The exchange of the fast substrate water in the S2 state of photosystem II is limited by diffusion of bulk water through channels – implications for the water oxidation mechanism†

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The molecular oxygen we breathe is produced from water-derived oxygen species bound to the Mn$_4$CaO$_5$ cluster in photosystem II (PSII). Present research points to the central oxo-bridge O5 as the ‘slow exchanging substrate water (W$_s$)’, while, in the S2 state, the terminal water ligands W2 and W3 are both discussed as the ‘fast exchanging substrate water (W$_f$)’.

A critical point for the assignment of W$_f$ is whether or not its exchange with bulk water is limited by barriers in the channels leading to the Mn$_4$CaO$_5$ cluster. In this study, we measured the rates of $^2$H$_2$O/$^18$O substrate water exchange in the S2 and S3 states of PSII core complexes from wild-type (WT) Synechocystis sp. PCC 6803, and from two mutants, D1-D61A and D1-E189Q, that are expected to alter water access to the O1 channel, respectively. We found that the exchange rates of W$_f$ and W$_s$ were unaffected by the D61A mutation (E189Q channel), but strongly perturbed by the D61A mutation (Cl1/O4 channel). It is concluded that all channels have restrictions limiting the isotopic equilibration of the inner water pool near the Mn$_4$CaO$_5$ cluster, and that D61 participates in one such barrier. In the D61A mutant this barrier is lowered so that W$_f$ exchange occurs more rapidly. This finding removes the main argument against Ca-bound W3 as fast substrate water in the S$_2$ state, namely the indifference of the rate of W$_f$ exchange towards Ca/Sr substitution.

Introduction

Photosynthesis performed by plants, algae and cyanobacteria is critical for life on Earth as it releases molecular oxygen into the atmosphere and stores solar energy as biomass. Utilizing sunlight, the protein complex photosystem II (PSII) generates the molecular oxygen we breathe is produced from water-derived oxygen species bound to the Mn$_4$CaO$_5$ cluster in photosystem II (PSII). Present research points to the central oxo-bridge O5 as the ‘slow exchanging substrate water (W$_s$)’, while, in the S$_2$ state, the terminal water ligands W2 and W3 are both discussed as the ‘fast exchanging substrate water (W$_f$)’.

A critical point for the assignment of W$_f$ is whether or not its exchange with bulk water is limited by barriers in the channels leading to the Mn$_4$CaO$_5$ cluster. In this study, we measured the rates of $^2$H$_2$O/$^18$O substrate water exchange in the S$_2$ and S$_3$ states of PSII core complexes from wild-type (WT) Synechocystis sp. PCC 6803, and from two mutants, D1-D61A and D1-E189Q, that are expected to alter water access via the CI1/O4 channels and the O1 channel, respectively. We found that the exchange rates of W$_f$ and W$_s$ were unaffected by the E189Q mutation (O1 channel), but strongly perturbed by the D61A mutation (CI1/O4 channel). It is concluded that all channels have restrictions limiting the isotopic equilibration of the inner water pool near the Mn$_4$CaO$_5$ cluster, and that D61 participates in one such barrier. In the D61A mutant this barrier is lowered so that W$_f$ exchange occurs more rapidly. This finding removes the main argument against Ca-bound W3 as fast substrate water in the S$_2$ state, namely the indifference of the rate of W$_f$ exchange towards Ca/Sr substitution.

The water oxidation reaction is catalyzed by a metal–oxygen cluster comprising the metals manganese and calcium in a 4 : 1 stoichiometry as well as five oxo bridges (O1–O5). During the reaction cycle, the Mn$_4$CaO$_5$ cluster is stepwise oxidized by light-induced charge separations in the chlorophyll containing reaction center of PSII. Thereby, it attains four discrete reaction intermediates (S$_0$–S$_4$) and one highly reactive transient (S$_5$). The S$_1$ state is dark-stable, and the S$_2$ → S$_3$ transition involves the association of a new water molecule (W$_{N1}$), yielding a Mn$_4$CaO$_6$ cluster as the last stable intermediate before O$_2$ formation. The next light-induced charge separation triggers the S$_3$ → S$_4$ → S$_5$ transition, which not only involves the O–O bond formation, but also O$_2$ release and the concomitant filling of the open coordination site by one of the terminal water ligands (W3 or W2) and the release of molecular oxygen.

The Mn$_4$CaO$_5$ cluster is frequently described as having a ‘chair’-like structure, with the base formed by a Mn$_3$CaO$_4$ chair.
hetero-cubane and the back by the fourth Mn ion (Mn4) that is connected to the base via the oxygen bridges O5 and O4 (Fig. 1). As there is no bond between O5 and Mn1, the structure is referred to as ‘open cubane’.

Fig. 1 Structure of the Mn4CaO5 cluster with selected ligands and water molecules in the S2 (panels A and B) and S3 (C and D) states of photosystem II (PDB: 6DHF & 6DHO). Note that the cluster has a sixth oxygen bridge labelled X in the S3 state. Panels A & C highlight the position of D61 and panels B & D that of E189 in relation to the Mn4CaO5/6-cluster and the O4 (blue), C11 (green) and O1 (pink) water/proton channels. Potential hydrogen bonds are shown as dashed lines, while the coordination of E189 to Ca and Mn is indicated with solid lines. The position of W20, which is not resolved in the S2- and S3-state structures, is indicated by a dashed circle. E: Cartoon of the D to A mutation (left) and the E to Q mutation (right). Color code: large black sphere – peptide backbone; red - oxygen; blue - nitrogen; purple – manganese; yellow – calcium; green – chloride; grey - methyl group. The molecular representations were generated with VMD.

This is best documented for the S2 state, where the two oxidation states Mn4(III,IV,III,III) (oxidation states given in the Scheme 2) in each S state the cluster can attain at least two different conformations.18,38–41,56

The well-characterized open cube (S2c) structure gives rise to the S218 signal, while for the S2HS state several structures have been proposed: the closed cube S2c,16,41 the open cube water bound S2cAW,42–46 and the protonation isomer S2cAP47,48 (Scheme 2). Among these, the S2c and the S2cAP structures provide the best computational explanation for the g = 4 EPR signal, while the S2cAW state, which has a structure akin to the S2cAW state, is favored on the basis of substrate water exchange experiments, and because it provides a straightforward explanation for the low transition temperature of S2c – 18,38,41,56

Identification of the two substrate water binding sites in the four discrete intermediates of the reaction cycle would provide a solid basis for decoding the mechanism of biological water oxidation. While there are several ways to identify water molecules bound to or near the Mn4CaO5/6-cluster, only the determination of the isotopic composition of the O2 produced a unique experimental signature for the two substrates: their exchange rates with bulk water.18,50,51

Using this approach, it was shown that the two substrates are bound differently in the S1 and S3 states.18,52 The faster exchanging substrate water is referred to as Ws, while the slower one is denoted as Wf. For the S0 and S1 states, only the exchange rates of Ws were determined. However, since no water binding
events are known for the S0 → S1 and S1 → S2 transitions, both substrates must be bound already also in these early S states.46

Connecting the water exchange data with emerging structural and spectroscopic information led to the proposal that Wf is the central μ1-oxo bridge, today known as O5.9 This was subsequently supported by theoretical and spectroscopic12,15,34 as well as further MIMS studies.48

Exchange of O5 has been shown to be a multistep process in which O5 is brought into a terminal position on Mn4 where it is fully protonated. In this process, the Mn4CaO5/6 cluster attains several of the alternative conformations shown in Scheme 2.44,46,55 For example, O5 (Ws) exchanges via the S2^AW, S2^BW and S2^W states, while its exchange in the S3^AW state requires the equilibrium of S3^AW Yzw with S3^AW Yzw or alternatively the transition into the S3^BW and S3^B states. Color code: MnII purple, MnIII green, Ca yellow, O red, H white. The flash indicates a light-induced charge separation in PSII.

By contrast, the assignment of Wf is controversial. FTIR and snapshot crystallographic studies as well as a number of DFT calculations suggest that Wf is bound as W2 to Ca in the S0 state, but then forms a bridge between Ca and Mn upon S1 state formation via insertion pathways A or B (Scheme 1).14–17,21,33

On the other hand, present MIMS experiments favor the terminal water ligand W2 as Wf, because the exchange of Wf is first observed orders of magnitude slower than would be expected for a terminal water ligand on Ca,9,18,57 and secondly independent of Ca/Sr-substitution in both the S2 46 and S3 18,38,39 states. In addition, Wf exchange becomes observable first in the S2 state, and then slows upon S3 and S3yz state formation, making a diffusion limitation that could obscure the Ca/Sr dependence seemingly unlikely. By contrast, these two observations can be well explained with W2 as Wf by the known oxidation of Mn4 during the S1 → S2 transition and the need to involve electron back donation of Yz for Wf exchange in the S3 state.9,16,39 Absence of a diffusion limitation is apparently further supported by molecular dynamics (MD) calculations that predict water access in the 50 ns to 100 μs time range,60,61 i.e. orders of magnitude faster than Wf exchange (50–100 ms).44,46,57

Three channels have been identified that lead to the Mn4CaO5 cluster: the O1 or ‘large’ channel, the O4 or ‘narrow’ channel, and the Cl1 or ‘broad’ channel (Fig. 1). While the O1 and Cl1 channels both split into two branches (A, B),15,17 all three channels have been variously proposed to be involved in either proton, dioxygen and/or water transport during various S state transitions, for review see.17,21,45,62,63 Recent room temperature and cryogenic X-ray crystallography studies favor that water access to the catalytic site occurs via the O1 channel as it shows the largest variation in water positions between studies and S states.15,17,64 By contrast, previous theoretical studies suggested that water is delivered through the O4 channel to the Mn4 site and is inserted during the S2 → S3 transition via the pivot/carousel mechanism (Scheme 1C).45,57 Recent mass spectrometric studies analyzing the oxidative damage to the D1, D2 and CP47 proteins caused by the formation of reactive oxygen species (ROS) at the Mn4CaO5/6 cluster under illumination support both the B branch of the Cl1 channel and the O1 channel as water access pathways.6,8,65,66

To probe if the fast water exchange (Wf) in the S2 state is limited by diffusion through channels or by the chemical exchange process, we study here the effects of the D1-D61A and D1-E189Q mutations on the rates of substrate water exchange with bulk water in the S2 and S3 states.

The D61 residue is located close to Mn4 at the apex between the potential O4 and Cl1 substrate channels (Fig. 1). D61 hydrogen bonds W1 and some further waters in its surroundings. If this aspartate (D) residue is mutated to either asparagine (N) or alanine (A), O2 production decreases by ∼75–80%, and the S1 → S2 and S2 → S3 transitions are decelerated by factors of 2–3.67 Meanwhile, O2 release in the S3 → S0 transition is retarded 20–30 fold.67–69 These functional effects were attributed to poor proton abstraction from the mutants, identifying this residue as an important proton relay.68,70,71 It may be speculated that if W2 were a substrate, its exchange would be greatly affected by the D61A mutation. The S3 state exchange rates were previously measured for the D61N mutant, showing 6-fold and 3-fold slower exchange rates for Wf and Wg, respectively.72

E189 is located at the end of the O1 channel. In the S1 and S2 states, E189 is a ligand of Mn1, and it also weakly ligates Ca. Recently it was shown, by time-resolved X-ray crystallography, that during the S2 → S3 transition E189 detaches from Ca before Ox is inserted, and afterwards hydrogen bonds Ox (Fig. 1B and D).15,17,21 Consequently, this glutamate residue (E189) may be
important for the insertion of Ox during the S$_2 \rightarrow$ S$_1$ transition, the exchange of Ox by bulk water in the S$_1$ state, and O–O bond formation. Only a handful mutations of E189 yield active PSII centers, namely isoleucine (I), lysine (K), leucine (L), glutamine (Q) and arginine (R). E189Q is a conservative mutant, as it is of similar size and retains the ability to act as bidentate ligand (Fig. 1E). While the S$_2$ signal is not perturbed by the mutation, the oxygen evolution activity is decreased by ~30% indicating that some transition in the catalytic cycle does not function optimally. For the S$_1$ state, an up to 2-fold faster substrate water exchange was reported previously.

**Experimental procedures**

**Preparation of photosystem II core complexes**

*Synechocystis* sp. PCC 6803 strains, with a 6xHis-tag fused to the CP47 gene, expressing the psbA2-gene (WT, D1-D61A or D1-E189Q) were propagated in BG11 medium supplemented with glucose in glass carboys and grown as previously described. Thylakoid membranes and core complexes were prepared as described previously. The PSII core complexes were suspended in 1.2 M betaine, 10% (v/v) n-dodecyl β-D-maltoside, and were concentrated to ~1 mg of Chl mL$^{-1}$. The samples were then divided into 100 μL aliquots and flash-frozen in liquid N$_2$. Finally, samples were stored at −80 °C.

**Time-resolved membrane-inlet mass spectrometry**

Substrate–water exchange rates were measured at 10 °C employing an isotope ratio mass spectrometer (Finnigan Delta Plus XP) featuring 7 Faraday cups (m/z 32, 34, 36, 40, 44, 46 & 48) and a 165 μL rapid mixing reaction cell that was connected to the spectrometer through a stainless steel pipe that passed through a Dewar filled with liquid N$_2$. After thawing, the PSII core complexes were washed (total dilution factor: 100–1000) in 50 mM MES-NaOH pH/pD 6.5, 1 M betaine, 15 mM CaCl$_2$, 15 mM MgCl$_2$ using an Amicon Ultra-0.5 centrifugal filter unit and finally concentrated to 0.15–0.2 mg Chl per mL. After a saturating preflash (5 μs FWHM), the sample was dark-adapted for 1 hour at room temperature. Prior to loading in dim green light, 0.3 mM (final concentration) 2,6-dichloro-1,4-benzoquinone was added.

A modified gas-tight syringe (Hamilton CR-700-50) with an air pressure driven, computer triggered piston, previously loaded under N$_2$ atmosphere with ~22 μL 97% H$_2^{18}$O, was employed for rapid (~6 ms) isotope enrichment to a final level of ~12%.

Residual O$_2$ in the H$_2^{18}$O was estimated and removed from the data as described previously. The measurement sequences for all samples and S states are shown in ESI Fig. S2. The substrate exchange rates ($k_{f1}$, $k_{s1}$, $k_{f2}$ and $k_{s2}$) for the fast and slow substrate waters were determined by a simultaneous fit of the m/z 34 and the m/z 36 data (for details see ESI Text 1 and Table S1).
Table 1  Exchange rates of substrate water in the $S_2$ and $S_3$ states of photosystem II core complexes isolated from wild-type (WT), D1-D61A and D1-E189Q mutants of Synechocystis sp. PCC 6803. The rate constants and fractions of PSII centers were obtained from global fits of the $^{16,18}$O$_2$ ($m/z$ 34) and $^{18,18}$O$_2$ ($m/z$ 36) data displayed as lines in Fig. 2 and 3. The data were obtained at 10 °C and pH 6.5. For additional parameters see ESI Table S1

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Results

The substrate water exchange rates of WT-, D61A- and E189Q-PSII core complexes from Synechocystis sp. PCC 6803 were studied in the $S_2$ and $S_3$ states of the oxygen-evolving complex at 10 °C, pH 6.5. For WT-PSII, the canonical biphasic exponential rise with a fast and slow phase was observed for the $^{16,18}$O$_2$ signal from the $m/z$ 34 cup in the $S_2$ and $S_3$ states (symbols in Fig. 2A and 3A). The biphasic rise shows that the two substrate waters are bound di...
substrates [Fig. 3C and D]: 15-fold for Ws and more than 3.5-fold for Wf, of which the rate could no longer be resolved with our present mixing system (Table 1).

However, detailed analysis showed that the exchange of both Wf and Ws were biphase, and that in the smaller fraction, about 15%, the exchange of Wf and Ws occurred with rates that were slower than those of WT-PSII (Table 1). Thus, the m/z 34 data were fit with 4 kinetic phases instead of 2. This showed that in the S2 state of D61A-PSII two stable populations of the Mn4CaO5 cluster with possibly different substrates, exchange pathways or water accessibility must exist.

To probe the effects of H-bonding and of O–H bond breaking/formation on the exchange of substrate water in the S2 state of WT- and D61A-PSII, we performed the same experiments also in D2O (Fig. S3 and Table S2†). In general, the exchange rates of Wf and Ws were slower in D2O. Wf showed a corrected H/D isotope effect of ≈1.3. By contrast, Ws displayed an H/D isotope effect of 1.5 [WT] to 1.9 (D61A, larger fraction) and 2.8 (D61A, smaller fraction). In D61A-PSII, the smaller phase of Wf and Ws exchange increased from 15% (H2O) to 24% (D2O) (Table S2†).

Water exchange in the S2 and S3 states of the D1-E189Q mutant occurred with nearly identical rates as in WT-PSII. Only the exchange of Wf was retarded by ~20% in the S2 state of the E189Q samples (Table 1; Fig. S4†). We note that a ~2-fold acceleration was previously observed in the S1 state exchange rates of E189Q-PSII thylakoid membranes.74

**Discussion**

In this study, we observed that the mutation of D61 to alanine had a strong effect on the exchange of both substrate waters in the S2 and S3 states, while the mutation of E189 to glutamine had essentially no influence on either Wf or Ws exchange. As D61 is close to W2, while E189 is near W3 and Ox, these results appear, at first glance, to favor W2 over W3 as fast exchanging substrate Wt. However, because we previously showed that the substrate water exchange rates in PSII are strongly affected by conformational equilibria of the Mn4CaO5/6 cluster, and because the mutations are also located at the end points of water channels and may thereby affect the diffusion of water to the catalytic site, a more detailed analysis is required.

For example, our recent studies have shown that the exchange rate of Ws in the S2 state depends on the equilibria of bulk water through the channels leading to the Mn4CaO5 cluster with possibly different substrates, exchange pathways or water accessibility must exist.

If diffusion of water through channels determines the exchange kinetics, then the Ca-ligated W2 would remain an option for Wf exchange, because this limitation would explain that Wt exchange is comparatively slow for a Ca-bound water ligand and that its exchange is unaffected by Ca/Sr substitution. In this case, it would be impossible to distinguish W2 or W3 as the fast exchanging substrate in wild-type PSII in the S2 state on the basis of substrate water exchange rates, unless some treatment shifted the equilibrium between S2A and S2B strongly towards S2A, as this would keep W2 bound to an exchange-inert Mn(iv) ion, leading to a very slow exchange of W2.

In the following, we will first analyze if the faster water exchange in D61A-PSII is due to a shift of conformational equilibria, or if the truncation of this amino acid from aspartate to alanine increases water accessibility to the catalytic site. Subsequently, we will elucidate the consequences of this result for (i) understanding the exchange rates in the other S states and (ii) the assignment of Wf. Finally, we will discuss the remaining options for the mechanism of water oxidation.

**Wf exchange in the S2 state**

In the S2 state, Wf exchanges significantly faster than in WT-PSII in the majority of D61A-PSII centers (85%; Table 1). If a shift in conformational equilibria accounts for this observation, the Mn4-bound W2 would be the most likely assignment for Wf, as outlined above. In this case, the D61A mutation would induce a change in the conformational equilibria of the Mn4CaO5 cluster towards the S2B state (or another S2HS state), because this allows W2 to exchange much more readily compared to WT-PSII.46 Therefore, a faster exchange of W2 in D61A-PSII would imply that the activation barrier for reaching the S2B state would be lower and/or the relative stability of the S2B state would be increased in the mutant. However, previous experimental data show that a stabilization of the HS S2B state can be excluded, as only the LS S2 multiline signal was observed in the D61A-PSII samples and its signal intensity was comparable to that of WT-PSII (see ESE-EPR spectra in ref. 75). This is supported by theoretical calculations that find the equilibrium between the S2A and S2B state unchanged or even slightly shifted in favor of the S2A state.72 These calculations also indicate that in D61A-PSII one proton is lost from the W1/W2/Mn4 site of the cluster.71 Such a proton loss would slow the W2 exchange. In conclusion, the direct chemical changes that can be expected to occur would either leave the water exchange the same or likely even slow the exchange of W2, the opposite to what is observed experimentally for Wf exchange. This analysis shows that a shift.
of the conformational equilibrium between $S_2^A$ and $S_2^B$ cannot explain the present data.

On this basis, we conclude that the exchange of $W_f$ by isotopically labelled bulk water must be slowed by a steric constraint in all the channels that supply substrate to the Mn$_4$CaO$_5$ cluster in WT-PSII. The D61A mutation then appears to remove one of these diffusion barriers so that $W_f$ exchange can occur at the experimentally observed faster rate. Indeed, barriers for water transport were described previously for all channels, and D1-D61 was identified as forming a barrier for water access together with D2-K317 and Cl1. We propose that shortening D1-D61 via the D61A mutation creates a void that is filled by one or two water molecules, which promotes faster water diffusion to the Mn$_4$CaO$_5$ cluster. This idea is in line with a recent theoretical study that shows water redistributions and faster movements of water molecules in the D61A mutant.

**Model for $W_f$ exchange via the Cl1 channel in the $S_2$ state**

Our data strongly indicate that D61 forms a steric barrier for water access to the catalytic site that contributes to limiting the rate of $W_f$ exchange in the $S_2$ state. However, comparison of the measured water exchange rates to water transport rates estimated from MD simulations appears to contradict this conclusion: in WT-PSII, the rate for $W_f$ exchange is about 80 s$^{-1}$ (at 283 K), while barriers of 10–14 kcal mol$^{-1}$ calculated for all channels for moving a water molecule from the bulk to the Mn$_4$CaO$_5$ cluster would predict exchange rates up to a 1000-fold faster than our observation (see ESI TEXT 3†). However, the two processes are not directly comparable. MD simulations of water movements always employ a force to achieve concerted or directed water movement along a certain trajectory. This force can be provided for example by inserting extra water molecules near the Mn$_4$CaO$_5$ cluster, or by pulling water molecules through the channels at a constant velocity. By contrast, isotopic equilibration involves random swapping of neighboring water molecules driven by thermal energy. It thus requires many swapping events to reach isotopic equilibrium between an inner water pool and bulk water.

As D61 is located at a branching point of the O4 channel and the Cl1 channel, the faster water access may occur through either or both of these channels. The O4 pathway (channel 2 in ref. 61) has been proposed to facilitate substrate water entry$^{36,77–80}$ because binding sites for the substrate analogues ammonia$^{75,81–83}$ and methanol$^{78,84–86}$ are located in the vicinity of Mn4, O4, and D1-D61. Also, the D1 residue at position 87, which is near the origin of the O4 pathway, is Ala in spinach and Asn in cyanobacteria, a fact that appears to correlate with the finding that methanol has a much larger effect on EPR signals of the Mn$_4$CaO$_5$ cluster of plants than cyanobacteria.$^{77,78}$ However,
other reports find that the O4 channel is rather narrow and possibly unsuitable for water transport and instead favor the Cl1 channel (or O1 channel) as main water access pathway.6,44,65

To test the validity of our conclusion we examined the expected substrate water exchange rates through the shorter (25 Å) arm of the Cl1 channel (‘channel 1’ in ref. 61). This channel is reported to have two barriers: the first is formed by the D1-E65/D1-R334/D2-E312 triad and has a barrier of 11.5 kcal mol\(^{-1}\), while the second is formed by D1-D61, D2-K317 and Cl1 and has a barrier of 7 kcal mol\(^{-1}\) in the inward direction, and about 11 kcal mol\(^{-1}\) in the outward direction (Scheme 3). Using these parameters, we constructed a model that included two significant barriers, while other waters can exchange essentially freely. Eight water molecules, including W3 (but not W1, W2 and W4), formed the inner pool. To further simulate the water channel characteristics observed in crystal structures,44,63,65 four water molecules were placed between the two barriers, and five crystal waters are in rapid exchange with bulk water (Scheme 3; ESI Text 3†). We achieved excellent agreement with our experimental data by assuming that the inner barrier, formed by D1-D61, D2-E317 and Cl1, has an energy of 12.8 kcal mol\(^{-1}\), and the barrier closer to the bulk formed by D1-E65, D1-P66, D1-V67 and D2-E312 has a height of 11.5 kcal mol\(^{-1}\) (Fig. S5 and Table S3†). The inner barrier is slightly higher than determined for the outward direction by MD simulations, but this value is presumably within the accuracy of the MD method. It is also possible that the barrier for swapping two water molecules is actually higher (or the frequency factor lower; see SI Text S3) than for pulling water molecules through a channel,44 as this process requires two water molecules to pass each other in a bottleneck. This simulation thus shows that our proposal of an access limitation of the fast water exchange in the S2 state is realistic.

\(W_w\) exchange in the S0, S1 and S2 states of the majority of D61A-PSII centers

In the S3 state, \(W_w\) exchange is slower than in the S2 state and thus no longer controlled by water access. This implies that \(W_w\) is now more tightly bound, in line with the suggested movement of \(W_w\) into the Ox or O5 positions (Scheme 1). Because in the S3 state all Mn ions are in oxidation state Mn(IV), the rate of the fast water exchange is limited instead by the redox equilibrium between the S3\(^{AW}\)Y\(_2\) and S3\(^{AW}\)Y\(_2^+\) states.44,46 The exchange of \(W_w\) in the S3 state most likely occurs by a reversal of the insertion pathway (Scheme 1).

The exchange of \(W_w\) becomes observable for the first time in the S2 state, which might be taken as indication of a faster exchange of \(W_w\) in the S0 and S1 states. This would be inconsistent with an S state independent water access barrier. However, simulations show that the required dark-times of 10 ms between the subsequent flashes employed for producing O2 (Fig. S2†) are long enough to scramble basically all isotopic information regarding the exchange kinetics of \(W_w\) in S0 and S1 (see44 and ESI Text 2†). Thus, the unresolved \(W_w\) exchange in the S0 and S1 states is consistent with an S state independent water access barrier; that is, with a diffusion limited exchange in the S0, S1 and S2 states, and thus with W3 or W2 as \(W_w\) in these states.

\(W_w\) exchange in the S2 state of the majority of D61A-PSII centers

While improved substrate access provides a satisfying rationale for the unresolved and therefore more than 3-fold faster \(W_w\) exchange in D61A-PSII, it does not explain the 15-fold faster exchange of \(W_w\) in the dominant fraction of D61A-PSII centers. We recently observed a similar acceleration in WT-PSII at pH 8.6 and in Sr-PSII core complexes at pH 8.3.48 In this earlier study, the accelerated exchange correlated well with a stabilization of the S2\(^{HS}\) state, indicating that at normal pH the conversion from the S2\(^{LS}\) configuration into the S2\(^{HS}\) configuration is limiting the rate of \(W_w\) exchange. We assigned the alkaline-induced S2\(^{HS}\) state to the S2\(^{AW}\) state, as this state allows an easy transition into the S2\(^{BW}\) state (Scheme 2) in which O5 exchange can occur rapidly.44,46,55 As discussed above, the situation is different in the D61A mutant because the available data clearly exclude the stabilization of a S2\(^{HS}\) form.44,46,55 However, since water exchange in the S2\(^{BW}\) state is presumably very fast, and the S2\(^{AW}\) to S2\(^{BW}\) transition also has a comparatively low barrier,42,55 a similar acceleration of \(W_w\) exchange can be achieved by lowering the barrier for the rate limiting transformation of S2\(^{A}\) into the S2\(^{AW}\) state.

As shown in Scheme 1, water insertion during the S2 \(\rightarrow\) S3 transition requires the deprotonation of W3. This is the true for the formation of S2\(^{AW}\) from S2\(^{A}\), which likely occurs in a similar fashion to mechanism A in Scheme 1. In the S2 state of WT-PSII, this proton needs to be transported away from the positively charged catalytic site into the bulk phase. In D61A-PSII, W1/W2 have collectively lost one proton,74 and should thus be able to transiently act as a nearby base that accepts the W3 proton during S2\(^{AW}\) and S2\(^{BW}\) formation. We propose that this lowers the energy barrier for S2\(^{AW}\) formation enough to allow the observed 15-fold increase in \(W_w\) exchange rate. That the breakage of an OH bond is rate determining for O5 exchange in the S2 state is supported by the H/D isotope effect of 1.9 \(\pm\) 0.2 determined for \(W_w\) exchange in the mutant (Fig. S3; Table S2†).

\(S_w\) state water exchange in the minority of D61A-PSII centers

We found that in about 15% of the D61A centers the exchange rates for \(W_w\) and \(W_s\) were similar to each other and to \(W_w\) exchange in WT-PSII (Table 1). This means that \(W_w\) exchange in this minority fraction was 10-fold slower than \(W_w\) exchange in the majority fraction, 60-fold slower than \(W_w\) exchange in WT-PSII, and more than 200-fold slower than \(W_w\) exchange in the majority fraction. By contrast, \(W_w\) exchange was slowed only 2–3 fold compared to WT-PSII, but nearly 40-fold relative to the majority fraction.

We see two options to explain the slow and comparatively similar rates of exchange of \(W_w\) and \(W_s\) in this fraction of the D61A-PSII. Firsty (Option 1), in these centers the D61A mutation induces a secondary structural change that restricts the water access at a different point of the channel even more than in WT-PSII. For example, if the Cl1 channel would be the
dominant substrate entry pathway, such a secondary structural change might occur at the D1-E65/D1-R334/D2-E312 triad, which was suggested previously to be another bottleneck for water transport through the C11 channel.\textsuperscript{48} As this triad provides a rather narrow path for water, a small change in protein conformation or dynamics may be enough to further restrict water passage. As the D1-D61A mutation is only 4 amino acids away from D1-E65, such an allosteric effect cannot be excluded. Secondly (Option 2), both W3 and W2 serve as W\textsubscript{f}, but in different populations of D61A PSII centers, with one serving as W\textsubscript{f} in the majority fraction and the other serving as W\textsubscript{f} in the minority fraction. This idea is motivated by the similar rates of exchange found for W\textsubscript{f} and W\textsubscript{c} in the minority fraction of D61A-PSII, which suggest that their exchange may be limited by the same critical steps. This would be the case for W2 and O5, as substrate exchange \textit{via} the S\textsubscript{2}⁰, S\textsubscript{2}\textsubscript{AW} and S\textsubscript{1}BW route places both at terminal positions of Mn4(III) in the S\textsubscript{2}BW state. This option would indicate a substantially increased barrier for the S\textsubscript{2}⁰ to S\textsubscript{1}⁰ conversion in the D61A-PSII (from 6–10 kcal mol\textsuperscript{–1} in WT\textsuperscript{41} to >16 kcal mol\textsuperscript{–1}).

\section*{W\textsubscript{e} exchange in the S\textsubscript{3} state}

In contrast to the S\textsubscript{2} state, no heterogeneity is observed in the W\textsubscript{e} exchange in the S\textsubscript{3} state. Thus, if it is correct that W\textsubscript{f} is different for the two fractions in the S\textsubscript{2} state (Option 2, above), then rearrangements of the cluster must happen during the transition from S\textsubscript{2} → S\textsubscript{3} that bring the substrates into the same binding sites in the S\textsubscript{3} state. This would indeed be possible, if in one fraction of PSII centers W3 and O5 are the substrates in the S\textsubscript{3} state and W3 is inserted into the Ox position in the S\textsubscript{3} → S\textsubscript{3} transition (Scheme 1A), while in the other fraction W2 and O5 are the substrates that reach the same two binding sites \textit{via} a pivot insertion (Scheme 1C).

Exchange of W\textsubscript{e} (O5) in the S\textsubscript{3} state thus occurs most likely \textit{via} the S\textsubscript{2}\textsubscript{BW}Y\textsubscript{Z} state, which further transitions into the S\textsubscript{1}BWY\textsubscript{Z} state where O5 is bound in a terminal position at Mn4 and can be replaced \textit{via} the S\textsubscript{1}BWY\textsubscript{Z} intermediate (Scheme 2).\textsuperscript{14,46,55} The much slower exchange of W\textsubscript{e} in the S\textsubscript{3} state of D61A-PSII as compared to WT-PSII indicates that in the D61A mutant the much slower exchange of W\textsubscript{s} in the S\textsubscript{3} state of D61A-PSII as compared to WT-PSII indicates that in the D61A mutant the substrate exchange \textit{via} the S\textsubscript{2}⁰, S\textsubscript{2}\textsubscript{AW} and S\textsubscript{1}BW route places both at terminal positions of Mn4(III) in the S\textsubscript{2}BW state. This option would indicate a substantially increased barrier for the S\textsubscript{2}⁰ to S\textsubscript{1}⁰ conversion in the D61A-PSII (from 6–10 kcal mol\textsuperscript{–1} in WT\textsuperscript{41} to >16 kcal mol\textsuperscript{–1}).

\section*{Absence of effects of E189Q mutation}

The analyses of recent XFEL studies favor water delivery \textit{via} the O1 channel, and some of the authors suggest a gating of water access by the observed movement of E189 during the S\textsubscript{2} → S\textsubscript{3} transition.\textsuperscript{14,15,17,21} As the W\textsubscript{f} exchange rates in the S\textsubscript{2} and S\textsubscript{3} states are nearly identical between WT-PSII and E189Q-PSII, the present data do not support a role of E189 as gate keeper for substrate access to the Mn\textsubscript{4}CaO\textsubscript{5} cluster, at least not during water exchange in the studied semi-stable S states. This is in line with the MD calculations by Vassiliev, which suggest that D1-E329, D1-D342, CP43-V410 and CP43-T412 form the main bottleneck for water transport through the O1 channel system,\textsuperscript{39} and thus any subtle effects of E189 would be masked.

\section*{Relation of water exchange and water binding}

While our data show that in D61A-PSII water exchange occurs through the O4 and/or one or both branches of the C11 channel, they do not reveal which of the channels, including the O1 channel, has the lowest barrier in WT-PSII. Furthermore, it is important to note that water binding during the S\textsubscript{2} → S\textsubscript{3} transition is a fundamentally different and much faster (100–400 \textmu s)\textsuperscript{15,17} process than water exchange in the S\textsubscript{s} and S\textsubscript{1} states (10–500 ms). During water binding, a nearby water attaches to an open binding site of the cluster and thereby initiates a bucket brigade of refilling vacant sites, while reaching the isotopic equilibrium with bulk water requires full equilibration of all exchangeable water molecules in the channels and around the catalytic site. Thus, our present data do not identify through which of the three water channels the substrate water is delivered in WT-PSII.

Is the control of water access functionally important?

It has previously been hypothesized that regulation of substrate accessibility is crucial to minimize side reactions that would lead to the production of reactive oxygen species at the Mn\textsubscript{4}CaO\textsubscript{5} cluster.\textsuperscript{86,87} This hypothesis assumed that in intact PSII complexes only substrate water can interact in a specific way with the Mn\textsubscript{4}CaO\textsubscript{5} cluster. Recent crystal structures have shown that the Mn\textsubscript{4}CaO\textsubscript{5} cluster is surrounded by several additional water molecules. Nevertheless, the present data and the previous calculations by Vassiliev\textsuperscript{44} show that water access is not completely free. This somewhat regulated access likely evolved to stabilize the Mn\textsubscript{4}CaO\textsubscript{5} cluster, and to allow for the formation of a highly specific hydrogen bonding network, which is crucial for removing protons from substrate water during the water oxidation reactions. By contrast, the access of water is fast when compared to the maximal turnover frequency of PSII, which is limited by the acceptor side reactions of PSII to about 50 Oe s\textsuperscript{–1} (20 ms),\textsuperscript{86} while water is delivered through the channels with a time constant in the order of 100 \textmu s.\textsuperscript{44} Interestingly, the time constant for water delivery is in the same order as that for water binding during the S\textsubscript{2} → S\textsubscript{3} transition. It might thus be speculated that the restriction of water access is a compromise between excluding other redox active molecules and ions from the Mn\textsubscript{4}CaO\textsubscript{5} cluster, while allowing fast enough water access to promote efficient S state turnover. This idea is supported by the finding that partial dehydration of PSII increases the misses specifically of the S state transitions that involve binding of water molecules.\textsuperscript{88} Similarly, addition of the water analog methanol increases the miss parameter and allows the observation of a water deprived S\textsubscript{3} state.\textsuperscript{92,93}

\section*{Implications for the mechanism of water oxidation}

The significance of the present results is that they remove the strongest arguments against the assignment of W\textsubscript{f} to W3 in the S\textsubscript{3} state, namely (i) the indifference of the W\textsubscript{f} exchange rate to
Ca/Sr substitution and (ii) the significant mismatch with reported exchange rates for water ligated to Ca.\textsuperscript{46,94}

The present data are fully consistent with O5 as slowly exchanging substrate water $W_s$, and $W_2$ or $W_3$ as fast exchanging substrate water $W_f$. A further distinction between $W_2$ and $W_3$ as $W_f$ is not possible on the basis of substrate water exchange data alone because the rate limitation provided by the barriers in the channels obscures small perturbations such as Ca/Sr substitution that could otherwise be used to distinguish the binding sites. However, other recent experimental data favor $W_3$ over $W_2$ as substrate water. FTIR experiments by the groups of Noguchi and Debus have provided evidence for the involvement of $W_3$ in water binding during the $S_2$/$S_3$ transition.\textsuperscript{11,16,95} Similarly, femtosecond X-ray crystallography measurements have revealed that the largest changes in water positions during this transition occur in the O1 channel that leads to the Ca site and found no evidence for the predicted closed cube $S_2$\textsuperscript{81}-like intermediate that would be required if $W_2$ were the fast substrate (Scheme 1).\textsuperscript{15,17} By contrast, the support for $W_2$ is mostly based on substrate analogs like methanol or ammonia,\textsuperscript{75,77–83} which we regard as more indirect. On this basis, we propose that O5 and $W_3$ are the two substrate water molecules under normal circumstances, but that $W_2$ may serve as the fast exchanging substrate under some circumstances, such in a minority of D61A PSII centers. The resulting experimentally supported ‘molecular S state cycle’ is summarized in Scheme 4.

Scheme 4 Proposed molecular Kok cycle illustrating the binding of the two substrate waters $W_f$ and $W_s$ in the various $S$ states. The center shows the traditional $S$ state scheme indicating water binding as well as proton and dioxygen release, while the outer circle depicts schematically the corresponding dominant structures of the Mn$_4$CaO$_{6-5}$ complex based on X-ray crystallography\textsuperscript{6,15,17,21} as well as calculated structural models of key intermediates during O–O bond formation.\textsuperscript{12} In dark-adapted PSII, the reaction cycle starts with the $S_1$ state that has two Mn$^{III}$ and two Mn$^{IV}$ ions and in which all bridges are deprotonated.\textsuperscript{10} During the $S_1 \rightarrow S_2$ transition, Mn4 is oxidized. While the $S_2^A$ state is in equilibrium with other conformations (see Scheme 2), it is proposed that $W_3$ is inserted directly into the Ox binding site between Ca and Mn1, concomitant with Mn1 oxidation and the binding of a new water, $W_{N1}$, to the $W_3$ site (dashed grey arrows; for details, see Scheme 1A).\textsuperscript{17} In $S_3$, the dominant state is $S_3^{AW}$. Upon further oxidation, the $S_3^{AWY_2}$ state is formed, which under proton release converts into the $S_4^{AWY_2}$ state (lag phase; not shown).\textsuperscript{103} This may be coupled to unknown rearrangements within the H-bonding network of the OEC. Only thereafter, the Mn$_4$CaO$_6$ cluster can be oxidized to $S_4$. Instead of Mn oxidation, $S_4$ state formation involves the oxidation of the fast substrate water, indicated by a black dot on $W_3$ (in the Ox position).\textsuperscript{12} By rearranging the electrons of the chemical bonds (black half-arrows), the $S_4$ state rapidly converts into the $S_4^+$ state, which contains a complexed peroxide. The further conversion of $S_4^+$ into $S_3 + O_2$ requires the binding of one water and the release of a proton. We suggest that a pre-bound water ligand ($W_2$ or $W_3$) fills the empty O5 binding site,\textsuperscript{6} and that this ligand is concomitantly replaced by a new water ($W_{N2}$; dashed grey arrows). In the $S_5$ state, the O5 bridge is protonated, in line with the faster exchange of $W_s$ and spectroscopic data.\textsuperscript{6,104,105} Oxygen atoms are labeled red, and the two substrate ‘waters’ are shown in blue. Hydrogen atoms are shown as small white spheres (protonation states based on $S_2$ state assignment in ref. 106).
Presently no experimental data are available that allow to determine the actual O–O bond formation mechanism during the $S_3 \rightarrow S_4 \rightarrow S_0$ transition, but the present data are fully consistent with the best worked out theoretical mechanism for O–O bond formation, which involves oxo-oxyl radical coupling between oxygens in the O5 and Ox binding sites via a low-energy path paved by favorable spin pairing.12,51

However, the recently revived idea that the formation of a peroxidic intermediate (<5–10%) in the $S_3$ state is required for further oxidation to the $S_4$ state cannot be excluded on the basis of our present data (Fig. S1E and F†),1,2,17,27,28 because the same substrates and main state conformations are involved, and such a small equilibrium population of a peroxidic intermediate would easily escape detection by, for example, femtosecond X-ray crystallography. Nevertheless, a very recent theoretical study considers a peroxidic intermediate in the $S_3$ state as unlikely.29 By contrast, our substrate water exchange data are inconsistent with nucleophilic attack mechanisms between W3 and W2,25,97–99 and geminal coupling between W2 and O5 at Mn4 (ref. 30, 100) (for details see ESI Text 4 and Fig. S1).

Conclusions

In this study, we demonstrate that the fast water exchange in the $S_0, S_1, S_2$ states is rate limited by specific diffusion barriers in all the channels connecting bulk water with the Mn$_4$CaO$_5$ cluster in PSII, and that the D619 mutation reduces one of these barriers so that $W_1$ exchange is accelerated. This finding removes previous arguments that appeared to exclude W3 as the fast exchanging substrate water. Combining our present results with recent FTIR and XFEL data supporting the insertion of W3 into the Ox position during the $S_3 \rightarrow S_1$ transition,1,15–17,95,101 now make W3 the prime candidate for $W_1$. As our previous experiments identified O5 as the slow substrate water,9,18,44,46,54 this study clarifies the fate of the substrate waters during the $S_3$ state cycle, and thereby limits the possible mechanisms for O–O bond formation to a few that all involve coupling between O5 and W3, while they are bound in the O5 and Ox positions of the $S_3^{\text{aw}}$ or $S_4^{\text{aw}}$ states (Scheme 4).

Data availability

All relevant data is presented in the paper and ESI.† Raw data is available upon request by email to JM.

Author contributions

CDL, RJD and JM conceived and designed the research; CDL, CJK and PC performed the research; CDL and JM analyzed the data; CDL, RJD and JM wrote the paper with input from all authors.

Conflicts of interest

There are no conflicts to declare.

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