

Spin state transition in active center of hemoglobin molecule: DFT + DMFT study

*D. Novoselov^{+*1)}, Dm. M. Korotin⁺, V. I. Anisimov^{+*}*

⁺*Institute of Metal Physics, 620990 Yekaterinburg, Russia*

^{*}*Ural Federal University, 620002 Yekaterinburg, Russia*

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An *ab initio* study of electronic and spin configurations of the iron ion in the active center of the human hemoglobin molecule is presented. With a combination of the Density Functional Theory (DFT) method and the Dynamical Mean Field Theory (DMFT) approach the spin state transition description in the iron ion during the oxidation process is significantly improved in comparison with previous attempts. It was found that the origin of the iron ion local moment behavior both for the high-spin and for the low-spin states in the hemoglobin molecule is caused by the presence of a mixture of several atomic states with comparable statistical probability.

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Metal-porphyrin complexes play an important role in many biological processes such as photosynthesis process with a chlorophyll assistance in plant cells or the transport of oxygen by hemoglobin in living beings through reversible binding of a hemoglobin molecule with an oxygen molecule as well as they widely used for therapeutic purposes [1]. It is not surprising that the interest to this kind of system isn't being quenched until now [2–4]. Undoubtedly, one of the most interesting features of the hemoglobin molecule is an ability to reversibly attach itself to oxygen molecules. This process is accompanied by the spin state transition of the iron ion. A number of papers [5–9] indicate that the transition occurs between closely energy located low- and high-spin states. In addition it is noted that there are energy close-lying excited states with unknown spin multiplicity [5]. At the same time, in the works [4, 9, 10] the assumption of the mixed nature of the spin state is discussed, pointing to the possibility of existence a contributions of several atomic states with different values of valence and spin moment. This indicates that the detailed and complete interpretation of the spin transition scenario in this metal-porphyrin complex is currently insufficient.

In the works [6–8, 10] it was shown that the electronic correlations play an important role in the iron-porphyrin complexes. Therefore, we have selected a modern *ab initio* approach that combines the density functional theory and the dynamical mean field theory (DFT+DMFT) to describe the state of the iron ion.

This method allows one to take into account many-body effects in paramagnetic systems as well as thermal fluctuation effects. Through applying the continuous time quantum Monte-Carlo algorithm (CT-QMC) as an impurity solver it is possible to perform a statistical analysis of the atomic states of the impurity site. The investigation of iron-porphyrin complex was performed with the similar method recently in paper [10]. However authors didn't reproduce a clear spin state transition picture from high- to low-spin state for the structures without and with the oxygen molecule bonded to the iron ion. Instead of significant spin moment change between the high- and the low-spin states the difference of $\Delta s \approx 0.25 \mu_B$ was obtained [10]. In the present work we not only improve the description of magnetic state transition in the iron-porphyrin complex but in addition perform the statistical analysis of obtained multiplets and describe the origin of the iron ion local moment behavior.

The human hemoglobin molecule consist of several thousand atoms. In this work the model is investigated (see Fig. 1) including only the active center of the molecule that directly involved in the formation of the chemical bond with the oxygen molecule. This structural model is based on the existing experimental data [11–13]. It includes the ferroporphyrin and two ligands – proximal and distal, playing a leading role in the functional activity of the hemoglobin molecule. The active center is formed by almost flat porphyrin ring consisting of nitrogen and carbon atoms. At the center of the ring the iron ion is placed. The nearest neighbours of the transition metal ion are four nitrogen atoms of

¹⁾e-mail: novoselov@imp.uran.ru

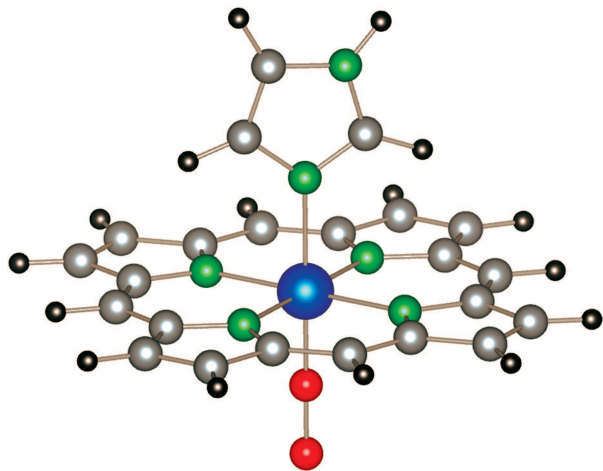


Fig. 1. (Color online) The schematic image of structure model of active center of the human hemoglobin molecule. The blue sphere corresponds to the iron atom, the red spheres – the oxygen atoms, the dark grey – the hydrogen atoms, the light grey – the carbon atoms, green – the nitrogen atoms

the porphyrin ring. Fifth nearest neighbour of the iron ion is the nitrogen from the imidazole (Im) molecule that is located almost perpendicular to the plane of the porphyrin-metal complex (see Fig. 1). Therefore the transition metal ion is surrounded by the pyramid of the nitrogen atoms.

In this paper the structural model containing 46 atoms for the deoxy-molecule and 48 atoms for the oxy-molecule was considered. We started from the hemo group of the *d*-chain of real HHB molecule [12]. Then the hemo group was enforced to be flat and located in a *xy*-plane, the iron ion was placed in the center of the hemo ring and the missing chemical bonds were saturated by the hydrogen atoms. Then an atomic relaxation for the obtained FeP crystal structure was performed.

The calculations were done with Quantum-ESPRESSO package [14] within the ultrasoft pseudopotential formalism in plane waves basis. We used GGA (PBE) exchange correlation functional, plane waves energy cutoff was set to 75 Ry. The modeled molecule was placed in the center of the cubic cell with the edge length of 40 Bohr radius. This cell size is enough to prevent any influence of the nearest cell molecules.

To obtain the FeP(Im) structure, we placed the imidazol molecule at 2.13 Å [12] distance from the iron ion of the FeP group and the imidazole molecule atoms positions were relaxed keeping Fe–N(Im) distance constant.

To get the last structure – FeP(Im)(O₂), the dioxygen molecule was placed on the opposite to the Im molecule side of the FeP plane at 1.76 Å [13] distance

and then relaxed keeping the Fe–O distance fixed. The second oxygen ion position was allowed to relax, therefore the obtained Fe–O–O angle close to 180 degrees arises from the symmetry of the porphyrin ring, not from arbitrariness.

As a result of this procedure we have obtained two relaxed molecular structures that are simple and symmetric enough to analyze the splitting of the energy levels of the Fe ion placed in the center. On the other hand, local surroundings of the Fe ion remains close to the experimental data. The distances Fe–Im and Fe–O₂ are kept fixed to 2.13 and 1.76 Å, respectively [12, 13]. The obtained distance between the Fe and N atoms of the porphyrin ring equals 2.07 Å, that is close to the experimental value 2.05 Å [12].

To take into account electronic correlations in the *d*-shell of the iron ion the DMFT approach was used. As an input this approach requires an uncorrelated Hamiltonian matrix, typically obtained from the DFT calculation, and the values of Coulomb interaction parameter and Hund exchange parameter. To obtain the Hamiltonian matrix we used the projection procedure to the basis of Wannier functions [15]. All energy bands and all atomic states for all atoms of the system were used for projection. Therefore, the Wannier functions coincide with atomic orbital by the construction. The five Wannier functions with symmetry of the five Fe-*d* atomic orbitals were considered as correlated wavefunctions. When we refer to a some *d*-state occupation below, for example the $x^2 - y^2$ state, we mean the occupation number of the Wannier function centered on the Fe ion with the corresponding spacial symmetry.

It is stated in the work [10] that the results of the DMFT calculation for deoxy-molecule show the weak dependence on the temperature used in the calculation. We carried out the DMFT calculations with the inverse temperature parameter $\beta = 25$ corresponding to the electronic subsystem temperature $T \approx 464$ K. For the construction of the interaction matrix the parameter of Coulomb repulsion ($U = 4$ eV) and Hund exchange parameter ($J = 0.9$ eV) were chosen to be the same as in earlier works [3, 7, 10]. Typically the Hubbard interaction parameter is used for a transition metal *d*-shell electrons interaction calculation, since the *d*-electrons are localized and the *d*-shell is partially filled. However it was shown in paper [16], that it is possible to improve description of electronic and magnetic properties of transition metal oxides if one takes into account Coulomb interaction of oxygen *p*-electrons. In the present work we include this correction [17, 18].

Subsequently the obtained Hamiltonian was solved within the DMFT approach using the AMULET pack-

age [19]. DMFT is applicable to a wide class of physical systems with the presence of strong correlation effects. This method reduces a many body lattice problem to the impurity one [20, 21] and it considers the single atom placed in the external environment with allowed the electrons swap between the impurity and the environment. To solve the auxiliary impurity problem we used continuous time quantum Monte-Carlo algorithm (CT-QMC) [22–24]. The hybridization expansion CT-QMC solver provides the site-reduced statistical operator (density matrix) [25]. This quantity describes the probability of finding an atom in a particular many-body state and an expectation value of any local operator can be easily obtained from it. Therefore, this instrument is well suited to analyze a statistical probability of the various atomic configurations of the Fe ion in the active center of the molecule.

The statistical probability of the different atomic configurations of the iron ion obtained by the DMFT calculations for FeP(Im) and FeP(Im)(O₂) structures is presented in Fig. 2. This result explicitly indicates the

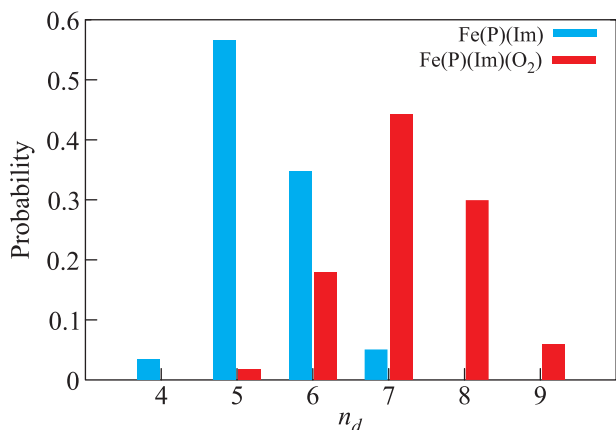


Fig. 2. (Color online) The statistical distribution of the different valence states probabilities for the iron ion for FeP(Im) and FeP(Im)(O₂) structures

presence of the strong valence fluctuations. As it can be seen from Fig. 2 the centers of mass of the histograms presented for FeP(Im) and FeP(Im)(O₂) are different. This is related to the fact that the occupancy of the Fe- d orbitals is increased due to the oxidation following the occurrence of the strong p - d hybridization effect.

In the FeP(Im) the dominant contribution to the valence state is provided by d^5 configuration (57%), whereas d^7 prevails (44%) for FeP(Im)(O₂). It should be noted that for FeP(Im) the contributions of d^6 (35%) configuration is very significant, as well as for FeP(Im)(O₂) d^6 (18%) and d^8 (30%). This observation allows one to conclude that the state of the system un-

der consideration has an entangled superposition type and the contribution of the dominant state configuration doesn't exceed 57%. Due to the fact that the iron ion d -states in this complex porphyrin and ligand surrounding isn't a pure d^6 -states, then the observed entangled superposition could be explained as the result of the strong hybridisation [7] of the iron states with the states of the neighbouring atoms, as well as by the fact that the possible spin states are energetically very close to each other [8]. Besides, from the presented figure it can be seen that during the oxidation of the hemoglobin molecule, the iron ion transits to the state with the higher oxidation degree.

For every electronic configuration, i.e. for the number of valence electrons in the d -shell, several spin configurations are possible. We calculated the probability of every spin state for the iron ion in FeP(Im) and FeP(Im)(O₂) systems. Resulting histograms are shown in Fig. 3.

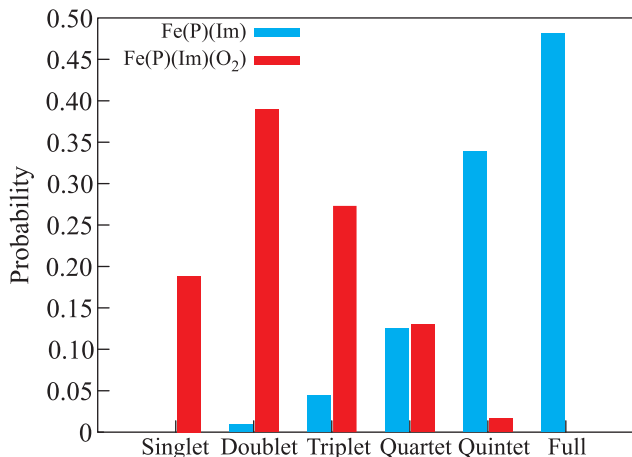


Fig. 3. (Color online) The statistical distribution of the probability for the different spin configurations for the FeP(Im) and the FeP(Im)(O₂) systems

The oxidized and deoxidized molecules have different spin configuration of the Fe ion as it clear from Fig. 3. The maximum weight has the doublet (39%) state in FeP(Im)(O₂) and the fully polarized (48%) state in the FeP(Im). At the same time, for both molecules the maximum weight doesn't exceed 48%.

This clearly indicates, that there is the transition between two entangled quantum states during the oxidation process. The spin state of the Fe ion in both, FeP(Im) and FeP(Im)(O₂) systems, is a mixture of at least four spin configurations with different total moment. The effective spin moment of the Fe ion decreases when oxygen molecule is attached. The difference of the

effective spin moment between the FeP(Im) ($s \approx 2.1$) and the FeP(Im)(O₂) ($s \approx 0.7$) has the value about 1.4.

Thereby, an additional Coulomb interaction correction for oxygen p -states results in the significant improvement of magnetic spin state transition description which in good agreement with the data of corresponding experiments [9, 26]. In contrast to [10] we obtain the evident difference in the effective spin moment of Fe ion for structures with and without oxygen molecule²⁾.

To emphasize the entangled state of the Fe ion, the contributions from the dominant valence and spin configurations to the final state of the ion are shown in Fig. 4. Here we can see that the d^5 , and in a less degree

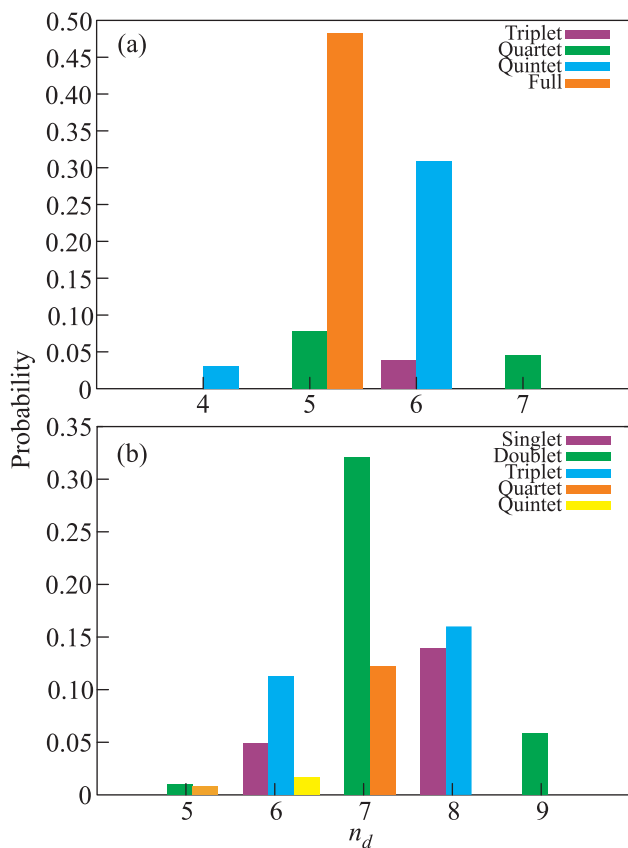


Fig. 4. (Color online) The statistical distribution of the probability of the dominant atomic configurations of the iron ion for the FeP(Im) (a) and the FeP(Im)(O₂) (b) systems

the d^6 , valence configurations contribute to the high-spin state for FeP(Im) full polarized and the quintet cases respectively. Two most probable configurations for FeP(Im)(O₂) are the doublet formed by the d^7 and in

²⁾At the same time, with absence of Coulomb correction for oxygen states, the calculated effective moments are in agreement with [10].

a less degree d^9 states and the triplet formed by the d^6 and the d^8 states.

As we can see from Fig. 4 the number of the major states with more than 5% probability in FeP(Im) equals three but for FeP(Im)(O₂) it is twice as much that indicates the growth of the quantum entanglement. This behavior can be caused by the occurrence of the hybridization between the oxygen p - and iron d -states during the molecule oxidation.

In conclusion, in this paper within the non-empirical DFT + DMFT approach it was successfully reproduced the spin-state transition from the ground high-spin to the low-spin state appearing in the process of the hemoglobin molecule oxidation observed experimentally. The values obtained for the spin magnetic moment in the high- and low-spin states are 2.1 and 0.7 μ_B respectively. It is found that the local magnetic moment of the Fe ion originates from the mixture of the wave functions of the valence electrons with several possible valences and spin configurations with comparable probability of realization.

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