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EXCITATION OF GIANT RESONANCES THROUGH INELASTIC SCATTERING

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ABSTRACT

In the last few years, exciting developments have taken place in the study of giant resonances (GR). In addition to the already well known giant dipole resonance (GDR), the presence of atleast two more new GR, viz. giant quadrupole resonance (GQR) and giant monopole resonance (GMR) has been experimentally established. The systematics covering these GR is found to be consistent with the theoretical expectation. Though the existence of higher multipoles has been predicted by theory, so far only some of these have been found to be excited experimentally. Various probe particles - electrons, protons (polarized and unpolarized), light- and heavy ions and pions- at different bombarding energies have been used to excite the GR region, primarily through the inelastic scattering process. Detailed experiments, looking at the decay modes of GR region, have also been performed. These studies have contributed significantly to a better understanding of the phenomenon of nuclear collective excitation. In this report, the current status of 'GR' research is reviewed.

EXCITATION OF GIANT RESONANCES THROUGH INELASTIC SCATTERING

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INTRODUCTION

In the last few years exciting developments have taken place in the study of giant resonances (GR)[1-4]. In addition to the already well known giant dipole resonance (GDR), the presence of atleast two more new GR, the giant quadrupole resonance (GQR) and the giant monopole resonance (GMR) has been experimentally established. The systematics covering these GR is found to be consistent with the theoretical expectations. In fact, with the advent of accelerators having beams of higher and variable energy and with improvements in detection techniques, a grand revival of GR research has taken place.

Historically, the GDR was the first to be discovered in photonuclear measurements, in the late forties. It was followed by considerable activity mainly consisting of photonuclear and capture measurements. It took almost 25 years before a new GR viz. GQR[5] was experimentally established through inelastic scattering technique. More recently the GMR has also been discovered and there has been growing interest in this field of GR. In the present work, the current status of GR research will be reviewed.

GIANT RESONANCES: BASICS

A typical proton energy spectrum from a (p,p') reaction is shown in fig.1. On the high energy end of Ep one can see the familiar low lying discrete states of the target. These are generally well understood by direct reaction mechanism. On the low energy side the prominent evaporation peak which is well explained in terms of a compound nucleus statistical model is seen. The intermediate energy region apparently looks to be featureless but for a broad bump around 10 to 20 MeV excitation. The following discussion will be pertaining to this region of excitation where the GRs are strongly excited.

GRs are considered to be highly collective modes of nuclear excitation in which an appreciable fraction of the nucleons of a nucleus move together. The motion is so collective that it is appropriate to think of these modes of excitation, according to the hydrodynamic model, as the oscillations of a liquid drop. In fig.2 some of these modes of oscillation are described. The monopole (L = 0) is a spherically symmetric oscillation or compression of the nucleus. The dipole (L= 1) mode is due to the oscillation of p and n in bulk against each other. An oscillation of a spherical nucleus to oblate and then to prolate shape represents the quadrupole mode. As the nuclear fluid has n,p, spin up (↑) and spin down (↓) components, one can think of several combinations of these for each multipolarity, L. Modes in which p and n oscillate in phase are isoscalar in character (T= 0) and the ones in which they oscillate out of phase are called isovector modes (T= 1). Similarly, ↑ and ↓ nucleons oscillating in phase yield $S = 0$ modes while the so called spin flip modes ($S = 1$) are produced by ↑ and ↓ nucleons oscillating out of phase. The $S = 0$ oscillations are the electric modes while the $S = 1$ oscillations are the magnetic modes. The present report will deal primarily with the current status of the giant electric modes of excitation.

According to the shell model picture, the GR are considered to be coherent 1p-1h excitations. Considering the shell model states of a hypothetical nucleus (fig.3), the major shells are separated by $1\hbar\omega$ or $41 A^{-1/3}$ MeV. GR are supposed to result from transitions of nucleons from one major shell to another, under the influence of an interaction that orders these transitions into a coherent motion. The GDR is supposed to be a $1\hbar\omega$ excitation but it occurs around $E_x \simeq 78\ A^{-1/3}$ MeV. This increase in E_x value from that expected is explained as arising from spin-isospin parts of effective N-N interaction, which is found to push up $S = 1$ or $T = 1$ states and move down $S = T = 0$ states from the expected energy. The GMR is a $2\hbar\omega$ excitation and it occurs around $\simeq 80\ A^{-1/3}$ MeV. The quadrupole can be either $0\hbar\omega$

(within a shell and responsible for low-lying 2^+ states) or $2\hbar\omega$ (GQR) excitation. The GQR is found at $E_x \simeq 64\ A^{-1/3}$ MeV. Similarly one can have $1\hbar\omega$ (Low Energy Octupole Resonance-LEOR) and $3\hbar\omega$ (High Energy Octupole Resonance-HEOR) excitations for the $L = 3$ octupole mode.

As several giant modes are predicted to be excited around the same region of excitation and also as they occur at E_x above particle emission threshold, to make the GRs fairly wide, the GR region is complicated and one has to do considerable unfolding of these overlapping modes to select out the multipole of interest. From the foregoing discussions it is very clear that the experimental problem in studying these giant modes will be very challenging. It is conceivable that by performing appropriate experiments, selective excitation or enhancement of a particular mode could be achieved. Photonuclear reactions (and their inverse) have been successfully used to populate and study the GDR. Inelastic scattering technique involving isoscalar projectiles like alphas, has been used to selectively excite $T = 0$ mode. The inelastic scattering of electrons has the advantage that the electrons has the advantage that the electron-nucleus interaction is known thus simplifying interpretation of the data. But as it excites both the isoscalar and isovector modes equally strongly, it leads to a rather messy energy spectra and extraction of strengths of various multipoles excited is quite involved. Proton inelastic scattering is another useful technique for studying the GR. In this case the isovector modes are supposed to be excited weakly as compared to isoscalar modes as the isovector part of the interaction potential is considerably smaller than the isoscalar part. Charge exchange reactions like (p,n), (^{3}He,t) are generally favoured to populate the isovector modes.

All these features come out clearly and quite naturally if one considers the effective interaction between a nucleon in the projectile and one is the target nucleus. This interaction is both spin and isospin dependent and phenomenological in nature. The central part of the interaction may be written as:

$$V_{TS}(r_{ij}) = \underset{(T=S=0)}{V_{00}(r_{ij})} + \underset{(T=1\ S=0)}{V_{10}(r_{ij})}\, \tau_i \cdot \tau_j + \underset{(T=0\ S=1)}{V_{01}(r_{ij})}\, \sigma_i \cdot \sigma_j + \underset{(T=1=S)}{V_{11}(r_{ij})(\sigma_i \cdot \sigma_j)(\tau_i \cdot \tau_j)}$$

The four modes for each multipolarity arise from a term in the effective interaction. For example, the low-lying 2^+ and 3^- states as well as GQR are populated via $T=S=0$ term; the GDR and isobaric analogue state (IAS) are examples of excitations from the isospin term, $T=1$ $S=0$. Spin-flip transitions occur due $T=0$ $S=1$ part of the interaction. M1 and Gamow-Teller transitions are due spin-isospin part ($T=1$ $S=1$) of the interaction. Thus it is clear by a proper selection of the projectile and reaction type it is possible to study various aspects of the complicated GR spectra and effective N-N interaction.

One way of representing the collective nature of these GR is by defining an appropriate sum rule. An energy weighted sum rule (EWSR) is commonly used in estimating the transition strengths of various modes of excitation. In the inelastic scattering technique which has turned out to be most popular method to excite the GR, the experimental $\sigma(\theta)$ are normalised to the theoretical estimates of the same and the resultant normalisation constant is related to the sum rule strength. Collective model inelastic scattering calculations (DWBA) - both microscopic and macroscopic- are performed to be compared with the experimental data and the values (deformation parameter) obtained from normalisation reveal the collective nature of the GR modes. The relation between the experimental and theoretical $\sigma(\theta)$ which will lead to 100% EWSR is given as follows:

L	Relation (for 100% EWSR)	Form factor used (in collective model calculation
0	$\sigma_{exp} = \frac{4\pi}{3A} \frac{\hbar^2}{2mE_x} \frac{5}{R^2} \sigma_{the}$	$\delta U \rightarrow 3U + R\frac{dU}{dr}$
1	$\sigma_{exp} = 16\pi \frac{NZ}{A^3} \frac{\hbar^2}{2mE_x} \sigma_{the}$	$\delta U \rightarrow \frac{dU_{isovect}}{dr}$
2 (AND HIGHER L)	$\sigma_{exp} = \frac{4\pi}{3A} \frac{\hbar^2}{2mE_x} \frac{L(2L+1)}{R^2} \sigma_{the}$	$\delta U \rightarrow R\frac{dU}{dr}$

Details of these calculations are given in Ref.6.

With this background of GR, the discussion will proceed to the more specific details of the various GR modes excited.

GIANT DIPOLE RESONANCE (GDR)

The best known GR is the GDR. In fig.4, the excitation function for photonuclear reaction is shown and the strong excitation of GDR is clearly seen. As E1 excitation is several times stronger than E2 mode, one normally finds the photonuclear data dominated by GDR excitation. The bulk of our present knowledge about the GDR and its properties are obtained from the photo-absorption process using monoenergetic photons. The characteristics of the GDR are shown in fig.5. More details on this subject can be found from Ref.7.

GIANT QUADRUPOLE RESONANCE (GQR)

The most studied of the non-dipole resonances is the GQR[2,3,8,9]. From a systematic study this collective mode has been found to be excited in nuclei ranging from ^{14}N to ^{232}Th. In fig.6, alpha spectra from (α,α') reaction on ^{120}Sn are shown. One finds besides the low lying states, the strong excitation of at least two GR bumps above the continuum. The lower excitation bump is supposedly the low energy octupole resonance (LEOR). The higher energy bump is now considered to be consisting of the GMR and the GQR. The procedure procedure popularly followed in the analysis of GR is to shape fit the GR bump as consisting of two gaussians on top of a smooth underlying continuum background. This way the $\sigma(\theta)$ for GQR and GMR regions have been obtained. As can be seen from fig.7, the angular distribution for the GQR region follows a $L = 2$ pattern, justifying the procedure described above. It should be pointed out that the main problem in getting proper $\sigma(\theta)$ values lies in the correct estimation of the underlying background continuum. As no theory at present is capable of reproducing quantitatively this underlying continuum, it is customary to take a suitable shape and magnitude for the continuum with the added assumption that the GR peak cross section does not mix with the underlying continuum and the peak is stripped off of the continuum by extrapolating the magnitude and shape from higher excitation energies. Even though there is no complete justification for several of the methods followed in GR analysis and unfolding of GR the fact remains that the results obtained are in general reasonable and meaningful.

The GQR as mentioned earlier are excited in many nuclei (fig.8). Their strength distribution is such that they appear to be fragmented in light nuclei and concentrated is medium and heavy nuclei. This aspect of GQR is brought out nicely in fig.9. Several groups[10,11,12] have studied in detail the GR region for light nuclei.

The spectra so far discussed are from (α,α') reaction. Another technique which is quite useful in not only establishing the presence of GQR but also other multipoles, is the inelastic scattering of high energy polarized protons[13]. Combining the $\sigma(\theta)$ and $A(\theta)$ measurements for the GR region it has been possible to estimate the strengths of the various multipoles excited. Results of the analysis for the GQR region excited in $(\vec{p},p')$ reaction are shown in fig.10. This work clearly establishes the presence of $L=2$ mode and also gives evidence for $L=4$ mode in the same region of excitation. The salient features of GQR are shown in fig.11. The average excitation energy of GQR tallies very well with the theoretical estimation[14]. It is found, for light nuclei 30-50% of $L=2$ strength is exhausted in this high lying GQR region and about 20-30% in the low lying 2^+ states ($0\hbar\omega$). However, for nuclei having $A \gtrsim 100$, essentially 100 %, of the EWSR is found to be depleted in the GQR region.

So far, the discussion has been about the isoscalar GQR. Isovector GQR ($L=2$ $S=0$ $T=1$) is predicted to be excited around $E_x \simeq 130\ A^{-1/3}$ MeV. Most of the data for this mode of excitation have come from (e,e') and capture reactions and the systematics[15] for this mode are shown in fig.12. One observes that essentially all the strength lies in the isovector GQR region and there is no apparent change in %EWSR strength going from heavier to lighter nuclei.

GIANT MONOPOLE RESONANCE (GMR)

The GR which has generated the most interest is the GMR. Observation of monopole or compressional mode of nuclear excitation is of special significance because knowledge of its excitation energy provides direct information on the nuclear compressibility. The GMR excitation energy E_x is related to the compressibility (K_A) of a finite nucleus as[16,17]

$$E_x = \frac{\hbar}{r_0}\sqrt{\frac{K_A}{m}}$$

where r_0 = radius parameter and m = nucleon mass. The incompressibility of a finite nucleus (K_A) differs from that of nuclear matter by surface, Coulomb and symmetry effects. The relation is[2]

$$K_A = K_{nm} + K_{sur} A^{-1/3} + K_{sym}\left(\frac{N-Z}{A}\right)^2 + K_{Cou}$$

The coefficients in the above equation can be viewed as second derivatives with respect to r of corresponding coefficients in the mass equation. However, the derivatives of the coefficients in the mass equation can not be evaluated with sufficient accuracy to obtain meaningful estimates of K_{sur}, K_{sym} and K_{nm}; they may, however, be obtained from experimental values of K_A.

With the discovery of GQR through inelastic scattering, in the early seventies, there was intense study of GR region with a number of probes. However, there was not much evidence for the excitation of GMR from these studies. There were a few instances[18,19,20] where presence of GMR was suggested though in a somewhat indirect manner. Unambiguous identification of GMR came from the small angle measurements of inelastic scattering of alpha[21)23)] and helium-3[22] particles. In fig.13 the (α,α') spectra measured[23] at forward angles are shown. The shape, noticably the width of GR bump changes in going from $\theta \simeq 0°$ to 6°. This clearly indicates the presence of more than one L in this region. Following the procedure of fitting with two Gaussiens, one for GMR and the other for GQR, one ends up with angular distributions which are characteristic of $L=0$ and $L=2$ excitation. The dip around $\theta = 4°$ for $L=0$ distribution is significant. The importance of forward angle data in establishing the GMR excitation could be appreciated if one considers the angular distribution data backward of say, $\theta = 6°$. It can be seen from fig.13 that both $L=0$

and $L=2$ distributions are very similar and it is almost impossible to separate the two from angular distribution data alone. This type of uncertainty was there in the earlier measurements which did not extend to extreme forward angles. Similar results obtained from (^{3}He,^{3}He$'$) reaction[22] are shown in fig.14. Once again one finds the dip around $\theta = 4°$ for $L=0$ distribution and a rise for $L = 2$ distribution which clearly distinguishes between these two multipoles. Recently, from a reanalysis of (p,p')[24] data with the proper estimation of GDR strength it has been possible to deduce considerable GMR strength. The (p,p') spectra obtained for several targets are shown in fig.15. It should be mentioned that the GMR strength estimated from this study is strongly dependent on the calculated contribution due to the GDR. Willis et al[25] have performed small angle (d,d') experiments, again to determine the GMR strengths. In carrying out small angle (p,p') and (d,d') experiments, one should be aware of the strong excitation of GDR[26] due to Coulomb excitation process and hence should be cautious in analysing the data to estimate the GMR strength. Projectile energy dependence of GQR and GMR cross section has been successfully utilised to identify the GMR strength by Marsch and collaborators[27]. From the large body of experimental data, the systematics of GMR[1,2,28] as shown in fig.16 has been obtained. It appears that the presence of considerable GMR strength is well established for medium and heavy nuclei The GMR picture for $A \lesssim 50$ is still not very clear.

The present data on GMR yield a value of $\simeq$ 200 MeV for the incompressibility of nuclear matter K_{nm}. This value is in agreement with several microscopic calculations as discussed by Blaizot[16].

GIANT OCTUPOLE RESONANCE (GOR)

From the shell model picture of GR, it is evident there can be two classes of octupole resonances possible viz. $1\hbar\omega$ and $3\hbar\omega$ excitations. The former one has been identified[29] through inelastic scattering of alpha particles. In fig.17 the spectra clearly reveal the presence of a bump at E_x around 32 $A^{-1/3}$ MeV. This is close to the energy expected for the low energy octupole resonance (LEOR, $1\hbar\omega$) and the angular distribution is characteristic of $L = 3$. The LEOR exhausts about 30-40% of EWSR. It is found that the LEOR bump is absent for some nuclei for example in, ^{40}Ca and ^{208}Pb. Part of the explanation comes from the fact in these cases most of the LEOR strength goes to lower lying 3^- states and this in turn leads to the weakening of LEOR bump.

More recently high energy (p,p') experiments[30] have located the $3\hbar\omega$ excitation viz. high energy octupole resonance (HEOR) at an $E_x \simeq 110\ A^{-1/3}$ MeV. The HEOR appears as a weak broad bump (fig.18) and seems to follow again a $L = 3$ angular distribution. It is very clear the results of these experiments are strongly dependent on the way the background continuum is estimated and subtracted. This in turn will lead to larger uncertainties in EWSR estimates. The present results in general suggest that GOR has been located.

HIGHER MULTIPOLES

So far there has been no direct evidence for excitation of $L = 4$ ($4\hbar\omega$) giant resonance. However, as the $2\hbar\omega$ component of $L = 4$ GR is expected to occur around the same excitation energy of GQR, several experiments[31] have indicated the possible presence of $L = 4$ strength around the GQR. In these experiments, it was found that the inclusion of $L = 4$ strength in addition to $L = 2$ excitation improved the fits to the angular distribution data. Recent (p,p') experiments[13, 32] have found $L = 4$ strength not only around GQR region of excitation but also near GMR+GDR region, thereby indicating perhaps the hexadecapole strength is distributed and this GR is fairly broad and fragmented. Again, the identification of $L = 4$ strength is sensitive to the continuum estimation and hence the location of $L = 4$ and high multipole strengths present a considerable experimental challenge.

NEW PROBES FOR STUDY OF GR

From the foregoing discussions it is apparent that the main problem in estimating the GR strengths lies in the proper estimation of the continuum background. The continuum is supposed to arise from 1) collective excitation of various multipoles 2) quasi free scattering and knock out process 3) preequilibrium and multistep process 4) breakup-pick up contributions in the case of composite particles. When comparing the GR region excited in inelastic scattering of various projectiles, (fig.19)[33] one observes that the underlying continuum is practically flat for p and α ; for ^{3}He and d it is becoming steeper decreasing towards the low energy end of spectra. For projectiles more massive than α the continuum drops off very rapidly as the energy of excitation increases. However, it appears that just near the GQR, the ratio of GR peak to the background continuum is nearly the same for all the projectiles. It look like that the use of heavy ions (HI) for studying the GR region has certain experimental adventages. Notably in the HI inelastic scattering, the spectra will be free from quasi free and preequilibrium contributions, through there could be problems due to break up-pick up process. Further it is expected[34] that high energy HI ($A \lesssim 20$) will be useful for exciting higher multipoles. In fig.20 we have the spectra for the GR region excited from inelastic scattering of Li, C, N and O.[35-38] A prominent GR bump appears in all the spectra. This field of investigation is still in its a infancy and HI inelastic scattering appears to have a bright future in the study of GR. Pion inelastic scattering[39] is also considered as a suitable probe for exciting the GR. Pion inelastic scattering is expected to favour $S = 1$ transitions as compared to $S = 0$ excitations. Further the pion inelastic scattering angular distributions for $L = 0$ and $L = 2$ multipoles show significant differences even at angles more than 20° and this is an encouraging feature as one will avoid problems normally associated with small angle scattering which is a technique used, to separate $L = 0$ and $L = 2$ in the case of other projectiles. Charge exchange multipole reactions[40] like (p,n), (^{3}He,t) have been recently employed to populate Gamow-Teller (J=1 T=1) magnetic modes. There is still a lot of work to be done in the case of magnetic modes of GR.

Another useful technique which is gaining importance in the GR study, is the measurement of the decay branches of the GR[3,41]. These measurements can give insight into the microscopic properties of the GR. It could reveal to what extent the 1p-1h collective states mix with more complicated states. Further this method of studying the GR can offer the experimental advantage of measuring the GR strength more accurately with less interference from background continuum. It is also possible to enhance the presence of weak 0^+ strength in the presence of strong 2^+ excitations by this technique. This technique needs to be exploited.

Theoretical calculations by Broglia et al[42] indicate that the GR plays a central role in the energy damping observed in deep inelastic reactions. The theoretical aspects of GR are dealt with in great detail in Ref.43. It is clear that knowledge of GR will lead to a better understanding of the various aspects of the atomic nucleus.

CONCLUSION

From the above discussions, it is clear the research on GR has progressed a great deal in the last few years. The general features of the GMR and the GQR (besides the GDR) are all reasonably established. There are compelling evidence to believe the existence of higher multipoles as well. The general features of the GR can be summarised as follows: a) GR are general properties of nuclei b) Excitation energy of GR varies smoothly with A. e.g. for the GDR the E_x is $\simeq 78\ A^{-1/3}$ MeV, for GQR it is $\simeq 64\ A^{-1/3}$ MeV and for GMR $\simeq$ $80\ A^{-1/3}$ MeV and so on. c) GR exhausts appreciable fraction

of an appropriate sum rule i.e. they are highly collective.
d) GR strength is generally localized in E_x .

There are a still few open problems and unanswered questions. Apparent missing of some $L = 2$ strength in a few light nuclei; Absence of LEOR in some nuclei, GMR strength in light nuclei, Reliable determination of higher multipole strengths; Quantitative estimation of continuum background; Better micro and macroscopic DWBA calculations; Need for detailed RPA calculations Magnetic modes of GR.

To conclude, one finds that apparently featureless and uninteresting continuum region of excitation has turned out to be very challenging and "rich" in substance, and one can hope to see more of GR in the years to come.

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REFERENCES

1) F.E. Bertrand, Proc. Intern. Conf. on Nuclear Physics, Berkeley, U.S.A. (1980)
F.E. Bertrand, Varenna summer school on nuclear structures and heavy ion collisions, Varenna, Italy (1979)
F.E. Bertrand, Ann. Rev. Nuc. Sci. 26, 457 (1976)

2) D.H. Youngblood, Proc. RCNP Intern. Symp. on highly excited states in Nuclear Reactions, Osaka, Japan (1980), Proc. GMR Conf. (see ref.4) p.113 (1980)

3) A van der Woude, Lecture Notes KVI-254, Groningen, Holland (1980); Proc. GMR Conf. (see ref.4) p.65 (1980)

4) Proc. of Giant Multipole Resonance topical conf., (GMR Conf.) Oak Ridge, Ed. F.E. Bertrand, Harwood Academic Publishers, (1980)

5) R. Pitthanand T. Walcher, Phys. Lett. 36B, 563 (1971); M.B. Lewis and F.E. Bertrand, Nucl. Phys. A196, 337 (1972)

6) G.R. Satchler, Proc. Intern. School. "Enrico Fermi", Elementary modes of excitations in nuclei, Varenna, Italy (1976)

7) B.L. Berman and S.C. Fultz, Rev. Mod. Phys. 47, 713 (1975)

8) F.E. Bertrand, G.R. Satchler, D.J. Horen, J.R. Wu, A.D. Bacher, G.T. Emery, W.P. Jones, D.W. Miller and A. van der Woude, Phys. Rev. C22, 1832 (1980)

9) D.H. Youngblood, J.M. Moss, C.M. Rozsa, J.D. Bronson, A.D. Bacher and D.R. Brown, Phys. Rev.C13, 994 (1976)

10) D.H. Youngblood, C.M. Rozsa, J.M. Moss, D.R. Brown and J.D. Bronson, Phys. Rev. C15, 1644 (1977)

11) K. van der Borg, M.N. Harakeh, A. van der Woude and F.E. Bertrand, Nucl. Phys. A341, 219 (1980); K. van der Borg, Ph.D. Thesis, University of Groningen, Holland (1979)

12) K.T. Knopfle, G.T. Wagner, A. Kiss, M. Rogge, C. Mayer Böricke and Th. Bacher, Phys. Lett. 64B, 263 (1976)

13) S. Kailas, P.P. Singh, A.D. Bacher, C.C. Foster, D.L. Friesel, P. Schwandt and J. Wiggins, to be published

14) J.R. Nix and A.J. Sierk, Phys. Rev. C21, 396 (1980)

15) R. Pitthan, in Proc. GMR Conf. (see Ref.4) p.161 (1980)

16) J.P. Blaizot, Phys. Rep. 64, 171 (1980)

17) O. Bohigas, A.M. Lane and J. Martorell, Phys. Rep. 51, 267 (1979)

18) N. Marty, M. Morlet, H.Willis, V. Comparat, R. Frascaria and J. Kallne, Proc. of Intnl. Conf. on highly excited states in nuclei, Jülich, p.17 (1975)

19) S. Fukuda and Y. Torizuka, Phys. Lett. 62B, 146 (1976); M. Sasao and Y. Torizuka, Phys. Rev. C15, 217 (1977)

20) M.N. Harakeh, K.van der Borg, T. Ishimatsu, H.P. Morsch, A. van der Woude and F.E. Bertrand Phys. Rev. Lett 38, 676 (1977)

21) D.H. Youngblood, C.M. Rozsa, J.M. Moss, D.R. Brown and J.D. Bronson, Phys. Rev. Lett. 39, 1188 (1977)

22) M. Buenerd, C. Bonhomme, D. Lebrun, P. Martin, J. Chauvin, G. Duhamel, G. Perrin, P. de Saintignon, Phys. Lett. 84B, 305 (1979)

23) C.M. Rozsa, D.H. Youngblood, J.D. Bronson, Y.W. Lui and U. Garg, Phys. Rev. C21, 1252 (1980)

24) F.E. Bertrand, G.R. Satchler, D.J. Horen and A. van der Woude, Phys. Lett. 80B, 198 (1979);
F.E. Bertrand, G.R. Satchler, D.J. Horen and A. van der Woude, Phys. Rev. C18, 2788 (1978)

25) A. Willis, M. Morlet, N. Marty, R. Frascaria, C. Djalali and V. Comparat and P. Kitching, Nucl. Phys. A344, 137 (1980)

26) G. Djalali, N. Marty, M. Morlet, A. Willis, V. Comparat and R. Frascaria, to be published in Zeits. fur Physik A (1980)

27) H.P. Morsch, M. Rogge, P. Turek, C. Sukosd and C. Mayer-Bor::cke, Phys. Rev. C20, 1600 (1979)

28) M. Buenerd, D. Lebrun, Pl. Martin, P. de Saintignon and C. Perrin Phys. Rev. Lett. 45, 1667 (1980)

29) J.M. Moss, D.R. Brown, D.H. Youngblood, C.M. Rozsa and J.D. Bronson, Phys. Rev. C18, 741 (1978)

30) T.A. Carey, W.D. Cornelius, N.J. DiGiacomo, J.M. Moss, G.S. Adams, J.B. McClellard, G. Pauletta, C. Whitten, M. Gazzaly, N. Hintz and C. Glashausser, Phys. Rev. Lett. 45, 239 (1980)

31) E.C. Halbert, J.B. McGrory, F.R. Satchler and J. Speth, Nucl. Phys. A245, 189 (1975); M.N. Harakeh, B. Van Heyst, K. vander Borg and A. van der Woude, Nucl. Phys. A327, 373 (1979) J. Wambach, F. Osterfeld, J. Speth and V.A. Madsen, Nucl. Phys. A324, 77 (1979)

32) P. Martin, Y. Gaillard, P. de Saintignon, G. Perrin,

J. Chauvin, G. Duhamel and J.M. Loiseaux Nucl. Phys. A315, 291 (1979)

33) C.C. Chang, In Proc. GMR Conf(See ref.4) p. 191 (1980)

34) C.K. Gelbke, In Proc. GMR Conf. (see ref.4) p.333 (1980)

35) P. Doll, D.L. Hendrie, J. Mahoney, A. Menchaca Rocha, D.K. Scott, T.J.M. Symons, K. van Bibber, Y.P. Viyogi and H. Wieman, Phys. Rev. Lett. 42, 366 (1979) (^{16}O)

36) U. Garg, P. Bogucki, J.D. Bronson, Y.W. Lui, K. Nagatari, E. Takada, N. Takahashi, T. Tanya, D.H. Youngblood, Phys. Lett. 93B, 31 (1980) (^{14}N)

37) R. Kamermans, J. van Driel, H.P. Morsch, J. Wilczynski and A. van der Woude, Phys. Lett. 82B, 221 (1979) (^{12}C)

38) H.J. Gils, H. Rebel, J. Buschman and H. Klewe-Nebenius, Phys. Lett 68B, 427 (1977) (^{6}Li)

39) M. Buenerd and J. Arvieux, in Proc. GMR Conf.(see ref.4) p.381 (1980)

F.E. Bertrand, 2nd Intern. Conf. on Meson Nuclear Physics, Houston (1979)

J. Arvieux, J.P. Albanese, M. Buenerd, D. Lebrun, E. Boschety, C.H.Q. Ingram and J. Jansen, Phys. Rev. Lett. 42, 753 (1979)

40) C.D. Goodman, in Proc. GMR Conf.(see ref.4) p.419 (1980)

41) G.J. Wagner, in Proc. GMR Conf. (see ref.4) p.251 (1980)

42) R.A. Broglia, C.H. Dasso and A. Winther, Phys. Lett. 53B, 301 (1974) and Phys. Lett. 61B, 113 (1976)

43) J. Speth, in Proc. GMR Conf. (see ref.4) p. 33 (1980)
G.E. Brown, In Proc. GMR Conf. (see ref.4) p.177 (1980)
J. Speth and J. Wambach, Nucl. Phys. A347, 389 (1980)

FIGURE CAPTION

Fig.1. Proton spectrum at 27° from ^{54}Fe(p,p') reaction for $E_p \simeq 62$ MeV (Ref.1)

Fig.2. Modes of oscillation of a nucleus

Fig.3. Shell model representation of electric multipole transitions

Fig.4. Giant dipole resonance excited in ^{60}Ni, ^{92}Zr and ^{120}Sn targets through (γ,n) reaction (Ref.7)

Fig.5. Systematics of GDR (Ref.7)

Fig.6. Alpha spectra at 12°, 13° from ^{120}Sn(α,α') reaction using 152 MeV incident alpha particle. The location of LEOR, GQR, GMR and continuum background is as indicated. (Ref.1,8)

Fig.7. Angular distribution for the GQR peak (Ref.8)

Fig.8. GQR excitation in various nuclei through (α,α') reaction (Ref.9)

Fig.9. The spectra in the GR region after background subtraction are shown for ^{90}Zr, ^{40}Ca, ^{28}Si, ^{27}Al and ^{24}Mg (Ref.10)

Fig.10. Angular distribution for $\sigma(\theta)$ and $A(\theta)$ for the GQR region excited in ^{92}Zr, ^{120}Sn and ^{208}Pb through inelastic scattering of $\simeq$ 104 MeV polarized protons.

Fig.11. Salient features of GQR (Ref.1 and 3)

Fig.12. Systematics of isovector quadrupole resonance (Ref.4, 15)

Fig.13. Alpha spectra for GR region from ^{116}Sn (α,α') reaction. The decomposition of GR bump into GMR and GQR and the resultant angular distributions are shown (Ref.23)

Fig.14. Small angle ^{3}He spectra. Angular distributions for GMR and GQR are shown (Ref.22)

Fig.15. GR spectra from (p,p') reaction. Two gaussian fits to GR region are shown (Ref.24)

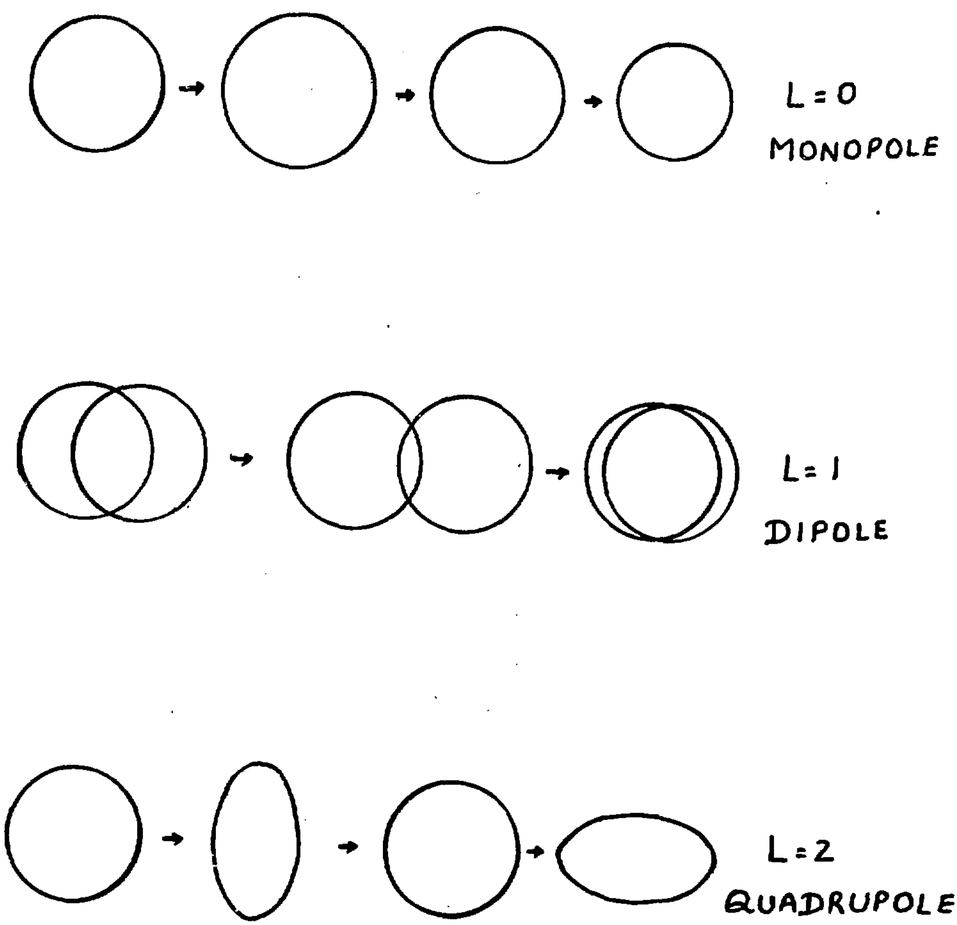
Fig.16. Salient features of GMR (Ref.1,2,28)

Fig.17. LEOR excited through (α,α') reaction. LEOR appears as a bump around $E_x \sim 32\ A^{-1/3}$ MeV (Ref.29)

Fig.18. (p,p') spectra revealing the presence of HEOR at $E_x \simeq 110\ A^{-1/3}$ MeV (Ref.30)

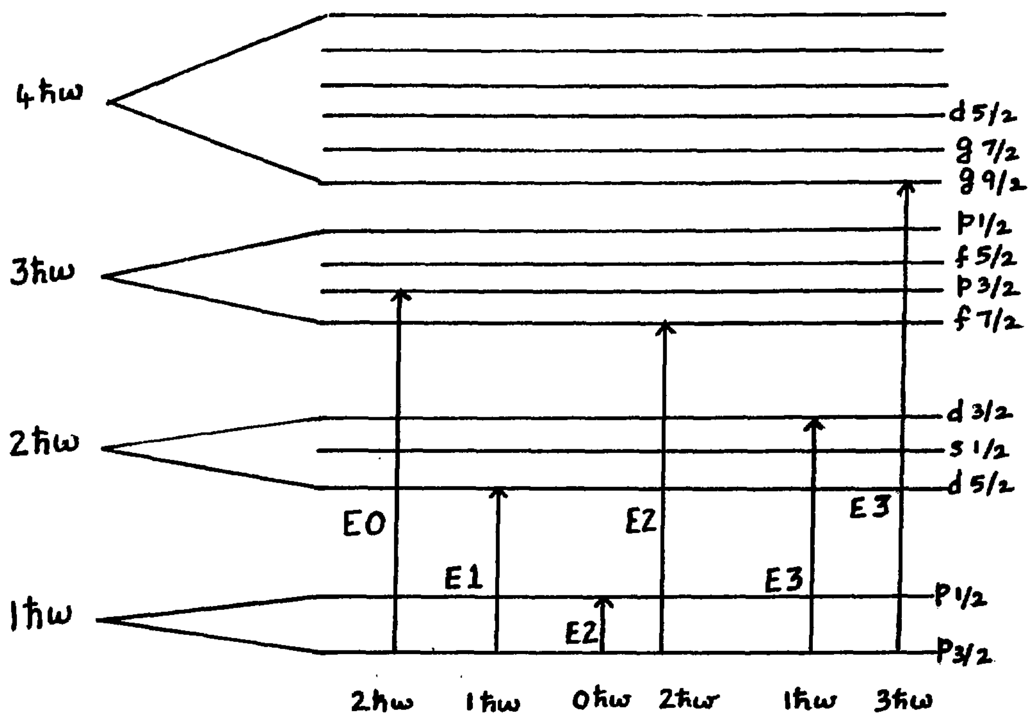
Fig.19. Inelastic proton, deuteron, ^{3}He, α particle, ^{6}Li and ^{12}C scattering spectra on ^{58}Ni (Ref.33)

Fig.20. Heavy ions to probe the GR region (Ref.35,36,37,38)



MODES OF OSCILLATION OF A NUCLEUS

FIG. 1



SHELL MODEL REPRESENTATION OF ELECTRIC MULTIPOLE TRANSITIONS

FIG. 2

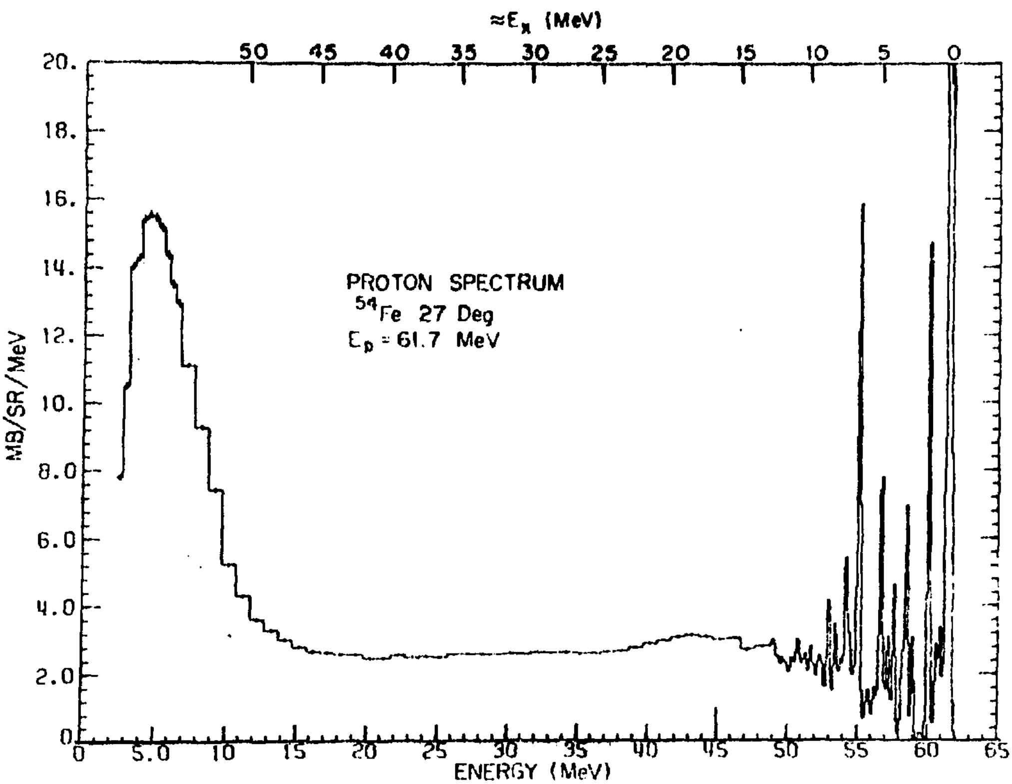

≈Ex (MeV)
50 45 40 35 30 25 20 15 10 5 0
20.
18.
16.
14.
12.
10.
8.0
6.0
4.0
2.0
0
MB/SR/MeV
PROTON SPECTRUM
54Fe 27 Deg
Ep = 61.7 MeV
0 5.0 10 15 20 25 30 35 40 45 50 55 60 65
ENERGY (MeV)

Fig. 3

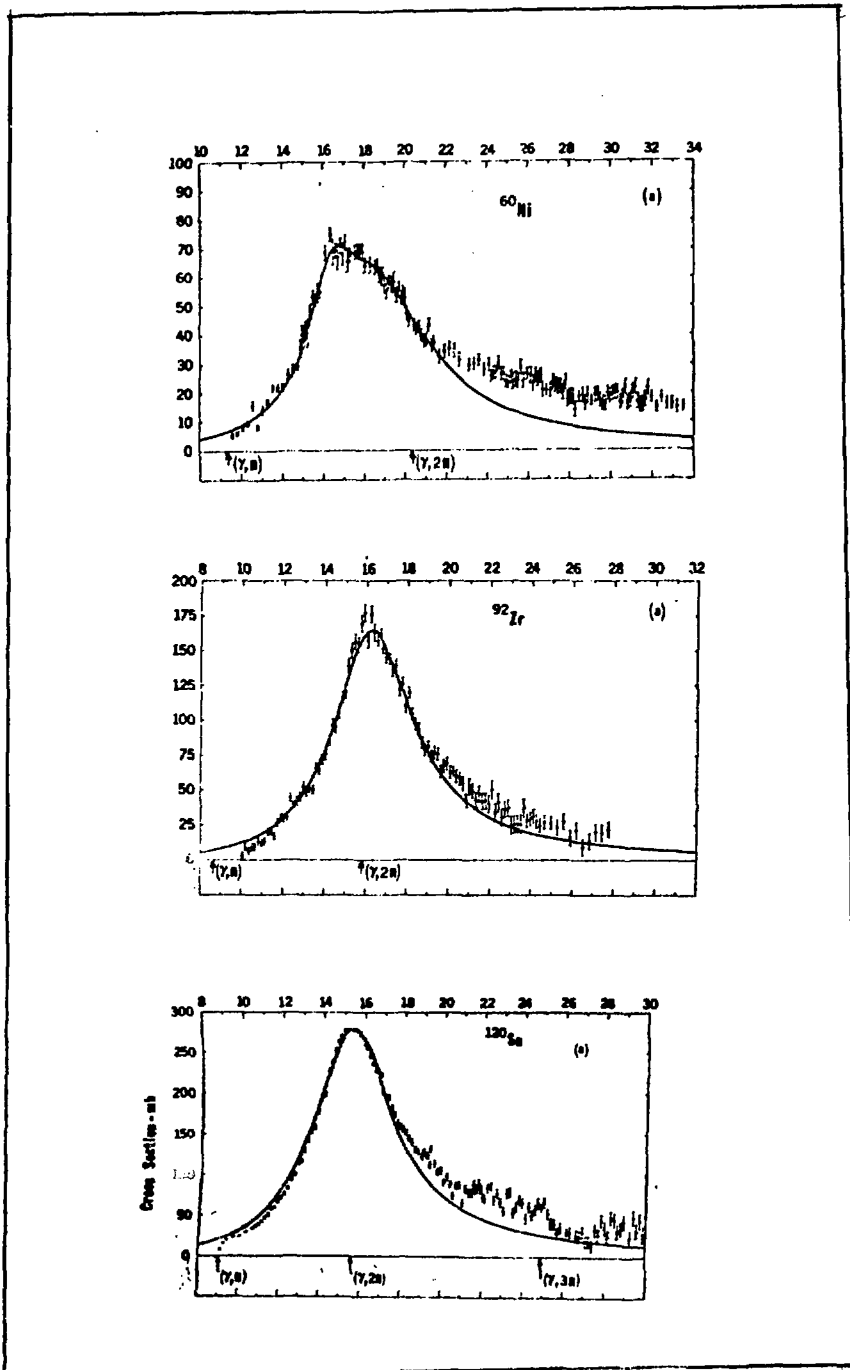


FIG. 4

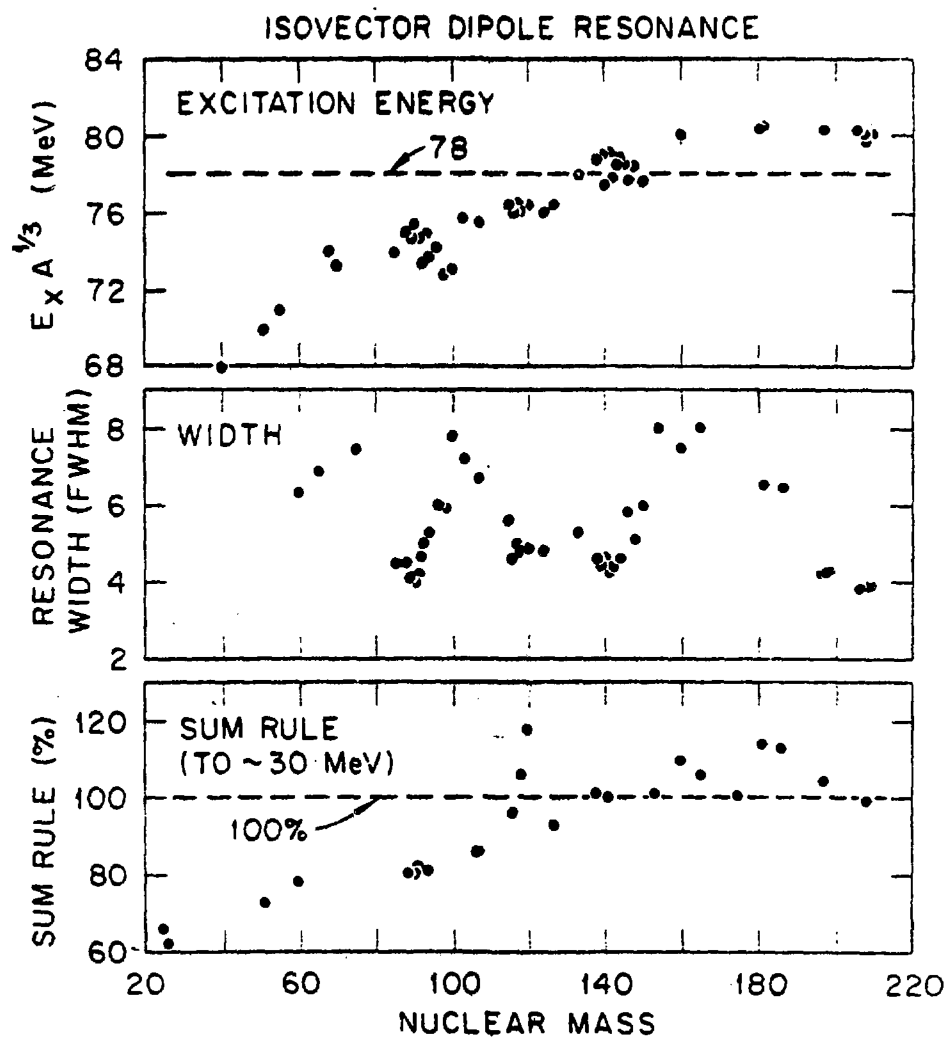
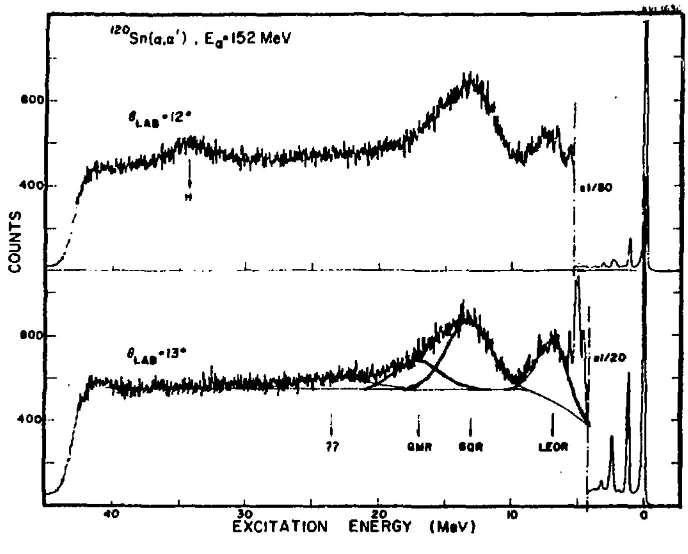
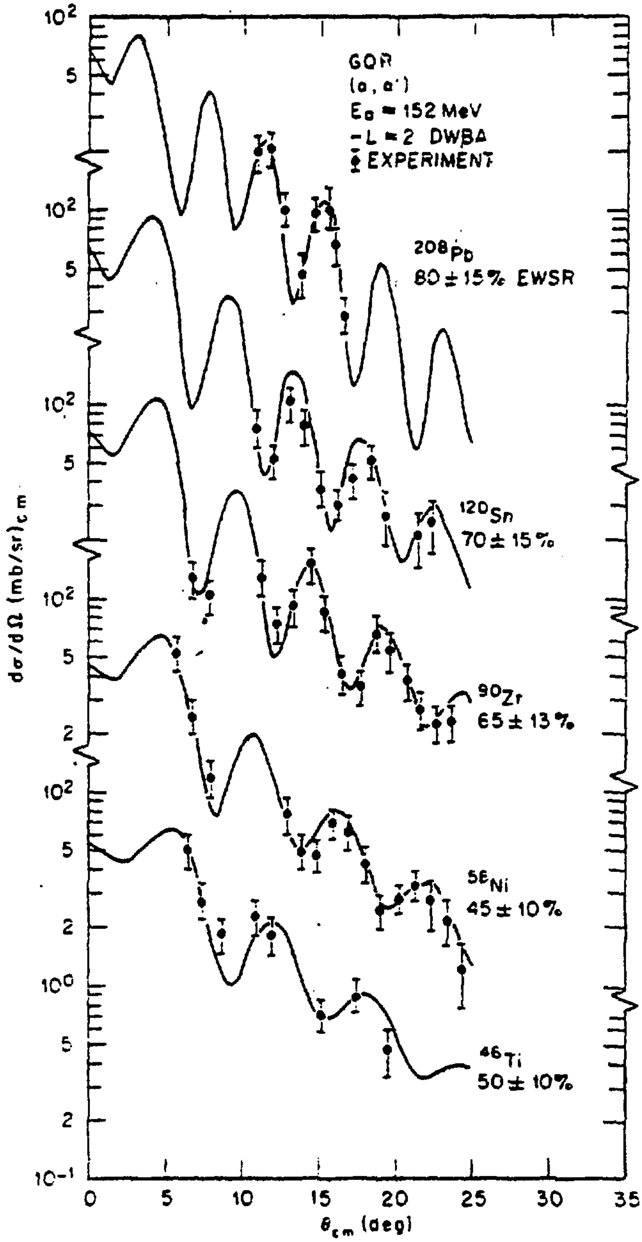

ISOVECTOR DIPOLE RESONANCE
EXCITATION ENERGY
78
$E_x A^{1/3}$ (MeV)
84
80
76
72
68
WIDTH
RESONANCE WIDTH (FWHM)
8
6
4
2
SUM RULE
(TO ~30 MeV)
100%
SUM RULE (%)
120
100
80
60
20
60
100
140
180
220
NUCLEAR MASS

Fig. 5



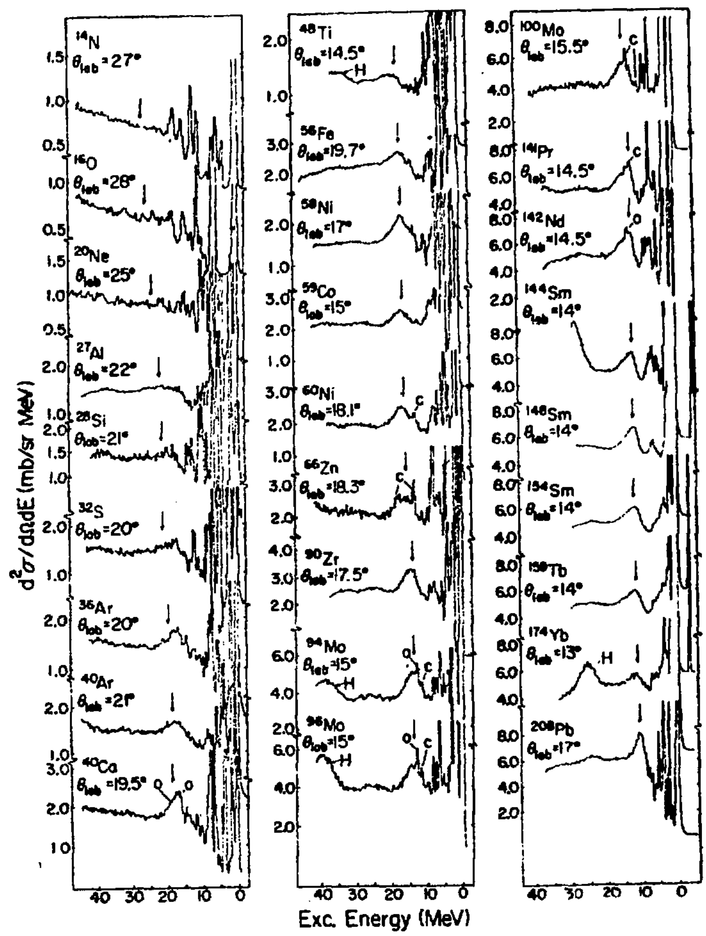
$^{120}Sn(\alpha,\alpha')$, E_α=152 MeV
θ_{LAB}=12°
θ_{LAB}=13°
800
400
800
400
COUNTS
H
x1/80
x1/20
??
GMR
GQR
LEOR
40
30
20
10
0
EXCITATION ENERGY (MeV)

FIG. 6



GQR
(α, α')
Eα = 152 MeV
— L = 2 DWBA
EXPERIMENT
208Pb
80 ± 15% EWSR
120Sn
70 ± 15%
90Zr
65 ± 13%
58Ni
45 ± 10%
46Ti
50 ± 10%
dσ/dΩ (mb/sr)c.m.
θc.m. (deg)
0
5
10
15
20
25
30
35

FIG. 7



d²σ/dΩdE (mb/sr MeV)
Exc. Energy (MeV)
¹⁴N θlab = 27°
¹⁶O θlab = 28°
²⁰Ne θlab = 25°
²⁷Al θlab = 22°
²⁸Si θlab = 21°
³²S θlab = 20°
³⁶Ar θlab = 20°
⁴⁰Ar θlab = 21°
⁴⁰Ca θlab = 19.5°
⁴⁸Ti θlab = 14.5°
⁵⁶Fe θlab = 19.7°
⁵⁸Ni θlab = 17°
⁵⁹Co θlab = 15°
⁶⁰Ni θlab = 18.1°
⁶⁶Zn θlab = 18.3°
⁹⁰Zr θlab = 17.5°
⁹⁴Mo θlab = 15°
⁹⁶Mo θlab = 15°
¹⁰⁰Mo θlab = 15.5°
¹⁴¹Pr θlab = 14.5°
¹⁴²Nd θlab = 14.5°
¹⁴⁴Sm θlab = 14°
¹⁴⁸Sm θlab = 14°
¹⁵⁴Sm θlab = 14°
¹⁵⁹Tb θlab = 14°
¹⁷⁴Yb θlab = 13°
²⁰⁸Pb θlab = 17°

FIG. 8

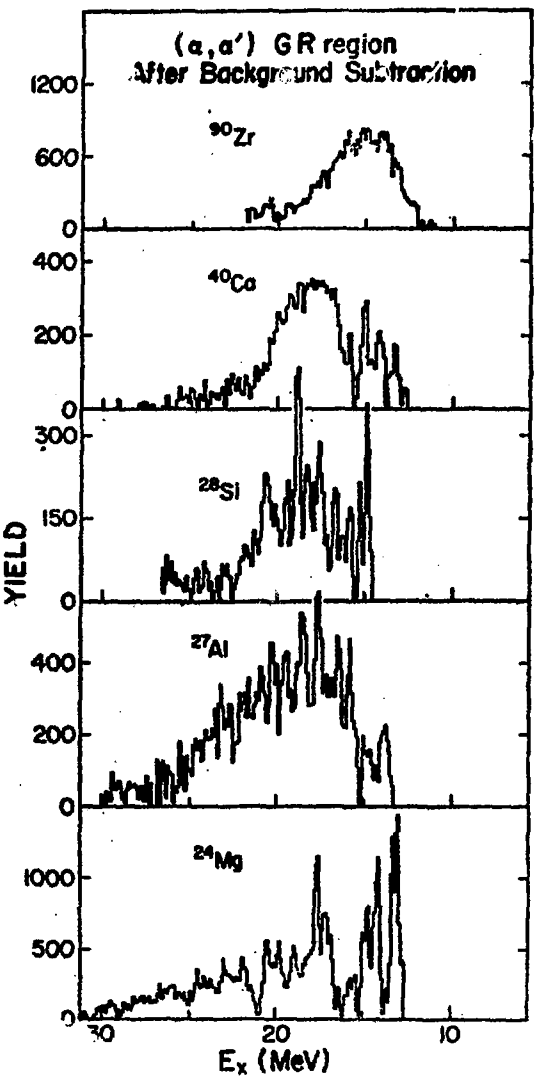
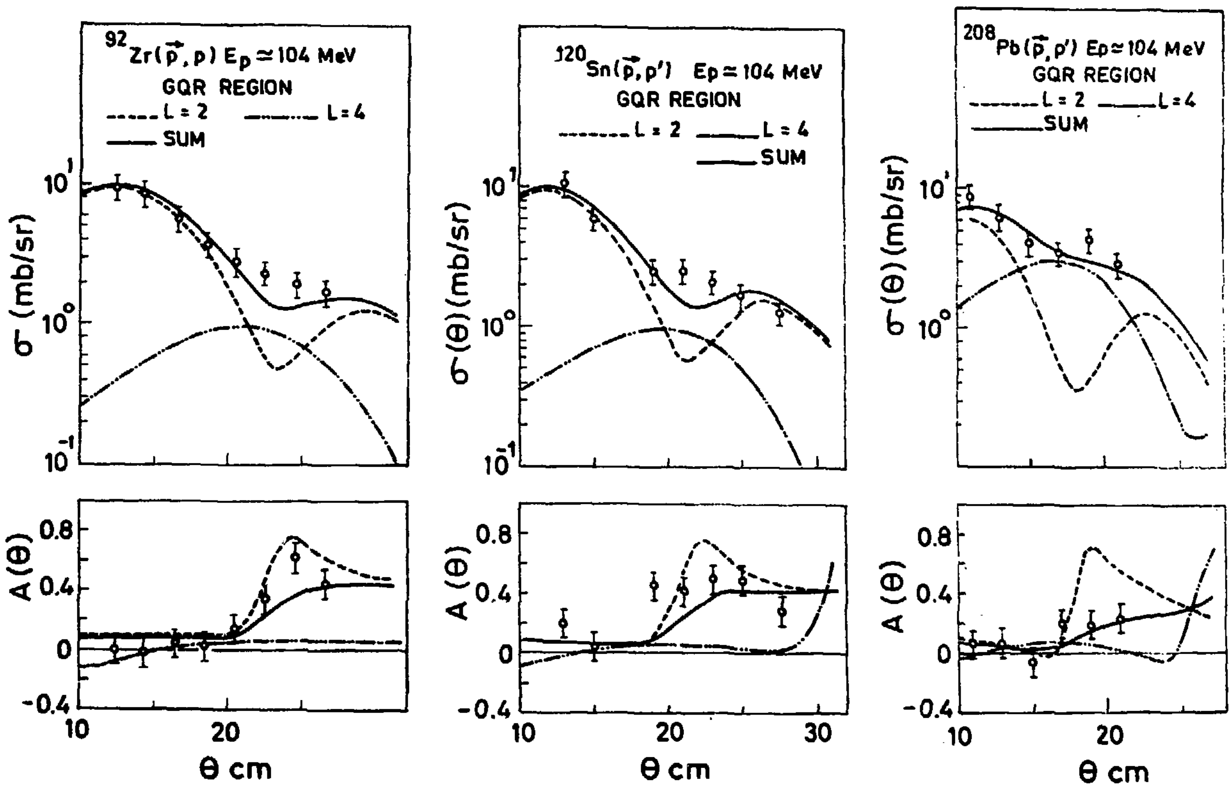

(α,α') GR region
After Background Subtraction
90Zr
40Ca
28Si
27Al
24Mg
YIELD
1200
600
0
400
200
0
300
150
0
400
200
0
1000
500
0
30
20
10
Ex (MeV)

FIG. 9



92Zr(p, p) Ep ≃ 104 MeV
GQR REGION
L = 2
L = 4
SUM
σ (mb/sr)
A (θ)
θ cm
120Sn(p, p') Ep ≃ 104 MeV
GQR REGION
L = 2
L = 4
SUM
σ (θ) (mb/sr)
A (θ)
θ cm
208Pb(p, p') Ep ≃ 104 MeV
GQR REGION
L = 2
L = 4
SUM
σ (θ) (mb/sr)
A (θ)
θ cm

FIG. 10

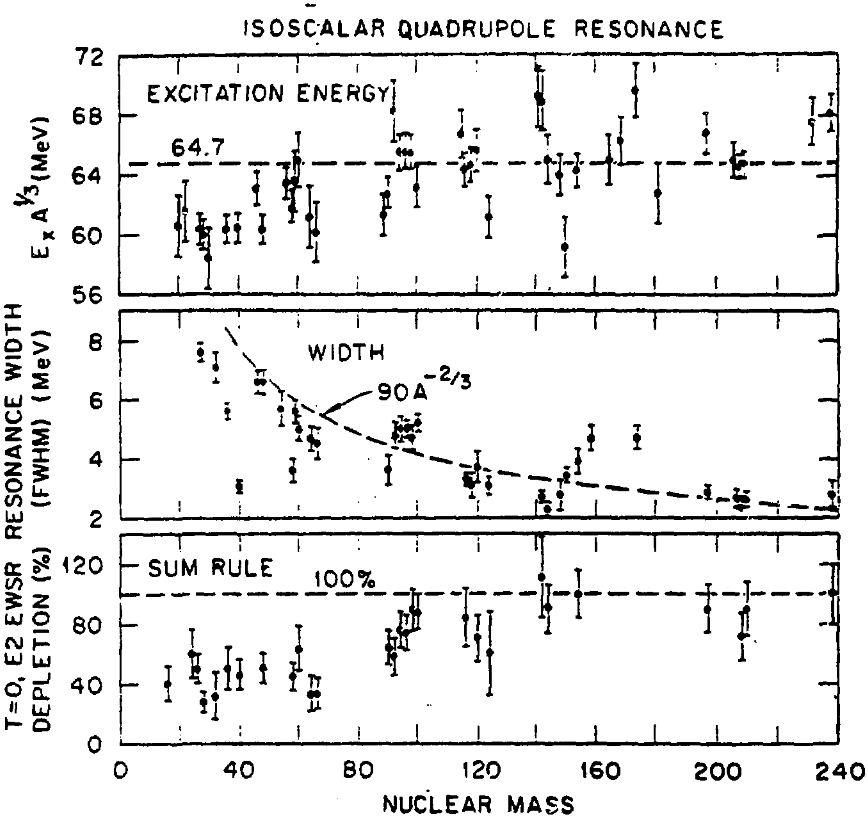

ISOSCALAR QUADRUPOLE RESONANCE
EXCITATION ENERGY
64.7
$E_x A^{1/3}$ (MeV)
WIDTH
$90A^{-2/3}$
RESONANCE WIDTH (FWHM) (MeV)
SUM RULE
100%
T=0, E2 EWSR DEPLETION (%)
NUCLEAR MASS
72
68
64
60
56
8
6
4
2
120
80
40
0
0
40
80
120
160
200
240

FIG. 11

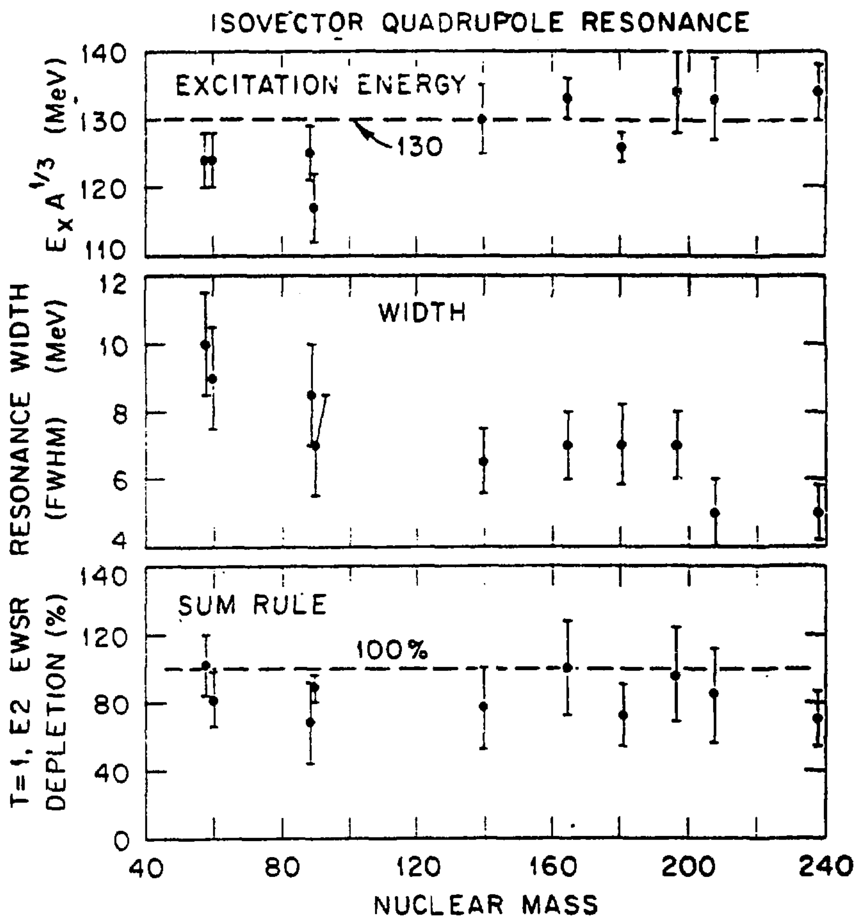
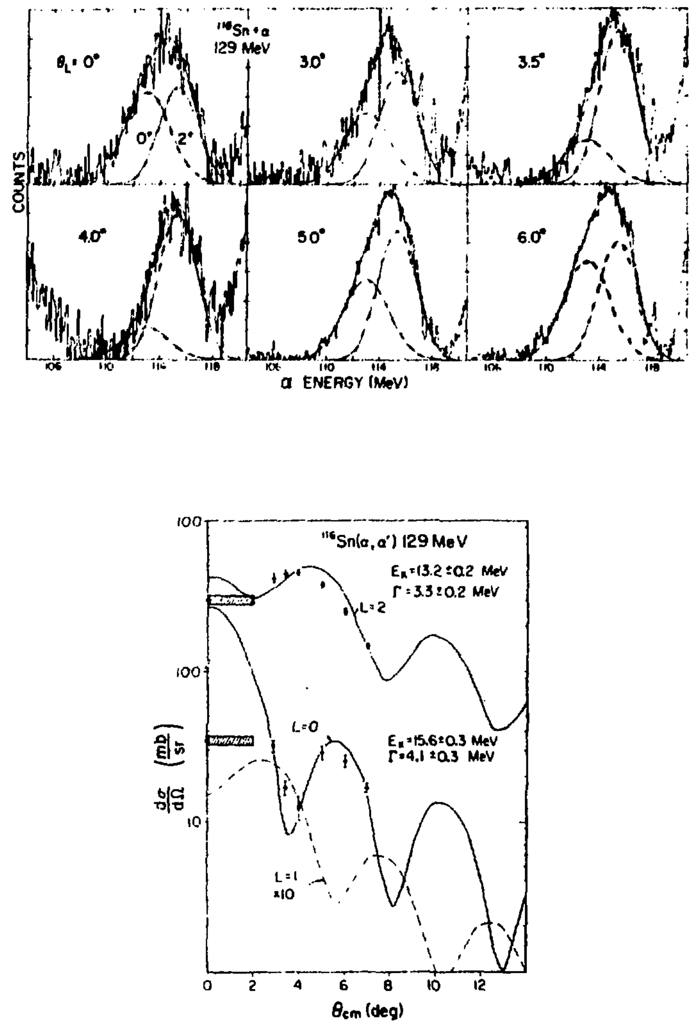

ISOVECTOR QUADRUPOLE RESONANCE
EXCITATION ENERGY
130
$E_x A^{1/3}$ (MeV)
140
130
120
110
WIDTH
RESONANCE WIDTH (FWHM) (MeV)
12
10
8
6
4
SUM RULE
100%
T=1, E2 EWSR DEPLETION (%)
140
120
80
40
0
40
80
120
160
200
240
NUCLEAR MASS

Fig. 12



¹¹⁶Sn + α
129 MeV
θL = 0°
0°
2°
3.0°
3.5°
4.0°
5.0°
6.0°
COUNTS
106
110
114
118
α ENERGY (MeV)
¹¹⁶Sn(α, α') 129 MeV
Ex = 13.2 ± 0.2 MeV
Γ = 3.3 ± 0.2 MeV
L = 2
L = 0
Ex = 15.6 ± 0.3 MeV
Γ = 4.1 ± 0.3 MeV
L = 1
x10
dσ/dΩ (mb/sr)
θcm (deg)

Fig. 13

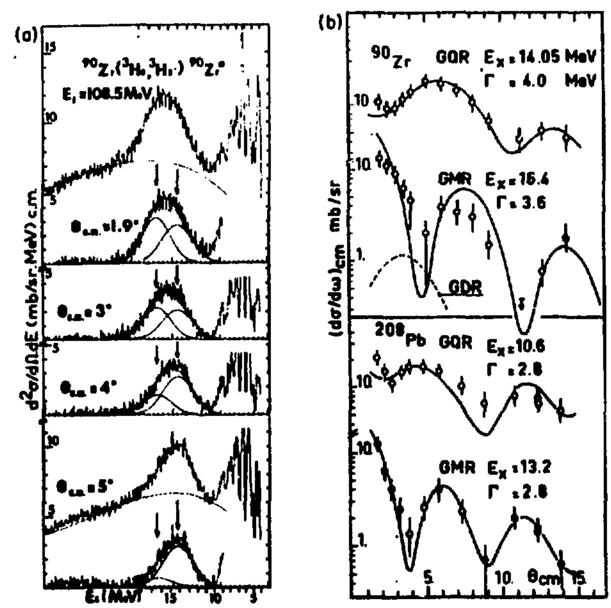
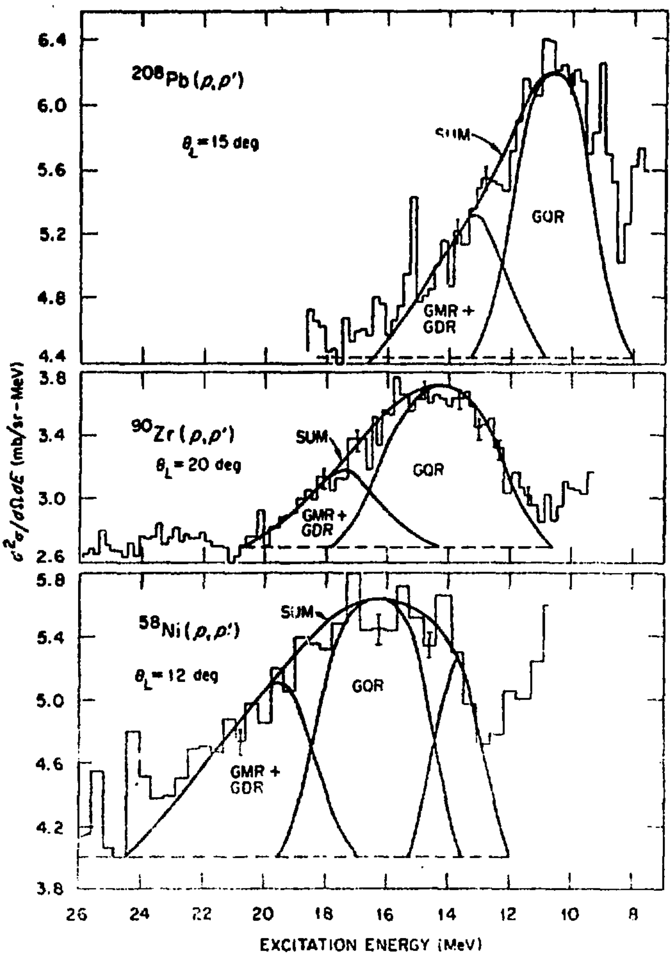
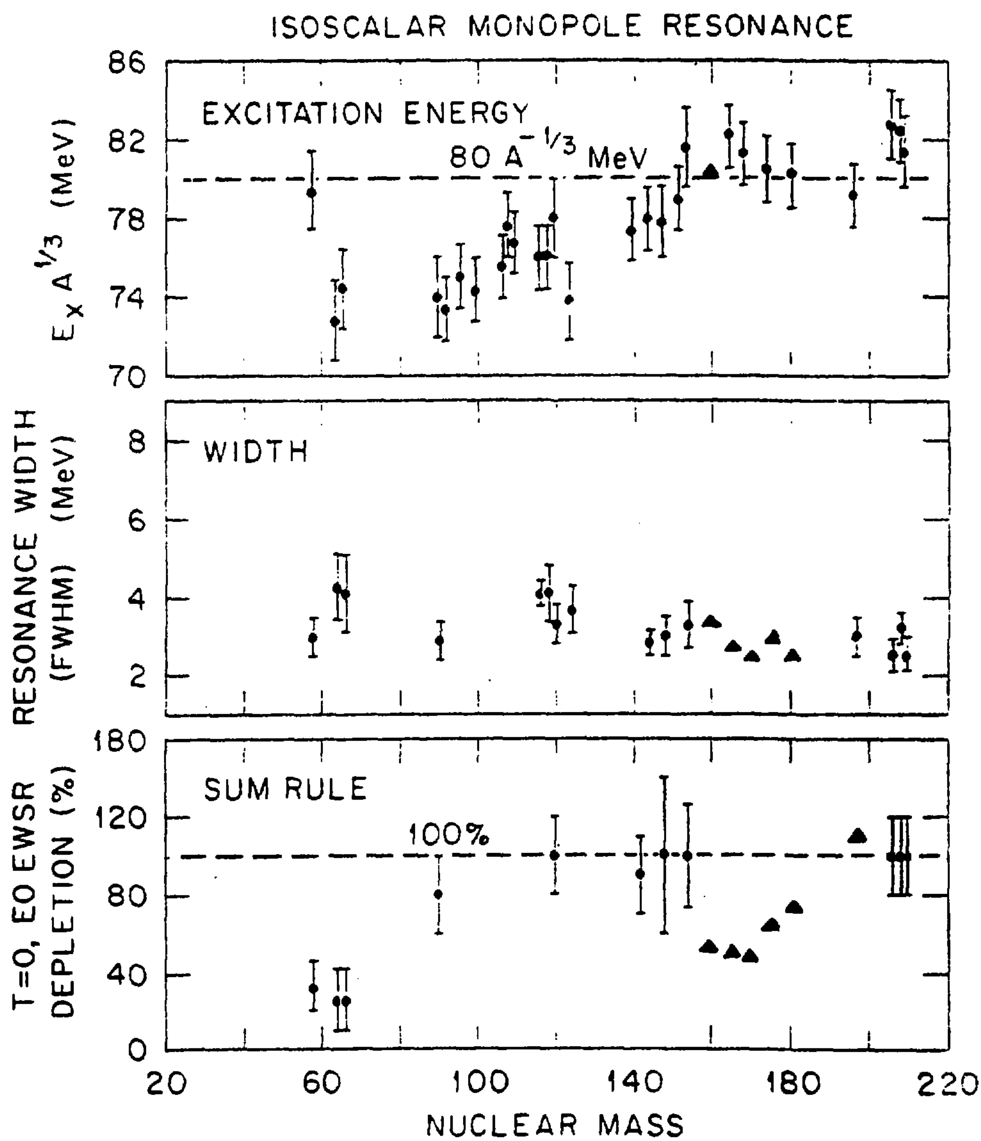

(a)
⁹⁰Zr(³He,³H) ⁹⁰Zr*
E = 108.5 MeV
θc.m. = 1.9°
θc.m. = 3°
θc.m. = 4°
θc.m. = 5°
d²σ/dΩdE (mb/sr MeV) c.m.
Ex (MeV)
(b)
⁹⁰Zr GQR Ex = 14.05 MeV
Γ = 4.0 MeV
GMR Ex = 16.4
Γ = 3.6
GDR
²⁰⁸Pb GQR Ex = 10.6
Γ = 2.8
GMR Ex = 13.2
Γ = 2.8
(dσ/dω)cm mb/sr
θcm

Fig. 14.



^{208}Pb(p,p')
θ_L = 15 deg
SUM
GQR
GMR + GDR
^{90}Zr(p,p')
θ_L = 20 deg
SUM
GQR
GMR + GDR
^{58}Ni(p,p')
θ_L = 12 deg
SUM
GQR
GMR + GDR
$d^2\sigma/d\Omega dE$ (mb/sr-MeV)
EXCITATION ENERGY (MeV)

FIG.15



ISOSCALAR MONOPOLE RESONANCE
EXCITATION ENERGY
80 A^-1/3 MeV
E_x A^1/3 (MeV)
86
82
78
74
70
WIDTH
RESONANCE WIDTH (FWHM) (MeV)
8
6
4
2
SUM RULE
100%
T=0, E0 EWSR DEPLETION (%)
180
120
80
40
0
20
60
100
140
180
220
NUCLEAR MASS

Fig. 16

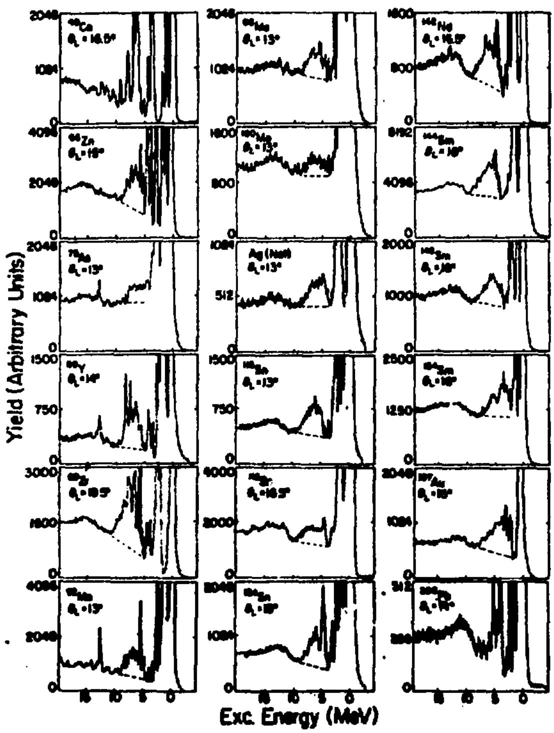
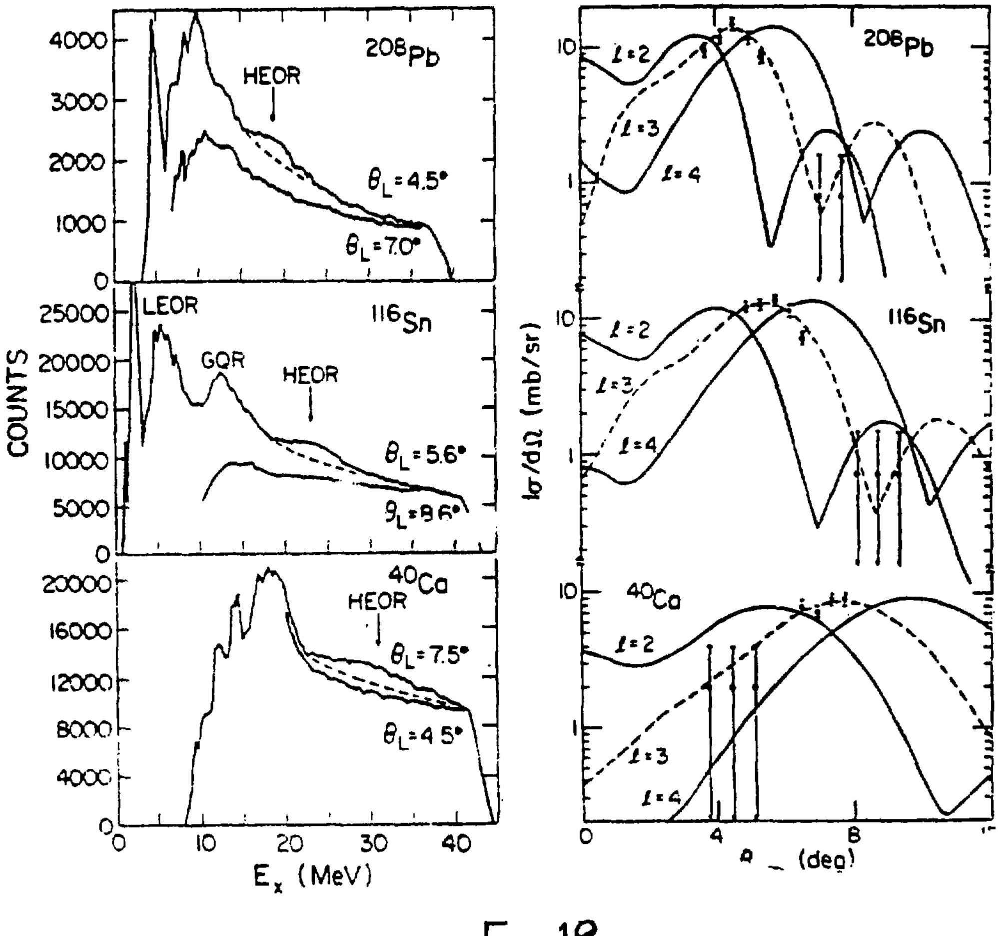
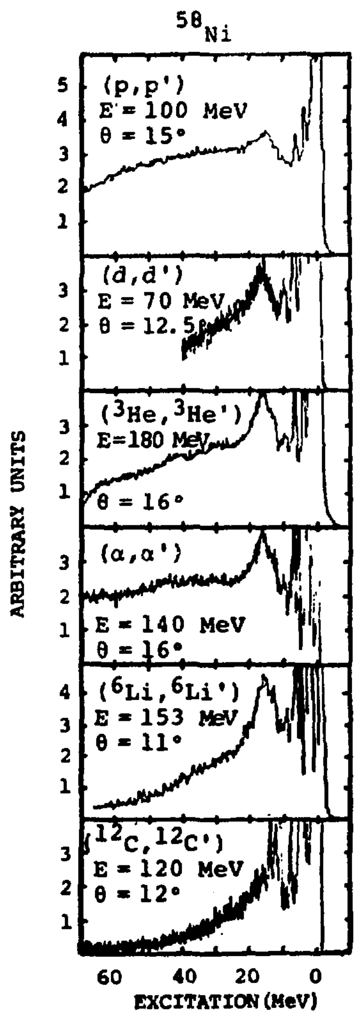


Fig. 17



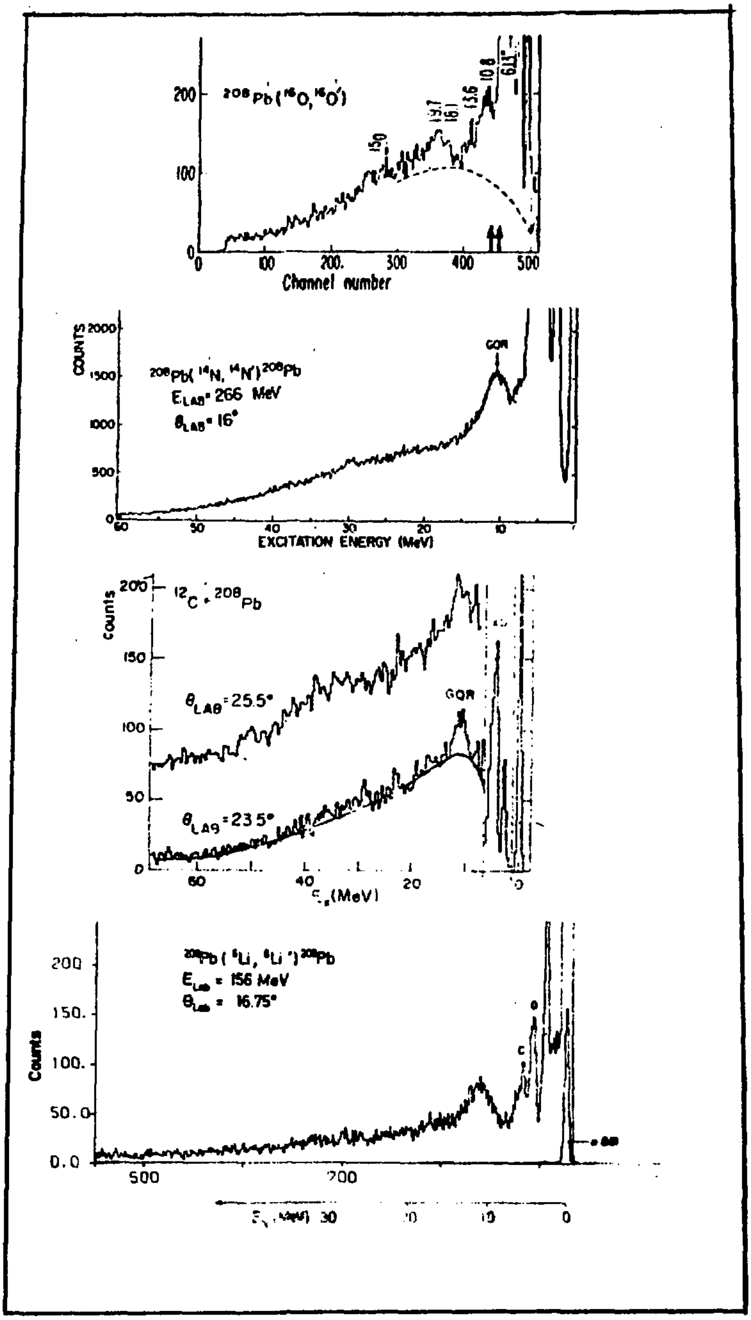
208Pb
HEOR
θL=4.5°
θL=7.0°
116Sn
LEOR
GQR
HEOR
θL=5.6°
θL=8.6°
40Ca
HEOR
θL=7.5°
θL=4.5°
COUNTS
Ex (MeV)
dσ/dΩ (mb/sr)
ℓ=2
ℓ=3
ℓ=4
(deg)

Fig. 18



58Ni
(p,p')
E = 100 MeV
θ = 15°
(d,d')
E = 70 MeV
θ = 12.5°
(3He,3He')
E=180 MeV
θ = 16°
(α,α')
E = 140 MeV
θ = 16°
(6Li,6Li')
E = 153 MeV
θ = 11°
(12C,12C')
E = 120 MeV
θ = 12°
ARBITRARY UNITS
EXCITATION (MeV)
60
40
20
0

Fig. 19



^{208}Pb(^{16}O,^{16}O')
Channel number
COUNTS
^{208}Pb(^{14}N,^{14}N')^{208}Pb
E$_{LAB}$= 266 MeV
θ$_{LAB}$= 16°
GQR
EXCITATION ENERGY (MeV)
^{12}C + ^{208}Pb
Counts
θ$_{LAB}$=25.5°
θ$_{LAB}$=23.5°
GQR
^{208}Pb(^{6}Li,^{6}Li')^{208}Pb
E$_{Lab}$ = 156 MeV
θ$_{Lab}$ = 16.75°
Counts

FIG. 20