Fenton chemistry at aqueous interfaces

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Edited by Richard J. Saykally, University of California, Berkeley, CA, and approved December 9, 2013 (received for review August 6, 2013)

In a fundamental process throughout nature, reduced iron unleashes the oxidative power of hydrogen peroxide into reactive intermediates. However, notwithstanding much work, the mechanism by which Fe2+ catalyzes H2O2 oxidations and the identity of the participating intermediates remain controversial. Here we report the prompt formation of O=FeIVCl3− and chloride-bridged di-iron O=FeIVCl-FeIIICl4− and O=FeIVCl-FeIIICl5− ferryl species, in addition to FeIIICl2−, on the surface of aqueous FeCl2 microjets exposed to gaseous H2O2 or O3 beams for <50 μs. The unambiguous identification of such species in situ via online electrospray mass spectrometry let us investigate their individual dependences on Fe2+, H2O2, O3, and H+ concentrations, and their responses to tert-butanol (an -OH scavenger) and DMSO (an -OH acceptor) cosolutes. We found that (i) mass spectra are not affected by excess tert-butanol, i.e., the detected species are primary products whose formation does not involve -OH radicals, and (ii) the di-iron ferryls, but not O=FeIVCl3−, can be fully quenched by DMSO under present conditions. We infer that interfacial Fe (H2O)62+ ions react with H2O2 and O3 >103 times faster than Fe(H2O)62+ in bulk water via a process that favors inner-sphere two-electron O-atom over outer-sphere one-electron transfers. The higher reactivity of di-iron ferryls vs. O=FeIVCl3− as -OH atom donors implicates the electronic coupling of mixed-valence iron centers in the weakening of the FeIV-O bond in poly-iron ferryl species.

metal ions | reactive oxygen species | aerosols | advanced oxidation processes | nanoparticles

High-valent FeIV=O (ferryl) species participate in a wide range of key chemical and biological oxidations (1–4). Such species, along with -OH radicals, have long been deemed putative intermediates in the oxidation of FeII by H2O2 (Fenton’s reaction) (5, 6), O3, or HOCl (7, 8). The widespread availability of FeII and peroxides in vivo (9–12), in natural waters and soils (13), and in the atmosphere (14–18) makes Fenton chemistry and FeIV=O groups ubiquitous features in diverse systems (19). A lingering issue regarding Fenton’s reaction is how the relative yields of ferryls vs. -OH radicals depend on the medium. For example, by assuming unitary -OH radical yields, some estimates suggest that Fenton’s reaction might account for ~30% of the -OH radical production in fog droplets (20). Conversely, if Fenton’s reaction mostly led to FeIV=O species, atmospheric chemistry models predict that their steady-state concentrations would be ~104 times larger than [OH], thereby drastically affecting the rates and course of oxidative chemistry in such media (20). FeIV=O centers are responsible for the versatility of the family of cytochrome P450 enzymes in catalyzing the oxidative degradation of a vast range of xenobiotics in vivo (21–28), and the selective functionalization of saturated hydrocarbons (29). The bactericidal action of antibiotics has been linked to their ability to induce Fenton chemistry in vivo (9, 30–34). Oxidative damage from exogenous Fenton chemistry likely is responsible for acute and chronic pathologies of the respiratory tract (35–38).

Despite its obvious importance, the mechanism of Fenton’s reaction is not fully understood. What is at stake is how the coordination sphere of Fe2+ (39–46) under specific conditions affects the competition between the one-electron transfer producing -OH radicals (the Haber–Weiss mechanism) (47), reaction R1, and the two-electron oxidation via O-atom transfer (the Bray–Gorin mechanism) into FeIVO2−, reaction R2 (6, 23, 26, 27, 45, 48–51):

Fe2+ + H2O2 → Fe3+ + OH− + ·OH [R1]

Fe2+ + H2O2 → FeIVO2− + H2O. [R2]

Ozone reacts with Fe2+ via analogous pathways leading to (formally) the same intermediates, reactions R3a, R3b, and R4 (8, 49, 52, 53):

Fe2+ + O3 → Fe3+ + O3· [R3a]

O3· + H+ → O2 + ·OH [R3b]

Fe2+ + O3 → FeIVO2− + O2. [R4]

At present, experimental evidence about these reactions is indirect, being largely based on the analysis of reaction products in bulk water in conjunction with various assumptions. Given the complex speciation of aqueous FeIV=O/FeIV+ solutions, which includes diverse poly-iron species both as reagents and products, it is not surprising that classical studies based on the identification of reaction intermediates and products via UV-absorption spectra and the use of specific scavengers have fallen short of fully unraveling the mechanism of Fenton’s reaction. Herein we address these issues, focusing particularly on the critically important interfacial Fenton chemistry that takes place at boundaries between aqueous and hydrophobic media, such as those present interfaces.

Significance

The Fenton reaction, Fe2+ + H2O2, plays fundamental roles in vivo and in advanced oxidation processes. Its mechanism and the identity of the intermediates involved, however, remain controversial. Here we present direct, mass-specific evidence of the prompt formation of mono- and poly-iron FeIV=O (ferryl) species on the surface of aqueous FeCl2 microjets exposed to gaseous H2O2 or O3 beams. Remarkably, Fe2+ ions at the aqueous surface react with H2O2 and O3 >103 times faster than Fe(H2O)62+ in bulk water. Our results suggest that interfacial Fenton and Fenton-like chemistries could play a more significant role than hitherto envisioned.

Author contributions: S.E. designed research; S.E. and Y.S. performed research; S.E. conceived the paper.

Funding: Supported by Grants-in-Aid for Scientific Research (A) 24249067 to S.E. and for Young Scientists (B) 25800647 to Y.S., and by a grant from the Naito Foundation to A.J.C. AJC thanks the TAKAMURA foundation, the MEXT KAKENHI, and the United Nations University for financial support. AJC is grateful to R. Saykally for his mentorship and encouragement. AJC thanks the Fondation pour la Recherche Médicale for its financial support.

Editorial support: The authors declared no conflict of interest.

This article is a PNAS Direct Submission.

Freenly available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1314885111/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1314885111

PNAS | January 14, 2014 | vol. 111 | no. 2 | 623–628
Results and Discussion

We exploited the high sensitivity, surface selectivity, and unambiguous identification capabilities of a newly developed instrument based on online electrospray mass spectrometry (ES-MS) (58–62) to identify the primary products of reactions R1–R4 on aqueous FeCl₂ microjets exposed to gaseous H₂O₂ and O₃ beams under ambient conditions [in N₂(g) at 1 atm at 293 ± 2 K]. Our experiments are conducted by intersecting the continuously refreshed, uncontaminated surfaces of free-flowing aqueous microjets with reactive gas beams for τ ~ 10–50 μs, immediately followed (within 100 μs; see below) by in situ detection of primary interfacial anionic products and intermediates via ES-MS (Methods, SI Text, and Figs. S1 and S2). We have previously demonstrated that online mass spectrometric sampling of liquid microjets under ambient conditions is a surface-sensitive technique (58, 62–67).

Fig. 1. Negative ion ES mass spectra of 10 μM (A) and 100 μM (B) FeCl₂ aqueous microjets exposed to O₃(g) or O₂(g)/O₃(g) for ~10–50 μs. X and Y correspond to O⁻=FeIV⁺Cl⁻FeIVCl₄⁻ and O⁻=FeIV⁺Cl⁻FeIVCl₅⁻, respectively. See text for details.

Fig. 2 A–D shows the evolution of reactant and products as functions of [O₃(g)] at FeCl₂ concentrations spanning the 1–1000-μM range. It is apparent that although all signal intensities increase with [FeCl₂], the ratio α = [FeIV⁺Cl⁻]/[FeIVCl₄⁻] is not constant, as expected for the products of concurrent reactions R3α and R4, but both depend on O₃(g) and FeCl₂ concentrations (8, 51). It should be pointed out that mass signal intensities are chlorinated that microdroplets carried by the nebulizer gas issuing from the injector nozzle at typical v ~ 2 × 10⁶ cm s⁻¹ velocities would reach the inlet to the detection section of the mass spectrometer ~2 cm away from the tip of the nozzle in <100 μs. The net charges produced during the aerodynamic breakup of the liquid jet represent the raw information acquired by the mass spectrometer (58). We confirmed experimentally that in our instrument charge separation among the anions and cations present in interfacial layers is largely driven pneumatically (rather than electrostatically/electrochemically) (68) by showing that signal intensities and anion fractionation increase at higher nebulizer gas velocities v and extrapolate to zero as v → 0 (58). In Fig. 1A, the ES mass spectral multiplets at m/z = 161, 163, and 165 correspond to FeIVCl₄⁻. The characteristic multiplet patterns arising from natural abundance 35Cl (75%) and 37Cl (25%) chlorine isotopes let us establish the number of Cl⁻ contained in each detected species and, hence, the molecular composition of these singly charged ions (Fig. S3). In the presence of O₃(g)/O₂(g) mixtures, new ES mass spectral clusters appear at m/z = 177, 179, and 181 and m/z = 196, 198, and 200, which can be readily assigned to O⁻=FeIV⁺Cl⁻ and FeIV⁺Cl₅⁻, respectively. We verified that Cl⁻ is inert toward O₃(g) and does not participate in the oxidation process, in accord with the small value of k(Cl⁻ + O₃) = 0.1 × s⁻¹ in bulk water (69). Thus, ~50% FeIV⁺ is oxidized by 6 parts per million by volume (ppmw) (6 × 10⁻⁶ atm) O₃ into FeIV⁺ and FeIV⁺ at the air-water interface within τ ~ 10–50 μs. This is a remarkable result because from (i) the (maximum) equilibrium concentration of dissolved O₃ in the experiments of Fig. 1—[O₃(g)] = 6 × 10⁻⁸ M (from Henry’s law constant for O₃(g) in bulk water at ambient temperature H = 0.01 M atm⁻¹) (70)—and (ii) the rate coefficients of reactions R3α—kₐ = (1.7 ± 0.4) × 10⁵ M⁻¹ s⁻¹ and R4—k₈ = (8.2 ± 0.3) × 10⁶ M⁻¹ s⁻¹—in bulk water (7), we estimate that less than 0.1% FeIV⁺ should have been consumed under present conditions. In other words, reactions R3α and R4 proceed ~10⁻⁶ times faster at the gas–water interface than in bulk water. The modest concentration enhancements of many gases at the air–water interface predicted by theoretical simulation (70) and demonstrated experimentally (71–74) would not substantially alter the above statement. We tentatively ascribe the significant acceleration of reaction R4 at the gas–water interface to the enhanced lability and/or distorted geometry (75) of the hydration shell of FeIV⁺ at the air–water interface predicted by (76) (see below).

Fig. 1B shows additional peaks at higher masses. The ES mass signals at m/z = 287, 289, and 291 correspond to FeIV⁺Cl⁻. The group at m/z = 303, 305, and 307, hereafter labeled X, can be assigned to O⁻=FeIV⁺Cl⁻FeIV⁺Cl₄⁻ on the basis of peak masses and the characteristic Cl⁻-multiplet pattern. Similarly, we assign the group at m/z = 339, 341, 343, 345, and 347, hereafter labeled Y, to O⁻=FeIV⁺Cl⁻FeIV⁺Cl₅⁻. Our results are qualitatively consistent with previous reports based on the UV-absorption detection of O⁻=FeIV⁺ species during the bulk ozonolysis of acidic FeIV⁺ (8, 23, 49, 52).

Fig. 2 A–D shows the evolution of reactant and products as functions of [O₃(g)] at FeCl₂ concentrations spanning the 1–1000-μM range. It is apparent that although all signal intensities increase with [FeCl₂], the ratio α = [FeIV⁺Cl⁻]/[FeIVCl₄⁻] is not constant, as expected for the products of concurrent reactions R3α and R4, but both depend on O₃(g) and FeCl₂ concentrations (8, 51). It should be pointed out that mass signal intensities are not linear functions of bulk concentrations throughout, because the interfacial concentrations detected herein will plateau as the interface becomes saturated. Also, reactant signals may bottom out rather than vanish at sufficiently large O₃(g) or [H₂O₂(g)] concentrations because interfacial layers are continuously replenished present in atmospheric clouds (16), living tissues, biomembranes, bio-microenvironments (38, 54, 55), and nanoparticles (56, 57).
The addition of DMSO as a cosolvent, in contrast, has marked effects on product distribution. DMSO quenches most (but not all) ozonation products, such as $\text{O}_2 \cdot \text{Cl}^{-} \cdot \text{Fe}^{3+} \cdot \text{Cl}^{-}$ and $\text{O} = \text{Fe}^{3+} \cdot \text{Cl}^{-} \cdot \text{Cl}^{-}$, and all higher-mass poly-iron species. Remarkably, the mono-iron ferryl $\text{O} = \text{Fe}^{3+} \cdot \text{Cl}^{-}$ (and, as expected, $\text{Fe}^{3+} \cdot \text{Cl}^{-}$) is not affected.

Similar experiments in which aqueous microjets containing 10 $\mu$M and 1 mM FeCl$_3$ in the absence and presence of $t$-BuOH as a cosolvent, were exposed to H$_2$O$_2$(g)/N$_2$(g) mixtures led to the products shown in Fig. 5. A comparison of Figs. 1 and 5 confirms that H$_2$O$_2$ and O$_3$ react with interfacial Fe$_2$ to along reactions R1–R2 and R3a,b–R4, respectively, leading to (formally) the same products, albeit in different proportions. Note again that from Henry’s law constant for H$_2$O$_2$(g) in bulk water—$H = 10^5$ M atm$^{-1}$ ($\sim 10^7$ times larger than for O$_3$) (81)—the maximum equilibrium concentration of dissolved H$_2$O$_2$ in the experiments of Fig. 5A is $[\text{H}_2\text{O}_2(\text{aq})] = 0.03$ M. Therefore, from $k/(\text{Fe}^{II} + \text{H}_2\text{O}_2) \sim 50$ M$^{-1}$s$^{-1}$, we estimate that Fe$^{3+}$ half-lives would be on the order of seconds if reactions R1–R2 took place in bulk water, rather than a few tens of microseconds, as observed in our experiments (81). Note that in contrast to the O$_3$ case, $\text{O} = \text{Fe}^{3+} \cdot \text{Cl}^{-}$ would be consumed at the same rates via R5 in both systems. We confirmed that the addition of DMSO as a cosolvent in these experiments (Fig. 5A) has an effect similar to those displayed in Fig. 4C.

The prompt formation of products in our experiments, at rates several orders of magnitude larger than those estimated for the same reactants dissolved in bulk water, and the peculiar variation in the ratio of the products of parallel reactions R3a and R4 (Fe$^{3+} \cdot \text{Cl}^{-}$ and $\text{O} = \text{Fe}^{3+} \cdot \text{Cl}^{-}$) as a function of ozone and Fe$^{3+}$ concentrations reveal the exceptional characteristics of Fenton-like chemistry at the air–water interface. These phenomena, which could be typical of water–hydrophobe interfaces in general, reveal (i) the enhanced reactivity of interfacial Fe$^{3+}$ as an O-atom acceptor from O$_3$ and H$_2$O$_2$ and (ii) the progressive emergence of such species to the outermost interfacial layers at higher Fe$^{3+}$ bulk concentrations. Extensive ab initio molecular dynamics (Car–Parrinello) calculations that incorporate the water solvent explicitly would be required to elucidate the molecular details of these

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**Fig. 2.** ES mass spectral signal intensities of reactant and products at the surface of 1 $\mu$M (A), 10 $\mu$M (B), 100 $\mu$M (C), and 1,000 $\mu$M (D) FeCl$_3$ aqueous microjets as functions of the O$_3$(g) mixing ratio (1 ppmv = $2.5 \times 10^{13}$ molecules per centimeter$^{-3}$ at 1 atm, 293 K). All experiments in 1 atm N$_2$(g) at 293 K. Background signal was subtracted for Fe(III)Cl$_4$. 

**Fig. 3.** ES mass spectral signal intensities of reactant and products from 100 $\mu$M FeCl$_3$ aqueous microjets at pH 2.3 (A), pH 2.9 (B), pH 4.4 (C), and pH 5.6 (D) as functions of the O$_3$(g) mixing ratio (1 ppmv = $2.5 \times 10^{13}$ molecules per centimeter$^{-3}$ at 1 atm, 293 K). All experiments in 1 atm N$_2$(g) at 293 K. Background signal was subtracted for Fe(III)Cl$_4$. 

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unique events at the gas–water interface (26, 48, 82). The possibility that doubly charged Fe$^{2+}$ cations might be present in shallow interfacial layers is supported by molecular dynamics calculations, which predict that the concentration of doubly charged Mg$^{2+}$ peaks at ~4 Å below the Gibbs dividing surface at values twice as large as its concentration in bulk water (83). Recent X-ray reflectivity studies confirmed the existence of nonmonotonic cation density profiles within ~1-nm interfacial layers of aqueous electrolyte solutions (84). We cannot rule out the possibility that impinging gases are hydrated before colliding with the liquid surface (85, 86), but we deem it inconsequential because O$_3$ and H$_2$O$_2$ gas flows under present conditions.

By considering that O-atom transfer, in contrast to electron transfer (reactions R1 and R3a), requires direct contact of the O-atom donors (H$_2$O and O$_3$) with the metal ion, and that the hydration waters of Fe($H_2O$)$_6$$^{2+}$ in bulk water are exchanged approximately every 0.5 µs (87), whereas O$_3$(g) remains trapped on the water surface for only 0.1 ns (76), our results imply that either (i) dissociative ligand substitution in interfacial Fe($H_2O$)$_6$$^{2+}$ (IF) is much faster than in Fe($H_2O$)$_6$$^{2+}$ in bulk water (B) or (ii) interfacial Fe($H_2O$)$_6$$^{2+}$ has a distorted octahedral geometry, on account of the broken symmetry, that lets O$_3$ approach the Fe$^{2+}$ center via low-energy associative interchange pathways (88). Against this backdrop, our findings reveal that the dynamics and thermodynamics of ion hydration at aqueous interfaces are quite different from those in bulk water (75, 89). Thus, the roles and behavior of ions in many physical, chemical, and biological interfacial processes may not be predicted (or analyzed) from the properties of the corresponding ions in bulk water.

The dissimilar evolutions of O=Fe$^{IV}$Cl$_3^-$ and Fe$^{III}$Cl$_4^-$ in Figs. 2 and 3 are consistent with IF(z) depth profiles at the interface that depend on total [Fe$^{II}$. Everything happens as though the IF species involved in O-atom transfer are preferentially pushed to the surface of more concentrated Fe$^{2+}$ solutions. In this context, it is relevant to point out that we recently found that hydronium (H$_3$O$^+$) emerges at the surface of water less than pH 4 as a "superacid" (40) that protonates impinging gases having proton affinities larger than water (62, 64, 90). Thermodynamics dictates that this is possible only if interfacial H$_2$O$^+$ is weakly hydrated. If Fe$^{2+}$ behaves similarly, the enhanced reactivity of IF relative to B and its emergence at the surface of more concentrated solutions could be alternatively ascribed to an incomplete hydration shell of IF.

We associate the significantly enhanced reactivity of poly-iron ferryls relative to O=Fe$^{IV}$Cl$_3^-$ as O-atom donors to DMSO with the weakening of the O=Fe$^{IV}$ bond, and ascribe such weakening to electronic rather than inductive effects. Our view is based on the fact that strong electron-donating ligands, such as thiolate (24), in the axial position are known to weaken and elongate the Fe$^{IV}=O$ bond, in low-spin (S = 1) complexes by increasing the population of its σ- and π-antibonding molecular orbitals (45). Because a Cl$^-$ ligand coordinatively bound to Fe$^{II}$ (as in X) or Fe$^{III}$ (as in Y) should be less nucleophilic than unbound Cl$^-$, the enhanced reactivity of poly-iron ferryls appears to be a result of H$_2$O$_2$–(H$_2$O)$_n$ complexes represent a very small fraction of O$_3$ and H$_2$O$_2$ gas flows under present conditions.

![Fig. 4. Negative ion ESI mass spectra of aqueous microjet containing 100 µM FeCl$_2$ in the absence (A) and presence (B) of 10 mM t-BuOH and in the presence of 10 mM DMSO (C), exposed to O$_3$(g) for ~10–50 µs. X and Y correspond to O=Fe$^{IV}$Cl$_3^-$ and O=Fe$^{III}$Cl$_4^-$, respectively.](image)

![Fig. 5. Negative ion ESI mass spectra of 10 µM (A and B) and 1 mM (C and D) FeCl$_2$ aqueous microjets in the absence/presence of excess t-BuOH as a cosolute exposed to H$_2$O$_2$(g) for ~10–50 µs. X and Y correspond to O=Fe$^{IV}$Cl$_3^-$ and O=Fe$^{III}$Cl$_4^-$, respectively.](image)
the electronic coupling of the iron centers via $\text{Cl}^-$ bridges. Further experimental work and high-level quantum chemistry calculations are needed to fully elucidate the molecular basis of the O-donating power of poly-ion ferryls.

In summary, we present compelling evidence of the prompt formation of mono- and poly-ion Fe$^{IV}$ species on the surface of aqueous FeCl$_2$ microjets exposed to gaseous H$_2$O$_2$ or O$_3$ beams. The exceedingly fast reactions of interfacial Fe$^{IV}$-$\text{H}_2$O$_2$ with gas phase H$_2$O$_2$ and O$_3$ ($10^{14}$–$10^4$ times faster than similar reactions of Fe(H$_2$O)$_{5}$-$\text{Cl}$ in bulk aqueous media) are ascribed to a labile/incomplete hydration shell that favors inner-sphere O-atom transfer reactions over outer-sphere one-electron transfers. The finding that di-iron ferryls O=Fe$^{IV}$-Cl-Fe$^{IV}$-$\text{Cl}$ and O=Fe$^{IV}$-$\text{Cl}$-Fe$^{IV}$-$\text{Cl}$ are fully scavenged by the O-atom acceptor DMSO, whereas O=Fe$^{IV}$-$\text{Cl}$ is not, implicates the electronic coupling of mixed-valence iron centers in weakening the Fe$^{IV}$-$\text{Cl}$ bond. Present results suggest a more significant role than hitherto envisioned for the Fe$^{IV}$ species produced in Fenton and Fenton-like chemistries at aqueous interfaces opposite hydrophobic media, such as air in atmospheric aerosols and clouds, proteins in living tissues, bio-membranes, and bio-microenvironments.

**Methods**

Our experiments involve the injection of aqueous FeCl$_2$ jets into the spraying chamber of an ESI mass spectrometer (Agilent 6130 Quadrupole LC/MS Electrospray System) flushed with N$_2$(g) at 1 atm, 293 K. Jets are exposed therein to orthogonal gas-phase O$_3$ or H$_2$O$_2$ beams. The species produced on the surface of such jets are analyzed in situ via online ESI-MS. The present experimental setup essentially is the same as the one reported elsewhere therein, or rebound (94, 95). See Supporting Information for more details.

**Acknowledgments.** We are grateful to Dr. Himanshu Mishra and Profs. Michael Hoffmann, William Goddard, and Harry Gray of the California Institute of Technology for valuable discussions. S.E. thanks the Japan Science and Technology Agency PRESTO program, Grant for Environmental Research Projects from the Sumitomo Foundation, and Foundation for Environmental Protection Technology. Y.S. thanks the Grant-in-Aid for Japan Society for the Promotion of Science Fellows for financial support.

8. Logager T, Holmman J, Sehested K, Pedersen (1992) Oxidation of ferrous-ions by ultrapure O$_2$(g) under present conditions (Fig. S5). Teflon gas lines were cleaned and dried daily with ultrapure nitrogen gas. Ozone was generated by flowing ultrapure O$_3$(g) (>99.998%; Kyoto Teisan) through a silent discharge ozonizer (KSG-050; Kotoroha) and quantified via online UV-visible absorption spectrophotometry (Agilent 8453; Agilent Technologies) at 250 and 300 nm [absorption cross sections $\sigma_{250}$ nm = $1.1 \times 10^{-17}$, $\sigma_{300}$ nm = $3.9 \times 10^{-19}$ cm$^2$ molecule$^{-1}$ at 298 K] before entering the reaction chamber (Fig. S2).


