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High-Lying $M1$-States of Spherical Nuclei

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The cross section of inelastic scattering of slow electrons at large angles with excitation of high-lying 1^+-states in ^{208}Pb are calculated in DWBA. The calculations are carried out both in the random-phase approximation and with the interaction of one- and two-phonon states in the framework of semi-microscopic quasi-particle-phonon model. A group of noncollective 1^+-states with a large excitation probability in backward (e, e')-scattering is found in the excitation energy region of 17–21 MeV. We discuss also the problem of existence, properties, and possibility of discovery the high-lying collective 1^+-states ($2\hbar\omega$ $M1$-resonance) predicted by Speth et al.

1. Introduction

The existence of the collective $M1$-states in spherical even-even nuclei formed by single-particle transitions through two shells and situated at excitation energies $E_x = 15$–19 MeV, was for the first time pointed out in [1]. Calculations by Speth et al. [2] performed in ^{208}Pb within the framework of the finite Fermi-system theory have shown that despite the fact that these collective 1^+-states have small $B(M1, 0^+_{\text{g.s.}} \to 1^+) \simeq 0.001 \div 0.1\, \mu_0^2$, they should be strongly excited in the inelastic electron scattering. According to [2], the most intensively excited states should be the strongly collectivized 1^+-state with the excitation energy $E_x = 25.16$ MeV, the current transition density of which is of a surface nature. The excitation cross section of this state in backward (e, e') scattering was calculated to equal 150 nbarn/ster. In [2] an estimation is also given for the escape width of this state $\Gamma^\uparrow \simeq 1 \div 4$ MeV. However, an attempt to find such a resonance with $\Gamma \simeq 1$ MeV in inelastic scattering of electrons with energy $E_0 = 60$ MeV at angle $\theta = 180°$ [3] has failed. With a large uncertainty experimenters extracted a bump of the width $\Gamma \simeq 1.5$ MeV at energy $\bar{E}_x \simeq 24$ MeV. The total cross section in the peak (after extraction of a background) was 50 ± 20 nb/sr which is essentially smaller than that predicted theoretically.

An adequate description of collective nuclear excitations in the continuum spectrum region requires to overcome two difficulties. First, calculations should be carried out with a large enough single-particle basis including the continuum. Second, at high excitation energies the interaction of simple configurations (in the present case $1p-1h$) plays an important role with more complicated, in the first place $2p-2h$, configurations. As is shown in [4] such an interaction can drastically change the $M\lambda$-strength distribution calculated in the random-phase approximation (RPA). Therefore, results of RPA-calculations performed with a strongly limited single-particle basis can be considered as preliminary and require further verification.

A consistent overcoming of the above difficulties is a cumbersome problem and till now only first steps are undertaken [5]. In this work we shall consider what consequences will follow for the high-lying $M1$-resonance if we shall take into account the interaction of $1p-1h$ configurations with more complicated ones. For this aim we use the quasiparticle-phonon nuclear model (QPM). We discuss also some other problems related to the existence and possible discovery of the high-lying $M1$-resonance.

2. High-lying $M1$-States in the RPA

The QPM belongs to the class of the so-called semi-microscopic models. It treats the nucleus as a system

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of nucleons moving in an average potential and interacting through the effective nucleon forces. A detailed presentation of the model and results obtained can be found in [6, 7]. The most essential recent results are published in [8].

The separable multipole and spin-multipole forces are used in the model as the effective two-body forces in the particle-hole channel. These forces with radial dependence of the surface type are widely used to study the states with normal parity, both the low-lying and those in the continuous spectrum (see, for instance, [6, 9–12]). The separable forces have been used repeatedly for the description of the states with anomalous parity too, mainly of the $M1$ resonance. It should be noted that the results obtained in the RPA with the separable [4, 13, 14], finite radius [15] and Migdal [16] forces are close.

The effective force constants as well as the other model Hamiltonian parameters are determined by the known experimental data or on the basis of qualitative estimates [6, 10]. The values of the parameters, which are used in this paper, are given in [4]. In the RPA the structure of 1^+-states is determined by a relative contribution of two terms of the effective spin-multipole interaction, the simple spin and spin-quadrupole forces:

$$V^1_{\sigma 0} + V^1_{\sigma 2}(\mathbf{r}_1, \mathbf{r}_2) = \tfrac{1}{2}(\kappa_0^{(01)} + \kappa_1^{(01)} \tau_1 \tau_2)\, \boldsymbol{\sigma}_1 \boldsymbol{\sigma}_2 + \tfrac{1}{2}(\kappa_0^{(21)} + \kappa_1^{(21)} \tau_1 \tau_2)\, r_1^2 r_2^2 \sum_M (-)^M [\boldsymbol{\sigma}_1 y_{2\mu}(\Omega_1)]_{1M} \cdot [\boldsymbol{\sigma}_2 y_{2\mu}(\Omega_2)]_{1-M}. \tag{1}$$

It follows from the analysis of [17] that the term $V^1_{\sigma 2}(\mathbf{r}_1, \mathbf{r}_2)$ plays the dominating role at the excitation energies $E_x > 10$ MeV. The inclusion of these forces results in the appearance at the excitation energy $E_x > 20$ MeV of the collective 1^+-states, i.e. the states which are contributed by many $1p-1h$ (or two-quasiparticle) components. These $1p-1h$ states correspond to the single-particle transitions with changing orbital moment $\Delta l = 2$; therefore, the value of $B(M1, 0^+_{\mathrm{g.s.}} \to 1^+_i)$ for the high-lying collective excitations is small ($\lesssim 0.1\, \mu_0^2$).

We shall note take into account the isoscalar component of the spin-multipole interaction, using the following values for the constants $\kappa_{0,1}^{(\lambda L)}$ and effective gyromagnetic factors [4, 13, 14]:

$$\kappa_0^{(\lambda L)} = 0, \quad \kappa_1^{(\lambda L)} = -\frac{28 \times 4\pi}{A \langle r^{2\lambda} \rangle} \frac{\mathrm{MeV}}{\mathrm{fm}^{2\lambda}}$$
$$g_s^{\mathrm{eff}} = 0.8\, g_s^{\mathrm{free}}, \quad g_l^{\mathrm{eff}} = g_l^{\mathrm{free}}. \tag{2}$$

These values of the parameters allow one to satisfactorily describe the experimental data on the 1^+ and 2^- levels in ^{58}Ni, 2^--states in ^{90}Zr, ^{140}Ce and ^{208}Pb and on the $M1$ radiative strength functions in nuclei with $A \simeq 140$ [4, 14, 18]. In what follows the values of the constants $\kappa_{0,1}^{(\lambda L)}$ calculated by formulae (2) will be denoted by $\tilde{\kappa}_{0,1}^{(\lambda L)}$.

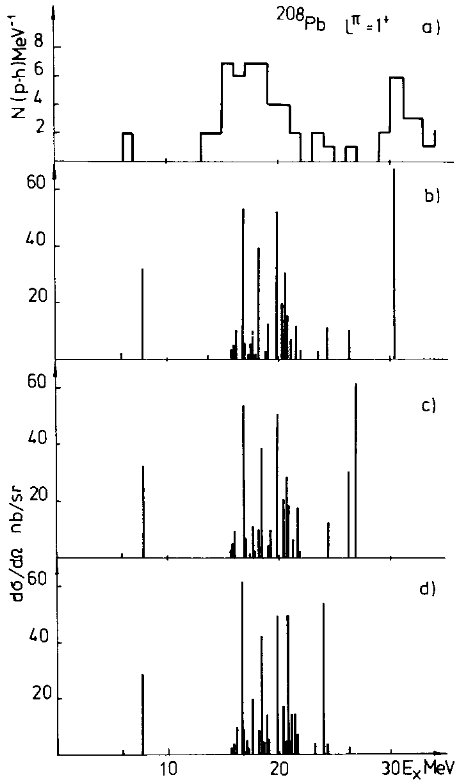

Fig. 1. One-phonon 1^+-states in ^{208}Pb: **a** number of $1p-1h$ states with $I^\pi = 1^+$ in the interval $\Delta E_x = 1$ MeV as a function of excitation energy E_x; **b–d** the excitation cross section of 1^+-states in (e, e') scattering for $E_0 = 60$ MeV and $\theta = 180°$. The value of $\kappa_1^{(21)}$ equals $\tilde{\kappa}_1^{(21)}$ (**b**), $0.5\, \tilde{\kappa}_1^{(21)}$ (**c**), and $0.1\, \tilde{\kappa}_1^{(21)}$ (**d**)

The single-particle energies and wave functions have been calculated with the Saxon-Woods potential with the parameters of Chepurnov [19]. All the bound and quasibound states with width $\Gamma \leqq 0.5$ MeV of the proton and neutron systems have been taken into account in the calculations. The states with large angular momenta predominate among the quasibound states. Figure 1a demonstrates the histogram of the density of the $1p-1h$ states with $I^\pi = 1^+$ in ^{208}Pb up to the excitation energy $E_x = 35$ MeV, calculated with our single-particle spectrum. The particle-hole states in the interval $15 < E_x < 25$ MeV correspond to the transitions over two shells, and the states with an energy of $E_x > 30$ MeV correspond to the transitions over four shells. In papers [1, 2] a more truncated single-particle spectrum than ours has been used. Therefore, the $1p-1h$ states with an energy of $E_x > 21$ MeV were absent.

The electroexcitation cross sections of the one-phonon 1^+-states of ^{208}Pb have been calculated by the DWBA-code [20]. The current transitional densities (CTD) have been calculated taking into account only the convective and magnetic constituents of the nuclear current under the assumption that the contribution of the charge exchange current has been effectively taken into account by the renormalization of gyromagnetic factors [21]. The formulae for the convective $\rho^c_{LL}(r)$ and magnetic $\rho^m_{LL}(r)$ CTD are given in paper [22]. The results of calculation of the backward (e, e') scattering cross sections ($\theta = 180°$) at the energy of incident electrons $E_0 = 60$ MeV (these are the experimental conditions [3]) are shown in Fig. 1b–d). The calculation is performed for three values of the constant $\kappa_1^{(21)} = \tilde{\kappa}_1^{(21)}$; $0.5\,\tilde{\kappa}_1^{(21)}$ and $0.1\,\tilde{\kappa}_1^{(21)}$. At all three values of the constant in Fig. 1 one can separate three regions of excitation energy E_x in which the one-phonon 1^+-states are intensively excited in the backward (e, e')-scattering.

The most low-lying state ($E_x = 7.8$ MeV) is the usual $M1$ resonance. As is known, its existence has been predicted by numerous calculations (see, e.g. [13–16]). In recent years its existence became a matter of serious doubt and raised a great discussion [23–25]. However, this is an open question as yet, and we shall not dwell upon it in this paper.

The following group of strongly excited 1^+-states is in the excitation energy interval $15 < E_x < 22$ MeV. Its position coincides with maximum of the density of $1p-1h$ states. The decrease in the constant $|\kappa_1^{(21)}|$ does not lead to essential changes in the position of this group, its width and the sum excitation probability. The group of the one-phonon 1^+-states includes both collective and noncollective states. They are formed by the $1p-1h$ states corresponding to the transitions through two oscillators shells. The most intensively excited states in this group are noncollective states formed by a particle on the level $N+1, l, j$ and a hole on the level N, l, j. Figure 2 exemplifies the CTD of two states from region II: noncollective state with $E_x = 19.8$ MeV and collective with $E_x = 19.2$ MeV. Both CTD are of the volume nature. The oscillating behaviour of the CTD of the collective state leads to a small probability of its excitation in the (e, e')-scattering.

The third group of states, one or two (depending on $\kappa_1^{(21)}$) strongly excited states, is concentrated in the region of low density of the $1p-1h$ states. Their position is very sensitive to the value of the constant $\kappa_1^{(21)}$. At $\kappa_1^{(21)} = \tilde{\kappa}_1^{(21)}$ the energy of this (in this case single) state is $E_x = 30.4$ MeV. It is a strongly collectivized state. A considerable contribution to its structure comes from many $1p-1h$ components, corresponding to the spin-flip transitions $\Delta l = 2$, $\Delta j = 1$, the contribution of the transitions through four

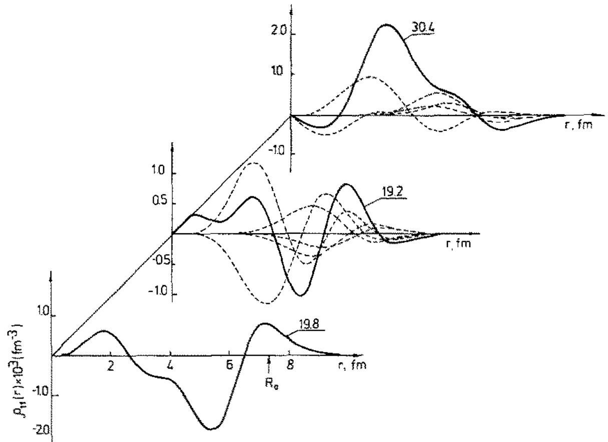

Fig. 2. Current transition densities of one-phonon 1^+-states in ^{208}Pb (solid lines). Number show the excitation energy of states (in MeV). Dashed lines are CTD of $1p-1h$ components, which give the main contribution to the structure of collective ($E_x = 19.8$ and 30.4 MeV) levels

oscillator shells being noticeable. With decreasing spin-quadrupole interaction the energy of this state decreases and the collectivity becomes less. At $\kappa_1^{(21)} = 0.5\,\tilde{\kappa}_1^{(21)}$ the contribution of the $4\hbar\omega$ transitions to its structure is almost insignificant. At $\kappa_1^{(21)} = 0.1\,\tilde{\kappa}_1^{(21)}$ the state becomes noncollective and lies near the second group of 1^+-states, which has been discussed above (Fig. 1d). The CTD of this state is also of a volume nature (Fig. 2). However, in contrast with the CTD of the collective state with an energy of $E_x = 19.2$ MeV, it does not oscillate. Therefore, the state under consideration is excited with a far larger intensity. A different behaviour of the CTD of collective states with $E_x = 19.2$ MeV and $E_x = 30.4$ MeV is apparently due to the fact that the CTD of different $1p-1h$ components composing their structure (they are denoted by the dashed line in Fig. 2) in the first case are summed destructively and in the second case coherently.

The strongly collectivized 1^+-state with the $E_x \simeq 30$ MeV resembles by a number of properties the high-lying $2\hbar\omega$ $M1$-resonance, which has been predicted in [2]. It has a small $B(M1)$-value but is excited strongly in the inelastic electron scattering at large angles and is very sensitive to the effective force constants. The latter makes the difference between our excitation energy for this state and the results of [2] insignificant. The excitation energy 25.16 MeV pointed out in [2], is reproduced in our calculations at $\kappa_1^{(21)} = 0.3 \div 0.25\,\tilde{\kappa}_1^{(21)}$. What is more important, the structure of this state obtained in our calculations should considerably differ from that obtained in [2]. The point is that the main contribution to it comes from the $1p-1h$ states, in which the particle is on the quasistationary level with a large angular momentum. Speth et al. disregarded these states in their calculations. This is apparently the reason of different behaviour of the CTD: the CTD of the $2\hbar\omega$ $M1$ resonance, calculated in [2], was of a surface nature. The excitation probability of the collective state under the conditions of the experiment [3] in our case is 2-2.5 times as less as in [2]. This difference is just partially due to the use of the effective rather than free gyromagnetic factors.

Even in the RPA we have obtained for the high-lying $M1$ states the results different from those of paper [2]. In our calculations at certain values of the effective force constants there also arises a collective 1^+-state with an energy of $E_x \simeq 25$–30 MeV, which is intensively excited in the (e,e')-scattering, but it has a different structure and the excitation probability of it is less than in [2]. These differences are mainly due to a different truncation of the single-particle basis. Besides our calculations predict the existence of the group of noncollective one-phonon 1^+-excitations at the energies $15 < E_x < 22$ MeV, which is excited with almost the same intensity.

3. Influence of the Interaction of One- and Two-Phonon States on the High-Lying $M1$ Excitations

Since the excitation energy of the states under consideration is large, the results may be expected to be influenced considerably not only by the truncation of the single-particle basis but also by the interaction of one-phonon states with those of a more complex structure. In this paragraph we study the influence of the interaction of one- and two-phonon states on the (e,e') scattering cross section.

To take into account in the framework of the QPM the interaction of one- and two-phonon states, the wave function of the ν-excited state with momentum and partiy L^π is written as

$$\Psi_\nu(L^\pi M) = \{\sum_i R_i(L\nu)\, Q^+_{LMi} + \sum_{\substack{\lambda_1\lambda_2\\ i_1 i_2}} P^{\lambda_2 i_2}_{\lambda_1 i_1}(L\nu)\, [Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{LM}\}\,\Psi_0 \qquad (3)$$

where $Q^+_{\lambda\mu i}$ is the phonon creation operator with momentum, projection $\lambda\mu$ and number i which distinguishes the phonons with the same values of $\lambda\mu$ and different excitation energies [6], Ψ_0 is the ground state wave function which is the phonon vacuum.

The phonon interaction operator $H_{\rm int}$ does not contain new parameters in comparison with the initial model Hamiltonian. Its matrix elements $U^{\lambda_2 i_2}_{\lambda_1 i_1}(Li) \sim \langle \Psi_0 Q_{LMi} \| H_{\rm int} \| [Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{LM}\Psi_0\rangle$ are expressed through the quadrature combinations of forward-going and backward-going amplitudes entering the expression for the phonon operators through the quasiparticle creation and annihilation operators [6]. To find the excitation energies $\eta_{L\nu}$ of the states $\Psi_\nu(LM)$ and their structure, one should solve the system of nonlinear equations, the dimension of which coincides with the number of terms in the one-phonon part of the wave function (3). This is a very cumbersome computational problem. Besides, we are forced to calculate the electroexcitation cross section for each state with a complex structure. One can overcome these difficulties using the strength function method, the most simple form of which is presented in the book by Bohr and Mottelson [26], and for more complex cases it has been developed in papers [6, 27]. The strength function for the electroexcitation cross section of the states, described by the wave function (3), is determined as

$$b_2(d\sigma/d\Omega, \eta) = \frac{\Delta}{2\pi}\sum_\nu \frac{1}{(\eta-\eta_{L\nu})^2+\Delta^2/4}\left(\frac{d\sigma}{d\Omega}\right)_{L\nu}. \qquad (4)$$

It has been shown in [28] that for the function $b_2(d\sigma/d\Omega, \eta)$ one can obtain an expression which does not depend explicitly on the energy $\eta_{L\nu}$ and coefficients $R_i(L\nu)$ and $P^{\lambda_2 i_2}_{\lambda_1 i_1}(L\nu)$. The strength function is determined by the matrix elements of the phonon interaction $U^{\lambda_2 i_2}_{\lambda_1 i_1}(Li)$ and by the amplitudes Φ_{Li} of the electroexcitation of one-phonon states $Q^+_{LMi}\Psi_0$. The physical grounds for the obtained in [28] expression for $b_2(d\sigma/d\Omega, \eta)$ is the assumption that excitation of the state proceeds through the one-phonon components and $(d\sigma/d\Omega)_{L\nu} \sim |\sum_i R_i(L\nu)\Phi_{Li}|^2$.

The function analogous to $b_2(\eta)$ can be constructed also for the calculation of the (e,e')-scattering cross section with excitation of the one-phonon states, though from the computational point of view it is not necessary. In what follows we shall however use this way of presentation of the RPA-results for the sake of comparison. We shall denote this function by $b_1(d\sigma/d\Omega, \eta)$.

The quantity Δ entering the definition of the strength function (4) is strictly speaking the parameter. But its value can be chosen so that it would not influence the physical results [27]. In the present calculations we use $\Delta = 0.5$ MeV.

Constructing the two-phonon components in the wave function (3), we have taken into account all the phonons with momenta and parities $\lambda^\pi = 1^\pm, 2^\pm, \ldots 7^\pm$ and the excitation energy $\omega_{\lambda i} \lesssim 30$ MeV. Since all the model equations, used in this paper, are obtained under the assumption that the phonon operators satisfy the boson commu-

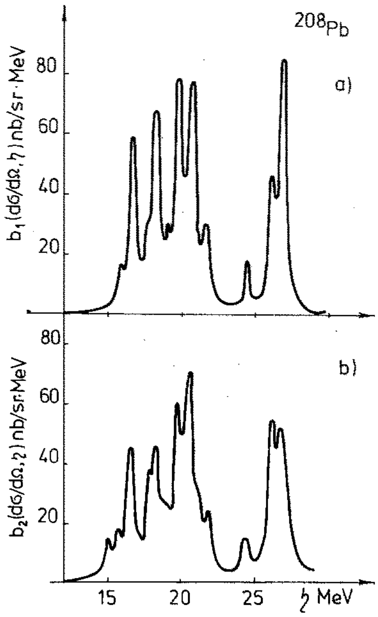

Fig. 3. The strength functions of 1^+-states excitation in ^{208}Pb in (e,e')-reaction with $E_0=60$ MeV and $\theta=180°$. Calculations are performed in RPA (**a**) and with one- and two-phonon states interaction (**b**). Parameters $\Delta=0.5$ MeV

tation relations, it is possible the violation of the Pauli principle while constructing the two-phonon states. Though there is a possibility to take the Pauli principle into account accurately within the model [29], it encounters considerable computational difficulties. Therefore, we have neglected those two-phonon components in (3) for which the Pauli principle is strongly violated; these are the components including two noncollective phonons. Thus, the two-phonon part of (3) includes the states in which either both phonons $Q^+_{\lambda_1\mu_1 i_1}$ and $Q^+_{\lambda_2\mu_2 i_2}$ or one of them is collective. It should be noted that the two-phonon components left in (3) interact most strongly with the one-phonon states. One more approximation should be noted. Since in the present paper we are interested first of all in the 1^+ states with an energy of $E_x>10$ MeV, to simplify the calculations of the strength function $b_2(d\sigma/d\Omega,\eta)$ we take into account the spin-quadrupole part only of the interaction (1) while calculating the structure of one-phonon 1^+ states. Figure 3b exemplifies the calculated strength function $b_2(d\sigma/d\Omega,\eta)$. The calculation is performed for the case when $\kappa_1^{(21)}=0.5\,\bar{\kappa}_1^{(21)}$. The results of RPA-calculation with the same values of the parameters have been presented in Fig. 1c. For the sake of convenience in Fig. 3a these results are presented by the corresponding strength function $b_1(d\sigma/d\Omega,\eta)$ with $\Delta=0.5$ MeV. The comparison of Figs. 3a and 3b shows that the interaction of one- and two-phonon states slightly influence the distribution of the electroexcitation probability of 1^+ states in the ^{208}Pb spectrum at $E_x>12$ MeV. The position and width of the regions with intensively excited 1^+-states are preserved. This means that the one-phonon states are slightly fragmented; the distribution of strength of the one-phonon state proceeds over a small region in the close proximity to it. Therefore, the fragmentation manifests itself in the decrease of the amplitude of peaks in the strength function $b_2(d\sigma/d\Omega,\eta)$ in comparison with $b_1(d\sigma/d\Omega,\eta)$. The reason of a slight fragmentation of one-phonon states is their weak interaction with the two-phonon states, that follows from the values of the matrix elements of this interaction $U^{\lambda_1 i_1}_{\lambda_2 i_2}(Li)$.

4. Masking Effect of $M2$- and $M3$-States

In this paragraph we should like to call attention to the fact which makes it difficult to observe the high-lying $M1$ resonance in the (e,e') scattering. In the experiment [3] it has not been attempted to determine spin and parity of a weakly expressed bump ($\bar{E}_x\simeq 24$ MeV), which can be imagined as a resonance. One can state that the observed bump is related to just the $M1$ resonance if he is sure that other states in this region are excited with a considerably less intensity. In the given case there is no such a confidence. The experimenters indicate that in the same energy region a noticeable contribution of the cross section will come from the transversal electric part of the isovector $E2$ resonance. Our calculations show that the magnetic states of other moltipolarities will be excited as strongly as the $M1$ states. Figure 4 shows the strength functions $b_1(d\sigma/d\Omega,\eta)$ for $M1$-, $M2$- and $M3$-states ($E_0=60$ MeV, $\theta=180°$). The calculation has been per-

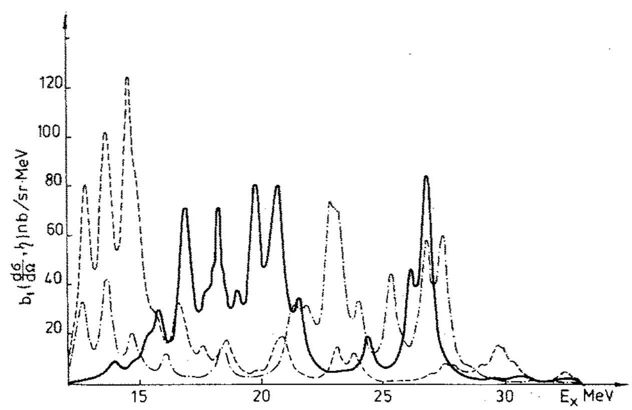

Fig. 4. The strength functions of 1^+-, 2^-- and 3^+-state excitation in ^{208}Pb in (e,e')-reaction with $E_0=60$ MeV and $\theta=180°$. The solid line is for $M1$-states, the dash-dotted line for $M2$-states, the dashed line for $M3$-states

formed in the RPA with the constants (2). The one-phonon $M2$- and $M3$-states lying in the region $10<E_x<27$ MeV are either weakly collective or noncollective, and the corresponding values $B(ML, 0^+_{g.s.}\to L^\pi_i)$ for them are not large. It is seen from Fig. 4 that the electroexcitation cross section for them is sufficiently large. The regions with intensively excited states of different multipolarities are very wide ($\Gamma\sim 5$ MeV) and overlap between themselves. Therefore, the sum cross section will change flatly, and the arising "resonance-like" structures will be related to the excitation of states of different multipolarity. With the large density of levels at $E_x\simeq 20$–30 MeV, the experimental difficulties to separate the contribution to the cross section of different multipolarities will be large.

5. Conclusion

Let us summarize the basic results of the investigations performed in this paper. They have shown that in spherical nuclei* at energies $\bar{E}_x=19\div 20$ MeV there exists a group of noncollective 1^+ states intensively excited in the backward (e,e')-scattering. The states are localized in the excitation energy interval with width of $\Gamma\sim 5$ MeV. The position of the group, dimension of the region of localization and the sum electroexcitation probability depend weakly on the parameters of the effective interaction. At certain values of the constants of the spin-quadrupole forces $|\kappa_1^{(21)}|>0.2\div 0.3|\tilde{\kappa}_1^{(21)}|$ there arise one-two collective 1^+ states ($E_x\geqq 25$ MeV) which are also intensively excited in the backward (e,e')-scattering. The excitation energy and structure of these states depend strongly on the values of $\kappa_1^{(21)}$ and truncation of the single-particle basis. Therefore, even within the QPM we cannot make definite conclusions neither about their position and excitation probability nor the existence itself of these states. At least the calculations with the full single-particle basis including single-particle continuum are needed. It follows from the calculations that the interaction with the two-phonon states does not change considerably the results of calculation in the RPA. The interaction with complicated configurations does not cause disappearance of the collective high-lying $M1$ state (if any). However, the experimental observation of the high-lying $M1$ levels in the (e,e')-scattering is difficult, because in the same region E_x there are intensively excited states with $L^\pi=2^+,3^-$.

All the above mentioned conclusions have been obtained within the simple model using separable effective forces in the spin-isospin channel. Therefore it is legitimate to inquire whether the change of the results presented will be essential, if one uses more realistic effective forces, in particular, the tensor components of these forces and finite range forces [30]. There exists also the assumption [24] that the values of the effective gyromagnetic factors in heavy nuclei are strongly quenched (in ^{208}Pb $g_s^{eff}\sim 0.5\,g_s^{free}$). If this assumption is justified, the (e,e')-scattering cross section will decrease sharply (approximately by a factor of 2.5). Further investigations are needed to answer all these questions profoundly.

* In this paper we present the results for ^{208}Pb alone. In [28] the calculations for ^{90}Zr have been performed, and the obtained results coincide qualitatively with those for ^{208}Pb

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