1978

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Pitthan, Rainer

Monterey, California; Naval Postgraduate School

Invited Seminar given at the 11th Masurian Summer School in Nuclear Physics, Mikolajki, Masuria, Poland August 30 - September 10, 1978, 29 p.

NAVAL POSTGRADUATE SCHOOL

Monterey, California

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IN GIANT RESONANCE RESEARCH*

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Rainer Pitthan[$]
Department of Physics and Chemistry
Naval Postgraduate School
Monterey, California 93940 USA

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Abstract

A review of the main existing (e,e') data on the giant resonance region of atomic nuclei is given. Open and controversial questions are pointed out. While most of the examples are taken from the Monterey data, which in fact constitutes the largest body of such data, experiments from Darmstadt, Saskatoon and Sendai have been incorporated in the systematics.

Summer School lectures give you the opportunity to mention your co-workers where they belong: at the beginning. Over the last five years they have been F.R. Buskirk, E.B. Dally, J.N. Dyer, and X.K. Maruyama. I am especially indebted to F.R. Buskirk, without whom the enterprise of studying giant multipole resonances in Monterey never would have started, and without whose continuous support it could not have progressed as far as it did.

1. History and Physical Framework

Looking at the history of any subfield of physics is always a good idea. It teaches you some modesty, because you realize on how many shoulders you stand, and that you are not such a giant. Looking at the history of giant resonances is especially gratifying because it goes back to the very beginning of nuclear structure research. Table 1 shows an overview over the developments which led to the discovery and explanation of the classical, E1, giant resonance and this even twice. One train of events started with the discovery of the nuclear photo effect by Chadwick and Goldhaber[1], continued with Bohr's[2] explanation of the nuclear photoeffect and led to Bothe and Gentners[3] (γ,n) experiments (in fact, they measured the daughter activities induced with 17.2 MeV γ's from the (p,^{7}Li) reaction at 500 keV).

Their results were explained in the following year by

Bohr[4]. Using an optical analogue, he ended up with a Breit-Wagner type formula for the supposed resonant absorption, which was quite compatible with the Bothe and Gentner results, who in turn, using 12.8 MeV γ's from the (p,B) reaction verified Bohrs explanation. Thus the stage was set for Migdals paper[5], which, for the first time, used the omnious words: the E1 absorption of the nucleus is due to an oscillation of the protons against the rest (i.e., the neutrons). Migdals numerical estimate, $E_x = 24\ A^{-1/3} \sqrt{\beta \cdot Z/A}$, with β being the symmetry coefficient in the Bethe-Weizsacker[6] semi-empirical mass formula, still today does a lot better than many current theories.

While from a historical point of view the pioneering experiments and theoretical work had been done by 1944, this process was repeated after 1947 in the U.S. (Table 1). In 1947 Baldwin and Klaiber[7], using continuous Bremsstrahlung beams, mastering the unfolding problems which plagued photonuclear physics until today, found very sharp peaked (γ,n) and (γ,f) cross sections in a variety of nuclei. The explanation followed promptly by Goldhaber and Teller[8], describing the E1 oscillation, as an oscillation of the protons against the neutrons. In fact, they proposed two models. One assumed two separate neutron and proton liquids, each within its own fixed boundary, yielding an $(33)A^{-1/3}$ MeV law for the excitation energy. The other proposal, assuming an interpenetrating neutron-proton oscillation within one fixed boundary, was worked out in greater detail by Steinwedel and Jensen[9], and leads to an $(80)A^{-1/3}$ MeV dependence of the excitation energy.

Since all these models were based on hydrodynamic considerations, the next step was looking for higher hydrodynamic modes. This was done by Danos[10], using the mathematical apparatus derived by Lord Raleigh[11]. The next higher mode, quadrupole, was predicted to occur at 1.6 times the dipole energy.

The next great advance in the hydrodynamical model was the prediction by Danos[12] and Okamoto[13] (independent from each other) that the E1 would split in a deformed nucleus, because the oscillations along short and long axis would have different frequencies. Their theories were quantitatively verified by Fuller and Weiss[14].

Microscopic models were not put forward until 1957 to 1959 and were developed by Elliott and Flowers[15], Brink[16], Brown and Bolsterli, and Brown[17], Castillejo and Evans[18]. They explained the discrepancy between the expected shell model energy of the GDR, i.e., the energy of one shell spacing, $1\ \hbar\omega_o = 40\ A^{-1/3}$ MeV, and the experimental energy, $80\ A^{-1/3}$ MeV, with the existence of a particle-hole interaction, which is repulsive for the isovector dipole force.

Bohr and Mottelson in an attempt to unify the microscopic and macroscopic pictures[19] predicted existence of two E2 modes, at $60\ A^{-1/3}$ MeV (isoscalar, i.e., neutron

Table 1

1934	Chadwick and Goldhaber discover nuclear photoeffect
1936	N. Bohr explains nuclear photoeffect
1937	Bothe and Gentner do systematic investigation with 17 MeV γ-rays
1938	N. Bohr introduces resonance idea
1939	Bothe and Gentner extend their study with 12 MeV γ-rays
1944	Migdal explains nuclear photoeffect as being due to dipole oscillation of protons against neutrons
1947	Baldwin and Klaiber investigate (γ,n) and (γ,f) with continuous Bremstrahlung beam
1948	Goldhaber and Teller propose their model
1949	Steinwedel and Jensen expand GT model
1952	Danos proposes E2 giant resonance
1958	Danos and Okamoto predict splitting of dipole in deformed nuclei
1958	Fuller and Weiss verify splitting
1957-59	Development of shell models of giant dipole resonance by Elliott and Flowers; Brink; Brown and Bolsterli; and Brown, Castillejo and Evans
1960	Self-consistent model by Bohr and Mottelson predict other multipolarities, splitting into isoscalar and isovector modes
1971	Verification of higher multipoles and isosplitting by Pitthan and Walcher
1971	Microscopic calculations by Kamerdzhiev

and proton oscillation in phase) and 130 $A^{-1/3}$ MeV (isovector, out of phase). These modes, so "eagerly expected"[20], were not discovered until much later, 1971, when (e,e') experiments by Walcher and co-worker[21] revealed E2 strength below the giant dipole resonance and, in addition, other magnetic and electric resonances, whose nature still today has not been established without doubt. In the same year the first truly microscopic prediction of E2 GR (isoscalar and isovector) takes place by Kamerdzhiev[22], whose results are in excellent agreement with experiment.

Figure 1 shows how the nuclear continuum was thought to look like before 1971, and figure 2, how the situation changed with the experiments of ref. 21.

While most of the interest has focused on the E2 and M1 resonances, the spectra (figure 2) after subtraction of background clearly show a disturbance of the smooth tail of the E2 resonance at 10 MeV (53 $A^{-1/3}$) and at 24-25 MeV (isovector E2), so that all in all four new modes of coherent continuum oscillations were added to our knowledge[23]. If one known where the E2 strength is, as we do nowadays, it can be found too.

To summarize the theoretical framework: two complimentary descriptions are possible, which are very nicely illustrated in figure 3 and 4 (taken from Schwierczinski's Dissertation[24]). Either the (virtual or real) photon excites the nucleus into collective oscillations of protons against neutrons, or the photons lift particles out of their shells

into other shells allowed by spin and parity. In general the Bohr-Mottelson concept has been found to be true. As we will see later, transitions are shifted from the unperturbed shell model energies downwards for IS, upwards for IV excitations. E.g., for an E3 excitation where four combinations are possible, the $1\hbar\omega$ transitions were predicted by Hamamoto[25] to occur at 0.7 $\hbar\omega$ (IS) and 1.3 $\hbar\omega$ (IV), the corresponding $3\hbar\omega$ states are at 2.6 $\hbar\omega$ (IS) and 4.7 $\hbar\omega$ (IV). Table 2 summarizes Hamamotos RPA results for λ = 2, 3 and 4. For electric monopole transitions the results from Suzuki[26], which are based on sum rule considerations, are included.

TABLE 2

		ΔT = 0		ΔT = 1	
λ	$\hbar\omega_o$ a)	E_x ($A^{-1/3}$ MeV)	R b) (%)	E_x ($A^{-1/3}$ MeV)	R (%)
2	2	58	100	135	100
3	1	25	28	53	2
	3	107	72	197	98
4	2	62	51	107	3
	4	152	49	275	97
0	--	58	100	178	100

a) $\hbar\omega_o = 41\ A^{-1/3}$ MeV

b) $R = E_x \cdot B(E\lambda, q = 0)/EWSR\ (E\lambda, \Delta T) \cdot 100$

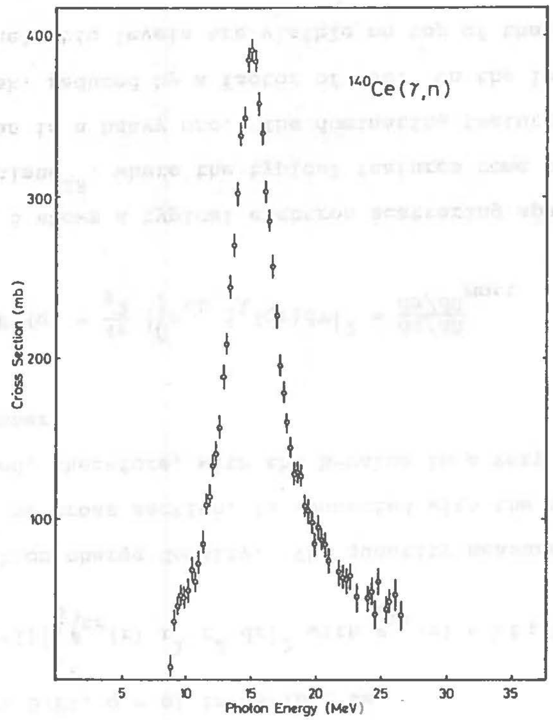

Fig. 1

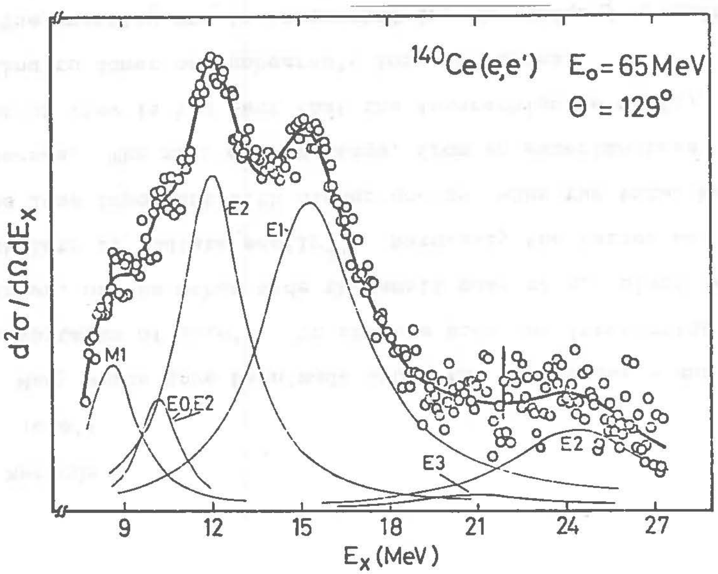

Fig. 2

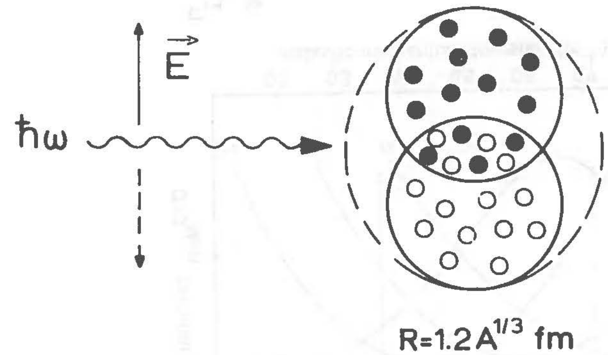

Figure 3

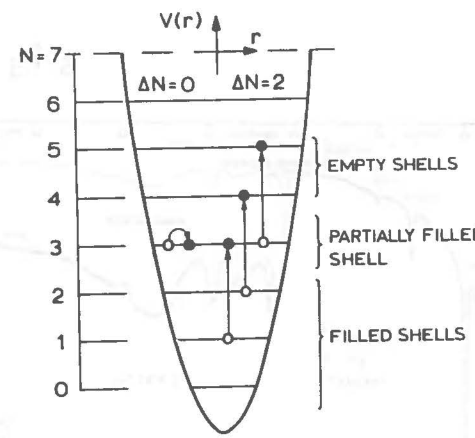

Figure 4

2. Methods

2.1 (e,e')

Many words have been made about the advantages - and disadvantages of (e,e'). On the one side the interaction is known, on the other side the small mass of the electron which lets it radiate easily[27]. Naturally the latter becomes less important with higher energy, when the total mass increases. The main disadvantage, from an experimenters point of view is the fact that the interaction is small, leading to sometimes unbearable long run times.

The quantity one is interested in, the reduced transition probability $B(E\lambda,\ q = \omega)$ is defined as

$$B(E\lambda) = (2\lambda+1)\left|\int \rho_{tr}(r)\ r^{\lambda}\ r^{2}\ dr\right|^{2} \quad \text{with} \quad \rho_{tr}(r) = |\langle f | \rho | i \rangle|^{2}$$

the transition charge density. The quantity measured, the formfactor or cross section, is connected with the transition density, and, therefore, with the B-value in a very straightforward manner

$$F^{2}(q) = \frac{4\pi}{Z^{2}}\left|\int \rho_{tr}\ j_{\lambda}(qr)\,d\tau\right|^{2} = \frac{d\sigma/d\Omega}{d\sigma/d\Omega_{Mott}}$$

Figure 5 shows a typical electron scattering spectrum in a light nucleus[28], where the typical features come out more clearly than in a heavy one. The dominating feature is the elastic peak, reduced by a factor of 100. On the low energy side the inelastic levels are visible on top of the radiative

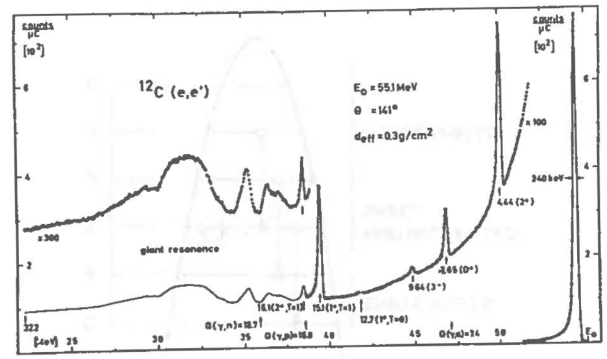

Fig. 5

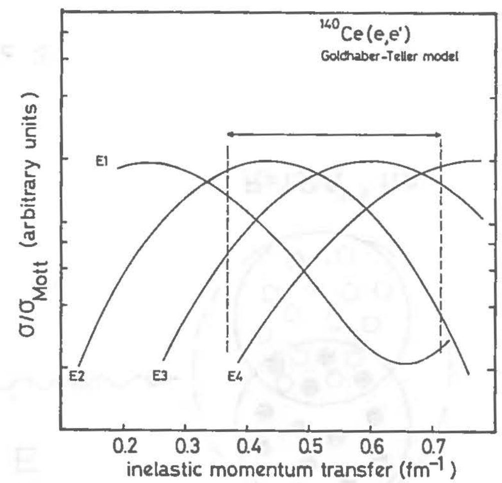

Fig. 6

tail of the elastic peak. As one goes up in energy the level density increases until above the (γ,p) and (γ,n) threshold the natural (damping) width of the giant resonances becomes larger than the resolution.

2.2 Models

The transition density for collective oscillations has been mainly taken from the hydrodynamic (Tassie[29], Goldhaber-Teller[8]) model, which derives it from the groundstate charge distribution $\rho_o(r)$ which leads to the expression

$$\rho_{tr}^{GT}(r) = C^{GT} r^{\lambda-1} d\rho_o(r)/dr$$

The Steinwedel-Jensen model[9], only used for the giant resonances, leads to

$$\rho_{tr}^{GT}(r) = C^{SJ} j_\lambda (rk)\rho_o(r)$$

with j_λ being the λ spherical Bessel function and $k = M_l/c$, with M_l denoting first maximum (derivative zero) and c nuclear half density radius. Figure 6 shows a typical dependence of the formfactor on q. Strictly speaking the formfactor concept does not exist in heavy nuclei, because due to the finite charge the Bonn approximation is no longer valid, and the expression $(d\sigma/d\Omega)/(d\sigma/d\Omega)_{Mott}$ depends on more than just one variable, namely two of the three variables primary energy, scattering angle, and momentum transfer. The

momentum transfer region between the broken lines in figure 6 is approximately the range necessary to differentiate between E1, E2, E3 and E4 transitions.

The equation $\rho_{tr}(r) = |\langle f \| \hat{\rho} \| i \rangle|^2$ shows that microscopic wave functions could be easily used. That they have been used only in a few cases is due mostly to the following reasons:

1. There are no generally accepted microscopic wave functions, and use of in-house ones would destroy compatibility of results.
2. RPA[30] and other microscopic calculations[31] for collective giant resonance modes show that GT model and RPA transition densities are very similar (figure 7).
3. There are more fundamental arguments by Fallieros, et al.,[32] to the effect that if the sum rule strength of a certain mode of excitation is concentrated in one state, the transition densities will be hydrodynamical[33].

2.3 DWBA

The DWBA concept of (e,e') has its foundation in the relatively weak (compared to the nuclear) interaction. The main approximation is the restriction to one-photon exchange[34]. Since the ground state charge distributions of nuclei is a well measured quantity the distorting potential can be calculated with great accuracy. None of the problems in hadron DWBA calculations enter. The main problem is the choice of model for the inelastic transition density as discussed above.

Figure 8 shows a comparison between Goldhaber-Teller[8] and Steinwedel-Jensen model[9] for ^{208}Pb and 90 MeV electrons calculated with the program of Tuan, et al[35]. Since the Goldhaber-Teller model corresponds to a larger transition radius, R_{tr} = 7.01 fm, compared to the 5.92 fm of the SJ model, the first minimum of the formfactor^2, σ/σ_{Mott}, is at lower momentum transfer (or scattering angle). Nevertheless, it is apparent that the angular dependence in the region of the first maximum is characteristic of a dipole excitation, although the strength is different by a factor of two. Thus the accuracy in determining a certain multipolarity seems to be much less model-dependent than the extraction of the sum rule strength. Figure 8 also shows the GT formfactor for the planewave case: the minimum is shifted from 75 to 105°, the height of the first maximum area is off by a factor of three, but the angular dependence in the region of the first maximum follows an E1 behavior closely.

In summary, one might thus state that although the current methods are not perfect, they are suited to measure multipolarities in a nearly model-independent way at low momentum transfer. This point comes out more clearly in figure 9, which shows the cross section, $d\sigma/d\Omega$, and not $(d\sigma/d\Omega)/(d\sigma/d\Omega)_{Mott}$, for 90 MeV electrons scattered on ^{208}Pb. The graph shows two reasons why experiments, up to now, have taken place at roughly the same momentum transfer, approximately 0.5 - 1.0 fm^{-1}, despite very different primary

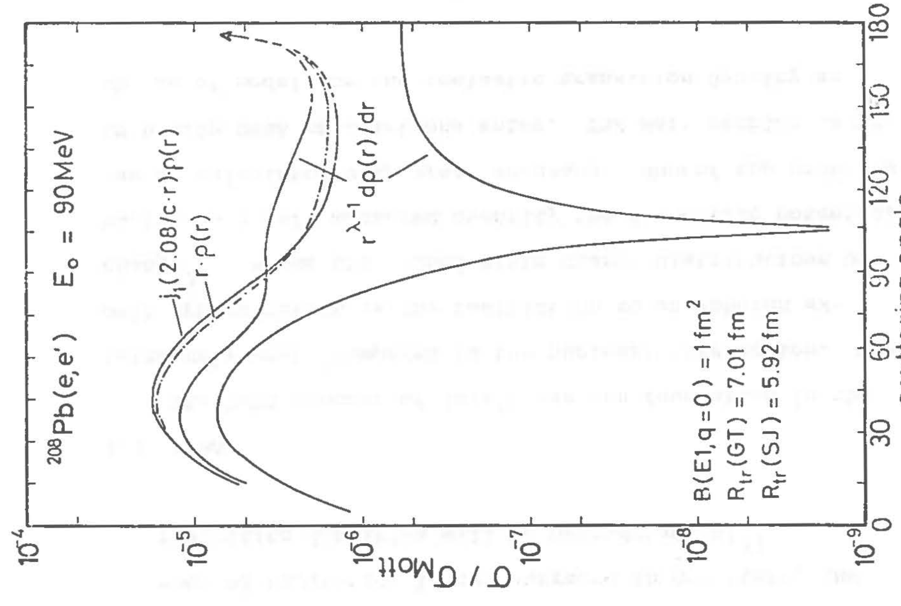

Fig. 8

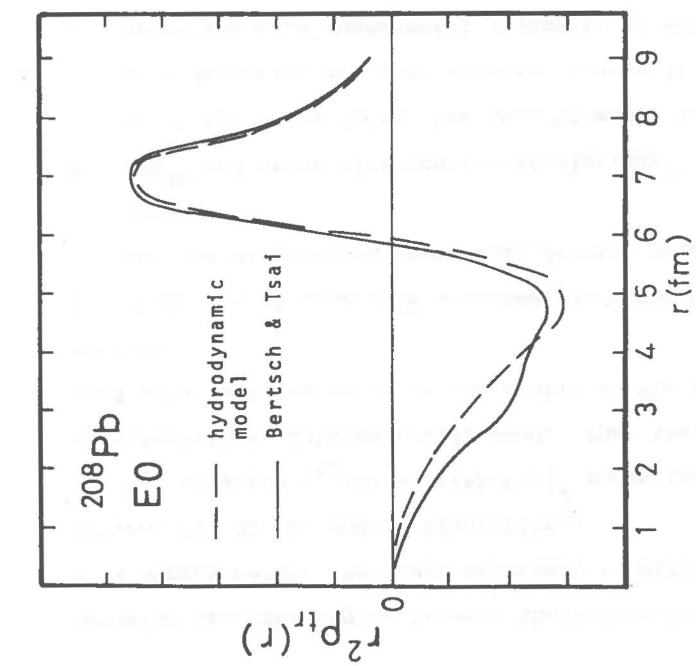

Fig. 7

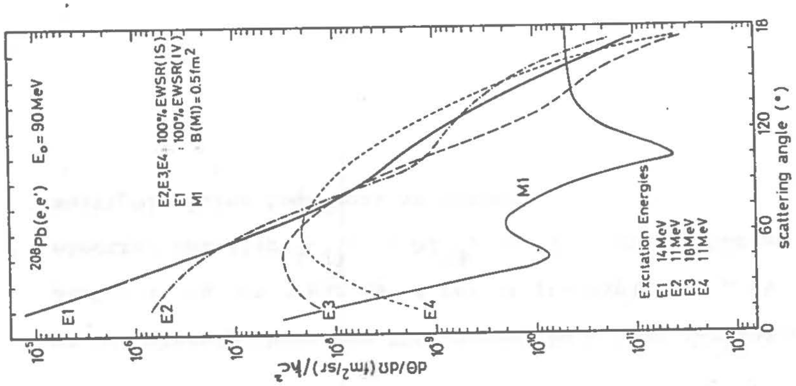

Fig. 9

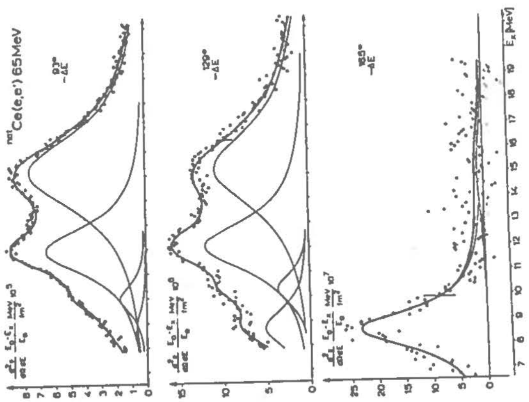

Fig. 10

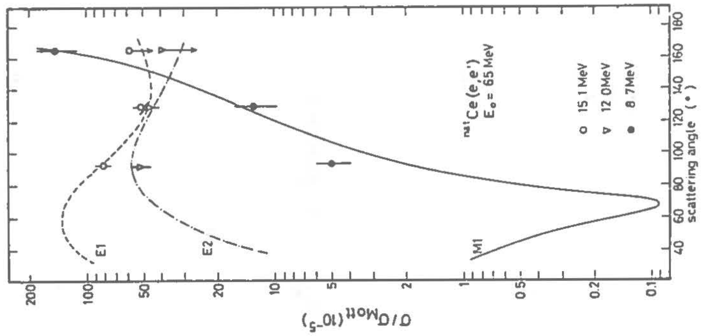

Fig. 11

energies ranging from 50 MeV in Darmstadt to 300 MeV in Sendai:

1. The cross sections drop off very fast, approximately four orders of magnitude between 30° and 150° for E2.
2. The best chance of measuring a significant difference in the slope of the cross section, which is indicative of the multipolarity, is at lower q.

At higher momentum transfers the variation in cross section is much less pronounced for different multipolarity (and also more model dependent). The figure, in addition, shows very clearly the typical enhancement of a transverse (here M1) transition at backward angles. Figures 10 and 11, adapted from ref. 23, give an illuminating example from the measurements discussed before (see figure 2). The two resonances at 12 and 15 MeV are electric in nature (they practically disappear at 165°) and of different multipolarity. The one at 9 MeV is magnetic (or at least transverse) because it comes out strongly at backward angles. Comparison with DWBA calculations show them to be M1 (with the possibility of a strong M2 contribution, not shown), E2 and E1. Figure 12 (adapted from ref. 23, 36 and 37) shows, however, that life is not always that simple, because corresponding backward angle measurements for ^{197}Au and ^{208}Pb show additional resonances in the region of interest and/or a transverse enhancement of the resonances known in this region compared to what one expects from forward angle measurements. These difficulties, with transverse excitations at and closely above the GDR energy, have been recognized early; it is not clear as of yet if the explanation as electric spinflip[21,23], or M2[23], or M3[38], or all these multipolarities together, is correct.

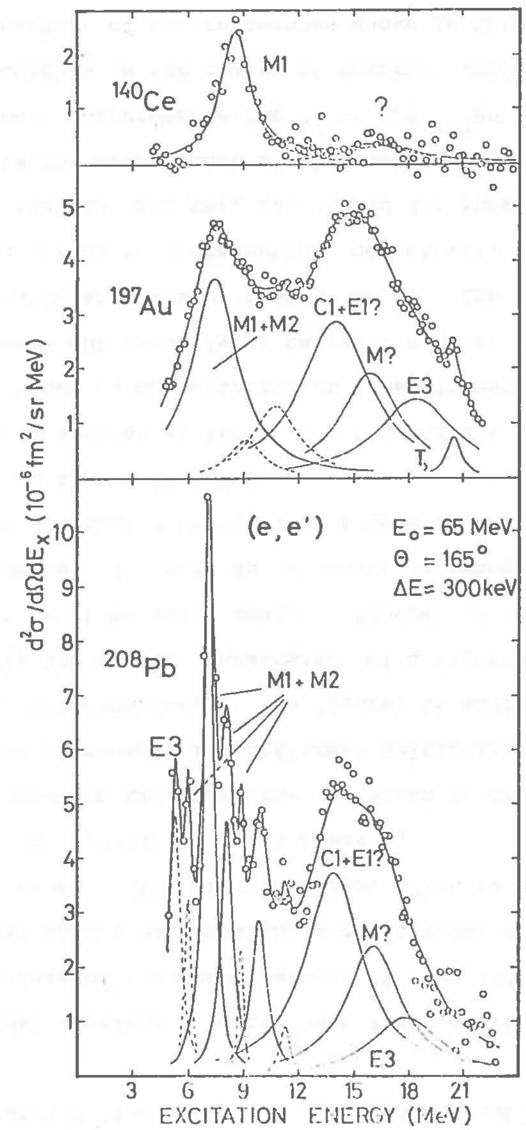

Fig. 12

3. Overview over Existing Data

While at this point I could start showering you with spectra and formfactors of various multipolarity from a magnitude of nuclei, I rather will concentrate on the systematic features as they have emerged from the work of the last few years.

Figure 13, therefore, shows an overview over most of the existing data from (e,e') on giant resonances, i.e., concentrations of cross sections in the continuum which appear to have resonant form. Plotted is the excitation energy in units of $A^{-1/3}$ MeV as a function of A. The data shown correspond to the nuclei ^{54}Fe (ref. 39), ^{58,60}Ni (ref. 40), ^{89}Y (ref. 41), ^{90}Zr (ref. 39,42), ^{140}Ce (ref. 43), ^{142,150}Nd (ref. 24), ^{165}Ho (ref. 44), ^{181}Ta (ref. 45,46), ^{197}Au (ref. 47), ^{208}Pb (ref. 47,48), and ^{238}U (ref. 49). The data around A $\simeq$ 60 with E $\simeq$ 30 $A^{-1/3}$ MeV were taken from Überalls compilation[27]. The lines are drawn solely to aide the eye. Although this plot does not enable one to decide on the multipolarity or other properties of these states, certain systematic features are apparent. Excitation energies are constant for resonances around ~30, 53, 63 and 105 $A^{-1/3}$ MeV, but seem to drop systematically with A for the resonances grouped around 130 $A^{-1/3}$ MeV. Since the behavior of the latter resonance is reminiscent of the GDR, an isovector state, and since the 130 $A^{-1/3}$ MeV state has been assigned as isovector E2, one may conclude that isovector states fall off in excitation energy, while

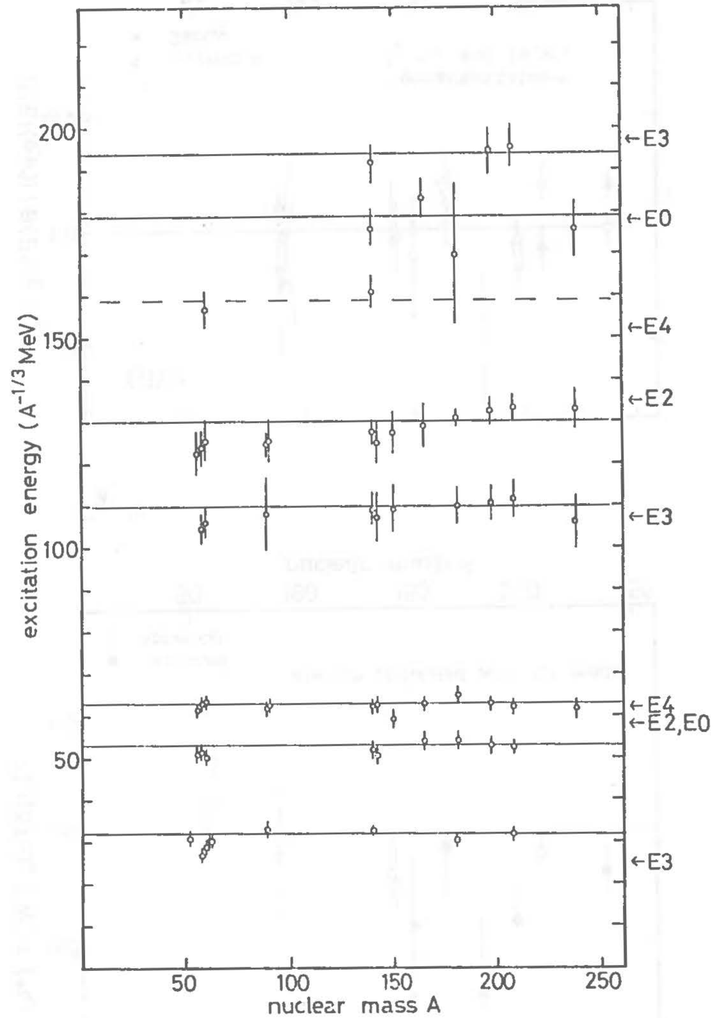

Fig. 13

isoscalar states do not. In fact, the resonances at 30, 63 and 105 $A^{-1/3}$ MeV have been identified as isoscalar E3 ($1\hbar\omega$), E2, and E3 ($3\hbar\omega$), respectively. To some irregular features concerning the 53 and 190 $A^{-1/3}$ MeV state we will return later. The GDR is not shown, because its energy is much better known from (γ,n) measurements[50], nor is the supposed monopole[51], which is difficult to locate in (e,e'), since it is hidden under the giant dipole.

The comparison of figure 13 with table 2 shows a surprising agreement between the predictions[25,26], which, in fact, were made before the measurements were done, and the experiments, at least for the main modes expected from the shell model.

How reliably can the continuum resonance cross sections be extracted from (e,e')? One way to check on this important question is a comparison between sum rule values of (γ,n) and (e,e') for the GDR. Figure 14 therefore, shows the strength in units of the classical E1 sum rule. The upward trend known from (γ,n) is clearly visible. Figure 15 shows a more significant property, the B-value extracted from (e,e'), set in relation to the (γ,n) value. It is evident that the data scatter around 1, as they should, and that the deviation of the values from 1 is not larger than the deviation between the (γ,n) values from Livermore and Saclay data itself. Thus one may estimate from figure 15 that the accuracy achievable for relatively strong resonances

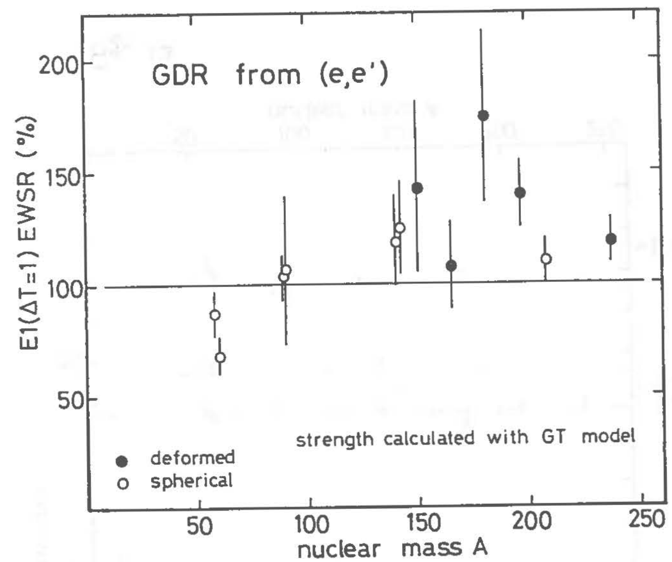

Fig. 14

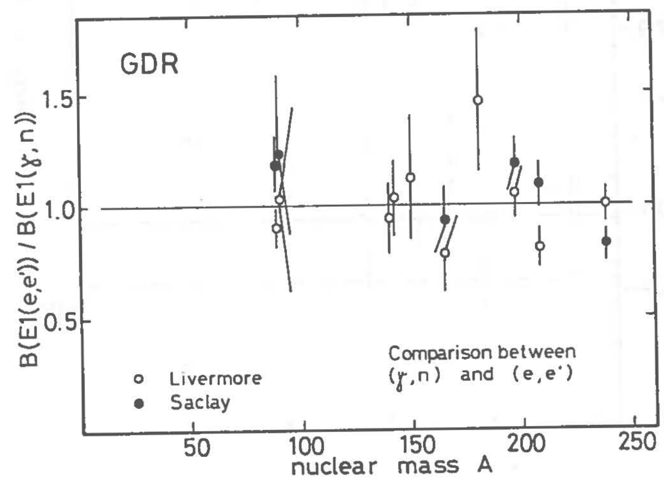

Fig. 15

like the GDR is of the order of 10 to 20%.

The one member of the new resonances, which by now is best known, is the E2 isoscalar state. Since it is accessible with many more particles than the GDR, in fact, many of its properties including decay branches[52] are even better known than the GDR. Here we concentrate on the properties of strength and width. Figure 16 shows the strength in units of the isoscalar E2 sum rule as a function of A. The line is drawn solely to guide the eye. The drastic and consistent fall-off in strength from heavy to light nuclei is clearly visible. The one point which is an exception belongs to ^{238}U. We are currently investigating whether or not this low strength is real (it is contradicted by recent virtual photon measurements where 80% of the E2 sum rule have been found in the fission channel alone[53]), or if it is due to the breakdown of the hydrodynamical model. It has been shown[54] that the transition charge density for a deformed nucleus is different from that of a spherical one. It may be even more different for a fissioning nucleus. A scaling of the radial dependence of the transition density by 20% would bring the strength in ^{238}U up to the value expected from figure 16.

In addition to energy and reduced transition strength (radiative width) continuum states are characterized through their total width, which is of the order of several MeV. Using a parameterization of either Breit-Wigner or Lorentz shape, figure 17 shows the width of the isoscalar E2 state

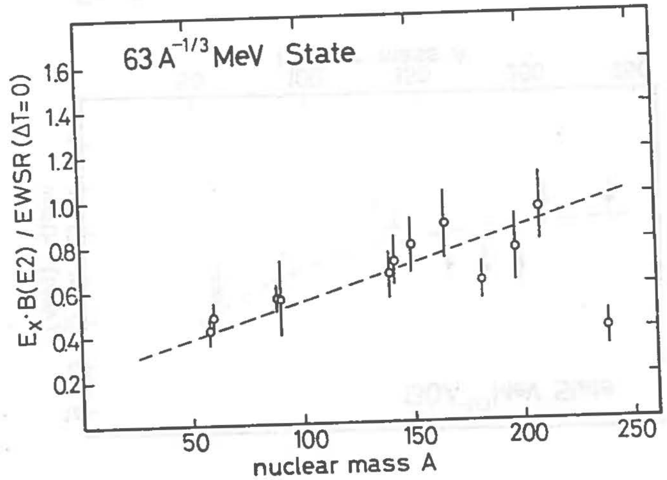

Fig. 16

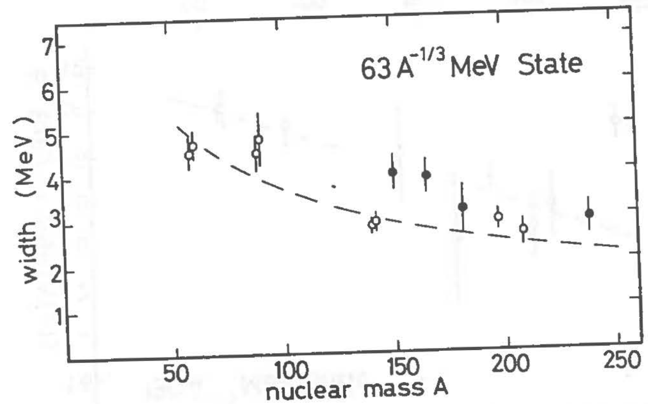

Fig. 17

in comparison with a curve calculated from the viscosity model of Auerbach and Yeverechyahu[55]. The curve was lowered by 20% compared to the original calculation because the latter was normalized to a ^{208}Pb width which was 25% to high. After this correction, the theory describes the A-dependence in spherical nuclei very well; as one may naively expect from collective considerations in analogy to the Danos-Okamoto[12,13] model the resonance is broadened in deformed nuclei[54].

The isovector E2 GR has not been as extensively studied in the past as the isoscalar state mainly because it can only be weakly excited by inelastic scattering of hadronic particles[56] and has, therefore, been mainly open to investigation by capture reactions[57,58] and (e,e'). The main features, strength and width, are shown in figure 18 and 19, respectively. The general trend is very similar to that of the isoscalar state, including the very low sum rule value in the case of ^{238}U. The theoretical curve for the width in figure 19 was, unlike the isoscalar case, not changed.

The strength of isoscalar E3 resonances are shown in the next figures (20,21). The low-lying (1ħω) branch lies at 32 $A^{-1/3}$ MeV and exhausts between 10 and 20% of the sum rule. The spreading width is more difficult to define. This state lies below the particle thresholds and couples more directly to single particle configurations. In most cases it is split into more than just one coherent resonance (the use of the term resonance is therefore somewhat deceiving), but

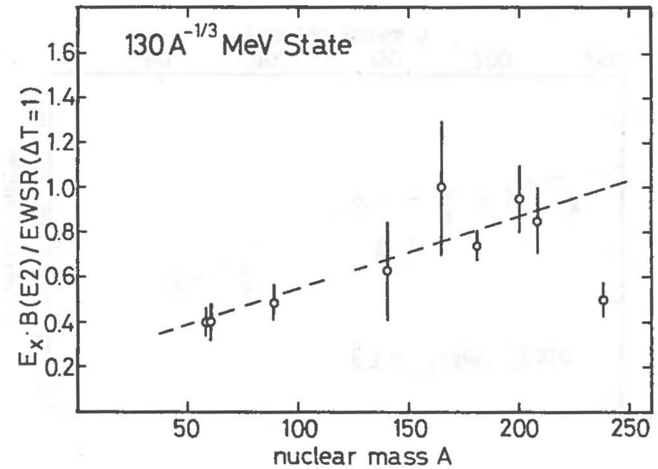

Fig. 18

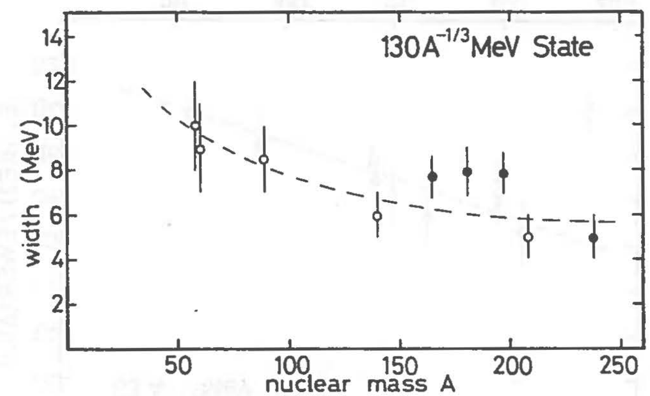

Fig. 19

generally the strength stretches over (1-2) MeV in excitation energy.

In medium-light nuclei (A ~40 - 60) these states have been known since a long time.[27] The most complete systematic survey has been done with (α,α')[59]. Some of the (α,α') results are indicated with black circles in figure 20. Although they seem to be systematically somewhat higher than the (e,e') results, the general agreement is good.

The higher-lying E3 state at 110 $A^{-1/3}$ MeV is more difficult to measure. It lies higher in the continuum, exhausts, therefore, the sum rule with lower B-values, and has a larger spreading width. Nevertheless, as figure 13 shows, it has been found systematically at a constant excitation energy in a variety of nuclei which indicates its being due to a resonant nuclear excitation. In those cases the formfactor could be measured, it has been found to be at least compatible with E3; in some cases other multipolarities could be excluded with certainty. Figure 21 and 22 show strength and width, respectively. Similar to the E2 resonances, the strength falls off with A. The point for ^{208}Pb is rather high in comparison and should be subject to scrutiny since it was derived from only one angle. However, it might as well be possible that the E3 strength in other nuclei is more fragmented than the E2 and E1 strength and is just not concentrated in resonant form. The widths shown in figure 22 follow the general trend of the viscosity model[55] to rise with lower A.

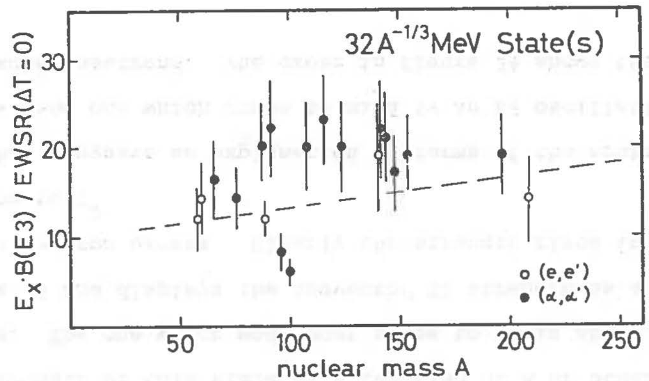

Fig. 20

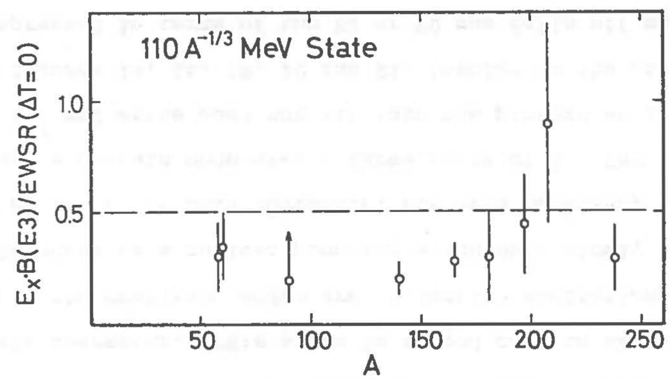

Fig. 21

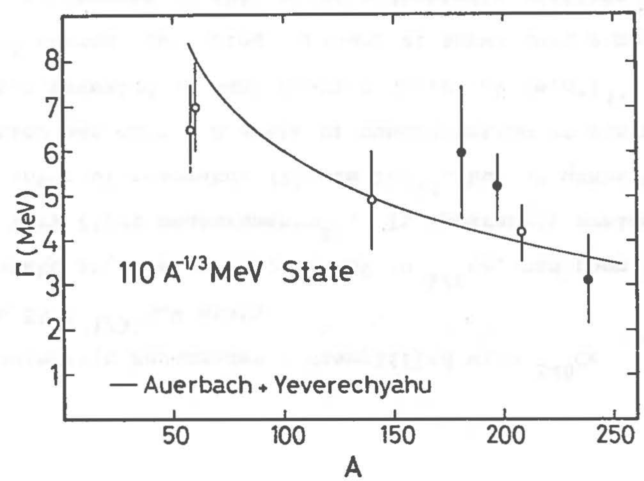

Fig. 22

The foregoing describes the situation as far as well established resonances are concerned, although one might argue to which extent the distribution of the E3, $3\hbar\omega$ strength is understood. The generally weak point is that certain assumptions about line shapes have been made in the analysis, mostly choosing Lorentz or Breit-Wigner form. While the occurrence of a definite line shape is proven, and provable, for the GDR[60] and perhaps for the GQR ($\Delta T = 0$) in heavy nuclei, one should not lose sight of the fact that it is an, however reasonable, assumption. But it is also evident, that within these limitations great progress has been made in the localization of various multipole strength in the nuclear continuum.

4. Problematic Resonances - Exemplified with ^{140}Ce

a. The 53 $A^{-1/3}$ MeV state

A state at this energy, 10 MeV in ^{140}Ce, had been found in the very first measurements[21]. It apparently scaled with the E2 ($\Delta T = 0$) resonance (figure 10)[23], but no quantitative evaluation was made. A state or concentration of strength was later revealed in many heavier nuclei by (e,e')[47], but not with hadron scattering. Figure 23 shows that a more recent measurement of this state undoubtedly confirms it E2 (or E0) character. THis state is a good case to show that because the continuum modes are collective excitations, which should occur as a nuclear property which only slowly changes with A, it is not only advisable, but even necessary to measure a certain mode over a large range of A. The 53 $A^{-1/3}$ MeV state does not fit into the picture as it evolves from figures 14, 16, 18, 20 and 21, insofar as the strength, if expressed in terms of the E2 or E0 sum falls off more rapidly with A. There are several possibilities to display the strength of this state as a function of A or other parameters. The one which made most sense to us is shown in figure 24 and displays the isovector E2 strength as a function of the neutron excess. Clearly the strength rises in proportion to T^2.

This suggests an explanation in terms of the neutron excess, and one which comes to mind is an E2 oscillation of the excess neutrons. The cross in figure 24 shows the result

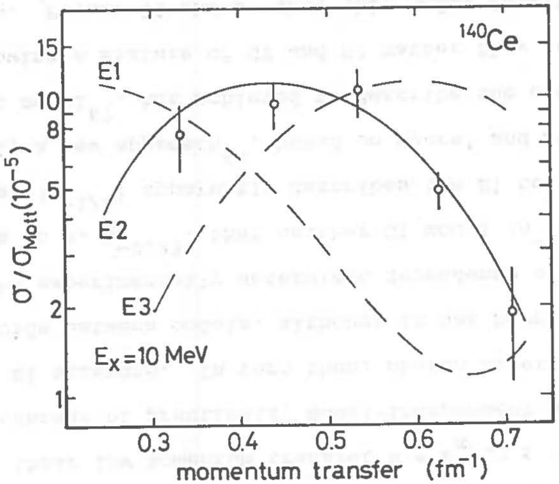

Fig. 23

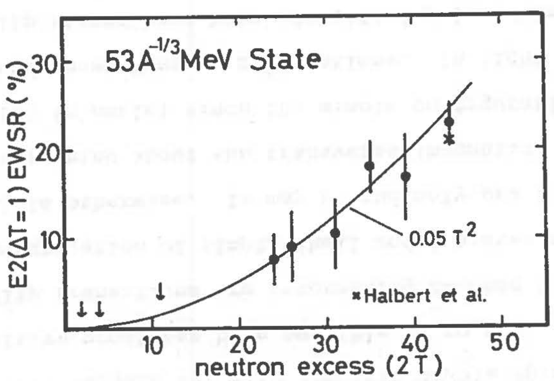

Fig. 24

of a RPA calculation by Halbert, et al.[61], of the amount of T = 1 strength which is expected in the T = 0 region. A mass oscillation model[61] would only produce isovector strength of order $(N - Z)^2/A^2$, or 1/5 of the microscopic result. There have been similar considerations as to the role of the excess neutrons in the nucleus and its contribution to the E2 matrix element by Bohr and Mottelson[62], but these should not be interpreted as suggesting a special mode of oscillation associated with the excess neutrons, because it would be difficult to imagine a force which holds the excess neutrons together in a separate motion[63].

It seems to be clear from the experimental evidence that this state is an isovector state (it does not appear in the hadron spectra[64]) and, therefore, not just a second branch of the GQR at 63 $A^{-1/3}$ MeV.

4.2 The "Well-Known" Giant Dipole Resonance and the Monopole Breathing Mode

The E1 state, the dominant feature in photon work, is generally called "well-known". It was pointed out earlier that much of the knowledge we have on the E2 is from hadron scattering. Excitation of isovector states by this method is suppressed, therefore no comparable information exists on the GDR. From this point of view alone the E1 state is less well known.

In addition there have been indications from electromagnetic interaction studies of not so well understood transverse components in the GDR region. Figure 12 already showed some examples for such contributions. While these transverse cross sections in heavy nuclei have been found compatible (figure 25) with electric dipole spin flip[23,47], no positive proof has been possible up to now. Electric spin flip transitions are interesting because they allow the investigation of simple shell model states not easily accessible otherwise. It may be the only practical way to learn something about the transverse (magnetic) current distribution in nuclei since the simple configurations taking part lend themselves to calculations. In light nuclei electric spin flip states have been identified a long time ago[65].

Another not well understood feature has been the transition charge density. As outlined earlier, two models have been traditionally used to describe ρ_{tr} (GT[8], SJ[9]). Most of the E1 experiments have been carried out with photons, which due to their low momentum transfer $k = E_x/\hbar c \leq 0.1$ fm have the advantage of practically model-independent measurement of the E1 strength. In turn then, photon experiments cannot decide between models, although it has been concluded from the experimentally determined dependence of the GDR maximum on A, $A^{-0.23}$, that neither GT model ($A^{-1/6}$) nor SJ model ($A^{-1/3}$) apparently describes the E1 correctly. Recently a new approach[66], based on Myers' and Swiatecki's droplet model[67], has achieved to describe the energy correctly by allowing a mixture of GT and SJ matter flow inside the nucleus. Figure 26 shows that this model describes the

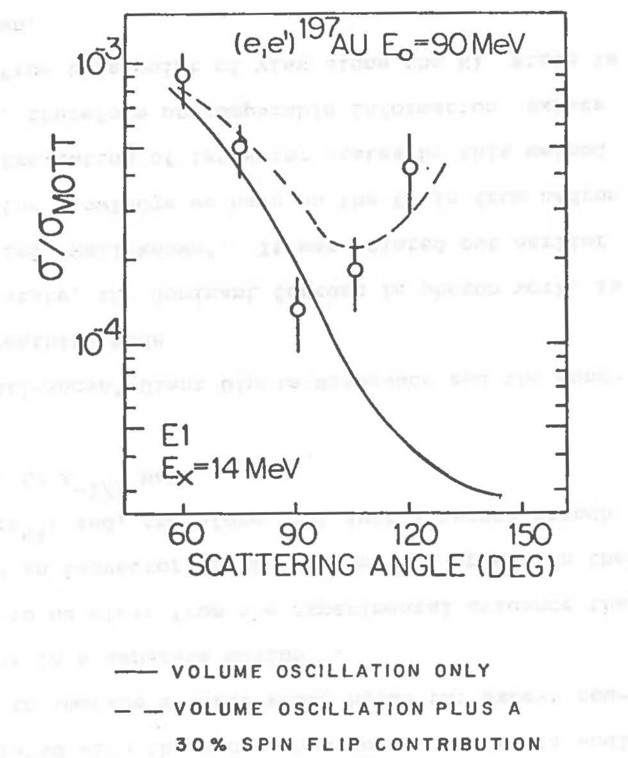

Fig. 25

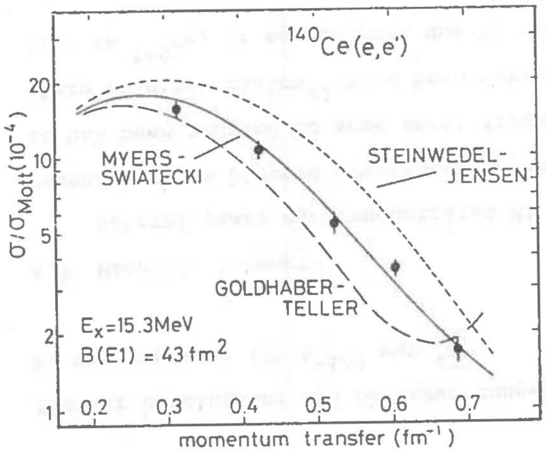

Fig. 26

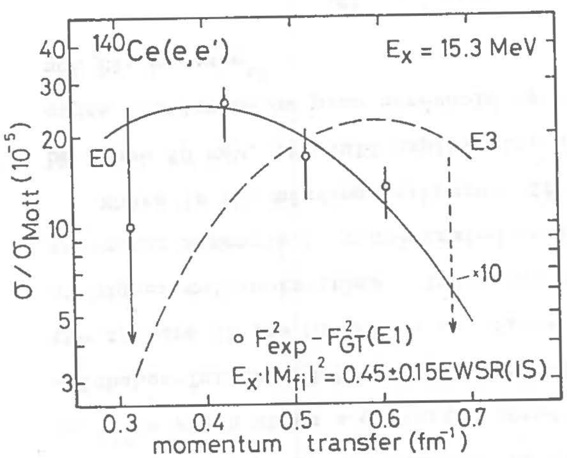

Fig. 27

(e,e') cross section better as well. The curves in this figure are normalized to (γ,n) data, because these give a model-independent strength. While this result looks nice, one ambiguity should be pointed out. The GT model would still be able to describe the data if one attributes the difference between experiment and GT formfactor to a different underlying resonance. Figure 27, therefore, displays this difference and indeed the difference follow an E2 or E0 formfactor. It has been claimed that 100% of the E0 EWSR (IS) is located directly at the GDR,[51] but to date most (e,e') experiment have been unable to locate the full amount of this strength [see, e.g., ref. 38].

4.3 Problems of Quadrupole Strength

The GQR is now firmly established in principle, but details like decay modes have not been studied extensively yet. The predominant decay in light nuclei seems to be by α-emission,[52] changing to proton decay with growing Z. The isoscalar E2 has been massively investigated by (α,α'), but the isovector E2 is mainly accessible by capture reactions, especially a variety of (p,γ) experiments have been performed[68].

The gross picture of the hadronic probe studies is consistent with (e,e'), but the isoscalar strength from (α,α') is consistently higher[43]. Since α-scattering is mainly dependent on the nuclear radius, many details of the charge density cannot be investigated. In (e,e') the many overlapping resonances preclude to date definite answers. Figure 28 shows a recent measurement of the 12 MeV state in ^{140}Ce which shows a deviation between experiment and Goldhaber-Teller model, which may be either indicative of the failure of the GT model, or (figure 29) of the presence of higher multipolarities. In either case only 50% of the isoscalar strength is concentrated in this state[43].

Where is the missing strength? If one assumes it to be above 50 MeV, it would explain 50% of the γ-absorption cross section below pion threshold as being due to E2, and not E1, because[60]

$$\sigma_\gamma^{E1} \sim E_x \cdot B(E1,k) \ ,$$

but,

$$\sigma_\gamma^{E2} \sim E_x^{\,3} \cdot B(E2,k) \ .$$

Similar conclusions can be drawn concerning the isovector E2 resonance at 130 $A^{-1/3}$ MeV.[43]

4.3 Magnetic Strength

Several years ago concentrated M1 strength in giant resonance form bloomed everywhere in heavy nuclei; nowadays it has been reduced to some small fragments[69]. In cases where original claims[23] have been verified to some extent[70] like in ^{140}Ce, it may be more due to the fact that one has

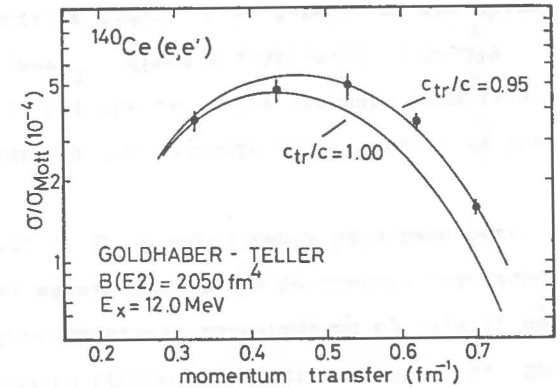

Fig. 28

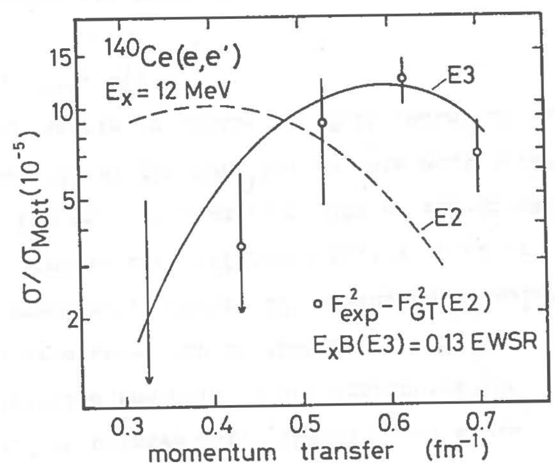

Fig. 29

not yet reinvestigated the M1 strength with enough scrutiny. M2 states have been found in the $1\hbar\omega$ region in ^{208}Pb[71] and an M2 resonance[23] is suspected to be responsible for the cross section just above the GDR in figure 12 , but the same resonance has been proposed to be of M3 character[38]. So the exploration of giant magnetic strength, if it exists in concentrated form, still has to begin.

4.4 Higher Multipoles

In contrast to the quadrupole strength, the octupole strength expected from the Bohr-Mottelson picture (table 1, figure 13), has been more elusive. This is understandable because two main shell transitions, as outlined in the beginning, may contribute. The strength which is known to some extent is the isoscalar $1\hbar\omega$ strength from (α,α') and (e,e') (figure 20) and the isoscalar $3\hbar\omega$ strength from (e,e') (figure 21). The isovector strength is expected[31] to be nearly totally pushed up into the $3\hbar\omega$ state (figure 30), high up in the continuum which makes a definite measurement very difficult. Schematic model[25] (table 1) and more refined calculations[31] (figure 30) agree on an excitation energy of 190 to 200 $A^{-1/3}$ MeV. Figure 13 shows, that although there is a resonance at about this energy in spherical nuclei it is lowered to about 170 $A^{-1/3}$ MeV in deformed ones. From the very good constancy of excitation energy of the other giant resonances it is very difficult to believe that this is the

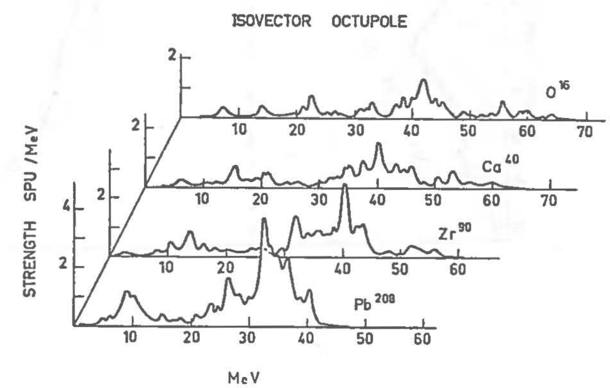

Fig. 30

same state. Since the isovector monopole has been predicted in this energy region (178 $A^{-1/3}$ MeV) the structure seen may indeed be a mixture of both isovector monopole and octupole. The measured excitation energy can be explained consistently if we assume the higher resonance to be E3. Similar to the lower E3 states it might be spread out in deformed nuclei as to disappear in the background. The monopole, which in first order does not couple to the deformed potential, is normally bracketed between the strong isovector E2 and the E3, and shows only up in deformed nuclei, when the latter gets spread out. The generally messy situation is demonstrated in figure 31, where a spectrum of ^{140}Ce up to 45 MeV excitation energy is shown before and after background subtraction. Figure 32 shows the formfactors for the discernable resonances above 20 MeV. It is clear that the results are somewhat ambiguous.

While one is at least in the beginning of getting a picture of the gross E3 distribution in nuclei, nearly nothing is known for even higher multipoles.

Table 3 shows the results for the two nuclei where we have found E4 strength[40,43]. Both resonances found are presumably isoscalar, because similar to the E3 case, the isovector strength is expected to be nearly totally concentrated in the $4\hbar\omega$ state at 275 $A^{-1/3}$ MeV, pushing it out of reach of currently possible experiments. Since some of the strength in ^{140}Ce is inferred from differences of resonances of other multipolarity to certain model-dependent formfactors

one should be cautious and await confirmation by other experiments.

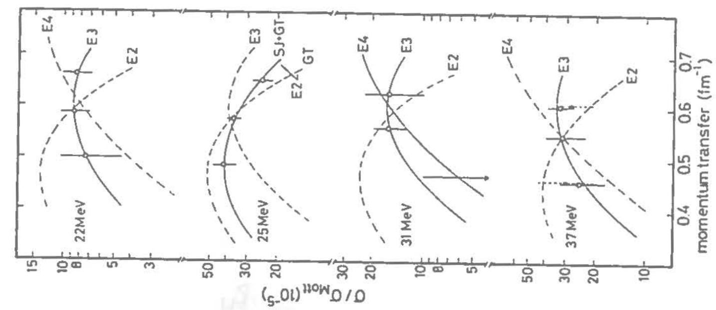

Fig. 32

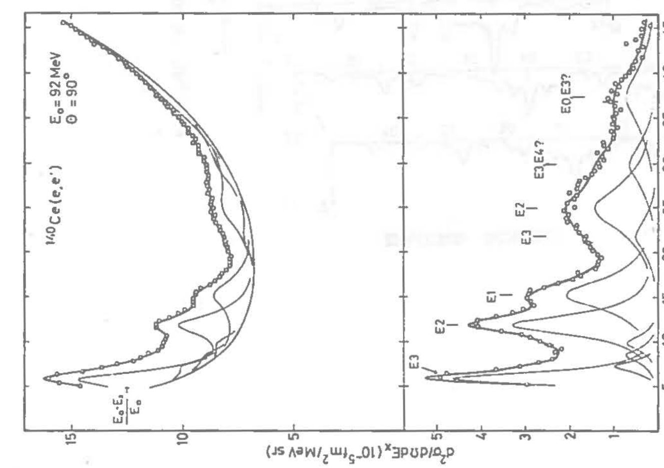

Fig. 31

Table 3 Known E4 (isoscalar?) continuum excitations

^{58}Ni [a]			^{60}Ni [a]			^{140}Ce		
E_x (MeV)	E_x ($A^{-1/3}$MeV)	R [b]	E_x (MeV)	E_x ($A^{-1/3}$MeV)	R [b]	E_x (MeV)	E_x ($A^{-1/3}$MeV)	R [b]
9.6	37	5 ± 2	11.4	43	3 ± 2	7.4	38	7 ± 3
15.1	58	40 ± 15	14.9	58	20 ± 10	~12 c)	~ 62 c)	20 ± 10 c)
						~25 c)	~130 c)	60 ± 30 c)
			40	157	150 ± 75	31	161	80 ± 40

a) ref. 92

b) $R = E_x \cdot B(E4)/EWSR(E4, \Delta T = 0)$

c) inferred from difference to E2 form factor

5. Outlook

The investigation of the giant multipole resonances discovered in recent years has been hampered by several factors. In hadron scattering, which has the advantage of being more selective towards isovector modes and where, therefore, the problem of resonance overlap is reduced, the background is of nuclear origin and presently, not even in principle, accessible to theoretical treatment.

Although in (e,e') the background is of radiative nature which can be calculated to some extent, it is very large at low momentum transfer, where, as shown in figure 8, the best selectivity for multipolarity determination and the smallest model dependency occur. In addition, since electromagnetic probes do not differentiate between isoscalar and isovector excitations, the problem of overlapping resonances causes ambiguities.

Much hope and effort (development of high duty cycle accelerators) is put into coincidence measurements, e.g., (e,e'p) or (e,e'γ), which will give the possibility to unambiguously determine the multipolarity by measuring in plane and out of plane angular correlations between the ejected particle (or the emitted de-excitation γ-ray) and the scattered electron.

While this method will practically eliminate the radiative background, the rate with which data will be produced will be extremely low. As complained in section 2, the electromagnetic interaction is relatively weak and that in itself prevents taking data at a rate comparable to (α,α'). In addition, when the outgoing particle is to be observed, targets will have to be a factor of 20 to 100 thinner then currently customary, i.e., typically 1 mg/cm^2 in heavy nuclei, versus 100 mg/cm^2 customary for inclusive (e,e') measurements and many spectra will have to be taken to get a kinematically complete set of data.

The problem of the overlapping resonances however, will persist. To some extent it will get worse, because of interference effects between resonances of different multipolarity which do not occur in (e,e'). And finally, the formalism for coincidence experiments to data has only been developed for PWBA, limiting experiments to light nuclei.

Figure 9 showed that it is difficult to learn in the case of overlapping resonances about higher multipolarities from (e,e'). One exciting possibility to at least determine excitation energy and shape of such resonances has been demonstrated recently in Berkeley, where the experimentally well-known E3 state at 19 MeV in ^{208}Pb was strongly enhanced compared to the background through angular momentum matching of inelastic scattering of ^{16}O at 310 MeV[72]. There the problem to date seems to rest with the determination of the isoscalar strength.

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