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N.K.Kuzmenko[1], V.M.Mikhailov[2],
V.O.Nesterenko

PAIRING IN MANY-QUASIPARTICLE STATES

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[1] Radium Institute, Leningrad
[2] Leningrad State University

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1. Introduction

The methods developed in the theory of superconductivity and superfluidity as applied to the description of nuclear properties allowed one to elucidate a wide range of phenomena (see, e.g., ref.[1]). However, a relatively small number of nucleons in the nuclear system necessitated the study of the effects of exact conservation of particle number that is conserved in the theory of superconductivity and superfluidity only on an average.

Already in early sixties it has been pointed out[2] that the overlapping of the particle-number-projected BCS-function with an exact wave function is more than 99% whereas in the typical cases the component of the BCS function with exact particle number is about 40%.

In subsequent years many papers have emerged in which various methods of more exact conservation of particle number than in the BCS-method were developed (see for example refs.[1,3,10] and refs. therein). However, the particle-number projection before variation (FBCS) turned out to be the most accurate method. In it varying of u_s and v_s parameters is made after particle-number projecting out of the BCS-state. In the present paper this method is used to analyse pairing in quasiparticle states.

It is known that the BCS-method covers mainly the case of considerable pairing ($G \gg G_{crit}$) which is not always the case in real nuclei. The drawbacks of the BCS method caused by nonconservation of particle number become essential at G close to G_{crit}. Such situations occur when a single-particle spectrum becomes rather rarefied near the Fermi level or in the rotational bands at high frequency of rotation due to the Coriolis antipairing effect. A considerable attenuation of pairing correlations occurs also in the states containing one or several unpaired particles (the blocking effect)[1]. In all those cases the nuclear system approaches the point of phase transition from a superfluid to a normal state near which one cannot use the BCS formalism. In this case the BCS method leads to values of pair correlation energies or gap parameter Δ that turn out to be considerably less than the same quantities calculated within the FBCS method. For instance, it has been shown in ref.[4] that for ^{168}Hf at the rotation moment larger than $20\hbar$, the calculations without particle-number projecting give $\Delta = 0$, whereas the value of the effective gap parameter Δ_{eff} within the FBCS method is only twice as less as its value for the ground state. Another example concerns the two-quasiparticle states. It follows from ref.[5] that the blocking of two levels near the Fermi level often leads to $\Delta = 0$ in the framework of the BCS method. The FBCS method provides in these cases a nonzero value of the effective gap parameter and the correlation energy of two-quasiparticle states is twice as less as in the ground state.

In the present paper we study attenuation of the pairing with increasing number of unpaired quasiparticles located close to the Fermi surface in deformed nuclei of the rare-earth region. For this purpose we calculate the energies of states containing one and more (up to four) quasiparticles of the same type (neutron or proton) by using the model Hamiltonian allowing for the average field and monopole pairing forces. We do not take into account the residual interactions leading to splitting of quasiparticle states and their fragmentation over more complex states. To prevent maximally the influence of residual interactions, we have chosen two- and more quasiparticle states with large values of K (the angular-momentum projection onto the nucleus-symmetry axis).

2. The Method of Calculation

The FBCS formalism used in this paper is based on the method developed in ref.[3]. We shall describe the basic features of this method and its modification for describing the states with several unpaired particles.

In the FBCS method the BCS function

$$|BCS\rangle = \prod_s (u_s + v_s a_s^+ a_{\bar{s}}^+)|0\rangle \qquad (1)$$

projected onto the state with a definite number of particles N_c is used as the ground state wave function. Before projecting, it is convenient to represent the function (1) through the creation operators of particles and holes α_s^+ acting on the Hartree-Fock vacuum

$|HF\rangle$ that corresponds, for axially symmetric nuclei, to the complete occupation $n=N_0/2$ of twice degenerate levels (the Fermi level is denoted by F):

$$|BCS\rangle = \Big(\sum_{s\le F} v_s\Big)\Big(\sum_{s>F} u_s\Big)\exp\Big\{\sum_{s\le F}\frac{u_s}{v_s}\alpha_s^+\alpha_{\bar s}^+ + \sum_{s>F}\frac{v_s}{u_s}\alpha_s^+\alpha_{\bar s}^+\Big\}|HF\rangle, \quad \alpha_s|HF\rangle=0. \qquad (2)$$

In this representation the particle-number operator is expressed through the difference of particle and hole number operators :

$$\hat N = N_0 + \sum_{s>F}\alpha_s^+\alpha_s - \sum_{s\le F}\alpha_s^+\alpha_s \qquad (3)$$

which allows one to derive easily from (2) the function $|n\rangle$ projected onto N_0 :

$$|n\rangle = \frac{1}{2\pi}\int_0^{2\pi}\exp(i\varphi(\hat N - N_0))\,d\varphi\,|BCS\rangle = \Big(\prod_{s\le F} v_s\Big)\Big(\prod_{s>F} u_s\Big)\times$$
$$\times\sum_{K=0}^{n}\Big(\frac{1}{K!}\Big)^2\Big(\sum_{s\le F}\frac{u_s}{v_s}\alpha_s^+\alpha_{\bar s}^+\Big)^K\Big(\sum_{s>F}\frac{v_s}{u_s}\alpha_s^+\alpha_{\bar s}^+\Big)^K|HF\rangle. \qquad (4)$$

Since the amplitudes with which the pairs of hole operators (u_s/v_s, $s\le F$) and the pairs of particle operators (v_s/u_s , $s>F$) enter into (4) decrease rapidly as passing from the Fermi level; the series in (4) rapidly converge.

The projected function $|n\rangle$ may have other expressions as well, that differ from (4). However, from the computational point of view, it is more convenient to use the function $|n\rangle$ in the form of (4), since in this case the normalization of $|n\rangle$ and matrix elements of different operators are easily expressed through rapidly converging sums of $(u_s/v_s)^2$, where $s\le F$, and $(v_s/u_s)^2$, where $s>F$. Consider, for example, the normalization condition:

$$\langle n|n\rangle = \Big(\prod_{s\le F} v_s^2\Big)\Big(\prod_{s>F} u_s^2\Big)\sum_{K=0}^{n} S_K T_K, \qquad (5)$$

$$S_K = \sum_{s_1<s_2<\dots<s_K,\ s_i\le F}\Big(\frac{u_{s_1}}{v_{s_1}}\Big)^2\Big(\frac{u_{s_2}}{v_{s_2}}\Big)^2\dots\Big(\frac{u_{s_K}}{v_{s_K}}\Big)^2, \quad \frac{u_s}{v_s}<1, \quad S_0=1, \qquad (5a)$$

$$T_K = \sum_{s_1<s_2<\dots<s_K,\ s_i>F}\Big(\frac{v_{s_1}}{u_{s_1}}\Big)^2\Big(\frac{v_{s_2}}{u_{s_2}}\Big)^2\dots\Big(\frac{v_{s_K}}{u_{s_K}}\Big)^2, \quad \frac{v_s}{u_s}<1, \quad T_0=1. \qquad (5b)$$

Sums S_K and T_K can readily be calculated by using the recurrence relations which for S_K are (for T_K they are analogous)

$$S_{K+1} = \frac{1}{K+1}\sum_s\Big(\frac{u_s}{v_s}\Big)^2 S_K(s), \quad S_K(s) = S_K - \Big(\frac{u_s}{v_s}\Big)^2 S_{K-1}(s), \quad S_0(s)=1, \qquad (6)$$

where $S_K(s)$ are deduced by removing in sum (5a) the levels s.

The model Hamiltonian used in this paper contains the average field and the pairing interaction

$$H = \sum_s e_s(a_s^+a_s + a_{\bar s}^+a_{\bar s}) - G\sum_{st} a_s^+a_{\bar s}^+a_{\bar t}a_t \qquad (7)$$

(e_s is the energy of the single-particle level s ; $K_s, K_t>0$).
Expression for the system energy in the ground state is

$$E_0 = \frac{\langle n|H|n\rangle}{\langle n|n\rangle} =$$
$$= 2\sum_s\Big(e_s - \frac{G}{2}\Big)v_s^2[n-1]_s - G\sum_{s\ne t}u_sv_su_tv_t[n-1]_{st}. \qquad (8)$$

The one- and two-particle density matrices have the form

$$\langle n|a_s^+a_s|n\rangle\cdot\frac{1}{\langle n|n\rangle} = v_s^2[n-1]_s, \qquad (9)$$
$$\langle n|a_s^+a_{\bar s}^+a_{\bar t}a_t|n\rangle\cdot\frac{1-\delta_{st}}{\langle n|n\rangle} = u_sv_su_tv_t(1-\delta_{s,t})[n-1]_{st}.$$

The correcting factors

$$[n-1]_s = \frac{{}_s\langle n-1|n-1\rangle_s}{\langle n|n\rangle}, \quad [n-1]_{st} = \frac{{}_{st}\langle n-1|n-1\rangle_{st}}{\langle n|n\rangle} \qquad (10)$$

arise under the particle-number projecting. The functions $|n-1\rangle_s$ and $|n-1\rangle_{st}$ ($s\ne t$) are defined in the same manner as $|n\rangle$, i.e., are the wave functions with $n-1$ pairs of particles. The lower indices indicate numbers of the levels nonoccupied by particle pairs.

The coefficients u_s and v_s entering into (8) and (9) are found from the energy minimum which is equivalent, as has been shown in ref. /3/, to the condition of stationarity of the ground state wave function. The calculation of the coefficients u_s and v_s as well as the calculation of average values of the Hamiltonian and other operators is essentially simplified by using the relations derived in ref. /3/ that connect the correcting factors (of the type (10)) with several indices, in which the factors have one index less. For instance

$$[n-1]_{st} = \frac{v_s^2[n-1]_s - v_t^2[n-1]_t}{v_s^2 - v_t^2}, \quad [n-2]_{st} = \frac{u_s^2[n-1]_s - u_t^2[n-1]_t}{u_s^2 - u_t^2}.$$

The state containing p unpaired particles is described by the function

$$a^+_{s_1} a^+_{s_2} \dots a^+_{s_p} |n\rangle_{s_1 s_2 \dots s_p} , \qquad (11)$$

where the function $|n\rangle_{s_1 s_2 \dots s_p}$ is defined similarly to those entering into (10). Expression for the system energy in state (11) within the FBCS has the form

$$E_{s_1 s_2 \dots s_p} = e_{s_1} + e_{s_2} + \dots + e_{s_p} + 2 \sum_{s \neq s_1, s_2, \dots, s_p} \left(e_s - \frac{G}{2}\right) v_s^2 [n-1]_{s_1 s_2 \dots s_p s} \qquad (12)$$
$$- G \sum_{s \neq t,\ s,t \neq s_1, s_2, \dots, s_p} u_s v_s u_t v_t [n-1]_{s_1 s_2 \dots s_p s t} ,$$

The correcting factors entering into (12) due to particle-number projecting are defined similarly to (10). Appearance of several unpaired particles on the Fermi and adjacent levels prevents these levels to be populated by pairs of nucleons (blocking effect). This effects the values of the parameters u_s and v_s. Their values are found from the minimum of the energy (12).

We shall further use the notation: BCS is the BCS method with blocking effect, IQM is the independent quasiparticle model (the BCS method without blocking effect), IPM is the independent particle model. It is convenient to represent the energy ω_i of the excited state i with p unpaired quasiparticles within the FBCS in the form

$$\omega_i(FBCS) = E_i(FBCS) - E_0(FBCS) = \omega_i(IPM) - \Delta E_c^i(FBCS), \qquad (13)$$

where

$$\Delta E_c^i(FBCS) = E_c^0(FBCS) - E_c^i(FBCS),$$

$$E_c^{i(0)}(FBCS) = E_{i(0)}(IPM) - E_{i(0)}(FBCS).$$

Here $\omega_i(IPM)$ is the energy of the excited state i within the IPM, $E_c^{i(0)}$(FBCS) and $E_{i(0)}$(FBCS) are the correlation and system energies of the excited (ground) state within the FBCS (for the latter see expressions (8) and (12)). Within the BCS expression analogous to (13) is used (the correcting factors arising due to particle-number projecting are eliminated from (8) and (12)). Within the IQM we have

$$\omega_i(IQM) = \varepsilon_{s_1} + \varepsilon_{s_2} + \dots + \varepsilon_{s_p} , \qquad \varepsilon_s = \sqrt{e_s^2 + \Delta^2} .$$

As the calculations have shown both for even and odd systems with any number of unpaired nucleons the FBCS provides a gain in the correlation energy, as compared to the BCS, that is always larger for the ground state than for the excited one

$$E_c^0(FBCS) - E_c^0(BCS) > E_c^i(FBCS) - E_c^i(BCS) \qquad (14)$$

hence

$$\omega_i(FBCS) > \omega_i(BCS) . \qquad (15)$$

For the one-quasiparticle states $\Delta E_c^i < 0$ ($E_c^0 < E_c^i$ since in the ground state the Fermi level is blocked), and from (14) and (15) we get the inequality (see also ref. [7])

$$\omega_i(IPM) > \omega_i(FBCS) > \omega_i(BCS). \qquad (16)$$

For the states with more than one unpaired nucleons the calculations give $\Delta E_c^i > 0$ ($E_c^0 > E_c^i$).

3. The Results of Calculations

In the calculations we used the Saxon-Woods single-particle scheme with the parameters from ref. [6]. We took into account 30 neutron and 30 proton levels in the energy interval of about ± 10 MeV from the Fermi level. The pairing interaction constants G_N and G_Z were chosen by pairing energies within the BCS and FBCS in the dependence on a version of calculation. However, the values of pairing constants in these cases differed very slightly (< 2%).

The results of calculations are listed in tables 1-6. By F +1, F +2, ... we denote the first, second, etc. particle levels, by F -1, F -2, ... the first, second, etc. hole levels.

3.1. Quasiparticle States with the Number of Particles of the Same Type k = 1 and 2

It is known that the BCS method overestimates the density of low-lying one-quasiparticle states as compared with the experimental data. It follows from (15) that the use of the FBCS leads to less density of one-quasiparticle states than in the case of the BCS.

The results of calculations for one-quasiparticle states are shown in table 1. The third column of the table presents the contributions of one-quasiparticle components to normalization of the state wave functions in the case of inclusion of the quasiparticle-phonon interaction [6]; they indicate that these states are single particle to a great extent.

T a b l e 1. Excitation energies ω_i and correlation energies E_c of low-lying one-quasiparticle states.

Nucleus	Configuration	One-quasiparticle component	ω_i, keV					E_c, MeV	
			Exp.	IQM	BCS	FBCS	/6/	BCS	FBCS
^{165}Ho	p523↑ F	98%	0	0	0	0	0	0.07	1.30
	p411↑ F-1	94%	360	20	310	400	230	0.28	1.42
	p411↓ F+1	88%	429	470	460	650	370	0.52	1.57
^{175}Lu	p404↓ F	99%	0	0	0	0	0	0.15	1.36
	p514↑ F+1	99%	396	150	160	210	100	0.26	1.45
	p411↓ F-1	97%	627	-50	370	560	310	0.78	1.81
^{177}Hf	n514↓ F	98%	0	0	0	0	0	0.13	0.93
	n642↑ F+1	99%	324	130	110	220	110	0.49	1.18
	n512↑ F-1	97%	504	60	200	260	150	0.26	1.00

It is seen from table 1 that for one-quasiparticle states the FBCS improves the agreement with ω_i^{exp} only insignificantly. This is due to the fact that we used in the calculations the single-particle schemes [6] whose parameters were on the average chosen for large groups of nuclei and did not take into account the interaction of quasiparticles with phonons, the Coriolis interaction and other effects that provide almost the same changes in the state energy as the use of the FBCS. However, the FBCS provides a better description of the density of low-lying one-quasiparticle states than the BCS. As a rule, in the calculations E_c(FBCS) $\gtrsim$ 1 MeV whereas E_c (BCS) $\sim$ 0.5 MeV.

Table 2 exemplifies the excitation energies ω_i, correlation energies E_c^i and ratios G/G_{crit} for two-quasiparticle states. The same quantities for the ground states are given in parenthesis. It is seen from table 2 that the blocking of two single-particle levels

near the Fermi level leads to that in some cases the BCS does not provide a "superfluid" solution (E_c^i = 0 and Δ = 0).

T a b l e 2. Excitation energies ω_i, correlation energies $E_c^{i(0)}$ and ratios G/G_{crit} for low-lying two-quasiparticle states.

Nucleus	K^π	Configuration	ω_i, MeV				$E_c^i(E_c^0)$, MeV		G/G_{crit}
			Exp.	IQM	BCS	FBCS	BCS	FBCS	$(G/G_{crit})_0$
^{164}Dy	6^-	F F+1 n523↓+n633↑	1.68	2.01	1.59	1.67	0.01(0.6)	0.8(1.6)	1.0(1.4)
^{168}Er	3^+	F+1 F+2 n521↓+n512↑	1.65	1.90	1.67	1.75	0.08(1.1)	0.9(2.0)	1.2(7.6)
^{172}Yb	6^-	F-1 F+1 n633↑+n512↑	1.55	1.75	1.32	1.40	0 (0.8)	0.7(1.6)	1.0(2.2)
^{174}Yb	6^+	F F+1 n512↑+n514↓	1.53	1.70	1.27	1.37	0(0.6)	0.7(1.4)	1.0(1.5)
^{176}Yb	8^-	F F+1 n514↓+n624↑	1.04	1.46	0.93	1.12	0(0.4)	0.6(1.2)	1.0(2.2)
^{176}Hf	7^-	F F+2 n512↑+n624↑	1.86	1.82	1.53	1.63	0.1(0.9)	0.8(1.7)	1.3(6.0)
^{174}Yb	5^-	F F+2 p411↓+p514↑	1.88	2.52	1.98	2.14	0(0.7)	1.0(1.9)	1.0(1.3)
^{176}Hf	8^-	F F+2 p404↓+p514↑	1.48	1.64	1.08	1.25	0(1.2)	0.9(2.2)	1.0(110)

In these cases the excitation energy was calculated by

$$\omega_i(BCS) = E_i(IPM) - E_0(BCS).$$

Within the FBCS there always exists a "superfluid" solution, and the correlation energy amounts to E_c^i (FBCS) $\approx$ 1 MeV $\approx$ 0.5 E_c^0 (FBCS). As ω_i(FBCS) > ω_i(BCS) and for most of the low-lying two-quasiparticle states in the rare-earth nuclei ω_i(BCS) < ω_i^{exp}, then ω_i(FBCS) is on the average in better agreement with ω_i^{exp}. However, it should be noted that a more correct definition of the single-particle scheme and the inclusion of residual interactions may give corrections to the excitation energy ω_i of two-quasiparticle states (and three-quasiparticle states to be considered below) of the same order as the use of the FBCS.

Let us consider three- and four-quasiparticle states of the type (p, $2n$), (n, $2p$) and ($2n$, $2p$) in which the number of quasiparticles of the same kind does not exceed two ($k \leq 2$). It is seen from tables 3 and 4 that the FBCS provides a better agreement with experiment than the BCS, especially for four-quasiparticle states.

T a b l e 3. Excitation energies ω_i of low-lying three-quasiparticle states of the type (p,2n) and (n,2p).

Nucleus	K^{π}	Configuration	ω_i, MeV Exp.	IQM	BCS	FBCS
^{177}Ta	$21/2^-$	F F+1 F p514↑+n514↓+n512↑	1.36	1.71	1.23	1.28
	$23/2^+$	F F+2 F p514↑+n624↑+n512↑	1.70	1.82	1.53	1.63
	$25/2^+$	F F+2 F+1 p514↑+n624↑+n514↓	1.84	1.78	1.61	1.78
^{179}Hf	$25/2^-$	F F F+1 n624↑+p404↓+p514↑	1.11	1.86	1.09	1.32
^{177}Hf	$23/2^+$	F F F+1 n514↓+p404↓+p514↑	1.32	1.64	1.08	1.25
^{177}Lu	$23/2^-$	F F+1 F n404↓+p624↑+p514↓	0.97	1.46	0.93	1.12
	$11/2^+$	F+1 F F+1 p514↑+n514↓+n624↑	1.23	1.60	1.07	1.27

This is due to the fact that uncertainties in the positions of the single-particle levels may be compensated when the number of quasiparticles increases whereas the second term in (13) is in a much weaker dependence on a detailed notion of the positions of levels of an average field and is mainly determined by the density of single-particle levels near the Fermi surface. A further consideration of the excitation energy of many-quasiparticle states (with the number of quasiparticles of the same type $k \geq 3$) confirms the above conclusion.

T a b l e 4. Excitation energies ω_i of low-lying four-quasiparticle states of the type ($2n$, $2p$).

Nucleus	K^{π}	Configuration	ω_i, MeV Exp.	IQM	BCS	FBCS
^{176}Hf	14^-	F+1 F F+1 F p514↑+ p404↓+ n514↓+ n512↑	2.87	3.64	2.37	2.65
	15^+	F+1 F F+2 F p514↑+ p404↓+n624↑+ n512↑	3.08	3.77	2.69	3.01
	16^+	F+1 F F+2 F+1 p514↑+p404↓+ n624↑ +n514↓	3.27	3.71	2.76	3.16
^{178}Hf	16^+	F F+1 F F+1 p404↓+ p514↑+ n514↓+ n624↑	2.45	3.50	2.16	2.57
	14^-	F F+1 F F−1 p404↓+ p514↑+ n514↓+ n512↑	2.57	3.80	2.95	3.27

3.2. Quasiparticle States with the Number of Quasiparticles of the Same Type $k \geq 3$

Now we consider a five-quasiparticle state of the type ($2p$, $3n$) with $K^{\pi} = 37/2^-$ in ^{177}Hf and three six-quasiparticle states of the type ($2p$, $4n$) with $K^{\pi} = 19^-$, 20^- and 21^- in ^{176}Hf. The state with $K^{\pi} = 37/2^-$ has been found in the reaction ^{176}Yb(α, $3n$) ^{177}Hf [8] and the six-quasiparticle states in the reaction ^{176}Yb(α, $4n$)-^{176}Hf [9]. All these states have a large lifetime. The configurations were attributed to these states (see table 5) on the basis of estimations of the state excitation energies and the analysis of the scheme of their de-excitation [8,9].

First, we consider the states with $K^{\pi} = 37/2^-$ and $K^{\pi} = 19^-$ and 20^-. It is seen from table 5 that the BCS provides for these states far too low values of the excitation energies ω_i and the IQM highly overestimated ones whereas the FBCS method allows one to get a very good agreement with ω_i^{exp} (in particular, the agreement is much better than for the case of empirical estimates of the excitation energies in ref. [8,9]. Thus, our calculations, first, confirm the interpretation of these states proposed in refs. [8,9] (quantum numbers

T a b l e 5. Excitation energies ω_i and correlation energies E_c of a five-quasiparticle state in ^{177}Hf and three six-quasiparticle state in ^{176}Hf (for state with ω_i^{exp} = 4.86 MeV there are two versions of state interpretation: 1) $K^{\pi} = 22^{-}$/9/ and 2) $K^{\pi} = 21^{-}$ as is proposed in the present paper)

K^{π}	Configuration	ω_i, MeV				$E_c^i(E_c^0)$, MeV	
		Exp.	IQM	BCS	FBCS	BCS	FBCS
$37/2^{-}$	F F+1 F F+1 F+2 p404↓+ p514↑+ n512↑+ n514↓+ n624↑	2.74	3.75	2.10	2.61	0(0.1)	0.6(0.9)
19^{+}	F F+1 F-2 F F+1 F+2 p404↓+p514↑+n521↓+ n512↑+ n514↓+ n624↑	4.38	5.83	3.77	4.34	0(0.9)	0.4(1.7)
20^{-}	F F+1 F-2 F-1 F+1 F+2 p404↓+ p514↑+ n521↓+ n633↑+ n514↓+ n624↑	4.77	6.00	3.91	4.67	0(0.9)	0.4)1.7)
22^{-}/9/	F F+1 F-1 F F+1 F+2 p404↓+ p514↑+ n633↑+ n512↑+ n514↓+ n624↑	4.86	5.66	3.49	4.11	0(0.9)	0.4(1.7)
21^{-}	F F+1 F-3 F F+1 F+2 p404↓+ p514↑+ n642↑+ n512↑+n514↓+ n624↑	4.86	6.20	4.21	4.78	0(0.9)	0.5(1.7)

K^{π} and configuration) and second, show the necessity of particle-number projecting in considering many-quasiparticle states. Note that we managed to achieve a good agreement with ω_i^{exp} for these states within the FBCS without taking into account any residual interactions.

It is easy to explain why for the states with a large number of quasiparticles the FBCS method improves considerably the agreement with ω_i^{exp} compared to the BCS and IQM. On the one hand, this is due to the fact that inaccuracies of the BCS and IQM in calculating ω_i and E_c^i are the stronger the larger the number of single-particle levels is blocked in close proximity to the Fermi surface, i.e., for the low-lying many-quasiparticle states. On the other hand, as has been mentioned above, with increasing number of quasiparticles inaccuracies in the position of single-particle levels compensated each other.

It is seen from table 5 that our calculations do not confirm interpretation/9/ of level 4.86 MeV as the state with $K^{\pi} = 22^{-}$ and configuration p404↓+ p514↑+ n633↑+ n512↑+ n514↓+ n624↑ . The state with such a configuration should be lower in energy than the state with $K^{\pi} = 19^{-}$ and 20^{-} since it consists of quasiparticles lying closer to the Fermi surface. The FBCS method provides ω_i =4.11 MeV for the state $K^{\pi} = 22^{-}$, i.e., the value lower than the experimental one by 0.7 MeV. In our opinion level 4.86 MeV should be interpreted as the state with $K^{\pi} = 21^{-}$ and configuration p404↓+ p514↑+ n642↑+ + n512↑+ n514↓+n624↑ . In this case the calculated excitation energy ω_i = 4.78 MeV is in better agreement with experiment, and assignment of quantum numbers $K^{\pi} = 21^{-}$ to this level does not contradict the way of its de-excitation (E2 transition to the state with $K^{\pi} = 20^{-}$). According to our calculations the level with $K^{\pi} = 22^{-}$ should be searched for at an energy of 4.1 MeV. Its de-excitation should greatly be hindered since, according to experiment, below there are levels with $K^{\pi} = 16^{-}$only.

It is seen from table 5 that contrary to the BCS predictions on the complete disappearance of pairing in the states considered, the FBCS method shows that pairing in them does not disappear and the correlation energy E_c^i = 0.5 MeV differs noticeably from zero. Table 6 shows that with increasing quasiparticle number k in the neutron system of ^{176}Hf the value E_c^i(FBCS) decreases much slower than E_c^i (BCS) and differs from zero even at k = 6 (the case k = 6 corresponds to the hypothetical state of six unpaired neutron quasiparticles lying on the Fermi level and on the adjacent levels). However, it should be noted that to make a final conclusion on the nondisappearance of pairing in many-quasiparticle states one needs additional theoretical investigations (taking into account residual forces and effects of reconstruction of the average field) and experimental tests.

T a b l e 6. Dependence of correlation energy E_c on quasiparticle number k in the neutron system of ^{176}Hf .

k	0	2	4	6
E_c(BCS), MeV	0.9	0.1	0	0
E_c(FBCS), MeV	1.7	0.8	0.4	0.3

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Кузьменко Н.К., Михайлов В.М., Нестеренко В.О. E4-86-288
Спаривание в многоквазичастичных состояниях

В рамках метода пректирования по числу частиц до варьирования /ПДВ/ с учетом эффекта блокировки рассмотрены энергии возбуждения и корреляционные энергии квазичастичных состояний деформированных ядер с числом квазичастиц одного сорта $1 \le k \le 4$. Проводится сравнение с расчетами в рамках БКШ. Для пятиквазичастичного состояния типа (1p, 4n) в ^{177}Hf и шестиквазичастичных состояний типа (2p, 4n) в ^{176}Hf получено хорошее согласие с экспериментом, продемонстрирована важность проектирования по числу частиц при рассмотрении многоквазичастичных состояний. В отличие от БКШ метод ПДВ предсказывает сохранение спаривания в многоквазичастичных состояниях.

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Kuzmenko N.K., Mikhailov V.M., Nesterenko V.O. E4-86-288
Pairing in Many-Quasiparticle States

Excitation and correlation energies of quasiparticle states of deformed nuclei with the number of quasiparticles of the same type $1 \le k \le 4$ are considered allowing for the blocking effect within the method of particle-number projecting before variation (FBCS). Our results are compared with the calculations within the BCS. A good agreement with experiment is obtained for a five-quasiparticle state of the type (1p,4n) in ^{177}Hf and six-quasiparticle states of the type (2p, 4n) in ^{176}Hf; the necessity of particle-number projecting while considering many-quasiparticle states is demonstrated. In contrast with the BCS, the FBCS method predics that the pairing in many-quasiparticle states does not disappear.

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

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