

# The Spontaneous Electron-Mediated Redox Processes on Sprayed Water Microdroplets

Shuihui Jin,<sup>¶</sup> Huan Chen,<sup>¶</sup> Xu Yuan,<sup>¶</sup> Dong Xing, Ruijing Wang, Lingling Zhao, Dongmei Zhang, Chu Gong, Chenghui Zhu, Xufeng Gao, Yeye Chen, and Xinxing Zhang\*



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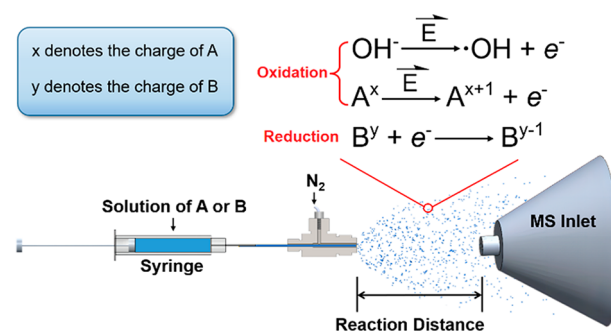
**ABSTRACT:** Water is considered as an inert environment for the dispersion of many chemical systems. However, by simply spraying bulk water into microsized droplets, the water microdroplets have been shown to possess a large plethora of unique properties, including the ability to accelerate chemical reactions by several orders of magnitude compared to the same reactions in bulk water, and/or to trigger spontaneous reactions that cannot occur in bulk water. A high electric field ( $\sim 10^9$  V/m) at the air–water interface of microdroplets has been postulated to be the probable cause of the unique chemistries. This high field can even oxidize electrons out of hydroxide ions or other closed-shell molecules dissolved in water, forming radicals and electrons. Subsequently, the electrons can trigger further reduction processes. In this Perspective, by showing a large number of such electron-mediated redox reactions, and by studying the kinetics of these reactions, we opine that the redox reactions on sprayed water microdroplets are essentially processes using electrons as the charge carriers. The potential impacts of the redox capability of microdroplets are also discussed in a larger context of synthetic chemistry and atmospheric chemistry.

**KEYWORDS:** microdroplet chemistry, air–water interface, mass spectrometry, redox reactions, aerosols



## 1. INTRODUCTION

Water microdroplet chemistry has drawn tremendous attention in recent years for its ability to accelerate chemical reactions by several orders of magnitude compared to the same reactions in bulk water, and to trigger spontaneous reactions that cannot occur in bulk water.<sup>1,2</sup> Among the unique properties of water microdroplets, the strong spontaneous redox power is especially intriguing.<sup>3–22</sup> Several groups deduced that there is a high electric field ( $\sim 10^9$  V/m) at the air–water interface of microdroplets due to the formation of electric double layers, the alignment of the free O–H bonds of the interfacial water molecules, or the partial charge transfer that results in the interfacial  $\text{H}_2\text{O}^+\cdots\text{H}_2\text{O}^-$  pairs.<sup>23–31</sup> This high field is large enough to pull electrons out of the hydroxide ions ( $\text{OH}^-$ ) in water,<sup>14–18</sup> yielding hydroxyl radicals ( $\cdot\text{OH}$ ) and electrons (Figure 1). A combination of electrochemical experiment and theory shows that the oxidation potential of  $\text{OH}^-$  to  $\cdot\text{OH}$  is at least 0.7 V below tabled values on the aerial surface of air bubbles in water,<sup>30</sup> so the reaction of  $\text{OH}^-$  that yields an electron as shown in Figure 1 should be easier to take place at the air–water interface compared to the bulk. However, a recent theoretical work showed that the strength of the solvent-induced electric field at the interface was not larger than that in bulk solution,<sup>32</sup> and that the main reason for the large changes observed for interfacial redox potentials was due



**Figure 1.** Setup of a typical mass spectrometry experiment for microdroplet chemistry and the electron-mediated redox mechanisms that occur at the air–water interface of the droplets.

to partial solvation, which made the interfacial electrostatic potential differ considerably from the bulk. Mass spectrometry

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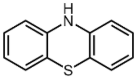
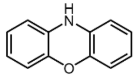
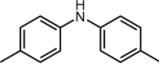

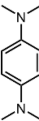
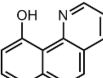
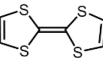
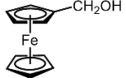


has been utilized as the major tool for studying microdroplet chemistry; however, the  $\cdot\text{OH}$  radicals generated in microdroplets are not charged, so they cannot be directly observed by a mass spectrometer. Fortunately,  $\cdot\text{OH}$  was captured in the form of a  $\text{H}_4\text{O}_2^+$  cation, whose structure is an  $\cdot\text{OH}$  combined with an  $\text{H}_3\text{O}^+$  via a hydrogen bond:  $\cdot\text{OH}\cdots\text{H}_3\text{O}^+$ .<sup>13</sup> The detection of  $\cdot\text{OH}$  and the recombination of two  $\cdot\text{OH}$  radicals to yield hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) are examples of the water microdroplets' power to promote one-electron oxidation (see the first row of Table 1).<sup>13–18</sup> Later, our group observed the

$\text{C}_6\text{F}_5\text{I}^{\bullet-}$ ,<sup>10</sup> the reduction of  $\text{Fe}^{3+}$  and  $\text{Cu}^{2+}$  complexes into  $\text{Fe}^{2+}$  and  $\text{Cu}^+$  complexes,<sup>11</sup> and the reduction of three *ortho*-quinone molecules into radical anions.<sup>20</sup> In most of these cases, the reduction was achieved solely by the electrons, but some needed the participation of other species such as the protons in water.

In this Perspective, by summarizing the electron-mediated redox reactions in water microdroplets including published studies and some new data collected by our group, we provide evidence that the generation and capture of the electrons in water microdroplets is the key to most of the redox reactions. Based on these discussions, we anticipate that water microdroplet chemistry will be an avenue rich in opportunities in understanding key problems and providing new methodologies in the fields such as synthetic chemistry and atmospheric chemistry.

**Table 1. A List of Species Showing One-Electron Oxidation on Water Microdroplets<sup>a</sup>**

Name	Structure	Product
Hydroxide <sup>13–18</sup>	$\text{OH}^-$	$\cdot\text{OH}$ , $\text{H}_2\text{O}_2$ , $\text{H}_4\text{O}_2^+$
Phenothiazine <sup>19</sup>		Radical cation
Phenoxazine <sup>19</sup>		Radical cation
4,4-Dimethyldiphenylamine <sup>19</sup>		Radical cation
N,N-dimethylaniline <sup>19</sup>		Radical cation
Iodide ion <sup>12</sup>	$\text{I}^-$	$\text{I}^\bullet$ , $\text{I}_2$ , $\text{I}_3^-$
N,N,N',N'-tetramethyl-1,4-phenylenediamine <sup>a</sup>		Radical cation
10-Hydroxybenzo[h]quinoline <sup>a</sup>		Radical cation
Tetrathiafulvalene <sup>a</sup>		Radical cation
Ferrocenemethanol <sup>a</sup>		Radical cation

<sup>a</sup>Data new to this Perspective. Typical mass spectra supporting the new data are provided in the SI.

formation of the radical cations of phenothiazine, phenoxazine, and dimethyldiphenylamine by spraying their water solutions, whose oxidation potentials are lower than  $\text{OH}^-$ .<sup>19</sup> These results suggest that oxidation potential can be used as an indicator to predict whether or not a molecule can be oxidized by one electron in water microdroplets. The strong reducing power of water microdroplets is a result of the electron, which has been demonstrated in the formation of pyridyl anions in spraying an aqueous solution containing dissolved pyridine,<sup>3</sup> the reduction of dissolved chloroauric acid in water microdroplets to yield gold nanoparticles and nanowires,<sup>4</sup> the reduction of doubly charged viologen compounds to singly charged viologens,<sup>5</sup> the reduction of organic compounds by hydrogenation,<sup>6</sup> the reduction of  $\text{CO}_2$  into formate,<sup>7,8</sup> the reduction of  $\text{Hg}^{2+}$  into atomic  $\text{Hg}$ ,<sup>9</sup> the reduction of  $\text{C}_6\text{F}_5\text{I}$  into

## 2. CHARACTERIZATION METHODS

On the technical front, mass spectrometry has been used as the major probe for the microdroplet reactions in most of the references cited in this Perspective, not only for its advantages in tracing reactions by identifying the structures of the reactants and products, but also because the sprayed microdroplet is a form that can be directly injected into a commercial mass spectrometer, facilitating fast and in situ monitoring of the reactions, and sometimes helping to capture short-lived radical intermediates that bear key mechanistic information on the reactions. The radical cations and anions in this Perspective are such intermediates that reveal the electron-mediated redox processes (*vide infra*). The water solution of a certain substrate is forced by a syringe pump through a fused silica capillary that sits inside a larger coaxial capillary through which high-pressure  $\text{N}_2$  sheath gas flows. The resulting plume of microdroplets is aimed toward the inlet of a mass spectrometer (Figure 1). The sizes of the droplets generated in this manner depend on the sheath gas pressure, and are in the range of several to several tens of microns.<sup>33</sup>

A variation of the setup installs the sprayer into a glovebox filled with pure  $\text{N}_2$ , and a mass spectrometer's inlet is inserted into the glovebox with a tight seal.<sup>34</sup> Such an arrangement has succeeded in the observation of fragile radical products that are vulnerable to ambient air.<sup>10,11</sup> These examples alert us that ambient sampling mass spectrometry, even though convenient to use, might diminish key mechanistic information due to the loss of fragile ions.

More caution needs to be taken when using mass spectrometry to characterize the products from microdroplets, because the voltages on the ion optics of a mass spectrometer can occasionally cause collision-induced reactions,<sup>35</sup> giving information that might be mistaken as microdroplet reactions. For example, the tube lens region has relatively high pressure ( $\sim 1$  Torr), causing frequent ion–molecule collisions therein. A reliable protocol is to turn off the voltages on some of the lenses of the mass spectrometer at a cost of lower ion intensity. In addition, a key factor of microdroplet experiment is the reaction distance between the end of the microdroplet sprayer and the mass spectrometer inlet, which needs to be adjusted to change the microdroplet flying (reaction) time (Figure 1). If the product/reactant relative intensity changes with the reaction time, one can safely conclude that the reaction is indeed a microdroplet reaction but not an artifact from the gas-phase collisions inside the mass spectrometer. Depending on

the sheath gas pressure and distance, the reaction time varies from tens to hundreds of microseconds.<sup>33</sup>

Another warning is the inlet temperature of the mass spectrometer, which may cause reactions to occur and influence the observed kinetics. Two effects, the evaporative cooling versus the heating of ejected bare ions from microdroplets, were thought to play competitive roles. When the temperature is lower than the boiling point of water, the heat is mainly utilized to evaporate water, yielding a cooling effect and a lower reaction efficiency. When the temperature exceeds 100 °C, the evaporation of water in microdroplets is more complete, and the heat is mainly applied to accelerate the reactions.<sup>36</sup>

Other in situ characterization methods include Raman spectroscopy,<sup>37</sup> fluorescence spectroscopy,<sup>14</sup> and stimulated Raman excited fluorescence microscopy<sup>21</sup> of individual microdroplets deposited on a hydrophobic surface. It is worth mentioning that stimulated Raman excited fluorescence microscopy was also utilized to measure the electric field at the surface of microdroplets.<sup>21</sup> Some studies collected sprayed microdroplets and characterized the products with conventional methods such as NMR.<sup>6,38,39</sup> However, in this manner, fragile intermediates generated in the microdroplet reactions can no longer exist due to extensive sample handling.

### 3. THE ONE-ELECTRON OXIDATION PROCESSES

The potential for removing electrons from OH<sup>-</sup> is 2.72 V in the bulk solution.<sup>40</sup> At the air–water interface, this value should be lower.<sup>30,41</sup> As a result, the electric field, 3 V across 5 Å,<sup>14</sup> at the surface of water microdroplets should be sufficient to oxidize electrons not only from OH<sup>-</sup>, but potentially a large plethora of other molecules. However, it should be noted that the oxidation potential value measured in the bulk solution is a helpful but not guaranteed way to determine whether or not a molecule can be oxidized in microdroplets, because the redox potentials at the air–water interface can be very different from the bulk.<sup>41</sup> Based on these rationales, one can anticipate that microdroplet chemistry promises a highly efficient, green, and convenient method to generate radicals by removing electrons from the species dissolved in aqueous solutions, and the radicals generated in this manner can be further utilized in scenarios such as organic synthesis. In addition, since atmospheric water droplets such as those in clouds and fogs are also micrometers in size,<sup>42</sup> the spontaneous generation of radicals in atmospheric water provides an alternative but previously neglected perspective to understand some redox processes in the atmosphere.

Our group performed several studies taking advantage of the spontaneous oxidation of one electron in water microdroplets. The first example is the oxidative C–H/N–H cross-coupling reactions.<sup>19</sup> Oxidative C–H/N–H cross coupling has emerged as an atom-economical method for the construction of C–N bonds.<sup>43</sup> Conventional methods require at least one of the following: high temperatures, strong oxidizers, transition metal catalysts, organic solvents, light, and electrochemical cells to oxidize electrons from the substrates, forming corresponding radical cations. The resulting radicals can further recombine to yield the final C–N coupled products. Not surprisingly, with the help of microdroplets, the rate-limiting step that removes electrons from the substrate becomes spontaneous and ultrafast. As a proof-of-concept study, we sprayed the water solutions of four substrates (the second to fifth rows of Table 1),<sup>19</sup> and unambiguously observed their radical cations in the

mass spectra. When the mixtures of the substrates were sprayed, C–N coupled products from the combination of two different radicals were also observed. This study deepens our understanding of the oxidizing properties of water microdroplets and brings opportunities for unique redox chemistry, especially in green organic synthesis. Microdroplet synthesis is green in the sense that no catalysts, strong oxidizers, elevated temperatures, light, and electrochemical cells are needed.

Another example for the oxidation of one electron by water microdroplets is in the context of atmospheric chemistry. Atomic and molecular iodine, I<sup>•</sup> and I<sub>2</sub>, play important roles in the atmosphere, such as the catalytic depletion of ozone and the oxidation of gaseous elemental mercury.<sup>44</sup> It is known that the major source of I<sup>•</sup> and I<sub>2</sub> in the atmosphere is the photodissociation of organoiodine molecules released by algae in the sea.<sup>44</sup> But in sprayed water microdroplets, the iodide ion, I<sup>-</sup>, can be spontaneously oxidized into I<sup>•</sup>, which further evolves into I<sub>2</sub><sup>-</sup> and I<sub>3</sub><sup>-</sup> (Table 1), presenting a previously unknown source of I<sup>•</sup> and I<sub>2</sub> in atmospheric water.<sup>12</sup> The formation of I<sup>•</sup> might be a result of the direct removal of an electron by the high electric field in microdroplets, or the oxidation by •OH. In that study, we also collected the sprayed droplets and characterized the I<sub>3</sub><sup>-</sup> ion with UV–vis absorption spectroscopy. This work implies that this vast surface area of airborne water microdroplets might have been functioning as previously unknown electrochemical cells for the spontaneous and ultrafast redox reactions that are very different from bulk water, and these redox reactions are highly important in many atmospheric chemical processes.


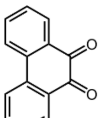
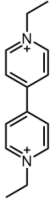
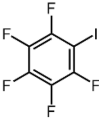
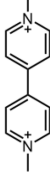

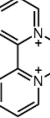
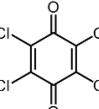
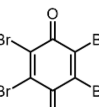
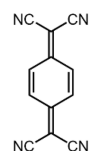
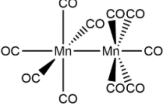
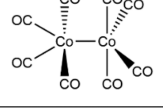


As mentioned above, the electric field on water microdroplets should be sufficient enough to oxidize potentially a large plethora of other molecules. To provide more examples, Table 1 also presented some new data showing the formation of the corresponding radical cations by spraying their aqueous solutions. These molecules include aromatic amines, transition metal complexes, and heterocycles. The mass spectra showing the radical cations are presented in Figures S1 to S4, respectively. The oxidation potentials of all of these molecules are not high. Among these examples, the radical cations of amines and heterocycles open new opportunities for organic synthesis. The observation of the tetrathiafulvalene (TTF) cation is especially interesting because TTF<sup>•+</sup> is an aromatic radical that is relatively stable,<sup>45</sup> so the oxidation potential of TTF is only 0.34 V. In the last row of Table 1, ferrocenemethanol (FM) was chosen instead of ferrocene because the former has a higher water solubility. The oxidation potential of ferrocene into ferrocenium is only 0.4 V (*E*<sub>1/2</sub> versus SCE) with the Fe<sup>2+</sup> core oxidized into Fe<sup>3+</sup> (Figure S4).

An important question remains upon the formation of these radical cations: what's the fate of the electrons removed from the substrates? We opine that the electron will still linger on the surface of water microdroplets for some time until captured by another molecule, i.e. to initiate a reduction reaction. In the following sections of this Perspective, more evidence will be provided to support this statement.

### 4. THE ELECTRON-INDUCED REDUCTION PROCESSES

Previous studies have provided evidence that there are spontaneously generated electrons on water microdroplets.<sup>3–11,20</sup> The OH<sup>-</sup> ion in water has been considered to be the electron donor when pure water is sprayed. From the discussions in Section 3, we can anticipate that those molecules whose electrons are removed in microdroplets could also

Table 2. A List of Species Showing Electron-Induced Reduction on Water Microdroplets<sup>a</sup>

Name	Structure	Product	Name	Structure	Product
Pyridine <sup>3</sup>		Radical anion	9,10-Phenanthrenequinone <sup>20</sup>		Radical anion
1,1'-Diethyl-4,4'-bipyridinium diiodide <sup>5</sup>		Radical cation	Pentafluoroiodobenzene <sup>10</sup>		Radical anion
1,1'-Dimethyl-4,4'-bipyridinium dichloride <sup>5</sup>		Radical cation	C <sub>60</sub> <sup>a</sup>		Radical anion
1,1'-Ethylene-2,2'-bipyridinium dibromide <sup>5</sup>		Radical cation	Tetrachlorobenzoquinone <sup>a</sup>		Radical anion
Fe <sup>III</sup> complexes <sup>11</sup>	Fe <sup>III</sup> -L	Fe <sup>II</sup> -L	Tetrabromobenzoquinone <sup>a</sup>		Radical anion
Cu <sup>II</sup> complexes <sup>11</sup>	Cu <sup>II</sup> -L	Cu <sup>I</sup> -L	7,7,8,8-Tetracyanoquinodimethane <sup>a</sup>		Radical anion
Hg <sup>II</sup> species <sup>9</sup>	MeHg <sup>+</sup> , Hg <sup>2+</sup>	Hg <sup>0</sup>	Iodine <sup>a</sup>	I <sub>2</sub>	I <sub>2</sub> <sup>-</sup>
Au <sup>III</sup> complexes <sup>4</sup>	HAuCl <sub>4</sub>	Au <sup>0</sup>	Dimanganese decacarbonyl <sup>b</sup>		Mn(CO) <sub>5</sub> <sup>-</sup>
Nitrogen dioxide <sup>11</sup>	NO <sub>2</sub>	NO <sub>2</sub> <sup>-</sup>	Dicobalt octacarbonyl <sup>b</sup>		Co(CO) <sub>4</sub> <sup>-</sup>
Oxygen <sup>11</sup>	O <sub>2</sub>	O <sub>2</sub> <sup>-</sup>			
Carbon dioxide <sup>11</sup>	CO <sub>2</sub>	HCO <sub>2</sub> <sup>-</sup>			
Sulfur dioxide <sup>11</sup>	SO <sub>2</sub>	SO <sub>2</sub> <sup>-</sup>			
1,2-Benzoquinone <sup>20</sup>		Radical anion			
1,2-Naphthoquinone <sup>20</sup>		Radical anion			

<sup>a</sup>Data new to this Perspective. Typical mass spectra supporting the new data are provided in the SI.

function as electron donors. We avoid naming the electron as “solvated electron” or “hydrated electron” because its status remains unknown. The hydrated electron has been a topic full of debate.<sup>46–49</sup> The electron could interact with water in manners such as dipole-bound state, surface-bound state, partially embedded in water, occupation of a cavity, or occupation of a small region with enhanced water density.<sup>46,49</sup> However, the bottom-line that we want to draw here is that there are indeed electrons on sprayed water microdroplets even though how they interact with the water molecules is elusive.

Table 2 lists what we know so far on the electron-induced reduction processes on water microdroplets. The first and most striking example is the observation of the pyridyl anion in spraying an aqueous solution containing dissolved pyridine (the first row of Table 2).<sup>3</sup> This study is surprising because the anion of pyridine, Py<sup>•-</sup>, has been considered to be extremely unstable and short-lived in the gas phase, and can only be observed indirectly.<sup>50,51</sup> Imagine our surprise to detect the

pyridyl radical anion when room-temperature dissolved pyridine is sprayed to form microdroplets in ambient air.<sup>3</sup> The lifetime of the Py<sup>•-</sup> anion was roughly estimated to be at least 50 ms by trapping the ion using the linear ion trap of the mass spectrometer.<sup>3</sup> The Py<sup>•-</sup> anion was also captured by CO<sub>2</sub>, producing a (Py-CO<sub>2</sub>)<sup>•-</sup> complex with the excess electron delocalized on the whole complex.<sup>3</sup> Since Py<sup>•-</sup> was once generated in the condensed phase by mixing anhydrous Py and alkali metal,<sup>52</sup> this study suggests that the reducing power of water microdroplets can be as high as alkali metals.

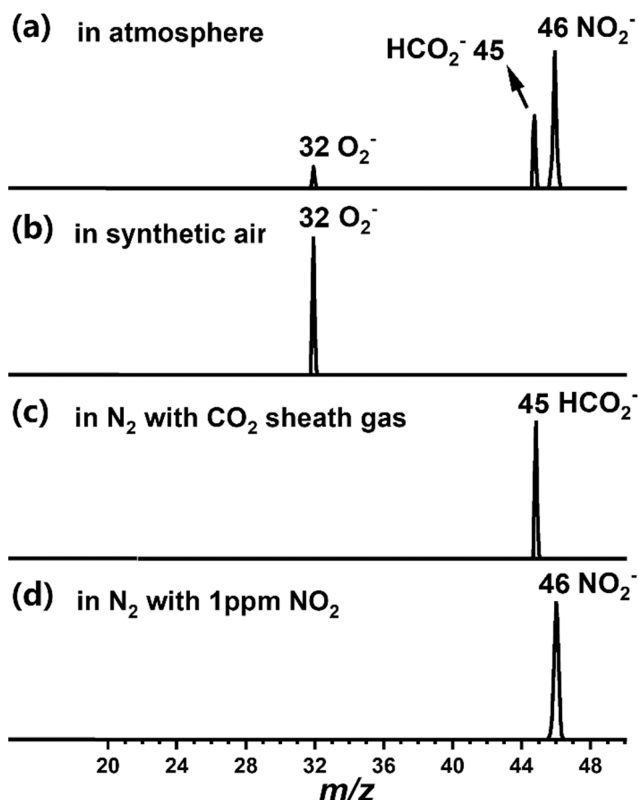
Further, by spraying the water solutions of a group of doubly charged viologen compounds including 1,1'-diethyl-4,4'-bipyridinium diiodide (known as ethyl viologen, EV for short), 1,1'-dimethyl-4,4'-bipyridinium dichloride (known as paraquat, PQ for short), and 1,1'-ethylene-2,2'-bipyridinium dibromide (known as diquat, DQ for short), the corresponding radical cation products, EV<sup>•+</sup>, PQ<sup>•+</sup>, and DQ<sup>•+</sup> after capturing one electron were observed (Table 2).<sup>5</sup> These molecules were

chosen because the double charges make them very good electron scavengers.

The spontaneous reduction by electrons in water microdroplets also has high atmospheric implications. Aqueous transition metal ions (TMIs) play important roles in the atmosphere, including the direct effects on atmospheric chemistry and the indirect effects by modifying cloud radiative properties and climate.<sup>53</sup> The key to TMI's high reactivity in the aqueous phase is their changing oxidation states, allowing them to participate in numerous chemical reactions by donating and accepting electrons, affecting the overall oxidative capacity of the atmosphere. As a result, an important factor that affects the reactivity of TMIs in the atmosphere is the ratios of the different oxidation states, i.e. speciation. Several ligated TMIs that have high atmospheric relevance, including Fe<sup>III</sup>, Cu<sup>II</sup>, and Hg<sup>II</sup> complexes were found to be spontaneously reduced by electrons to yield Fe<sup>II</sup>, Cu<sup>I</sup>, and Hg<sup>0</sup> species by spraying their water solutions into microdroplets.<sup>9,11</sup> Water microdroplets containing HAuCl<sub>4</sub> were also able to reduce Au<sup>III</sup> into Au<sup>0</sup> nanomaterials.<sup>4</sup>

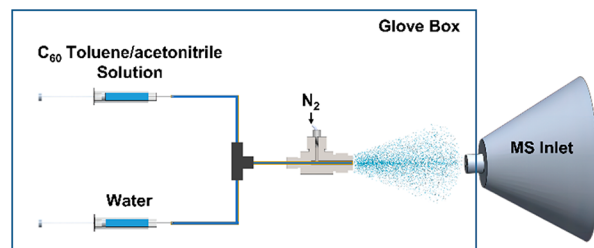
In the case of ligated Fe<sup>III</sup> and Cu<sup>II</sup>, we performed the spray experiments both in the atmosphere and in a glovebox protected by pure N<sub>2</sub>.<sup>11</sup> The intensity of the reduction products in the N<sub>2</sub>-filled glovebox was at least five folds greater compared to the experiments in ambient air, indicating that there must be some species in the atmosphere that are competing for the electrons. This provided a chance to tackle the long-sought problem in microdroplet chemistry, i.e. the fate of the spontaneously generated electrons on the microdroplets sprayed in air. By spraying pure water microdroplets both in the atmosphere and in the glovebox in which the gaseous contents were controlled, we identified several competitors for the electrons in air. The spectrum obtained in air has three peaks (Figure 2a). The peaks at *m/z* 32 and *m/z* 46 are O<sub>2</sub><sup>-</sup> and NO<sub>2</sub><sup>-</sup>, corresponding to the reduction products of O<sub>2</sub> and NO<sub>2</sub> formed through resonance electron capture processes. The peak at *m/z* 45 is formate (HCO<sub>2</sub><sup>-</sup>), a reduction product of ambient CO<sub>2</sub>. Please note that the formation of formate needs the participation of not only two electrons but also a proton. The control experiment in the glovebox filled with synthetic air (70% N<sub>2</sub>/30% O<sub>2</sub>) showed only the O<sub>2</sub><sup>-</sup> peak, confirming that O<sub>2</sub><sup>-</sup> was indeed a product from the O<sub>2</sub> in air. By changing the sheath gas from N<sub>2</sub> to CO<sub>2</sub> under a pure N<sub>2</sub> environment, only formate was observed (Figure 2c), confirming that formate was a reduction product from the CO<sub>2</sub> in air. Finally, by filling the glovebox with pure N<sub>2</sub> and 1 ppm of NO<sub>2</sub> and spraying water microdroplets with N<sub>2</sub>, only NO<sub>2</sub><sup>-</sup> was observed (Figure 2d), confirming that NO<sub>2</sub><sup>-</sup> was a one-electron reduction product of NO<sub>2</sub>. Taken together, we conclude that atmospheric O<sub>2</sub>, CO<sub>2</sub>, and NO<sub>2</sub> are competing for the electrons spontaneously generated on water microdroplets, resulting in O<sub>2</sub><sup>-</sup>, HCO<sub>2</sub><sup>-</sup>, and NO<sub>2</sub><sup>-</sup>, respectively (Table 2).

From the above discussions, it is clear that the atmosphere is an environment that is oxidative in nature due to the existence of oxidizers including O<sub>2</sub>, O<sub>3</sub>, •OH, NO<sub>x</sub>, and SO<sub>x</sub>, etc. Consequently, some species that can be reduced on microdroplets might not survive in the ambient air, making the setup in a glovebox very important in capturing these fragile species. We next show several such examples. The first example is the C<sub>6</sub>F<sub>5</sub>I<sup>•-</sup> radical from the reduction of the C<sub>6</sub>F<sub>5</sub>I molecule in sprayed water microdroplets, which can only be observed in an N<sub>2</sub>-protected glovebox but not in the atmosphere even though



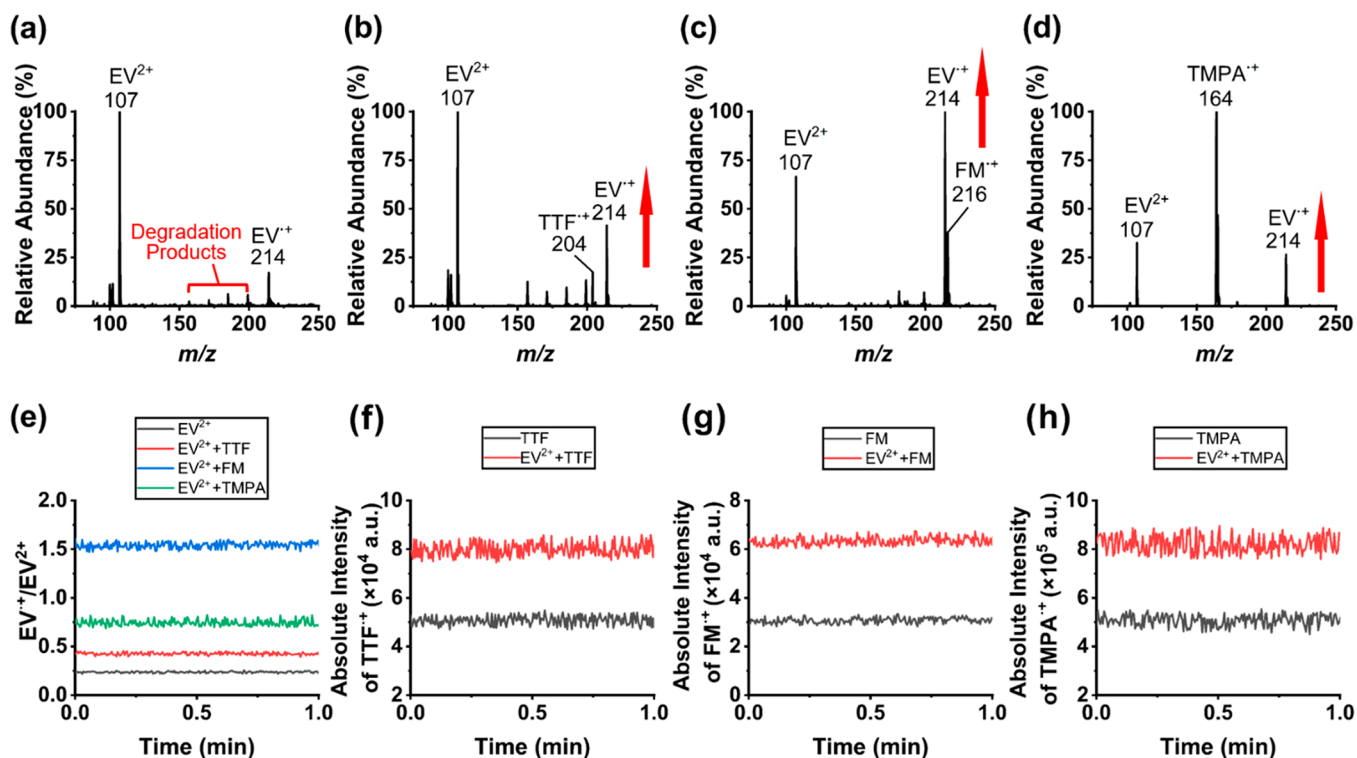
**Figure 2.** Whereabouts of the electrons on water microdroplets sprayed in ambient air, reproduced with permission from ref 11. Copyright (2023) American Chemical Society.

the electron affinity of C<sub>6</sub>F<sub>5</sub>I is positive.<sup>10</sup> C<sub>6</sub>F<sub>5</sub>I<sup>•-</sup> is unique because the excess electron counterintuitively locates on the σ\* antibonding orbital of the C–I bond but not on the π\* antibonding orbital on the benzene ring as revealed by anion photoelectron spectroscopy. As a result, the C–I bond is weakened, facilitating the formation of the C<sub>6</sub>F<sub>5</sub><sup>-</sup> anion, which was further utilized to attack CO<sub>2</sub>, yielding a C<sub>6</sub>F<sub>5</sub>CO<sub>2</sub><sup>-</sup> product.<sup>10</sup> Another example is the observation of the C<sub>60</sub><sup>-</sup> radical anion in a glovebox (Figure 3), which is not surprising since the electron affinity of C<sub>60</sub> is as high as 2.68 eV.<sup>54</sup> The mass spectrum of C<sub>60</sub><sup>-</sup> is shown in Figure S5.



**Figure 3.** Method to study the water microdroplet chemistry of chemicals that are insoluble in water using C<sub>60</sub> as an example.

The example of C<sub>60</sub> is unique also because it presents a good example of performing the water microdroplet chemistry with a chemical that is insoluble in water. Zare and co-workers studied the oxidation chemistry of toluene by the •OH radicals in water microdroplets.<sup>55</sup> Toluene is immiscible with water, so one cannot directly spray the water solution of toluene. Zare sprayed toluene and water with two separate syringes and a



**Figure 4.** Kinetic studies of the one-electron redox processes on water microdroplets. (a) A typical mass spectrum obtained by spraying a solution of (a) EV<sup>2+</sup>, (b) EV<sup>2+</sup> and TTF, (c) EV<sup>2+</sup> and FM, and (d) EV<sup>2+</sup> and TMPA. (e) The relative intensities of EV<sup>•+</sup>/EV<sup>2+</sup> in the four systems obtained from mass spectra collected for at least 1 min. (f–h) The absolute intensity change comparing the signals of TTF<sup>•+</sup>, FM<sup>•+</sup>, and TMPA<sup>•+</sup> with or without the addition of EV<sup>2+</sup>.

Tee mixer, and they still observed the oxidation reactions with the collisions between toluene microdroplets and water microdroplets. With this setup, we observed the microdroplet reduction of C<sub>60</sub> with C<sub>60</sub> dissolved in toluene/acetonitrile in one channel, and pure water in another channel (Figure 3). This method has paved the way for water microdroplet chemistry with chemicals that are insoluble in water.

Electron affinity can be used as an indicator for the formation of radical anions in microdroplets. With pyridine as the only exception,<sup>3</sup> the rest in Table 2 have positive electron affinities. Other such examples include three *ortho*-quinone molecules,<sup>20</sup> tetrachlorobenzoquinone (Figure S6), tetrabromobenzoquinone (Figure S7), tetracyanoquinodimethane (Figure S8), and the I<sub>2</sub> molecule (Figure S9).

In the last two rows of Table 2, we show two unique examples of transition metal complexes, including dimanganese decacarbonyl and dicobalt octacarbonyl. Upon attachment of an electron, the metal–metal bond is cleaved, yielding the Mn(CO)<sub>5</sub><sup>−</sup> anion (Figure S10) and the Co(CO)<sub>4</sub><sup>−</sup> anion (Figure S11), providing a chance for further synthesis using these anionic metal complexes. Both Mn(CO)<sub>5</sub><sup>−</sup> and Co(CO)<sub>4</sub><sup>−</sup> are stable because they fulfill the 18-electron rule, explaining their high signal intensities in the mass spectra.

Please note that Figures S1 to S11 are new data collected for this Perspective.

## 5. THE KINETICS OF THE REDOX REACTIONS

The OH<sup>−</sup> ions can function as electron donors on water microdroplets. If other molecules that are prone to yield electrons (such as those molecules in Table 1) are added to the solution, more electrons should be available on water microdroplets, and kinetically the reduction reactions should

be accelerated. This will further consolidate the idea that electrons are indeed the charge carriers that mediate the redox reactions on water microdroplets.

To test this assumption, we choose three electron donors from Table 1, including TTF, ferrocenemethanol (FM), and N,N,N',N'-tetramethyl-1,4-phenylenediamine (TMPA), and EV<sup>2+</sup> as the electron scavenger. Figure 4a provides a typical mass spectrum showing the reduction of EV<sup>2+</sup> (*m/z* = 107) into EV<sup>•+</sup> (*m/z* = 214) by spraying the water solution of EV<sup>2+</sup> into water microdroplets, in which OH<sup>−</sup> is the sole electron donor. The peaks in the *m/z* range of 150–200 are the degradation products from the unstable EV<sup>•+</sup>, reproducing the results of ref 5. Figure 4b–4d presents the mass spectra by spraying the mixture solutions of TTF and EV<sup>2+</sup>, FM and EV<sup>2+</sup>, and TMPA and EV<sup>2+</sup>, respectively. The intensity of the reduction product, EV<sup>•+</sup>, unambiguously increased in these mixture systems, suggesting that the addition of electron donors accelerates the reduction of EV<sup>2+</sup>. Figure 4e exhibits the comparisons of the relative intensities of EV<sup>•+</sup>/EV<sup>2+</sup> in four systems deduced from mass spectrometric measurements for at least 1 min, which also clearly shows the increase of the reduction products by 2 to 7 folds after adding the electron donors. Figure 4a–4e show the accelerated kinetics of the reduction processes in the mixture systems, and the oxidation processes of TTF, FM, and TMPA should also be accelerated with the addition of EV<sup>2+</sup> because the latter removes the product (the electron) in the chemical equilibrium. This assumption is evidenced by Figure 4f–4h, where the absolute intensities of TTF<sup>•+</sup>, FM<sup>•+</sup>, and TMPA<sup>•+</sup> increase by ~2 folds with the addition of EV<sup>2+</sup>.

Taken together, we have provided solid evidence that electrons are indeed the key reagents that mediate the redox

reactions on water microdroplets, and electron donating and scavenging are two mutually accelerating processes as evidenced by the simple kinetics study. The data in Figure 4 is also new to this Perspective.

## 6. OUTLOOK

Microdroplet chemistry has already been widely recognized in organic synthesis, mostly in the sense that it can greatly accelerate reaction rates.<sup>1</sup> Here, we emphasize that microdroplet reactions can also be utilized as a simple and green method for the generation of radicals for the use of organic synthesis because most of the electron-mediated redox reactions in this Perspective yield radical species. Organic reactions that produce radicals might require high energies or other complicated experimental setups, but all it takes here is to spray the water solutions of the substrates into microdroplets. We anticipate that many more examples of oxidative or reductive radical/radical coupling and radical/molecule coupling reactions can be achieved with the microdroplet method.

With regard to large-scale synthesis, spraying and collection of microdroplets can only yield a small amount of products. Even though some efforts have been made to scale up microdroplet synthesis,<sup>38,39</sup> much work still needs to be done to produce large amounts of products with microdroplet chemistry.

Another important implication is for atmospheric chemistry. The overall redox capacity of the atmosphere dictates the formation and change of pollution, weather, and even climate. Atmospheric water such as clouds, fogs, and seaspray are micrometers in size. The surface area of these atmospheric droplets is tremendous. Since water microdroplets can facilitate spontaneous redox reactions, we suggest that atmospheric studies need to take the microdroplet effect into consideration in the future just as some studies already have.<sup>11,12,18,56</sup>

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacsau.3c00191>.

Typical mass spectra supporting the one-electron redox reactions on water microdroplets in Table 1 and Table 2 (PDF)

## ■ AUTHOR INFORMATION

### Corresponding Author

**Xinxing Zhang** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China; Beijing National Laboratory for Molecular Sciences, Beijing 100190, China; [orcid.org/0000-0001-5884-2727](https://orcid.org/0000-0001-5884-2727); Email: [zhangxx@nankai.edu.cn](mailto:zhangxx@nankai.edu.cn)

### Authors

**Shuihui Jin** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage

Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Huan Chen** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Xu Yuan** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Dong Xing** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Ruijing Wang** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Lingling Zhao** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Dongmei Zhang** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Chu Gong** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Chenghui Zhu** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of

Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Xufeng Gao** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

**Yeye Chen** – College of Chemistry, Key Laboratory of Advanced Energy Materials Chemistry (Ministry of Education), Renewable Energy Conversion and Storage Centre, Tianjin Key Laboratory of Biosensing and Molecular Recognition, Frontiers Science Centre for New Organic Matter, Nankai University, Tianjin 300071, China; Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

Complete contact information is available at:  
<https://pubs.acs.org/10.1021/jacsau.3c00191>

### Author Contributions

<sup>†</sup>These authors contributed equally. CRediT: **Shuihui Jin** formal analysis, investigation, writing-original draft; **Huan Chen** formal analysis, writing-original draft; **Xu Yuan** writing-original draft; **Dong Xing** writing-original draft; **Ruijing Wang** writing-original draft; **Lingling Zhao** writing-original draft; **Dongmei Zhang** writing-original draft; **Chu Gong** writing-original draft; **Chenghui Zhu** writing-original draft; **Xufeng Gao** writing-original draft; **Yeye Chen** writing-original draft; **Xinxing Zhang** conceptualization, funding acquisition, investigation, methodology, supervision, writing-original draft.

### Notes

The authors declare no competing financial interest.

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### REFERENCES

- (1) Yan, X.; Bain, R. M.; Cooks, R. G. Organic Reactions in Microdroplets: Reaction Acceleration Revealed by Mass Spectrometry. *Angew. Chem., Int. Ed.* **2016**, *55*, 12960–12972.
- (2) Lee, J. K.; Banerjee, S.; Nam, H. G.; Zare, R. N. Acceleration of Reaction in Charged Microdroplets. *Q. Rev. Biophys.* **2015**, *48*, 437–444.
- (3) Zhao, L.; Song, X.; Gong, C.; Zhang, D.; Wang, R.; Zare, R. N.; Zhang, X. Sprayed Water Microdroplets Containing Dissolved Pyridine Spontaneously Generate Pyridyl Anions. *Proc. Natl. Acad. Sci. U.S.A.* **2022**, *119*, e2200991119.
- (4) Lee, J. K.; Samanta, D.; Nam, H. G.; Zare, R. N. Spontaneous Formation of Gold Nanostructures in Aqueous Microdroplets. *Nat. Commun.* **2018**, *9*, 1562.

- (5) Gong, C.; Li, D.; Li, X.; Zhang, D.; Xing, D.; Zhao, L.; Yuan, X.; Zhang, X. Spontaneous Reduction-Induced Degradation of Viologen Compounds in Water Microdroplets and Its Inhibition by Host–Guest Complexation. *J. Am. Chem. Soc.* **2022**, *144*, 3510–3516.

- (6) Lee, J. K.; Samanta, D.; Nam, H. G.; Zare, R. N. Micrometer-Sized Water Droplets Induce Spontaneous Reduction. *J. Am. Chem. Soc.* **2019**, *141*, 10585–10589.

- (7) Qiu, L.; Cooks, R. G. Simultaneous and Spontaneous Oxidation and Reduction in Microdroplets by the Water Radical Cation/Anion Pair. *Angew. Chem., Int. Ed.* **2022**, *134*, e202210765.

- (8) Song, X.; Meng, Y.; Zare, R. N. Spraying Water Microdroplets Containing 1,2,3-Triazole Converts Carbon Dioxide into Formic Acid. *J. Am. Chem. Soc.* **2022**, *144*, 16744–16748.

- (9) He, Q.; Zhang, N.; Qiao, Y.; Li, C.; Zhang, J. Vapor Generation of Mercury and Methylmercury in Aqueous Microdroplets Produced by Pneumatic Nebulization. *J. Anal. At. Spectrom.* **2022**, *37*, 1894–1901.

- (10) Chen, H.; Wang, R.; Xu, J.; Yuan, X.; Zhang, D.; Zhu, Z.; Marshall, M.; Bowen, K.; Zhang, X. Spontaneous Reduction by One Electron on Water Microdroplets Facilitates Direct Carboxylation with CO<sub>2</sub>. *J. Am. Chem. Soc.* **2023**, *145*, 2647–2652.

- (11) Yuan, X.; Zhang, D.; Liang, C.; Zhang, X. Spontaneous Reduction of Transition Metal Ions by One Electron in Water Microdroplets and the Atmospheric Implications. *J. Am. Chem. Soc.* **2023**, *145*, 2800–2805.

- (12) Xing, D.; Yuan, X.; Liang, C.; Jin, T.; Zhang, S.; Zhang, X. Spontaneous Oxidation of I<sup>−</sup> in Water Microdroplets and Its Atmospheric Implications. *Chem. Commun.* **2022**, *58*, 12447–12450.

- (13) Xing, D.; Meng, Y.; Yuan, X.; Jin, S.; Song, X.; Zare, R. N.; Zhang, X. Capture of Hydroxyl Radicals by Hydronium Cations in Water Microdroplets. *Angew. Chem., Int. Ed.* **2022**, *134*, e202207587.

- (14) Lee, J. K.; Walker, K. L.; Han, H. S.; Kang, J.; Prinz, F. B.; Waymouth, R. M.; Nam, H. G.; Zare, R. N. Spontaneous Generation of Hydrogen Peroxide from Aqueous Microdroplets. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116*, 19294–19298.

- (15) Gao, D.; Jin, F.; Lee, J. K.; Zare, R. N. Aqueous Microdroplets Containing only Ketones or Aldehydes undergo Dakin and Baeyer–Villiger Reactions. *Chem. Sci.* **2019**, *10*, 10974–10978.

- (16) Lee, J. K.; Han, H. S.; Chaikasetsin, S.; Marron, D. P.; Waymouth, R. M.; Prinz, F. B.; Zare, R. N. Condensing Water Vapor to Droplets Generates Hydrogen Peroxide. *Proc. Natl. Acad. Sci. U.S.A.* **2020**, *117*, 30934–30941.

- (17) Mehrgardi, M. A.; Mofidfar, M.; Zare, R. N. Sprayed Water Microdroplets Are Able to Generate Hydrogen Peroxide Spontaneously. *J. Am. Chem. Soc.* **2022**, *144*, 7606–7609.

- (18) Li, K.; Guo, Y.; Nizkorodov, S. A.; Rudich, Y.; Angelaki, M.; Wang, X.; An, T.; Perrier, S.; George, C. Spontaneous Dark Formation of OH Radicals at the Interface of Aqueous Atmospheric Droplets. *Proc. Natl. Acad. Sci. U.S.A.* **2023**, *120*, e2220228120.

- (19) Zhang, D.; Yuan, X.; Gong, C.; Zhang, X. High Electric Field on Water Microdroplets Catalyzes Spontaneous and Ultrafast Oxidative C–H/N–H Cross-Coupling. *J. Am. Chem. Soc.* **2022**, *144*, 16184–16190.

- (20) Jin, S.; Wang, R.; Chen, H.; Yuan, X.; Zhang, X. Spontaneous and Simultaneous Oxidation and Reduction of o-Quinones in Water Microdroplets. *J. Phys. Chem. A* **2023**, *127* (12), 2805–2809.

- (21) Qiu, L.; Psimos, M. D.; Cooks, R. G. Spontaneous Oxidation of Aromatic Sulfones to Sulfonic Acids in Microdroplets. *J. Am. Soc. Mass Spectrom.* **2022**, *33*, 1362–1367.

- (22) Qiu, L.; Morato, N. M.; Huang, K. H.; Cooks, R. G. Spontaneous Water Radical Cation Oxidation at Double Bonds in Microdroplets. *Front. Chem.* **2022**, *10*, 903774.

- (23) Xiong, H.; Lee, J. K.; Zare, R. N.; Min, W. Strong Electric Field Observed at the Interface of Aqueous Microdroplets. *J. Phys. Chem. Lett.* **2020**, *11*, 7423–7428.

- (24) Zhou, Z.; Yan, X.; Lai, Y. H.; Zare, R. N. Fluorescence Polarization Anisotropy in Microdroplets. *J. Phys. Chem. Lett.* **2018**, *9*, 2928–2932.



- (25) Lhee, S. M.; Lee, J. K.; Kang, J.; Kato, S.; Kim, S.; Zare, R. N.; Nam, H. G. Spatial Localization of Charged Molecules by Salt Ions in Oil-Confined Water Microdroplets. *Sci. Adv.* **2020**, *6*, eaba0181.
- (26) Hao, H.; Leven, I.; Head-Gordon, T. Can Electric Fields Drive Chemistry for an Aqueous Microdroplet? *Nat. Commun.* **2022**, *13*, 280.
- (27) Chamberlayne, C. F.; Zare, R. N. Simple Model for the Electric Field and Spatial Distribution of Ions in a Microdroplet. *J. Chem. Phys.* **2020**, *152*, 184702.
- (28) Heindel, J. P.; Hao, H.; LaCour, R. A.; Head-Gordon, T. Spontaneous Formation of Hydrogen Peroxide in Water Microdroplets. *J. Phys. Chem. Lett.* **2022**, *13*, 10035–10041.
- (29) Sun, Z.; Wen, X.; Wang, L.; Ji, D.; Qin, X.; Yu, J.; Ramakrishna, S. Emerging Design Principles, Materials, and Applications for Moisture-enabled Electric Generation. *eScience.* **2022**, *2*, 32–46.
- (30) Vogel, Y. B.; Evans, C. W.; Belotti, M.; Xu, L.; Russell, I. C.; Yu, L.-J.; Fung, A. K. K.; Hill, N. S.; Darwish, N.; Gonçalves, V. R.; et al. The Corona of a Surface Bubble Promotes Electrochemical Reactions. *Nat. Commun.* **2020**, *11*, 6323.
- (31) Liang, Q.; Zhu, C.; Yang, J. Water Charge Transfer Accelerates Criegee Intermediate Reaction with  $\text{H}_2\text{O}^-$  Radical Anion at the Aqueous Interface. *J. Am. Chem. Soc.* **2023**, *145*, 10159.
- (32) Martins-Costa, M. T. C.; Ruiz-López, M. F. Electrostatics and Chemical Reactivity at the Air–Water Interface. *J. Am. Chem. Soc.* **2023**, *145*, 1400–1406.
- (33) Lai, Y.; Sathyamoorthi, S.; Bain, R. M.; Zare, R. N. Microdroplets Accelerate Ring Opening of Epoxides. *J. Am. Soc. Mass Spectrom.* **2018**, *29*, 1036–1043.
- (34) Zhang, D.; Lu, Y.; Wang, J.; Gong, C.; Hou, X.; Zhang, X.; Chen, J. Revisiting the Hitherto Elusive Cyclohexanehexone Molecule: Bulk Synthesis, Mass Spectrometry, and Theoretical Studies. *J. Phys. Chem. Lett.* **2021**, *12*, 9848–9852.
- (35) Mayer, P. M.; Poon, C. The Mechanisms of Collisional Activation of Ions in Mass Spectrometry. *Mass Spectrom. Rev.* **2009**, *28*, 608–639.
- (36) Banerjee, S.; Zare, R. N. Influence of Inlet Capillary Temperature on the Microdroplet Chemistry Studied by Mass Spectrometry. *J. Phys. Chem. A* **2019**, *123*, 7704–7709.
- (37) Li, K.; Wang, L.; Liu, J.; Gong, K.; Wang, W.; Ge, Q.; Liu, Y.; Zhang, L. A Protocol to Study Microdroplet Photoreaction at an Individual Droplet Level using In Situ Micro-Raman Spectroscopy. *STAR Protocols* **2022**, *3*, 101704.
- (38) Nie, H. G.; Wei, Z. W.; Qiu, L. Q.; Chen, X. S.; Holden, D. T.; Cooks, R. G. High-Yield Gram-Scale Organic Synthesis Using Accelerated Microdroplet/Thin Film Reactions with Solvent Recycling. *Chem. Sci.* **2020**, *11*, 2356–2361.
- (39) Liu, C. Y.; Li, J.; Chen, H.; Zare, R. N. Scale-Up of Microdroplet Reactions by Heated Ultrasonic Nebulization. *Chem. Sci.* **2019**, *10*, 9367–9373.
- (40) Schwarz, H.; Dodson, R. Equilibrium between Hydroxyl Radicals and Thallium(II) and the Oxidation Potential of  $\text{OH}(\text{aq})$ . *J. Phys. Chem. Lett.* **1984**, *88*, 3643–3647.
- (41) Martins-Costa, M. T. C.; Anglada, J. M.; Francisco, J. S.; Ruiz-Lopez, M. F. Reactivity of Atmospherically Relevant Small Radicals at the Air–Water. *Interface. Angew. Chem. Int. Ed.* **2012**, *51*, 5413–5417.
- (42) Miles, N. L.; Verlinde, J.; Clothiaux, E. E. Cloud Droplet Size Distributions in Low-Level Stratiform Clouds. *J. Atmos. Sci.* **2000**, *57*, 295–311.
- (43) Louillat, M. L.; Patureau, F. W. Oxidative C-H Amination Reactions. *Chem. Soc. Rev.* **2014**, *43*, 901–910.
- (44) Saiz-Lopez, A.; Plane, J. M. C.; Baker, A. R.; Carpenter, L. J.; von Glasow, R.; Gómez Martín, J. C.; McFiggans, G.; Saunders, R. W. Atmospheric Chemistry of Iodine. *Chem. Rev.* **2012**, *112*, 1773–1804.
- (45) Bendikov, M.; Wudl, F.; Perepichka, D. F. Tetrathiafulvalenes, Oligoacenes, and Their Buckminsterfullerene Derivatives: The Brick and Mortar of Organic Electronics. *Chem. Rev.* **2004**, *104*, 4891–4945.
- (46) Jacobson, L. D.; Herbert, J. M. Theoretical Characterization of Four Distinct Isomer Types in Hydrated-Electron Clusters, and Proposed Assignments for Photoelectron Spectra of Water Cluster Anions. *J. Am. Chem. Soc.* **2011**, *133*, 19889–19899.
- (47) Herbert, J. M.; Coons, M. P. The Hydrated Electron. *Annu. Rev. Phys. Chem.* **2017**, *68*, 447–472.
- (48) Gaiduk, A. P.; Pham, T. A.; Govoni, M.; Paesani, F.; Galli, G. Electron Affinity of Liquid Water. *Nat. Commun.* **2018**, *9*, 247.
- (49) Larsen, R. E.; Glover, W. J.; Schwartz, B. J. Does the Hydrated Electron Occupy a Cavity? *Science* **2010**, *329*, 65–69.
- (50) Nenner, I.; Schulz, G. J. Temporary Negative Ions and Electron Affinities of Benzene and N-heterocyclic Molecules: Pyridine, Pyridazine, Pyrimidine, Pyrazine, and s-Triazine. *J. Chem. Phys.* **1975**, *62*, 1747–1758.
- (51) Huebner, R. H.; Compton, R. N.; Schweinler, H. C. Temporary Negative Ion Resonance of Pyridine. *Chem. Phys. Lett.* **1968**, *2*, 407–408.
- (52) Schmulbach, C. D.; Hinckley, C. C.; Wasmund, D. Solutions of Alkali Metals in Anhydrous Pyridine. *J. Am. Chem. Soc.* **1968**, *90*, 6600–6602.
- (53) Deguillaume, L.; Leriche, M.; Desboeufs, K.; Mailhot, G.; George, C.; Chaumerliac, N. Transition Metals in Atmospheric Liquid Phases: Sources, Reactivity, and Sensitive Parameters. *Chem. Rev.* **2005**, *105*, 3388–3431.
- (54) Huang, D.; Dau, P. D.; Liu, H.; Wang, L. High-Resolution Photoelectron Imaging of Cold  $\text{C}_{60}^-$  Anions and Accurate Determination of the Electron Affinity of  $\text{C}_{60}$ . *J. Chem. Phys.* **2014**, *140*, 224315.
- (55) Meng, Y.; Gnanamani, E.; Zare, R. N. Direct  $\text{C}(\text{sp}^3)$ –N Bond Formation between Toluene and Amine in Water Microdroplets. *J. Am. Chem. Soc.* **2022**, *144*, 19709–19713.
- (56) Chen, B.; Xia, Y.; He, R.; Sang, H.; Zhang, W.; Li, J.; Chen, L.; Wang, P.; Guo, S.; Yin, Y.; Hu, L.; Song, M.; Liang, Y.; Wang, Y.; Jiang, G.; Zare, R. N. Water–solid Contact Electrification Causes Hydrogen Peroxide Production from Hydroxyl Radical Recombination in Sprayed Microdroplets. *Proc. Natl. Acad. Sci. U.S.A.* **2022**, *119*, e2209056119.