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CHARGE FORM FACTORS AND ALPHA-CLUSTER INTERNAL STRUCTURE OF ^{12}C

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The transition densities and form factors of 0^+, 2^+, and 3^- states in ^{12}C are calculated in alpha-cluster model using the triangle frame with clusters in the vertices. The wave functions of nucleons in the alpha clusters are taken as they were obtained in the framework of the models used for the description of the ^{4}He form factor and momentum distribution which are based on the one-body density matrix construction. They contain effects of the short-range NN correlations, as well as the d-shell admixtures in ^{4}He. Calculations and the comparison with the experimental data show that visible effects on the form and magnitude of the ^{12}C form factors take place, especially at relatively large momentum transfers.

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

Зарядовые формфакторы и внутренняя структура альфа-кластеров ядра ^{12}C

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Рассчитаны переходные плотности и формфакторы 0^+-, 2^+- и 3^--состояний ядра ^{12}C с использованием альфа-кластерной модели на базе треугольного каркаса с кластерами в его вершинах. Волновые функции нуклонов в альфа-кластерах взяты из расчетов в рамках моделей ядра ^{4}He, которые основаны на различных конструкциях одночастичной матрицы плотности с параметрами, полученными подгонкой формфакторов и импульсных распределений нуклонов ^{4}He. В этих моделях включались как короткодействующие NN-корреляции, так и примеси $1d$-оболочки в ^{4}He. Расчеты и их сравнения с экспериментом показывают, что наблюдается заметное влияние изменения структуры альфа-кластеров на форму и величину формфакторов ядра ^{12}C, особенно в области больших передач импульса.

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1. INTRODUCTION

Many investigations in the last decade are devoted to the residual NN correlations in nuclei, especially in processes with large momentum transfers. In this connection, a great attention is paid to studying mesonic and quark degrees of freedom in nuclei at short distances. Therefore, it is important to develop the well-grounded models for construction of realistic many-body wave functions and thus to exclude, e.g., a possible substitution of the NN-correlation effects by an approachable parameterization of the mean-field potential.

This work aims to test the models for calculating the one-body density matrix developed in [1–7] which have been applied to describe the form factor and the momentum distribution in ^{4}He. In these considerations the role of the short-range NN correlations is analysed, as well as the influence of the d-shell admixtures to the ^{4}He wave function. The introduction of both ingredients needs some parameters which cannot be established unambiguously if one uses the ^{4}He data themselves. From this point of view one can hope to preclude the ambiguity by considering ^{4}He to be inside ^{12}C, the latter being linked of alpha clusters. On the other hand, it is interesting to study the role of the other surrounding nucleons which makes it possible to renormalize the residual NN interactions with the increasing of the atomic number of the system. To this aim one should deal with an appropriate cluster model which presents itself in a good light, i.e., includes antisymmetrization over all nucleons and creates the low-lying collective states, inherent in a semihard internal construction of ^{12}C with clusters in the fixed positions. We have selected the alpha-cluster model implemented in [8] and then developed for calculations of form factors in [9–11]. As a first step, only one possible configuration, namely three alpha clusters in the vertices of an equilateral triangle in ^{12}C, has been considered. One should remember also that the linear frame for a disposition of alpha clusters can bring some additional effects on the form factors (see, e.g., [12]).

2. WAVE FUNCTIONS OF NUCLEONS IN ^{4}He

In this section we give a brief review of a one-body matrix approach used for consideration of basic properties of nuclei and, in particular, to construct the respective one-body functions which can be considered as realistic one-nucleon wave functions in a given nucleus. In this direction, a sufficient success was achieved in explanation of form factors and one-nucleon momentum distributions of the double closed-shell nuclei as well as their binding energies and rms radii (see, e.g., [6,7]).

The procedure consists in the following steps. First, one should calculate the one-body density matrix (OBDM) associated with the ground state A-nucleon wave function $\Psi^{(A)}$

$$\rho(\mathbf{r},\mathbf{r}') = \langle\Psi^{(A)}|a^{\dagger}(\mathbf{r})a(\mathbf{r}')|\Psi^{(A)}\rangle. \tag{2.1}$$

Subsequently, one needs to introduce the so-called natural orbitals $\psi_\alpha(\mathbf{r})$ [13] and overlap functions $\phi_\alpha(\mathbf{r})$ [14] both related to the single-particle wave function of the nucleon $u_\alpha(\mathbf{r})$ in the A-nucleus. Natural orbitals are defined as a complete orthonormal set of functions which diagonalize the OBDM (2.1) with occupation numbers N_α

$$\rho(\mathbf{r},\mathbf{r}') = \sum_\alpha N_\alpha \psi^*_\alpha(\mathbf{r})\psi_\alpha(\mathbf{r}'), \tag{2.2}$$

where $\psi_\alpha(\mathbf{r}) = \psi_{nl}(r)Y_{ljm}(\Omega,\sigma)$ for spherical nuclei. Also, inserting between a operators in (2.1) the complete set of the residual (A-1)-nucleus wave functions $\Psi_\alpha^{(A-1)}$ one gets

$$\rho(\mathbf{r},\mathbf{r}') = \sum_\alpha \phi_\alpha^*(\mathbf{r})\phi_\alpha(\mathbf{r}') \quad \text{with} \quad \phi_\alpha(\mathbf{r}) = \phi_{nl}(r)Y_{ljm}(\Omega,\sigma)\ , \tag{2.3}$$

where by definition

$$\phi_\alpha(\mathbf{r}) = \langle \Psi_\alpha^{(A-1)} \mid a(\mathbf{r}) \mid \Psi^{(A)} \rangle \tag{2.4}$$

is the overlap function corresponding to the state α of the residual nucleus. In the following we will use in our work the results for ^{4}He which have been obtained in the frameworks of two different methods developed for calculations of natural orbitals [4] and [5], respectively, and the method to calculate the overlap functions [1–3]. Here we give briefly the three approaches for obtaining the nucleon s.p. wave function in ^{4}He.

First approach. In the method suggested in [15], the radial part of the natural orbitals is expanded in terms of three single-particle wave functions

$$\psi_{nl}(r) = \sum_{n_1=1,2,3} C_{n_1}^{nl}\varphi_{n_1 l}(r). \tag{2.5}$$

Here the coefficients $C_{n_1}^{nl}$ satisfy the orthonormalization conditions, and the s.p. wave functions $\varphi_{nl}(r)$ are taken in the form corresponding to the square-well (SW) and the harmonic-oscillator (HO) potentials. In Ref.4, in the framework of this method calculations of the ^{4}He one-body density matrix, the density distribution, as well as of the momentum distribution have been performed. The parameters of the potentials, the occupation numbers N_{nl} and the coefficients $C_{n_1}^{nl}$ were fitted so that to give the best fit to the form factors and the momentum distribution behaviour. As a result, the phenomenological one-nucleon natural orbitals in ^{4}He have been obtained, and in our work they are utilized as single-nucleon wave functions in the construction of the alpha-cluster wave functions of ^{12}C.

Second approach. Another method to obtain the nucleon wave function in ^{4}He using the natural orbital representation was developed in [5]. It consists in determining of proper natural orbitals and occupation numbers which give a realistic description of both density and momentum distributions in ^{4}He:

$$\rho(r) = \frac{1}{4\pi}(2\lambda_{1s}|R_{1s}(r)|^2 + 10\lambda_{1d}|R_{1d}(r)|^2), \tag{2.6}$$

$$n(k) = \frac{1}{4\pi}(2\lambda_{1s}|R_{1s}(k)|^2 + 10\lambda_{1d}|R_{1d}(k)|^2), \tag{2.7}$$

with $2\lambda_{1s} + 10\lambda_{1d} = 2$, where λ_{1s} and λ_{1d} are the occupation numbers and R_{1s} and R_{1d} are the natural orbitals accounting for the short-range NN correlations. These orbitals have been chosen to be s.p. wave functions corresponding to the multiharmonic Hamiltonian of the Isomorphic Shell Model [16, 17]. By fitting the values of both oscillator parameters (for $1s$ and $1d$ state) and one of the occupation numbers, a good description of the density and momentum distributions as well as of the charge rms radius and the mean-kinetic energy has been achieved in [5]. It was obtained that the hole-state natural orbital $R_{1s}(r)$ is the expected one from the mean-field approximation, while the particle-state natural orbital $R_{1d}(r)$ can be interpreted as describing the internal (collective) rotation of nucleons in ^{4}He, which is also

supported in [18]. It has been pointed out that the function $R_{1d}(r)$ is responsible for the high-momentum components of $n(k)$, for the large value of the mean-kinetic energy, for the small increase of the radius and for the bump of the point proton density distribution [5, 19].

In our calculations of the form factors we use the following radial nucleon wave function in ^{4}He related to the density distribution (2.6) and normalized to unity:

$$R(r) = \sqrt{2\pi\rho(r)}. \tag{2.8}$$

Third approach. The method which has been applied to calculate the overlap functions starts from the definition of the OBDM:

$$\rho(\mathbf{r}, \mathbf{r}') = C_A \int \Psi^{(A)*}(\mathbf{r}, \mathbf{r_2}, ...\mathbf{r_A})\Psi^{(A)}(\mathbf{r}', \mathbf{r_2}, ...\mathbf{r_A})d\mathbf{r_2}...d\mathbf{r_A}, \tag{2.9}$$

where C_A is the normalization constant and in the mean-field approximation $\Psi^{(A)}$ is a Slater determinant built from the s.p. wave functions. It is shown in [1, 2] that the standard Hartree-Fock approximation with the Skyrme forces, usually used for the Ψ calculations, cannot reproduce the one-nucleon high-momentum distributions. Instead, these components can be obtained in the framework of the density matrix method if one includes in $\Psi^{(A)}$ the short-range Jastrow correlation factor $f(r) = 1 - \exp(-\beta^2 r^2)$. For the double closed-shells nuclei calculations of (2.9) have been performed in [2] analytically making use of the code REDUCE and the HO s.p. wave functions. In the next step, one can use the density matrix (2.3) in order to obtain the overlap functions. Following [14], the respective restoration method was developed in [3]. To this aim one uses the known asymptotic behaviour of the bound-state functions, in particular, for

$$\phi_{nlj}(r) \;\rightarrow\; B_{nlj}\ \exp(-k_{nlj}\ r)/r\ , \tag{2.10}$$

where

$$k_{nlj} = \hbar^{-1}\sqrt{2m(E_{nlj}^{(A-1)} \;-\; E_0^{(A)})} \tag{2.11}$$

depends on the separation energy $E_\alpha = E_{nlj}^{(A-1)} - E_0^{(A)}$.

The asymptotic form of the overlap functions (2.10) determines the asymptotic behaviour of the respective radial part of the OBDM $\rho_{lj}(r, r')$ in (2.3). It is shown in [14] that at large values of $r' \equiv a \rightarrow \infty$ one can derive the lowest bound state overlap function by means of the radial part of the OBDM:

$$\phi_{n_0lj}(r) = \frac{\rho_{lj}(r, a)}{B_{n_0lj}\ \exp(-k_{n_0lj}a)/a} \tag{2.12}$$

as well as the separation energy

$$\epsilon_{n_0lj} = \hbar^2\ k_{n_0lj}^2/2m \tag{2.13}$$

and the spectroscopic factor as the norm of the overlap function $S_{n_0lj} = \langle\phi_{n_0lj}|\phi_{n_0lj}\rangle$. The coefficient B_{n_0lj} can be obtained from the asymptotic form of the diagonal part of the radial OBDM:

$$\rho_{lj}(a, a) \;\rightarrow\; |\ B_{n_0lj}\ |^2\ \ \exp(-2k_{n_0lj}a)/a^2\ . \tag{2.14}$$

As shown in [14], the overlap functions for all bound states of the $(A-1)$ nucleus can be in principle constructed from the OBDM repeating the above procedure.

The natural orbitals $\psi_{1s}(r)$ from Eq.(2.5) obtained in [4] using HO and SW single-particle wave functions $\varphi_{ns}(r)$, the function $R(r)$ (2.8) based on the results from [5] and the overlap function $\phi_{1s_{1/2}}$ (2.12) obtained by calculations following [3] are used to calculate the form factors and the transition densities of 0^+, 2^+, and 3^- states in the ^{12}C nucleus.

3. BASIC RELATIONSHIPS IN THE ALPHA-CLUSTER MODEL

For the calculations of quantities in ^{12}C we have used the model [8] developed for alpha-cluster nuclei and then adjusted in [9–11] for the form factor consideration. In the model the projection procedure is used to generate rotational states $|JMK\pi\rangle$ from the many-body wave function $U_\pi(\mathbf{R})$ where vectors $\mathbf{R} = \{\mathbf{R}_i\}$ stand for the positions of the alpha clusters in the nucleus:

$$\frac{8\pi^2 N^{1/2}_{JK\pi}}{2J+1}|JMK\pi\rangle = \int d\Theta D^{J\,*}_{MK}(\Theta)\hat{R}(\Theta)U_\pi(\mathbf{R}) = \int d\Theta D^{J\,*}_{MK}(\Theta)U_\pi(\mathbf{S}). \tag{3.1}$$

Here $N^{1/2}_{JK\pi}$ is the normalization constant, and

$$U_{\pi=\pm1}(\mathbf{R}) = U(\mathbf{R}) \pm U(-\mathbf{R}) \tag{3.2}$$

depends on the parity and is expressed through the antisymmetrized function

$$U(\mathbf{R}) = \sum_p \epsilon_p \prod_{a=1}^{A} u_a(pa), \tag{3.3}$$

where $\epsilon_p = +1$ or -1 corresponds to even or odd permutations of nucleons, respectively, and the wave functions of nucleons u_p are related to the centers i of the alpha clusters in the nucleus:

$$u_a(pa) = u_a(\mathbf{r} - \mathbf{R}_i) = \chi_\sigma\chi_\tau u(|\mathbf{r} - \mathbf{R}_i|)\ . \tag{3.4}$$

The total nuclear wave function is composed of $|LMK\pi\rangle$ as follows

$$|JM\pi\rangle = \sum_K C^J_K |JMK\pi\rangle, \tag{3.5}$$

where the superposition coefficients C^J_K are obtained using the D_{3h}-symmetry properties of the equilateral triangle with alpha clusters in vertices which is selected as a frame for ^{12}C:

$$K = 0, \pm3, \pm6, ...; \qquad P_\pi = (-1)^K; \qquad C^J_K = (-1)^J C^J_{-K}. \tag{3.6}$$

The transition matrix element between nuclear states for the charge density operator reads

$$\langle LM|\hat{\rho}|00\rangle = \langle L0|\mathcal{P}_{L0}|00\rangle Y^*_{LM}(\hat{r}) = \rho_L(r)Y^*_{LM}(\hat{r}), \tag{3.7}$$

where

$$\mathcal{P}_{L0} = \sum_{k=1}^{A} \mathcal{P}_{LM}^{(k)} = \sum_{k=1}^{A} \frac{e_k}{Z} \delta(r - r_k) \frac{1}{r^2} Y_{LM}^*(\hat{r}_k), \tag{3.8}$$

so that for elastic scattering we have $\rho_0(r) = (4\pi)^{1/2}\rho(r)$ with $\rho(r)$ being the spherically symmetrical nuclear charge density distribution normalized to unity.

Substituting (3.5) with (3.1) into (3.7) one can obtain the expression for the radial transition densities [9]- [11],

$$\rho_L = \frac{1}{4\pi^2 N_{00\pi_0}^{1/2}} \sum_K C_K^L \; N_{LK\pi}^{-1/2} \int d\Theta \left[\langle U(\mathbf{R}) | \mathcal{P}_{LK} | U(\mathbf{S}) \rangle + P_{\pi_0} \langle U(\mathbf{R}) | \mathcal{P}_{LK} | U(-\mathbf{S}) \rangle \right], \tag{3.9}$$

where

$$\langle U(\mathbf{R}) | \mathcal{P}_{LK} | U(\epsilon \mathbf{S}) \rangle = 2[\det \; B_{ij}(\epsilon)]^3 \sum_{n=1}^{A} \det \; B_{ij}^{(n)LK}(\epsilon), \tag{3.10}$$

$$B_{ij}^{(n)LK}(\epsilon) = \langle u(\mathbf{r} - \mathbf{R_i}) | \mathcal{P}_{LK}^{(i)} | u(\mathbf{r} - \epsilon \mathbf{S_j}) \rangle + B_{ij}(\epsilon)(1 - \delta_{ni}), \tag{3.11}$$

$$B_{ij}(\epsilon) = \langle u(\mathbf{r} - \mathbf{R_i}) | u(\mathbf{r} - \epsilon \mathbf{S_j}) \rangle. \tag{3.12}$$

Thus, the problem is reduced to calculations of the matrix elements with the wave functions of nucleons u_a belonging to the alpha clusters. They can be performed in impulse representation resulting in the certain forms for $B_{ij}(\epsilon)$ and $B_{ij}^{(i)LK}(\epsilon)$ which depend on .

$$F(k) = (2\pi)^{-3/2} \frac{4\pi}{k} \int r dr \; \sin(kr) u(r), \tag{3.13}$$

$\cos\varphi_{ij} = (\mathbf{R_i S_j})/R_i R_j$ and the Euler angles. Then the integration in the three-dimensional integral (3.9) can be performed numerically.

The form factors of the ^{12}C nucleus are calculated taking into account the distortion of the electron waves in the Coulomb field of the nucleus within the High Energy Approximation (HEA) method [20,21]. This leads to "filling in" the zeroes of the minima inherent in the form factors calculated in the Born approximation and also "deforms" slightly the Born form factors when the electron-nucleus interaction in the entrance and exit channels has been accounted for. It turns out that for the relatively light nucleus ^{12}C these effects are not so important.

The form factors in the HEA have the form [21]:

$$F_L^2(q) = G(q) \left| \int d\mathbf{r} \frac{q^2}{\tilde{q}^2} g(\mathbf{r}) \exp\left(i\mathbf{qr} + i\phi(\mathbf{r})\right) \rho_L(r) Y_{L0}^*(\hat{r}) \right|^2. \tag{3.14}$$

The functions $\tilde{q}$, $g(\mathbf{r})$ and $\phi(\mathbf{r})$ take into account the distortion of the plane waves [20]. In the plane wave Born approximation $\tilde{q} = q$, $\phi = 0$ and $g = 1$. $G(q)$ allows for the proton size and the center-of-mass motion:

$$G(q) = \exp\left[-\frac{q^2}{3} \left(\bar{R}^2(p) - \frac{\bar{R}^2(\alpha)}{A} \right) \right], \tag{3.15}$$

where $\bar{R}(p)$ and $\bar{R}(\alpha)$ are the rms charge radii of the proton and the alpha-particle in the target nucleus A.

4. RESULTS AND DISCUSSION

The transition densities and the form factors for the 0^+, 2^+, and 3^- states in the ^{12}C nucleus have been calculated using the theoretical scheme presented in Section 3 and nucleon wave functions described in Section 2. The results for the transition densities are given in Fig.1 and for the form factors in Fig.2 for the case when the overlap function (OV) obtained following [3] and natural orbitals [4] (with HO and SW s.p. wave functions in Eq.(2.5)) have been used. The form factors are plotted versus the effective momentum transfer

$$q_{eff} = q\left(1 + \frac{4}{3}\frac{Z}{137}\frac{1}{\bar{R}(A)E}\right) \tag{4.1}$$

which makes it possible to take into account the dependence on the energy (E) of the incident electrons, $\bar{R}(A)$ being the nucleus rms radius. The experimental data are taken from [22].The best value of the parameter R giving the distance between the center of the equilateral triangle and the alpha cluster for each case is given as well. In Fig.3 the form factors are presented for the case when the nucleon wave function $R(r)$ (2.8) with three sets of parameters has been used in the calculations and for the best choice of the parameter R for each form factor. The transition densities for this case will be given elsewhere.

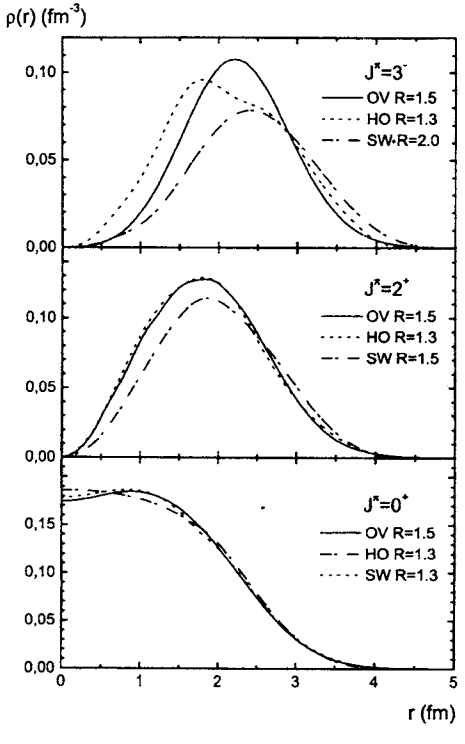

Fig. 1. The radial transition densities calculated using the overlap function (OV) obtained following [3] and natural orbitals [4] obtained by means of harmonic-oscillator (HO) and square-well (SW) s.p.wave functions in Eq.(2.5)

One can see from Figs.2 and 3 a satisfactory overall agreement of the theoretical form factors obtained using different nucleon wave functions with the experimental data for the three states in ^{12}C. It can be seen that for $q_{eff} < 2.5$ fm^{-1} the behaviours of the form factors calculated by means of the OV and HO-natural orbital are quite similar. At the same time, the result with the SW-natural orbital is in better agreement with the empirical data, in particular for the 2^+ and 3^- states and $q_{eff} \leq 3$ fm^{-1}. Concerning the regions of larger transfer momenta at $q_{eff} > 3$ fm^{-1}, all the three curves deviate from the experiment. We note that for the best fit of the SW results it is necessary to choose different values for the distance R of the triangle configuration of ^{12}C for the different states. The value of R increases 1.5 times from $R = 1.3$ fm for the ground state 0^+ to $R = 2$ fm for the 3^- rotational state, i.e., the size of the nucleus increases with the increase of the excitation energy.

Much better agreement with the data is achieved using the multiharmonic oscillator (MHO) nucleon wave function $R(r)$ from

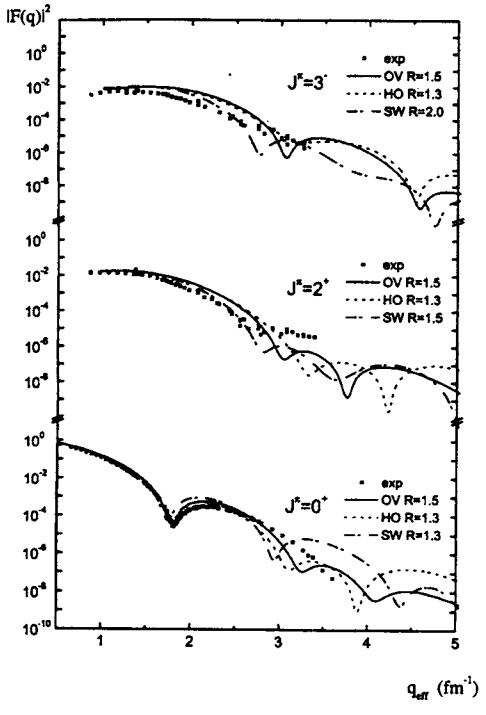

Fig. 2. Form factors of ^{12}C calculated using the functions from Fig.1 The experimental data are given by black squares. The best value of the parameter R for each case is given as well

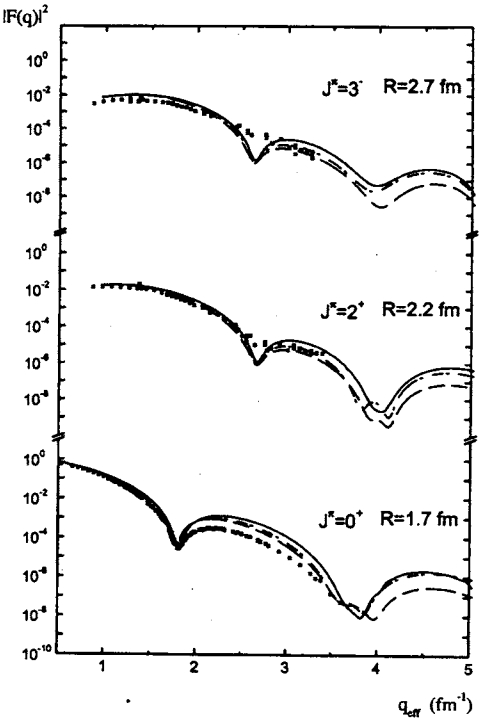

Fig. 3. Form factors of ^{12}C calculated using the nucleon wave function $R(r)$ from (2.8) using three sets of parameters. Solid line: $\lambda_{1s} = 0.55$, $\lambda_{1d} = 0.09$, $\hbar\omega_{1s} = 21.2$ MeV and $\hbar\omega_{1d} = 160$ MeV; dot-dashed line: $\lambda_{1s} = = 0.70$, $\lambda_{1d} = 0.06$, $\hbar\omega_{1s} = 22.50$ MeV and $\hbar\omega_{1d} = 150$ MeV; dashed line: $\lambda_{1s} = 0.86$, $\lambda_{1d} = 0.028$, $\hbar\omega_{1s} = 25$ MeV and $\hbar\omega_{1d} = = 150$ MeV

Eq.(2.8). It concerns in particular the results for the 2^+ and 3^- states (with the exception of the first minimum region) and for the 0^+ state up to $q_{eff} \approx 2$ fm^{-1}. It can be seen from Fig.3 that the curves for the form factors have more smooth behaviour in comparison with that in Fig.2. This is obviously due to the inclusion of the $1d$ component of the nucleon wave function in the alpha-cluster wave function. One can see again as in Fig.2 that the best fit with the data can be achieved increasing the value of the parameter R 1.5 times when the excitation energy increases from 0^+ state to the 3^- state.

Concluding, we would like to note that the results of this work are obtained by using s.p. nucleon wave functions which are identified either with natural orbitals or with overlap functions based on realistic density matrices and can serve for a comparative analysis of these functions. The OBDM used give correct simultaneous descriptions of both momentum and density distributions of the ^{4}He nucleus which constructs the ^{12}C configuration. In this

sense the results for ^{12}C are grounded on reasonable OBDM in which the short-range NN correlations are incorporated. We emphasize that the only free parameter in our theoretical scheme is the distance R. The still remaining differences between the theoretical results and the experimental data can serve as a justification of the necessity to include into consideration an admixture of the linear cluster configuration in ^{12}C. We should note also the necessity to account for a possible change of the structure of the alpha-cluster wave functions inside the ^{12}C nucleus. In our work these wave functions have been used as they are for the ^{4}He nucleus. These additional studies are now in progress.

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