Excitation of 0^- states in reactions of proton inelastic scattering at intermediate energies

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In the distorted-wave impulse approximation we calculate the excitation of one-phonon states with $L^\pi = 0^-$ of the ^{90}Zr nucleus in inelastic proton scattering at $E_p = 200$ MeV. The central and tensor interactions of the incident proton and the nucleons of the nucleus are taken into account and it is shown that the tensor interaction plays an important role. The effects of exchange knockout are taken into account by means of a nonlocal form factor. The structure and transition densities of 0^- states are calculated with a separable spin-dipole interaction. The possibility of observation of the isovector 0^- resonance in (p,p') scattering is discussed.

In the spectrum of nuclear excitations the one-phonon states with $L^\pi = 0^-$ are distinguished by the fact that their direct excitation from the ground state of the nucleus by the electromagnetic interaction is strongly suppressed. In the approximation of one-photon absorption the reduced probability of the γ transition $0^+ \leftrightarrow 0^-$ is equal to zero and also the cross section for (e,e') scattering with excitation of 0^- states vanishes in this approximation.

Thus, for the study of 0^- states we must use reactions in which the main role is played by the strong interaction. The charge-exchange 0^- resonances have been already discovered in reactions induced by charged pions in a large group of nuclei[1] from ^{40}Ca to ^{208}Pb. There are indications that they have been observed also in the (p,n) reaction at low proton energies[2] $E_p = 200$ MeV. In regard to resonance excitation energies the experimental data[1,2] are in good agreement with a large number of theoretical calculations.[3–5]

The experimental information on 0^- states in the neutral channel (i.e., $\Delta T_z = 0$) is much scarcer. Individual 0^- levels with the energies $E_x = 10.952$ MeV ($T = 0$) and $E_x = 12.795$ MeV ($T = 1$) in the ^{16}O nucleus have been discovered with the help of proton inelastic scattering at $E_p = 65$ and 135 MeV. These data have been successfully explained theoretically.[6] However, no data exist at those excitation energies where 0^- resonance is expected.

At present the most appropriate method of study of 0^- states with $\Delta T_z = 0$ is (p,p') scattering at energies $E_p = 100$–300 MeV. This reaction is familiar for both experimenters and theorists, and it is very convenient for the study of spin-isospin excitations in nuclei.[7] With the help of this reaction extensive experimental information has already been obtained[8] on the states with $L^\pi = 1^+$ and $\Delta T_z = 0$ in nuclei from ^{40}Ca to ^{208}Pb. Therefore, in the present paper we calculate the excitation probability of 0^- states in (p,p') scattering at $E_p = 200$ MeV and try to answer the question concerning the possibility of discovery of these states in medium and heavy nuclei. The calculations are performed for the ^{90}Zr nucleus.

We calculated the structure of 0^- states in the random phase approximation with separable spin–dipole forces, whose radial form factor is chosen in the form $f(r) = dU/dr$, where U is the Woods-Saxon potential which describes the mean field of the nucleus:

$$V(\mathbf{r}_1, \mathbf{r}_2) = \frac{1}{2} (\varkappa_0^{(1L)} + \varkappa_1^{(1L)} \boldsymbol{\tau}_1 \boldsymbol{\tau}_2) \frac{dU}{dr_1} \frac{dU}{dr_2} [\boldsymbol{\sigma}_1 Y_{1\mu}(\Omega_1)]_L [\boldsymbol{\sigma}_2 Y_{1\mu}(\Omega_2)]_L. \quad (1)$$

The separable residual interaction is used in the quasiparticle-phonon nuclear model (QPM). The method and equations of this model are described in detail in the reviews of Ref. 9, and here we shall not dwell on these questions. The parameters of the mean field and of the pairing superfluid interaction have been taken from Ref. 10, where the spin–dipole 2^- states have been investigated.

The constants of the effective forces in the QPM are parameters of the model. Their values are determined by experimental data, as a rule by excitation energies of these or other nuclear states or resonances.[9] Such data do not exist for 0^- states of a particle-hole nature in medium and heavy nuclei. Hence, the constants of the spin-dipole forces $\varkappa_{0,1}^{(10)} (L = 0)$ must be determined in an indirect way. For separable multipole forces with the radial form factor $f(r) = dU/dr$ the approximation in which the constants $\varkappa_0^{(\lambda)}$ and $\varkappa_1^{(\lambda)}$ do not depend on multipolarity is quite satisfactory. If this approximation is valid also for spin-multipole forces, then the value of $\varkappa_1^{(1L)}$ could be determined using data on the location of the $M1$ resonance.[8] On the other hand, the closeness of excitation energies of the Gamow-Teller and isobaric-analog resonances in heavy nuclei shows that the strength of the spin-isospin component of the effective interaction of the nucleons in the nucleus must be of the same order as the strength of the isospin component.[12] This means that for the nucleon interaction in the *QPM* $\varkappa_1^{(1L)}$ must be close to the constant of the isovector dipole interaction $\varkappa_1^{(1)}$, which can be determined on the basis of data on the $E1$ resonance.

These two methods of determination of $\varkappa_1^{(1L)}$ give results differing by a factor 1.5–3. The results of the calculations of other authors with more realistic effective *NN* forces[4,5,13] are close to our results if we use smaller values of $\varkappa_1^{(1L)}$, i.e., $\varkappa_1^{(1L)} \sim \varkappa_1^{(1)}$. The same value of the constant of the isovector spin-dipole forces was used in Ref. 14 in the analysis of possibilities of the separation of the contribution from

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the twisting mode in the spectrum of inelastically scattered slow electrons. In the largest part of our calculations we use the same values of $\varkappa_1^{(10)} \sim \varkappa_1^{(1)}$. In what follows, we shall call these values of $\varkappa_1^{(10)}$ "basic" and denote them by $\tilde{\varkappa}_1$.

We can use experimental data[15] on the isoscalar 1^+ state in ^{208}Pb for the choice of the ratio of the constants $\varkappa_0^{(10)}$ and $\varkappa_1^{(10)}$. The theoretical analysis of these data shows[16] that the location and the excitation probability of this state can be explained only in the assumption that the isoscalar spin-spin interaction is much weaker than the isovector interaction. In the present paper we use the value $\varkappa_0^{(10)} = 0.1\varkappa_1^{(10)}$.

For the preliminary qualitative analysis of the spectrum of the one-phonon 0^- states we calculated the response of the nucleus to an external field of the form

$$\sum_i r_i[\sigma_i Y_{1\mu}(\Omega_i)]_0, \qquad (2)$$

$$\sum_i r_i[\sigma_i Y_{1\mu}(\Omega_i)]_0 \tau_i^3. \qquad (3)$$

The results of the calculations are shown in Fig. 1. We investigated the dependence of the results on the quantity $\varkappa_1^{(10)}$. For the "basic" value $\varkappa_1^{(10)} = \tilde{\varkappa}_1$ the maximum of the "isovector" response function (3) is located at the excitation energy $E_x \sim 19$ MeV (Fig. 1b*2*). This is the isovector 0^- resonance. It is a collective state; seven two-quasiparticle components make a contribution to its normalization larger than 1%. The increase of the constant $\varkappa_1^{(10)}$ leads to a large increase of energy of the isovector 0^- resonance (Fig. 1c*2*). For the values $\varkappa_1^{(10)} \sim \varkappa_1^{(01)}$ the excitation energy of the resonance is $E_x \sim 30$ MeV. The decrease of the constant $\varkappa_1^{(10)}$ by a factor of 2 in comparison with $\tilde{\varkappa}_1$ causes the descent of the resonance by ~ 1 MeV. Already for this value of the constant the isovector 0^- state is no longer collective, i.e., it becomes essentially a purely quasi-two-particle state; further weakening of the interaction essentially has no influence on its structure and location. We note that essentially for any value of $\varkappa_1^{(10)}$ the largest part of the strength of isovector transitions is concentrated in one 0^- state.

The concentration of the "isoscalar" 0^- strength (2) is just as high (see Figs. (1a*1* − 1c*1*). The location of the isoscalar 0^- resonance is not sensitive to the value of the constant $\varkappa_{0,1}^{(10)}$.[1)] Its structure was found to be noncollective; in the wave function one or two two-quasiparticle components are dominant.

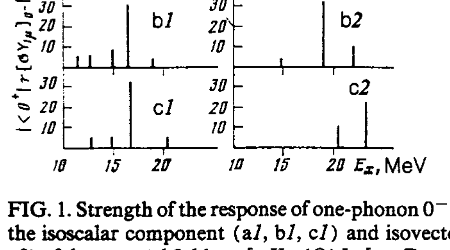

FIG. 1. Strength of the response of one-phonon 0^- states of the nucleus to the isoscalar component (a*1*, b*1*, c*1*) and isovector component (a*2*, b*2*, c*2*) of the external field $\sim r[\sigma Y_{1\mu}(\Omega)]_0$ [see Eqs. (2) and (3)] for different values of the constants $\varkappa_{0,1}^{(10)}$: (a)—$\varkappa_1^{(10)} = 0.5\tilde{\varkappa}_1$; (b)—$\varkappa_1^{(10)} = \tilde{\varkappa}_1$; (c)—$\varkappa_1^{(10)} = 2\tilde{\varkappa}_1$; $\varkappa_0^{(10)} = 0.1\varkappa_1^{(10)}$.

A large contribution to the structure of the resonance 0^- states (both isoscalar and isovector) comes from the particle-hole components which correspond to transitions with spin flip between single-particle states with large orbital angular momenta. For example, the wave function of the isoscalar 0^- resonance in ^{90}Zr contains two components $(1g_{9/2}^{-1}1h_{9/2})_\nu$ and $(1f_{7/2}^{-1}1g_{7/2})_\pi$ which add in phase. The resonance response of this state to the external field$^{(2)}$ is related, first of all, to the large value of the corresponding single-particle matrix elements. The calculations performed by us for ^{208}Pb give similar results.

It should be noted that the use of the separable residual interaction (1) in the study of 0^- states is a very great simplication. It is desirable to have some confidence in the correctness of reproduction of at least the integrated characteristics of strength distributions in these calculations. In Refs. 4, 5, and 13 the spin-dipole resonances with $\Delta T_z = 0$ have been studied with more realistic interactions (SG-II forces; contact interaction with inclusion of π and ρ exchanges, etc.) Here also the response function of the nucleus to external fields of the type (2) and (3) has been calculated. For the isovector 0^- resonance our results are in qualitative agreement with the results of Refs. 4, 5, and 13, although there the excitation energy in ^{90}Zr was found to be 3–4 MeV higher than our value for $\varkappa^{(10)} = \tilde{\varkappa}_1$. The tensor component of effective *NN* forces not taken into account by us has a very large influence on the shape of the isoscalar response function,[4] and therefore in what follows we shall not discuss it.

We use the schematic residual interaction and the discrete single-particle basis including only bound and quasibound states. This noticeably simplifies numerical calculations of the structure and of the transition densities of 0^- states and allows us to calculate the cross section for (p,p') scattering with a minimum number of approximations. We calculated the cross section at the energy $E_p = 200$ MeV of the incident protons in the so-called distorted-wave impulse approximation (DWIA), the gist of which is the choice of the interaction of the incident nucleon with the nucleons of the nucleus in the form of a free t_{NN}-matrix. The DWIA works satisfactorily at energies $E_p > 100$ MeV. The parametrization of the t_{NN}-matrix was chosen in the form of the sum of Yukawa potentials whose parameters were determined using the amplitude of nucleon-nucleon scattering[7] at 210 MeV. The free t_{NN}-matrix includes central and tensor components (the spin-orbit interaction makes no contribution to excitation of 0^- states). The phase shifts of the scattering by the field of the target nucleus were calculated with an optical potential which depends on the energy and the mass number. The parameters of the optical potential were adjusted to the cross section for proton elastic scattering and to the analyzing power.[17] The effects of exchange knockout of the nucleon have been included exactly by introducing a nonlocal form factor. In the calculations we have used the program of Ref. 18. In this program the wave functions of essentially any nuclear model can be used. For this purpose the corre-

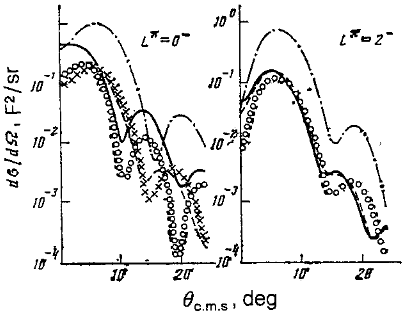

FIG. 2. Cross sections for excitation of the resonance 0^- ($E_x = 19$ MeV) and 2^- ($E_x = 8.4$ MeV) states of the ^{90}Zr nucleus as a function of the scattering angle θ calculated in different approximations for the t_{NN} interaction. The curves: dash-dot—the t_{NN} interaction has only central components and exchange knockout is not taken into account; dashed—the t_{NN} interaction has only central components, and exchange knockout is included exactly; solid—t_{NN} interaction has central and tensor components and exchange knockout is included exactly. The points: ×—the t_{NN} interaction has only central components and exchange knockout is taken into account by means of a pseudopotential; O—the t_{NN} interaction has central and tensor components and exchange knockout is taken into account by means of a pseudopotential.

sponding local and nonlocal transition densities must be calculated. Also the channel of exchange knockout of the nucleons and central and tensor components of the t_{NN}-matrix are taken into account exactly in that program. In the present paper the form factor was obtained by convolution of the t_{NN}-matrix parametrized as described above with the transition densities of one-phonon excited states calculated with the interaction (1) with the "basic" values of the constants.

As a first step we have studied the problem of validity of several simplifications and approximations which are often used within the framework of the DWIA. The results of the corresponding cross sections for excitations of the isovector 0^- resonance ($E_x = 19.05$ MeV) of the ^{90}Zr nucleus are shown in Fig. 2 (on the left-hand side). In the simplest approximation the t_{NN} interaction contains only central components and the effects of knockout are not taken into account. It is known that the latter effect is very important, but its exact inclusion is laborious and normally the procedure of introduction of a pseudopotential is used. As is seen in Fig. 2, for the purely central t_{NN} interaction this manner of inclusion of exchange knockout gives results which are close to the exact results, especially for the angles $\theta < 10°$. For the tensor component of the t_{NN} interaction the description of exchange effects in the pseudopotential-type approximation is not valid. However, if exchange is completely neglected in this channel, the result is very different from the exact result (see the corresponding curves in Fig. 2). The comparison of the curves in Fig. 2 leads to the conclusion that tensor components of the t_{NN} interaction strongly influence the theoretical cross section for (p,p') scattering with excitation of 0^- states. The changes of the cross section at small angles $\theta < 5°$ are most important.

The strong dependence of the theoretical cross section for excitation in proton inelastic scattering on the tensor components of the t_{NN} interaction is a distinctive feature of 0^- states. For other spin-dipole states, for example, for the states with $L^\pi = 2^-$ their inclusion is not so important. This is seen in Fig. 2 (on the right-hand side), where we show the cross section for excitation of the state[2)] 2^- with the energy $E_x = 8.4$ MeV in ^{90}Zr calculated with the same approximations as in Fig. 2 (on the left-hand side). In this case the approximations related to exchange knockout of the nucleons influence the behavior of the cross section more strongly at small angles.

Would it be possible to observe the 0^- resonance in the (p,p') scattering? First of all, it is clear that one must search for it at small angles in order to suppress the contribution from transitions with large momentum transfer. Then the main competition will be between the transitions with $\Delta l = 0$ and $\Delta l = 1$, i.e., between the excitations of states with $L^\pi = 1^+, 2^-, 1^-$, and 0^-. The calculations in the random phase approximation show that the strength of these excitations in the spectrum of ^{90}Zr is distributed as follows[10,19,20]: in the region of energies $E_x \sim 8$–10 MeV there are the $M1$ and $M2$ resonances known from (p,p') and (e,e') scattering[8,11]; at $E_x \approx 17$–20 MeV there is the high-lying branch of the $M2$ resonance, and at $E_x \approx 21$–25 MeV the spin-dipole (transverse) $E1_T$ resonance and the high-lying $M1$ resonance (produced by transitions with $\Delta l = 2$). The probability of a γ transition from some of these resonances ($E1_T$ and the high-lying $M1$) to the ground state is small, but all of them are intensively excited in electron inelastic scattering at large angles. Also the giant dipole resonance (GDR) must be mentioned; this is seen clearly in (p,p') scattering at intermediate energies at small angles. However, the GDR is situated at energy $E_x \sim 16$ MeV and it should not make a noticeable contribution to the cross section in the region of the isovector 0^- resonance ($E_x \sim 19$ MeV).

As we see, in the region of E_x where the isovector 0^- resonance is located, the main competitors are 2^- states. However, the tensor part of the interaction of the incident proton with the nucleons of the nucleus is responsible for the significantly different behavior of the cross sections for excitation of 0^- and 2^- states at small angles. For clearness we have shown the corresponding cross sections in a single figure (Fig. 3), where also the cross section for excitation of the resonance 1^+ state with $E_x = 8.9$ MeV is shown. At $\theta = 0°$ the intensity of excitation of the isovector 0^- resonance is an order of magnitude larger than the $M2$ resonance, and the

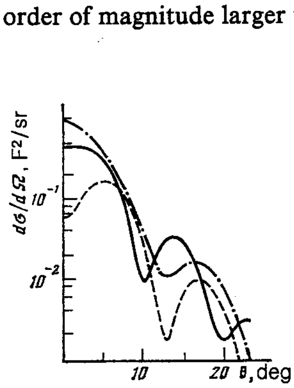

FIG. 3. Cross section for excitation of the 1^+ state with $E_x = 8.9$ MeV (dash-dot curve), of the 2^- state with $E_x = 17.9$ MeV (dashed curve), and of the 0^- state with $E_x = 19$ MeV (solid curve) of the ^{90}Zr nucleus as a function of the scattering angle θ.

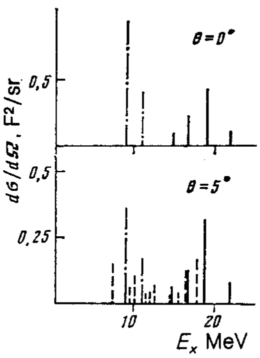

FIG. 4. Cross section for excitation of 1^+ (dash-dot curves), 2^- (dashed) and 0^- (solid) states of the ^{90}Zr nucleus in (p,p') scattering at $E_p = 200$ MeV.

behavior of the cross section $d\sigma/d\Omega(0^-)$ as a function of θ at small angles is closer to the behavior of $d\sigma/d\Omega(1^+)$ than to the behavior of $d\sigma/d\Omega(2^-)$. Therefore, at $\theta = 0°$ 1^+ and 0^- states are excited preferentially, which can be seen in Fig. 4 (upper part).[3)] the contribution from 2^- states becomes noticeable for $\theta \geqslant 5°$, i.e., after the first maximum in the cross section for excitation of the 2^- level with $E_x = 8.4$ MeV (Fig. 4, lower part).

But in reality the resonance structures related to excitation of 2^- states are even less pronounced, for at least two reasons. In the present calculations we have not taken into account the influence on the structure of 2^- levels of the spin-octupole forces, which cause a larger spread of the $M2$ strength in one-phonon 2^- states in the energy interval 17–20 MeV, i.e., they decrease the excitation probability of individual single-phonon states.[13,22] The second reason is the interaction of one-phonon and two-phonon states. As the calculations performed within the framework of the QPM show,[10,20] this interaction "washes out" the strength of the high-lying spin-dipole 1^- and 2^- states and spreads it over an interval of excitation energy $\Delta E_x \sim 10$ MeV. As a result, the spin-dipole 1^- and 2^- states at $E_x \sim 20$ MeV must form a background of the (p,p') reaction. The high-lying $M1$ resonance is not so strongly fragmented,[19] but it is located slightly above the region of E_x interesting for us.

Of course, in order to be consistent, we must investigate the influence of the interaction with two-phonon states also on the 0^- resonance. As long as this is not done, we can only refer to the results of Ref. 4, where the response functions of the ^{90}Zr nucleus to an external field of the type of Eqs. (2) and (3) have been calculated with inclusion of the interaction of $1p - 1h$ and $2kp$–$2h$ configurations. In those calculations the fragmentation of 0^- resonance was found to be weaker than that of the high-lying $M2$ and $M1$ resonances, and the amplitude of the strength function in the resonance region is the largest for 0^- states.

Experiment does not provide definite indications of the existence of resonance structures related to excitation of spin-isospin states in the neutral channel at excitation energies $E_x \sim 20$ MeV. In Ref. 23 [(p,p') scattering, $E_p = 200$ MeV, $\theta = 4°$] the region of excitation energies $3 < E_x \leqslant 30$ MeV of the ^{90}Zr nucleus has been studied. In the cross section the M1 resonance ($E_x \sim 9$ MeV) and the giant dipole resonance ($E_x \sim 16$ MeV) are clearly visible, but at higher energies there are no clearly pronounced resonance structures. The same result has been obtained[24] in inelastic scattering of polarized protons at the energy $E_p = 319$ MeV. However, it should be noted that in the latter experiment a large contribution to the cross section for transitions with spin flip has been discovered in the energy region $8 < E_x < 25$ MeV. Since there exist reasons to think that the width of the 0^- resonance is not too large (according to Ref. 4 $\Gamma \sim 5$ MeV) and that it stands out against the background, one can try to discover this resonance by increasing the measurement statistics.

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[1)]In the calculations shown in Fig. 1 the value of $\varkappa_0^{(10)}$ was varied in proportional to $\varkappa_1^{(10)}$.

[2)]For the "basic" values of $\varkappa_1^{(1L)}$ this state has the maximum value of $B(M2, 0^+_{g.s.} \to 2^-)$ among all 2^- states.

[3)]The giant dipole resonance is not considered here (see preceding paragraph).

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