1}{2}R_0^3\left(1-\ell(\ell+1)/k_{\ell n}^2R_0^2\right)\right]^{\frac{1}{2}}\right\}^{-1} \qquad (3)$$

At $q = \omega$, the SJ model exhausts only ~ 87% of the TRK sum rule.

However, the GT model (in its original form) is more realistic[11] because it assumes a smeared nuclear surface, while in the SJ model this is taken as sharp.

PHOTONUCLEAR FORM FACTOR

If only electric transitions are considered, the absorption line integral of the nuclear photoabsorption cross section $\sigma(\omega)$ is given by

$$\sigma^{int} = \int_{abs.line} \sigma(\omega)\, d\omega = (2\pi)^3 \frac{\alpha}{\omega} \sum_\ell \left| \mathcal{F}_\ell^T(\omega) \right|^2 \cong$$

$$(2\pi)^3 \frac{\alpha}{\omega} \left| \mathcal{F}_1^T(\omega) \right|^2 \qquad (4)$$

where $\mathcal{F}_1^T(\omega)$ is the E1 transverse electric form factor evaluated at the photon point ($q = \omega$), that is

$$\mathcal{F}_1^T(\omega) = \langle 1^- \| \hat{T}_1^{el}(\omega) \| 0 \rangle \qquad (5)$$

Therefore, the integrated photoabsorption cross section gives us

one value of the inelastic form factor. It is worth remembering that the form factor $\mathcal{F}_\ell^T$ relates to the well known electric-reduced transition probability by

$$\left|\mathcal{F}_\ell^T(\omega)\right|^2 = \frac{(\ell+1)}{\ell[(2\ell+1)!!]^2}\, \omega^{2\ell} B(E\ell,\omega) \qquad (6)$$

In the present work we calculated $\left|\mathcal{F}_{1(\omega)}^T\right|^2$ from the experimentally determined σ^{int}[12] (eqn.4) for spherical and near-spherical* nuclei with A values ranging from 6 to 209 (data points in Fig.1). The curves labeled GT and SJ, in Fig.1, represent our model calculation of the E1-form factor according to the Goldhaber-Teller model (eqn.1) and the Steinwedel-Jensen model (eqn. 2), respectively. In this calculation we assumed a sharp nuclear surface with $R_o=1.2A^{1/3}$ (fm), the symmetry energy K equal to 25 MeV, and the excitation energy ω_1 of the GDR given by experimental results[12] (for both the GT and SJ models).

MESONIC EFFECTS

In deriving the results from equations 1 and (Fig. 1), it has been assumed the mass participating in the charge vibrations to be the mass of the free nucleon. However, owing to the exchange character of the nuclear forces, a charge can be displa

---

*(small static deformation)

ced from one nucleon to another one without a mass displacement. This affects the energy and the transition probability for exciting the giant resonances. As a first approximation we can take into account mesonic effects by introducing an effective mass m^* (mass renormalization): $m^* = m/(1+\alpha)$, where α is experimentally determined by the comparison of the integrated absorption cross section and the corrected classical sum rule:

$$\int \sigma(\omega)\, d\omega = 0.06 \left(\frac{NZ}{A}\right)(1+\alpha) \qquad (\text{MeV.b}) \qquad (7)$$

The physical quantity α is given by

$$\alpha = \left(\frac{A}{NZ}\right) \frac{m_p}{\hbar^2} \langle \phi_o | [[V, D_z], D_z] | \phi_o \rangle \qquad (8)$$

where D_z is the z - component of the electric dipole operator , $|\phi_o\rangle$ is the ground-state nuclear wave function, and V is the nucleon potential. The value of the factor α differs from zero if V includes exchange terms. Large values for α are mostly caused by the 2-body correlations in $|\phi_o\rangle$ and by the effect of the tensor force. We calculated the factor $(1+\alpha)$, using σ^{int} from experiment[12], and plotted it as a function of A (Fig. 2). As we observe, for A>90 we have the factor $(1+\alpha)$ fluctuating around 0.98 with a dispersion of ± 0.02. For $A \lesssim 90$ (and $Z \lesssim 40$) we obtained $(1+\alpha) < 1$. For light nuclei, however, Fujii[13] has shown that if a spin-orbit coupling is introduced which mixes 1^- - (isospin) and 1^-- (spin-isospin) states in the GT model, part of the dipole strength may get shifted up above the giant resonance, where it may be dispersed over a wide region of energy. Another mecha-

nism for shifting dipole strength to higher energies[14] would be the quasideuteron effect, i.e., the electromagnetic interactions taking place on a two-particle cluster[15].

DISCUSSION OF THE RESULTS

According to the macroscopic description of the GDR developed by Myers et al.[8] the motion is treated as a combination of the GT displacement mode and the SJ acoustic mode. In Fig. 3, taken from Ref. 8, is shown the ratio α_2/α_1, where the amplitudes α_2 and α_1 represent the amounts of the SJ and GT modes, respectively, as a function of the mass number A for three different cases: a) the "Super-Simple" solution; b) the Droplet Mode; and c) the "Exact Solution".

However, observing Fig. 1 we note, surprisingly, that , within the uncertainties, the GT mode alone describes reasonable well the photonuclear E1-form factor for A>50. Below A ≈ 50 the E1-strength is much more spread out in a wider energy region, as discussed before; that explains why the theoretical GT curve overestimates the experimental data for light nuclei. On the other hand, the E1-form factor deduced from the SJ mode overestimates the points till A ≈ 80 and underestimates above this value. The small structures in the GT and SJ curves arise from fluctuations in the experimental values of the GDR-centroid energies used in the calculation of those curves.

The main conclusion of the present work concerns the fact that the GT mode, in its simplest form, explains the main trend of the E1-form factor as a function of A, with no need of any amount of SJ mode mixture, in sharp contrast with the results of Ref. 8. We found that it is impossible to generate a curve, from a combination of the GT and SJ modes, which improves the accordance with the experimental data (shown in Fig. 1).

We hope that the questions raised in the present work do estimulate, in the near future, new theoretical approaches for the hydrodynamic description of the nucleus.

ACKNOWLEDGMENTS

The author wishes to thank the able assistance of Mrs. Sonia Maria A.P. Cavalcante in revising the English version of the manuscripts.

REFERENCES

1. B.L. Berman and S.C. Fultz, Rev. Mod.Phys. 47, 713 (1975).
2. M. Goldhaber and E. Teller, Phys.Rev. 74, 1046 (1948).
3. H. Steinwedel and J.H.D. Jensen, Z. Naturforsch A5, 413 (1950).
4. M. Danos, Bull. Am.Phys.Soc. 1, 135 (1956) and Nucl.Phys. 5, 23 (1958); K. Okamoto, Prog.Theor.Phys. (Kyoto) 15, 75 (1956).
5. M. Danos and W. Greiner, Phys.Rev. 134B, 284 (1964).
6. Le Tourneux, Phys. Lett. 13, 325 (1964).
7. M.G. Huber, M. Danos, H.J. Weber and W. Greiner, Phys.Rev. 155, 1073 (1967).
8. W.D. Myers, W.J. Swiatecki, T. Kodama, L.J. El-Jaick, and E.R. Hilf, Phys.Rev. C15, 2032 (1977).
9. H. Überall, "Electron Scattering from Complex Nuclei" (Part B), Academic Press, New York, 1971.
10. T. de Forest and J.D. Walecka, Adv. in Phys. 15, 1 (1966).
11. R. Bach and C. Werntz, Phys.Rev. 173, 958 (1968); J.G. Brennan and C. Werntz, Phys.Rev. C1, 1679 (1970).
12. B.L. Berman, "Atlas of photoneutron cross sections obtained with monoenergetic photons", Lawrence Livermore Laboratory UCRL-78482 (1976).
13. S. Fujii, Progr.Theor.Phys.Suppl. Extra Number 1968, p.97 (1968).
14. E. Hayward, in "Nuclear Structure and Electromagnetic Interactions" (N. Mac.Donald, ed.), Plenum, New York, 1965.
15. J.S. Levinger, Phys.Rev. 84, 431 (1951).

FIGURE CAPTIONS

Fig. 1 - Photonuclear E1-form factors as a function of the mass number A. Data points: obtained from the experimental cross sections compiled in Ref. 12. Curves SJ and GT: calculated from the theoretical previsions of the Steinwedel-Jensen and Goldhaber--Teller models, respectively, as described in the text.

Fig. 2 - Enhancement factor $(1+\alpha)$ to the classical sum rule, defined in eqn. 7, as a function of A, obtained from the experimental integrated cross sections compiled in Ref.12.

Fig. 3 - (adapted from Ref. 8). Ratio of the SJ to the GT components as a function of the mass number A. The meaning of the curves labeled (a), (b), and (c), is described in the text and in details in Ref. 8.

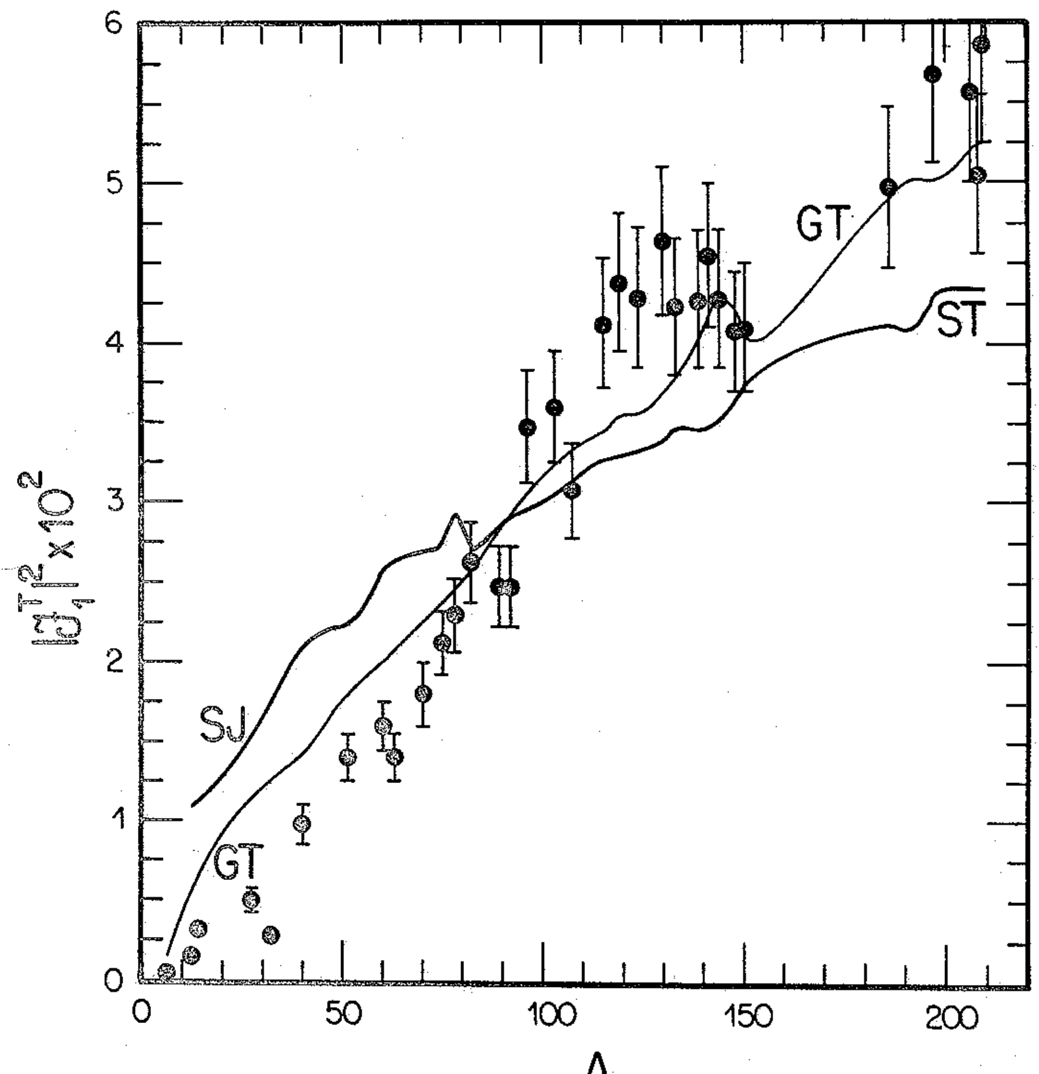


Fig.1

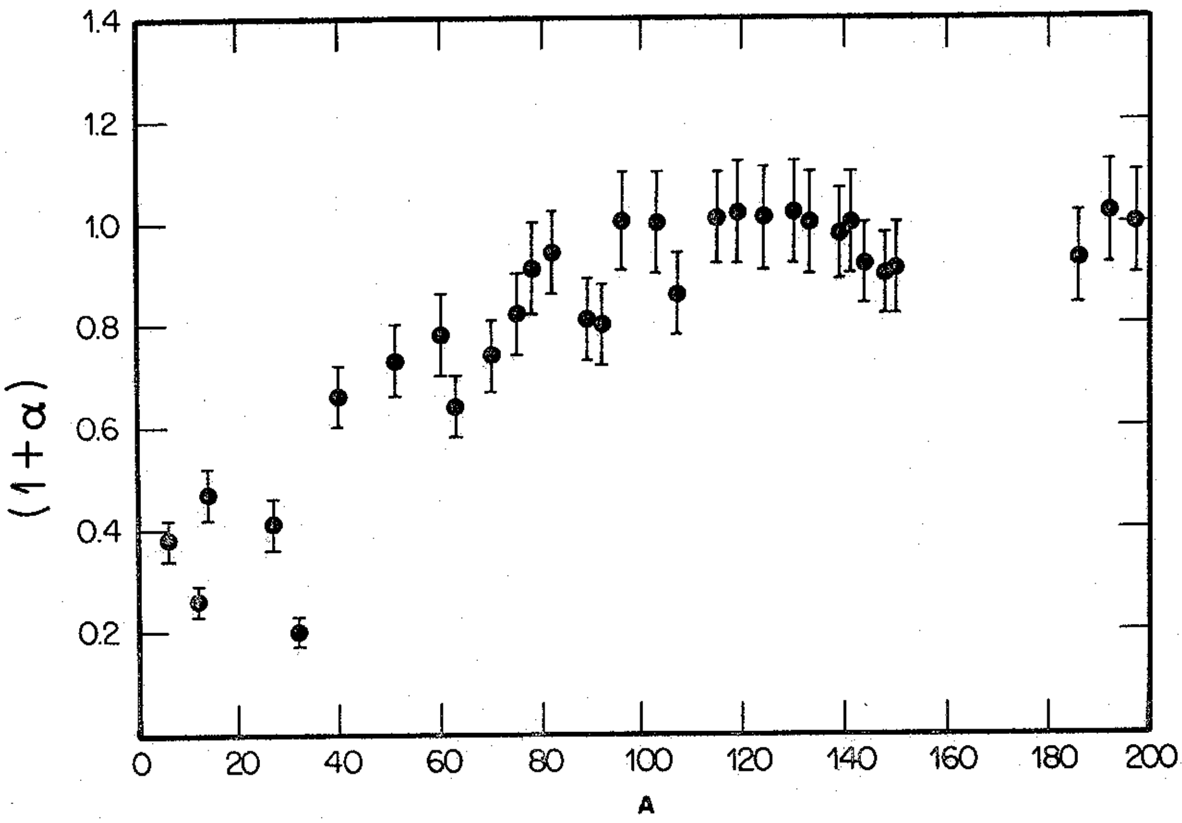
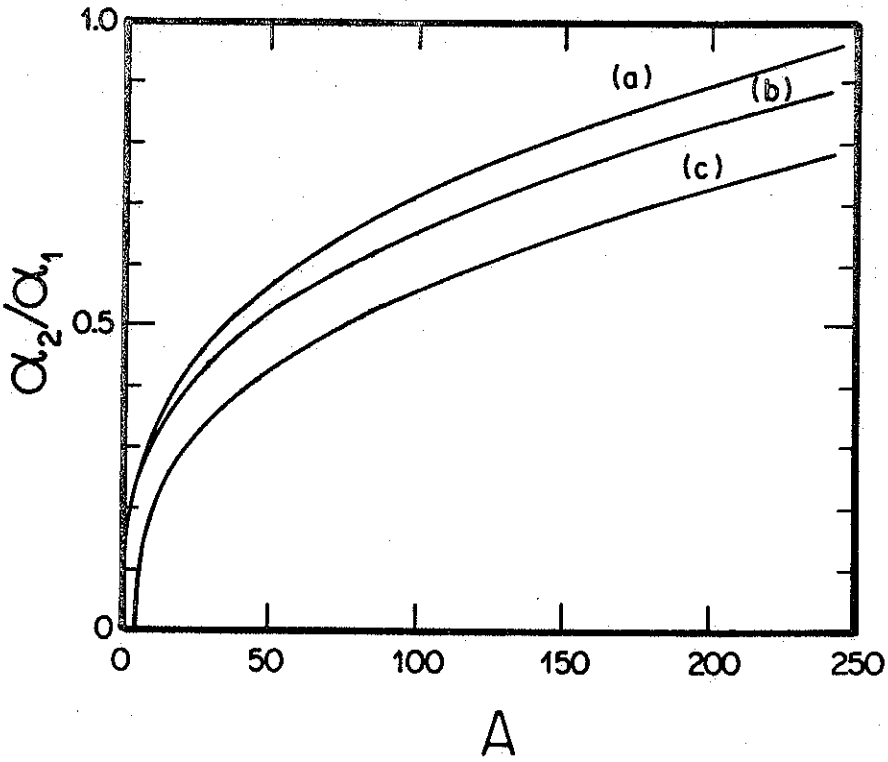

(1+α)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
160
180
200
A

Fig. 2

Fig. 3


1.0
0.5
0
50
100
150
200
250
A
(a)
(b)
(c)