Mechanism of photocatalytic water oxidation on small TiO₂ nanoparticles†

Mikko Muuronen,*a Shane M. Parker,a Enrico Berardo,b,c Alexander Le,a Martijn A. Zwijnenburgc and Filipp Furche*a

We present the first unconstrained nonadiabatic molecular dynamics (NAMD) simulations of photocatalytic water oxidation by small hydrated TiO₂ nanoparticles using Tully surface hopping and time-dependent density functional theory. The results indicate that ultrafast electron–proton transfer from physisorbed water to the photohole initiates the photo-oxidation on the S₂ potential energy surface. The new mechanism readily explains the observation of mobile hydroxyl radicals in recent experiments. Two key driving forces for the photo-oxidation reaction are identified: localization of the electron–hole pair and stabilization of the photohole by hydrogen bonding interaction. Our findings illustrate the scope of recent advances in NAMD methods and emphasize the importance of explicit simulation of electronic excitations.

2H₂O + 4h⁺ → O₂ + 4H⁺.  \(1\)

The first of the four one-electron oxidation steps is likely rate-limiting;\textsuperscript{10,12-14} however, the mechanism of this step is controversial and several conflicting models have been proposed. The earliest models based on spectroscopic experiments suggested that the photohole (h⁺) oxidizes a surface bound hydroxyl group \(\text{Ti}^{IV}−\text{OH} \rightarrow \text{Ti}^{IV}−(\text{OH})^+\). \(2\)

This mechanism was challenged by the results of density functional theory (DFT) calculations suggesting that \(\text{Ti}^{IV}−\text{OH}\) groups trap electrons, not holes.\textsuperscript{17} An alternative mechanism,\textsuperscript{18}

\(\text{Ti}^{IV}−\text{OH}_2 + h^+ \rightarrow \text{Ti}^{IV}−(\text{OH})^+ + \text{H}^+\), \(3\)

involves oxidation of a surface bound water \(\text{Ti}^{IV}−\text{OH}_2\) instead of \(\text{Ti}^{IV}−\text{OH}\) by the photohole.\textsuperscript{19} The high barrier of this step can be lowered by deprotonation of \(\text{Ti}^{IV}−\text{OH}_2\) with base, resulting a barrierless hole transfer.\textsuperscript{18,19} The resulting proton-coupled electron transfer (PCET) mechanism, where a strongly localized photohole h⁺ is transferred from a bridging oxygen Obr to the \(\text{Ti}^{IV}−(\text{OH})^−\) species, is consistent with the observed pH dependence of the OER.\textsuperscript{19} However, the recent experimental detection of mobile rather than surface bound OH radicals in three different experiments casts doubts on the hypothesis that the oxidized water is bound to the TiO₂ surface.\textsuperscript{21-23} Based on scanning tunneling microscopy (STM) experiments, Hou and co-workers suggested that mobile \(\cdot\text{OH}\) species result from protonated O₅H₃ sites as a reaction intermediate:\textsuperscript{22}

\(\text{Ti}^{IV}−\text{OH}_2 + h^+ \rightarrow \text{Ti}^{IV}−(\text{O₅H₃})^+ −\text{Ti}^{IV}−(\cdot\text{OH})^− + \cdot\text{OH}^−\). \(4\)

\(\text{Ti}^{IV}−\text{OH}_2 + h^+ \rightarrow \text{Ti}^{IV}−(\text{O₅H₃})^+ −\text{Ti}^{IV}−(\cdot\text{OH})^− + \cdot\text{OH}^−\). \(4\)
Recent Ehrenfest NAMD simulations of periodic TiO$_2$ surfaces also considered this mechanism, but the simulation times were too short (up to 20 fs) to be conclusive. Nakato and coworkers suggested that nucleophilic attack of water on a Obr, activated by H$, might initiate the OER,\textsuperscript{26,27}

\[
\text{Obr(h$^+$)} + \text{H}_2\text{O(l)} \rightarrow \text{ObrOH} + \text{H}^+.
\]

generating a surface-bound hydroperoxyl radical. Later, Imahashi and coworkers suggested that this mechanism will dominate at low and intermediate pH, while at high pH the photohole could readily oxidize the Ti–O$^-$ species present in high pH.\textsuperscript{28} Based on a transition state (TS) study for Ti(OH)$_4$, Kazaryan and coworkers questioned mechanism (5) and proposed that Ti(OH)$_4$, the smallest model of a hydroxylated TiO$_2$ surface, can readily oxidize H$_2$O(l) in the S$_1$ excited state via hydrogen transfer mechanism from H$_2$O(l) to electronically excited Ti(OH)$_4$,\textsuperscript{28}

\[
\text{Ti(OH)}_4^+ + \text{H}_2\text{O(l)} \rightarrow \text{[Ti(OH)]}_3^+(\text{H}_2\text{O}) + \cdot\text{OH}^+, \tag{6}
\]

thus producing an intermediate similar to the one proposed in mechanism (4).

**Methods**

The PBE0 (ref. 29) hybrid functional and polarized double-\(\zeta\) valence def2-SVP\textsuperscript{30} basis sets were used for NAMD simulations. To account for van der Waals interactions, D3 dispersion corrections were employed.\textsuperscript{31} The forces on the S$_1$ and S$_0$ potential energy surfaces (PESs) and the non-adiabatic couplings between them were computed analytically at each time step.\textsuperscript{32,33} The nuclear dynamics used Tully’s surface hopping algorithm and a leapfrog–Verlet integrator with time-step of 40 a.u. (1 fs).\textsuperscript{34,35} 115 trajectories were initiated with random nuclear velocities consistent with a 350 K thermal ensemble, and the trajectories were propagated for up to 1 ps. To describe homolytic bond cleavage, the spin symmetry was allowed to break if triplet instability was found for the reference state. We recently showed that this methodology can treat both closed and open shell pathways semiquantitatively in photodissociation of acetaldehyde.\textsuperscript{8} To avoid convergence and stability problems close to the conical intersections (CIs), a surface hop was forced if the S$_1$–S$_0$ gap is below 0.5 eV.\textsuperscript{6,36} All computations were performed using a local development version based on Turbomole 7.1.\textsuperscript{37} See ESI$^\dagger$ for benchmark results and further details.

**Results and discussion**

To compare the reactivity of surface-bound vs. physisorbed water, we simulated small hydrated (TiO$_2$)$_4$(OH)$_4$ nanoparticles with two, four, eight or ten additional water molecules, see Fig. 1 and S3.$^\dagger$ These models can accommodate all proposed mechanisms (2)–(6) with the exception of mechanisms requiring deprotonation of water by added base, and enabled total simulation times up to 60 ps. Even though the initial one-electron oxidation is much faster, these long simulation times were necessary to capture reactive trajectories without imposing artificial bias on the system.

According to our simulations, the reaction starts by electron–proton transfer (EPT) from physisorbed water to the photohole strongly localized on Obr as depicted in Fig. 2a. In (TiO$_2$)$_4$(OH)$_4$(H$_2$O)$_8$, this reaction occurs on the S$_1$ potential energy surface (PES), close to the S$_1$–S$_0$ conical intersection (CI), see Fig. 2b. The reactive intermediate 1 forms approximately 200 fs after the trajectory was initiated and undergoes hydrogen-transfer reaction within 20 fs to form intermediate 2.

The electron transfer reaction is displayed in Fig. 3 for (TiO$_2$)$_4$(OH)$_4$(H$_2$O)$_8$. At 200 fs, the photohole (green) is localized...
strongly on bridging oxygen O\(^1\), forming the intermediate 1. The hole is transferred to physisorbed water at 213 fs and intermediate 2 forms at 219 fs via concerted proton transfer without substantial nuclear reorientation. Intermediate 2 subsequently decays rapidly to S\(_0\) through a CI and forms a stable ground state intermediate followed by dissociation of the hydroxyl radical (see ESI\(^\dagger\)).

The structure of the intermediate observed in the NAMD simulations is in close agreement with STM measurements.\(^{22}\) Moreover, our mechanism yields mobile OH radicals, in accordance with several recent experiments.\(^{21,23,24}\) The charge-transfer (CT) reactivity seen in our simulations is indirectly supported by a TS study of Ti(OH)\(_4\)\(^28\) and NAMD simulations of the oxidation of chemisorbed methanol on a TiO\(_2\) surface.\(^{28}\)

To further analyze the exciton dynamics and the resulting EPT, we consider the difference in atomic natural bonding orbital (NBO) charges between the S\(_1\) and the S\(_0\) states, see Fig. 4a. Positive values of the population difference indicate hole charge, i.e., loss of electron density on atoms relative to the ground state, and negative values indicate electron charge, i.e., gain of electron density relative to the ground state. In the Franck–Condor geometry, the hole is shared between all bridging oxygens, O\(^1\)–O\(^4\), and the electron is distributed equally to Ti\(^{IV}\) and Ti\(^{III}\). During the first 100 fs, the hole localizes strongly on the bridging oxygen O\(^1\) until EPT from the physisorbed water H\(_2\)O\(^\ast\) occurs at 213 fs. The other bridging oxygens, O\(^2\)–O\(^3\), gain electron density and thus act as electron traps. This allows them to hydrogen bond with liquid water more efficiently, but does not lead to any reactivity. A consequence of the hole localization is the subsequent localization of the electron on Ti\(^{III}\) adjacent to the reactive O\(^1\),

\[ \text{>Ti}^{	ext{IV}}\text{–O}_{\text{br}}\text{–Ti}^{	ext{IV}}< 
\text{S}_1 \text{ relaxation} \rightarrow \text{>Ti}^{	ext{III}}\text{–O}_{\text{br}}(\text{h}^+)\text{–Ti}^{	ext{IV}}< \]

(7)

The localization of the two opposite charges provides coulombic stabilization of the exciton and drives the reaction

\[ \text{>Ti}^{	ext{III}}\text{–O}_{\text{br}}(\text{h}^+)\text{–Ti}^{	ext{IV}}< + \text{H}_2\text{O}(\text{l}) \rightarrow \text{>Ti}^{	ext{III}}\text{–(O}_{\text{br}}\text{H})^\ast\text{–Ti}^{	ext{IV}}< + \cdot\text{OH}]^\ast \]

(8)

to form \(\text{>Ti}^{	ext{III}}\text{–(O}_{\text{br}}\text{H})^\ast\text{–Ti}^{	ext{IV}}<\) species, which are stable on a picosecond timescale in \textit{ab initio} molecular dynamics simulations.\(^{46}\) While less confinement may increase the exciton size, the energy gain from localization also increases in larger particles. Larger rutile hydrated and hydroxylated (TiO\(_2\))\(_{\ast}\) nanoparticles exhibit exciton localization after self-trapping (\textit{i.e.}, at the S\(_1\) PES minimum) on a similar scale as the ones studied here,\(^{41}\) suggesting that the self-trapped exciton size may not depend strongly on the particle size.

Photohole localization is not the only driving force of the reaction, however, since EPT only occurs 100 fs after the photohole localizes: starting at \(\sim 150\) fs, the reactive physisorbed water hydrogen bonds more strongly with the Ti\(^{IV}\) bound water (O\(^5\)–H\(^1\) distance decreases from 220 pm to 170 pm), see Fig. 4b; concurrently, the electron starts to localize on Ti\(^{III}\), see Fig. 4a. The EPT follows these changes as seen in the O\(^1\)–H\(^2\) and O\(^5\)–H\(^2\) distances. This suggests that the localized electron on Ti\(^{III}\) also favors EPT by some electron transfer to the water bound to Ti\(^{IV}\).

The electron rich water then stabilizes the nascent H\(_2\)O\(^\ast\) by solvating the hole, thus facilitating the reaction. This interpretation is also supported by the observation that the reaction is faster in the smaller (TiO\(_2\))\(_4\)(OH)\(_4\)(H\(_2\)O)\(_4\) model; Ti\(^{IV}\) is bound to only one water instead of two in (TiO\(_2\))\(_4\)(OH)\(_4\)(H\(_2\)O)\(_n\), which facilitates electron localization and concomitant stabilization of the photohole by hydrogen bonding interaction. Intermediate 1 is formed approximately at 150 fs in the reactive trajectory for (TiO\(_2\))\(_4\)(OH)\(_4\)(H\(_2\)O)\(_4\), similar to the reactivity observed for the larger (TiO\(_2\))\(_4\)(OH)\(_4\)(H\(_2\)O)\(_n\) particle (Fig. S5 and S6\(\dagger\)).

Why did previous simulations not show the present mechanism? These simulations were based on free charge carriers, \textit{i.e.}, cationic and anionic species in the electronic ground state, which do not include electron–hole interaction. For (TiO\(_2\))\(_{\ast}\)(OH)\(_4\)(H\(_2\)O)\(_n\), the reaction is exothermic by approximately 10 kcal mol\(^{–1}\) compared to the Franck–Condor geometry on the S\(_1\) PES (Fig. 2b). On the other hand, for a free hole the reaction is endothermic by approximately 7 kcal mol\(^{–1}\) (ESI\(^\dagger\)). This 17 kcal mol\(^{–1}\) difference is mainly due to coulombic stabilization of the exciton ("exciton binding energy"), of the H\(_2\)O\(^\ast\) species, and of the protonated bridging oxygen O\(^1\) by the electron component of the exciton. This was confirmed by BOMD simulations for free holes which did not show any reactivity up to 135 ps of total

---

\(\text{<Fig. 3> Snapshots from a NAMD trajectory at 200 fs (left), 213 fs (middle) and 218 fs (right) showing EPT for (TiO}_2\text{)(OH)}_4\text{(H}_2\text{O)}_8\text{. Blue and green colors indicate negative and positive computed excitonic (electron–hole pair) charges, respectively.}\)
Simultaneously, hydrogen bonding stabilizes the emerging and hole charges leads to a gain of coulombic stabilization. (ii) localization of the exciton with close proximity of the electron and hole charges, i.e., non-radiative decay to the ground state. This is seen in the vast majority of our trajectories. Similarly, the effective stabilization of the photohole by hydrogen bonding requires a specific orientation of surface bound water, which has a large entropic penalty. While additional validation of the proposed mechanism is desirable, e.g., by exploring the effects of the particle size and bulk solvation, the present results could inform future efforts to increase the water splitting activity of TiO₂-based photocatalysts by targeted synthetic modification.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy under Award DE-SC0008694. SMP is supported by an Arnold O. Beckman Postdoctoral Fellowship, and EB would like to thank the Thomas Young Centre for a Junior Research Fellowship which allowed him to visit University of California, Irvine. MZ acknowledges the UK Engineering and Physical Sciences Research Council (EPSRC) for funding (Grant EP/I004424/1). Helpful discussions with Shane A. Ardo are also acknowledged.

References

1. K. Hashimoto, H. Irie and A. Fujishima, *Jpn. J. Appl. Phys.*, 2005, **44**, 8269–8285.
2. M. Kapilashrami, Y.-S. Zhang, Y. S. Liu, A. Hagfeldt and J. Guo, *Chem. Rev.*, 2014, **114**, 9662–9707.
3. A. Fujishima and K. Honda, *Nature*, 1972, **238**, 37–38.
4. J. Schneider, *Chem. Rev.*, 2014, **114**, 9919–9986.
5. M. Barbatti, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.*, 2011, **1**, 620–633.
6. E. Tapavicza, G. D. Bellchambers, J. C. Vincent and F. Furche, *Phys. Chem. Chem. Phys.*, 2013, **15**, 18336–18348.
7. F. Furche, B. T. Krull, B. D. Nguyen and J. Kwon, *J. Chem. Phys.*, 2016, **144**, 174105.
8. J. C. Vincent, M. Muuronen, K. C. Pearce, L. N. Mohamed, E. Tapavicza and F. Furche, *J. Phys. Chem. Lett.*, 2016, **7**, 4185–4190.
9. J. Tang, J. R. Durrant and D. R. Klug, *J. Am. Chem. Soc.*, 2008, **130**, 13885–13891.
10. Á. Valdés, Z.-W. Qu, G.-J. Kroe, J. Rossmeisl and J. K. Nørskov, *J. Phys. Chem. C.*, 2008, **112**, 9872–9879.
11. Á. Valdés, J. Brillet, M. Gratzel, H. Gudmundsdottir, H. A. Hansen, H. Jonsson, P. Klupfel, G.-J. Kroe, F. Le Formal, I. C. Man, R. S. Martins, J. K. Nørskov, J. Rossmeisl, K. Sivula, A. Vojvodic and M. Zach, *Phys. Chem. Chem. Phys.*, 2012, **14**, 49–70.
12. J. Chen, Y. Li, P. Sit and A. Selloni, *J. Am. Chem. Soc.*, 2013, **135**, 18774–18777.
13 Á. Valdés and G.-J. Kroes, *J. Phys. Chem. C*, 2010, **114**, 1701–1708.
14 Y. Li, Z. Liu, L. Liu and W. Gao, *J. Am. Chem. Soc.*, 2010, **132**, 13008–13015.
15 R. H. Wilson, *J. Electrochem. Soc.*, 1980, **127**, 228–234.
16 M. R. Hoffman, S. T. Martin, W. Choi and D. W. Bahnemann, *Chem. Rev.*, 1995, **95**, 69–96.
17 C. Di Valentin, G. Pacchioni and A. Selloni, *Phys. Rev. Lett.*, 2006, **97**, 166803.
18 W.-N. Zhao and Z.-P. Liu, *Chem. Sci.*, 2014, **5**, 2256–2264.
19 Y.-F. Li and A. Selloni, *ACS Catal.*, 2016, **6**, 4769–4774.
20 A. Imanishi, T. i. Okamura, N. Ohashi, R. Nakamura and Y. Nakato, *J. Am. Chem. Soc.*, 2007, **129**, 11569–11578.
21 T. Hirakawa, K. Yawata and Y. Nosaka, *Appl. Catal., A*, 2007, **325**, 105–111.
22 S. Tan, H. Feng, Y. Ji, Y. Wang, J. Zhao, A. Zhao, B. Wang, Y. Luo, J. Yang and J. G. Hou, *J. Am. Chem. Soc.*, 2012, **134**, 9978–9985.
23 J. Zhang and Y. Nosaka, *J. Phys. Chem. C*, 2014, **118**, 10824–10832.
24 W. Kim, T. Tachikawa, G. h. Moon, T. Majima and W. Choi, *Angew. Chem.*, 2014, **126**, 14260–14265.
25 G. A. Tritsaris, D. Vinichenko, G. Kolesov, C. M. Friend and E. Kaxiras, *J. Phys. Chem. C*, 2014, **118**, 27393–27401.
26 R. Nakamura and Y. Nakato, *J. Am. Chem. Soc.*, 2004, **126**, 1290–1298.
27 R. Nakamura, T. Tanaka and Y. Nakato, *J. Phys. Chem. B*, 2004, **108**, 10617–10620.
28 A. Kazaryan, R. van Santen and E. J. Baerends, *Phys. Chem. Chem. Phys.*, 2015, **17**, 20308–20321.
29 J. P. Perdew, M. Ernzerhof and K. Burke, *J. Chem. Phys.*, 1996, **105**, 9982.
30 F. Weigend and R. Ahlrichs, *Phys. Chem. Chem. Phys.*, 2005, **7**, 3297–3305.
31 S. Grimme, J. Antony, S. Ehrlich and H. Krieg, *J. Chem. Phys.*, 2010, **132**, 154104.
32 F. Furche and R. Ahlrichs, *J. Chem. Phys.*, 2002, **117**, 7433.
33 R. Send and F. Furche, *J. Chem. Phys.*, 2010, **132**, 044107.
34 J. C. Tully, *J. Chem. Phys.*, 1990, **93**, 1061.
35 S. D. Elliott, R. Ahlrichs, O. Hampe and M. M. Kappes, *Phys. Chem. Chem. Phys.*, 2000, **2**, 3415–3424.
36 B. G. Levine, C. Ko, J. Quenneville and T. J. Martinez, *Mol. Phys.*, 2006, **104**, 1039–1051.
37 F. Furche, R. Ahlrichs, C. Hättig, W. Klopper, M. Sierka and F. Weigend, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.*, 2014, **4**, 91–100.
38 G. Kolesov, D. Vinichenko, G. A. Tritsaris, C. M. Friend and E. Kaxiras, *J. Phys. Chem. Lett.*, 2015, **6**, 1624–1627.
39 A. E. Reed, R. B. Weinstock and F. Weinhold, *J. Chem. Phys.*, 1985, **83**, 735.
40 S. Selcuk and A. Selloni, *Nat. Mater.*, 2016, **15**, 1107–1112.
41 E. Berardo and M. A. Zwijnenburg, *J. Phys. Chem. C*, 2015, **119**, 13384–13393.