Direct and indirect role of Fe doping in NiOOH monolayer for water oxidation catalysis

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Abstract

The oxygen evolution reaction (OER) activity of pristine NiOOH is enhanced by doping with Fe. However, the precise role of Fe is still being debated. Here, we use first-principles DFT+U approach to study three different types of active sites: one on pristine and the other two on Fe-doped NiOOH monolayers to account for the direct and indirect roles of Fe. To compare the activity of the active sites, we consider two mechanisms of OER based on the source of O-O bond formation. Our results show that the mechanism involving the coupling of lattice oxygen is generally more favorable than water nucleophilic attack on lattice oxygen. On doping with Fe, the overpotential of NiOOH is reduced by 0.29 V in excellent agreement with experimental findings. Doping Fe in NiOOH results in different potential determining steps (PDS) in the two mechanisms, whereas pristine NiOOH has the same PDS regardless of the mechanism.

Graphical TOC Entry

Keywords

Density-functional theory, transition metal oxyhydroxides, water oxidation, oxygen evolution reaction, heterogeneous catalysis, reaction mechanism

A key obstacle to the success of electrochemical water splitting is the oxygen evolution reaction (OER), a kinetically inefficient but crucial half-reaction.¹ OER is a significant contributor to the overpotential as it involves the exchange of four protons and electrons as well as an O-O bond formation, necessitating the use of catalysts.² Of the transition metal-based catalysts, nickel hydroxide/oxyhydroxides have emerged as the most promising catalysts for OER.³⁻⁷ Nickel hydroxide mainly exists in four different phases⁸ and among them, β -NiOOH and γ -NiOOH are more active than the others for OER.⁹⁻¹² NiOOH, with and without doping, has been extensively studied for OER at both experimental and computational levels.^{3,11,13-15} Compared with other transition metals, the doping of Fe in NiOOH has been shown to increase the OER activity significantly,^{9,16,17} with an optimal doping of 25%.^{17,18}

A direct role of Fe in the OER was proposed given its lower electronegativity compared to Ni and, hence, easier oxidation at OER conditions.¹⁹ However, it has also been argued that Fe can influence the oxidation state of Ni active sites and hence improve their OER activity.²⁰⁻²² A cooperative effect between the two metal sites in facilitating the stabilization of key intermediates, has also been proposed.²³ Despite the extensive studies on the active sites and mechanisms of OER,^{12,24-29} the role of Fe doping remains a source of debate.^{30,31} The lattice oxygen coupling (LOC) mechanism in OER^{32,33} is largely ignored for the metal hydroxide/oxyhydroxide materials since it was deemed unfavorable for such systems.^{34,35} More recently lattice oxygen participation in OER was confirmed for Ni and NiCo LDHs and ruled out for NiFe-LDH and NiFeCo-LDH.³⁶ However, the LOC mechanism for OER has not been investigated for neither undoped nor Fe-doped NiOOH. Interestingly, it is anticipated that, unlike bulk, low-dimensional forms of metal oxyhydroxides can provide structural flexibility for LOC mechanism.^{37,38}

In this letter, we investigate the direct and indirect effects of Fe doping in NiOOH monolayer (with the structure of β -NiOOH) on improving the OER activity using density-functional

theoretic (DFT) methods. We compare the activity of an active site on undoped NiOOH (AS-1) with two types of active sites on Fe-doped NiOOH - one that involves the Fe atom (AS-3) and one that does not (AS-2). We assess the activity via two OER mechanisms for both undoped and Fe-doped NiOOH monolayers. The mechanisms differ in the source of O-O bond formation: in one case, the bond is formed between lattice oxygen and an oxygen atom from H₂O i.e., water nucleophilic attack (WNA) mechanism, while in another case, both oxygen atoms are from the catalyst lattice, i.e., lattice oxygen coupling (LOC) mechanism. We find that the LOC mechanism involves lower thermodynamic overpotentials in Fe-doped NiOOH regardless of the nature of the active site. Consequently, OER will proceed through LOC rather than WNA upon Fe-doping. The active site with Fe directly involved (AS-3) yields the lowest thermodynamic overpotential when O-O bond forms via LOC mechanism. OER through the WNA mechanism has a lower overpotential on AS-2 than AS-3 suggesting an indirect role of Fe in this case.

Structure of the catalyst Unlike bulk NiOOH, the proton distribution is not known for NiOOH monolayer. Herein, we investigated various kind of proton distribution on pristine and Fe-doped NiOOH monolayers. The detailed discussion is presented in section 2 in supplementary information (SI).

We found that the most stable structure has H_C proton distribution for NiOOH as depicted in Figure 1 (a). The H_C structure is composed of two type of octahedra: - i) O_A: four O and two OH, ii) O_B: two O and four OH. In Fe-doped NiOOH, the structure with Fe located in O_A has the lowest energy (Figure 1 (b)). Furthermore, in ground state, all the Ni are ferromagnetically (FM) aligned (Table S1 in SI) whereas Ni and Fe sublattices are in antiferromagnetic (AFM) alignment in Fe-doped NiOOH (Table S3 in SI).

Active sites. Since the (0001) surface is the most dominating and stable surface in NiOOH synthesis and at electrochemical conditions, we chose the active sites to be on the terraces of

Figure 1: The most stable of H-distributions over (a) NiO_2 , (H_C) and (b) NiFeO_2 ($\text{H}_\text{C-2}$) monolayers. Gray, brown, red, and white spheres represent Ni, Fe, O, and H, respectively.

the undoped and Fe-doped NiOOH monolayers.^{29,39–41} Among the two types of active sites - hydroxo and oxo (Figure S3 in SI), hydroxo sites have lower overpotential than oxo sites for OER on (0001) surface of β -NiOOH.¹⁵ Therefore, we considered hydroxo sites to evaluate OER mechanisms on pristine NiOOH monolayer (AS-1). On Fe-doped NiOOH, the active sites are further distinguished by their coordination environments. For example, the hydroxo groups on Fe-doped NiOOH monolayer are coordinated with either three Ni (AS-2) or two Ni and one Fe (AS-3). We considered both, AS-2 and AS-3, possibilities in this work. All considered active sites are depicted in Figure 2.

In AS-2, the Fe is not directly available to adsorbate species and presumably plays an indirect role by modifying the electronic structure of Ni on active sites. In contrast, in AS-3, one Fe is adjacent to the active site and can be directly involved in the oxygen evolution reaction.

Mechanisms for OER. Several OER mechanisms have been previously studied, includ-

ing single-site and dual-site mechanisms.^{9,12,42} Herein, we simulated and compared two mechanisms for OER based on two different ways of O-O bond formation. The first mechanism (WNA) involves the oxidation of O^{2-} from a water molecule. The second mechanism (LOC) involves the oxidation of lattice oxygen which is later recovered by consuming the water molecules. The mechanisms are depicted in Figure 3 and Figure 4 for undoped and Fe-doped NiOOH, respectively. The A-B-C-D-I-J sequence of reactions in the inner cycle and the A-E-F-G-H-I-J sequence in the outer cycle represent WNA and LOC mechanisms, respectively. The corresponding reaction free energies are presented in Table 1.

In the first step (A), the initial hydroxo group (HO^*) undergoes dehydrogenation by removal of coupled proton and electron in reaction to produce O^* . The first step A is common in both WNA and LOC mechanisms. In the next step O-O bond has to form. The two mechanisms differ in the next step of O-O bond formation. WNA mechanism proceeds by the adsorption of a H_2O molecule with simultaneous removal of coupled proton and electron to form HOO^* in step B. Next, in steps C and D, dehydrogenation and O_2 evolution lead to the creation of a vacancy on the catalyst. Subsequently, adsorption of a H_2O molecule (H_2O^*) in step I, followed by dehydrogenation in step J, regenerate the catalyst. On the other hand, LOC mechanism branches off to step E, forming O-O bond by coupling of two lattice oxygen atoms to form $(\text{O}-\text{O}_\text{L})^*$. After step E, O_2 evolution creates two O vacancies (V_O^*) in the lattice in step F. Then, the vacancies were filled by a H_2O adsorption followed by the removal of pairs of proton and electron in steps G, H, I, and J. Step I and J are also common in both WNA and LOC mechanisms. Steps D, E, F, and I are non-electrochemical. In contrast, all others are electrochemical as they include the exchange of proton and electron.

OER at AS-1. In the active site AS-1, the hydroxo group coordinated to three Ni atoms, out of which one Ni has an O_A octahedron while the other two Ni have O_B octahedra. The abstraction of the a pair of proton and electron

Figure 2: Three types of active sites. (a) pristine NiOOH; (b), and (c) Fe-doped NiOOH. The numbers in parentheses are the vacancy formation energies in eV.

Figure 3: OER mechanisms on pristine NiOOH at active site AS-1. Outer and inner cycles represent LOC and WNA mechanisms, respectively. LOC branches off after step A by forming O-O bond between two lattice oxygen atoms highlighted with small blue circles. The transition state structure for step G is presented in Figure S4 in SI. Violet and green spheres, respectively, represent adsorbate oxygen and hydrogen atoms.

from HO^* leads to oxidation of Ni^{3+} in O_B to Ni^{4+} ($t_{2g}^6 e_g^0$). The O-O bond formation in step B via nucleophilic attack of water and a simultaneous dehydrogenation is less energy demanding than step A. In step B, Ni^{4+} reduces

back to Ni^{3+} . Furthermore, the dehydrogenation of hydroperoxo (HOO^*) intermediate in step C and successive O_2 evolution in step D remains less energy demanding than step A. In the vacancy (*) formation in step D, one Ni

atom in O_B is reduced from Ni^{3+} (d^7) to Ni^{2+} (d^8). The reduction of Ni has also been reflected in Löwdin charge analysis as spin polarization changes from 1.19 to 1.68 after vacancy formation. Ni^{2+} remains unchanged during adsorption H_2O in step I. The reduced Ni^{2+} gets oxidized to Ni^{3+} in the last dehydrogenation step J. All steps in WNA mechanism are comparatively less energy-demanding than step A (see Table 1). Therefore, the formation of O^* in step A is the potential determining step (PDS) with an overpotential of 0.59 V via WNA mechanism in the case of pristine $NiOOH$. The PDS found in the pristine $NiOOH$ monolayer agrees well with the findings of Rajan et al. on (0001) surface of pristine β - $NiOOH$. The overpotential was predicted to be 0.69 V using PBE+U with $U(Ni)=5.5$ eV.¹⁵ Tripkovic et al. also found the formation of O^* from HO^* as the PDS with an overpotential (η) of 0.6 eV⁴² although they used the H_D type for the structure of the $NiOOH$ monolayer.

Step A continues to be the PDS even in LOC mechanism since all of the other electrochemical elementary steps in LOC mechanism require less energy to proceed. After step A has occurred, there will be competition between steps B and E. Step E is a chemical step independent of the applied potential. In contrast, step B is an electrochemical step, and its free energy demand decreases by applied potential. However, the endergonicity of step E is 0.11 eV which is not very high. Therefore, under the conditions in which water can adsorb on the surface, i.e., step I, the chemical coupling of lattice oxygen atoms in step E is thermodynamically possible. These findings are in line with the experimental study by Lee et al. that the lattice oxygen atom are involved in OER in pure Ni hydroxides.³⁶

OER at AS-2. On doping with Fe, Fe^{4+} replaces Ni^{3+} in pristine $NiOOH$ which can significantly change the potential of the active site. In the case of AS-2, when Fe is away from the active site all the effects coming from Fe will be by indirect modification of the electronic structure of Ni and O atoms near the active site. A schematic of the OER mechanism on Fe-doped $NiOOH$ is shown in Figure 4.

It is worth noting that the reaction-free en-

ergy of step A decreases by an amount of 0.1 eV on changing the active site from AS-1 to AS-2 (see Table 1). As indicated by reaction free energies of steps A and B in Table 1, the presence of Fe^{4+} stabilizes the O^* and destabilizes the HOO^* , which leads to a decrease in the reaction free energy of step A and an increase in that of step B. The Fe remains in +4 oxidation state along WNA mechanism whereas one of the Ni^{3+} (in O_B type octahedron) at active site oxidizes to Ni^{4+} in step A. Step A turns into PDS when the reaction occurs through WNA mechanism and exhibits a 0.54 V overpotential. For OER via WNA mechanism, the inclusion of Fe dopant away from the active site lowers the overpotential by 0.05 V. In LOC mechanism, the reaction-free energy and PDS trends remain the same as in the case of AS-1. It should be noted that when, in step E on AS-2, two oxygen atoms from lattice combine to form an O-O bond then the Fe becomes part of the active site in LOC mechanism (see Figure 4 (a)). The reaction free energy of O-O bond formation in step E is negligible (2 meV). The oxidation state of Fe remains unaltered in LOC mechanism as well. On comparing the thermodynamic overpotentials of WNA and LOC mechanisms on AS-2, OER is most likely to occur via LOC mechanism (see Table 1). However, the active sites involving only Ni atoms proceed with WNA mechanism with step B as PDS. The indirect effect of Fe has also been observed experimentally in Fe-doped Ni oxide films by Li et al. where Fe^{3+} act as Lewis acid in nickel oxide host and facilitates the formation of Ni^{4+} which in turn promotes O-O bond formation and hence, the OER activity.²² In step I at AS-2, it is more challenging to remove proton and electron from the H^* than at AS-1 in the pristine $NiOOH$. The H is bound to O and bonded more firmly to Fe^{4+} at AS-2 than to Ni^{3+} at AS-1. Still, at AS-2, LOC mechanism is thermodynamically more favorable than WNA mechanism. In addition, The Gibbs free energy change of the water adsorption process in step I is nearly identical in pristine (AS-1) and Fe-doped $NiOOH$ (AS-2 and AS-3).

OER at AS-3. The presence of Fe at the active site leads to the same PDS in WNA mech-

(a) OER mechanisms on AS-2

(b) OER mechanisms on AS-3

Figure 4: OER mechanisms on Fe-doped NiOOH at active sites - (a) AS-2 and (b) AS-3. Other features are same as Figure 3.

anism as in AS-2. The stabilization of O^* by Fe is more pronounced at AS-3 where Fe oxidizes from Fe^{4+} to Fe^{5+} whereas at AS-2 Ni oxidizes from Ni^{3+} to Ni^{4+} . Therefore, the strong adsorption of O and high stability of O^* intermediate lead to the lowest free energy of step A on AS-3 among all three active sites. Notably, the O-O bond formation in step B at AS-3 is the least feasible among all active sites considered in this work. Consequently, step B becomes the PDS when the reaction proceeds through WNA mechanism (see Table 1). In LOC mechanism, the reaction-free energy of step E at AS-3 (0.12 eV) is similar to that at AS-1 (0.11 eV). Like AS-1 and AS-2, the free energy step E is smaller than water adsorption in step I. Consequently, step I can proceed under the conditions that the water can adsorb on the surface. In LOC mechanism at AS-3, unlike AS-1 and AS-2, the O-H bond breaking in step H is the PDS with an overpotential of 0.3 V. In fact, the thermodynamic overpotential in LOC mechanism (0.30 V) is much smaller than in WNA mechanism (0.86 V).

The overpotential of AS-1 in undoped NiOOH (0.59 V) is decreased by 0.29 V by doping of Fe (0.30 V in LOC mechanism). These findings are in good agreement with the experimental study by Klaus et al., where the overpotential of NiOOH (0.53 V) decreased by 0.25 V when there Fe impurities in the system (0.28 V).¹⁶

Lee et al. recently investigated similar kinds of active sites to study the WNA type of mechanism on the Ir-doped NiOOH monolayer.⁴¹ They found that the Ni sites near Ir show the lowest overpotential followed by Ni sites on pure NiOOH then Ir sites on Ir-doped NiOOH. For the WNA mechanism case, our results are in good agreement with Liu et al.⁴¹

A recent experimental study presented evidence of the involvement of lattice oxygen in OER in NiFe oxyhydroxide catalysts.⁴³ In that study, the O-O bond formation is shown to be a rate-limiting step and not the O-H bond breaking. This distinction in the potential determining step in our work and rate-limiting step in work by Hao et al.⁴³ could be due to the kinetics of OER in the experiment which is omitted here. Furthermore, in the theoretical part of

the study by Hao et al., undercoordinated Fe sites at edges in Fe-doped γ -NiOOH are considered as active sites, whereas in our work, active sites are at the terrace of the NiOOH monolayer (with the structure of β -NiOOH). The key difference is that at edge sites, the intermediates not involving lattice oxygen are solely adsorbed on Fe. In contrast, on the terrace site, adsorbed species are shared by three metal atoms.

For the Fe doping case, our results of AS-3 ($\eta=0.86$ V) disagree with Tripkovic's work ($\eta=0.43$ V). It could be because of the different structural models in the two studies. In our work, Fe has the oxidation state of +4 in the H_C -2 structure, whereas, in Tripkovic's work, Fe is in the oxidation state of +3 in the H_D -3 type structure. As mentioned earlier, H_C -2 has a lower formation energy and would hence be the more likely structure.

Overall, in WNA mechanism, pure NiOOH shows the formation of O^* as PDS, while doping with Fe changes the PDS to O-O bond formation. By changing the mechanism from WNA to LOC at the Fe site in Fe-doped NiOOH, the PDS changes from chemical O-O bond formation to the electrochemical O-H breaking. Consequently, the thermodynamic overpotential on AS-3 decreases significantly from 0.86 V to 0.30 V. The free energies for WNA and LOC mechanisms for all three active sites are shown in Table 1.

The thermodynamics of elementary steps suggest that the LOC mechanism is the dominant mechanism. However, this could completely be changed if kinetic barriers are taken into account. We calculated the activation barriers of chemical step G at AS-1, AS-2, and AS-3 using the climbing image nudged elastic method (NEB-CI) and the free energies are 1.14 eV, 1.20 eV, and 1.31, respectively. The activation barrier of O-O bond formation via nucleophilic attack of water (step D) is calculated in very few cases. For example, at OER conditions (1.8 V), the activation barrier on IrO_2 and RuO_2 surfaces is 0.5 eV or less.^{44,45} Using metadynamics, another study reported the barrier of 0.96 eV (PBE) and 0.79 eV (B3LYP) for Ru-complex.⁴⁶ Furthermore, the formation of HOO^* from O^* in step D can also be thought of as a combi-

Table 1: Reaction Gibbs free energy of OER on all three active sites - AS-1, AS-2, and AS-3. The Gibbs free energies and overpotentials are presented in the units of eV and V, respectively. WNA mechanism: A–B–C–D**–I–J; LOC mechanism: A–**E–F–G–H**–I–J.**

Reaction step		AS-1		AS-2		AS-3	
		ΔG	η	ΔG	η	ΔG	η
A	$\text{HO}^* \rightarrow \text{O}^* + \text{H}^+ + \text{e}^-$	1.82	0.59	1.72	0.49	1.33	
B	$\text{O}^* + \text{H}_2\text{O} \rightarrow \text{HOO}^* + \text{H}^+ + \text{e}^-$	1.73		1.77	0.54	2.09	0.86
C	$\text{HOO}^* \rightarrow \text{OO}^* + \text{H}^+ + \text{e}^-$	0.68		0.67		0.97	
D	$\text{OO}^* \rightarrow \text{O}_2 + *$	-0.42		-0.46		-0.86	
E	$\text{O}^* + \text{O}_L \rightarrow (\text{O-O}_L)^*$	0.11		0.002		0.12	
F	$(\text{O-O}_L)^* \rightarrow \text{O}_2 + \text{V}_\text{O}^*$	-0.12		-0.34		-0.48	
G	$\text{V}_\text{O}^* + \text{H}_2\text{O} \rightarrow \text{H}^* + \text{H}^+ + \text{e}^-$	0.55		0.66		1.03	
H	$\text{H}^* \rightarrow * + \text{H}^+ + \text{e}^-$	1.44		1.67		1.53	0.30
I	$* + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O}^*$	0.23		0.19		0.25	
J	$\text{H}_2\text{O}^* \rightarrow \text{HO}^* + \text{H}^+ + \text{e}^-$	0.88		1.03		1.14	

nation of an electrochemical step (O-H bond breaking), and a chemical step (O-O bond formation).²³ At Ni site in γ -NiOOH, Xiao et al. calculated the free energy barrier of exergonic chemical O-O bond formation between an adsorbed O and an O from water as in WNA mechanism to be 0.48 eV at the $U=2.28$ eV.²³ The activation barrier for the electrochemical O-H bond breaking is clearly less than typical values for the O-O bond formation estimated from these works.⁴⁵ Since step G has a high barrier, presumably higher than step D, LOC mechanism is likely to be kinetically slow. A more accurate assessment can result from computation of the barrier for step B in our case. However, such a calculation has not been done in the present study.

Electronic structure of key intermediates. Doping of Fe into NiOOH monolayer increases the stability of O^* intermediate by creating extra local positive charge and destabilizes HOO^* . Spin density analysis of the O-O bond in HOO^* indicates a triplet nature of the O-O bond (see Figure S5 in SI). After deprotonation of HOO^* , the triplet like nature of the adsorbed O_2 is retained in the case of AS-1 and AS-2 (see Figure 5 (a,b)). Interestingly, in the case of AS-3, the adsorbed O_2 attains singlet

character resembling the $^1\Sigma_g^+$ state of molecular O_2 . It can be clearly seen in Figure 5 (c) that the π_x and π_y orbitals of the adsorbed O_2 have antiparallel spin densities. In step C, the O_2 desorbs from the surface as a triplet oxygen. Note that spin density in adsorbed O_2 is antiferromagnetically coupled with metal atoms at all active sites. In the case of AS-1 and AS-2, spin density on Ni atoms is antiferromagnetic to that on O_2 adsorbate. In the case of AS-3, the spin density in π_x is antiferromagnetic with spin density on Fe, whereas spin density in π_y is antiferromagnetic with Ni atoms. This configuration is preferred because the metal atoms are antiferromagnetically coupled to each other. To validate our argument, we calculated the spin density with all metal atoms in ferromagnetic configuration (See Figure 5 (d)). This magnetic configuration is 0.25 eV higher in energy than a configuration where Ni atoms and Fe atoms are antiferromagnetically aligned. It is observed that in the higher energy configuration O_2 attains triplet character antiferromagnetically aligned with surrounding metal atoms. Thus, it is the antiferromagnetic coupling between Ni and Fe, that drives the O_2 adsorbate to a singlet state.

The O-O bond formation through the lattice

Figure 5: Spin density of O_2^* intermediate for undoped and Fe-doped NiOOH . The isosurface value used is 0.02 a_0^{-3} . The shaded region presents the active region for OER.

oxygen in LOC mechanism always results in a triplet state for bound oxygen. It is worth noting that, in contrast to Ni atoms, the adsorbed O_2 is weakly bound to adjacent Fe atom. The adsorbed O_2 in the intermediate $(\text{O}-\text{O}_\text{L})^*$ remains as triplet by maintaining antiferromagnetic coupling with adjacent Ni atoms.

Conclusions. We have studied several proton distributions for pristine and Fe-doped NiOOH monolayer and found the most stable structure to be the one with asymmetrical octahedral coordination. Considering the lowest energy structure for pristine and Fe-doped NiOOH , we have investigated the three types of active sites, one on NiOOH and two on Fe-doped NiOOH , for two mechanisms based on the source of O to form O-O bond including the lattice oxygen is coupling mechanism which largely overlooked in the literature. Fe doping into NiOOH lattice changes the PDS by stabilizing the O^* intermediate and involving the lesser energy-demanding oxidation of Fe^{4+} to Fe^{5+} than Ni^{3+} to Ni^{4+} . We also find that for pristine NiOOH , the PDS is independent of the mechanisms considered. In the Fe doped case, the mechanism involving the oxidation of lattice oxygen to form O-O bond (LOC mechanism) shows lower overpotential than WNA mechanism. This study reveals that doping of Fe in NiOOH has both direct and indirect effects on the OER mechanism. The direct effect via presence of Fe in the active site is more pronounced for stabilization of O^* intermediate,

whereas the indirect effect via Fe atom adjacent to the active site is vital for decreasing the overpotential Ni sites. In the presence of Fe, the PDS for OER changes, and reaction preferentially proceeds through the oxidation of water rather than the oxygen atoms. Our findings that the doping of Fe decreases the overpotential by 0.29 V is in excellent agreement with the experimental observation.¹⁶

Conflicts of interest

There are no conflicts to declare.

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Supporting Information Available

The following files are available free of charge.

- supplementary.pdf: This file contains supplementary information, including the computational methods, structures of pristine and Fe-doped NiOOH , tables

of energies of various structures in different magnetic states, image highlighting oxo and hydroxo sites on NiOOH, comparison of transition state structure and free energy barriers of step E at all active sites, and spin density plot of HOO* at AS-3.

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