

Modeling enzyme function at surfaces

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The high chemical reactivity of unsaturated metal sites is a key factor for the development of novel devices with applications in sensor engineering and catalysis. Open metal sites in nanostructured coordination compounds are also central in the research for sustainable energy concepts, e.g., the efficient and sustainable production and conversion of chemical fuels. Coordinatively unsaturated metal ions also play a key role in several biological processes, e.g., dinuclear metal centers are a common structural feature in the cofactor of many metalloproteins controlling respiration or metabolism. Several of these fundamental units are based on carboxylate-bridged Fe ions that catalyze the dissociation of molecular oxygen allowing the participation of oxygen into a large variety of chemical reactions controlling important processes such as the oxidation of methane to methanol, the conversion of nucleotides to deoxynucleotides, or the conversion of alkanes to alkenes. The structural characterization of these carboxylate-bridged iron units has been the subject of extensive work, and even more efforts have been dedicated to the understanding of their reaction mechanisms, a formidable challenge due to the complexity of the biological environment.

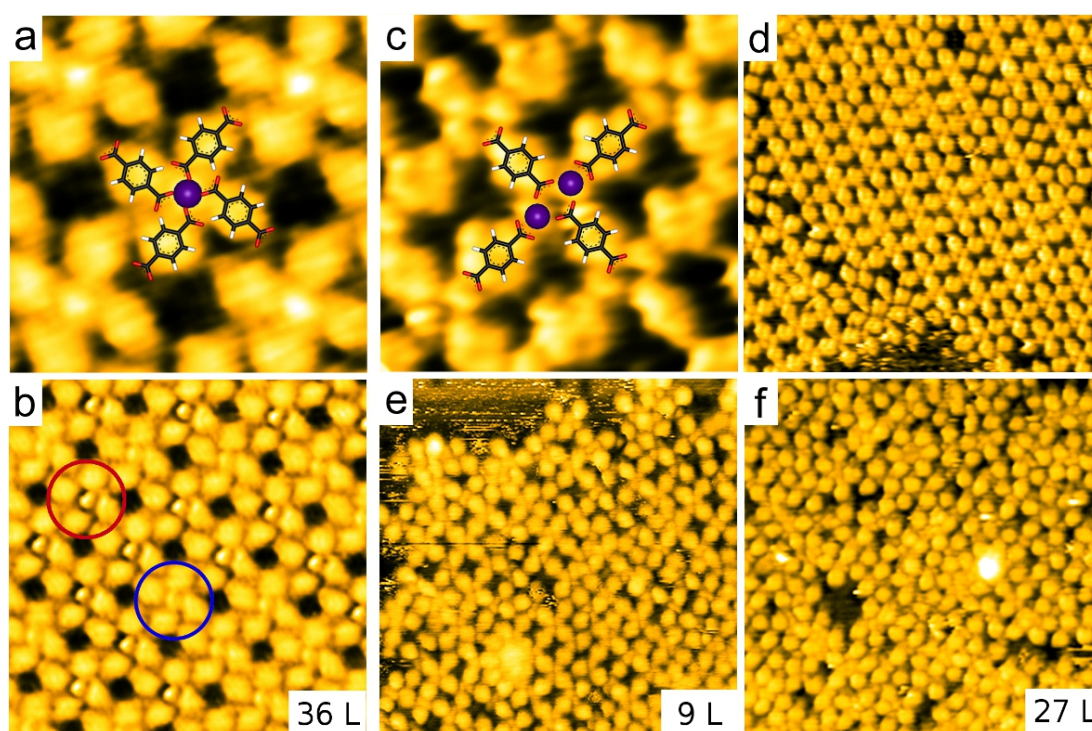


Figure 1: STM images of the pristine (a,c,d) metal-organic coordination networks and exposed to oxygen (b,e,f). Reaction of mono-iron (a-b) and di-iron (d-f) networks with molecular oxygen as a function of O_2 dosage (in Langmuir, L). Purple spheres represent the Fe centers in panel a and c. In panel b selected pristine and O_2 -modified units are highlighted by blue and red circles, respectively. Image sizes: (a,c) $3.5 \times 3.5 \text{ nm}^2$, (b) $8 \times 8 \text{ nm}^2$, (d,e,f) $14.3 \times 14.3 \text{ nm}^2$. STM imaging conditions: $I = 0.1 \text{ nA}$, $U = 0.3\text{-}0.5 \text{ V}$, and $T=300\text{K}$.

Here, we explore the reactivity of coordinatively unsaturated metal centers under well-controlled conditions. This approach is based on supramolecular engineering of surface-confined coordination networks that display close structural analogies with the cofactors of non-heme enzymes.[1] We synthesized a two-dimensional array comprising of mono- and di-iron sites coordinated to the carboxylate groups of terephthalic acid (TPA) on a Cu(100) surface. The process of oxygen adsorption and dissociation is studied combining scanning tunneling microscopy (STM), x-ray absorption spectroscopy (XAS), and density functional theory (DFT) calculations. The latter identifies a novel mechanism for O_2 dissociation controlled by the cooperative catalytic action of two Fe^{2+} ions. The high structural flexibility of the organic ligands and the mobility of the metal centers are shown to be essential for the functionality of these active centers.

Figure 1a and c show high-resolution STM images with superposed structural models of the mono- and di-iron coordination networks. The STM images in Fig. 1d-f reveal the structural modification of the di-iron networks as a function of O₂ exposure at 300 K (partial O₂ pressure of 3 × 10⁻⁸ mbar). The initially highly ordered di-iron structure (Fig. 1d) gradually collapses with increasing oxygen dosage (Fig. 1e,f). At this partial pressure the reaction proceeds in the order of minutes. The active response of di-iron centers contrasts with the behavior of the mono-iron centers, which selectively bind oxygen molecules but do not undergo a structural transition even at larger doses of O₂ (Fig. 1b).[2] Such a drastically different behavior of mono- and di-iron centers illustrates the extreme sensitivity of the O₂ dissociation reaction with respect to their atomic structure.

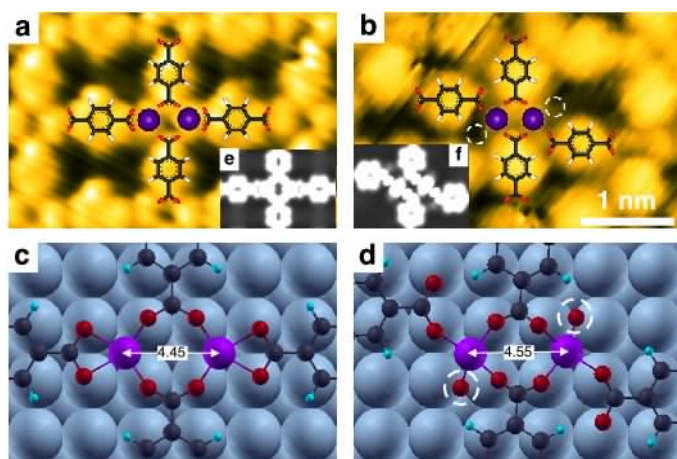


Figure 2: High-resolution STM topograph of the di-iron network before oxygen exposure (a) and oxygen modified phase after 27L of O₂ exposure (b), corresponding equilibrium geometries (c and d) and simulated STM images predicted by the DFT calculations (insets, e and f). Color code: carbon in grey, Fe in purple, oxygen in red, hydrogen in cyan, and Cu in light blue.

Figure 2a displays a high-resolution STM image of the pristine di-iron structure together with the corresponding equilibrium structure predicted by DFT calculations (Fig. 2c). The molecule-surface coupling enforces the planar adsorption of the ligands. Each di-iron unit is coordinated by two chelating axial and by two bridging carboxylates with respect to the Fe-Fe axis. This results in a distorted square-planar Fe coordination with a Fe-Fe spacing of 4.45 Å and a height of 2.06 Å over the surface. The strong Fe-carboxylate bonding results in an increased height of the Fe atoms compared to isolated Fe adatoms (1.51 Å). The metal ions are in a high-spin Fe²⁺ state. Figure 2b shows a characteristic modified arrangement that is observed at the initial steps of oxygen exposure and appears more and more often with increasing oxygen dosage. At sufficiently high oxygen exposure disorder induced by the diffusion of the adsorbates is observed. In the modified structure the di-iron configuration persists but the axial ligands are displaced by ~2 Å with respect to the di-iron axis. The lowest energy structure predicted by DFT for this arrangement is shown in Fig. 2d. We presume that the O* atoms resulting from the O₂ dissociation become the fourth ligand, which recovers the four-fold coordination. The simulated STM image (Fig. 2f) is in good agreement with the experimental findings showing that the predicted structure is indeed compatible with the presence of two additional O* atoms (dashed circles in Fig. 2b and d). We note that instead of a single O*, molecular O₂ would result in strong features in the STM image. The calculated position of the O* atoms is below the plane of the ligands and in contact with the Cu surface. Thus, we correlate the shift of the axial ligands with the presence of O* adatoms. Upon reaction of the di-iron unit with dioxygen the Fe net charge (Löwdin) decreases by ~0.16e while the O* charge increases by 0.44e with the carboxylate oxygen atoms nearly unaltered. This charge transfer from the Fe ions is attributed to the change of the oxidation state from +2 to +3. The theoretical analysis is supported by the XAS investigations of the Fe L-edge for the pristine and oxygenated networks (not shown here).

The minimum energy reaction path for the adsorption and dissociation of oxygen predicted by the DFT analysis is reported in Fig. 3. The calculations show that the relevant mechanism is governed by the reactivity of the dinuclear Fe centers rather than the Cu substrate. Moreover, the non-reactivity of the mono-Fe phase excludes the reaction channel via the Cu surface since the small cavities in the mono-iron structure would lead to a similar reaction path. The numerical simulations predict that an O₂ molecule adsorbs on one of the Fe²⁺ ions with a binding energy of 0.79 eV. The large initial Fe-Fe

distance prevents the direct formation of a Fe-O-O-Fe bridging intermediate (Fig. 3b) that is usually considered for these systems. Instead, another O₂ molecule can be accommodated on the second metal center of the same unit, with a binding energy of 0.57 eV. The first dissociation starts from this very stable O₂-Fe-Fe-O₂ configuration (Fig. 3c) and constitutes the rate-limiting step (Fig. 3d). The activation energy of the dissociation of the first O₂ is 0.74 eV, while the second molecule requires only 0.25 eV (Fig. 3e). The reason for this lower value lies in the specific dinuclear structure of the reaction center. While breaking the O-O bond of the second molecule a new O₂ molecule forms from the recombination of O atoms located on the neighboring Fe ion (Fig. 3e). This meta-stable Fe-O-O-Fe bridging configuration is different from the single O₂ bridging case discussed above (Fig. 3b). It is now stabilized by the concerted displacement of the metal centers induced by the presence of the O adsorbates. This signifies the high flexibility of the di-iron unit. In the last step of the reaction the newly formed oxygen molecule desorbs leaving an O atom on each of the metal centers. Finally the axial ligand displacement further lowers the total energy by 1.3 eV (per Fe center) and requires an activation energy of 0.53 eV. This yields the experimentally observed structure (Fig. 2b).

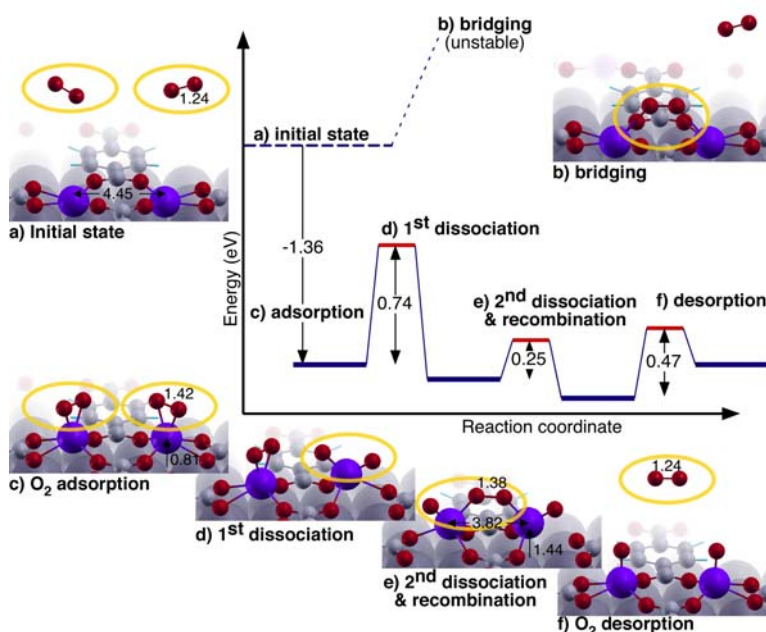


Figure 3: Reaction mechanism for O₂ dissociation predicted by the DFT calculations. The relative energies of the reaction intermediates (a-f) as well as the activation barriers are expressed in eV.

The different reactivity displayed by mono- and di-nuclear Fe centers towards dioxygen dissociation stems from both structural and electronic effects, namely the presence of the bridging ligands and the ability to assist multi-electron processes. In this context, the reaction mechanism we propose establishes a new element into the structure/function relationship of these active sites: Besides bridging ligation, the reactivity of dinuclear sites is controlled by the structural flexibility of the organic ligands as well as by the possibility of the metal centers to undergo coordinated structural displacements. The mechanism proposed here differs in several aspects from other dinuclear Fe systems. Most reactions involve the presence of bridging O₂ across the Fe centers. This bridging configuration is present also in our reaction mechanism, however it originates from two O₂ molecules interacting with the dinuclear site. The likelihood of forming the bridging dioxygen strongly depends on the distance between the Fe ions which can vary in the range from 2.85 Å to 5.01 Å in other systems. Moreover, the square-planar structure of the surface supported model complex is distinct from the 3D coordination environment of the synthetic di-iron complexes. Here, the surface enforces the co-planar coordination of the components. The supporting surface might play a role similar to steric hindrance ligands in 3D compounds and stabilizes the unsaturated four-coordinated structure. Further, it provides a source of electrons for the reactions. Besides these differences, the key structural resemblance with the carboxylate-bridged dinuclear iron complexes is still remarkable.

In conclusion, our results provide a direct correlation between the reactivity of di-iron active sites and the concerted displacement of metal centers and ligand flexibility. Our study reveals the interaction of di-iron coordination networks supported on a metal surface with O₂ and identifies a novel reaction mechanism. This mechanism displays a cooperative catalytic action of the Fe ions, is rate-limited by the first O₂ dissociation, and exploits the structure of the dinuclear site. Since the di-iron structure displays carboxylate ligand shifts analogous to that exhibited by synthetic biomimetic systems and biological metalloenzymes sensitive to dioxygen, our characterization and conclusions may be useful for the design of artificial units capable to mimic the function of enzymes' active sites.[3]

References:

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