Identical Spin Multi-State Reactivity Towards C-H Bond Activation in High-valent Fe/Mn-Oxo/Hydroxo Species

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Activation of C-H bonds using an earth-abundant metal catalyst is one of the top challenges of chemistry where high-valent Fe/Mn-O/OH biomimic species play an important role. There are several open questions related to the comparative oxidative abilities of these species, and a unifying concept that could accommodate various factors influencing the reactivity is lacking. To shed light on these open questions, here we have used a combination of the DFT (B3LYP-D3/def2-TZVP) and ab initio (DLPNO-CCSD(T); CASSCF/NEVPT2) calculations to study a series of high-valent metal-oxo/hydroxo species, $[M^{n+}H_3buea(X)]$ (M = Fe and Mn, n = II to V, X = O/OH; H_3buea = tris[(N'-tert-butylureaylato)-N-ethylene)]aminato) towards the activation of dihydroanthracene (DHA). Detailed analysis unveils the following reactivity trend $Fe^{v}=0 > Mn^{|v|}=0 > Mn^{|v|}=$ > Fe^{III}=O > Mn^V=O > Fe^{II}-OH > Mn^{II}-OH > Mn^{IV}-OH > Fe^{IV}-OH > Fe^{IV}=O > Fe^{III}-OH > Mn^{III}-OH and suggests that neither higher oxidation nor high-spin ground state yields superior reactivity. The secondary coordination sphere is found to play a vital role in controlling the reactivity wherein the H-bonding interactions reduce the crystal field strength, and this brings several excited states of the same spin multiplicity closer to the ground state resulting in the observation of identical spin multistate reactivity (ISMR) in Mn^{III}/I^V=O and Fe^{II}-OH species. For Fe^V=O species, strong ligand spin polarization was detected, diminishing the crystal field leading to the exhibition of ISMR reactivity. The ISMR is found to control the basicity of the oxo/hydroxo group as well as the redox potentials. Further, when pKa > 15, a PT-ET mechanism for C-H bond activation is detected, and a higher E_{1/2} value directs the reaction via the concerted HAT/PCET mechanism. On the other hand, for species that exhibit classical SSR/TSR reactivity, such as Mn^{II}-OH, Fe^{IV}=O, the secondary coordination sphere effect is found to be lethal. As the multireference character is absent in these species, they lack the electronic flexibility that ISMR species enjoy during the reaction, leading to sluggish/no reactivity for many species, including the popular Fe^{IV}=O species. As metalloenzymes' active sites have several H-bonding networks resembling the species studied here, this unlocks the possibility of having ISMR type reactivity for metalloenzymes to rationalize their superior catalytic abilities.

Introduction

Aliphatic C-H bond activation is challenging in synthetic chemistry due to its very high thermodynamic stability.¹ Studies over the past few decades have proven that the non-heme high-valent manganese and iron complexes with terminal oxo ligand are potential in various oxidative transformations, including C-H bond functionalization and oxygen-atom transfer reactions, having resemblance with the active site of many biological systems such as peroxidases, halogenases,^{2, 3} and in the oxygen-evolving complex (OEC) of photosystem II.⁴ One of the most important aspects behind the high reactivity and selectivity of these naturally occurring metalloenzymes is the involvement of the secondary coordination sphere. While the primary coordination sphere regulates the electronic structure and other fundamental properties (Lewis acidity, spin states, etc.), the secondary coordination sphere controls the substrate accessibility and positioning. The combination of these two is ultimately responsible for the reactivity of the metalloenzymes.⁵ The primary coordination sphere is mainly influenced by the nature of the metal ions in the active site, its oxidation state, the geometry around the metal, the nature of the ligands, and the type of donor atoms on the ligand, etc. The cumulative effect of all these factors is paramount for the stability and catalytic reactivity of native enzymes and their biomimic models.

In the past few decades, several experimental groups have been working extensively in this area, optimizing various parameters mentioned above to structurally and functionally mimic the reactivity of the naturally occurring metalloenzymes. In this direction, the first prototypical Fe^{IV}=O intermediate, TauD-J (taurine:

 α -ketoglutarate dioxygenase having five-coordinate TBP geometry), has been trapped and spectroscopically characterized to possess a high-spin (S = 2) ground state⁶ followed by the synthesis and characterization of numerous non-heme Fe^{IV}=O complexes to comprehend their role in biomimic chemistry⁷⁻¹⁰. These terminal non-heme Fe^{IV}=O species are found to be the most powerful and extensively studied oxidants targeting aliphatic C-H bonds. On the other hand, one-electron reduced Fe^{III}=O and one-electron oxidized Fe^v=O derivatives are comparatively rare and less explored. While a handful of biomimic complexes of Fe^V=O have been reported and characterized,¹¹⁻¹³ only two terminal Fe^{III}=O complexes are reported to date, and both of them are known to stabilize in the presence of secondary coordination sphere.¹⁴⁻¹⁶ Besides the Fe-oxo complexes, Mn-oxo model complexes also stimulate inorganic chemists owing to their possible roles in water oxidation carried out by photosystem II. In Mn chemistry, Mn^{III/IV/V}=O species are relevant¹⁷⁻²⁴, and several high-valent Mn^{IV/V}=O complexes have been synthesized, characterized, and found to possess aggressive oxidizing abilities sometimes even higher than the popular Fe^{IV}=O species.^{25, 26} In enzymes such as chloroperoxidases (compound II) and lipoxygenases, the active site was found to have Fe^{IV}-OH and Fe^{III}-OH groups, respectively. Though there are some isolated reports, very little is known on the oxidizing abilities of the protonated metal oxo species of this type, which is found to regulate the net charge, M-O bond-order, redox potential, and therefore expected to influence the reactivity of these complexes.

One of the most crucial factors in the biomimic-chemistry of highvalent transition metal-oxo/hydroxo species is the participation of several possible spin states. In all the metalloenzymes, the Fe^{IV}=O intermediates were found to possess a high-spin (S = 2) as the ground state, while a significant majority of the biomimic models synthesized to date have an S = 1 ground state.^{10, 27} Large body literature collected over the years suggests that spin-states are crucial in dictating reactivity, and complexes with high-spin states are expected to react faster than those with intermediate/low-spin states. While significant efforts were undertaken to synthesis a true S = 2 Fe^{IV}=O complex, only a handful of examples are reported so far. Among others, trigonal-bipyramidal Fe^{IV}=O complexes are perhaps the best characterized.²⁸ Additionally, the geometry around the metal ion also plays a vital role in dictating the reactivity, which is evident from the fact that octahedral Fe^{IV}=O species are very aggressive oxidants while their trigonal-bipyramidal counterparts are generally sluggish.

Another important factor that controls the oxidizing potential of these species is the basicity of the metal-oxo/hydroxo part, which in turn dictates the mechanism by which the C-H bond activation should take place. Various possible mechanisms such as proton transfer followed by electron transfer (PT-ET), H-atom transfer (HAT), proton-coupled electron transfer (PCET), or a HAT blended PCET, have been proposed in this chemistry.²⁹ Earlier studies revealed higher reactivity for species if the basicity of the metal-oxo complexes is larger, and this is also accompanied by the HAT mechanism. While there are some isolated experimental reports, a concrete understanding of how the oxidation state alters the pKa value, and this, in turn, alters the C-H bond activation is not fully comprehended.

Upon C-H bond activation, the high-valent metal-oxo species accepts an electron from the substrate to undergo reduction. There are various possibilities depending on the nature of the substrate, its orientation, and the availability of the d-based frontier orbitals. Over the years, multiple channels such as σ (d_z²), π (d_{xz}/d_{yz}) and δ (d_{xy}/d_x². v^2) are proposed based on which d-orbitals of the metal ion accepts the electrons and the barrier height for the C-H bond activation is strongly correlated to the chosen pathway.³⁰⁻³³ Various metal-oxo species are found to react differently, and in general, metal-oxo species that are found to respond via σ channels are termed as more reactive due to the availability of exchange enhanced reactivity (EER). While this is purely a theoretical concept based on the orientation of the substrate at the transition state, the concept has been utilized on various occasions to explain the slower/higher reactivity rate observed for intra vs. intermolecular hydroxylation/aminations.³¹

The above factors which influence the reactivity are correlated to the primary coordination sphere of metal-oxo intermediates. There are cases where attempts have been made to alter the secondary coordination sphere to enhance the reactivity.^{23, 34} The importance of the outer sphere influences enzymatic reactivity is phenomenal. Examples include the work of Burton and co-workers and Siegbahn group have studies the active site model of Syringomycin halogenase (SyrB2), a non-heme Fe(II)/ α -ketoglutarate (α KG)-dependent halogenating metalloenzyme, and found that amino acid groups in the secondary coordination sphere are playing a crucial role in the product selectivity. Visser and co-workers studied a biomimetic model complex of TauD and pointed towards the role of other ligated groups in determining selectivity. In biomimic front, halogenation by Fe^{IV}=O species was attributed to a ferryl bending and C-H•••O interactions.^{8, 35-37}

In this regard, the work of Borovik and co-workers on a series of tris[(N'-tert-butylureaylato)-N-ethylene)]aminato, [H₃buea]³⁻ based monomeric manganese and iron complexes with terminal oxo/hydroxo groups varying the metal oxidation states from +II to +V

gain attention.³⁸⁻⁴⁹ These species are structural analogs²⁴ and offer a unique set of structures to probe these species' relative oxidative abilities. The use of [H₃buea]³⁻ ligand is proven to be tactically very important because of its ability to control the secondary coordination sphere by forming a constrained hydrogen-bonding cage as well as providing a double shield by the *tert*-butyl groups around the metal-oxo/hydroxo moiety, lessening the probability of dimerization, facilitating the formation of a variety of structurally similar monomeric metal oxo/hydroxo complexes in various oxidation states. The reactivity of $[M^{n+}H_3buea(X)]^{m-}$ (here M = Mn or Fe, n = +II to +V and X = O or OH) was found to vary significantly depending on the nature of the metal ion and its oxidation state. In this series, the experimentally observed reactivity trend defies the regular trend noticed in other biomimic models. For example, among the complexes studied [Mn^{III}H₃buea(O)]²⁻ found to be the most reactive followed by [Fe^{III}H₃buea(O)]²⁻ and [Mn^{IV}H₃buea(O)]⁻ while the popular [Fe^{IV}H₃buea(O)]⁻ is very sluggish even with substrates such as 1,9-dihydroanthracene (DHA). The reactivity pattern observed for the hydroxo counterpart is different and found to be correlated to the pK_a values. While the role of spin-states in reactivity is well established, how this is correlated to the experimental observables such as pK₂ value is hitherto not known.

In the present study, we have employed a combination of the DFT method (B3LYP-D3/def2-TZVP) and ab initio DLPNO-CCSD(T); CASSCF/NEVPT2 calculations to shed light on the geometry, electronic structure, spectral features, and reactivity of a series of high-valent metal-oxo/hydroxo complexes, namely. $[M^{II}H_3buea(OH)]^{2-}$, $[M^{III}H_3buea(O)]^{2-}$, [M^{III}H₃buea(OH)]⁻, $[M^{V}H_3buea(O)]^{-}$, $[M^{V}H_3buea(OH)]$ and $[M^{V}H_3buea(O)]$ (here M = Fe and Mn, Scheme 1(a), towards dihydroanthracene (DHA). In this work, we aim to answer the following intriguing questions (i) Is a high-valent oxidation state or a high-spin ground state necessarily leads to greater reactivity? (ii) Is the secondary coordination sphere play a role in biomimic model reactivities? (iii) do the ligand architecture and multireference character of metal-oxo/hydroxo species regulate their reactivity?

Computational Details

Density Functional Theory (DFT) calculation: All geometry optimizations were carried out with the Density Functional Theory (DFT) method using the Gaussian 09 suit of program.⁵⁰ The geometries of all stationary points involved in the reaction mechanism were first optimized in the gas phase without any constraints using dispersion-corrected unrestricted B3LYP hybrid density functional.⁵¹ The functional in the present study has been chosen based on our previous works^{52, 53} and the literature on similar



Scheme 1. (a) Schematic representation of $[M^{n+}H_3buea(X)]$ (M = Mn/Fe, n = II to V, X = O/OH) species and the model-1 to model-4, and (b) Schematic representation of the C-H bond activation of 9,10 dihydroanthracene (DHA) using $[M^{n+}H_3buea(X)]$ species.

Mn/Fe-oxo/hydroxo complexes (Computational method section in ESI). A LACVP basis set has been employed, comprising the 6-31G* description for all light atoms (H, C, N, O), and a double- ξ quality LanL2DZ basis set with Los Alamos effective core potential has been incorporated for the Mn and Fe center. The harmonic vibrational frequency and Intrinsic reaction coordinate (IRC) calculations were performed to characterize the nature of the species. ⁵⁴ Gas-phase electronic energies are refined by the single-point energy calculations on the optimized geometries using a def2-TZVP basis set⁵⁵ for all the atoms in the same level of theory using Grimme's D3 version of dispersion.⁵⁶ The solvation energies have been incorporated using the solvation model based on density (SMD) solvation model⁵⁶ and def2-TZVP basis set for all. As in experiments ^{40, 44, 49, 57} N, N-Dimethylacetamide (DMA) was used as a solvent in our calculations. The B3LYP-D3 computed solvation energies, incorporating the free-energy corrections obtained from the vibrational frequency calculations, have been used to estimate the potential energy surface. The spin-contamination, if found, on the broken-symmetry state, the energies were corrected using Yamaguchi's spin-projected correction formula.58 The natural bonding orbital (NBO)⁵⁹ and the spin natural orbital (SNO)^{60, 61} analysis have been performed using the Gaussian 09 suit of program. Energy decomposition analysis (EDA) has been carried out using AOMix software⁶² to get an insight into the various contributing factors playing an essential role in dictating the stability of the transition states involved. Distortion around the metal has been explored by SHAPE analysis.

The deformation energy (ΔE_{def}) has been calculated to get the destabilizing steric energy associated with the transition states, which is known to be the main factor behind the energy barrier.

The transition states are divided into two fragments, A (catalyst part) and B (substrate part). The solvent phase single-point calculation, as

well as frequency calculations, have been performed on them. We have estimated the energy using the following equation $\Delta E_{def} = TS(A+B)(E_{solvation + Gibbs}) - A(E_{solvation + Gibbs}) - B(E_{solvation + Gibbs})$

Ab initio calculations: All spectroscopic properties such as UV-Vis spectra, electron paramagnetic resonance (EPR), and Mössbauer (MB) parameters were calculated using the ORCA 4.0.1 program.^{63, 64} The spectroscopic data have been used to get confidence on our methodology applied by comparing with the available experimental data. These calculations were performed on the DFT-optimized ground state geometries of the $M^{n+}=O(OH)$ (M = Mn/Fe) complexes. The Time-dependent (TD) DFT method has been used to obtain the electronic transitions associated with the free catalysts using B3LYP hybrid density functional along with the TZVP basis set for all the atoms. The RIJCOSX approximation with def2/J auxiliary basis set has been employed. The zero-field splitting (ZFS) parameters were estimated by utilizing state-averaged complete active space selfconsistent field (SA-CASSCF) theory^{65, 66} along with the incorporation of N-Electron Valence State Perturbation Theory (NEVPT2).67 Scaler relativistic Hamiltonian has considered using the zeroth-order approximation (ZORA) method⁶⁸ (see details in regular Computational method section in ESI). Further, the domain-based local pair natural orbital approximation to coupled-cluster theory with single, double, and perturbative triple excitations, DLPNO-CCSD(T)/cc-PVTZ (tightPNO) method has been employed to gain confidence on the spin-state energetics.⁶⁹ The DLPNP-CCSD(T) error limit has been recently analysed, and a ballpark number of ~20 kJ mol^{-1} has been suggested. In this manuscript, we have used the following denotation, ${}^{2S+1}M_{\sigma\text{-}Mn}{}^{III}{}_{=0}$ where superscript 2S+1 describe the multiplicity of the species, M the name of the species, subscript $\sigma/\pi/\delta$ describe their respective orbital, which is vacant based on CASSCF configuration. The last subscript denotes the nature of the species.



Figure 1: A comparative potential energy diagram depicting the energy separation between the ground state and other excited states of the Mn^n -X (n = II to V, X = O/OH) Species. Red lines – DFT energies and blue lines are DLPNO-CCSD(T) computed energies. The black line is the ground state for both methodology which is set to be zero.

Results

Spin state energetics and spectral Features of Mⁿ⁺-X (M = Mn/Fe, n = II to V, X =O/OH) Species: To understand in detail the relative oxidative abilities of various M^{II/III/IV}=O/OH (M = Mn/Fe) species, we have performed DFT calculations which reveal that all Mn/Feoxo/hydroxo complexes in the series possess a high-spin ground state which is in agreement with the available experimental results (Figure 1, Figure S1-S2, Table 1 and Table S1).^{38, 41, 42, 44, 45, 48, 49} While the other intermediate/low spin states of the various Mn-species are lying between 44.9 kJ/mol (Mn^{IV}-OH species, S = 1) and 201.5 kJ/mol (except the low-spin state of Mn^{IV}-OH species), the intermediate spin states of the Fe-series are comparatively closely placed, lying within 71 kJ/mol for all species and much closer for Fe^{III}=O, Fe^{III/IV} -OH species (Figure 1). This is indicating of a greater possibility of twostate reactivity in the Fe-series. Anomalous to the previously reported experimental as well as computational studies on the nonheme Fe^v=O species with σ -donor N-ligands that generally stabilize an S = $\frac{1}{2}$ doublet ground state, herein we found an S = $\frac{3}{2}$ state of being the ground state.^{12, 70, 71} For Fe^V=O species, our calculations detect spin contamination, which was then eliminated using a spinprojection formula to obtain reliable results.72, 73 The d-orbitals extracted from the ab initio ligand field theory (AILFT) approach using CASSCF/NEVPT2 method reveals that [H₃buea]³⁻ ligand imposes a local trigonal geometry around the metal, generating a relatively weak ligand field, and all the occupied orbitals are placed within a limit of ~2 eV for both Mn and Fe species (Figure S3-S4). The S = $3/_2$ state as the ground state for Fe^V=O can also be correlated to the close-spaced AILFT orbitals. The H-bond cavity around the metal generates a relatively weaker ligand field with the $\pi^*_{yz} \pi^*_{xz} \delta_{xy}$ lying within 0.6 eV (Figure S4f), resulting in the high-spin state.

The ab initio DLPNO-CCSD(T)/cc-PVTZ/TIGHTPNO calculations (Figure 1)^{74, 75} confirm the high-spin as the ground state for all the species, which is consistent with the available experimental data and the DFT calculations except for the Fe^{IV}-OH species where S = 0 is suggested as the ground state by the *ab initio* method. As the DFT computed gap between S = 2 and S = 0 is substantially small for Fe^{IV}-OH species (7.9 kJ/mol), this leads to this switching, as noted earlier. However, the energy gap among various spin-states was found to vary compared to DFT methods, but the trend of spin-state ordering was retained in these calculations. Computing various spectral parameters such as absorption, IR/Raman, Mossbauer (isomer shift and quadrupolar splitting), and EPR (D and E/D) values. The computed parameters are in agreement with available experiments (Figure S5-S6 and Table S2).

The computed M-O bond length and spin-density are given in Figure S7, and the computed Wiberg bond indices for the M-O(H) bond reveal increasing bond order in the following sequence Fe^{II}-OH < Mn^{II}-OH < Fe^{III}-OH < Mn^{III}-OH < Mn^{IV}-OH < Fe^{IV}-OH < Fe^{III}=O < Mn^{III}=O < Fe^{IV}=O < Mn^{IV}=O < Fe^V=O < Mn^V=O (Table S2). In the previous studies, the ability of C-H bond activation by the metal-oxo/hydroxo species is correlated to their MO-H bond dissociation energies, pKa values of the M=O/OH moiety, and also to the reduction potential of the half-reaction involved during the reaction.^{76, 77} Keeping this in mind, we have computed the gas-phase O-H bond dissociation

| catalyst | Spin | % of mixing from CASSCF | Species | Reaction Type |
|-----------------------|-------|--|---|------------------------------------|
| Mn ^{II} -OH | S=5/2 | $\delta^{*}_{xy^{1}}\pi^{*}_{yz^{1}}\pi^{*}_{xz^{1}}\delta^{*}_{x^{2}-y^{21}}\sigma^{*}_{z^{21}}(100\%)$ | ⁶ TS _{Mn} ^{II} -OH | ΡΤ-ΕΤ (δ) |
| Mn ^{III} -OH | S=2 | $\pi^*_{yz^1}\pi^*_{xz^1}\delta^*_{x^{2-y^{21}}}\delta^*_{xy^1}(72\%)$ | ⁵ TS _{σ-Mn} ^{III} -OH | ΗΑΤ (σ) |
| Mn ^{III} -O | S=2 | $\pi_{xz^{1}}^{*}\pi_{yz}^{*}\delta_{xy^{1}}^{*}\delta_{xz^{2}-y^{21}}^{*}(49\%) + \pi_{xz^{1}}^{*}$ | $5TS_{\pi-Mn}III_{=O}$ | ΡΤ-ΕΤ (δ) |
| | | $\delta^{*}_{xy^{1}}\delta^{*}_{x^{2}-y^{21}}\sigma_{z^{21}}(48\%)$ | $5TS_{\sigma-Mn}^{III}=0$ | ΡСΕΤ (σ) |
| Mn ^{IV} =O | S=3/2 | $\pi^{*}_{yz} \delta^{*}_{xy} \delta^{*}_{xy} \delta^{*}_{x^{2}-y^{21}} (55\%) + \pi^{*}_{yz} \pi^{*}_{xz} \delta^{*}_{x^{2}-y^{21}} \delta^{*}_{x^{2}-y^{21}}$ | $4TS_{\sigma-Mn}^{IV} = 0$ | HAT (45%) + PCET (9%, σ) |
| | | $(24\%) + \pi^{*}_{yz} \delta^{*}_{xy} \pi_{xz} (10\%)$ | $4TS_{\sigma-Mn}^{IV} = 0$ | HAT (53%) + PT-ET (5.5%, σ) |
| | | | $4TS_{\delta'-Mn}^{IV} = 0$ | HAT (49%) + PCET (6.8%, σ) |
| Mn ^{IV} -OH | S=3/2 | $\pi^{*}_{yz}\pi^{*}_{xz}\delta^{*}_{x}\delta^{*}_{x}{}^{-}_{y}{}^{21}(49\%) + \pi^{*}_{yz}\delta^{*}_{x}\delta^{*}_{x}{}^{-}_{y}{}^{21}$ | ${}^{4}TS_{\pi-Mn}{}^{IV}_{-OH}$ | HAT (77) + pcet (22) (π) |
| | | $\sigma_{z^{1}}^{*2^{1}}(14\%) + \pi_{xz^{1}}^{*5}\delta_{x^{2}-y^{2}}^{*2^{1}}\sigma_{z^{2}}^{*2^{1}}(12\%)$ | | |
| Mn ^v =O | S=1 | $\pi^*_{xz^1}\delta_{xy^1}(60\%) + \pi^*_{yz^1}\delta_{xy^1}(11\%)$ | ${}^{3}TS_{Mn}{}^{V}_{=O}$ | PCET (61%) + HAT (26%) + PT-ET |
| | | | | (12%) (δ and σ) |
| Fe ⁿ -OH | S=2 | $\pi_{yz}^{*1}\pi_{xz}^{*1}\delta_{xy}^{*2}\delta_{x}^{*2}-\gamma^{21}\sigma_{z}^{*21}(32\%) +$ | $5'I'S_{\pi-Fe}$ "-OH | $PT-ET(\delta)$ |
| | | $\pi_{yz}^{*}\pi_{xz}^{*}\partial_{xy}^{*}\partial_{x}^{*}z^{-}y^{21}\sigma_{z}^{*}z^{1}(30\%) +$ | ⁵ TS _{δ-Fe} ^{II} - _{OH} | ΡΤ-ΕΤ (δ) |
| | | $\pi^{*}_{yz} \pi^{*}_{xz} 0^{*}_{xy} 0^{*}_{x}^{-}_{y}^{2} \sigma^{*}_{z}^{2} (10\%) + \pi^{*}_{x} 1 \pi^{*}_{x} 1 \delta^{*}_{x} 1 \delta^{*}_{x} 2^{-}_{z} 21 \sigma^{*}_{z} 22 (15\%)$ | | |
| Fe ^{III-} O | S=5/2 | $\frac{\pi_{yz}}{\delta_{xy}^* \pi_{yz}^* \pi_{xz}^* \delta_{x}^{*2} - y^{21}} \frac{\sigma_{z}^{*21}}{\delta_{xz}^{*2}} (100\%)$ | ⁶ TS _{Fe} ^{III} _{=O} | ΡΤ-ΕΤ (δ) |
| Fe ^{III} -OH | S=5/2 | $\delta^{*}_{xy^{1}}\pi^{*}_{yz^{1}}\pi^{*}_{xz^{1}}\delta^{*}_{x^{2}-y^{21}}\sigma^{*}_{z^{21}}(100\%)$ | ⁶ TS _{Fe} ^{III} -OH | ΡΤ-ΕΤ (δ) |
| Fe ^{IV} =O | S=2 | $\delta^{*}{}_{xy}{}^{1}\pi^{*}{}_{xz}{}^{1}\pi^{}_{yz}{}^{o}\delta^{*}{}_{x}{}^{2}-{}_{y}{}^{21}\sigma^{*}{}_{z}{}^{21}(99\%)$ | ⁵ TS _{Fe} ^{IV} =O | ΗΑΤ + ΡΤΕΤ (δ) |
| Fe ^{IV} -OH | S=2 | $\pi^*_{yz} \delta_{xy} \delta_{x^2-y^{21}} \sigma^*_{z} (62\%) + \pi^*_{yz} \pi^*_{xz}$ | ⁵ TS _{Fe} ^{IV} -OH | ΡСΕΤ (δ) |
| | | $\delta_{xy}^{1} \delta_{x}^{2} - \gamma^{21} (22\%)$ | | |
| Fe ^v =O | S=3/2 | $\pi^{*}_{yz} \delta^{*}_{xy} \delta^{*}_{x^{2}-y^{21}}(43\%) + \pi^{*}_{yz} \delta^{*}_{xy} \pi_{xz}^{1}$ | $4TS_{\pi-Fe}V_{=O}$ | ΗΑΤ (85%, δ) + ΡΤΕΤ (6%, σ) |
| | | (25%) | $4TS_{\delta-Fe} = 0$ | HAT (7%, δ) + PT-ET (28%,13%, σ) |

Table 1: Table containing the ground state of all species with CASSCF computed electronic configurations, reaction types, and reaction channels involved in various species during the transition.

energy for Mn^{II/III/IV}-OH species, and these are 262.9 kJ/mol, 279.8 kJ/mol, and 271.5 kJ/mol, respectively suggesting a stronger driving force towards the formation of Mn^{III}=O compared to Mn^V=O and Mn^{IV}=O species. Similar to the Mn-OH species, the gas-phase FeO•••H bond dissociation energies for the Fe^{II}-OH, Fe^{III}-OH, Fe^{IV}-OH species are estimated to be 192.7 kJ/mol, 270.8 kJ/mol, and 200.4 kJ/mol, respectively, indicating that a higher driving force in the conversion of Fe^{III}=O species to Fe^{II}-OH, followed by Fe^{IV}-OH and Fe^{III}-OH. A very large value estimated for Fe^{III}-OH stems from the lesser number of hydrogen bonding interactions (only two interactions) compared to three interactions noticed for Fe^{II}-OH and Fe^{IV}-OH species. The Lewis acidity (pKa) of the M-O/OH moiety decreases as $Mn^{III}=O > Fe^{III}=O > Fe^{II}-OH > Mn^{II}-OH > Mn^{IV}=O > Fe^{IV}=O > Mn^{III}-OH$ > Fe^{III}-OH > Mn^V=O > Mn^V=O > Fe^{IV}-OH > Mn^{IV}-OH in the DMA medium while the calculated one-electron reduction potential values $(E_{1/2})$ of the corresponding half-reaction for each species follows the order Fe^{IV}-OH > Fe^V=O > Mn^{IV}-OH > Mn^V=O > Fe^{IV}-OH > Mn^{IV}=O > Fe^{III}-OH > Mn^{III}-OH > Fe^{III}=O > Mn^{III}=O > Mn^{II}-OH > Fe^{II}-OH against the Fc⁺/Fc couple (Table S2).

Recent DFT as well as CASSCF studies on the $[Mn^{IV}(O)(N4Py)]^{2+}$ and $[Mn^{IV}(O)(BnTPEN)]^{2+}$ complexes have shown very rich electronic properties and pointing towards the involvement of multiple electronic states in the same spin surfaces.⁷⁸⁻⁸⁰ These energetically close-lying electronic states cannot be defined well by a single determinant approach, and therefore, the complete active space self-consistent field (CASSCF) method gives a better perspective of all states by defining the electronic wavefunction in all possible

configurations distributing the electrons in the active space. In the present study, the state-average CASSCF calculations reveal a strong mixing of ground-state configuration with other electronic excited states indicating a strong multiconfigurational character in Mn^{III/IV}=O, Mn^{IV}-OH, Fe^{II/IV}-OH, and Fe^V=O species (Table 1). For example, for the Mn^{III}=O species, CASSCF yields $\pi^*_{xz} \pi^*_{yz} \delta^*_{xy} \delta^*_{x}^{-2}_{y}$ configuration has a weightage of 49% with another 48% contribution arise from the excitation of electrons from $\pi^*_{yz} \rightarrow \sigma_{z^2}$ orbital, suggesting that both π^*_{yz} and σ_z^2 orbitals are strongly mixed. Similar to the Mn^{III}=O species, a strong multideterminant character was found in Fe^v=O species, where the significant contribution to the total wavefunction is arising from $\delta_{xy} \pi^*_{yz} \pi^*_{xz}$ (44%) configuration which is found to be mixed with the $\delta_{xy^1}\pi^*_{yz^1}\sigma^*_{z^{21}}$ configuration (25%) (see ESI for other species details). Further to quantify the secondary interactions and their relation with the existence of multiconfigurational character, the NBO donor-acceptor interactions for the N-H ... O moiety are analyzed. NBO analysis yields a very strong N-H•••O interaction for Mn^{III}=O and Fe^{III}=O species (> 35 kJ/mol), and this is followed by the Mn/Fe^{II}-OH and Mn^{IV}=O species (> 30 kJ/mol), Mn^{IV}-OH, and Fe^{III}-OH (> 25 kJ/mol) species. The interaction is found to be much weaker for Mn^{III}-OH, Fe^{IV}=O, Fe^{IV}-OH and Mn/Fe^V=O species (< 20 kJ/mol). This quantitative strength estimated acts as a tool of whether to have a multideterminant character or not. Although having stronger secondary interactions, the Mn^{II}-OH/Fe^{III}=O(OH) species are highspin d⁵ electronic configurations and do not have any d-electronic excited states of the same multiplicity. The N-H•••O donor-acceptor interactions are weaker in Fe^v=O species, yet multideterminant character was observed. To understand this anomaly, we carefully

analyse the computed electronic structure, which reveals that a spinup α -electron density from one of the N_{eq}-donor sites is transferred to the oxyl centre through the iron centre, resulting in a spinpolarized state with oxyl and nitrogen centres having opposite ~ 0.5 and ~-0.5 spins, respectively (Figure S7m). This spin polarization is expected to diminish the N-H•••O donor-acceptor interactions and also results in weaker N_{eq}–Fe/Fe–O interactions. This leads to the close-lying excited state of the same multiplicity and observation of orbital mixing. This is in agreement with the previous characterization of Fe^v=O species, where the Fe-O centre is found to be antiferromagnetically coupled with the directly coordinating ligands.⁷⁰

Reactivity of Mnⁿ⁺-X (n = II to V, X =O/OH) species towards C-H bond activation: Scheme 1(b) demonstrates the mechanism of the C-H activation step for the conversion of 9,10-dihydroanthracene (DHA) to anthracene using M^{n+} -X (where M = Mn/Fe, n = II to V, X =O/OH) species as catalysts. The reaction initiates by the formation of a Van der Waal complex (RC) of free catalyst and the substrate (DHA), which undergoes hydrogen atom transfer reaction either by stepwise (PTET) mechanism or by a concerted (PCET/HAT) pathway forming either a monoanionic MHA⁻ or a mono-radical MHA• (INT) species, respectively. Herein we have concentrated only upon the C-H activation step, which is reported to be the rate-determining one for the overall conversion (Figure 2, Figure S1-S2). 2a). Considering the five d-orbitals on Mn, CAS (4,5) calculations reveal that, for ${}^{5}RC_{\pi-Mn}{}^{III}_{=0}$ the ground state configuration of $\pi^{*}_{yz^{1}}$ $\pi^*_{xz^1} \delta^*_{xv^1} \delta^*_{x^2-v^{21}}$ is contributing 42% to the total wave function while the next highest contribution (28%) is originating from the $\pi^*_{xz} \rightarrow$ $\sigma_z^*^2$ excitation. On the contrary, for ${}^{5}RC_{\sigma-Mn}{}^{III}_{=0}$, the contribution from the ground state configuration, $\pi^*_{yz} \delta^*_{xy} \pi^*_{xz} \delta^*_{xz'} \gamma^{21}$ is increased to 75%, indicating a lesser mixing to the ground-state configuration (Table S4). The low-lying ${}^{5}RC_{\pi-Mn}{}^{III}{}_{=O}$ state is connected to the lowest energy barrier of 50.7 kJ/mol (${}^{5}TS_{\pi-Mn}{}^{III}{}_{=0}$) for activating the C-H bond while ${}^{5}TS_{\sigma-Mn}{}^{III}=0$ is lying at 12.2 kJ/mol uphill from ${}^{5}TS_{\pi-Mn}{}^{III}=0$. The CAS (4,5) calculations reveal that in ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$; the total wave function is comprised of the 59% contribution from a $\pi^*_{yz^1} \delta^*_{x^2-y^{21}} \delta^*_{xy^1} \pi^*_{xz^1}$ configuration with a significant mixing of a singly excited $\sigma_z^{21} \pi_{yz^1}^*$ $\delta^*_{xy^1} \pi^*_{xz^1}$ configuration (30%) (Table 2). This mixing is found to be less in ${}^{5}TS_{\sigma-Mn}{}^{III}_{=0}$ as expected. In ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$, the spin density on the metal remains unaltered ($\Delta \rho_{Mn} = 0.088$) from ${}^{5}RC_{\pi-Mn}{}^{III}_{=0}$ with no residual spin density (ρ_{DHA} = 0.011) and a significant negative Mulliken charge (e_{DHA} = -0.495) on the DHA moiety. This indicates that a proton is getting transferred from DHA to the catalyst forming MHA⁻ species during the transition state (Figure 3c-d). This fact is supported further by the SNO analysis performed on both ${}^{5}RC_{\pi-Mn}$



Figure 2: B3LYP-D3 computed energies for the C-H bond activation of 9,10-dihydroanthracene (DHA) by (a) $[Mn^{III}H_3buea(O)]^2$, (b) $[Mn^{V}H_3buea(O)]^2$, (c) $[Fe^{III}H_3buea(O)]^2$, and (d) $[Fe^{V}H_3buea(O)]$ catalysts. (Energies are in kJ/mol).

The intrinsic barrier for the C-H bond activation by Mn^{II/III/IV-}OH and Mn^V=O species are estimated to be very high, 103.4 kJ/mol, 151.5 kJ/mol, 106.0 kJ/mol, and 85.5 kJ/mol respectively in the high-spin surface, suggesting these are unlikely candidates to activate sp³-C-H bonds (see details in the ESI and Figure S1, Figure S8-S12, Table S3). Interestingly for [Mn^{III}H₃buea(O)]²⁻, we have found two reactant-complexes, ${}^{5}RC_{\pi-Mn}{}^{III}{}_{=O}$ and ${}^{5}RC_{\sigma-Mn}{}^{III}{}_{=O}$ on the S = 2 surface with the DHA found to approach either on a side-on fashion (π) or a head-on fashion (σ) (Figure 3a-b). Both RCs are computed to be endothermic by 9.0 and 26.6 kJ/mol from the free catalyst, respectively (Figure

and ${}^{5}TS_{\pi-Mn}{}^{III}{}_{=0}$ species, revealing no change in residual spin in each d-orbitals (Figure S13a-b). The Mn-O-H bond angle is found to be 107.7°, while this angle is wider for ${}^{5}TS_{\sigma-Mn}{}^{III}{}_{=0}$ (149.5°) (Figure

3c,3e,4b). We have analyzed the SNO orbitals corresponding to the type orbital with a negligible contribution of spin on the carbon



Figure 3: The DFT optimised structures (a-c) ⁵RC_{n-Mn}III₌₀, ⁵RC_{o-Mn}III₌₀, ⁵TS_{n-Mn}III₌₀ respectively, (d) spin densities on Mn, oxo and C1 (DHA) of ${}^{5}TS_{\pi-Mn}{}^{III}{}_{=0}$, (e-j) DFT optimised structures of ${}^{5}TS_{\sigma-Mn}{}^{III}{}_{=0}$, ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$, ${}^{4}RC_{\delta'-Mn}{}^{IV}{}_{=0}$, ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$, ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$, and (k) spin densities on Mn, oxo and C1 (DHA) of ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=0}$, (I) DFT optimised structure of ${}^{4}TS_{\delta'-Mn}{}^{IV}{}_{=0}$.

low-lying transition state ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$, and they show a pure metal-dp center (DHA) ([$\sigma^{*}z^{2} + 2P_{z}(O)$], Figure 4a), indicating a PT-ET

mechanism. The SNO orbital in the high-lying ${}^{5}TS_{\sigma-Mn}{}^{III}=_{O}$, consist of a σ -lobe on the oxo and a π -lobe on C1, perpendicularly situated indicating electron transfer between σ - and π -orbitals resulting in a PCET mechanism (Figure 4b and Figure S13c-d and Figure S14). Therefore a PT-ET pathway is operating in the rate-determining transition state (${}^{5}TS_{\pi-Mn}{}^{III}=_{O}$), and this agrees well with the experiments/theory where the PT-ET mechanism for this species has been suggested.³⁹ The Mn-O-H bond angle during the transition state indicates that the lowest-lying ${}^{5}TS_{\pi-Mn}{}^{III}=_{O}$ is operational via a δ -pathway for proton transfer.

In [Mn^{IV}H₃buea(O)] species, three different reactant complexes were optimized, namely, ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$, ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=0}$, and ${}^{4}RC_{\delta'-Mn}{}^{IV}{}_{=0}$ (Figure 3f-h) with ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$ being the lowest-lying among all RC and endothermic by 17.9 kJ/mol from the free catalyst. The other two reactant complexes, ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=0}$ and ${}^{4}RC_{\delta'-Mn}{}^{IV}{}_{=0}$, are lying at 4.2 kJ/mol and 20.4 kJ/mol higher, respectively, from the ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$, species. The CAS(3,5) calculations on the reactant complexes and the transition states indicate the presence of strong multiconfigurational characters in all these species, which is responsible for their intriguing reactivity pattern. The lowest-lying ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$ species possesses a (δ_{xy})¹ (π_{xz} , π_{yz})² configuration, which is contributing 54% to the total wavefunction. This state is found to be mixed with the other singly excited states with contributions of 14% and 12%, arising from the transfer of α -electron from π_{yz} and π_{xz} orbital to σ_z^2 orbital, respectively (Table S4). We have optimized another reactant

complex species, ${}^{4}RC_{\delta'-Mn}{}^{IV}{}_{=0}$, and similar to the lowest energy ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=0}$, the major contribution for this species is also originating from the $(\delta_{xy})^1$ $(\pi_{xz}, \pi_{yz})^2$ configuration (56%). These two configurations differ in their second-highest contributing configuration to the wave function. For ${}^{4}RC_{\delta'-Mn}{}^{IV}{}_{=0}$ species, the second contribution is originating from the transfer of α -electron from the δ_{xy} to $\delta_{x}{}^2\gamma^2$ orbital $(\pi_{xz}{}^1\pi_{yz}{}^1\delta_{x}{}^2\gamma^{21},27\%)$. In contrast, for ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=0}$, several equal weightage excitations such as $\delta_{xy} / \pi_{xz} \rightarrow \delta_{x}{}^2\gamma^2 / \sigma^{*}{}_{z}{}^2$ (17%), $\pi_{xz} \rightarrow \sigma^{*}{}_{z}{}^2$ (17%), $\delta_{xy} \rightarrow \delta_{x}{}^2\gamma^2$ (15%), $\pi_{yz} / \pi_{xz} \rightarrow \delta_{x}{}^2\gamma^2 / \sigma^{*}{}_{z}{}^2$ (15%), and $\delta_{xy} \rightarrow \sigma^{*}{}_{z}{}^2$ (12%) dominate the wave-function (Table 2). To gain confidence about the choice of our chosen active space, we have increased it to CAS (9,8) by incorporating the two oxo p_{π} orbitals (π_x and π_y), one oxo p_{σ} orbital (σ_z) and this yields very similar results (Table S4).

The reactant complex ${}^4\text{RC}_{\delta\text{-Mn}}{}^{IV}{}_{=0}$ has the highest oxyl radical character (0.232) among all (Table S3) and is connected to the lowest energy barrier for the C-H activation, 66.8 kJ/mol associated with ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=0}$ transition state. The energy barrier associated with the ${}^4RC_{\sigma\text{-}Mn}{}^{IV}{}_{=0}$ and ${}^4RC_{\delta^{\text{-}}Mn}{}^{IV}{}_{=0}$ is 115.6 and 95.6 kJ/mol, respectively (Figure 2b). In ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=0}$, the highest contribution (44%) to the total wave function is coming from a doubly excited $\pi^*_{xz^1} \sigma^*_{z^{21}} \delta^*_{x^2-y^{21}}$ configuration originating from the $\delta^*_{xy}/\pi_{yz} \rightarrow \delta^*_{x^2-y^2}/\sigma^*_{z^2}$ electronic transition. This majorly contributing state is found to be heavily admixed with other doubly excited states arising from the π_{yz}/π^*_{xz} to σ_{z}^{*2} / $\delta_{x_{z}^{-}y_{z}^{2}}^{*2}$ (27%) and δ_{xy}^{*} / π_{xz}^{*} to $\sigma_{z}^{*2}^{*2}$ / $\delta_{x_{z}^{-}y_{z}^{2}}^{*2}$ (11%) electron transfer (Table 2). These mixing in the configurations are in line with the CAS (9,8) calculations on the rate-determining ${}^{4}TS_{\delta\text{-}Mn}{}^{1V}{}_{=0},$ where the highest contributing (29%) doubly excited state ($\sigma_z{}^1\delta^*{}_x{}^2{}_y{}^{21}\pi^*{}_y{}^1$ $\pi^*_{xz} \sigma^*_{z}$ is found to be mixed with another doubly and singly excited state $\delta_{x^2-y^{21}}^{*}\pi_{xz^1}^{*}\sigma_{z^{21}}^{*}$ (24%) and $\delta_{x^2-y^{21}}^{*}\pi_{yz^1}^{*}\pi_{xz^1}^{*}$ (19%) respectively. From both CAS (3,5) and CAS (9,8) calculations on all the transition states (Table S4), it is revealed that higher mixing of the excited state configurations to the ground state $(\delta_{xy})^1$ $(\pi_{xz}, \pi_{yz})^2$ configuration lowers the energy barrier for the hydrogen atom transfer. For instance, the contribution of $(\delta_{xy})^1 (\pi_{xz}, \pi_{yz})^2$ is decreased in the order from ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$ (38%) to ${}^{4}TS_{\delta'-Mn}{}^{IV}{}_{=0}$ (27%) to ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=0}$ (0%), and the barrier height decreases in the same manner, even the

ratio of decrease in barrier height matches closely the percentage of contribution.

In the rate-determining ${}^{4}\text{TS}_{\delta\text{-Mn}}{}^{IV}{}_{=0}$ species, spin density analysis suggests a transfer of spin-up $\alpha\text{-}electron$ from the sp3C-H bond of DHA to the metal orbital (Figure 3k). The SNO calculations on both



Figure 4: SNOs in TSs: (a) PT-ET in ${}^{5}TS_{\pi-Mn}{}^{III}{}_{=0}$, (b) PCET in ${}^{5}TS_{\sigma-Mn}{}^{III}{}_{=0}$, (c-f) HAT in ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=0}$, ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$, ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$ and ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=0}$ respectively.

 ${}^{4}\text{RC}_{\delta-Mn}{}^{IV}_{=0}$ and ${}^{4}\text{TS}_{\delta-Mn}{}^{IV}_{=0}$ species show a significant increase of spin density of 0.48 [δ^*_{xy} (0.23e) $\rightarrow \delta^*_{xy}$ (0.71e)] in the δ^*_{xy} orbital and 0.05 $[\sigma_{z^2}^* (0.14e) \rightarrow \sigma_{z^2}^* (0.19e)]$ in the $\sigma_{z^2}^*$ orbital (Figure S15a-b). The TS- $[\pi_{ring}+\phi_{C}+2P(O)]$ (Figure 4c) spin natural orbital shows two antibonding lobes with a node and H in transit, indicating towards a HAT mechanism, while another TS-2P_z(O) spin natural orbital shows a pure dp-metal-oxo orbital, indicating mixing of HAT with a minor amount of the PT-ET mechanism. This H-atom transfer phenomenon is in agreement with the experimental observation during the C-H activation process by this type of catalyst species.^{22, 39, 81-83} Moreover, the Mn-O-H angle of 113.9° and the spin-transfer to the metal δ^*_{xy} and $\sigma^{*}{}_{z}{}^{2}$ orbitals in ${}^{4}TS_{\delta\text{-}Mn}{}^{IV}{}_{=0}$ indicate a $\delta\text{-}pathway$ blended with a slight σ -pathway. The spin natural orbital calculations for ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$ and ${}^{4}TS_{\delta'-Mn}{}^{IV}{}_{=0}$ species also indicate a similar mechanistic pattern with the only difference being their % of HAT character (Figure 4d-e, and Figure S15c-f). In high-lying transition states, the HAT property has been decreased, 45% and 49% for ${}^4TS_{\sigma\text{-}Mn}{}^{IV}{}_{=0}$ and ${}^4TS_{\delta'\text{-}Mn}{}^{IV}{}_{=0}$, as compared to the 53% of the lowest energy, ${}^{4}\text{TS}_{\delta\text{-Mn}}{}^{\text{IV}}{}_{=\text{O.}}$ Therefore, it is observed that a higher HAT character facilitates the electron transfer and lowers the energy barrier. Moreover, the Mn-O-H bond angle is also increased from 113.9°, 120.2°, 131.6° for ${}^{4}\text{TS}_{\delta\text{-Mn}}{}^{IV}{}_{=0},$ ${}^{4}TS_{\delta'-Mn}{}^{IV}{}_{=0,}$ and ${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=0}$, respectively, reflecting the higher occupancy of $\sigma^*_{z^2}$ orbital following the same order (Figure 3i-j, 3l). Also, this can be correlated with occupancy of δ -type orbital during the HAT process; the highest occupancy (0.71) tends to the lowest Mn-O-H bond angle (113.9°). This analysis suggests that the rate of the reaction is governed by the magnitude of α -spin-transfer to the specific d-orbitals as well as the chosen pathway (HAT/PCET or PT-ET) of the reaction.

All these states possess the same number of unaired spins on the metal d-orbitals, avoiding any d-orbital spin-pairing. For a hexacoordinate Mn^{IV} =O species, the ground state term is ⁴F, which in the ligand field split further as ⁴A₂, ⁴T₂, and ⁴T₁. The reactivity thus can be originated from any one of the quartet states in the presence



Figure 5: The DFT optimised structures (a-c) ${}^{4}RC_{\pi-Fe}{}^{V}{}_{=0}$, ${}^{4}RC_{\delta-Fe}{}^{V}{}_{=0}$ and ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=0}$, (d) spin densities on Mn, oxo and C1 (DHA) of ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=0}$ and (e) DFT optimised structure of ${}^{4}TS_{\delta-Fe}{}^{V}{}_{=0}$

of a ligand field. Similarly, in TBP complexes, as mentioned earlier in Mn^{IV}=O species, three reactant complexes ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=O}$, ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=O}$, ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=O}$, ${}^{4}RC_{\delta-Mn}{}^{IV}{}_{=O}$, and corresponding three transition states (${}^{4}TS_{\sigma-Mn}{}^{IV}{}_{=O}$, ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=O}$, ${}^{4}TS_{\delta-Mn}{}^{IV}{}_{=O}$) were involved in the C-H activation of DHA. While ${}^{4}RC_{\sigma-Mn}{}^{IV}{}_{=O}$ is the ground state originating mainly from $\delta_{xy}{}^{1}\pi_{xz^{1}}$, the other two states originate from the $\delta_{xy}/\pi_{xz/yz} \rightarrow \delta_{x}{}^{2}{}_{-y}{}^{2}/\sigma^{*}{}_{z}{}^{2}$ transition. These electronically excited states do not require spin-crossover as demanded by the observation of two-state reactivity. Further, as states with two different multiplicities are not involved, this does not necessitate the need for spin-orbit coupling to mix and allow the reaction at their MECP juncture.

Reactivity of Feⁿ-X (n = II to V, X = O/OH) Species towards C-H bond activation: The barrier heights computed for the C-H bond activation of DHA by Fe^{II}-OH, Fe^{III}=O, Fe^{III}-OH, Fe^{IV}=O, and Fe^{IV}-OH species are calculated to be 95.1 kJ/mol (See Figure S2a, Figure S16-S17a-b, Figure S18-S19 and related discussion on the sluggish reactivity of this species), 67.7 kJ/mol, 144.0 kJ/mol, 119.6 kJ/mol, and 106.7 kJ/mol in their high-spin surface, respectively (Figure S2), indicating that only Fe^{III}=O species can activate an aliphatic C-H bond (Figure 2c) while others are unreactive. Here to mention, for the Fe^{IV}-OH species, the DFT predicted ground state (S = 2) is not matching with the DLPNO-CCSD(T) computed one (S = 0). Still, both methods are pointing towards the involvement of two-state reactivity as all spinstates are found to be very close-lying. Although the energy ordering of these spin-states differs in the two methods, the energies are not varied significantly, and the rate-determining transition barrier is expected to not shift much in the two methods. Therefore, we have

chosen to proceed with the DFT computed energetics for Fe^{IV}-OH, which at the same time would be helpful to compare the reactivity. The Fe^{III}=O and Fe^{IV}=O species were studied earlier using DHA as substrate, and the barriers estimated are in agreement with the value computed here.²⁹ The spin densities on Fe^{III}=O, Fe^{III}-OH, Fe^{IV}=O, and Fe^{IV}-OH transition states (Figure S17c-j), indicating that a proton is transferred from DHA. A β -electron transfer from DHA occurs during ${}^{5}TS_{Fe}{}^{IV}{}_{=0}$ leaving behind a residual spin of 0.270 on C1. Our SNO calculations reveal that while going from reactant-complex to transition state, no change in the spin-population in metal 3dorbitals has been found for Fe^{III}=O and Fe^{III}-OH complexes. While no change is also detected for the 3d orbital occupation of Fe^{IV}=O species, the nature of the orbitals was found to alter from reactant complex to the transition state (π^*_{xz} to δ_{xy}) (Figure S20-S23). The Fe-O-H angles are found to be 108.9°, 109.5°, 110.6°, and 106.1° in the above four complexes, indicative towards a δ -pathway followed by all of the species.

The multiconfigurational character is very prominent in the reactivity of the highest oxidized species in the series, [Fe^VH₃buea(O)] (Table 1, Table S1). Similar to the previous Mn-complexes, we found two reactant complexes, ${}^{4}RC_{\pi-Fe}{}^{V}{}_{=0}$ and ${}^{4}RC_{\delta-Fe}{}^{V}{}_{=0}$, varying the dominant electronic configuration contributing to the wavefunction (Figure 5a-b). The ${}^{4}RC_{\pi-Fe}{}^{V}{}_{=0}$ species is comprised of several equally weighted configurations, i.e., $\delta_{xy}{}^{1}\pi_{yz}{}^{1}\delta_{x}{}^{2}{}_{y}{}^{21}$ (19%), $\sigma_{z}{}^{21}\pi_{yz}{}^{1}\delta_{x}{}^{2}{}_{y}{}^{21}$ (17%), $\delta_{xy}{}^{1}\pi_{xz}{}^{1}\delta_{x}{}^{2}{}_{y}{}^{21}$ (14%), $\pi_{xz}{}^{1}\sigma_{z}{}^{21}\sigma_{x}{}^{2}{}_{y}{}^{21}$ (14%) and $\delta_{xy}{}^{1}\sigma_{z}{}^{21}\pi_{yz}{}^{1}$ (13%) electronic states while in ${}^{4}RC_{\delta-Fe}{}^{V}{}_{=0}$, the significant contribution is originating from the ground state electronic configurations, $\pi_{xz}{}^{1}\delta_{xy}{}^{1}\pi_{yz}{}^{1}$ (42%) (Table S4). The configuration,

which is predominantly governed by the doubly and singly excited electronic states, is found to be the lowest-lying (21.9 kJ/mol), with the other one at 9.1 kJ/mol higher in energy than ${}^{4}RC_{\pi-Fe}V_{=0}$ (Figure 2d). The highly admixed ${}^{4}\text{RC}_{\pi\text{-}\text{Fe}}{}^{V}{}_{=0}$ species is connected to the lowest energy barrier, 35.3 kJ/mol ($^4TS_{\pi\text{-}Fe} ^{V}{}_{=0})$ and this transition state is exclusively dominated by doubly excited state electronic states, π_{xz^1} $\sigma_z{}^{21}\,\delta_x{}^2-{}_y{}^{21}$ and $\delta_{xy}{}^1\,\sigma_z{}^{21}\,\delta_x{}^2-{}_y{}^{21}$ contributing 48% and 19% to the total wavefunction (Table 2). The other one, ${}^{4}TS_{\delta-Fe}{}^{V}{}_{=O}$, is lying 51.4 kJ/mol higher in energy from ${}^{4}TS_{\pi\text{-}Fe}{}^{V}{}_{=0}.$ The SNO calculations on both transition states indicate towards the β -electron transfer to the δ_{xy} and $\delta_{x^2-v^2}$ orbitals in ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=0}$ and ${}^{4}TS_{\delta-Fe}{}^{V}{}_{=0}$ respectively (Figure 4f and Figure S24-S25). For lower energy ${}^4TS_{\pi\text{-}Fe}{}^{V}{}_{=0},$ the amount of $\beta\text{-}$ electron transfer is higher [δ_{xy} (0.85e) $\rightarrow \delta_{xy}$ (0.28e)] compared to the high-lying ${}^{4}TS_{\delta-Fe}{}^{V}{}_{=0} [\delta_{x}{}^{2}{}_{-v}{}^{2} (0.44e) \rightarrow \delta_{x}{}^{2}{}_{-v}{}^{2} (0.28e)]$, pointing to the more favorable orbital overlap in ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=0}$. In the rate-limiting, ${}^{4}TS_{\pi-Fe}{}^{V}$ $_{Fe}V_{=O}$, the Fe-O-H angle is found to be 112.6°, a bit wider than that of ${}^{4}TS_{\delta-Fe} = 0$ (109.9°) (Figure 5c-e). This slightly higher bond angle provides the optimum positioning of the orbitals for the electron transfer during the transition state. Moreover, in both transition states, a small amount of β -electron transfer is occurring in σ_{z^2} orbital, and this transfer is also higher for ${}^4TS_{\pi\text{-}Fe}{}^{V}{}_{=0}\left[\sigma_{z}{}^2\left(0.19e\right) \rightarrow \sigma_{z}{}^2\right.$ (0.13e)], supporting a better overlap for this species. As the Fe-O bond length in the free catalyst is very short, 1.655 Å, the Fe-O moiety is situated deep inside the hydrogen bond cavity, making it less accessible for reactivity. Therefore, the approach of an sp³-CH bond from the above is more favorable than a side-on approach, facilitating the electron transfer when the Fe-O-H angle is broader and lowering the CH activation barrier. The Fe^V=O species is therefore following a δ -pathway mixed with a little σ -pathway for the hydrogen atom abstraction.

Quantifying the role of Secondary-Coordination Sphere in Reactivity: To elucidate the effect of the secondary coordination sphere in the reactivity of the metal catalyst, we have chosen the Fe^{IV}=O and Mn^{III}=O species and modeled four complexes where hydrogen bonding interactions are excluded sequentially by altering the peripheral attachment in the [H₃buea]³⁻ ligand as shown in Scheme 1(a) (model-1, 2, and 4) (Figure S26). The additional model with longer ester groups is also constructed to check the effect of the wider cavity (model 3). For Fe^{IV}=O species, the elimination of peripheral hydrogen bonds was found to turns things around. From model-1_{Fe} to model-4_{Fe}, the C-H activation barriers have reduced

from 119.0 kJ/mol for the original species to 77.1 kJ/mol, 70.3 kJ/mol, 76.5 kJ/mol, and 110.4 kJ/mol, respectively (Table S5-S6, Figure S27 for computed transition state geometries). Although model-4 with no hydrogen-bonding interactions is expected to be the most reactive due to the elimination of the H-bond cavity entirely, its barrier height is comparable to the original [H₃buea]³⁻ catalyst. In the case of Mn^{III}=O, unlike Fe^{IV}=O, model-1 and model-3 are showing a reduced barrier height of 45.3 kJ/mol and 43.4 kJ/mol, respectively, while in model-2 and model-4, there is an increment in the barrier, 56.8 kJ/mol. and 58.1 kJ/mol (Table S5). From these energetics values, it is evident that the effect of the peripheral hydrogen-bond cavity is playing a very crucial role in these complexes and the effect on the Fe^{IV}=O species is visibly drastic, and the impact on the Mn^{III}=O complexes are not so prominent. The spin density on the Fe and the oxo group are also changing as 2.982/0.496, 2.982/0.547, 2.936/0.609, 2.938/0.616, respectively, while for the Mn-complexes, the spin densities are 3.717/0.140, 3.720/0.152, 3.811/0.100, and 3.685/0.200, respectively (Figure S26). Moreover, from the spin density values on the metal center, oxo, and the C1-centre, it is revealed that all of the Mn^{III}=O model complexes are reacting via PT-ET mechanism, while for the Fe^{IV}=O species, the model-1, model-2, and model-3 are reacting via a HAT/PCET mechanism and model-4 is reacting via PT-ET mechanism. The reactivity of the Mn^{III}=O model complexes can be directly correlated to the oxyl character in the model complexes. The higher the oxyl radical character, the lower is the reactivity. Therefore, reactivity increases as $R_{4-}Mn^{III}_{=0} < R_{2-}Mn^{III}_{=0}$ $< R_1.Mn^{III}_{=0} < R_3.Mn^{III}_{=0}$. This does not hold if the reaction occurs via a HAT/PCET mechanism. The higher reactivity of the R1-Fe^{IV}=O, R2- $_{Fe}$ IV=O, and R_{3-Fe} IV=O species from the aforementioned $[Fe^{IV}H_3buea(O)]^-$ complex is owing to the higher oxyl character in these complexes compared to the original catalyst. The difference in trend observed in the models is due to the intrinsic difference in their basicity with Mn^{III}=O computed to be seven times larger than Fe^{IV}=O species (see below), and for this reason, the Mn^{III}=O species are less susceptible to hydrogen bonding interaction while Fe^{IV}=O species strongly dependent. The model-4 in both species is the worst because both the species follow the PT-ET mechanism for C-H bond activation and, therefore, the presence of at least one H-bonding interaction provides structural/electronic flexibility at the transition states. Therefore, excluding one or two hydrogen-bonding interactions around the cavity helps lower the barrier height, while complete exclusion has steep energy penalties.



Figure 6: A schematic description for (a) single state reactivity (SSR), (b) two state reactivity (TSR), and (c) identical spin multistate reactivity (ISMR).

Discussions

Structure and Spin state energetics of $Mn/Fe^{n}-X$ (n = II to V, X = O/OH) Species: The rigid ligand framework of [H₃Buea]³⁻ enforces trigonal bipyramidal geometry with slight variation in the distortions (see Table S7 for SHAPE analysis). The trigonal bipyramidal geometry in these species leads to a 2π -2 δ -1 σ splitting pattern for the dorbitals and results in a high-spin ground state for all the species studied. Further, the oxo/hydroxo groups are involved in strong Hbonding interactions with the cavity imposed by the [H₃Buea]³⁻ ligand. This results in a weaker ligand field than bare Fe^{IV}=O/OH species, which stabilize an intermediate S = 1 state.⁸⁴ The overall CF splitting of the d-orbitals is in the range of ~1.0 eV to ~3.5 eV, and this is nearly two times smaller than the other six-coordinate metaloxo species.⁷⁹ The AILFT computed orbitals suggest that the splitting increases with the oxidation state of metal ions for both Mn/Fe=O(OH) species with the exception of Fe^v=O species. Among Fe=O species, the Fe^V=O has the lowest gap of \sim 1.6 eV, while the largest d-orbital CF splitting is found for Fe^{IV}=O species (~2.75 eV). Among the Mn-OH complexes, the d-orbital CF splitting is very large for the MnIII/IV-OH species (~2.5-3.5 eV). Interestingly, this crystal field splitting is correlated to the reactivity, with MnIII/IV-OH and Fe^{IV}=O species being unreactive and the Fe^V=O species showing the highest reactivity. Similarly, Mn^{III}=O has a gap of ~2.25 eV, and $Mn^{V}=O$ has a slightly larger gap (~3.0 eV), while both are reactive here, but the former is more reactive compared to the latter. The experiments reported earlier support these observations.³⁹ Our DFT computed results are further validated by state-of-the-art DLPNO-CCSD(T) calculations.⁶⁹ As the oxidation state increases, the energy spread of different spin-states computed with DFT calculations matches better with DLPNO-CCSD(T) method, and this suggests a better description of spin-state energetics with DFT calculations for larger (IV or V) oxidation state species.

Single-State vs. Two-State vs. Identical spin multistate reactivities: The conventional two-state reactivity concept is well established for both heme and non-heme Fe^{IV}=O species wherein reactivity is often observed via the high-spin state.^{30, 85} Here, high-spin is the default ground state, and hence the necessity for a spin-crossover to another state does not arise; and therefore, one could expect a pure singlestate reactivity (SSR) for all these species. By performing ab initio CASSCF calculations on these species, we have found the following classifications (Figure 6), (i) pure SSR reactivities are observed in S = 5/2, and S = 2 surfaces with pure single reference configuration for Mn^{II}-OH, Fe^{III}=O, and Fe^{IV}=O species, respectively. Also, SSR with multireference configuration is detected for Mn^{III}-OH, Mn^{IV}-OH, $Mn^{v}=O$, and $Fe^{iv}-OH$ species, (ii) a conventional TSR is observed for Fe^{III}-OH species where one minimum energy crossing point (MECP)⁸⁶ is required for the product formation, and the ground state has no mixing with excited states (Figure S2c). (iii) In addition to this, we have also detected a multistate reactivity where states are strongly admixed with excited stated of the same spin multiplicity (identical spin multistate reactivity; ISMR) in Mn^{III}=O, Mn^{IV}=O, Fe^{II}-OH, and Fe^v=O species. We analyzed the AILFT orbitals, which reveal that SSR with single-reference character observed for Mn^{II}-OH and Fe^{III}=O species is due to the absence of d-electronic excited states, and in Fe^{IV}=O species, the σ_{z}^{*2} is strongly destabilized ($\Delta E (\pi_{yz}^{*} - \sigma_{z}^{*2}) = \sim 1.75$ eV). Also, when the frontier d-orbital gap between the highest occupied and lowest unoccupied falls in the region of ~1.0 to 1.5 eV (as in the case of Mn^{III}-OH, Mn^{IV}-OH, Mn^V=O, and Fe^{IV}-OH), strong mixing of the states is noticeable within the ground state. However, excited states are still far away, leading to an SSR-type reactivity for these species. When this gap is much lower (<1.0 eV), for example, in case of Mn^{IV}=O, Fe^{II}-OH and Fe^V=O, many close-lying states mix with each other, leading to ISMR type reactivity.

Reactivity towards C-H Activation: The first hydrogen atom abstraction from DHA is established to be the rate-limiting step in metal-oxo chemistry,³⁹ and based on the computed barrier height (Table S1), the order of reactivity expected is $Fe^{v}=O > Mn^{III}=O >$ $Mn^{iv}=0 > Fe^{iii}=0 > Mn^{v}=0 > Fe^{ii}-OH > Mn^{ii}-OH > Mn^{iv}-OH > Fe^{iv}-OH >$ Fe^{IV}=O > Fe^{III}-OH > Mn^{III}-OH having the barrier height in the range of 35.3 to 145.3 kJ/mol for the two extreme examples. There are several interesting features that emerge from this trend. (i) the Fe^v=O, Mn^{III}=O, Mn^{IV}=O, and Fe^{III}=O species having an activation barrier of less than 70 kJ/mol can be considered reactive while others do not. This is consistent with available experimental results. This is attributed to the presence of multireference character in these species as well as comparatively low-lying unoccupied orbital to accommodate electron transfer from the substrate during the C-H activation process. For Mn^{III}=O and Fe^{III}=O species, a proton is getting transferred during the transition state; therefore, the presence of a low-lying vacant orbital is not mandatory (see next section). (ii) A high-oxidation state does not necessarily mean greater reactivity. While Fe^V=O is the most aggressive oxidant, this is followed by the MnIII=O species. Similarly, the MnIII/IV=O species are highly reactive, but Mn^{v} =O is sluggish or shows no reactivity. This suggests that the oxidation state alone cannot decide the reactivity pattern. For the Mn^{II}/Fe^{III}-OH species being a half-filled d⁵ species, there are no delectronic excited states, though crystal field splitting are smaller. For the Mn^{IV}-OH and Fe^{IV}-OH species, the respective highest lying $\delta^*_{x^2-y^2}$ and π^*_{vz} orbitals are too high to accommodate the electron during the C-H activation process, making them unreactive. Similarly, although Fe^{II}-OH species shows multiconfigurational character, one needs to keep in mind that metal-hydroxo species are generally less reactive than metal-oxo species. This is because the protonation of the oxo group diminishes the oxyl radical character substantially and reduces the electrophilicity of the oxo group. The presence of proton also enforces steric strain in the abstraction of C-H bonds leading to less reactivity. Thus, though the reactivity of Fe^{II}-OH is highest among all hydroxide species studied due to ISMR, significantly less reactive if we compare it with oxo species.

To bifurcate the steric and the electronic contributions to the reactivity, we have performed deformation energy (ΔE_{def}) analysis on the transition state (see computational details), which reveals that the lowest deformation energy is computed for the ${}^{4}TS_{\pi-Fe}{}^{V}{}_{=O}$ transition state (34.8 kJ/mol), and this is consistent with aggressive reactivity observed for the Fe^v=O species. The Mn^{III}=O, Mn^{IV}=O, and Fe^{III}=O species have the deformation energy values of 71.2 kJ/mol, 55.5 kJ/mol, and 84.4 kJ/mol, respectively. Although ΔE_{def} energy is larger for Mn^{III}=O and Fe^{III}=O species, the orbital stabilization here is much more favorable (Eorb: -433.6 kJ/mol and -419.3 kJ/mol, respectively), and this reduces the barrier substantially. For Fe^{IV}=O species, the ΔE_{def} is 77.3 kJ/mol; while this is similar to Mn^{III}=O species, the orbital interaction is unfavorable (-301.4 kJ/mol), leading to a substantial barrier. However, for other unreactive species, either deformation energies are very large, or orbital stabilization is unfavorable, leading to sluggish/no reactivity (Table S8).

Reaction channels (σ , π , and δ) perspective on the reactivity: Reactivity of metal-oxo species and their preference to react via particular channels (σ -, π -, or δ -channel) is well documented.^{61, 87-91} The preference for particular channels depends on (i) the nature of the substrate and how it approaches the catalyst (ii) the d-orbitals availability on the catalyst for an efficient overlap with the substrate at the transition state to facilitate proton and/or electron transfer. Among various channels, σ -channel is the most common and preferred path for biomimic metal-oxo complexes in the octahedral environment, while π -channels are preferred if the axial positions are hindered or for electronic reasons such as in Mn^{IV}=O and Fe^{IV}=NTS species reported earlier.^{31, 92} The δ -channel, on the other hand, is rare and often very high in energy as the δ -type orbitals (δ_{xy} and $\delta_{x^2-y^2}$) are not easily accessible in the octahedral environment.^{84, 93, 94} In

species were found to react via the rare δ -pathway. Here both σ - and π -channels are hindered due to the formation of the cavity by strong H-bonding interactions around the metal-oxo moiety and the TBP geometry (hinder the substrate attack between 120° to 180°). The Mn^{III}-OH (Mn^{IV}-OH) species reacts via σ -(π -) channel as the protonation of the oxo bond significantly destabilizes the $\sigma_{z^2}^*(\pi_{xz}^*)$



Figure 7: The DFT optimiszed structures of (a) ${}^{5}RC_{\pi-Mn}{}^{III}_{=0}$ and ${}^{5}TS_{\pi-Mn}{}^{IV}_{=0}$, (b) ${}^{4}RC_{\delta-Mn}{}^{IV}_{=0}$ and ${}^{4}TS_{\delta-Mn}{}^{IV}_{=0}$ showing a shifting from trigonal bipyramidal to square pyramidal geometry during the transition state. (c) and (d) are showing the orbital interaction diagram between the ϕ (CH) and $\delta_{xy}/\delta_{x}^{2}\gamma^{2}$ orbital during the transition. (e and f) are the frontier molecular orbital diagram of ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$ and ${}^{4}TS_{\delta-Mn}{}^{IV}_{=0}$ respectively, and (g) the pKa and $E_{1/2}$ value are plotted against the studied species.

our study, with the exceptions of Mn^{IV} -OH and Mn^{III} -OH, all the orbital and disturbs the H-bonding network opening up the σ -(π -)

channel. In species except for Mn^{III}-OH (Mn^{IV}-OH), a change in geometry from trigonal bipyramidal to square pyramidal is observed during transition state, which enables easy access to the $\delta_{xy}/\delta_{x}^{2}-\gamma^{2}$ orbitals (Figure 7a-d), and hence this is found to be the preferred pathway for most of the species studied. Figure 7a-b shows the approach of the substrate by a black arrow in ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$ and ${}^{4}TS_{\delta-Mn}{}^{IV}_{=0}$. In these transition states, the initial TBP geometry has already been converted to the square pyramidal one to facilitate the substrate along the $\delta_{xy}/\delta_{x}^{2}-\gamma^{2}$ orbitals. This is also favourable from the steric point of view as in the square pyramidal geometry, one of the apical sides is empty to accommodate the substrate (the black arrow side). The metal-substrate ($\delta_{xy}/\delta_{x}^{2}-\gamma^{2}$) orbital overlap is shown in Figure 7c-d. The frontier molecular orbital diagram of ${}^{5}TS_{\pi-Mn}{}^{III}_{=0}$ and ${}^{4}TS_{\delta-Mn}{}^{IV}_{=0}$ in Figure 7e-f, has also confirmed the involvement of the $\delta_{xy}/\delta_{x}^{2}-\gamma^{2}$ orbitals in the electron transfer.

Thermodynamic Contributions to Reactivity: To further understand the origin of the reactivity of all species, we have analyzed the computed pKa values of the conjugate acid-base pairs and the redox potential $E_{1/2}$ values of the half-reactions involved in the C-H abstraction process. As we discussed already, the C-H activation by [Mⁿ⁺=O/OH] species can occur in two ways (i) a PT-ET mechanism and (ii) a PCET/HAT mechanism (Figure S28). In the PT-ET path, the species undergoes protonation forming [Mⁿ⁺=OH/OH₂]⁺ species and abstraction, undoubtedly follow a PT-ET mechanism with a greater rate. The Mn^{II}-OH, Mn^{III}=O, Fe^{II}-OH, Fe^{III}=O, and Fe^{III}-OH species are showing a PT-ET mechanism, having the computed pKa values of 10.2, 24.4, 9.4, 19.4, -2.5, respectively. From the pKa values, it can be expected that the proton transfer is greatly aided in the case of Mn^{III}=O and Fe^{III}=O species. In contrast, although the pKa values of Mn^{II}-OH and Fe^{II}-OH suggest the presence of a basic M-OH moiety, the basicity is not high enough for an efficient PT-ET mechanism. Therefore, the latter pairs are expected to show sluggish reactivity. In a similar way, Fe^{III}-OH being comparatively more acidic found to be unreactive. The probability of the other pathway such as PCET/HAT for Mn/Fe^{II}-OH and Fe^{III}-OH species can be eliminated here on the ground that their reduction potentials are highly negative (E1/2 for Mn^{II}-OH, Fe^{II}-OH, and Fe^{III}-OH is -9.1, -10.5, -1.57 eV, respectively, against the Fc⁺/Fc couple) for accepting an electron, (ii) species that are strongly oxidizing, with positive one-electron redox potential, are following a concerted HAT/PCET mechanism. Examples of this category include Fe^v=O species. The pKa value of -6.5 for the $Fe^{V}=O$ species eliminates the possibility of a PT-ET mechanism. However, the $[Fe^{V/IV}H_3buea(O)]^{0/-1}$ couple have a positive $E_{1/2}$ value of 0.15 eV versus Fc⁺/Fc couple, and this offers a strong driving force for one-electron reduction facilitating a HAT pathway, (iii) the species which are moderately basic (pKa < 12) and also have a less



Figure 8: Summary of ISMR reactivity observed in metal-oxo/hydroxo species and its implication in reactivity.

an electron transfer follows. The first step depends on the pKa value of the reactant, while the electron transfer step is dependent on the $E_{1/2}$ value of the half-reaction involved with the protonated species. In contrast to the PT-ET process, the PCET/HAT mechanism involves a concerted transfer of proton as well as an electron, and this is governed either by the pKa or $E_{1/2}$ value of the reactants. Our computed data reveals there are three different scenarios (i) species that are strongly basic (pKa >15) and hence enable facile proton

negative $E_{1/2}$ value compared to the PT-ET scenario, the reactivity was found to be controlled by both parameters. The Mn^{IV}=O species follow this route. The Mn=O moiety in the Mn^{IV}=O species is found to have a pKa of 7.8, and the $E_{1/2}$ value of $[Mn^{IV/III}H_3buea(O)]^{-1/-}$ ² couple is computed to be -1.26 eV, and thus it ticks both the boxes in terms of reactivity, (iv) the unreactive nature of Mn^{III/IV}-OH, Mn^V=O, and Fe^{IV}=O is attributed to their low pKa values (< 5) as well as highly negative one-electron redox potentials. Thus, these species

do not tick on any of the boxes and hence are unreactive. For the Fe^{IV}-OH species, although the redox potential is positive (0.21 eV) but found to follow a PCET mechanism rather than a HAT mechanism, as the basicity of Fe^{IV}-OH moiety is too low (pKa = -10.7), the PCET path has a substantial barrier leading to sluggish/no reactivity (Figure 7g, Table S1).

Role of the secondary coordination sphere: The secondary coordination sphere plays a vital role in dictating the reactivity of the high-valent metal-oxo complexes, and its role in altering the reactivity by modulating variation in the electronic structure basicity, geometry, reaction channels is explained above, particularly the secondary coordination sphere has an influence on (i) weakening the crystal field of M=O moiety and not only stabilize the high-spin as the ground state but also destabilize the other spin states eliminating classical two-state reactivity in most of the complexes studied. This is validated in the model studies where stepwise elimination of Hbonds stabilizes the excited states. (ii) The H-bonding network leads to the enhancement of radical character on the metal-oxyl atom, pushing the equilibrium $M^{n+}=O \longrightarrow M^{(n-1)+}O^{\bullet}$ towards the forward direction, which results in a multireference character of the metaloxo/hydroxo species. Secondly, the weakening of the ligand field by the H-bonding cavity reduces the overall CF splitting of the d-orbital, and this also brings the excited states closer, leading to stronger mixing and a new type of reactivity termed ISMR is observed. (iii) the H-bonding cavity also influences the approach of the substrate and hence varies the channel via which the C-H bond activation takes place. While a δ -pathway is observed when all the H-bonding interactions are intact, in model studies, when they are removed sequentially, this destabilizes the $\sigma^{*}{}_{z}{}^{2}$ orbital, leading to the observation of σ -pathway (in model-4). (iv) Also, species that participate in ISMR type reactivity were found to exhibit a varying number of H-bonding interactions at the transition state (example Mn^{IV}=O), with the lowest barriers found when all the H-bonding interactions are intact. This facilitates a HAT mechanism with lower mixing with other mechanisms (PCET/PT-ET). However, in other reaction channels, when one or more H-bonding interactions are ruptured in the transition state, these are higher in energy as HAT is found to mix here with the PCET mechanism. The per cent of PCET mechanism mixing with HAT is found to be proportional to the number of H-bonding interactions ruptured and is inversely proportional to the computed barrier height. Thus, the H-bonding interactions are crucial in dictating reactivity for species showing ISMR reactivity. (v) For the Fe^{IV}=O species (likely also for other species which exhibit conventional TSR or SSR reactivity), the hydrogen bond cavity around the metal-oxo is a major hurdle to its reactivity as sequential elimination of these bond lead to 41% reduction in the barrier height. Further, the strong H-bonding also renders a smaller pKa value for this species compared to other Fe^{IV}=O species (3.4 vs. 6.9 ±0.5 observed for [Fe^{IV}(O)(TMC)(OH₂)]²⁺ species.⁹⁵

Conclusions

The structure, properties, and reactivities of metal-oxo species are of great interest due to their relevance in enzymatic and biomimetic chemistry. In this work, we have studied Mn/Feⁿ⁺-X (n = II to V, X = O/OH) species with [H₃buea]³⁻ as their ligand backbone employing the Density Functional Theory (DFT) and ab initio-CASSCF/NEVPT2; DLPNO-CCSD(T) methods. Conclusions derived from this work is given below;

(i) Our calculations predict the reactivity trend of $Fe^{V=O} > Mn^{III}=O > Mn^{IV}=O > Fe^{III}=O > Mn^{V}=O > Fe^{II}-OH > Mn^{II}-OH > Mn^{IV}-OH > Fe^{IV}-OH > Fe^{IV}=O > Fe^{III}-OH > Mn^{III}-OH for reaction with DHA. Among the Mn-series, Mn^{III}=O is predicted to be the highest reactive species, while$

in Fe-series, $Fe^{v}=O$ is the most reactive, with $Fe^{iv}=O$ at the near bottom of the list. This trend suggests that neither higher oxidation nor high-spin ground state yields superior reactivity.

(ii) The secondary-coordination sphere linked to the H-bonding cavity was found to play an important role in controlling the reactivity. The H-bonding interactions weaken the metal-ligand bonding, reduce the crystal field splitting. This brings several excited states of the same spin multiplicity closer to the ground state resulting in a multireference character in Mn^{III/IV}=O, and Fe^{II}-OH species and observation of identical spin multistate reactivity (ISMR). For Fe^V=O species, the presence of radical character on the ligand diminishes the overall crystal field splitting, bringing the excited state closer, resulting in ISMR reactivity (see Figure 8). The removal of the secondary-coordination sphere interactions in models was found to unalter the reactivity for Mn^{III}=O species; however, for Fe^{IV}=O, a significant enhancement is witnessed. This is also attributed to the presence of ISMR. Further, the H-bonding interactions were found to alter the thermodynamic properties such as basicity and redox potential. An increase in the oxyl character can alter the basicity/redox potentials. While the pKa > 15 leads to the PT-ET mechanism, the higher one-electron redox potential directs the reaction towards the concerted HAT/PCET mechanism. When both the values are moderate, the species are still reactive but exhibit a concerted mechanism. Very low pKa and unfavorable (highly negative) redox potentials are directly related to sluggish/no reactivity observed for Mn^v=O, Fe^{II}-OH, Mn^{II}-OH, Mn^{IV}-OH, Fe^{IV}-OH, Fe^{IV}=O, Fe^{III}-OH, and Mn^{III}-OH species. Further, they also dictate the course of the reaction (σ -, π -, δ -channel) by facilitating the approach of the substrate in a δ -fashion in most of the examples studied. Moreover, it is found that if all the H-bonding interactions are intact, this leads to the purest HAT mechanism and lowest barrier for ISMR species. For species that exhibit classical SSR/TSR reactivity, such as Mn^{II}-OH, Fe^{IV}=O, the secondary coordination sphere effect is found to be toxic. As the multireference character is absent in these species, they lack the electronic flexibility that ISMR species enjoy during the course of the reaction, leading to sluggish/no reactivity for many species, including the popular Fe^{IV}=O species.

To this end, we have studied a series of Fe/Mn-oxo/hydroxo species using DFT and ab initio methods where the secondary coordination sphere plays a critical role in invoking multireference character that is solely responsible for the absence/presence of reactivity in many of these species. As metalloenzymes' active sites have several Hbonding networks, a similar effect could be responsible for their superior catalytic abilities.

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TOC graphic



Various factors contributing to the reactivity of Fe/Mnoxo/hydroxo species are analyzed, and the primary role of the secondary coordination sphere in dictating the reactivity is established.