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V.G.Soloviev, A.V.Sushkov, N.Yu.Shirikova

CHARGE-EXCHANGE DIPOLE AND SPIN-DIPOLE RESONANCES IN DEFORMED NUCLEI

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1. INTRODUCTION

The Gamow-Teller resonances in deformed nuclei are described in refs. [1,2]. In paper [2] the charge-exchange phonons are introduced, and the secular equations in the random-phase approximation are obtained. The strength functions for the (p, n) and (n, p) transitions with excitation of charge-exchange states are also presented in this paper.

In the present paper we use formulae [2] to study the strength functions of the (p, n) and (n, p) transitions with $\ell = 1$, i.e., the charge-exchange electric dipole and spin-dipole states in even deformed nuclei.

2. STRENGTH FUNCTIONS OF THE (p, n) AND (n, p) TRANSITIONS

The model Hamiltonian is given in ref. [2] and has the form $H_v^{np} = \sum_{s\rho} \epsilon(s) a^+_{s\rho} a_{s\rho} + \sum_{r\rho} \epsilon(r) a^+_{r\rho} a_{r\rho} + H^{np}_{coll}$, where $a_{r\rho}$ is the quasiparticle absorption operator, $\epsilon(r)$ is the quasiparticle energy, H^{np}_{coll} describes the multipole-multipole or spin-multipole - spin-multipole charge-exchange isovector interaction in the particle-hole channel.

Now we shall discuss how the secular equation becomes complicated in the case of a simultaneous inclusion of the multipole and spin-multipole interaction. A part of the Hamiltonian corresponding to these interactions can be written as

$$H^{np}_{coll} = 2(\kappa_1^{\lambda} \sum_{\rho\mu} \beta^+_{\lambda\rho\mu} \beta_{\lambda\rho\mu} + \kappa_1^{L\lambda} \sum_{\rho\mu} \beta^+_{L\lambda\rho\mu} \beta_{L\lambda\rho\mu}). \qquad (1)$$

Here

$$\beta_{\lambda\rho\mu} = \sum_{\substack{rs \\ \rho'}} \{ f^{\lambda\mu} \delta_{\rho'(K_p - K_n),\rho\mu} a^+_{r\rho'} a_{s\rho'} + \bar{f}^{\lambda\mu}_{rs} \delta_{\rho'(K_p + K_n),\rho\mu} \rho' a^+_{r\rho'} a_{s\rho'} \},$$

$a_{r\rho'}$ and $a_{s\rho'}$ are the proton and neutron absorption operators, $r\rho'$ and $s\rho'$ are the quantum numbers of proton and neutron single-particle states including the angular momentum projection onto the symmetry axis of nucleus K_p and K_n, $\rho = \pm 1$, and κ_1^{λ} is the isovector constant of the multipole-multipole interaction. The operators $\beta_{\lambda\rho\mu}$ and $\beta_{L\lambda\rho\mu}$ differ by the matrix elements $f^{\lambda\mu}_{rs}$ and

$f_{rs}^{L\lambda\mu}$. Expressing (1) through the np-phonon operators and using the variational principle, we get, as under a simultaneous inclusion of quadrupole and spin-quadrupole forces [3], the following secular equation:

$$\mathcal{F}(\Omega_g) = \det(A) = \begin{vmatrix} X_1^g - \frac{1}{\kappa_1^\lambda} & X_{12}^g & W_1^g & W_{12}^g \\ X_{12}^g & X_2^g - \frac{1}{\kappa_1^\lambda} & W_{12}^g & W_2^g \\ W_1^g & W_{12}^g & X_1^{Lg} - \frac{1}{\kappa_1^{L\lambda}} & X_{12}^{Lg} \\ W_{12}^g & W_2^g & X_{12}^{Lg} & X_2^{Lg} - \frac{1}{\kappa_1^{L\lambda}} \end{vmatrix} . \qquad (2)$$

Here $g = \lambda\mu i$,

$$X_1^g = \sum_{rs} 4\{(f_{rs}^{\lambda\mu})^2 + (\bar{f}_{rs}^{L\lambda\mu})^2\}\{\frac{u_r^2 v_s^2}{\epsilon(rs) - \Omega_g} + \frac{v_r^2 u_s^2}{\epsilon(rs) + \Omega_g}\},$$

$$X_2^g = \sum_{rs} 4\{(f_{rs}^{\lambda\mu})^2 + (\bar{f}_{rs}^{L\lambda\mu})^2\}\{\frac{v_r^2 u_s^2}{\epsilon(rs) - \Omega_g} + \frac{u_r^2 v_s^2}{\epsilon(rs) + \Omega_g}\},$$

$$X_{12}^g = \sum_{rs} 4\{(f_{rs}^{\lambda\mu})^2 + (\bar{f}_{rs}^{L\lambda\mu})^2\}\{\frac{1}{\epsilon(rs) - \Omega_g} + \frac{1}{\epsilon(rs) + \Omega_g}\} u_r v_s v_r u_s ,$$

$$W_1^g = \sum_{rs} 4\{f_{rs}^{\lambda\mu} f_{rs}^{L\lambda\mu} + \bar{f}_{rs}^{\lambda\mu} \bar{f}_{rs}^{L\lambda\mu}\}\{\frac{u_r^2 v_s^2}{\epsilon(rs) - \Omega_g} + \frac{v_r^2 u_s^2}{\epsilon(rs) + \Omega_g}\},$$

$$W_1^g = \sum_{rs} 4\{f_{rs}^{\lambda\mu} f_{rs}^{L\lambda\mu} + \bar{f}_{rs}^{\lambda\mu} \bar{f}_{rs}^{L\lambda\mu}\}\{\frac{v_r^2 u_s^2}{\epsilon(rs) - \Omega_g} + \frac{u_r^2 v_s^2}{\epsilon(rs) + \Omega_g}\},$$

$$W_{12}^g = \sum_{rs} 4\{f_{rs}^{\lambda\mu} f_{rs}^{L\lambda\mu} + \bar{f}_{rs}^{\lambda\mu} \bar{f}_{rs}^{L\lambda\mu}\}\{\frac{1}{\epsilon(rs) - \Omega_g} + \frac{1}{\epsilon(rs) + \Omega_g}\} u_r v_s v_r u_s ,$$

$\epsilon(rs) = \epsilon(r) + \epsilon(s)$.

The quantities X_1^g and X_1^{Lg} differ by the matrix elements $f_{rs}^{\lambda\mu}$ and $f_{rs}^{L\lambda\mu}$.

In the secular equation (2) W_1^g, W_2^g and W_{12}^g are the sums of terms, taking positive and negative values. Therefore, they are much less than the values of X_i^g, which are the coherent sums. Assuming $W_1^g = W_2^g = W_{12}^g = 0$, eq. (2) disintegrates into two independent equations (8) from ref. [2], taking into account

the multipole-multipole interaction and the other spin-multipole - spin-multipole interaction. Equation (2) has the same properties as eq. (8) in ref. [2].

In the case of a simultaneous inclusion of multipole and spin-multipole forces the strength functions for the (p, n) multipole and spin-multipole transitions are

$$b^{\lambda\mu}(p, n; \Omega) = \frac{1}{\pi}(2 - \delta_{\mu 0}) \, \mathrm{Im}\{\frac{A_{11}(\Omega + i\Delta/2)}{2(\kappa_1^\lambda)^2 \mathcal{F}(\Omega + i\Delta/2)}\}, \qquad (3)$$

$$b^{L\lambda\mu}(p, n; \Omega) = \frac{1}{\pi}(2 - \delta_{\mu 0}) \, \mathrm{Im}\{\frac{A_{33}(\Omega + i\Delta/2)}{2(\kappa_1^{L\lambda})^2 \mathcal{F}(\Omega + i\Delta/2)}\}; \qquad (4)$$

and for the (n, p) multipole and spin-multipole transitions,

$$b^{\lambda\mu}(n, p; \Omega) = \frac{1}{\pi}(2 - \delta_{\mu 0}) \, \mathrm{Im}\{\frac{A_{22}(\Omega + i\Delta/2)}{2(\kappa_1^\lambda)^2 \mathcal{F}(\Omega + i\Delta/2)}\}, \qquad (5)$$

$$b^{L\lambda\mu}(n, p; \Omega) = \frac{1}{\pi}(2 - \delta_{\mu 0}) \, \mathrm{Im}\{\frac{A_{44}(\Omega + i\Delta/2)}{2(\kappa_1^{L\lambda})^2 \mathcal{F}(\Omega + i\Delta/2)}\}. \qquad (6)$$

Here A_{ii} are minors of the determinant (2).

Now we introduce the total (p, n) and (n, p) transition strength $S(p, n) = S_- = \int_0^\infty b(p, n; \Omega) d\Omega$, $S(n, p) = S_+ = \int_0^\infty b(n, p; \Omega) d\Omega$. The following sum rules are used to study the charge-exchange resonances:

for the electric resonances

$$S_-^\lambda - S_+^\lambda = \sum_\mu \{\sum_i |\langle | r^\lambda Y_{\lambda\mu} t^{(-)} | \lambda\mu i\rangle|^2 - \sum_i |\langle | r^\lambda Y_{\lambda\mu} t^{(+)} | \lambda\mu i\rangle|^2\} = \frac{2\lambda + 1}{4\pi}(N\langle r_n^2\rangle - Z\langle r_p^2\rangle), \qquad (7)$$

for the spin-multipole resonances

$$S_-^{L\lambda} - S_+^{L\lambda} = \sum_\mu \{\sum_i |\langle | r^L (\sigma Y_L)_{\lambda\mu} t^{(-)} | L\lambda\mu i\rangle|^2 - \sum_i |\langle | r^L (\sigma Y_L)_{\lambda\mu} t^{(+)} | L\lambda\mu i\rangle|^2\} = \frac{2\lambda + 1}{4\pi}(N\langle r_n^2\rangle - Z\langle r_p^2\rangle). \qquad (8)$$

Here $<r_n^2>$ and $<r_p^2>$ are the squares of neutron and proton radii averaged over the ground nuclear state. It is usually assumed that

$$N<r_n^2> - Z<r_p^2> = (N-Z)<r_A^2>, \quad <r_A^2> = \frac{3}{5}(r_0 A^{1/3}), \quad r_0 = 1.25. \qquad (9)$$

For the E1 and spin-dipole resonances our calculations exceed by (10-20)% the values obtained by formulae (7) and (8) with the value (9). The properties of the strength functions are considered in ref. /2/.

The parameters of the Saxon-Woods potential and the pairing constants in our calculations are the same as in ref. /4/. The calculations are performed for the ranges with $A = 155$, 165 and 239 with the parameters of equilibrium deformation β_2^0 and β_4^0 given in ref. /4/. The largest possible number of single-particle levels is taken into account. The isovector dipole constants obtained by calculating the giant E1 resonances are taken from ref. /4/. The isovector constants for the spin-dipole forces are obtained from the comparison of our calculations with the experimental data on ^{169}Tm and the empirical curve of the position of spin-dipole resonances given in ref. /5/. For the spin-dipole forces the isovector constant is

$$\kappa_1^{\ell=1} = 0.75 \frac{4\pi}{<r_A^2>} \kappa_1^{\ell=0} \quad .$$

At $\kappa_1^{\ell=1} = \frac{4\pi}{<r_A^2>} \kappa_1^{\ell=0}$ the (p,n) resonance lies too high. If the factor is taken to be equal to 0.6, 0.75, 1.05 the centroid energies for ^{166}Er are 22.7, 23.5, 26.1 MeV. Here $\kappa_1^{\ell=0}$ = = 17/A MeV, the choice of this constant is considered in ref. /2/.

3. RESULTS AND DISCUSSION

The calculations for charge-exchange spin-dipole and E1 resonances are made for many nuclei in the range $A = 155$, 165 (rare-earth region) and 239 (actinide region).

The results of calculations of the (p,n) and (n,p) transition strength functions with excitation of spin-dipole states are shown in tables 1,2 and figs.1,2. The spin-dipole resonance consists of the states with $\lambda^\pi = 0^-, 1^-, 2^-$. Table 1 exemplifies the centroid energies $\bar{E}$ and $\bar{E}_{\lambda^-}$ for the (p,n) transitions to the states with $\lambda^\pi = 0^-, 1^-, 2^-$ for the low-energy maximum regions and the fraction of total strength in three energy re-

Table 1

Centroid energies of the spin-dipole states $\lambda^\pi = 0^-, 1^-, 2^-$ excited in (p,n) reaction with $\ell = 1$ and the fraction of the total strength in three energy regions

Nucleus	E<14 MeV		14 MeV<E<33 MeV								E>33 MeV
	$\bar{E}$	fraction of S(p,n) %	$\bar{E}_{0^-}$	fraction of S(p,n) %	$\bar{E}_{1^-}$	fraction of S(p,n) %	$\bar{E}_{2^-}$	fraction of S(p,n) %	$\bar{E}$	fraction of S(p,n) %	fraction of S(p,n) %
^{156}Gd	9.2	9.5	28.6	11.2	25.9	33.0	22.3	43.8	24.4	88.0	2.8
^{158}Gd	9.5	9.0	29.0	10.9	26.4	32.7	22.7	44.2	24.8	87.2	2.8
^{160}Gd	9.5	9.0	29.4	10.1	26.9	32.2	23.0	44.4	25.2	86.8	4.8
^{160}Dy	9.4	9.7	28.4	11.5	25.8	33	22.0	43.3	24.2	88.0	2.6
^{162}Dy	9.3	8.3	28.0	10.9	25.6	32.6	22.8	44.6	24.5	88.6	3.2
^{164}Dy	9.2	8.2	28.4	11.3	24.0	32.6	23.0	44.7	24.8	88.6	3.3
^{164}Er	9.4	9.6	27.4	11.7	24.8	32.7	22.2	43.4	23.8	87.1	3.3
^{166}Er	9.2	8.7	28.2	11.5	25.6	32.7	22.6	44.2	24.4	88.2	3.0
^{168}Er	9.1	8.2	28.8	11.3	26.1	32.7	23.0	44.6	24.9	88.5	3.3
^{168}Yb	9.5	9.8	27.6	11.7	24.9	32.8	22.2	43.0	23.9	87.6	2.6
^{236}U	9.2	7.7	28.8	10.4	26.4	31.2	23.8	46.4	25.3	88.1	4.2
^{238}U	9.1	7.5	29.0	9.6	26.7	31.2	24.1	46.6	25.6	88.0	4.5
^{238}Pu	9.2	8.1	28.3	10.6	25.8	31.6	23.3	45.9	24.8	88.1	3.8
^{240}Pu	9.2	7.9	28.7	10.5	26.2	31.5	23.6	46.1	25.1	88.1	4.0

gions. The (p,n) strength is distributed within 2-40 MeV. The maximum region of the spin-dipole resonance (14-33) MeV contains (87-89)% of the (p,n) strength. The low-energy part (2-14) MeV has only the states with $\lambda = 2$. For $\lambda = 0$ there is one pronounced maximum within 30-32 MeV; for $\lambda = 1$, two maxima at 24-25 MeV and 29-30 MeV, for $\lambda = 2$ the strength maximum is distributed in a wide energy region of 14-30 MeV. The high-energy part gives a (3-4)% contribution to the total strength. The strength distribution for different λ is shown in fig.1. The total strength has a broad maximum within 14-33 MeV for all calculated nuclei, this is seen in figs.1 and 2. In the region of maximum the strength of the nuclei in $A = 155$ range

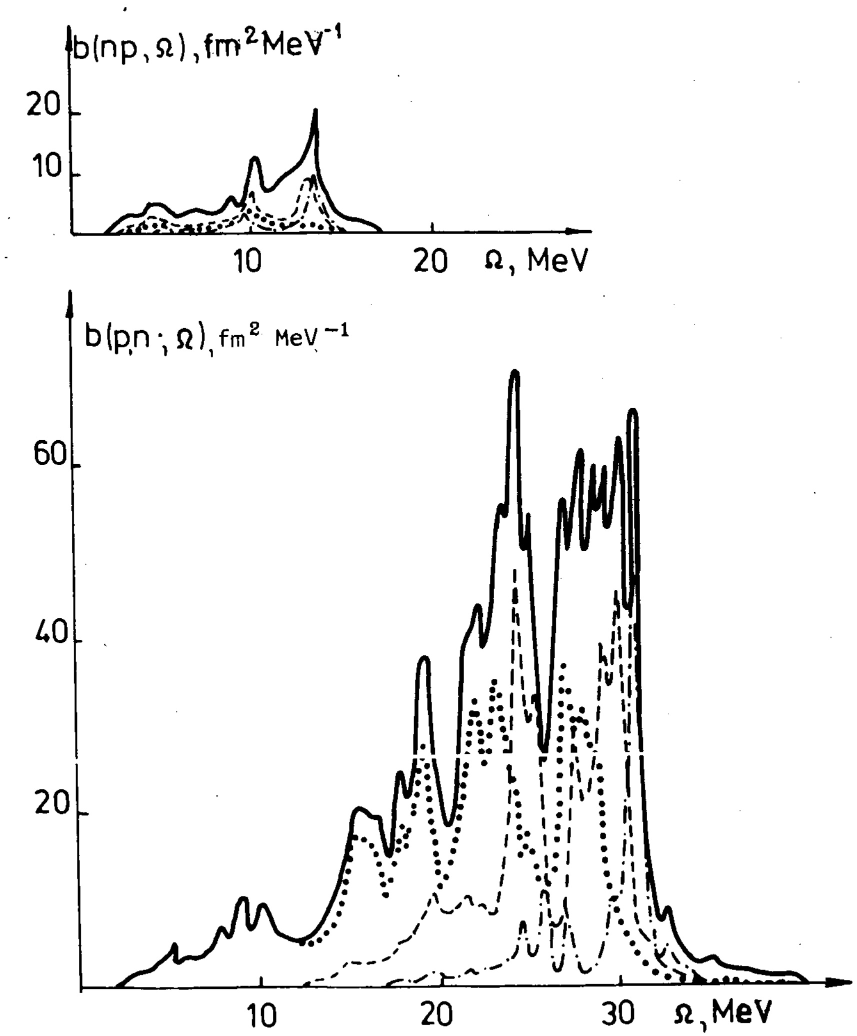

Fig.1. Strength functions of (p,n) and (n,p) transitions with $\ell = 1$ to the spin-dipole states with $\lambda^\pi = 0^-, 1^-, 2^-$ on ^{162}Dy. The dashed-dotted line denotes transitions to $\lambda^\pi = 0^-$, the dashed line is the transition to $\lambda^\pi = 1^-$, the dotts are transitions to $\lambda^\pi = 2^-$ states, the solid line is their sum. $\Delta = 0.5$ MeV.

is distributed more uniformly than in A = 165, 239 ranges. For nuclei in A = 165 and 239 ranges the strength is concentrated to a large extent in the upper part of the distribution.

Table 2

Centroid energies of the spin-dipole states $\lambda^\pi = 0^-, 1^-, 2^-$ excited in (n,p) reaction with $\ell = 1$ and the ratio of the total (n,p) transition strength to the total strength of (p,n) transitions

Nucleus	$\bar{E}_{0^-}$	$\bar{E}_{1^-}$	$\bar{E}_{2^-}$	$\bar{E}$	$S(np)/S(p,n)$
^{156}Gd	13.0	11.2	10.6	11.4	0.14
^{158}Gd	12.7	11.0	10.7	11.3	0.12
^{160}Gd	12.3	10.8	10.7	11.1	0.11
^{160}Dy	13.4	11.5	10.8	11.7	0.14
^{162}Dy	12.4	10.8	10.2	11.0	0.11
^{164}Dy	11.9	10.5	10.0	10.7	0.10
^{164}Er	13.1	11.3	10.3	11.4	0.14
^{166}Er	12.7	11.0	10.2	11.2	0.12
^{168}Er	12.2	10.5	10.0	10.8	0.10
^{168}Yb	13.6	11.5	10.6	11.6	0.14
^{236}U	8.9	8.3	9.1	8.7	0.05
^{238}U	8.6	8.1	8.9	8.5	0.05
^{238}Pu	9.3	8.5	9.2	8.9	0.06
^{240}Pu	9.0	8.4	9.1	8.8	0.06

The centroid energies $\bar{E}_{\lambda^-}$ for the (n,p) transitions with $\lambda^\pi = 0^-, 1^-, 2^-$ and the total value $\bar{E}$ as well as the ratio of the total (n,p) transition strength to the total (p,n) transition strength are depicted in table 2. The spin-dipole (n,p) strength is distributed in the region of 2-25 MeV, this can be seen in fig.1. The distribution has a well pronounces maximum at 12-13 MeV for A = 155, 165 and 9 MeV for A = 239. The total strength S(n,p) increases slightly with A. The values of S(n,p) for the rare-earth nuclei are 10% as small as for the actinides.

According to the calculation the position of the charge-exchange E1 and spin-dipole resonances overlap strongly. Therefore, the calculations have been performed with a simultaneous inclusion of the dipole and spin-dipole electric forces, the secular equation for which is (2). Figure 3 exemplifies the charge-exchange E1 resonance on ^{162}Dy calculated with and

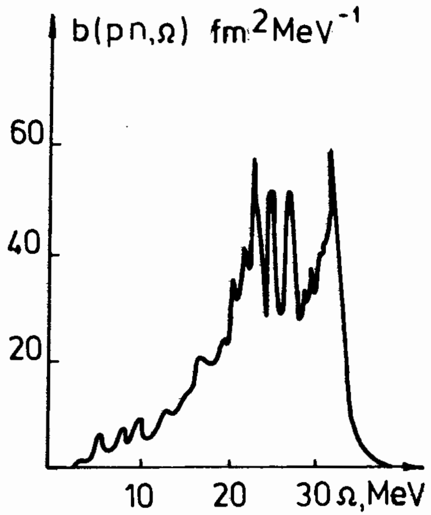

Fig.2. Strength function of (p, n) transitions with $\ell = 1$ to the spin-dipole states on ^{156}Gd. $\Delta = 0.5$ MeV.

Fig.3. Strength function of (p, n) E1 transitions on ^{162}Dy. The points denote the strength function calculated without the $r(\sigma Y_1)_{\lambda=1}$ forces. The dashed line denotes the change of the strength function with inclusion of the $r(\sigma Y_1)_{\lambda=1}$ forces. $\Delta = 0.5$ MeV.

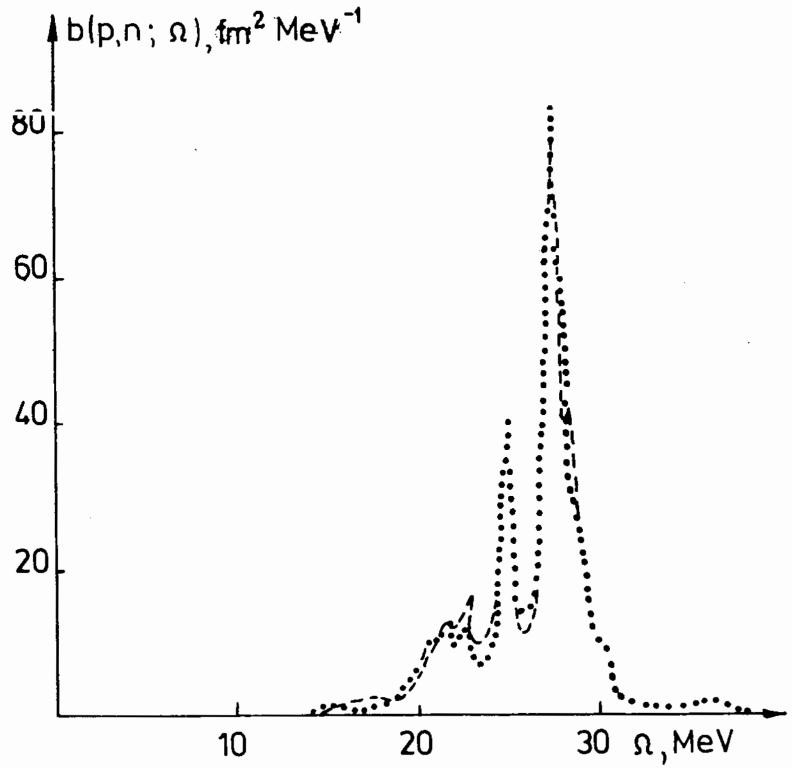

Table 3

Centroid energies of the E1 states excited in (p, n) reaction and the fraction of the total strength in three energy intervals

Nucleus	$E<E_1^*$		$E_1^*<E<31$ MeV						$E>31$ MeV
	$\bar{E}$	fraction of S(p,n) %	$\bar{E}_{1^-0}$	fraction of S(p,n) %	$\bar{E}_{1^-1}$	fraction of S(p,n) %	$\bar{E}$	fraction of S(p,n) %	fraction of S(p,n) %
^{156}Gd	20.2	21.5	25.2	15.3	28.3	58.1	27.6	73.4	5.0
^{158}Gd	20.1	19.0	25.6	17.6	28.6	57.9	27.9	75.5	5.6
^{160}Gd	20.0	16.9	26.0	19.7	29.2	56.6	28.3	76.3	6.8
^{162}Dy	20.3	21.4	25.4	17.8	27.8	55.2	27.2	73.1	5.5
^{164}Dy	20.2	16.8	26.0	21.9	28.5	54.6	27.8	76.5	6.7
^{166}Er	20.3	21.3	25.3	18.1	27.7	55.5	27.1	73.6	5.1
^{168}Er	20.1	17.0	25.9	21.7	28.3	55.0	27.7	76.7	6.2
^{238}U	20.1	17.7	27.4	24.6	28.2	50.8	28.0	75.4	6.8

* E_1 is equal to 24 MeV for $A = 155$ and 165 and 27 MeV for $A = 239$.

without spin-dipole forces. It is seen from fig.3 that the inclusion of spin-dipole forces almost does not change the resonance form. The values of individual peaks are weakly changed in the low-energy part. The inclusion of spin-dipole forces increases the centroid energy by 0.1 MeV. Thus, the inclusion of spin-dipole forces does not change the form and position of the E1 charge-exchange resonance. So small is the influence of the inclusion of dipole electric forces in calculating the strength functions for the transitions to the spin-dipole electric states.

The results of calculation of the (p, n) transition strength functions with excitation of the 1^- states without spin-flip are given in table 3 and fig.3. The centroid energies $\bar{E}_{1^-0}$, $\bar{E}_{1^-1}$ for transitions to the states with K = 0 and 1 and $\bar{E}$ for their sum, which have been obtained by integration over the low-energy and maximum regions, are shown in table 3. The fractions of the total (p, n) strength in three energy regions are also given in table 3. The (p, n) transition strength is distributed within 15-40 MeV and has two pronounced maxima at 25-27 MeV and 29 MeV. These maxima correspond to the transitions to the states with K = 0 and 1. As well as for the E1 giant resonances their position does not coincide, the splitting is about 2 MeV. About 75% of strength is concentrated in the region of maximum 24-31 MeV; and (17-22)% of strength, in the low-energy part. The centroid energy in the low-energy part is 20 MeV and does not change with A.

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Соловьев В.Г., Сушков А.В., Ширикова Н.Ю. E4-83-754

Зарядово-обменные дипольные и спин-дипольные резонансы в деформированных ядрах

В приближении хаотических фаз рассчитаны силовые функции (p,n)- и (n,p)-переходов с возбуждением спин-дипольного(с $\lambda^{\pi} = 0^-, 1^-, 2^-$)и E1 зарядово-обменных резонансов на деформированных ядрах в областях $156 \leq A \leq 168$ и $236 \leq A \leq 240$. Показано, что максимум спин-дипольного резонанса с $\lambda^{\pi} = 0^-, 1^-, 2^-$ распределен в области 14-33 МэВ. В области максимума этого резонанса сосредоточено 87-89% силы (p,n)-перехода. В низкоэнергетической части (2-14 МэВ)находятся только состояния с $\lambda = 2$. Максимум E1 зарядово-обменного резонанса соответствует энергии 25-29 МэВ,он расщеплен с ΔE,равным 0,6-2 МэВ, на два пика,с $I^{\pi}K = 1^-0$ и 1^-1. Сила этого резонанса сконцентрирована в более узкой энергетической области по сравнению с обычным E1 гигантским резонансом. В области 4-7 МэВ около максимума сосредоточено 73-77% силы. Полная сила (n,p) -переходов в 10-200 раз меньше полной силы (p,n)-переходов.

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Charge-Exchange Dipole and Spin-Dipole Resonances in Deformed Nuclei

The (p,n) and (n,p) transition strength functions with excitation spin-dipole(with $\lambda^{\pi} = 0^-, 1^-, 2^-$)and E1 charge-exchange resonances in deformed nuclei in the regions $156 \leq A \leq 168$ and $236 \leq A \leq 240$ are calculated in the RPA. It is shown that the spin-dipole resonance with $\lambda^{\pi} = 0^-, 1^-$ and 2^- strength is distributed within 14-33 MeV. The maximum region of this resonance contains (87-89)% of the (p,n) strength. The low-energy part 2-14 MeV has only the states with $\lambda = 2$. The E1 charge-exchange resonance is distributed within 25-29 MeV. It is splitted with ΔE equal to 0.6-2 MeV into two peaks with $I^{\pi}K = 1^-0$ and 1^-1. This resonance strength is concentrated in a narrower energy region in comparison with the ordinary E1 giant resonance. In the region of 4-7 MeV around maximum (73-77)% of E1 strength is concentrated. The total (n,p) transition strength is 10-200 times as small as the total (p,n) transition strength.

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

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