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FRAGMENTATION OF SPIN-DIPOLE CHARGE-EXCHANGE STATES IN SPHERICAL NUCLEI

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1. INTRODUCTION

Experimental measurement of charge-exchange spin-dipole and Gamow-Teller resonances in some spherical nuclei /1-4/ stimulated theoretical investigations in this region. Most attention is paid to the reasons for the missing of part of strength of the Gamow-Teller and spin-dipole resonances in comparison with the relevant sum rules. One of the reasons for the quenching of the charge-exchange transition strength is the fragmentation of charge-exchange states due to the coupling with 2p-2h states /5-12/ and to the mixing with the Δ-isobar-nucleon hole configurations /6,13-17/ It has been shown /18/, that the Δ-hole coupling decreases the transition strength spin-dipole states but to a lesser extent than in the case of Gamow-Teller strengths. What is the role of the Δ-hole interactions in the quanching of spin-flip states is not quite clear. It has been shown /19,20/ that the isoscalar transition strength decreases to the same extent as the isovector strength in the excitation of 1^{+} states in (p,p′) reactions. The influence of the Δ-isobar effects on the isoscalar states must be insignificant. For the experimental study of the quenching of the spin-dipole strength it is important to correctly subtract the background since the calculated background is not large /21/.

Most of the calculations of the transition strength to the charge-exchange spin-dipole states in spherical nuclei have been performed in the RPA /22-27/. We think it sensible to calculate the fragmentation of charge-exchange spin-dipole states caused by the quasiparticle-phonon interaction. This is important for elucidating how the fragmentation is respondible for missing of the spin-dipole strength in the maximum region. The calculations have been performed within the quasiparticle-phonon nuclear model /28-31/. In the present paper we use the same formalism and notation as in the previous paper /32/.

2. FRAGMENTATION OF SPIN-DIPOLE CHARGE-EXCHANGE PHONONS AND STRENGTH FUNCTIONS OF (p,n) TRANSITIONS

Formulae for the description of the fragmentation of charge-exchange states are given in /32/. We will not repeat them again but point out necessary changes. The RPA secular equations and the model Hamiltonian terms H_{csmv} and H_{csmvq} for the spin-multipole states in the general case can be obtained from the formulae [32] by changing the constants $\kappa_1^{\lambda-1,\lambda}$ by $\kappa_1^{L\lambda}$ and the matrix elements $f(\lambda; j_p j_n)$ by

$$f(L\lambda; j_p j_n) = \langle j_p || i^L r^L [Y_L(\theta,\phi),\sigma]_\lambda t^{(-)} || j_n \rangle.$$

The charge-exchange spin-dipole states with $\Delta L = 1$ and $\Delta S = 1$ have negative parities and spins $\lambda = 0, 1$ and 2. States with $\lambda^\pi = 1^-$ can also be generated by dipole forces. The dipole and spin-dipole 1^- states in deformed nuclei have been calculated simultaneously [34]. It was shown that in spite of the closeness of energies of these states, they do not mix considerably, and therefore, they can be calculated independently. In spherical nuclei the dipole and spin-dipole 1^- state energies are noticeably separated and in this paper we treat them as independent.

To study the fragmentation of charge-exchange phonons, like in [32] we use the wave function of an odd-odd nucleus in the following form:

$$|JM\nu\rangle = [\sum_k R_k^{J\nu}\Omega_{JMk}^+ + \sum_{\lambda_1 i_1 \lambda_2 i_2} P_{\lambda_2 i_2}^{\lambda_1 i_1}(J\nu)[Q_{\lambda_1 i_1}^+, \Omega_{\lambda_2 i_2}^+]_{JM}]|\rangle, \quad (1)$$

where $|\rangle$ is the ground state wave function of a doubly even nucleus (phonon vacuum); Ω_{JMk}^+ and $Q_{\lambda\mu i}^+$ are the creation operators of neutron-proton and usual phonons. Using the variational principle we get the secular equation

$$\tilde{\mathfrak{F}}(\eta_\nu) = 0 \quad (2)$$

the explicit form of which is given in [32].

The strength functions for coherent transitions from the states $|\rangle$ to those described by the wave function (1) are

$$b^{(\pm)}(J,\eta) = \frac{1}{\pi}\,\mathrm{Im}\,\frac{\sum_{k,k'}(-1)^{k+k'}\mathfrak{M}_{kk'}(\eta + i\frac{\Delta}{2})\Phi_{Jk}^{(\pm)}\Phi_{Jk'}^{(\pm)}}{\tilde{\mathfrak{F}}(\eta + i\frac{\Delta}{2})}, \quad (3)$$

where $\mathfrak{M}_{kk'}$ are the minors of determinant (2), $\Phi_{\lambda k}^{(-)}$ is the transition amplitude of multipolarity λ and parity $(-1)^L$ from the ground state of the target-nucleus N_0, Z_0 to the one-phonon states of the nucleus $N_0 - 1$, $Z_0 + 1$; $\Phi_{\lambda k}^{(+)}$ is the transition amplitude to the states of the nucleus $N_0 + 1$, $Z_0 - 1$. Their explicit form can also be found in [32].

3. RESULTS AND DISCUSSION

The Saxon-Woods potential parameters, the pairing constant and the chemical potential for the systems with closed shells

are the same as in [32]. The isovector constant of the spin-dipole interaction is

$$\kappa_1^{1\lambda} = \frac{\kappa_1^{01}}{\langle r^2\rangle} = -\frac{23}{A\langle r^2\rangle}, \quad \frac{\mathrm{MeV}}{\mathrm{fm}^2}, \quad (4)$$

where $\kappa_1^{01} = -\frac{23}{A}$ MeV is the Gamow-Teller interaction constant.

The two-phonon part of the wave function (1) includes the same multipole and spin-multipole phonons as in ref. [32].

The results of the RPA calculations and of the fragmentation of charge-exchange spin-dipole $p\bar{n}$ (proton-neutron hole) states with $\lambda^\pi = 0^-$, 1^- and 2^- are shown in figs. 1-5 and tables 1-6. The excitation energies, given in the figures and tables, are reckoned from the ground states of doubly even nuclei. Table 1 contains the average values of the excitation energy of spin-dipole states calculated in the RPA and by formula (3) (denoted by $\Omega^+ + Q^+\Omega^+$). The energies are given for the states with the definite spin and for total transitions with $\Delta L = 1$. The last column of the table contains the experimental average values of the energy of $\Delta L = 1$ states [2]. In this case, since uncertainty of the experimental data amounts to 1.0 MeV, there is agreement between these and our calculations. The quasiparticle-phonon interaction does not lead to considerable changes in comparison with the RPA calculations.

Now we proceed to discuss briefly the results of calculations of the fragmentation of charge-exchange spin-dipole states for several spherical nuclei. As is seen from fig. 1 and table 2, the RPA calculations for ^{90}Zr provide the following strength distribution: For $\lambda^\pi = 0^-$ strength is concentrated in one state at 31 MeV, for $\lambda^\pi = 1^-$ at about 28 MeV, and for 2^- it is distributed from 15 to 25 MeV. The quasiparticle-phonon interaction results in a strong fragmentation of one-phonon states. In this case the main part of the total strength of spin-dipole $p\bar{n}$-transitions is in the energy interval from 13 to 35 MeV, about 8% of the total strength is shifted to the region above 35 MeV.

The data on the spin-dipole $p\bar{n}$ strength distribution on ^{120}Sn and ^{124}Sn are represented in figs. 2,3 and in tables 3,4. The quasiparticle-phonon interaction leads to a considerable redistribution of strength within the energy interval of 10-30 MeV. About 10% of the total strength in ^{120}Sn and 12% in ^{124}Sn are shifted to the energy region above 30 MeV. About 3% of strength in ^{124}Sn is lowed below 5 MeV. Most probably, the influence of low-lying 2^- states in ^{124}Sb is essential. A similar situation is observed in ^{124}Te (fig.4 and table 5). The excitation energy region above 30 MeV receives 10% of $p\bar{n}$ transition strength and about 2% is shifted into the region below 5 MeV and to the ground state of ^{124}I ($\lambda^\pi = 2^-$). In ^{208}Pb (fig.5 and table 6) the influence of two-phonon components of the wave function leads to a considerable redistribution of transition strength within the interval of 20-30 MeV, 25% of the total transition strength being shifted to the energy region above 30 MeV. Approximately 1% of the total strength is below 5 MeV.

The calculations show that the quasiparticle-phonon interaction leads to the formation of widths of spin-dipole charge-exchange resonances in spherical nuclei, the main part of the transition strength (from 60 to 75%) is in the range from 15 to 25 MeV (from 15 to 30 MeV in ^{90}Zr). From 10 to 25% of strength is at energies larger than 30 MeV, and about 10% below 15 MeV. In ^{124}Sn and ^{124}Te this part of strength is rather low due to the influence of low-lying 2^- states in odd-odd nuclei. The total missing of the spin-dipole transition strength from the maximum region is by 1.5 times less than in the case of Gamow-Teller transitions /32/. It should be noted that in spherical nuclei with open shells the strength distribution is the same as in the nuclei with one open shell. Thus, within the quasiparticle-phonon nuclear model with the use of central separable residual forces, one succeeds in describing correctly the centroid energies of spin-dipole states of the $p\bar{n}$-type and their widths.

According to our calculations with the wave function (1), only (10-25)% of the spin-dipole strength is shifted above 30 MeV due to the quasiparticle-phonon interaction. For the calculation of strength distribution of charge-exchange states, it is desirable to improve the description of the fragmentation of neutron-proton one-phonon states. A new method for a more accurate description of the fragmentation of one-phonon states forming giant resonances has been developed in /34/. The method consist in that the one-phonon states already fragmented are used in the two-phonon part of the wave function (1). In this case one may expect the fragmentation of charge-exchange one-phonon states to be stronger in comparison with the present calculations.

Table 1

Centroid energies for spin-dipole charge-exchange states of the type $p\bar{n}$ (in MeV)*

Nucleus	Approxin. for wave functions of excited states	For partial transitions 0^-	1^-	2^-	$\Delta L = 1$	Experiment**)
^{90}Zr	RPA	29.5	26.6	20.8	24.1	23.4
	$\Omega^+ + Q^+\Omega^+$	27.8	25.7	20.1	23.1	
^{120}Sn	RPA	26.6	24.1	19.5	22.0	21.5
	$\Omega^+ + Q^+\Omega^+$	24.2	22.4	20.1	21.4	
^{124}Sn	RPA	27.8	25.1	20.1	22.8	20.4
	$\Omega^+ + Q^+\Omega^+$	23.8	22.9	20.1	21.5	
^{124}Te	RPA	26.6	23.9	19.6	22.0	22.7
	$\Omega^+ + Q^+\Omega^+$	24.0	22.5	19.8	21.2	
^{208}Pb	RPA	28.29	25.89	22.01	24.08	25.3
	$\Omega^+ + Q^+\Omega^+$	27.80	25.58	22.36	24.05	

*) averaging was over the states with energies from 5 to 35 MeV

**) from /2/

Table 2

Strength distribution of charge-exchange spin-dipole transitions on ^{90}Zr (in fm^2)

Type of transition	Approxim. for wave functions of excited states	Energy intervals in MeV					
		5÷15	15÷20	20÷25	25÷30	30÷35	5÷35
0^-	RPA	0.28	0.69	1.27	-	31.26	33.50
	$\Omega^+ + Q^+\Omega^+$	0.42	1.58	3.75	13.40	8.96	28.12
1^-	RPA	2.12	4.90	7.65	75.20	-	89.87
	$\Omega^+ + Q^+\Omega^+$	3.01	8.53	22.25	34.36	14.39	82.55
2^-	RPA	7.09	41.09	77.62	-	-	126.00
	$\Omega^+ + Q^+\Omega^+$	25.10	29.15	48.55	9.64	6.75	119.19
$\Delta L = 1$	RPA	9.49	46.68	86.74	75.20	31.26	249.47
	$\Omega^+ + Q^+\Omega^+$	28.53	39.26	24.55	57.40	30.10	229.85

Table 3

Strength distribution of charge-exchange spin-dipole transitions on ^{120}Sn (in fm^2)

Type of transition	Approxim. for wave functions of excited states	Energy intervals in MeV					
		5÷15	15÷20	20÷25	25÷30	30÷35	5÷35
0^-	RPA	-	2.42	9.92	40.80	6.69	59.83
	$\Omega^+ + Q^+\Omega^+$	1.41	3.90	25.25	16.31	3.75	50.61
1^-	RPA	-	11.99	50.60	93.10	3.18	158.87
	$\Omega^+ + Q^+\Omega^+$	5.04	25.67	81.02	22.02	8.22	141.98
2^-	RPA	14.53	15.63	72.68	135.35	-	238.19
	$\Omega^+ + Q^+\Omega^+$	24.62	67.90	115.05	13.50	3.50	224.57
$\Delta L = 1$	RPA	14.53	30.04	133.20	269.25	9.87	456.89
	$\Omega^+ + Q^+\Omega^+$	31.07	97.47	221.32	51.83	15.47	417.16

Table 4

Strength distribution of charge-exchange spin-dipole transitions on ^{124}Sn (in fm^2)

Type of transition	Approxim. for wave functions of excited states	Energy interval in MeV					
		5÷15	15÷20	20÷25	25÷30	30÷35	5÷35
0^-	RPA	-	2.65	7.38	48.18	9.46	67.67
	$\Omega^+ + Q^+\Omega^+$	3.63	6.68	21.09	13.95	6.05	51.39
1^-	RPA	2.28	11.39	38.59	123.13	5.91	181.29
	$\Omega^+ + Q^+\Omega^+$	8.89	16.87	91.80	28.26	11.58	157.39
2^-	RPA	30.15	88.40	158.20	-	-	276.75
	$\Omega^+ + Q^+\Omega^+$	31.97	85.75	102.47	20.86	11.16	252.21
$\Delta L = 1$	RPA	32.43	102.47	204.17	171.31	15.37	525.72
	$\Omega^+ + Q^+\Omega^+$	44.49	109.30	215.36	63.07	28.79	460.99

Table 5

Strength distribution of charge-exchange spin-dipole transitions on ^{124}Te (in fm^2)

Type of transition	Approxim. for wave functions of excited states	Energy intervals in MeV					
		5÷15	15÷20	20÷25	25÷30	30÷35	5÷35
0^-	RPA	-	2.59	8.95	43.16	3.93	58.63
	$\Omega^+ + \Omega^+ Q^+$	1.35	3.67	26.89	13.57	3.29	48.76
1^-	RPA	3.89	12.53	45.67	98.39	3.10	163.67
	$\Omega^+ + \Omega^+ Q^+$	6.32	15.80	101.29	20.30	4.93	148.65
2^-	RPA	29.33	76.43	132.96	-	-	238.72
	$\Omega^+ + \Omega^+ Q^+$	24.89	84.55	91.13	12.16	5.87	218.60
$\Delta L = 1$	RPA	33.31	91.55	187.58	141.55	7.03	461.02
	$\Omega^+ + \Omega^+ Q^+$	32.56	104.02	219.31	46.03	14.09	416.01

Table 6

Strength distribution of charge-exchange spin-dipole transitions on ^{208}Pb (in fm^2)

Type of transition	Approxim. for wave functions of excited states	Energy intervals in MeV					
		5÷15	15÷20	20÷25	25÷30	30÷35	5÷35
0^-	RPA	-	4.93	7.42	123.34	5.61	141.30
	$\Omega^+ + Q^+\Omega^+$	1.36	6.60	24.90	50.13	51.20	134.18
1^-	RPA	5.29	27.13	39.78	326.55	6.39	405.13
	$\Omega^+ + Q^+\Omega^+$	15.01	31.82	61.95	228.26	54.95	391.98
2^-	RPA	71.20	98.51	235.86	231.71	-	637.27
	$\Omega^+ + Q^+\Omega^+$	83.74	91.25	235.24	156.29	42.51	609.04
ΔL =1	RPA	76.49	130.57	283.06	681.60	12.00	1183.71
	$\Omega^+ + Q^+\Omega^+$	100.11	129.67	322.09	434.68	148.66	1135.22

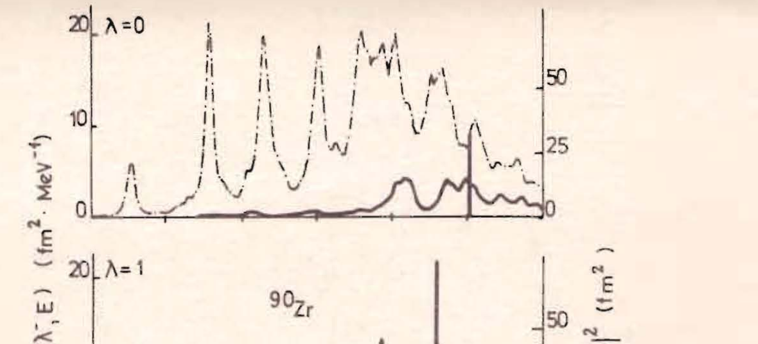

Fig.1. Fragmentation of charge-exchange spin-dipole states of the $p\bar{n}$-type in ^{90}Zr. Solid curve is the strength function of the fragmentation of states with the definite spin. Dashed curve is the strength function of the total strength distribution of transitions with $\Delta L = 1$. Vertical fragments are the transition strength calculated in the RPA. Energies are reckoned from the ground state of ^{90}Zr..

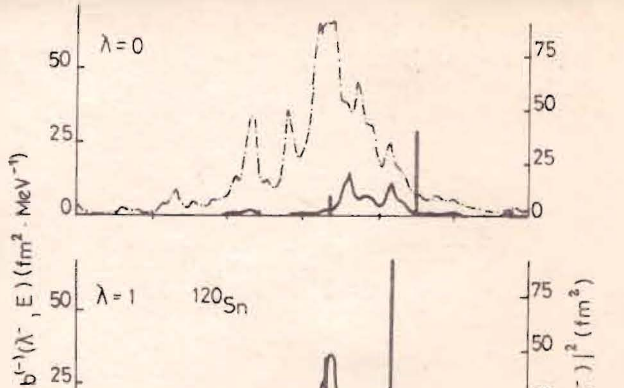

Fig.2. Fragmentation of charge-exchange spin-dipole states of the $p\bar{n}$-type on ^{120}Sn. Energies are reckoned from the ground state of ^{120}Sn. Notation is as in fig.1.

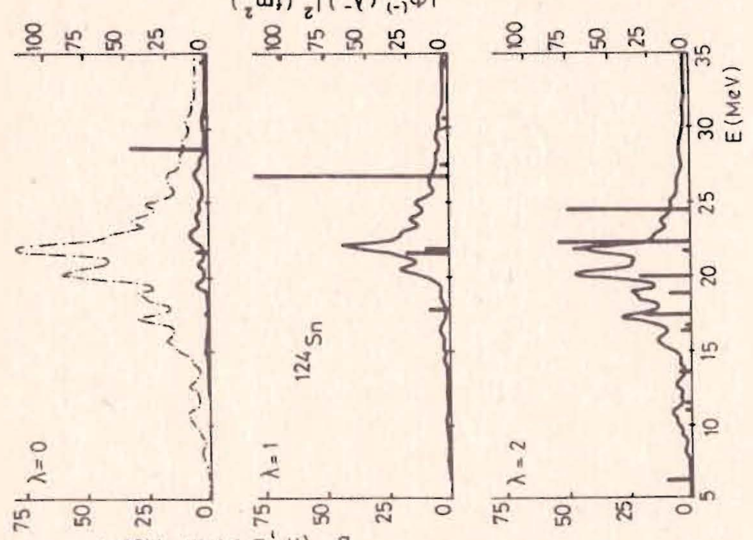

Fig.3. Fragmentation of charge-exchange spin-dipole states of the $p\bar{n}$-type on ^{124}Sn. Energies are reckoned from the ground state of ^{124}Sn. Notation is as in fig.1.

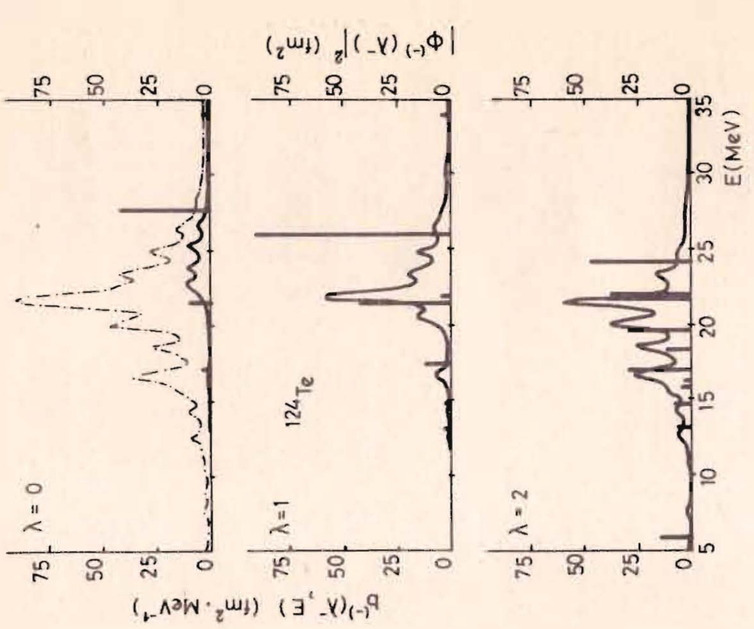

Fig.4. Fragmentation of charge-exchange spin-dipole states of the $p\bar{n}$-type on ^{124}Te. Energies are reckoned from the ground state of ^{124}Te. Notation is as in fig.1.

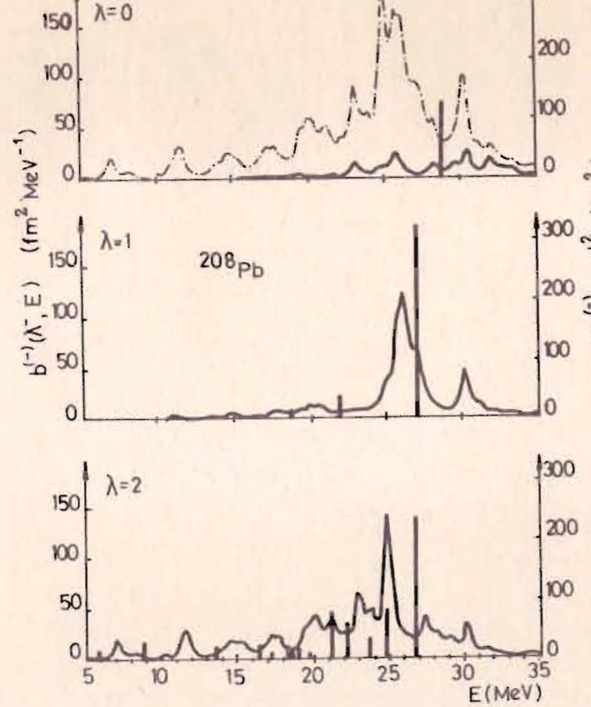

Fig.5. Fragmentation of charge-exchange spin-dipole states of the $p\bar{n}$-type on ^{208}Pb. Energies are reckoned from the ground state of ^{208}Pb. Notation is as in fig.1.

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Кузьмин В.А., Соловьев В.Г. E4-84-550

Фрагментация спин-дипольных зарядово-обменных состояний в сферических ядрах

В рамках квазичастично-фононной модели ядра с использованием центральных остаточных сил изучена фрагментация спин-дипольных зарядово-обменных состояний в сферических ядрах. Проведены расчеты для ^{90}Zr, $^{120,124}Sn$, ^{124}Te и ^{208}Pb. Показано, что из области максимума уходит до 30% силы переходов, из них 10-25% в сторону больших энергий возбуждения.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Kuzmin V.A., Soloviev V.G. E4-84-550

Fragmentation of Spin-Dipole Charge-Exchange States in Spherical Nuclei

Fragmentation of spin-dipole charge-exchange states in spherical nuclei is studied within the quasiparticle-phonon nuclear model with the use of central residual forces. Calculations are made for ^{90}Zr, $^{120,124}Sn$, ^{124}Te and ^{208}Pb. It is shown that 10-25% of the transition strength is shifted from the region of maximum towards large excitation energies, on the whole this region loses about 30%.

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

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