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ELECTROEXCITATION OF MAGNETIC RESONANCES IN SPHERICAL NUCLEI

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The inelastic electron scattering is one of the traditional tools for studying the excited states of atomic nuclei. In recent years the increasing availability of the experimental technique made it possible with the help of the (e,e') -scattering to obtain many new, interesting data on the giant resonances - collective nuclear excitations in the continuous spectrum region [1,2]. In the present paper we dwell upon the data on the resonances of magnetic type only - dipole and quadrupole resonance.

When the first data on the magnetic quadrupole resonance have appeared in 1975-1976 [3,4], the existence of the M1 resonance was thought to be practically established. Being a natural consequence of the simplest ideas based on the shell nuclear model, the M1 resonance was predicted in many theoretical papers. All the theoretical calculations with different effective intranuclear NN-interactions, with the so-called "realistic" NN -forces, within the RPA and taking into account interactions with the 2p-2h (or two-phonon) configurations confirmed the existence of 2-3 states with $L^{\pi}=1^{+}$ and a large value of $B(M1)\uparrow$ in medium and heavy atomic nuclei at excitation energies $E_x \simeq 6 \div 10$ MeV. However, the total M1 transition strength predicted theoretically for the concrete nuclei varied strongly. For instance, in ^{208}Pb various authors obtained for $\Sigma B(M1)$ the values from $17\mu_0^2$ to $50\mu_0^2$ [5].

The theoretical results seemed to agree with the experimental data [4,6-10]. However, these data were scarce and not always reliable. They mainly referred to ^{208}Pb in which $\Sigma B(M1)$ was equal to $67\mu_0^2$ for all the states observed with any degree of reliability in the experiments performed until 1977 [9]. There were consistent data on the (e,e')- and (γ,n)-measurements in ^{140}Ce [7,8] and reliable data on the M1 resonance in ^{58}Ni obtained in the (e,e')-scattering by Lindgren et al. [4].

However in 1977-1978 the situation began to change owing to the new results of precise experiments on the inelastic scattering of slow electrons at large angles [11,12] and to the (γ,n) -experiments with high resolution [13]. Those data stimulated experimenters and theoreticians to reconsider the traditional views on the M1 resonance.

The critical analysis of the experimental data, performed by Raman and reported at the III International symposium on

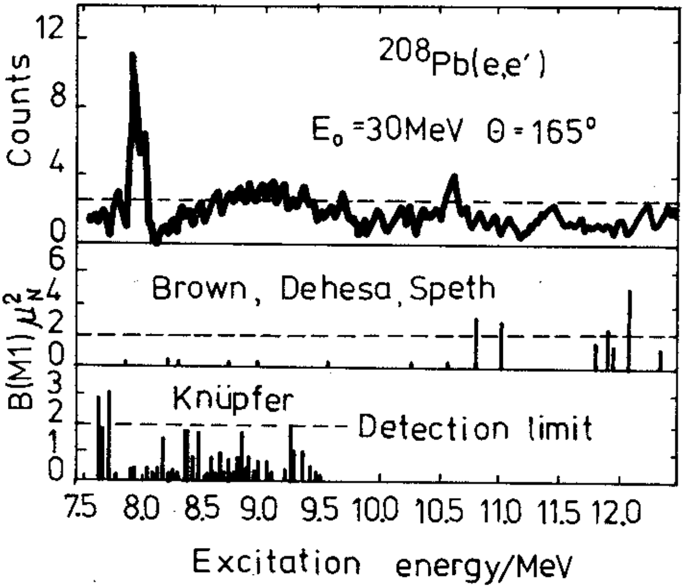


Fig.1. A spectrum obtained in the ^{208}Pb (e,e')reaction with high resolution. Pronounced peaks at $E_x \simeq 8$ MeV are the 2^--states (upper part). Strong M1 states in ^{208}Pb, as they are calculated by Brown et al.[19] (middle part). Calculations of the M1 states in ^{208}Pb within the MSI-model taking into account the interaction of 1p-1h and 2p-2h states and quenched g_s-factors [2].

neutron capture γ-ray spectroscopy (Brookhaven 1978)[9],has shown that the sum M1 transition strength $47.5\mu_0^2$ has been observed in ^{208}Pb but the experimental data on the 1^+- states with $\Sigma B(M1) = 30.6\mu_0^2$ were doubtful. Further investigations worsened the situation. Richter et al.[2,12] have observed in ^{208}Pb none 1^+-levels with $B(M1) \geq 2\mu_0^2$ (the experimental detection limit). In the upper part of fig.1 (from paper [2]) one can see a typical spectrum of scattered electrons, obtained in these experiments (the group of strong peaks at $E_x \simeq 8$ MeV are the levels with $L^\pi = 2^-$). At present the existence of the group of weak 1^+-states only ($E_x = 7.5$ MeV, $\Sigma B(M1) \simeq 8\mu_0^2$)in ^{208}Pb is well established and there are data on seven 1^+-levels in the interval $\Delta E_x = 8.22 \div 9.40$ MeV ($\Sigma B(M1) \simeq 8{,}5\mu_0^2$)[14], which have not been specially verified. The data obtained by the group of Richter for other nuclei are the following[2]:in ^{58}Ni 60% of the expected M1-strength is detected, in ^{90}Zr - 10%, in ^{140}Ce, as well as in ^{208}Pb, the 1^+-states have not been observed. It is important to note that the detected 1^+-levels are very weak, i.e., the experiment indicates a strong fragmentation of M1-strength. For instance, in ^{90}Zr ten magnetic dipole states with $B(M1) \simeq 0.2 \div 0.3 \mu_0^2$ and $\Sigma B(M1) \leq 2.6 \mu_0^2$ [15] have been identified more or less accurately in the excitation energy interval $7.7 < E_x < 9.8$ MeV.

In the same 1978 year the theoreticians threw upon the traditional picture of M1-excitations in nuclei [16]. Since the interaction with complex configurations, turned out to be insufficient to explain the absence of 1^+-states with a large B(M1)-value in nuclear excitation spectra [17,18], the most natural explanation of the arisen experimental situation became invalid. Brown and Speth have considered a cunning mechanism of influence of complex configurations on the M1-resonance [14,16,19]. In short it is the following. The single-particle and single-hole energies, extracted from the experimental data, can be reproduced in the calculations with the statical single-particle potential when the nucleon effective mass m^* coincides with the free nucleon mass ($m^* = m$). However, one should take into account that the experimentally observed levels are contracted due to the interaction of single-particle and vibrational degrees of freedom. This means that the density of "bare" single-particle levels should be less (according to the estimates it corresponds to $m^* = 0.5 \div 0.6$ m). The renormalization of the 1p and 1h energies, contributing to the structure of different collective excitations, depends on the properties of the last. According to the estimates of Brown and Speth, the isovector part of M1-strength should be shifted towards higher excitation energies ($E_x \geq 10$ MeV). In this case, due to a high density of 2p-2h states with $L^\pi = 1^+$ the M1-strength is strongly fragmented. There are no consistent calculations in the framework of this approach, and all the above cited numbers as well as the picture in the middle part of fig. 1 [19] are of a qualitative nature. However, the comparison of these provisional calculations with the results of the (e,e′)-experiments [12] shows that the contradiction with experiment remains.

We should have mentioned that the theoretical B(M1)-values depend strongly on the value of spin gyromagnetic factors g_s^* entering the expression for nuclear current. The fact that the predictions of various nuclear models about $\Sigma B(M1)$ in nuclei differ considerably is in many respects due to the use of different values of g_s^*-factors. Therefore, no wonder that the attempts to explain "disappearance" of the M1 resonance has been accompanied by reconsideration of the value of this

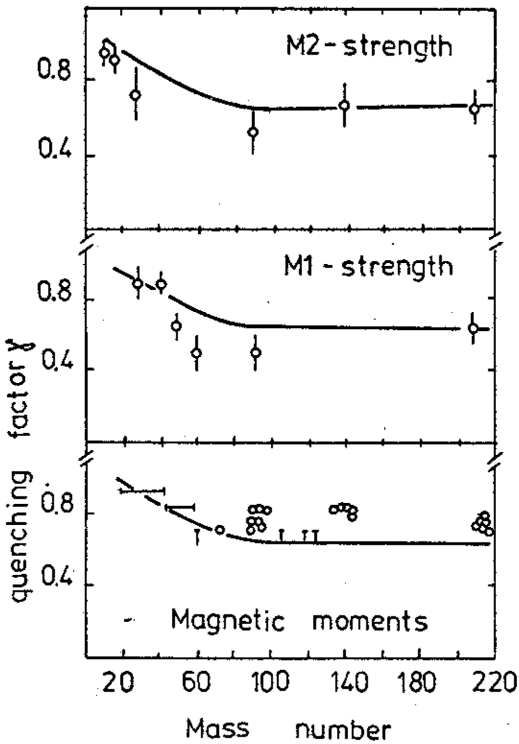


Fig.2. Dependence of the quenching factor $\gamma = g_s^*/g_s^{fr}$ on the mass number A, which has been obtained from the analysis of the experimental data on M1 strength (middle part) M2 strength (upper part) and magnetic moments (lower part).

parameter too, that resulted in the hypothesis about "quenching" of g_s^* - factors [12].

Indeed, if one determines g_s^*, knowing $\Sigma B(M1)_{ex}$ and $\Sigma B(M2)_{ex}$ in each nucleus so that $\Sigma B(ML)_{ex} = \Sigma B(ML)_{th}$ then the value of $\gamma = g_s^*/g_s^{free}$ will decrease with increasing A (see fig.2, which is taken from ref. [20]). It is seen from this figure that for $A \simeq 210$, $\gamma \simeq 0.5 \div 0.6$. According to the data in the lower part of the figure, the same behaviour of γ is seen from the analysis of nuclear magnetic moments. It should be mentioned, however, that such a reasoning is model-dependent to a great extent. We have already mentioned that the predictions of various theoretical papers about $\Sigma B(M1)_{th}$ in ^{208}Pb differ three times (!). The same can be said about the M2-strength and especially about magnetic moments. For instance, in paper [21] $\Sigma B(M2)$ has been calculated in ^{58}Ni, ^{90}Zr, ^{140}Ce and ^{208}Pb. A satisfactory agreement with experiment has been obtained in all the nuclei for one value of $g_s^* = 0.8 g_s^{free}$ (see the table). At the same time, the magnetic moments in ^{61}Ni calculated within the same approach coincide with the experimental ones at $g_s^* = 0.6 \div 0.7 g_s^{fr}$ [22].

Soon the attempts have been made for a more profound treatment of the hypothesis about "quenching" of g_s^{free} factors [22-24]. All of them tried to evaluate the influence of virtual excitations of the N-Δ-isobar in nuclear matter on the renormalization of spin and spin-isospin components of the effective nuclear forces and photon vertex. According to the calcula-

Table

Experimental[2,4,11,12] and theoretical[21,32] values of the sum M2 strength for some spherical nuclei

	^{58}Ni	^{90}Zr	^{140}Ce	^{208}Pb
ΔE_x, MeV	6÷8	8÷10	7.5÷10	6.1÷8.4
B(M2) $\mu_0^2 Fm^2$ exp.	500	1100±100	6000±600	8500±750
B(M2) $\mu_0^2 Fm^2$ theor.	700	1090	4500	9700

tions of the authors of the hypothesis on "quenching"[20], the empirical dependence of γ on A as well as the value of γ can be explained by the action of two factors, giving almost the same contribution, - the polarization of nuclear core and the above mentioned renormalization of the coupling πNN - constant and photon vertex. The last two effects were calculated for an infinite nuclear matter and the estimated for finite nuclei were obtained by a qualitative extrapolation. The calculations of Toki and Weise for finite nuclei[23] though confirm the decrease in γ with increasing A, but give the values $\gamma \simeq 0.8 \div 0.9$ for A ~150. It should be noted also that according to the calculations[23] $\gamma(2^-) > \gamma(1^+)$, but this difference is not large (≤ 0.1). In paper[24] the influence of the Δ - isobar-hole excitations in nucleus has been estimated on the basis of the representations on the nucleon and Δ-isobar quark structure. For the M1 resonance the following result has been obtained: in ^{208}Pb the M1 resonance energy is $E_x \simeq 7$ MeV and $\Sigma B(M1) \simeq 26\mu_0^2$.

Thus, the present situation concerning the existence of the M1 resonance in medium and heavy nuclei is highly uncertain. First of all, we are obviously far from an adequate theoretical understanding of the properties of spin and spin-isospin excitations of atomic nuclei. But there are problems for the experiment. For instance, there is an evident discrepancy between the data of the (e,e′)- and (γ, n)-reaction concerning the M1 resonance in ^{140}Ce. The available (γ, n)-data on the strengthening of the M1 radiative strength function at the neutron binding energy in nuclei with A ~ 140 have been earlier interpreted as a result of the influence of the M1 resonance, whose parameters were in agreement with the (e, e′)-experiments of Pitthan and Walcher[7]. At present the 1^+-levels with $B(M1) > 1\mu_0^2$ (experimental detection limit) are not observed in the inelastic electron scattering on ^{140}Ce. The data of the (γ, n)-experiments are not disproved. Moreover, quite recently Anantaraman et al.[26] have announced the M1 resonance in the $^{90,92,94}Zr$ isotopes, which has been observed in the inelastic scattering of protons with E_p = 200 MeV at small angles. The observed in the (p,p′)-reaction cross section peak at an energy of $\bar{E}_x = 8.6 \div 8.9$ MeV with width $\Gamma = 1.5 \div 1.7$ MeV has been assigned as the M1 resonance by the form of the angular distribution (the theoretical calculation has been performed within the DWBA). A similar peak in the forward (p,p′)-scattering cross section has been observed in ^{90}Zr by Bertrand et al.[27]

The data on the M2 resonance, which have been compiled since 1975, are more determined than on the M1 resonance. The states with $L^{\pi} = 2^-$ have been observed in ^{58}Ni, ^{90}Zr, ^{140}Ce and ^{208}Pb[2,4,15]. The excitation energy interval under study is different in various nuclei but remains within $6 < E_x < 10$ MeV. The estimates for the sum value of the M2-strength detected in different nuclei are shown in the table. The form factors of individual 2^--levels are measured in ^{58}Ni, ^{90}Zr.

It should be noted that the M2 resonance is observed just at the same excitation energy as the levels with $L^{\pi} = 1^+$. Moreover, in ^{140}Ce and ^{208}Pb, with the largest concentration of the M2-strength, not a single 1^+- state (at least with $B(M1) > 1 \div 2\mu_0^2$) has been observed in the (e,e′) experiments of Richter et al.[2]. There arises a question whether the M1 resonance is masked by the 2^--states. To answer this question one should calculate in the framework of the same model the M1- and M2-excitation probabilities in the inelastic electron scattering.

Such calculations have been performed for ^{58}Ni and ^{140}Ce within the quasiparticle-phonon nuclear model[28]. The model Hamiltonian includes the average field for neutrons and protons (the Saxon-Woods potential), the pairing n-n and p-p interaction in the particle-particle channel and the effective separable multipole and spin-multipole forces in the particle-hole channel. The Hamiltonian parameters are chosen from the experimental data on the properties of the low-lying nuclear excitations and giant resonances (see refs.[18,21]). In the RPA the magnetic dipole and quadrupole states are generated by the isovector spin-multipole forces of the following form:

$$V^1_{\sigma 0} = \frac{1}{2}\kappa_1^{(01)}(\vec{\tau}_1 \vec{\tau}_2)(\vec{\sigma}_1 \vec{\sigma}_2),$$

$$V^2_{\sigma 1}(\vec{r}_1, \vec{r}_2) = \frac{1}{2}\kappa_1^{(12)}(\vec{\tau}_1 \vec{\tau}_2) r_1 r_2 \sum_M (-)^M [\vec{\sigma}_1 Y_{1\mu}(\Omega_1)]_{2M} [\vec{\sigma}_2 Y_{1\mu}(\Omega_2)]_{2-M},$$

$$\kappa_1^{(\lambda L)} = -\frac{4\pi \times 28}{A \langle r^{2\lambda} \rangle} \frac{\mathrm{MeV}}{\mathrm{fm}^{2\lambda}}.$$

It has been shown in papers[18,21], devoted to the study of the distribution of M1- and M2-strengths in the spectra of spherical nuclei with A > 50, that $\Sigma B(M2)$ for the magnetic quadrupole resonance (see tha table) and the data on the M1 radiative strength functions are well described at the above values of the constants and $\gamma = 0.8 (g_1^* = g_1^{free})$ [18,25].

The current transition densities $\rho_{LL}(r)$ contain the whole information on the structure of anomalous parity states, which is necessary for the calculation of the (e, e')-scattering cross section with excitation of these states. We have taken into account only the magnetic and convection parts of nuclear current, therefore $\rho_{LL}(r) = \rho^c_{LL}(r) + \rho^m_{LL}(r)$. The expressions for $\rho^{m,c}_{LL}(r)$ are presented in ref. [29]. The current transition densities $\rho_{LL}(r)$ for the one-phonon resonance 1^+- and 2^-- states in ^{90}Zr are shown in fig.3. We should like to note a specific difference in the behaviour of $\rho_{11}(r)$ and $\rho_{22}(r)$: the first have the surface nature and the second have the volume nature.

Figure 4 exemplifies the one-phonon 1^+ and 2^- excitation cross sections in ^{58}Ni, ^{90}Zr and ^{140}Ce in the backward (e, e')--scattering. The cross sections have been calculated within the DWBA [30]. The results allow one to conclude that the contribution of the 1^+ states to the sum cross section becomes less with increasing A. This is caused by two factors: a) the number of the 1^+-states is small and their excitation cross sections decrease with increasing A; b) the excitation cross sections of the one-phonon 2^- -levels increase with increasing A; moreover, the number 2^--levels also increases in heavy nuclei. Therefore, the 1^+-levels are hardly seen as compared to the 2^--levels in the (e, e')-scattering on heavy nuclei [29].

The calculations in the RPA do not always allow an adequate description of the experimental data. For instance, to reproduce the picture of the M1 and M2 strength distribution in ^{58}Ni, which follows from the (e,e') -scattering data obtained by Lindgren et al. [4] one should take into account the interaction of one- and two-phonon states [21]. Within the quasiparticle-phonon nuclear model the influence of this interaction on the (e, e') -scattering cross section can be taken into account by using the method of strength functions [28,31].

The excited state wave function of a doubly even nucleus, taking into account the one- and two-phonon states, has the form

$$\Psi_\nu(LM) = \{\sum_i R_i(L\nu) Q^+_{LMi} + \sum_{\substack{\lambda_1 \lambda_2 \\ i_1 i_2}} P^{\lambda_2 i_2}_{\lambda_1 i_1}(L\nu) [Q^+_{\lambda_1 \mu_1 i_1} Q^+_{\lambda_2 \mu_2 i_2}]_{LM}\} \Psi_0 , \quad (2)$$

where Q^+_{LMi} is the phonon creation operator with momentum, projection L,M and number i; Ψ_0 is the ground state wave function of a doubly even nucleus. Figure 5 shows the strength functions describing the behaviour of the averaged over the interval $\Delta = 0.1$ MeV (e,e') -excitation probability of states (2) with $L^\pi = 1^+$, 2^- as a function of the excitation energy E_x.

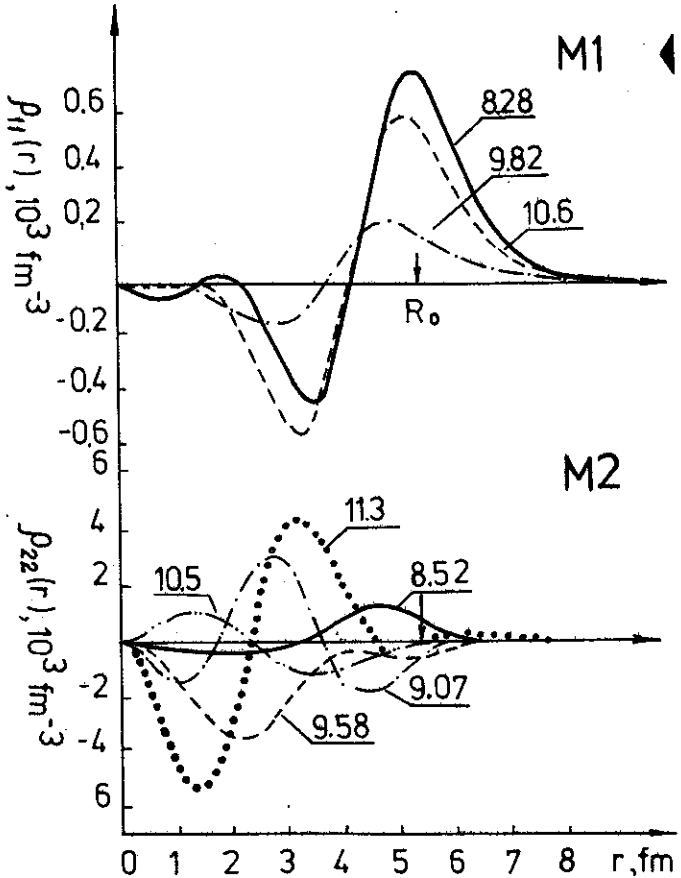
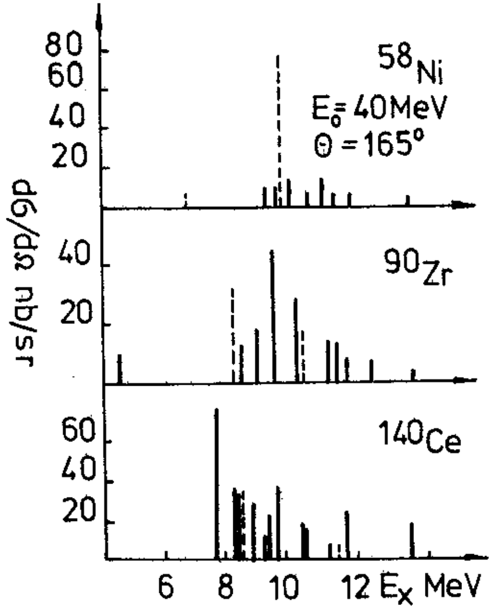


Fig.3. Current transition densities of the one-phonon 1^+- and 2^--states in ^{90}Zr. Numbers denote the state energies in MeV. The arrow denotes the nuclear radius position.

Fig.4. Electroexcitation cross sections of one-phonon 1^+- (dashed lines) and 2^--states (solid lines) in ^{58}Ni , ^{90}Zr and ^{140}Ce.



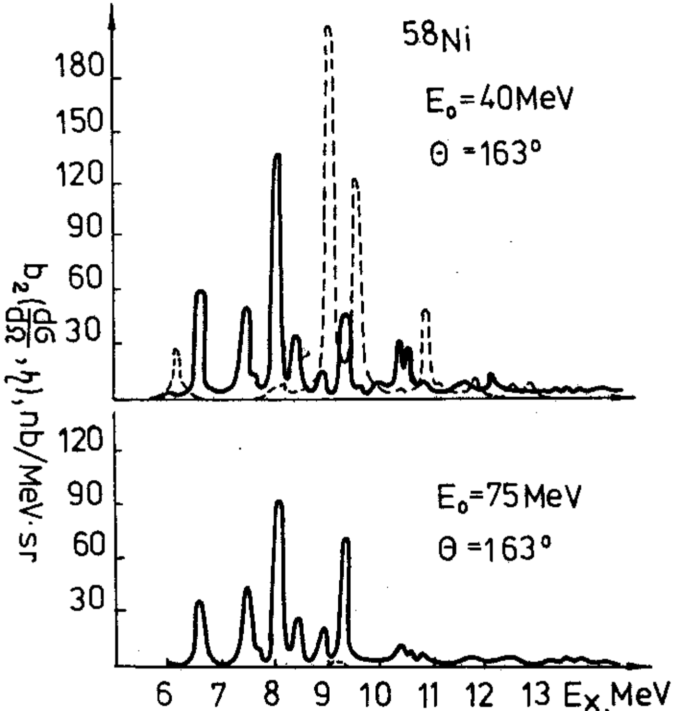


Fig.5. Strength functions describing the dependence of the excitation 1^+- (dashed lines) and 2^-- (solid lines) cross sections in ^{58}Ni on the excitation energy E_x. Calculations are performed taking into account the interaction of one- and two-phonon states.

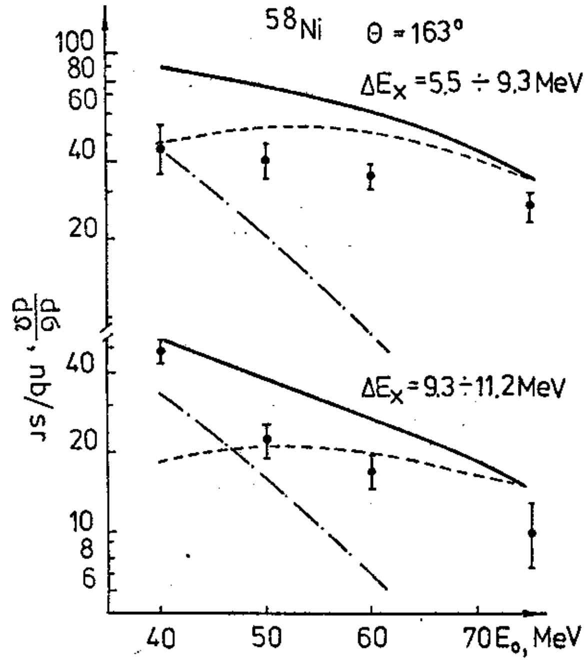


Fig.6. Dependence of the sum excitation 1^+- (dashed-dotted line) and 2^-- (dashed line) cross sections in two excitation intervals ΔE_x on the energy of incident electrons E_0. Solid lines are the sum of the 1^+- and 2^-- excitation cross sections. Calculation is performed taking into account the interaction of one- and two-phonon states. The experimental dots are from ref. /4/.

In this case the 1^+- and 2^--excitation wave functions have the form (2).

The comparison of figs.4 and 5 shows that the interaction with the two-phonon states in ^{58}Ni results in a notable fragmentation of M1 strength and in the lowering of a considerable part of M2 strength to the excitation energy region $E_x = 6 \div 8$ MeV. This result reproduces the picture which has been obtained earlier [21] for the B(M1) and B(M2) values, a satisfactory agreement with the experimental data being obtained (see fig.6). Figure 6 exemplifies also the sum 1^+- and 2^-- excitation cross sections in two excitation energy intervals ΔE_x. The experimental points have been obtained by summing over all states in this interval ΔE_x, which has been determined in ref. [4] as the 1^+-or 2^--levels. According to ref. [4] the interval $9.3 \div 11.2$ MeV includes mainly the 1^+-levels. Our calculations confirm this result. At $E_0 \leq 50$ MeV just the excited 1^+-states allow one to explain correctly the value of $d\sigma/d\Omega$ in this interval. However, with increasing E_0 the contribution to the sum cross section of 2^--states becomes larger and dominates at $E_0 > 60$ MeV in both the intervals. The predominance of the 2^--excitation cross section over the 1^+-excitation cross section is clearly seen in the lower part of fig.5.

Thus, in ^{58}Ni the (e,e′)-data are satisfactorily described within the traditional representations of the structure and properties of M1-and M2-excitations. At the same time the calculations show that even in the nucleus with rather a large 1^+-excitation cross section, which can be compared in value with the 2^--excitation cross section, one can hardly see the 1^+-levels among the 2^--levels at $E_0 > 60$ MeV. This problem is much complicated in heavy nuclei.

Now let us consider the sum experimental [2] and theoretical [29,32] form factors of the 1^+- and 2^--states from the excitation energy interval $7.5 \div 10$ MeV shown in fig.7 for ^{140}Ce. The interaction with the two-phonon states slightly influences the M1 and M2 strength distribution in this nucleus [18]; therefore we cite the results of calculation in the RPA. We should like to note that the strength parameters in these calculations were calculated by formula (1) as for ^{58}Ni, and the values of g_s^* -factors were not changed too. The absolute value of the (e,e′) -scattering cross section in ^{140}Ce agrees fairly well with experiment as in ^{58}Ni. The contribution of the 1^+-levels to the sum form factor is seen for even far less E_0 than in ^{58}Ni. Note, that owing to this contribution, the sum form factor at $E_0 < 30$ MeV decreases not so rapidly as the form factor of the 2^--states only; this fact describes the experimental data better. Thus, we describe fairly well the experimental data in ^{140}Ce within the usual representations.

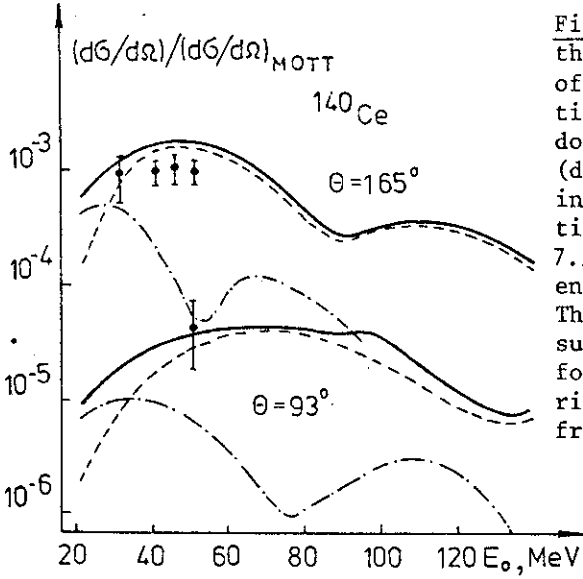


Fig.7. Dependence of the sum form factors of the (e,e')-excitation of the 1^+-(dashed-dotted lines) and 2^--(dashed lines) states in ^{140}Ce in the excitation energy interval 7.5÷10 MeV on the energy of electrons E_0. The solid lines are the sum of the 1^+- and 2^--form factors. The experimental points are from ref. /2/.

Based on the results presented in the second part of this report, we can make the following conclusions. First, the quasiparticle-phonon nuclear model allows one to describe fairly well the (e,e')-data in ^{58}Ni and ^{140}Ce without additional assumptions about "quenching" of g_s-factors with increasing A or shift of the M1 resonance. Second, these calculations show that in heavy nuclei the 1^+-states can hardly be seen among the 2^--excitations, since their excitation cross sections can be compared at small $E_0 \approx 20 \div 30$ MeV only. Therefore, the conclusions about the "disappearance" of the M1 resonance seem to us premature. To solve this problem, one should find a nuclear process with a predominant excitation of the 1^+-levels, which could be clearly seen among other states. Perhaps, the (p,p')-scattering at small angles /26,27/ possesses such a selectivity.

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