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MICROSCOPIC DESCRIPTION OF NEUTRON AND PROTON TRANSITION MOMENTS IN SPHERICAL NUCLEI

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Neutron and proton transition matrix elements for low-lying quadrupole transitions are calculated microscopically in the framework of the quasiparticle phonon nuclear model in some spherical nuclei. For isoscalar states M_n and M_p are of the same value and sign, and for the isovector states they are predicted to be of the same value and opposite sign. The isoscalar and isovector states are differently excited in inelastic scattering of protons and deuterons.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Микроскопическое описание нейтронных и протонных переходных моментов в сферических ядрах

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В рамках квазичастично-фононной модели микроскопически вычислены нейтронные и протонные переходные матричные элементы низколежащих квадрупольных состояний в некоторых сферических ядрах. Для изоскалярных состояний M_n и M_p имеют близкие значения и одинаковые знаки, а для изовекторных состояний – близкие значения и противоположные знаки.

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The dynamic properties of nuclear states manifest themselves in the behaviour of the proton and neutron transition multipole moments M_p and M_n. The former are directly obtained as square roots of the electromagnetic transition rates and are much better known than the neutron multipole moments M_n. The latter can be measured by comparing the inelastic scattering of different hadronic probes. These methods are based on different interactions between the probe and target protons and neutrons [1,2] and may be of great use in the investigation of the recently predicted new class of low-lying collective states [3]. These states are described in some microscopic [4] and geometrical models [5] and are known as isovector states. The existence of isovector states has been found in the case of 1^+ states in deformed nuclei.

The third 2^+ states in N = 84 nuclei and in ^{56}Fe have been considered as 2^+ — isovector candidates /6/. For isovector states M_p and M_n are predicted to be of opposite sign /5, 11/.

In /2/ a method is applied to the investigation of the isospin structure of the low-lying quadrupole states in nuclei. It is based on the comparison of the inelastic scattering of protons and deutrons on nuclei to different 2^+ states. It has been shown that an anomalous $\sigma(p,p')/\sigma(d,d')$ ratio indicates either an isovector state or a state with a dominant n or p component. In both of the cases these states are predicted to be excited differently in (p, p′) and (d,d′) reactions. A 2^+ state equally excited by the two probes cannot, on the other hand, have a sizable isovector component. The transition matrix elements of the reactions $M(p,p')$ and $M(d,d')$ can be expressed as a sum of M_n and M_p that manifest the properties of the target nucleus, weighed by the interaction strengths (dependent on the probe). At given incident energies /2/ we can assume an affective p−n interaction three times larger than the p−p interaction and then for $M(p,p')$ and $M(d,d')$ the following relations are obtained:

$$M(p,p') = 0.25M_p + 0.75M_n,$$
$$M(d,d') = 0.5M_p + 0.5M_n. \qquad (1)$$

For the case of collective isoscalar transitions, M_p and M_n are of the same sign and order of magnitude and lead to similar values of $M(p,p')$ and $M(d,d')$. For transitions with a large isovector component M_p and M_n moments are of opposite sign and may differ in magnitude so that the ratio $M(p,p')^2/M(d,d')^2 \sim \sigma(p,p')/\sigma(d,d')$ can be far from unity.

In the present paper we shall consider from the microscopic point of view the neutron and proton matrix elements.

We have already treated the problem of existence of low-lying isovector states /4/ within the framework of the microscope quasiparticle-phonon nuclear model (QPM) /7/.

The Hamiltonian of the model includes an average field as the Saxon — Woods potential, pairing interactions with constant matrix elements and separable multopole-multipole and spin-multipole-spin-multipole (isoscalar and isovector) particle-hole interactions. We perform the Bogolubov-Valatin canonical transformations and then through Ψ, Φ transformation from pairs of the Bogolubov quasiparticle operators $\alpha^+_{jm}\alpha^+_{j'm'}$, $\alpha_{j'm}\alpha_{jm}$, $\alpha^+_{jm}\alpha_{j'm'}$, we pass to the phonon operators $Q^+_{\lambda\mu i}$, $Q^+_{\lambda'\mu' i'}$, to yield the Hamiltonian in doubly-even nuclei:

$$H = \sum_{\lambda\mu i} \omega_{\lambda i} Q^{+}_{\lambda\mu i} Q_{\lambda\mu i} + 0.5 \sum_{\substack{\lambda_1\lambda_2 J \\ i_1 i_2 i}} \sum_{\substack{\mu_1\mu_1 \\ M}} \langle\lambda_1\mu_1\lambda_2\mu_2 | J-M\rangle \times$$

$$\times [U^{\lambda_2 i_2}_{\lambda_1 i_1}(Ji)\, Q^{+}_{\lambda_1\mu_1 i_1} Q^{+}_{\lambda_2\mu_2 i_2} Q_{J-Mi} + \tag{2}$$

$$+ (-)^{J-M} V^{\lambda_2 i_2}_{\lambda_1 i_1}(Ji)\, Q^{+}_{\lambda_1\mu_1 i_1} Q^{+}_{\lambda_2\mu_2 i_2} Q^{+}_{\lambda_3\mu_3 i_3} + H.C.].$$

This is the Hamiltonian of a system of interacting phonons with different energies, moments and parity. The wave function of the phonon is a linear superposition of forward- and backward-going two-quasiparticle amplitudes ψ and ϕ. The structure of the phonons is calculated in the RPA /7/ . The coefficients $U^{\lambda_2 i_2}_{\lambda_1 i_1}$ and $V^{\lambda_2 i_2}_{\lambda_1 i_1}$ depend on the amplitudes ϕ and ψ and are calculated microscopically /9/ . The parameters of the separable particle-hole forces are determined from the experimental data for the lowest-lying collective states and the giant resonances /8/ .

In the traditional approaches the phonon operators satisfy the boson commutation relations

$$[Q_{\lambda'\mu' i'}, Q_{\lambda\mu i}] = \delta_{\lambda\lambda'}\delta_{\mu\mu'}\delta_{ii'} .$$

However, as soon as we go beyond the RPA taking into accont the interaction between the phonons, multiphonon admixtures arise in the excited state wave function of a doubly-even nucleus. We include one- and two-phonon terms in the wave function of the excited state $|JM\rangle$, i.e.

$$|JM\rangle_\nu = \{ \sum_i R_i(J_\nu) Q^{+}_{JMi} + \sum_{\substack{\lambda_1\mu_1 i_1 \\ \lambda_2\mu_2 i_2}} P^{\lambda_2 i_2}_{\lambda_1 i_1} [Q^{+}_{\lambda_1\mu_1 i_1} Q^{+}_{\lambda_2\mu_2 i_2}]_{JM} \} \Psi_0 . \tag{3}$$

In this case the violation of the Pauli principle is possible in the two-phonon components of the wave function (3), especially if the phonons $Q^{+}_{\lambda_1\mu_1 i_1}\Psi_0$ and $Q^{+}_{\lambda_2\mu_2 i_2}\Psi_0$ are non collective.

In /9,12/ the effect of the Pauli principle on the wave function (3) was studied and expressions for the coefficients R and P were suggested.

Table 1

λ_i^π	E MeV		M_n		M_p			B	$B(E2, gr.s. \to 2_1^+)$ $e^2 fm^4$	
	Theor.	Exp.	Theor.	Exp.	Theor.	Exp. ref. /1/	Exp. ref. /10/	Theor.	Theor.	Exp.
^{56}Fe										
2_1^+	0.670	0.847	26.1	35.2	22	30.5	31.1	0.008	718	970
2_2^+	2.450	2.650	-5.5	13.1	1.1	8.6	4.2	0.98	1.05	10
2_3^+	2.880	2.960	-2.3	—	2.9	—	3.2	1.06	9	12
2_4^+	3.313	3.370	5.9	10.1	3.4	9.04	7.1	0.015	20	40
^{142}Ce										ref. /13/
2_1^+	0.658	0.641	70	—	60.8	—	—	0.0003	5450	4800
2_2^+	1.713	1.536	1.07	—	-7.22	—	—	1.33	61	< 80
2_3^+	1.980	2.004	2.09	—	6.04	—	—	0.08	48	700
2_4^+	2.062	2.542	-2.35	—	-1.80	—	—	0.012	5	—

A good indication of the isotopic character of the excited states is the ratio B of the isovector B(IV, E2) and isoscalar B(IS, E2) reduced quadrupole transitions

$$B(IV,E2) = |<2_i^+|| \sum_k^p r_k^2 Y_{2\mu}(\Omega_k) - \sum_k^n r_k^2 Y_{2\mu}(\Omega_k) || \Psi_0 >|^2,$$

$$B(IS,E2) = |<2_i^+|| \sum_k^p r_k^2 Y_{2\mu}(\Omega_k) + \sum_k^n r_k^2 Y_{2\mu}(\Omega_k) || \Psi_0 >|^2. \qquad (4)$$

Table 2

λ_i^π	$M_{pp'}$	$M_{dd'}$	$M^2_{pp'}/M^2_{dd'}$
^{56}Fe			
2_1^+	25	24	1.01
2_2^+	-3.87	-2.25	2.95
2_3^+	-1	0.30	11.1
2_4^+	5.35	4.1	1.28
^{142}Ce			
2_1^+	67.7	65.4	1.06
2_2^+	-1	-3.08	0.10
2_3^+	5.3	4.5	1.17
2_4^+	1.93	1.26	2.34

The results for the ratio B, which are given in table 1, show that the low-lying 2^+ states have mainly an isoscalar structure. For most of them $B \ll 1$. For these states M_n and M_p are of the same sign and differ in the magnitude about 1.2 to 2 times. It is seen from table 2 that the ratios $(M_{p,p'})^2/(M_{d,d'})^2$ calculated by (1) must not differ much from unity. These states are assumed to be isoscalar ones.

At the same time it is seen from table 1 that the states 2^+ (1.713 MeV) in ^{142}Ce and 2^+ (2.880 MeV) in ^{56}Fe show an isovector character as for these levels the ratio B is big, about ten times greater than for the other. In the case of 2_2^+ in ^{142}Ce (see table 2) we have an isovector state with a predominant proton component. For this state M_p is most larger than M_n and of the opposite sign. That is why it must be differently excited in (p, p′) and (d, d′) reactions. The ratio $M^2_{pp'}/M^2_{dd'}$ for this state is much less than unity.

For the 2^+ (2.880 MeV) state in ^{56}Fe M_p and M_n are of the same value and of opposite sign. In this case the ratio $M^2_{pp'}/M^2_{dd'}$ must be significantly greater than unity. We assume that this state has an isovector structure. The matrix elements M_n and M_p of the nearby lying state 2^+ (2.450 MeV) are also of the opposite sign. The ratio B for this state is almost equal to unity. The isospin structure of this state is very similar to that of 2^+ (2.880 MeV) state. This fact is reflected in experimental results of Hamilton et al.[6] where an assumption is given that the isovector strength is sheared between the two quadrupole states 2^+ (2.450 MeV) and 2^+ (2.880 MeV).

We have compared our microscopic calculations for ^{56}Fe with the experimental data on π^+/π^- inelastic scattering[1] and heavy ion reactions[10]. The calculations for ^{142}Ce have a predictive character. The theoretical results for ^{56}Fe are in satisfactory agreement with the experimental ones. Some discrepancies appear in B (E2, gr. st. → → 2^+_2) probability in ^{56}Fe. This is due to not very precise description of the distribution of the two-phonon component $\{2^+_1 \otimes 2^+_1\}$ over 2^+_i states with the wave function (3). The including of the three-phonon components in the wave function will change the distribution and some improvement can be achieved.

We summarize the present letter by mentioning the following: we have made use of the QPM-formalism to calculate microscopically the neutron and proton transition moments of low-lying quadrupole states in some spherical nuclei. The theoretical analyses point out that the low-lying states of an isovector character appear in the spectra of spherical nuclei. States of that type are 2^+ (1.713 MeV) in ^{142}Ce and 2^+ (2.880 MeV) in ^{56}Fe. The isospin structure of 2^+ (2.450 MeV) in ^{56}Fe is very similar to that of the third one. That is confirmed by the similar values of ratios B and the opposite signs of M_p and M_n of these states. Our microscopic calculations are in satisfactory overall agreement with experimental data.

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