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#### Broader context

# Cooperative water oxidation catalysis in a series of trinuclear metallosupramolecular ruthenium macrocycles<sup>†</sup>

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A series of trinuclear metallosupramolecular Ru(bda) macrocycles has been synthesized and the impact of the ring size on the catalytic activity in homogeneous water oxidation has been elucidated (bda = 2,2'-bipyridine-6,6'-dicarboxylate). Kinetic experiments revealed that for all macrocyclic catalysts a proton-coupled oxidation event is rate-determining. Distinct H/D kinetic isotope effects (KIE) have been observed for the individual macrocycles, which follow the same tendency like the catalytic activity where an intermediate ring size exhibits the best performance. To get insight into the different molecular properties, molecular dynamics simulations using a QM/MM approach have been performed for all reaction steps, revealing that the size of the cavity strongly influences the hydrogen-bonded water network inside the macrocyclic structure and thus, important proton-coupled reaction steps of the catalytic cycle. For the most active catalysts, all reactive sites point into the interior of the cavity, which is supported by a single crystal X-ray analysis of the largest macrocycle, and a cooperative effect between the individual Ru(bda) centers facilitating proton abstraction has been substantiated. On the other hand, different structural conformations predominate the smaller macrocycles, which prevent efficient interactions between the Ru(bda) centers.

In nature, the storage of solar energy in chemical bonds is accomplished by oxygenic photosynthetic organisms like algae, plants or cyanobacteria that split water into its elements after absorption of visible light. Elemental oxygen is thereby released into our atmosphere whereas the generated "hydrogen" is utilized in form of reducing equivalents to convert carbon dioxide into energy-rich carbohydrates. Aiming for a sustainable society and to mitigate climate changes, chemists increasingly focus on harnessing alternative energy sources by mimicking the elegance and efficiency of the natural photosynthetic apparatus. In this regard, our present study targets the complex oxidative half-reaction of water splitting by exploiting a principle found in many biocatalysts including the natural  $CaMn_4O_5$  oxygen evolving complex, *i.e.* the utilization of hydrogen-bonded water networks to lower reaction barriers of proton-coupled electron transfers. We demonstrate for differently sized metallosupramolecular macrocycles composed of three ruthenium water oxidation catalyst fragments that the precise control of the size and the geometry of the catalyst's interior is crucial to generate well-defined hydrogen-bonded water networks that facilitate substrate water binding and proton-coupled electron transfer processes, both of which determine the activity of water oxidation catalysis.

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## Introduction

The currently envisioned transformation towards a more sustainable society requires the exploitation of alternative energy sources together with cheap, efficient, and ecologically friendly methods for their generation.<sup>1-4</sup> Particularly promising are so called solar fuels, which are small energy-rich molecules that are obtained by photochemical transformations using sunlight in an artificial photosynthetic process starting from abundant and simple resources like water or  $CO_2$ .<sup>5-13</sup> In this regard, elemental hydrogen that can easily be obtained by the reduction of protons has an enormous potential since it exhibits a very high



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<sup>†</sup> Electronic supplementary information (ESI) available: Syntheses of new complexes, NMR-spectroscopy, mass spectrometry, X-ray crystallography, electrochemical measurements and details for all catalytic experiments, as well as a video based on MD simulations to illustrate water oxidation catalysis for MC3. CCDC 1554426 (MC4). For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c7ee01557g

gravimetric energy density and its combustion is clean.<sup>14–17</sup> The ideal and most abundant electron source for the generation of hydrogen is water, which can be oxidized to molecular oxygen resulting in an overall splitting of water into its elements. In this process, the oxidative half reaction is the major challenge, due to the complexity of this four-electron process and the resulting high overpotentials.<sup>17–20</sup> For this reason, efficient catalysts for the oxidation of water (WOCs) are highly desired. Since Meyer's discovery of the "blue dimer",<sup>21</sup> significant progress has been made with the development of various homogeneous metalorganic water oxidation catalysts based on Mn, Fe, Co, Ir, and Ru.<sup>22-26</sup> Especially promising is the catalyst class based on the Ru(bda) framework (bda = 2,2'-bipyridine-6,6'-dicarboxylate) developed by Sun and co-workers,<sup>24</sup> of which the best catalysts can compete with the activity of the natural oxygen evolving cluster (OEC).<sup>27</sup> In this CaMn<sub>4</sub>O<sub>5</sub> cluster each manganese atom acts as a reservoir for one oxidation equivalent, to cooperatively accomplish the fourfold oxidation of two water molecules under liberation of dioxygen.28-30

In nature, the catalytic activity is usually significantly improved by embedding the catalytic centers into complex supramolecular matrices in which weak non-covalent interactions lower the activation barrier or facilitate substrate transport. In many metallo-enzymes such proteinoic matrices are crucial for the overall reactivity since the catalytic subunit alone would not catalyze a chemical transformation by itself, like it has been illustrated with the preparation of artificial mimics of the OEC that exhibit considerably high overpotentials.<sup>29,31,32</sup> Inspired by this concept, supramolecular catalysis aims to improve the catalytic performance by fine-tuning the second coordination sphere of the catalytic center by providing appropriate binding sites for the substrates<sup>33-40</sup> or by generating defined cavities that closely resemble enzymatic pockets.<sup>41-45</sup> Focusing on ruthenium based water oxidation catalysts, there are several examples on how intermolecular interactions have been exploited to improve the catalytic activity depending on the prevalent reaction mechanism.46 The O-O bond formation can either be formed by the coupling of two ruthenium oxyl radicals (I2M) or by the nucleophilic attack of a substrate water molecule at a ruthenium oxide (WNA),<sup>18,47-50</sup> and in some cases even small structural changes can switch the mechanism from one to the other.<sup>51–55</sup> Generally, efficient proton-coupled electron transfer (PCET) processes are vital to reduce the required overpotential and inevitable for the development of high performance water oxidation catalysts.56-58 Both, quantum chemical calculations and infrared spectroscopy in the gas phase provide evidence that for ruthenium based water oxidation catalysts a hydrogen-bonded water network in the first solvation shell has a strong influence on the activation barriers of proton-coupled reaction steps of the catalytic cycle.<sup>59-65</sup> Similarly, an ordered hydrogen-bonded water network around the active center of the natural OEC is discussed to be essential for its remarkable efficiency.66-68

Very recently, our group has demonstrated that highly active water oxidation catalysts can be generated by incorporation of the catalytically active Ru(bda) complex fragment into

metallosupramolecular macrocycles.<sup>69,70</sup> The steric confinement and the reduced flexibility of the cyclic structure efficiently prevent O-O bond formation via an I2M mechanism like it is generally observed for other WOCs based on Ru(bda). Instead, kinetic studies and <sup>18</sup>O labelling experiments suggested that these metallosupramolecular catalysts operate via the water nucleophilic attack (WNA) mechanism in which highly oxidized Ru<sup>V</sup>=O species are nucleophilically attacked by water molecules. with the oxidation from Ru<sup>IV</sup> to Ru<sup>V</sup> being rate-determining. Although few other macrocyclic WOCs have been reported at about the same time,<sup>71-73</sup> our report was the first wherein the "macrocycle approach" has been proven to significantly increase the catalytic performance. The improved stability of these macrocyclic catalysts has been attributed to the chelate effect of the bridging ligand and the reduced self-oxidation due to steric constraints that only allow small molecules to reach the catalytic center. To rationalize the exceptionally high activity of this new type of catalysts operating via the WNA mechanism, we hypothesized that a hydrogen-bonded water network exists inside the macrocyclic cavity resulting in a low activation barrier for the water nucleophilic attack and any reaction sequence involving the abstraction of protons. Based on this assumption, one has to anticipate that the size of the macrocyclic interior will have a substantial impact on the hydrogen bonding network and thus on the catalytic activity. Accordingly, we present here the synthesis of a series of differently sized trinuclear Ru(bda) macrocycles by simply manipulating the length of the bridging ligands. The metallosupramolecular macrocycles exhibit different activities in the catalytic water oxidation reaction and the origin of this phenomenon has been elucidated by molecular dynamics simulations in a water box with explicitly described water molecules.

## Results and discussion

#### Macrocycle synthesis and characterization

To investigate the effect of the ring dimensions on the catalytic performance, a series of four differently sized macrocycles has been synthesized by self-assembly of equimolar amounts of the linear building block  $[Ru(bda)(dmso)_2]$  with ditopic N-heterocyclic bridging ligands, providing donor sites with angles of 60° (Fig. 1).<sup>74–77</sup>

The length of the axial bridging ligands (3,3'-bipyridine (bp), 1,2-bis(pyridin-3'-yl)ethyne (bpe), 1,4-bis(pyridin-3'-yl)benzene (bpb), and 4,4'-bis(pyridin-3"-yl)-1,1'-biphenyl (bpbp)) was adjusted by introducing different spacer groups in between the pyridyl binding sites, and all ligand systems were easily accessible through palladium-catalyzed cross-coupling reactions. Subsequently, the metallosupramolecular architectures **MC1–MC4** were isolated in moderate to high yields (16–55%), after heating the respective ligand together with the Ru(bda) precursor in a chloroform/methanol mixture under an atmosphere of nitrogen. Larger oligomeric by-products were removed by multiple filtrations over  $Al_2O_3$  and the pure products could be obtained after crystallization out of dichloromethane/methanol

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Fig. 1 (a) Schematic representation of the metallosupramolecular macrocycles **MC1–MC4** obtained by connecting Ru(bda) fragments with ditopic ligands of different length. (b) Space-filling models of **MC1–MC4** calculated for the  $[Ru^{II}]Ru^{II}]Ru^{II}]$  state using DFT with the PBE0 functional and the def2-SVP basis set (grey = carbon, white = hydrogen, red = oxygen, blue = nitrogen, turquoise = ruthenium).

solutions. Detailed synthetic procedures and the full characterization can be found in the ESI.†

The propensity of these macrocycles to crystallize adequately for X-ray diffraction experiments increases with their ring size. Whereas the smallest macrocycle **MC1** was exclusively obtained as an amorphous powder, the medium sized macrocycles **MC2** and **MC3** were isolated as microcrystalline materials for which a structure elucidation by X-ray diffraction was unfortunately not possible. However, for the largest cycle **MC4** suitable single crystals could be grown from a dichloromethane/methanol/ 2,2,2-trifluoroethanol mixture by slowly evaporating the solvent under an atmosphere of nitrogen to prevent partial oxidation of the ruthenium centers (Fig. 2). The macrocycle **MC4** crystallizes in the trigonal space group *R3c* with a slipped stacked packing arrangement giving rise to one-dimensional pores, which are filled with 2,2,2-trifluoroethanol (Fig. 2b and Fig. S13, ESI†). Furthermore, several solvent accessible voids exist within the refined structure as evidenced by the squeezed electron density of highly disordered solvent molecules that could not be modeled satisfactorily. The distances between the ruthenium centers and the axially coordinated pyridyl ligands (2.066(5) and 2.078(7) Å) are comparable to those of the acyclic mononuclear reference compound [Ru(bda)(pic)<sub>2</sub>] for which bond lengths of 2.070(6) and 2.084(6) Å have been reported.<sup>78</sup> Both complexes exhibit distorted octahedrally coordinated ruthenium centers with obtuse O–Ru–O angles of 123.0(2)°, providing an optimal seventh coordination site for small molecules like water. Minor differences are found for the N<sub>ax</sub>–Ru–N<sub>ax</sub> bond angles with 173.0(2)° for [Ru(bda)(pic)<sub>2</sub>] and 170.9(2)° for MC4. Due to the rigid cyclic structure, each one axial pyridyl ligand in MC4 is



**Fig. 2** (a) Solid state molecular structure of **MC4** determined by single crystal X-ray diffraction. The crystals were grown from a dichloromethane/ methanol/2,2,2-trifluoroethanol solvent mixture. Solvent molecules were omitted for clarity (ORTEP diagram with thermal ellipsoids set at 50% probability). (b) Crystal packing of **MC4** viewed along the cell axis *c* with 2,2,2-trifluoroethanol molecules in the pores (capped stick model) (grey = carbon, white = hydrogen, red = oxygen, blue = nitrogen, turquoise = ruthenium, green = fluorine).

considerably tilted towards the equatorial bda chelate, as it becomes obvious by the smaller Ru-Nax-Cpara angles (Fig. S14, ESI<sup>†</sup>). Whereas [Ru(bda)(pic)<sub>2</sub>] is characterized by almost perfectly linearly oriented picoline ligands (Ru-Nax-Cpara = 178.2(3)° and 177.2(3)°), MC4 exhibits Ru-Nax-Cpara angles of  $174.9(3)^{\circ}$  and  $159.9(3)^{\circ}$ . This tilting in MC4 causes the axial pyridyl ligands to be torsionally twisted by  $46.1(2)^{\circ}$  in contrast to  $22.3(9)^{\circ}$  in [Ru(bda)(pic)<sub>2</sub>] which should be beneficial for substrate water binding (Fig. S14, ESI<sup>+</sup>). The intramolecular distance between two ruthenium centers is 16.274(1) Å, giving rise to an aperture size of approximately 115 Å<sup>2</sup>. Most interestingly, the open coordination sites of all three ruthenium centers of MC4 point into the interior of this cavity, giving support to the assumption that the catalytic subunits might cooperatively interact for the oxidation of water. Since the solid state molecular structures of the smaller macrocycles could not be determined experimentally, the geometries of MC1-MC4 were optimized in their Ru(II) oxidation state in the gas phase using DFT calculations (Fig. 1b and Fig. S15, ESI<sup>+</sup>). Here, it turned out that in the smaller macrocycles some of the Ru(bda) centers are partially oriented to the outside with the largest degree of torsion for MC1. The respective space filling models clearly show that the size of the cavities continuously decreases from MC4 to MC1, with almost no water accessible void for the smallest macrocycle MC1 (Fig. 1b).

#### Electrochemistry and UV/vis spectroscopy

The electrochemistry of the macrocycles **MC1–MC4** was investigated by differential pulse voltammetry (DPV) in acidic aqueous media using organic co-solvents exclusively for solubilization, since in a purely organic environment only the Ru<sup>II/III</sup> oxidation can be observed.<sup>69</sup> In an aqueous solution, however, water can coordinate to the seventh coordination site of the ruthenium center, being a prerequisite to reach higher oxidation states. After substrate water binding, proton-coupled electron transfers (PCETs) become possible that contribute to prevent unfavorable charge accumulation.<sup>79</sup> For all macrocycles three subsequent oxidation events are thus observed that were assigned to the redox couples Ru<sup>II/III</sup>, Ru<sup>III/IV</sup>, and Ru<sup>IV/V</sup> in accordance to the electrochemistry reported for mononuclear [Ru(bda)L<sub>2</sub>] complexes (Fig. S16, ESI<sup>†</sup>).<sup>27,80</sup> However, it has to be noted that the existence of a Ru<sup>V</sup> state is under debate for many water oxidation catalysts,<sup>81,82</sup> and only few catalysts are known for which its existence has been proven experimentally. Thus, for cis,cis-[(bpy)2(H2O)RuORu(OH2)- $(bpy)_2^{4+}$  (ref. 83-85) and *cis*-[Ru(bpy)\_2(OH\_2)\_2^{2+} (ref. 86) and 87) a Ru<sup>V</sup> intermediate was substantiated by EPR spectroscopy, whereas no evidence for a Ru<sup>V</sup> species has been provided so far for the Ru(bda) catalyst family. The respective potentials of these oxidation events in non-coordinating 2,2,2-trifluoroethanol as co-solvent at pH 1 are very similar for all macrocycles and approximately 100 mV higher than those observed for the mononuclear reference complex  $[Ru(bda)(pic)_2]^{27}$ presumably due to the close proximity of the three redox centers. In the presence of acetonitrile as co-solvent the first oxidation from Ru<sup>II</sup> to Ru<sup>III</sup> is shifted to higher potentials by 250 mV, whereas the other oxidation events remain unaffected (Fig. S16, ESI<sup>+</sup>). This can be attributed to the fact that in the Ru<sup>II</sup> state, the ruthenium centers are preferentially coordinated by acetonitrile, which has to be exchanged by water upon oxidation to Ru<sup>III</sup> resulting in the observed overpotential.<sup>80,88</sup> Although in each oxidation event three electrons are removed simultaneously, different peak current intensities are found for the individual processes, which can be explained by the coupling of some oxidation events to proton transfer processes. In such cases, the oxidation is kinetically hindered giving rise to considerably decelerated reaction rates at the electrode and thus to lower peak current intensities.<sup>89</sup>

This can nicely be illustrated at differential pulse voltammograms of **MC2** for different pH values (Fig. 3). At pH 3.0, only the Ru<sup>II/III</sup> oxidation exhibits an intensive peak current, indicating that the subsequent oxidation steps from Ru<sup>III</sup> to Ru<sup>IV</sup> and Ru<sup>IV</sup> to



Fig. 3 (a) Differential pulse voltammograms of MC2 at three different pH values. (b) Pourbaix (E-pH) diagram of MC2. The experiments were performed in  $CH_3CN/H_2O1:1$  with an initial pH value of 1 (acid :  $CF_3SO_3H$ ). The higher pH values were adjusted by successive addition of aqueous NaOH.

 $Ru^{V}$  are proton-coupled. However, by increasing the pH value, the ratio between the peak current intensities of all oxidation events changes dramatically. At pH 8.2, the  $Ru^{IV/V}$  oxidation exhibits the strongest current, whereas at even higher pH values of >9 a completely new oxidation event emerges that can be attributed to the oxidation of a  $Ru^{III}$ -OOH intermediate, which is formed by the nucleophilic attack of water at the  $Ru^{V}$ =O moiety.<sup>90–92</sup>

To further investigate the proton coupling of the individual oxidation events in detail, pH-dependent differential pulse voltammetry was performed and the corresponding Pourbaix diagrams were constructed for all complexes (Fig. S17-S20, ESI<sup>†</sup>). Exemplarily for all macrocycles, the Pourbaix diagram of MC2 is shown in Fig. 3b, highlighting the stability regions of the different oxidation states. The changes of the potential with the pH value reflect the proton coupling of the individual processes with a Nernstian ideal of 59 mV per pH for a simple  $ne^{-}/nH^{+}$  process.<sup>24,93</sup> Under acidic and basic conditions, the slopes and the proton couplings are very similar for the macrocycles MC1-MC3. Merely at neutral pH values the situation is slightly more complicated, and minor differences can be observed. However, since the catalysis is usually driven by cerium(IV) ammonium nitrate (CAN) as sacrificial oxidant in highly acidic media (pH 1), only the oxidation events under those conditions are discussed in detail. The oxidations from Ru<sup>II</sup> to Ru<sup>III</sup> are independent of the pH values in all cases, and therefore proton-uncoupled. For the Ru<sup>III/IV</sup> redox couples, slopes of 42-49 mV per pH are found for the macrocycles MC1-MC3 indicating  $3e^{-}/2H^{+}$  processes. For MC4 however, a slope of 62 mV per pH is observed which is in line with a  $3e^{-1}$ 3H<sup>+</sup> PCET. This behavior is reversed for the subsequent oxidation from Ru<sup>IV</sup> to Ru<sup>V</sup>, for which MC1-MC3 still exhibit slopes corresponding to a 3e<sup>-</sup>/2H<sup>+</sup> process, whereas MC4 undergoes a  $3e^{-}/1H^{+}$  oxidation. Thus, for all macrocycles the same oxidized species are formed before the current strongly increases due to water oxidation. In an acidic environment, partially protonated [Ru<sup>V</sup>=O|Ru<sup>V</sup>-OH|Ru<sup>V</sup>-OH]<sup>5+</sup> species predominate, whereas in basic media completely deprotonated [Ru<sup>V</sup>=O|Ru<sup>V</sup>=O|Ru<sup>V</sup>=O]<sup>3+</sup> intermediates are obtained. At these highly oxidized Ru<sup>V</sup>=O electrophiles, the nucleophilic attack of water takes place, generating the O-O bond. The resulting (hydro)peroxide species has to be oxidized once more to finally liberate elemental oxygen. However, this fourth oxidation can only be observed at basic pH values like it has already been reported by Sun and coworkers for mononuclear WOCs based on Ru(bda).90,92

Since intriguing color changes were observed for the macrocycle **MC3** with proceeding oxidation,<sup>69</sup> spectroelectrochemistry and chemical titration experiments monitored by UV/vis spectroscopy using cerium(v) ammonium nitrate were performed for all macrocycles to gain further insights into the spectral changes that accompany the oxidation processes. The UV/vis absorption spectra of all macrocycles in the [Ru<sup>II</sup>|Ru<sup>II</sup>] oxidation state are very similar in CH<sub>3</sub>CN/H<sub>2</sub>O (pH 1) 1:1, and are characterized by L- $\pi \rightarrow$  L- $\pi^*$  transitions of the aromatic bridging ligands (L) around 300 nm together with several metal to ligand charge transfer (MLCT) bands between 350 and 500 nm.<sup>94</sup> With an increasing number of aromatic benzene rings within the  $\pi$ -system

of the axial ligands (L), the extinction coefficient of the  $\pi$ - $\pi$ \* band continuously increases (Fig. S21 and S22, ESI<sup>+</sup>). According to our calculations and previous reports, the bands between 450 and 500 nm can be explained by Ru-d  $\rightarrow$  bda- $\pi^*$  MLCTs, whereas the higher energetic ones at 350 nm are characteristic for Ru-d  $\rightarrow$  L- $\pi^*$ MLCTs.95 However, pronounced differences are observed in the UV/vis absorption spectra for the oxidized macrocycles as it has been substantiated by spectroelectrochemistry in CH<sub>2</sub>CN/H<sub>2</sub>O 1:1 at pH 1 (Fig. 4). Upon increasing the potential from 600 mV to approximately 1000 mV vs. NHE, [Ru<sup>II</sup>|Ru<sup>II</sup>|Ru<sup>II</sup>] becomes gradually oxidized to [Ru<sup>III</sup>-OH<sub>2</sub>|Ru<sup>III</sup>-OH<sub>2</sub>|Ru<sup>III</sup>-OH<sub>2</sub>]<sup>3+</sup> which is accompanied by drastic spectral changes. The MLCT bands at 350 and 450-500 nm are bleached and new transitions around 670 nm appear, which are absent for the mononuclear reference complex [Ru(bda)(pic)<sub>2</sub>]. From these measurements it becomes obvious that all Ru centers are oxidized at the same given potential, since the



**Fig. 4** (a) UV/vis absorption spectra of the Ru<sup>III</sup> state of **MC1–MC3** and [Ru(bda)(pic)<sub>2</sub>] in CH<sub>3</sub>CN/H<sub>2</sub>O 1:1 and of **MC4** in CH<sub>3</sub>CN/H<sub>2</sub>O 4:1 ( $c = 10^{-5}$  M, pH 1, acid: CF<sub>3</sub>SO<sub>3</sub>H). Spectra for the Ru<sup>III</sup> (b) and Ru<sup>IV</sup> (c) oxidation states obtained by spectroelectrochemistry for **MC1–MC3** and [Ru(bda)(pic)<sub>2</sub>] in CH<sub>3</sub>CN/H<sub>2</sub>O 1:1 and for **MC4** in CH<sub>3</sub>CN/H<sub>2</sub>O 4:1 ( $c = 6-7 \times 10^{-4}$  M, pH 1, acid: CF<sub>3</sub>SO<sub>3</sub>H).

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spectral features of Ru<sup>II</sup> completely disappear. During this oxidation process precipitation occurs for MC4 in the applied solvent mixture, so that higher contents of acetonitrile (80%) had to be used, making a direct comparison with MC1-MC3 difficult, although the general trends are preserved (Fig. S27, ESI<sup>+</sup>). The extinction coefficients of the low-energy transitions around 670 nm strongly depend on the size of the macrocycle with the most intensive absorption for MC3. Further oxidation of MC1-MC3 to  $[Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH_2]^{4+}$  or MC4 to  $[Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV}-OH|Ru^{IV$ OH|Ru<sup>IV</sup>-OH]<sup>3+</sup>, by applying potentials of 1200 mV vs. NHE, leads to a decrease of these low-energy absorption bands accompanied by an increase of new hypsochromically shifted transitions centered around 550 nm with the same intensity distribution. The spectral features of the [Ru<sup>V</sup>=O|Ru<sup>V</sup>-OH|Ru<sup>V</sup>-OH]<sup>5+</sup> species could not be ascertained, since its formation immediately triggers the nucleophilic attack of water, which leads to strong catalytic currents. Detailed analysis of the absorption spectral changes in dependence of the applied potential is provided in the ESI<sup>+</sup> (Fig. S23-S27).

#### Simulation of absorption spectra

Due to the strong intensity differences for the low-energy absorption bands of the Ru<sup>III</sup> and Ru<sup>IV</sup> states, theoretical simulations were performed within the hybrid QM/MM framework in order to identify the relevant transitions. Similar absorption maxima at higher wavelengths have previously been reported for µ-oxo bridged multinuclear Ru(bda) species94,96-99 as well as the "blue dimer"  $cis,cis-[(bpy)_2(H_2O)RuORu(OH_2)(bpy)_2]^{4+}$  (bpy = 2,2'-bipyridine).<sup>100</sup> For this well investigated catalyst, mixing of nonbonding Ru-d orbitals with p- $\pi$  orbitals of the  $\mu$ -oxo bridge was found to cause a significant bathochromic shift of the MLCT transition. DFT calculations further revealed a high solvent dependency due to hydrogen bonding and only under consideration of explicit water molecules a good agreement between experimental and calculated spectra could be obtained.<sup>101</sup> Moreover, Weber et al. have shown by photo-dissociation spectroscopy on mass selected catalyst-water clusters in the gas phase that an increasing number of water molecules induces a solvatochromic shift of MLCT bands in ruthenium polypyridine complexes.<sup>61</sup> According to their investigations, solvation of the ruthenium center by seven water molecules seems to be sufficient to approximate bulk solvent behavior.

Indeed, our initial attempts to reproduce the low-energy MLCT around 670 nm of **MC3** in the [Ru<sup>III</sup>|Ru<sup>III</sup>]<sup>3+</sup> state in a water box containing only three explicit water molecules failed. Accordingly, we optimized structures of **MC3** in the oxidation states Ru<sup>III</sup> and Ru<sup>IV</sup> by systematically increasing the amount of explicit water. Detailed analysis of all structures revealed that the amount of explicit water molecules strongly influences the Ru–OH and RuO–H bond lengths between the ruthenium center and the coordinated aqua or hydroxide ligands (Fig. 5a and Fig. S28, ESI†). Natural transition orbital (NTO) analysis of each structure provided evidence that the changes of these bond lengths significantly influence the energetic position of the individual MLCT transitions (Fig. 5b).



**Fig. 5** Influence of the amount of explicit water molecules on important properties of **MC3** in the Ru<sup>III</sup> state. (a) Mean Ru–O distances (blue squares) and standard deviations (error bars) for all Ru centers against the number of explicit water molecules. (b) Wavelength of the Ru(bda)- $\sigma \rightarrow$  Ru(bda)- $\sigma^*$  transition against the Ru–O distance (blue squares) and linear regressions for distances >2.3 Å (solid line) and <2.3 Å (dashed line). Note that excitations at Ru<sup>III</sup> centers with Ru–O bond lengths below 2.3 Å occur at unexpected low wavelengths in the spectra due to an induced change in the geometry in the near environment of the Ru atom resulting in an asymmetric bda-ligand with one carboxylic group shifted away from the Ru atom (Fig. S29, ESI†).

Obviously, the calculated excited state energies are very sensitive towards structural changes and a sufficient number of explicit water molecules has to be taken into account to properly describe important structural rearrangements and fluctuations within the QM/MM framework. Due to the shallow potential energy surfaces of solvated compounds, many geometries are expected to coexist in solution and one single geometry optimized structure might not be sufficient to explain the differences in the experimental spectra. In order to scan the potential energy surface taking structural fluctuations into account, molecular dynamics (MD) has proven to be a valuable tool. Examples from literature have shown that theoretically predicted absorption spectra, even of small molecules like nitrobenzene, are considerably improved by considering a whole ensemble of structures sampled from a molecular dynamics (MD) trajectory.<sup>102</sup> Therefore, QM/MM MD simulations have been performed for complexes [Ru(bda)(pic)<sub>2</sub>], MC1, and MC3 to correlate structural features with the experimentally



**Fig. 6** Top: Calculated ensemble spectra in the (a)  $Ru^{II}$ , (b)  $Ru^{III}$ , and (c)  $Ru^{IV}$  oxidation states of  $[Ru(bda)(pic)_2]$ , **MC1**, and **MC3** obtained from 30 geometries sampled along the MD trajectories. Bottom: NTOs of the low-energy transitions of **MC3** in the (a)  $Ru^{II}$ , (b)  $Ru^{III}$ , and (c)  $Ru^{IV}$  oxidation states. Only the relevant parts of the molecule are displayed for the sake of clarity (green = carbon, grey = hydrogen, red = oxygen, blue = nitrogen, yellow = ruthenium).

observed spectra. Calculations were performed in the oxidation states Ru<sup>II</sup>, Ru<sup>III</sup>, and Ru<sup>IV</sup> with well solvated Ru centers, and 30 structures were sampled from the molecular dynamics trajectories in steps of 50 fs. The averaged ensemble UV/vis spectra are in good agreement with the experimentally observed absorption maxima and the most relevant transitions that contribute to the low-energy absorption bands, have been identified for each oxidation state (Fig. 6).

In the Ru<sup>II</sup> oxidation state, Ru-d  $\rightarrow$  bda- $\pi^*$  transitions are located at wavelengths around 449 nm whereas the bathochromically shifted absorption maxima at 612 nm in the Ru<sup>III</sup> state could be attributed to Ru(bda)- $\sigma \rightarrow$  Ru(bda)- $\sigma^*$  transitions. In the Ru<sup>IV</sup> oxidation state RuO- $\pi \rightarrow$  bda- $\pi^*$  MLCTs give rise to the low-energy bands at 461 nm. The deviation of less than 0.4 eV of the calculated low-energy transitions from the experimental values is a reasonable accuracy for the applied CAM-B3LYP functional.<sup>103</sup> Thus, the origin of the new absorption bands at longer wavelengths of the higher oxidation states has been ascertained and it has been shown that the solvation of the catalytic center strongly influences the structural parameters as well as the energetic position of the MLCT transitions.

In the Ru<sup>III</sup> oxidation state, the low-energy absorption at 612 nm is mainly dependent on the Ru–OH bond length which has been sampled for all structures along the MD trajectories and its distribution is depicted in Fig. S30 (ESI†). None of the 30 structures of  $[Ru(bda)(pic)_2]$  exhibits water molecules within a distance of less than 2.5 Å to the Ru center and could thus be considered as strongly coordinated. On the other hand, for the structures of **MC1**, one Ru center is found on the average to be coordinated by a water molecule, whereas in **MC3** even two Ru centers are bound by water molecules in most of the structures. Recent EPR studies on a fully water soluble derivative of  $[Ru(bda)(pic)_2]$  revealed that in aqueous solution an equilibrium

exists between a six-coordinated [Ru<sup>III</sup>]<sup>+</sup> and a seven-coordinated  $[Ru^{III}-OH_2]^+$  species.<sup>104</sup> In our simulations, we note that the position of this equilibrium is different for each complex. In its most favorable conformation, the 4-picoline ligands of  $[Ru(bda)(pic)_2]$  with nearly perfectly eclipsed  $\pi$ -surfaces efficiently block the seventh coordination site of the ruthenium center allowing water to coordinate only very weakly. In contrast, the axial bridging ligands of the macrocyclic catalysts are rotationally restricted, readily providing access to the seventh coordination site and thus to a beneficial coordination of water. Since the appearance of Ru(bda)- $\sigma \rightarrow$  Ru(bda)- $\sigma^*$  transitions at longer wavelengths is strongly dependent on the Ru-OH bond lengths between the ruthenium centers and the coordinated aqua or hydroxide ligands, these findings rationalize the absence of such low-energy MLCTs for [Ru(bda)(pic)<sub>2</sub>] in its Ru<sup>III</sup> state. Likewise, in the Ru<sup>IV</sup> oxidation state, the positions of the energetically low MLCT bands mainly depend on the Ru-OH and the RuO-H bond lengths.

During our MD simulations, the Ru<sup>IV</sup> centers of all complexes are permanently coordinated by hydroxide ligands and the distributions of the bond lengths are displayed in Fig. 7. In [Ru(bda)(pic)<sub>2</sub>], Ru–OH bond lengths are most frequently found between 1.8 and 1.9 Å, while the RuO–H bond length is usually shorter than 1.4 Å. In the smallest macrocycle **MC1**, the distribution of the Ru–OH distances exhibits a maximum at 1.9 Å with a minor amount of shorter bond lengths near 1.7 Å, while the RuO–H distances exceed 1.4 Å only in rare cases. On the other hand, the maximum of the Ru–OH bond lengths distribution of **MC3** is shifted near 1.8 Å, accompanied with a considerable elongation of the RuO–H bonds up to 2.0 Å. These stretched RuO–H bonds account for the appearance of RuO- $\pi \rightarrow$  bda- $\pi^*$  transitions in the Ru<sup>IV</sup> oxidation state and rationalize the experimentally observed absorption maxima at 550 nm.



Fig. 7 Normalized distributions of the Ru–OH and the RuO–H bond lengths in the Ru<sup>IV</sup> oxidation state of (a) [Ru(bda)(pic)<sub>2</sub>], (b) **MC1**, and (c) **MC3** obtained by each 30 structures sampled along the MD simulation trajectories.

Altogether, our MD simulations reveal significant structural differences between the investigated complexes and elucidate the different intensities of the experimentally observed lowenergy transitions. The structural diversity is caused by the solvation of the Ru centers which is different for each catalyst and each macrocyclic cavity. For MC3, a network of hydrogenbonded water molecules has been elaborated inside its cavity resulting in an enhanced hydrogen bonding between the substrate water molecules and the coordinated aqua or hydroxide ligands and therefore in elongated RuO-H as well as shortened Ru-OH bonds. This effect is considerably reduced for MC1, since its cavity is not large enough to accommodate the required amount of water molecules. For MC1, two Ru centers are oriented towards the catalysts' exterior, being well solvated by water molecules from outside. These two subunits more closely resemble the isolated monomeric reference system without any hydrogen bonding between adjacent reaction centers. The different solvation behavior of the reactive Ru centers is expected to have a major influence on the catalytic activity.

#### Water oxidation catalysis

In our recent report on the catalytic behavior of **MC3**, we have demonstrated by <sup>18</sup>O labelling experiments that this catalyst oxidizes water *via* the "water nucleophilic attack" (WNA) mechanism with the oxidation from a Ru<sup>IV</sup> to a Ru<sup>V</sup> species being rate-determining.<sup>69</sup> A simplified mechanistic picture considering only one single Ru center is depicted in eqn (1)–(6), using the strong one-electron oxidant cerium(IV) ammonium nitrate (CAN) as sacrificial electron acceptor to drive the catalysis.<sup>105</sup> Upon oxidation of the initial Ru<sup>II</sup> state to Ru<sup>III</sup>,

water binds to the seventh coordination site (eqn (1)). In a sequence of proton-coupled electron transfer processes, this  $Ru^{III}$ -OH<sub>2</sub> intermediate is transformed into a  $Ru^{V}$ =O species (eqn (2) and (3)), which is nucleophilically attacked by water to form  $Ru^{III}$ -OOH (eqn (4)). Subsequent oxidation to  $Ru^{IV}$ -O<sub>2</sub> (eqn (5)) and reductive elimination of molecular oxygen (eqn (6)) eventually closes the catalytic cycle.

$$Ru^{II} + Ce^{IV} + H_2O \rightarrow Ru^{III} - OH_2 + Ce^{III}$$
(1)

$$Ru^{III}-OH_2 + Ce^{IV} \rightarrow Ru^{IV}-OH + Ce^{III} + H^+$$
(2)

$$Ru^{IV} - OH + Ce^{IV} \rightarrow Ru^{V} = O + Ce^{III} + H^{+}$$
(3)

$$Ru^{V} = O + H_2O \rightarrow Ru^{III} - OOH + H^+$$
(4)

$$Ru^{III}-OOH + Ce^{IV} \rightarrow Ru^{IV}-O_2 + Ce^{III} + H^+$$
 (5)

$$Ru^{IV} - O_2 \rightarrow Ru^{II} + O_2 \tag{6}$$

To study the catalytic performance of the new series of trinuclear WOCs (MC1-MC4), the chemical oxidant CAN has initially been added in large excess to ensure a pseudo-zeroth order for all reaction steps with respect to the CAN concentration. Thus, the catalytic rate should solely depend on the catalyst concentration.<sup>106</sup> After injection of the respective catalyst solution into an acidic CAN solution, immediate formation of gas bubbles could be observed and the pressure increase was measured with pressure transducers (for experimental details and reaction conditions see ESI<sup>+</sup>). Gas chromatographic head space analysis was performed after each run to prove that elemental oxygen is the only gaseous product formed during catalysis, and to confirm the determined turnover numbers (TONs). From the linear part of the first few seconds in pressure increase, the initial reaction rates have been determined and by plotting these rates vs. the amount of catalyst, the rate laws regarding the catalyst concentration as well as the turnover frequencies (TOFs) were obtained. For all experiments acetonitrile was chosen as organic co-solvent due to its strong oxidative resistance and its good miscibility with water. However, it is well known that with increasing amount of acetonitrile the catalytic reaction severely slows down due to competitive binding of acetonitrile to the seventh coordination site of the ruthenium center.<sup>88,107</sup> Thus, for an optimal catalytic performance the content of acetonitrile should not be higher than absolutely necessary to keep the macrocyclic catalysts and their intermediates in solution.<sup>70</sup> Since the solubility of MC1-MC4 in water strongly deviates from each other due to their different sizes, the catalytic experiments have been performed both under optimized and under comparable solvent compositions (Table 1).

Whereas the smallest macrocycle **MC1** is soluble in nearly pure water, containing only 2% (v/v) of acetonitrile as co-solvent, the amount of organic additive required to achieve sufficient solubility rises significantly with increasing ring size. To reach their best performances, 50% and 60% of acetonitrile, respectively, have to be added to the intermediate sized macrocycles **MC2** and **MC3**. The largest macrocycle **MC4** already requires at least 80% of organic co-solvent, and even then concentrations cannot be obtained as high as for the smaller analogues. To still properly

Table 1 Catalytic activity and kinetic isotope effects of the macrocyclic WOCs MC1-MC4

Method	CH <sub>3</sub> CN content (%)	MC1		MC2		MC3		MC4	
		TOF $(s^{-1})$	TON	TOF $(s^{-1})$	TON	TOF $(s^{-1})$	TON	TOF $(s^{-1})$	TON
Ce(ıv)-driven catalysis <sup>a</sup>	2	38	2500	_	_		_	_	
	50	_		70	3240	_	_	_	
	60	_		_		150	7400	_	
	80	0.3	660	1.6	680	7.9	3590	3.8	1810
H/D KIE <sup>b</sup>	50	1.2		1.5		2.8		1.8	
<sup><i>a</i></sup> (CH <sub>2</sub> CN/H <sub>2</sub> O mixtures.	pH 1. acid : CF <sub>2</sub> SO <sub>2</sub> H. [C	[AN] = 0.53 M.	[cat] = 10-	-240 µM), meas	sured with	pressure trans	sducers. b	(CH <sub>2</sub> CN/H <sub>2</sub> O 1	1:1 and

" (CH<sub>3</sub>CN/H<sub>2</sub>O mixtures, pH 1, acid: CF<sub>3</sub>SO<sub>3</sub>H, [CAN] = 0.53 M, [cat] = 10–240  $\mu$ M), measured with pressure transducers. " (CH<sub>3</sub>CN/H<sub>2</sub>O 1:1 and CH<sub>3</sub>CN/D<sub>2</sub>O 1:1 mixtures, pH 1, acid: CF<sub>3</sub>SO<sub>3</sub>H, [CAN] = 0.53 M, [cat] = 10–20  $\mu$ M), measured with a Clark-electrode.

compare all catalysts, concentration-dependent water oxidation experiments have been performed for **MC1–MC4** with a constant 80% acetonitrile content (Fig. 8 and Fig. S31–S34, ESI<sup>†</sup>). A linear dependency of the reaction rate on the amount of catalyst is obtained for all macrocycles within the first 50 s of the catalytic reaction. In such linear cases, the slope of the linear regression represents the turnover frequency of the individual catalyst. On the



**Fig. 8** Concentration-dependent water oxidation experiments for catalysts **MC1–MC4** and [Ru(bda)(pic)<sub>2</sub>] using cerium(IV) ammonium nitrate as sacrificial oxidant and pressure transducers for oxygen detection. (1.0 g CAN was dissolved in 3.0 mL CH<sub>3</sub>CN/H<sub>2</sub>O 4 : 1 (pH 1, CF<sub>3</sub>SO<sub>3</sub>H), 400  $\mu$ L of the catalyst solution in the same solvent mixture were injected). (a) Turnover numbers depending on the respective catalyst concentrations. (b) Plot of the catalyst amount vs. the initial rates of oxygen generation (determined for the first 50 s of catalysis).

other hand, a quadratic dependency on the catalyst concentration is observed for the mononuclear reference [Ru(bda)(pic)2], which is in line with its well-established bimolecular reaction mechanism (Fig. S35, ESI<sup>†</sup>).<sup>27</sup> The best performance is obtained for the catalyst MC3 (TOF = 7.9  $s^{-1}$ , TON = 3590) with TONs and TOFs being one order of magnitude higher compared to the smallest macrocycle MC1 (TOF = 0.3 s<sup>-1</sup>, TON = 660). The other two catalysts MC2  $(TOF = 1.6 \text{ s}^{-1}, TON = 680)$  and MC4  $(TOF = 3.8 \text{ s}^{-1}, TON = 1810)$ are intermediate representatives. The activity of the mononuclear complex [Ru(bda)(pic)<sub>2</sub>] is in the same range (TOF =  $0.09-1.17 \text{ s}^{-1}$ , TON = 450) as the slowest macrocyclic catalyst, however, operating via a different mechanism. Apparently, the size of the metallosupramolecular macrocycles MC1-MC4 has an enormous influence on their activity in catalytic water oxidation (vide infra). The catalytic performance of the more soluble macrocycles MC1-MC3 was further investigated under the respectively optimized solvent compositions mentioned above. Maximal TOFs of 38  $s^{-1}$ , 70  $s^{-1}$ , and 150  $s^{-1}$  as well as TONs of 2500, 3240, and 7400 have been measured for the catalysts MC1-MC3, respectively (Fig. S36-S38, ESI<sup>†</sup>). All catalysts are active for more than one hour, and gas chromatographic analysis of the head space at the end of each catalytic reaction confirms that the measured pressure increase is solely due to the formation of oxygen (Fig. S39 and S40, ESI<sup>+</sup>). Interestingly, macrocycle MC3 exhibits also the best performance under the optimized solvent composition, although higher amounts of acetonitrile as co-solvent are required compared to its smaller analogues.

Additional kinetic experiments have been performed using stoichiometric amounts of CAN to gain further insights into the mechanism of water oxidation. Under those conditions, the concentration of the oxidant cannot be neglected anymore and all oxidative steps in the reaction sequence should exhibit a first order dependence on its concentration. Furthermore, far less oxygen should be evolved which is why the previously described setup reaches its detection limit. Therefore, UV/vis spectroscopy has been used to study the consumption of CAN during the water oxidation reaction. Cerium(IV) ammonium nitrate was dissolved in a CH<sub>3</sub>CN/H<sub>2</sub>O (pH 1) 1:1 mixture and after addition of the catalysts, the decay of the characteristic CAN absorption band at 360 nm was monitored over time, applying Lambert-Beer's law to calculate the corresponding concentration changes. The dependence of the reaction rates on the concentrations of both, catalysts and oxidant, was studied with two different types of experiments. First, the CAN



**Fig. 9** Cerium(IV) ammonium nitrate consumption during the catalytic water oxidation reaction followed by monitoring the absorption decay of CAN at 360 nm in CH<sub>3</sub>CN/H<sub>2</sub>O 1:1 (pH 1, acid : HNO<sub>3</sub>). (a) Variation of the catalyst concentration with constant CAN concentration (2.0 mM). (b) Variation of the CAN concentration with constant catalyst concentration (3.0  $\mu$ M for **MC1–MC4** and 9.0  $\mu$ M for [Ru(bda)(pic)<sub>2</sub>]).

concentration was kept constant and only the respective catalyst concentration has been varied (Fig. 9a and Fig. S41-S45, ESI†). In a reversed series of measurements, the concentrations of the catalysts were kept constant, while the CAN concentration has been varied (Fig. 9b and Fig. S46-S50, ESI<sup>+</sup>). For all macrocyclic catalysts MC1-MC4 a linear dependence of the initial reaction rate on the catalyst concentration was observed. In contrast, the reference complex [Ru(bda)pic<sub>2</sub>] exhibits a quadratic dependence (Fig. S41, ESI<sup>†</sup>), as it has already been shown in previously described experiments using CAN in large excess. For this mononuclear catalyst, the O-O bond formation is known to proceed via the coupling of two ruthenium oxyl radicals in the ratedetermining step.<sup>78</sup> Since this process does not involve any further oxidation, the reaction rate of [Ru(bda)pic<sub>2</sub>] does not depend on the oxidant concentration as it has been proven by varying the amount of CAN (Fig. S46, ESI<sup>+</sup>). All macrocycles, however, exhibit a linear dependence of the reaction rate on the CAN concentration. Consequently, an oxidation step has to be rate-determining for those metallosupramolecular catalysts, as it has previously been investigated in great detail for MC3.69

Based on this information, redox titration experiments using the one-electron oxidant CAN have been performed and the absorption spectral changes were monitored by UV/vis spectroscopy (Fig. S51-S55, ESI<sup>†</sup>). Upon the successive addition of oxidant in portions of one equivalent per macrocycle, a stepwise oxidation of all ruthenium centers from Ru<sup>II</sup> to Ru<sup>III</sup> occurs. After addition of three equivalents CAN, the oxidation processes are completed and the respective low-energy transitions at approximately 670 nm reach their maxima. Subsequent addition of another three equivalents CAN leads to spectra that are characteristic for the Ru<sup>IV</sup> state without Ru<sup>III</sup> absorptions anymore. Any further addition of oxidant does not result in significant spectral changes, indicating that for all macrocycles the resting state is a Ru<sup>IV</sup> species, with the Ru<sup>IV</sup>/Ru<sup>V</sup> oxidation being ratedetermining. Altogether, we have proven that MC1-MC4 catalyze water oxidation following the WNA mechanism in which the O-O-bond formation proceeds via the nucleophilic attack of water at a Ru<sup>V</sup>=O species.

To verify that the metallosupramolecular macrocycles are the actual catalysts, post-catalytic analysis has been performed on reaction mixtures using MALDI-ToF mass spectrometry (Fig. S56-S59, ESI<sup>†</sup>). Therefore, 128 equivalents of CAN (corresponding to 32 catalytic cycles) were added to the respective catalyst solutions in CH<sub>3</sub>CN/H<sub>2</sub>O (pH 1) 4:1 and all samples were reduced with ascorbic acid after the gas evolution had ceased. In all cases the macrocycles are still present and give rise to the most prominent peaks in most of the mass spectra. Furthermore, minor fragmentation can be observed by the loss of one bridging ligand, which is known to be the main degradation pathway.<sup>108</sup> However, it seems to be most likely that fragmentation occurs within the mass spectrometer because only coordinatively unsaturated ruthenium centers could be detected. If the fragmentation would already occur during catalysis, coordination of acetonitrile should take place, which would result in appropriate mass signals. The macrocycle MC4 itself is hardly ionizable, for what reason high laser intensities had to be applied, resulting in a pronounced fragmentation behavior and a noisy baseline (Fig. S59, ESI<sup>+</sup>).

#### H/D kinetic isotope effects

Similar to previously described ruthenium polypyridyl water oxidation catalysts, the rate laws for water oxidation and the oxidative UV/vis titrations revealed that the oxidation from Ru<sup>IV</sup> to Ru<sup>V</sup> is rate-determining for all macrocycles **MC1–MC4**.<sup>89,109,110</sup> Using electrochemistry at different pH values, this step was found to be proton-coupled for all macrocycles under acidic conditions. Chemical reactions in which an element-hydrogen bond breaking is involved in the rate-determining step are characterized by different reaction rates regarding their protonated and deuterated isotopes, respectively. If the ratio of this H/D kinetic isotope effect exceeds the value of two, a direct covalent bond breaking or forming is usually involved.<sup>47,55,109</sup>

Therefore, we performed the catalytic water oxidation experiments in both normal and heavy water to get insights into the rate-determining step and its proton coupling (Fig. S60–S63, ESI†). All catalysts were tested under the same reaction conditions

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**Fig. 10** Kinetic isotope effects (KIEs) of the catalysts **MC1–MC4**. (a–d) Plot of the initial catalytic rates vs. the catalyst concentrations with the corresponding linear regression fits to determine the reaction rates  $k_{H_2O}$  and  $k_{D_2O}$ . (Measured with a Clark electrode in 2.0 mL aqueous pH 1 solutions (H<sub>2</sub>O or D<sub>2</sub>O) with 50% acetonitrile as co-solvent using CAN (0.525 M) as a sacrificial oxidant.)

in a CH<sub>3</sub>CN/H<sub>2</sub>O 1:1 mixture (pH 1, acid:CF<sub>3</sub>SO<sub>3</sub>H) using cerium(IV) ammonium nitrate (CAN) as sacrificial oxidant and a Clark electrode for O2 detection. From the slopes of the oxygen evolution curves, the initial rates of the catalysis have been determined. Plotting these rates against the catalyst concentrations allows the determination of the corresponding TOFs. Similar tendencies are obtained for their activities like in the water oxidation experiments described above, with a clear optimum for MC3 and the lowest activity for MC1. Accordingly, strong differences are also found in the kinetic isotope effects, which were calculated from the different reaction rates using H<sub>2</sub>O and D<sub>2</sub>O as the solvent (Fig. 10 and Table 1). The most active catalyst MC3 exhibits the highest KIE with a value of 2.8, whereas only a very low KIE of 1.2 is obtained for the least efficient catalyst MC1, with MC2 and MC4 being in between. Such different values indicate that the degree of proton coupling is different for each macrocycle in the rate-determining step, and that the overall catalytic rate depends on the proton abstraction during the oxidation from Ru<sup>IV</sup>–OH to Ru<sup>V</sup>=O. It is well established that even small structural changes in relatively simple systems can result in substantial changes of the proton coupling and thus in the KIE, since the proton transfer efficiency strongly depends on the right structural orientation and distance between the donor and acceptor side.111,112



Fig. 11 The three extreme pathways (A–C) for the conversion from a Ru $^{IV}-OH$  to a Ru $^{V}=\!O$  species.

In principle, there are three extreme cases how the Ru<sup>IV</sup>–OH species can be converted into Ru<sup>V</sup> $\equiv$ O intermediates (Fig. 11).<sup>57,58,113,114</sup> Under the applied acidic reaction conditions pathway A should not be of relevance since substrate water deprotonation is less favored. The other two extrema are characterized by an initial oxidation followed by subsequent deprotonation (B) or a simultaneous proton-coupled electron transfer process (C). The relatively small KIEs of **MC1–MC4** 



**Fig. 12** Evolution of the RuO–H bond lengths in the MD simulation after the oxidation from  $Ru^{IV}$  to  $Ru^{V}$  of **MC3**. For several key time steps, snapshots of the three ruthenium centers ( $Ru^{1}$ ,  $Ru^{2}$ ,  $Ru^{3}$ ) are given below. Hydrogen atoms are denoted as bonded with distances <1.4 Å, weakly coordinated with distances >1.4 Å and <2.5 Å, and non-bonded with distances >2.5 Å (green = carbon, grey = hydrogen, red = oxygen, blue = nitrogen, yellow = ruthenium).

suggest that the investigated PCETs are not fully concerted, but somewhere in between the extreme cases B and C.<sup>115,116</sup> Apparently, the proton-coupled oxidation of **MC3** from Ru<sup>IV</sup>–OH to Ru<sup>V</sup>=O is rather concerted with the highest KIE value of 2.8, whereas those of the other macrocycles are likely to proceed more stepwise.

#### Mechanistic investigations by molecular dynamics simulations

To fully understand the different activities of the macrocyclic catalysts, all proton-coupled oxidation processes of **MC3** and the mononuclear reference complex  $[Ru(bda)(pic)_2]$  have been investigated by QM/MM molecular dynamics simulations.<sup>117–119</sup> Therefore, the complexes were integrated into a box of water which is described by molecular mechanics (MM) containing a certain number of explicit water molecules. These water molecules were placed in close proximity to the catalytically active ruthenium centers and were fully described quantum-mechanically (QM).

First, we have calculated the oxidation potential of Ce<sup>IV</sup> and the ionization potentials of the different ruthenium oxidation states to verify that cerium(w) has a sufficient oxidation strength. Next, starting geometries have been optimized for every oxidation state of the catalytic cycle and one electron for  $[Ru(bda)(pic)_2]$  and three electrons for MC3 have been removed from each of those structures. The subsequent proton release from the catalysts to the explicit water molecules has finally been monitored by MD simulations. During the dynamics, changes of the spin multiplicity that might arise by the varying molecular distortion effected by the axial ligands has not been taken into account. The experimentally established PCETs of MC3 are well reproduced by our calculations. After oxidation from [Ru<sup>II</sup>|Ru<sup>II</sup>|Ru<sup>II</sup>] to [Ru<sup>III</sup>|Ru<sup>III</sup>]<sup>3+</sup>, water coordinates to the ruthenium centers without any proton transfer to adjacent water molecules (Fig. S64, ESI<sup>+</sup>). After removal of another three electrons, a shortening of the Ru-OH bond lengths can be observed in the MD simulations

which is accompanied by the release of two protons after 1100 fs and 1600 fs (Fig. S65, ESI<sup>+</sup>). Likewise, the abstraction of only two protons could be observed after removal of further three electrons from a predefined [Ru<sup>IV</sup>-OH|Ru<sup>IV</sup>-OH|Ru<sup>IV</sup>-OH]<sup>3+</sup> species, giving rise to the same odd 3e<sup>-/2H<sup>+</sup></sup> PCET experimentally determined by pH dependent differential pulse voltammetry (Fig. 12). Within this process, two of the RuO-H bonds become elongated after very short time, whereas the third one remains unaffected during the whole simulation, although several neighboring water molecules are present to further transfer the released proton. In the case of the monomeric  $[Ru(bda)(pic)_2]$ , the first oxidation to [Ru<sup>III</sup>]<sup>+</sup> also leads to the coordination of water (Fig. S67, ESI<sup>†</sup>). However, the coordination is much weaker compared to MC3 due to the sterical crowding of the axial 4-picoline ligands which partially block the seventh coordination site in their preferential orientation (vide infra). The subsequent two oxidation events exhibit  $1e^{-}/H^{+}$  PCETs generating  $[Ru^{IV}-OH]^{+}$  and  $[Ru^{V} = O]^{+}$ , respectively (Fig. S68–S69, ESI<sup>+</sup>). After removing three electrons from the default  $[Ru^{V}=O|Ru^{V}=O|Ru^{V}=O]^{3+}$ species of MC3 and one electron from the  $[Ru^V = O]^+$  species of the reference complex, O-O bond formation takes place in both cases by the nucleophilic attack of water, which is accompanied by the release of one proton. Ultimately, a change from singlet to triplet state enables the second proton transfer and liberation of elemental dioxygen (Fig. S66, S70, and S71, ESI<sup>†</sup>).<sup>52,63</sup> Note that the bimolecular coupling pathway is not possible in our simulations for [Ru(bda)(pic)<sub>2</sub>], because only one single catalyst molecule has been included in the calculations. Most interestingly, our simulations reveal that the released protons are cooperatively stabilized by a well-defined hydrogen bonding water network bridging the Ru centers inside the macrocyclic cavity of MC3. This cooperative effect is characteristic for the different catalytic activities of MC1-MC4, because the dimension and the geometry of the macrocycle interior should crucially affect the hydrogen-bonding water network.

Therefore, the critical oxidation from Ru<sup>IV</sup> to Ru<sup>V</sup> was investigated in an analogous way for the macrocyclic catalysts MC1 and MC2. In all three macrocycles, proton abstraction is observed at only two Ru-OH subunits. Unfortunately, in a system with multiple reaction centers and a large number of explicit water molecules, proton transfer cannot simply be traced by considering the solvent in close proximity to the ruthenium centers.<sup>120</sup> Instead, we defined dynamic proton delocalization cavities as a new dimension to measure the capability of specific protons to move between the individual reaction centers during our MD simulations. The number of bonded hydrogen atoms was determined for each oxygen atom in time steps of 5 fs, applying a threshold of 1.25 Å. If the final number adds up to at least three for water molecules and one for carboxylic substituents, a defined volume element has been added to the cavity at the position of the respective oxygen atom to visualize proton movement during the simulation. In Fig. 13, the dynamic proton delocalization cavities of MC1 and MC3 are depicted. The protons that are released at both Ru-OH subunits of MC1 are well separated from the other reaction centers and remain localized at solvent molecules in vicinity to



**Fig. 13** Dynamic proton delocalization cavities of (a) **MC1** and (b) **MC3** obtained by MD simulations in the time interval from 0 to 1715 fs after oxidation from  $Ru^{IV}$  to  $Ru^{V}$ . Structures from the last simulation step were used for illustration. Solvent molecules have been omitted for clarity (green = carbon, grey = hydrogen, red = oxygen, blue = nitrogen, yellow = ruthenium).

the oxygen atom from which they have initially been released. Apparently, two ruthenium binding sites of the small macrocycle are oriented to the exterior which efficiently prevents a cooperative stabilization of the released protons inside the macrocyclic cavity. The third Ru–OH group does not get into contact with solvent water molecules because it is trapped in between the carboxylic groups of the other two Ru(bda) subunits. In contrast, all three catalytic centers of **MC3** are pointing into its cavity and the proton transfer appears to be completely different. The two released protons are attracted by the carboxylic groups from the third Ru(bda) moiety, resulting in a dynamic proton delocalization cavity that is located inside the void of the macrocycle. Thus, the third Ru(bda) subunit

cooperatively facilitates the proton abstraction from the reactive centers by involving its carboxylate substituents, which are known to act as proton acceptors.<sup>121</sup> Recent DFT calculations on the "blue dimer" revealed that proton relays are highly important for the operation of multinuclear WOCs, and that the activation barriers of PCETs are mainly dependent on the structural reorganization of the hydrogen-bonded water network. Therefore, similar to the situation in many enzymes an appropriate preorganization of water molecules as proton relays in MC3 lowers crucial activation barriers and accelerates water oxidation.62-64 In the case of MC2, the dynamic proton delocalization cavity exhibits characteristics of both extreme cases, more closely resembling MC1 than MC3 (Fig. S72, ESI<sup>+</sup>), which is in good agreement with its intermediate catalytic activity. Our MD simulations demonstrate that cooperative effects facilitate proton abstraction in the rate-determining step and explain the enhanced catalytic activity of MC3.

## Conclusion

A series of trinuclear Ru(bda) macrocycles with varying ring sizes has successfully been synthesized using ditopic bridging ligands of different lengths. A distinct size dependence was observed for their catalytic activities in chemical water oxidation, and all our experiments revealed the smallest macrocycle MC1 to be least catalytically active, whereas the medium-sized macrocycle MC3 exhibits the best performance (Table 1). For all supramolecular WOCs, the catalytic rate of water oxidation depends linearly on the catalyst and oxidant concentration. The resting states of the catalysis are Ru<sup>IV</sup>-OH species with the oxidation from Ru<sup>IV</sup> to Ru<sup>V</sup> being rate-determining. The O-O bond formation steps proceed via the WNA mechanism like it has previously been proven for MC3 by <sup>18</sup>O labelling experiments.<sup>69</sup> Most interestingly, the catalytic activities are reflected in the magnitude of the H/D kinetic isotope effects (KIE), with a KIE of 2.8 for MC3 and a negligible KIE of 1.2 for MC1. The KIE values are related to the quality of the hydrogenbonded water network inside the macrocyclic cavities and a high degree of proton coupling in the rate-determining Ru<sup>IV</sup>-OH to Ru<sup>V</sup>=O oxidation is beneficial for the catalytic activity.

Molecular dynamics simulations revealed that the rigid cyclic structures of MC1–MC4 provide better access to the Ru binding sites than the flexible mononuclear complex [Ru(bda)(pic)<sub>2</sub>], facilitating substrate water binding. Theoretical examination of relevant proton-coupled oxidation processes of MC1 and MC3 provided evidence that each Ru(bda) center in MC1 catalyzes water oxidation solitary due to steric constraints that force the Ru(bda) centers to be partially oriented to the exterior. For the larger compound MC3, cooperative effects between the individual ruthenium centers have been substantiated with an extended hydrogen-bonded water network inside the macrocyclic cavity, acting as efficient proton relay between the catalytic subunits. The abstracted protons are therefore stabilized and can be quickly removed from the reactive centers giving rise to more concerted proton-coupled electron transfer processes with a

high experimental KIE value. Interestingly, the intensities of the low-energy absorption bands of the Ru<sup>III</sup> and Ru<sup>IV</sup> states of the macrocyclic WOCs mirror the catalytic activity and the KIE and can thus be used to estimate the catalytic performance. DFT calculations disclosed the nature of these transitions and molecular dynamics simulations revealed that the energetic positions of these bands are highly dependent on the Ru-OH and the RuO-H bond lengths. These bonds are mainly influenced by the degree of hydrogen bonding between the aqua or hydroxide ligands and the water molecules inside the macrocyclic cavity and thus strongly depend on the size of the macrocycle itself. Accordingly, we have shown that the incorporation of catalytically active Ru(bda) fragments into trinuclear metallosupramolecular macrocycles may result in new and beneficial cooperative effects similar as found in many natural catalysts (enzymes, natural oxygen evolving cluster, etc.) that rely on specific networks of water molecules in the vicinity of catalytic sites. By tuning the size of the macrocyclic cavity, the inner hydrogen bonding water network bridging the reactive Ru(bda) centers could be manipulated specifically to increase the catalytic activity. Based on these results we assume that the modification of the macrocyclic interior by endo-functionalization of the bridging ligands is a promising approach to further improve such metallosupramolecular water oxidation catalysts. The application of these metallosupramolecular macrocycles should be particularly advantageous under light-driven conditions where the diffusioncontrolled catalytic activity of catalysts working via the I2M pathway is significantly slowed down. Thus, we currently focus our attention on light-driven catalysis including the design of new photosensitizers that interact favorably with Ru(bda) macrocycles.

## Conflicts of interest

There are no conflicts of interest to declare.

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## References

- 1 N. Armaroli and V. Balzani, Angew. Chem., Int. Ed., 2007, 46, 52-66.
- 2 N. Armaroli and V. Balzani, Chem. Eur. J., 2016, 22, 32-57.
- 3 A. K. Ringsmuth, M. J. Landsberg and B. Hankamer, *Renewable Sustainable Energy Rev.*, 2016, **62**, 134–163.
- 4 M. Beller, G. Centi and L. Sun, *ChemSusChem*, 2017, 10, 6–13.
- 5 P. D. Frischmann, K. Mahata and F. Würthner, *Chem. Soc. Rev.*, 2013, **42**, 1847–1870.
- 6 J. J. Concepcion, R. L. House, J. M. Papanikolas and T. J. Meyer, Proc. Natl. Acad. Sci. U. S. A., 2012, 109, 15560–15564.

- 7 M. Natali and F. Scandola, in *Applied Photochemistry: When Light Meets Molecules*, ed. G. Bergamini and S. Silvi, Springer International Publishing, Cham, Switzerland, 1st edn, 2016, pp. 1–66.
- 8 D. G. Nocera, Acc. Chem. Res., 2012, 45, 767-776.
- 9 S. Berardi, S. Drouet, L. Francàs, C. Gimbert-Suriñach, M. Guttentag, C. Richmond, T. Stoll and A. Llobet, *Chem. Soc. Rev.*, 2014, 43, 7501–7519.
- K. J. Young, L. A. Martini, R. L. Milot, R. C. Snoeberger III, V. S. Batista, C. A. Schmuttenmaer, R. H. Crabtree and G. W. Brudvig, *Coord. Chem. Rev.*, 2012, 256, 2503–2520.
- 11 M. D. Kärkäs, E. V. Johnston, O. Verho and B. Åkermark, Acc. Chem. Res., 2014, 47, 100–111.
- 12 G. Bottari, O. Trukhina, M. Ince and T. Torres, *Coord. Chem. Rev.*, 2012, 256, 2453–2477.
- 13 M. R. Wasielewski, Acc. Chem. Res., 2009, 42, 1910-1921.
- 14 J. L. Inglis, B. J. MacLean, M. T. Pryce and J. G. Vos, *Coord. Chem. Rev.*, 2012, 256, 2571–2600.
- 15 D. Gust, T. A. Moore and A. L. Moore, Acc. Chem. Res., 2009, 42, 1890–1898.
- 16 L. Hammarström, Acc. Chem. Res., 2015, 48, 840-850.
- 17 R. L. House, N. Y. M. Iha, R. L. Coppo, L. Alibabaei, B. D. Sherman, P. Kang, M. K. Brennaman, P. G. Hoertz and T. J. Meyer, *J. Photochem. Photobiol.*, *C*, 2015, 25, 32–45.
- 18 H. Dau, C. Limberg, T. Reier, M. Risch, S. Roggan and P. Strasser, *ChemCatChem*, 2010, 2, 724–761.
- 19 D. G. H. Hetterscheid and J. N. H. Reek, Angew. Chem., Int. Ed., 2012, 51, 9740–9747.
- 20 M. Okamura and S. Masaoka, *Chem. Asian J.*, 2015, **10**, 306–315.
- 21 S. W. Gersten, G. J. Samuels and T. J. Meyer, *J. Am. Chem. Soc.*, 1982, **104**, 4029–4030.
- 22 L. Francàs, R. Bofill, J. García-Antón, L. Escriche, X. Sala and A. Llobet, in *Molecular Water Oxidation Catalysis*, ed. A. Llobet, John Wiley & Sons, Ltd, Chichester, UK, 1st edn, 2014, pp. 29–50.
- 23 M. D. Kärkäs, O. Verho, E. V. Johnston and B. Åkermark, *Chem. Rev.*, 2014, **114**, 11863–12001.
- 24 L. Duan, L. Wang, F. Li, F. Li and L. Sun, Acc. Chem. Res., 2015, 48, 2084–2096.
- 25 A. Singh and L. Spiccia, *Coord. Chem. Rev.*, 2013, 257, 2607–2622.
- 26 J. D. Blakemore, R. H. Crabtree and G. W. Brudvig, *Chem. Rev.*, 2015, **115**, 12974–13005.
- 27 L. Duan, F. Bozoglian, S. Mandal, B. Stewart, T. Privalov,A. Llobet and L. Sun, *Nat. Chem.*, 2012, 4, 418–423.
- 28 H. Dau and I. Zaharieva, Acc. Chem. Res., 2009, 42, 1861-1870.
- 29 J. Barber, Biochemistry, 2016, 55, 5901-5906.
- 30 N. Cox, D. A. Pantazis, F. Neese and W. Lubitz, Acc. Chem. Res., 2013, 46, 1588–1596.
- 31 C. Zhang, C. Chen, H. Dong, J.-R. Shen, H. Dau and J. Zhao, *Science*, 2015, 348, 690–693.
- 32 W. Lubitz, E. J. Reijerse and J. Messinger, *Energy Environ. Sci.*, 2008, 1, 15–31.
- 33 M. Raynal, P. Ballester, A. Vidal-Ferran and P. W. N. M. van Leeuwen, *Chem. Soc. Rev.*, 2014, 43, 1660–1733.

- 34 M. Raynal, P. Ballester, A. Vidal-Ferran and P. W. N. M. van Leeuwen, *Chem. Soc. Rev.*, 2014, 43, 1734–1787.
- 35 P. Dydio and J. N. H. Reek, Chem. Sci., 2014, 5, 2135-2145.
- 36 J. Meeuwissen and J. N. H. Reek, *Nat. Chem.*, 2010, 2, 615–621.
- 37 M. L. Helm, M. P. Stewart, R. M. Bullock, M. R. DuBois and D. L. DuBois, *Science*, 2011, 333, 863–866.
- 38 W.-H. Wang, J. F. Hull, J. T. Muckerman, E. Fujita and Y. Himeda, *Energy Environ. Sci.*, 2012, 5, 7923–7926.
- 39 T. B. Rauchfuss, Acc. Chem. Res., 2015, 48, 2107-2116.
- 40 C. J. Chang, L. L. Chng and D. G. Nocera, J. Am. Chem. Soc., 2003, 125, 1866–1876.
- 41 S. Zarra, D. M. Wood, D. A. Roberts and J. R. Nitschke, *Chem. Soc. Rev.*, 2015, 44, 419–432.
- 42 M. Yoshizawa, M. Tamura and M. Fujita, *Science*, 2006, 312, 251–254.
- 43 S. H. A. M. Leenders, R. Gramage-Doria, B. de Bruin and J. N. H. Reek, *Chem. Soc. Rev.*, 2015, 44, 433–448.
- 44 C. García-Simón, R. Gramage-Doria, S. Raoufmoghaddam, T. Parella, M. Costas, X. Ribas and J. N. H. Reek, *J. Am. Chem. Soc.*, 2015, 137, 2680–2687.
- 45 Z. Dong, Q. Luo and J. Liu, Chem. Soc. Rev., 2012, 41, 7890-7908.
- 46 V. Kunz, D. Schmidt, M. I. S. Röhr, R. Mitrić and F. Würthner, *Adv. Energy Mater.*, 2017, 7, 1602939.
- 47 X. Sala, S. Maji, R. Bofill, J. García-Antón, L. Escriche and A. Llobet, *Acc. Chem. Res.*, 2014, 47, 504–516.
- 48 R. Cao, W. Lai and P. Du, Energy Environ. Sci., 2012, 5, 8134–8157.
- 49 T. Kikuchi and K. Tanaka, *Eur. J. Inorg. Chem.*, 2014, 607–618.
- 50 R.-Z. Liao, M. D. Kärkäs, T. M. Laine, B. Åkermark and P. E. M. Siegbahn, *Catal. Sci. Technol.*, 2016, **6**, 5031–5041.
- 51 S. Maji, L. Vigara, F. Cottone, F. Bozoglian, J. Benet-Buchholz and A. Llobet, *Angew. Chem., Int. Ed.*, 2012, 51, 5967–5970.
- 52 L. Tong, L. Duan, Y. Xu, T. Privalov and L. Sun, Angew. Chem., Int. Ed., 2011, 50, 445–449.
- 53 D. W. Shaffer, Y. Xie, D. J. Szalda and J. J. Concepcion, *Inorg. Chem.*, 2016, 55, 12024–12035.
- 54 D. Scherrer, M. Schilling, S. Luber, T. Fox, B. Spingler, R. Alberto and C. J. Richmond, *Dalton Trans.*, 2016, 45, 19361–19367.
- 55 F. Li, K. Fan, L. Wang, Q. Daniel, L. Duan and L. Sun, *ACS Catal.*, 2015, 5, 3786–3790.
- 56 D. R. Weinberg, C. J. Gagliardi, J. F. Hull, C. F. Murphy, C. A. Kent, B. C. Westlake, A. Paul, D. H. Ess, D. G. McCafferty and T. J. Meyer, *Chem. Rev.*, 2012, **112**, 4016–4093.
- 57 S. Hammes-Schiffer and A. A. Stuchebrukhov, *Chem. Rev.*, 2010, **110**, 6939–6960.
- 58 S. Hammes-Schiffer, J. Am. Chem. Soc., 2015, 137, 8860-8871.
- 59 L. Vigara, M. Z. Ertem, N. Planas, F. Bozoglian, N. Leidel, H. Dau, M. Haumann, L. Gagliardi, C. J. Cramer and A. Llobet, *Chem. Sci.*, 2012, 3, 2576–2586.
- 60 E. M. Duffy, B. M. Marsh and E. Garand, J. Phys. Chem. A, 2015, 119, 6326–6332.

- 61 S. Xu, J. E. T. Smith and J. M. Weber, *J. Phys. Chem. A*, 2016, 120, 7650–7658.
- R. Bianco, P. J. Hay and J. T. Hynes, *J. Phys. Chem. B*, 2013, 117, 15761–15773.
- 63 R. Bianco, P. J. Hay and J. T. Hynes, *J. Phys. Chem. A*, 2011, 115, 8003–8016.
- 64 R. Bianco, P. J. Hay and J. T. Hynes, *Energy Environ. Sci.*, 2012, 5, 7741–7746.
- 65 L. Tong, Y. Wang, L. Duan, Y. Xu, X. Cheng, A. Fischer, M. S. G. Ahlquist and L. Sun, *Inorg. Chem.*, 2012, 51, 3388–3398.
- 66 B. C. Polander and B. A. Barry, *J. Phys. Chem. Lett.*, 2013, 4, 786–791.
- 67 B. C. Polander and B. A. Barry, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 10634–10639.
- 68 A. Sartorel, M. Bonchio, S. Campagna and F. Scandola, *Chem. Soc. Rev.*, 2013, 42, 2262–2280.
- 69 M. Schulze, V. Kunz, P. D. Frischmann and F. Würthner, *Nat. Chem.*, 2016, 8, 576–583.
- 70 V. Kunz, M. Schulze, D. Schmidt and F. Würthner, ACS Energy Lett., 2017, 2, 288–293.
- 71 W.-B. Yu, Q.-Y. He, H.-T. Shi, G. Yuan and X. Wei, *Chem. – Asian J.*, 2015, **10**, 239–246.
- 72 C. J. Richmond and A. Llobet, *Catal. Sci. Technol.*, 2016, 6, 6697–6704.
- 73 W.-B. Yu, Q.-Y. He, H.-T. Shi and X. Wei, New J. Chem., 2016, 40, 2354–2361.
- 74 D. K. Chand, K. Biradha, M. Kawano, S. Sakamoto, K. Yamaguchi and M. Fujita, *Chem. – Asian J.*, 2006, 1, 82–90.
- 75 F. A. Pereira, T. Fallows, M. Frank, A. Chen and G. H. Clever, Z. Anorg. Allg. Chem., 2013, 639, 1598–1605.
- 76 T. R. Cook and P. J. Stang, Chem. Rev., 2015, 115, 7001-7045.
- 77 C.-C. You, R. Dobrawa, C. R. Saha-Möller and F. Würthner, Supramolecular Dye Chemistry, in *Top. Curr. Chem.*, ed.
  F. Würthner, Springer-Verlag, Berlin, Heidelberg, Germany, 2005, vol. 258, pp. 39–82.
- 78 L. Duan, A. Fischer, Y. Xu and L. Sun, J. Am. Chem. Soc., 2009, 131, 10397–10399.
- 79 C. J. Gagliardi, A. K. Vannucci, J. J. Concepcion, Z. Chen and T. J. Meyer, *Energy Environ. Sci.*, 2012, 5, 7704–7717.
- 80 N. Song, J. J. Concepcion, R. A. Binstead, J. A. Rudd, A. K. Vannucci, C. J. Dares, M. K. Coggins and T. J. Meyer, *Proc. Natl. Acad. Sci. U. S. A.*, 2015, **112**, 4935–4940.
- 81 Y. Pushkar, D. Moonshiram, V. Purohit, L. Yan and I. Alperovich, *J. Am. Chem. Soc.*, 2014, 136, 11938–11945.
- 82 D. Moonshiram, Y. Pineda-Galvan, D. Erdman, M. Palenik,
  R. Zong, R. Thummel and Y. Pushkar, *J. Am. Chem. Soc.*,
  2016, 138, 15605–15616.
- 83 D. Moonshiram, J. W. Jurss, J. J. Concepcion, T. Zakharova,
  I. Alperovich, T. J. Meyer and Y. Pushkar, *J. Am. Chem. Soc.*,
  2012, 134, 4625–4636.
- 84 D. Moonshiram, I. Alperovich, J. J. Concepcion, T. J. Meyer and Y. Pushkar, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 3765–3770.
- 85 J. A. Stull, T. A. Stich, J. K. Hurst and R. D. Britt, *Inorg. Chem.*, 2013, **52**, 4578–4586.

- 86 N. Planas, L. Vigara, C. Cady, P. Miró, P. Huang, L. Hammarström, S. Styring, N. Leidel, H. Dau, M. Haumann, L. Gagliardi, C. J. Cramer and A. Llobet, *Inorg. Chem.*, 2011, **50**, 11134–11142.
- 87 D. Erdman, Y. Pineda-Galvan and Y. Pushkar, *Catalysts*, 2017, 7, 39.
- 88 L. Duan, L. Wang, A. K. Inge, A. Fischer, X. Zou and L. Sun, *Inorg. Chem.*, 2013, 52, 7844–7852.
- 89 Z. Chen, A. K. Vannucci, J. J. Concepcion, J. W. Jurss and T. J. Meyer, *Proc. Natl. Acad. Sci. U. S. A.*, 2011, **108**, E1461–E1469.
- 90 L. Wang, L. Duan, Y. Wang, M. S. G. Ahlquist and L. Sun, *Chem. Commun.*, 2014, **50**, 12947–12950.
- 91 J. J. Concepcion, M.-K. Tsai, J. T. Muckerman and T. J. Meyer, J. Am. Chem. Soc., 2010, 132, 1545–1557.
- 92 Q. Daniel, L. Wang, L. Duan, F. Li and L. Sun, *Dalton Trans.*, 2016, 45, 14689–14696.
- 93 D. J. Wasylenko, C. Ganesamoorthy, M. A. Henderson,
  B. D. Koivisto, H. D. Osthoff and C. P. Berlinguette, *J. Am. Chem. Soc.*, 2010, 132, 16094–16106.
- 94 J. J. Concepcion, D. K. Zhong, D. J. Szalda, J. T. Muckerman and E. Fujita, *Chem. Commun.*, 2015, **51**, 4105–4108.
- 95 J. An, L. Duan and L. Sun, *Faraday Discuss.*, 2012, 155, 267–275.
- 96 B. Zhang, F. Li, R. Zhang, C. Ma, L. Chen and L. Sun, *Chem. Commun.*, 2016, **52**, 8619–8622.
- 97 Y. Tsubonouchi, S. Lin, A. R. Parent, G. W. Brudvig and K. Sakai, *Chem. Commun.*, 2016, 52, 8018–8021.
- 98 F. P. Rotzinger, S. Munavalli, P. Comte, J. K. Hurst, M. Grätzel, F. J. Pern and A. J. Frank, *J. Am. Chem. Soc.*, 1987, **109**, 6619–6626.
- 99 M. K. Nazeeruddin, F. P. Rotzinger, P. Comte and M. Grätzel, J. Chem. Soc., Chem. Commun., 1988, 872–874.
- 100 J. A. Gilbert, D. S. Eggleston, W. R. Murphy, D. A. Geselowitz, S. W. Gersten, D. J. Hodgson and T. J. Meyer, *J. Am. Chem. Soc.*, 1985, **107**, 3855–3864.
- 101 J. W. Jurss, J. J. Concepcion, J. M. Butler, K. M. Omberg, L. M. Baraldo, D. G. Thompson, E. L. Lebeau, B. Hornstein, J. R. Schoonover, H. Jude, J. D. Thompson, D. M. Dattelbaum, R. C. Rocha, J. L. Templeton and T. J. Meyer, *Inorg. Chem.*, 2012, **51**, 1345–1358.
- 102 J. P. Zobel, J. J. Nogueira and L. González, J. Phys. Chem. Lett., 2015, 6, 3006–3011.
- 103 M. J. G. Peach, P. Benfield, T. Helgaker and D. J. Tozer, J. Chem. Phys., 2008, 128, 044118.
- 104 Q. Daniel, P. Huang, T. Fan, Y. Wang, L. L. Duan, L. Wang, F. S. Li, Z. Rinkevicius, F. Mamedov, M. S. G. Ahlquist, S. Styring and L. C. Sun, *Coord. Chem. Rev.*, 2017, 346, 206–215.
- 105 A. R. Parent, R. H. Crabtree and G. W. Brudvig, *Chem. Soc. Rev.*, 2013, **42**, 2247–2252.
- 106 R. Staehle, L. Tong, L. Wang, L. Duan, A. Fischer, M. S. G. Ahlquist, L. Sun and S. Rau, *Inorg. Chem.*, 2014, 53, 1307–1319.
- 107 V. Kunz, V. Stepanenko and F. Würthner, *Chem. Commun.*, 2015, **51**, 290–293.
- 108 L. Duan, C. M. Araujo, M. S. G. Ahlquist and L. Sun, Proc. Natl. Acad. Sci. U. S. A., 2012, 109, 15584–15588.

- 109 D. Moonshiram, V. Purohit, J. J. Concepcion, T. J. Meyer and Y. Pushkar, *Materials*, 2013, **6**, 392–409.
- 110 J. J. Concepcion, J. W. Jurss, J. L. Templeton and T. J. Meyer, *J. Am. Chem. Soc.*, 2008, 130, 16462–16463.
- 111 M.-T. Zhang, T. Irebo, O. Johansson and L. Hammarström, *J. Am. Chem. Soc.*, 2011, **133**, 13224–13227.
- 112 N. Iordanova and S. Hammes-Schiffer, J. Am. Chem. Soc., 2002, **124**, 4848–4856.
- 113 D. K. Bediako, B. H. Solis, D. K. Dogutan, M. M. Roubelakis, A. G. Maher, C. H. Lee, M. B. Chambers, S. Hammes-Schiffer and D. G. Nocera, *Proc. Natl. Acad. Sci. U. S. A.*, 2014, 111, 15001–15006.
- 114 J. S. Kretchmer and T. F. Miller, *Inorg. Chem.*, 2016, 55, 1022–1031.

- 115 D. J. Cárdenas, J. M. Cuerva, M. Alías, E. Buñuel and
   A. G. Campaña, *Chem. Eur. J.*, 2011, 17, 8318–8323.
- 116 H. Zhu, M. Sommerhalter, A. K. L. Nguy and J. P. Klinman, *J. Am. Chem. Soc.*, 2015, **137**, 5720–5729.
- 117 D. Balcells, in *Adv. Organomet. Chem.*, ed. J. P. Pedro, Academic Press, 2016, vol. 65, pp. 115–173.
- 118 R. Kang, J. Yao and H. Chen, J. Chem. Theory Comput., 2013, 9, 1872–1879.
- 119 A. Ozkanlar and A. E. Clark, J. Chem. Phys., 2012, 136, 204104.
- 120 A. Monti, J. M. de Ruiter, H. J. M. de Groot and F. Buda, J. Phys. Chem. C, 2016, **120**, 23074–23082.
- 121 T. Privalov, B. Åkermark and L. Sun, *Chem. Eur. J.*, 2011, 17, 8313–8317.