GIANT MULTIPOLE RESONANCES

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The review of the experimental discovery of and further research into giant multipole resonances performed at the Kharkov Institute of Physics and Technology is outlined. These results are compared with theoretical and experimental ones obtained in other laboratories.
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1. INTRODUCTION

A giant resonance (GR) was predicted theoretically by A.B. Migdal in 1945 [1] on the ground of calculations according to sum rules. In two years GR was observed in experiment by Baldwin and Klaiber [2]. Then there followed a large number of papers in which GR was studied in experiment with photon beams of bremsstrahlung of electrons.

The experiments revealed the GR excitation in all nuclei. It was established that the GR excitation in photonuclear reactions possesses a electric dipole (E1) pattern.

After some time the giant dipole resonance (GDR) was studied with monochromatic photon beams, electron scattering as well as with hadron scattering (protons, ^{3}He and α-particles).

Models based on collective motion of nuclei as well the shell model were proposed for explaining the ;experimental data on GDR [3].

The dynamic collective model (DCM) [4] predicts, apart from the electric dipole (E1) resonance, the electric quadrupole (E2) and monopole (E0) resonances, the ratio of excitation energies for these resonances having the following form: E(E1):E(E2):E(E0)= 1:1,6:2,16.

The first experimental evidence of the giant quadruple resonance was obtained from the experiments on photoabsorption by ^{159}Tb [5] and ^{165}Ho [6] nuclei. These data have shown that above the electric E1 resonance the E2 resonance is observed, whose cross section amounts to less than 7% of the dipole absorption cross section and it is well described within the DCM framework [7].

2. DISCOVERY OF GIANT MULTIPOLE RESONANCES

2.1. Electron scattering

2.1.1. Experiments in Kharkov

In 1968-1969 in Kharkov at the experimental installation [8], located at the exit of the LUE-300 KIPT AN UkrSSR electron linac there was performed the research into the GR electroexcitation in ^{28}Si [9], ^{60}Ni [10], ^{12}C [11] nuclei. The experiments were made with electron energies 150, 200, 225 MeV and scattering angles of 20^0 to 80^0. It was observed that with the increase of the momentum transfer q to the nucleus the relative contributions of the levels, shaping the GR, are redistributed in a way to enrich the low energy part of the spectrum. Figure 1 presents four spectra of inelastic electron scattering by the ^{28}Si nuclei for various q [9].

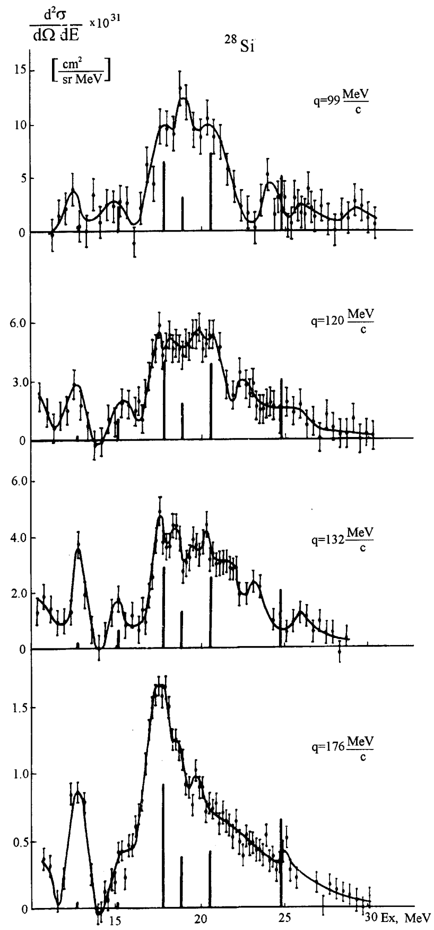

Fig. 1. *Inelastic electron spectra in ^{28}Si measured for different momentum transfers q. Radioactive tails from elastic and inelastic peaks are subtracted; ε is the excitation energy. Vertical lines represent the particle-hole model calculations of the longitudinal formfactor. The length of the lines is given in relative units*

As is seen from Fig. 1, the cross section in the range of excitation energies 16-19 MeV increases with respect to that for higher excitation energies with q increasing. This work pointed out that the enrichment at low energies can be explained assuming the electric quadrupole (E2) pattern of excitation in this part of the spectrum. The studies performed with the ^{60}Ni [10] and ^{12}C [11] nuclei also have shown that apart from the GR at lower energies there occurs the excitation of the levels with the quadrupole excitation pattern.

Before these experiments started there were no experimental or theoretical data pointing to the existence of such transitions in this energy range, therefore it was necessary to perform additional experiments in this energy range of nuclei excitation.

In two years such work started almost simultaneously in several laboratories. The experiments were performed with the beams of electrons, protons, ^3He-particles and α-particles.

2.1.2. Experiments in other laboratories

With the help of the inelastic electron scattering performed in Darmstadt (FRG) [12-14] in 1971-1973 with the initial energies 50 and 65 MeV at large angles (93^0, 129^0, 165^0) on natural targets out of Ce, La, Pr, there were found the magnetic dipole (M1) and electric quadrupole or monopole (E2 or E0) GR with the excitation energies below the E1 resonance.

In 1972-1973 in the Tohoku University (Japan) there were performed the experiments on inelastic electron scattering with the energies from 125 до 300 MeV on the ^{90}Zr, ^{208}Pb nuclei [15,16]. These experiments have shown the presence of the E2 (E0) GR with the excitation energies below the E1 resonance, and with the ^{208}Pb nucleus there were found with the excitation energies 19 and 22 MeV the E2 (or E0), E3 giant resonances, located above the E1 resonance. The resonance at the 22 MeV was interpreted as the isovector electric E2 (or E0) resonance.

It is known [3], that the energy position of the electric GR is well described by the formula: $80A^{-1/3}$ MeV. In the paper [17] in 1974 there were proposed the phenomenological formulas for the description of the energy position of some other electric multipole resonances: 53 $A^{-1/3}$ MeV (E0, isoscalar); 63 $A^{-1/3}$ MeV (E2, isoscalar); 105 $A^{-1/3}$ MeV (E3); 130 $A^{-1/3}$ MeV (E2, isovector); 195 $A^{-1/3}$ MeV (E0, isovector).

2.2. Scattering of hadrons

Experiments on inelastic scattering of protons have shown the E2 GR excitation for the energies below the E1 resonance. In paper [18] in 1973 there was performed the study of inelastic scattering of protons with the energy 66 MeV on the ^{27}Al, Cu, In, Pb nuclei. Proton spectra maxima were found to be systematically shifted to the lower energies compared with the location of the E1 resonance. The angular dependence of the excitation cross section with the energy below 11 MeV agrees the best with one calculated for the E2 transition with the $\Delta T=0$, i.e., for a isoscalar quadrupole transition.

Studies with the inelastic scattering of ^3He particles with the energy 41 MeV [19], performed in USA in 1973 on the ^{24}Mg, ^{26}Mg, ^{50}Cr, ^{60}Ni, ^{90}Zr nuclei did not furnish the encouraging results. The process cross section turned out to be 3 orders of magnitude less than the proton cross section for similar q. This was associated with a strong absorption of ^3He particles inside the nucleus. The successful performance of the experiment was also impeded by specific problems associated with a large background and low sensitivity of the equipment [19]. However the analysis [20] of the results on inelastic scattering of ^3He particles with the energy of 75 MeV and the alpha-particles with the energy of 90 MeV on the ^{208}Pb, ^{197}Au, ^{181}Ta nuclei made later has shown that these two methods can also be successfully applied for studying the excitation in nuclei of giant multipole resonance (GMR).

Here we have mentioned only a very small part of the works in which the GMR was studied before 1975. The GMR studies during this period are more fully outlined by us in the review [21].

2.3. Conclusions

Our assumptions on the quadrupole (E2) character of level excitation for the energies below GDR for the ^{28}Si[9], ^{60}Ni [10], ^{12}C[11] nuclei are supported by the data obtained with different methods on other nuclei in other laboratories. The data in the range of excitation energies agree with the classification for the isoscalar E2 resonance.

3. STUDY OF GIANT MULTIPOLE RESONANCES

For studying GMR we have processed the data on electron scattering on nickel isotopes [22] and performed measurements on the ^{64}Zn, ^{65}Cu and ^{124}Sn nuclei.

3.1. Isospin splitting of GDR in nickel isotopes

Isospin conservation for electromagnetic transitions in a nucleus leads to that the GDR in the nuclei with the isospin of the ground state $T_0 \neq 0$ (N>Z) is split into two components with $T_< = T_0$ and $T_> = T_0+1$ [23]. The value of the energy splitting amounts to several MeV, that permits to observe the isospin splitting (IS) of the GDR in experiment.

A number of studies [24-26], performed for the ^{58}Ni and ^{60}Ni nuclei with the help of partial photonuclear reactions and inverse to them have shown that the IS GDR is observed in these nuclei.

To study the isospin influence on the GDR electroexcitation in the nuclei with different T_0 in the ground state we have analyzed the spectra of electrons scattered inelastically on three nickel isotopes: ^{58}Ni, ^{60}Ni and ^{64}Ni [10], which were registered with equal value of the momentum transfer to the nucleus q=130 MeV/c. All section of the spectrum of scattered electrons was decomposed into three Gaussian peaks. The peaks located near the energy ω=13 MeV in all three isotopes are associated with the excitation of the isoscalar E2 resonance [27], and the peaks above the energy of 16 MeV were considered by us as associated with the excitation of GDR isospin components. Comparison between our results and the data on the (γ,n)-reaction [26] and the joint analysis of data for the (γ,n)-reaction [25] and the process of radiation capture of protons, performed in paper [24], shows a good agreement. The theoretical studies of the isospin effect for the GDR excitation show that this effect will lead to the energy splitting of the GDR, and the relation between isospin components will depend on the isospin value T_0 [25].

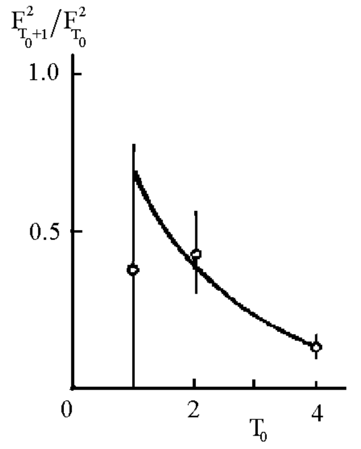

Fig. 2. *Ratio of the squares of form-factors F^2_{T0+1}/F^2_{T0} against T_0. Circles are for our experimental data, solid curve is for the calculations according to the formulas of papers [22,28]*

The calculations of ratios of isospin components with To and ($T_0 + 1$) show, they change fast with the change of the isospin To. Such calculations were performed up to date only for photonuclear reactions, what corresponds to the so-called photon point (q≈ 20 MeV/c*)*, and our data correspond to q=130 MeV/c. To calculate the ratios for such q we have obtained the theoretical xpressions for the form-factors [22,28]. The ratios of the GDR form-factors $F^2_{T0+1}(q)$ and $F^2_{T0}(q)$ for q=130 MeV/c, differing in an isospin are presented in Fig. 2 with a solid line. One sees from the figure that our results are in good agreement with the theoretical predictions [22,28].

Thus our data on electron scattering support the conclusions on the presence of the GDR isospin splitting in ^{58}Ni and ^{60}Ni, obtained from studying the photonuclear reactions in papers [24-26], and they show that the same splitting is also observed for ^{64}Ni.

The subsequent measurements on ^{58,60}Ni were performed in USA [29] and on ^{58}Ni in Germany [30]. In these papers the results of our studies were discussed. New data obtained in more than 10 years after our measurements, have revealed a more complicated structure in the distribution of the forces of multipole resonances. Thus in the resonance at the energy of 13 MeV that we have defined as the E2 resonance the E1 transitions make a contribution. This contribution amounts to about 2% [29] or more [30] from the total contribution calculated with the energy weighted sum rules (EWSR). And at the E1 resonance we had determined at the energy of 16 MeV there is observed the contribution of the E2 transitions. Thus, it was shown that a mixing of resonance of different multipolarity is observed at the same excitation energy.

3.2. Giant resonances of high multipolarity

For the continuation of studies there was improved in two times the monochromaticity of the electron beam at the target [31] and the multi-channel detector with a higher energy resolution was built [32]. A new technique of processing spectra was also developed. It consisted of the radiation deciphering, subtraction of the quasielastic scattering and of the method of separating the spectrum obtained into narrow bands of 0.5… 1 MeV in width. This technique permitted a more accurate separation of different multipoles for one excitation energy determined by the band width. For every band we have obtained the form-factors and the calculated curves in the form of the sum of several multipole form-factors were fitted to them.

With the improved experimental technique and a new technique for data processing the studies of the ^{64}Zn and ^{124}Sn nuclei were performed [33-35]. Earlier there were no such studies on these nuclei.

The fitting of calculated curves permitted to separate the excitations with different multipolarities and obtain the dependence of the reduced transition probabilities B(EL) on the excitation energy E_x. In Fig. 3 the dependence B(EL) of the E1-E5 transitions on the excitation energy E_x for the ^{64}Zn nucleus. Similar dependences of the reduced probabilities of E1-E7 transitions were obtained for the ^{124}Sn nucleus.

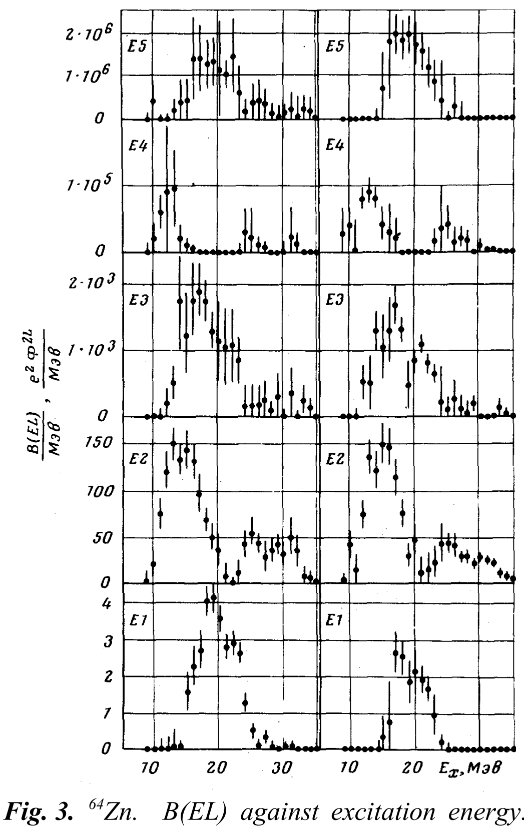

Fig. 3. *^{64}Zn. B(EL) against excitation energy. To the left is the Helm model, to the right is the High Energy Approximation*

The theoretical calculations of the magnitudes B(EL) of excitations for the ^{64}Zn nucleus are not available up to now. For the ^{124}Sn nucleus the calculations are made only for the E1 excitation within the framework of the theory of finite Fermi-systems [33].

The presence of resonances above the threshold of particle emission permitted to split the separated excitations into some sections. The magnitudes B(EL) for the E1, E2, E3 and E4 excitations was presented as a combination of two or three Gaussians fitted according to the mean square method to experimental points. Such fitting make possible the high accuracy determination of the energy locations E_x, half-widths Γ_x, reduced transition probabilities B(EL) and the exhausting the EWSR for GMR.

The obtained locations of the E1-E3 resonances coincide well with the results of calculations according to ДКМ, to the chaotic phase approximation technique, to the method of finite Fermi-systems and with the calculations based on the sum rules [33].

The location of the observed peaks in the E1 resonances in ^{64}Zn and ^{124}Sn match well the predictions of the isospin splitting of the isovector E1 resonance.

The distribution of E2 forces reveals the resonances at the energies 15.0±0.2, 25.1±0.7, 30.4±0.8 MeV in the ^{64}Zn nucleus and 11.7±0.5, 19.8±0.7, 24.9±0.2 MeV in the ^{124}Sn nucleus. The resonances at 15.0 and 11.7 MeV are isoscalar E2 resonances. The paper [36] has shown that for the nuclei with N≠Z, apart from the isovector E1 resonance, the isovector E2 resonance must also split according to the isospin The calculations performed according to paper [36] furnish the values of IS E2 resonance 2.6 and 5.8 MeV in ^{64}Zn and ^{124}Sn, respectively. The comparison of the experimental values with calculated ones shows a good agreement for ^{124}Sn and a somewhat worse one for ^{64}Zn. The data obtained are the first observation of IS E2 resonance [37]. A later theoretical paper [38] also permits to conclude that we have discovered the IS of the isovector E2 resonance.

In the ^{124}Sn nucleus there is observed the resonance at 16.5±1.0 MeV. We have determined it as a isoscalar electric monopole (E0) resonance that occupies (54± 25)% of the monopole EWSR. Our discovery [33] of the isoscalar monopole (E0) resonance in ^{124}Sn at 16.5±1.0 MeV is the first experimental evidence of the existence of the E0 resonance in nuclei. The energy position, width and exhaustion value for EWSR obtained for the resonance are in good agreement with the data obtained later with other techniques [39].

The first experimental proof of the existence of a giant hexadecapole resonance (HDR) was obtained by us in the paper [33]. This resonance was predicted theoretically earlier in several papers (See [40] and references therein). We discovered the GHR in the ^{64}Zn nucleus at the energies of 12.9±0.5 and 25.4±0.8 MeV. Presently we may treat these two resonances as the isoscalar and isovector hexadecapole resonances due to the $2\hbar\omega$ transitions. These resonances exhaust only a very small part of EWSR, but the main part, which must be due to the $4\hbar\omega$ transitions, is not sufficiently defined up to now. Theoretical calculations show [41], that the E4 force must be strongly scattered in the excitation spectrum and therefore it will be very difficult to observe it in the experiment.

The further development of the experimental technique was the creation of the system for energy compression of the electron beam [42] that permitted to get the energy resolution of 0.3%. Under these conditions the studies on electron scattering with the energies of 150 and 225 MeV on the ^{65}Cu nucleus were performed [43]. Obtained dependencies of the reduced transition probabilities B(EL) against the excitation energy are shown in Fig. 4.

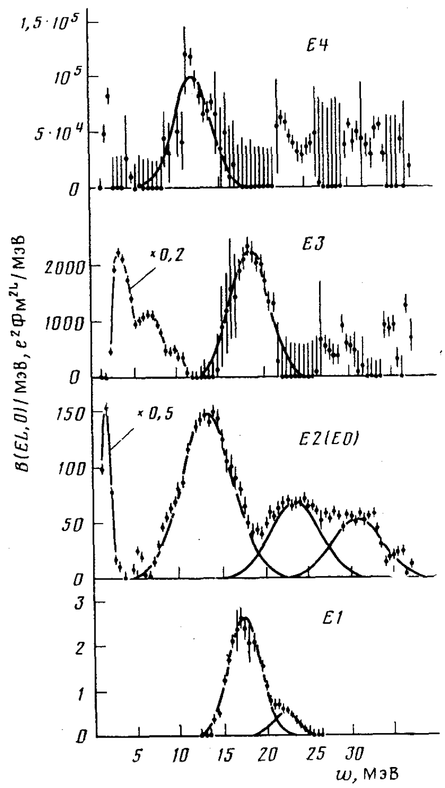

Fig. 4. *B(EL) against the excitation energy ω in the ^{65}Cu nucleus. Solid curves are the Gaussian lines fitted to data. The scale for the low energy sections of E2(E0)- and E3-transitions, connected with a line is changed in the noted number of times*

The data (Fig. 4) for the E1-transitions are well described by two Gaussian peaks with the distance between them ΔE=4.66±0.49 MeV and the ratio of intensities $B_{T<}/B_{T>}$=6.3±1.9. Such a behavior of the E1-transitions can be treated as associated with the IS on the ground of a not bad agreement of the data with the calculated values: ΔE=3.81 MeV and $B_{T<}/B_{T>}$ = 5.0 [38].

The electric monopole force (E0) can also be present in the distribution of the electric quadrupole force (E2), as the form-factors for the transitions of both types behave similarly as a function of q. Apart from the known low lying states, the distribution is approximated with three peaks. The first resonance (the most intensive one) in undoubtedly the $2\hbar\omega$ branch T=0, of the E2-resonance. Two other resonances can be interpreted differently. They can present the E2 resonance splitted with respect to the spin T=1. However, such an interpretation has substantial shortcomings. First, though the experimental value ΔE =7.4±0.3 MeV is comparable with the calculated one ΔE=6.37 MeV, however $B_{T<}/B_{T>}$=1.3±0. is in complete disagreement with the calculated value 4.7 [38]. Second, under this assumption the resonance exhausts more than 100%

T=1, E2 EWSR. It is more probable that the resonance at ω =23.31 MeV is the T=0, E0-resonance. The classification for the energy of this resonance obtained mainly from the study of the inelastic scattering of α-particles, gives the energy 18…19 MeV [39].

Distribution of the force E3 has a structural low energy branch and a resonance-like structure at ω =18.34 MeV. These structures are associated, correspondingly, with the $1\hbar\omega$ branches of the T=0 (T=1), E3-resonance. The additional force is higher than 25 MeV, and perhaps it is associated with the $3\hbar\omega$ branch of the T=0, E3-resonance, the energy of which from the existing classification must be ~27 MeV [40].

Electric hexadecapole (E4) force has three regions of accumulation. The first two regions may present the $2\hbar\omega$ and $4\hbar\omega$ branches of T=0, and the last one may be the $2\hbar\omega$ branch T=1, E4-resonance.

From the results obtained on the ^{65}Cu nucleus, we note the following general rules. First, the dipole and quadrupole (monopole) transitions exhaust almost all their force predicted by EWSR, and the octupole and hexadecapole ones are only a part of this force. Perhaps our assumption that all cross section of inelastic electron scattering in the region of the maximum of the quasi-elastic scattering peak is associated only with this process is sufficiently conditional. Second, a rather distinct link is observed between the energy locations of E1-и E3-, as well as also between E2- and E4-resonances, i.e., the predictions of the schematic model turn out to be sufficiently valid [35].

The studies of isotopes with the identical Z permit to obtain additional data on the effect of neutrons on the GMR excitation. Presently we are processing the experimental data on scattering of 226 MeV electrons on the ^{54}Fe and ^{56}Fe nuclei in the energy excitation range up to 40 MeV. We have already processed the discrete levels up to the excitation energy of 8 MeV for the momentum transfers q=0.6…1.7 Fm^{-1} [44]. A non-conventional technique was applied for processing. We have obtained the data on B(EL) and multipolarity of transitions for 12 states of the ^{54}Fe nucleus and 10 states of the ^{56}Fe nucleus. The five states of the ^{54}Fe nucleus and three levels in the ^{56}Fe nucleus were identified in the (e, e′) reaction for the first time [44]. The information about two of them are absent in the modern compilation of the data on discrete levels [45]. The processing of data in the excitation range of the GMR for these nuclei commenced

The studies of nuclear fission, using linearly polarized photons performed at the KIPT, is a new direction in the research within the GR excitation energy range [46-48]. In these experiments the uranium isotopes were first used for measurements. As a result, the Σ-asymmetry of the ^{232}Th, $^{233,235,236,238}U$ nuclei was measured and for even-even nuclei a dependence of the Σ-asymmetry against the mass number of nuclei A was obtained. The value of the Σ-asymmetry experiences considerable change with a not large change of A. The existence of the dependence of the Σ-asymmetry not only on Z, but also on N points out to the fact that either other multipoles (for example, E2 or M1) make a contribution to its value apart from the E1 resonance, or such changes are very sensitive to the relative height of the hills of the fission barrier, and this is observed in our experiment for the nuclei with identical Z.

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