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THE INTERIOR OF CHARGE TRANSITION DENSITY AND THE STRUCTURE OF LOW-LYING STATES IN DEFORMED NUCLEI

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The charge transition density is a very sensitive probe of the nuclear wave functions since it feels not only the collectivity of the states but also the radial dependence of the wave functions. Modern experimental facilities can provide information on CTD in both the surface and interior regions (see, for example, [1]). However, such investigations face a good deal of troubles in deformed nuclei where the density of states is very large [1,2]. In this situation, any properties of CTD which can be used as a ground or as a starting point for a more reliable analysis of the data on CTD are very important.

The interior of CTD is considered in this paper from this point of view. While the surface peak in CTD has been studied hard and its collective character is now well established, the theoretical and experimental information on the interior of CTD is very scarce. The aim of this paper is to show that in the interior of CTD strong peaks of the single-particle nature may exist and that they may be essential constituent of CTD. For this purpose, the CTD $\rho_{22\nu}(r)$ and $\rho_{20\nu}(r)$, corresponding to the transitions $0^+0_{gr} \to 2^+2_\nu$, 2^+0_ν to four ($\nu \le 4$) lowest quadrupole levels in ^{164}Dy, have been calculated. We choose ^{164}Dy since just for this nucleus the measurements of CTD are performed now [2].

Let us outline the model used for the calculations. The Hamiltonian includes an average field as the Saxon - Woods potential with parameters from ref. [3], a monopole pairing interaction and residual isoscalar quadrupole forces with $\lambda\mu$ =22 and 20. The single-particle spectrum was taken from the bottom of the potential well up to +5 MeV (77 proton and 59 neutron levels). The band head states were calculated within the RPA. The constants of the quadrupole forces were chosen so as to reproduce the experimental energy of γ-vibrational state $E_{2_1^+}$ = 0.761 MeV and the estimated energy of β-vibrational state $E_{0_1^+}$ = 1.5 MeV [4].

For $E\lambda\mu$ transition $0^+0_{gr} \to I^\pi K_\nu$, where $K=\mu$, $\pi = (-1)^\lambda$, CTD has the form

$$\rho_{\lambda\mu\nu}(r) = \sum_{q \geq q'} \rho^{\lambda\mu\nu}_{qq'}(r), \qquad (1)$$

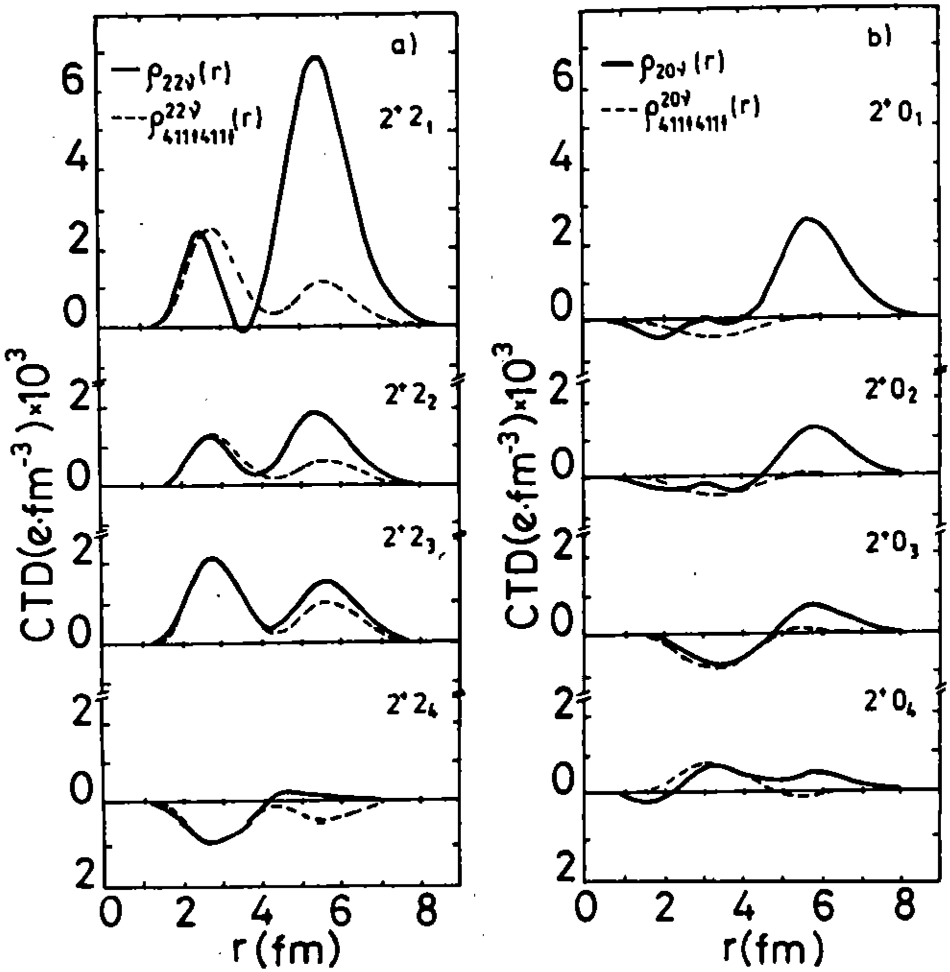

Fig.1. The calculated $\rho_{\lambda\mu\nu}(r)$ (full curves) and $\rho^{\lambda\mu\nu}_{qq'}(r)$ (broken curves) for E2 transitions $0^+0_{gr} \to 2^+2_\nu$ (a) and 2^+0_ν (b) in ^{164}Dy.

where

$$\rho^{\lambda\mu\nu}_{qq'}(r) = 1/\sqrt{2}\cdot(2-\delta_{qq'})\,\rho^{\lambda\mu}_{qq'}(r)\,(u_q v_{q'} + u_{q'} v_q)\,(\psi^{\lambda\mu\nu}_{qq'} + \phi^{\lambda\mu\nu}_{qq'}), \quad (2)$$

u_q and v_q are the Bogolubov coefficients, $\psi^{\lambda\mu\nu}_{qq'}$ and $\phi^{\lambda\mu\nu}_{qq'}$ are the direct and inverse amplitudes of a two-quasiparticle proton component qq' in the νth one-phonon state of multipolarity $\lambda\mu$, $\rho^{\lambda\mu}_{qq'}(r)$ is the single-particle CTD which can be folded to the single-particle matrix element of $E\lambda\mu$ transition:

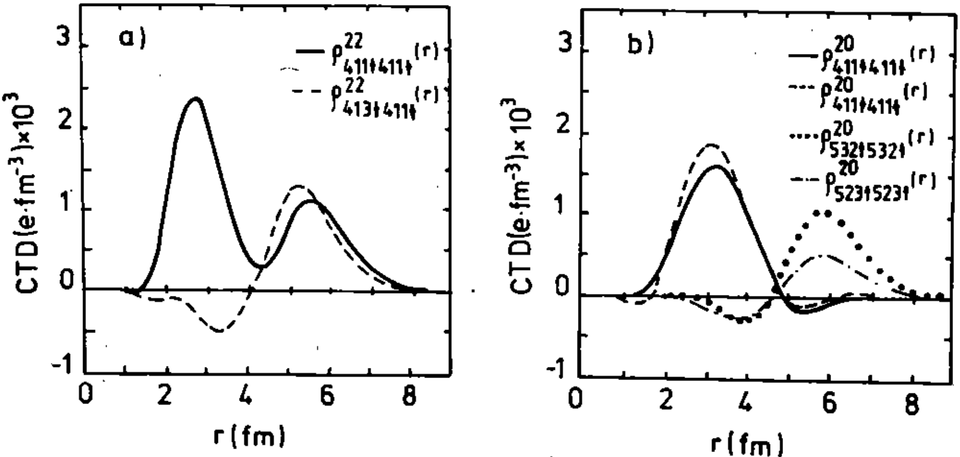

Fig.2. Some calculated single-particle $\rho^{\lambda\mu}_{qq'}(r)$ for $\lambda\mu$ = 22 (a) and 20 (b).

$$p^{\lambda\mu}_{qq'} = (2\lambda+1)^{-1/2}\int \rho^{\lambda\mu}_{qq'}(r)\, r^{\lambda+2}\, dr. \qquad (3)$$

The transition rate is written as

$$B(E\lambda\mu,\ 0^+0_{gr} \to I^\pi K_\nu) = (2\lambda+1)\left|\int \rho_{\lambda\mu\nu}(r)\, r^{\lambda+2}\, dr\right|^2 . \qquad (4)$$

The results of the calculations are given in tables 1,2 and figures 1,2. Let us firstly consider the 2^+2_ν states since they are the most clear case. Figure 1a shows that the CTD $\rho_{22\nu}(r)$ have the collective surface peak at r = 5.3 fm and rather strong peak in the interior at r = 2.6 fm. To understand the nature of the interior peak one should consider the main two-quasiparticle proton components of the 2^+2_ν states. It is seen from table 1 that these states contain large percentage of the two-quasiparticle configuration 411↑411↓. Further, the peak at r = 2.6 fm and the amplitude $\psi^{22\nu}_{411\uparrow\,411\downarrow} + \phi^{22\nu}_{411\uparrow\,411\downarrow}$ of this configuration change the sign simultaneously while one passes from the third to the fourth states. All these results can be easily explained if we assume that the peak in question has noncollective character and is mainly determined by the configuration 411↑411↓. Indeed, figures 1a and 2a show that positions of the interior peaks in $\rho_{22\nu}(r)$ and in single-particle $\rho^{22}_{411\uparrow\,411\downarrow}(r)$ coincide and that $\rho^{22\nu}_{411\uparrow\,411\downarrow}(r)$ representing the contribution of $\rho^{22}_{411\uparrow\,411\downarrow}(r)$ to the whole $\rho_{22\nu}(r)$ exhausts to a large extent the interior peak in $\rho_{22\nu}(r)$. Our numerical analysis has shown that the single-particle CTD corresponding to other two-quasiparticle proton components in the 2^+2_ν states have not strong interior peaks (see, for example, $\rho^{22}_{413\downarrow\,411\downarrow}$ in figure 2a) and their contribution to the peak at $r = 2.6$ fm is small.

The amplitudes $\psi^{\lambda\mu\nu}_{qq'}$ and $\phi^{\lambda\mu\nu}_{qq'}$ entering into expression (2) have energy denominators of the form

$$\psi^{\lambda\mu\nu}_{qq'} \sim \frac{1}{\epsilon_{qq'} - E_{\lambda\mu\nu}}, \quad \phi^{\lambda\mu\nu}_{qq'} \sim \frac{1}{\epsilon_{qq'} + E_{\lambda\mu\nu}}, \tag{5}$$

where $\epsilon_{qq'}$ and $E_{\lambda\mu\nu}$ are the excitation energies of the two-quasiparticle configuration qq′ and one-phonon state $\lambda\mu\nu$, respectively (note that usually we have $\psi^{\lambda\mu\nu}_{qq'} \gg \phi^{\lambda\mu\nu}_{qq'}$). The energy $\epsilon_{411\uparrow\,411\downarrow} = 2.22$ MeV is situated just between the energies of the 2^+2_3 and 2^+2_4 states. It explains the change of the sign of the peak at $r = 2.6$ fm, while one passes from 2^+2_3 to 2^+2_4 state, and confirms once more that this peak is determined by the single-particle CTD $\rho^{22}_{411\uparrow\,411\downarrow}(r)$.

The same analysis can be done for the interior peak at r = = 3.2 fm in CTD for 2^+0_3 and 2^+0_4 states (see figs.1b and 2b and table 1). It is easy to show that this peak is determined by the single-particle CTD $\rho_{411\uparrow 411\uparrow}(r)$ with $\epsilon_{411\uparrow 411\uparrow} = 2.11$ MeV.

It would be useful to make some predictions on the interior peak of the single-particle nature in CTD for the whole rare-earth region. For this aim, we have analyzed the single-particle $\rho^{22}_{qq'}(r)$ and $\rho^{20}_{qq'}(r)$ for the main proton two-quasiparticle components of low-lying 2^+2_ν and 2^+0_ν states in the nuclei over the whole rare-earth region. The data on the proton components have been taken from ref.[4], where the results of the calculation within the quasiparticle-phonon model for many rare-earth nuclei are presented. The analysis has shown that in $\rho_{22\nu}(r)$ strong interior peaks are possible more or less in all nuclei of the rare-earth region and all these peaks will be determined by $\rho^{22}_{411\uparrow\,411\downarrow}(r)$. For $\rho_{20\nu}(r)$ the situation is much more complicated. In this case, several single-particle $\rho^{20}_{qq'}(r)$ can lead to strong interior peaks. The corresponding predictions are listed in table 2. Note that all the single-particle CTD $\rho^{\lambda\mu}_{qq'}(r)$ noted before include the single-particle states q and q′ with the radial wave functions possessing the strong peak in nuclear interior.

One should make some comments on the obtained results. First of all, the existence of strong interior peaks of the single-particle nature in CTD gives the opportunity for very simple analysis of the interior of CTD from this point of view. One should consider only the characteristics of a rather small

Table 1

Excitation energies, B(E2) values and structure of low-lying 2^+2_ν and 2^+0_ν states in ^{164}Dy

$I^\pi K_\nu$	$E_{\lambda\mu\nu}$, MeV	$B(E2, 0{+}0_{gr} \to I^\pi K_\nu)$, $c^2fm^4 \cdot 10^3$	Main proton two-quasiparticle components		
			qq´	Percentage	$\psi^{\lambda\mu\nu}_{qq'} + \phi^{\lambda\mu\nu}_{qq'}$
2^+2_1	0.76	1.0	411↑411↓	22%	0.80
			413↓411↓	6%	0.50
			404↑402↑	1%	0.32
2^+2_2	1.79	0.08	411↑411↓	14%	0.41
			413↓411↓	1%	0.14
2^+2_3	2.13	0.06	411↑411↓	44%	0.68
			413↓411↓	0.3%	0.07
2^+2_4	2.44	$<10^{-3}$	411↑411↓	9%	-0.29
			413↓411↓	1%	0.10
2^+0_1	1.50	0.28	532↑532↑	5%	0.45
			411↑411↑	4%	-0.34
			523↑523↑	2%	0.22
2^+0_2	1.88	0.06	411↑411↑	5%	-0.35
			523↑523↑	4%	0.29
			532↑532↑	2%	0.24
2^+0_3	2.00	0.01	411↑411↑	19%	-0.64
			523↑523↑	19%	0.63
2^+0_4	2.16	0.02	523↑523↑	25%	-0.71
			411↑411↑	18%	0.62
			532↑532↑	4%	0.35

number of proton two-quasiparticle configurations qq´ for which q and q´ are close to the Fermi surface. The values of $\epsilon_{qq'}$ and $p^{\lambda\mu}_{qq'}$ give information at what excitation energy the configuration qq´ will exist and how much it will be fragmented between low-lying one-phonon states (in general, the larger the value of $p^{\lambda\mu}_{qq'}$ the bigger the fragmentation of the con-

Table 2

The regions of rare-earth nuclei for which the single-particle $\rho^{20}_{qq'}(r)$ can result in the strong peaks in the interior of $\rho_{20\nu}(r)$ for E2 transitions $0^+0_{gr} \to 2^+0_\nu$. (The values of r and $\rho^{20}_{qq'}(r)$ in second and third columns determine the position and magnitude of the interior peaks)

qq′	r, fm	$\rho^{20}_{qq'}(r)$, e fm$^{-3}10^3$	Regions of nuclei
420↑420↑	3.0	3.4	Nd, Sm
411↑411↑	3.2	1.6	Gd, Dy, Er
411↓411↓	3.0	1.9	Er, Yb, Hf, W
402↑402↑	2.6	-2.1	Hf, W

figuration qq′). The single-particle $\rho^{\lambda\mu}_{qq'}(r)$ show whether or not the configuration qq′ leads to a large interior peak in CTD. As a result, the predictions on the interior of CTD $\rho_{\lambda\mu\nu}(r)$ can be done. Further, such properties of the interior peaks as different positions of the peaks for the 2^+0_ν and 2^+2_ν states and the dependence of the height of the interior peak on the percentage of the corresponding two-quasiparticle configuration in the state may be useful for nuclear spectroscopy investigations.

Our calculations have shown that the concrete single-particle $\rho^{\lambda\mu}_{qq'}(r)$ considered above depend a little on the parameters of the single-particle potential. Therefore, we have used the parameters from ref. /3/ without any additional fit, although the careful adjusting of the parameters of the single-particle potential for each nucleus is desirable. It is possible, also, to improve reliability of the single-particle $\rho^{\lambda\mu}_{qq'}(r)$ by using the direct (e, e′) measurements of $\rho^{\lambda\mu}_{qq'}(r)$ in odd nuclei where q or q′ are the ground states and have approximately the pure one-quasiparticle character.

There are some troubles concerning the obtained results. Firstly, in this paper the simple version of the calculations (the RPA with monopole pairing and quadrupole forces) is used. In general, the Coriolis interaction, quadrupole pairing, coupling with multiphonon configurations and some other effects have to be also included and then the picture presented here may change. Some of these effects are planned to be taken into account in the following papers but the complete calculations seem to be very cumbersome to be performed now. Secondly, the experimental data on the interior of CTD have usually larger errors than ones for the surface region.

Nevertheless, these troubles seem not to be crucial. The modifications of the calculations listed above will result, most probably, only in some redistribution of the strength of the two-quasiparticle configuration $q\,q'$ between the states with excitation energies close to $\epsilon_{qq'}$. As a result, this will lead to analogous redistribution of strength of the interior peak but not to its disappearing. Also, there are no principal obstacles to increase the accuracy of experimental data, particularly, if the special attention is paid just to the interior of CTD.

In summary, the strong peaks of the single-particle nature are predicted in the interior of CTD for low-lying states in deformed nuclei. It is shown that these peaks can be predicted and analyzed in a very simple way. It gives an additional useful tool for investigating the structure of low-lying states in deformed nuclei, especially for the states with excitation energies in the region of 1.5 - 3 MeV. These states are known to be slightly collective and to have large two-quasiparticle components. So, the study of the interior of CTD is most important just for them. It should be noted that the interior of CTD seems to be a more informative and promising region than the surface one and is needed for very careful experimental and theoretical investigation.

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