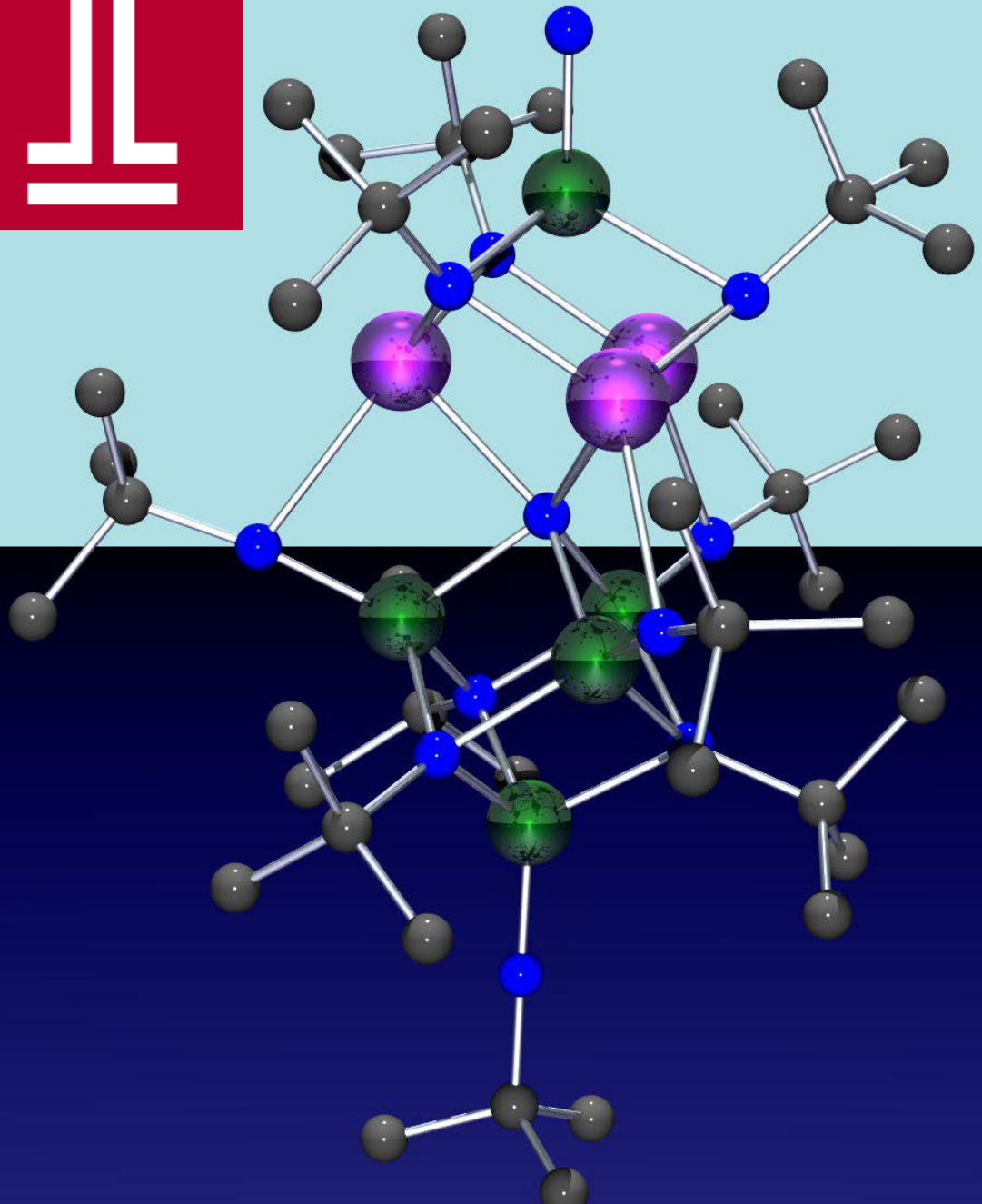
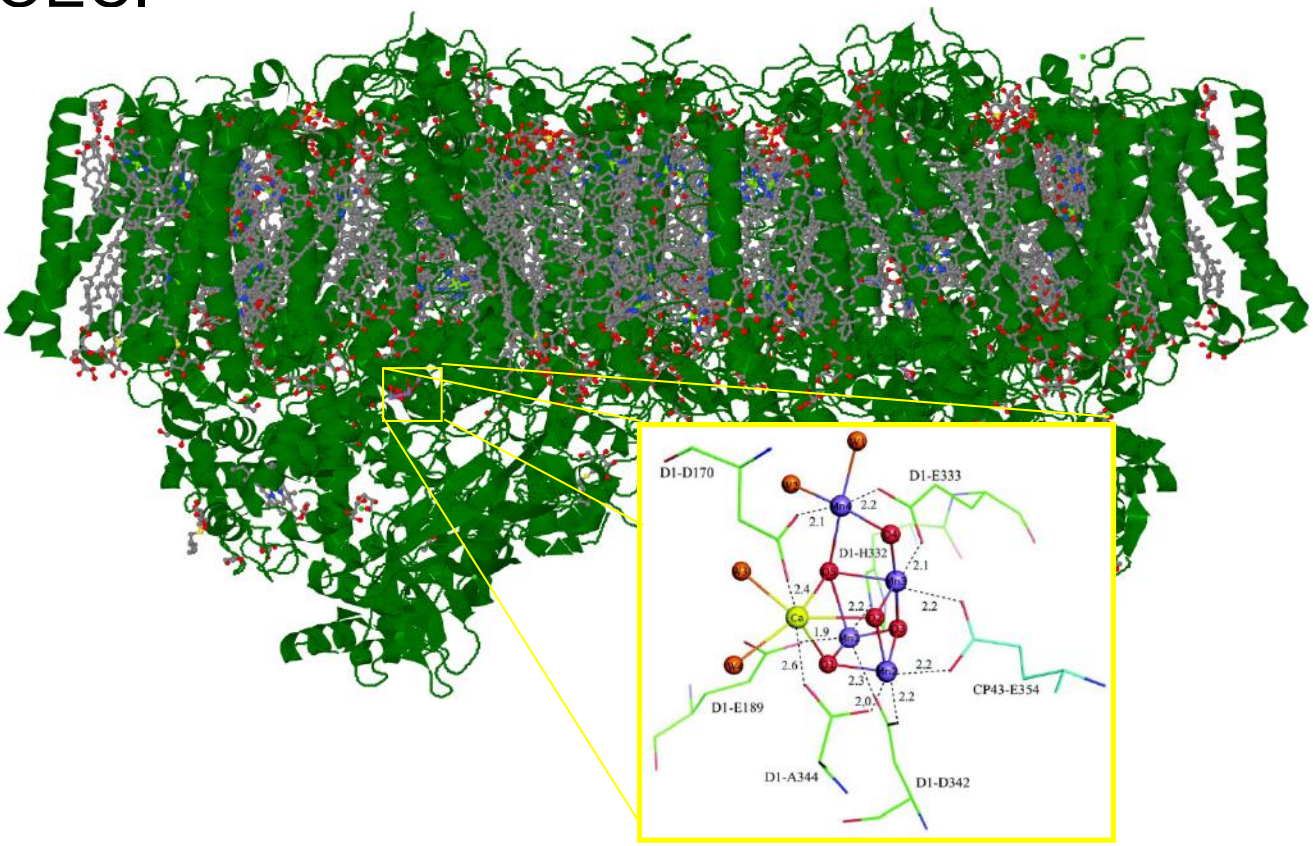


Geometrically flexible synthetic manganese-oxygen and manganese-nitrogen cubane clusters as reactive biomimics of the oxygen evolving complex of photosystem II

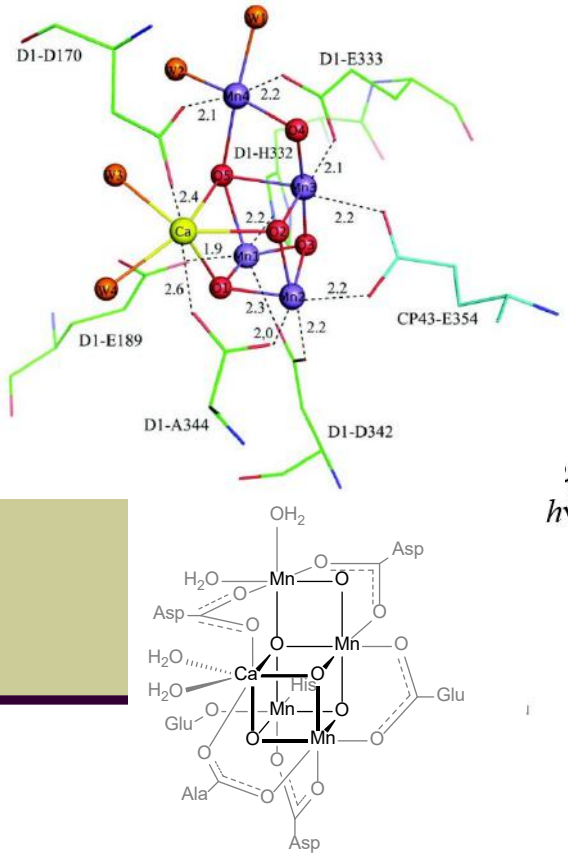
SciMeetings
ACS Spring 2020
Michael J. Zdilla
Temple University

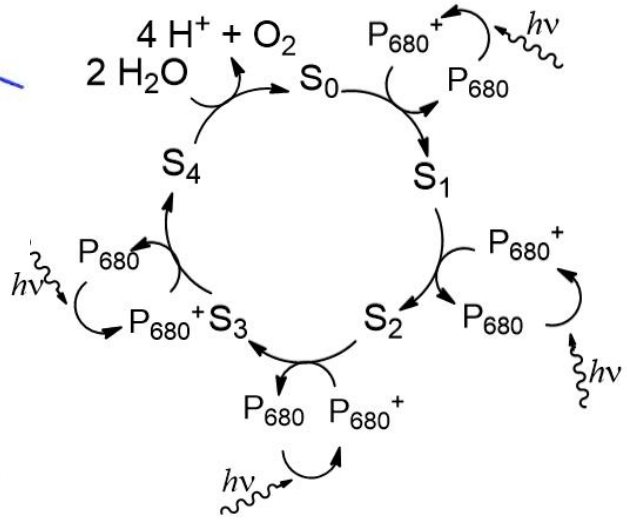
Photosystem II

- Photosystem II: Nature's water oxidation catalyst.
- Active site contains a unique Mn-Ca-O cluster, the OEC.



Photosystem II-photon driven water oxidation



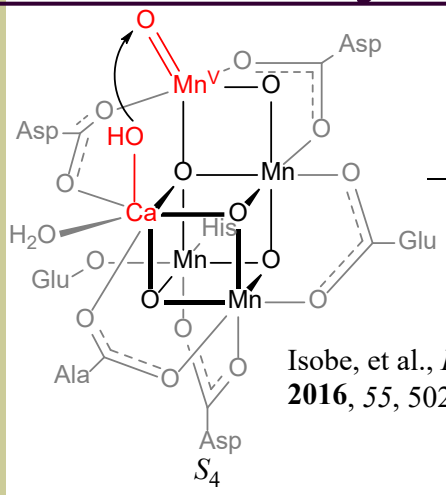


The Kok Cycle

- The OEC operates by a 5-step photooxidation cycle
- Red photons excite oxidation of chlorophyll P_{680}
- P_{680} in turn oxidizes the OEC (S_n)
- S_4 oxidizes water to O_2 to close the cycle.

Umena, Y et al. *Nature* **2011**, *473*, 55.

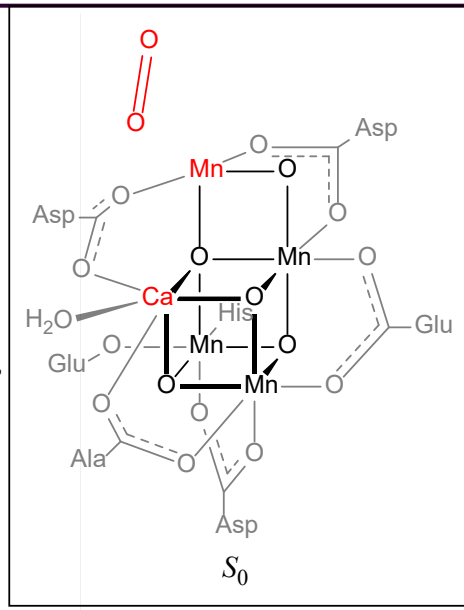
Proposed mechanisms of O-O bond formation from theory are shown below. There is not currently a consensus.



S_4

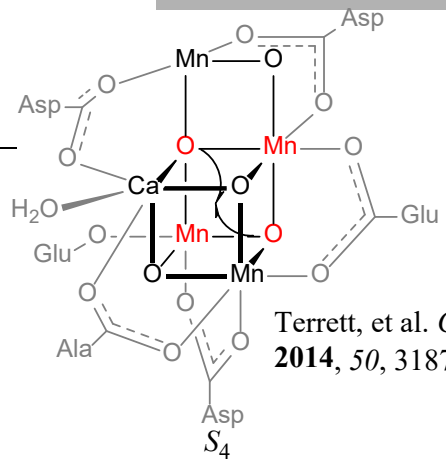
Isobe, et al., *Inorg. Chem.*, **2016**, *55*, 502-511

H_2O



S_0

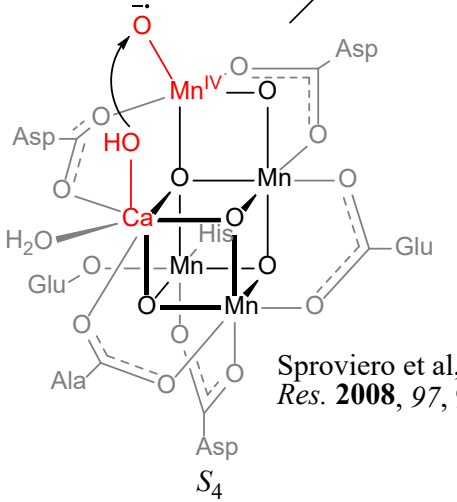
H_2O



S_4

Terrett, et al. *Chem. Commun.* **2014**, *50*, 3187-3190.

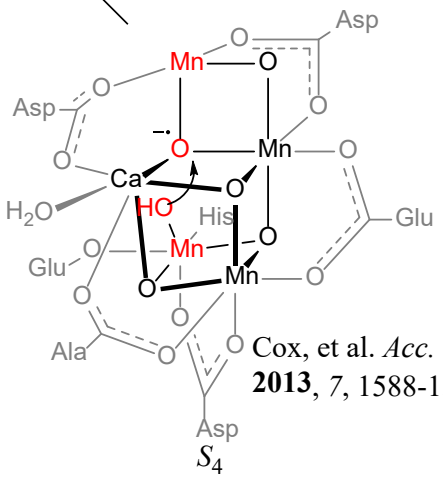
H_2O



S_4

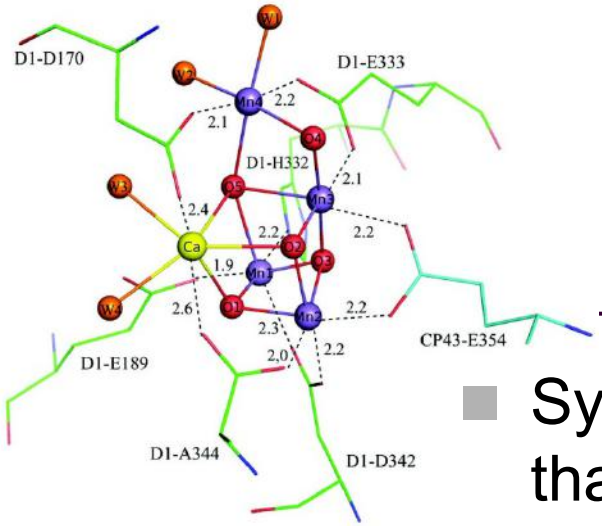
Sproviero et al, *Photosynth. Res.* **2008**, *97*, 91-114

H_2O



S_4

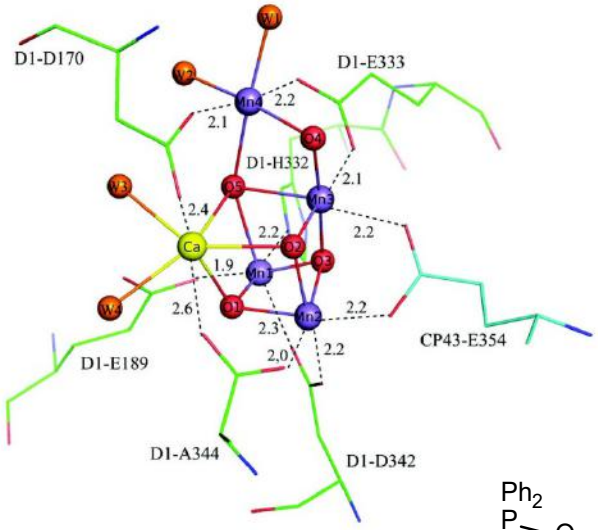
Cox, et al. *Acc. Chem. Res.*, **2013**, *7*, 1588-1596



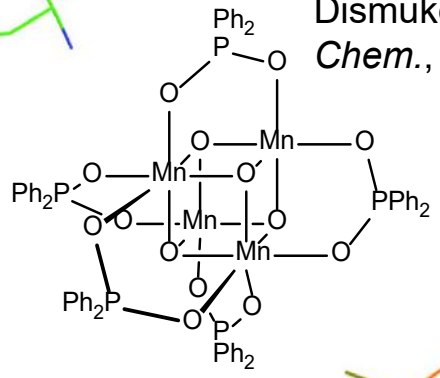
Modeling the OEC

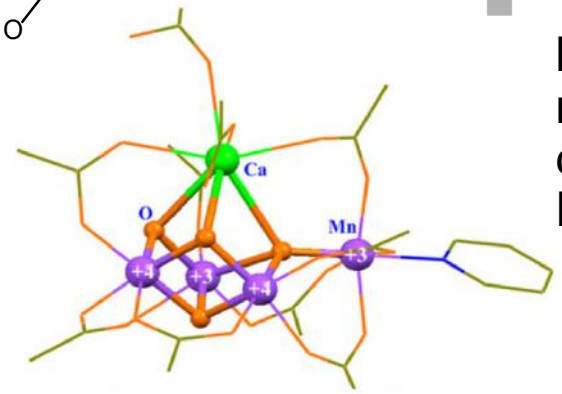
- Synthetic model complexes are one tool that may be used to examine potential reaction mechanisms.
- A model complex can never prove the mechanism of an enzyme, but they may be used to probe the reasonableness of certain mechanistic proposals.
- Many structural models are known, but functional models are rarer.Some examples are shown on the next page. Structural and functional models remain an important goal.

Structural models of the OEC

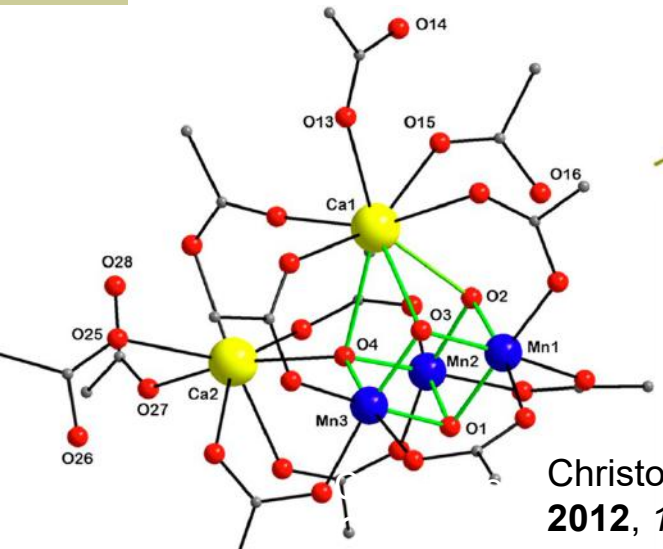


Dismukes et al, *Inorg. Chem.*, **1999**, *38*, 1036



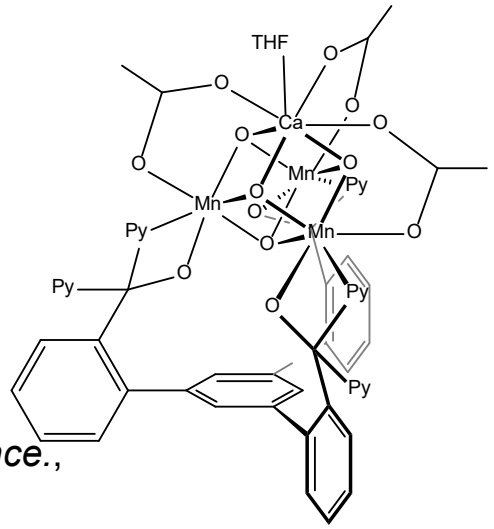


Zhang, et al. *Science*, **2016,** *348*, 690-693

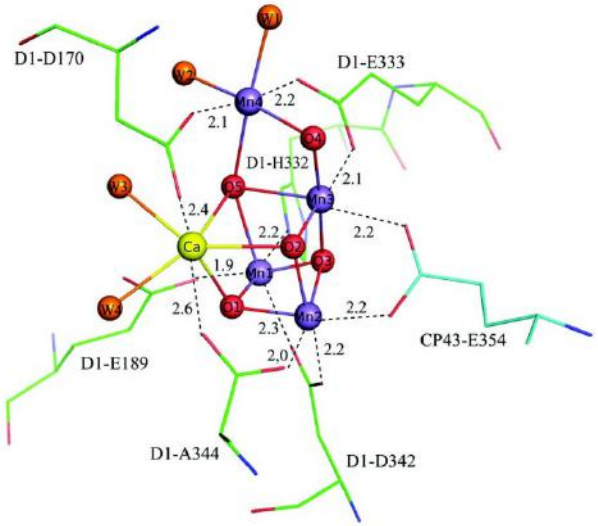


Christou et al,*PNAS*, **2012**, *109*, 2257

- These excellent structural models are useful for comparisons and calibrations to biophysical data, but do not show much biomimetic reactivity.
- This may be due to their being highly constrained by multidentate ligands, and 6-coordinate, leaving no place for H_2O to bind

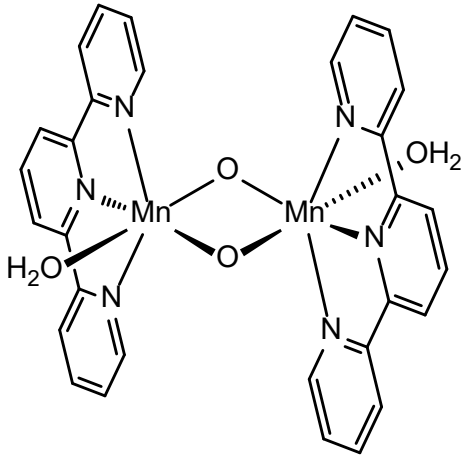


Agapie et al,*Science.*, **2011**, *333*, 733

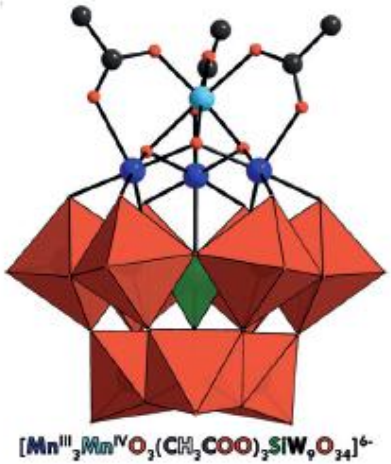


Functional models of the OEC

- Functional models typically use motifs dissimilar from biology, limiting translation of findings to biological system.



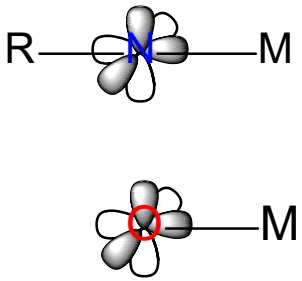
Brudvig et al, *Science.*, **1999**, *283*, 1524



Bonchio et. Al. *Angew. Chem. Int. Ed*. **2014**, *53*, 11182 – 11185

Preparation of unchelated clusters of reduced coordination number

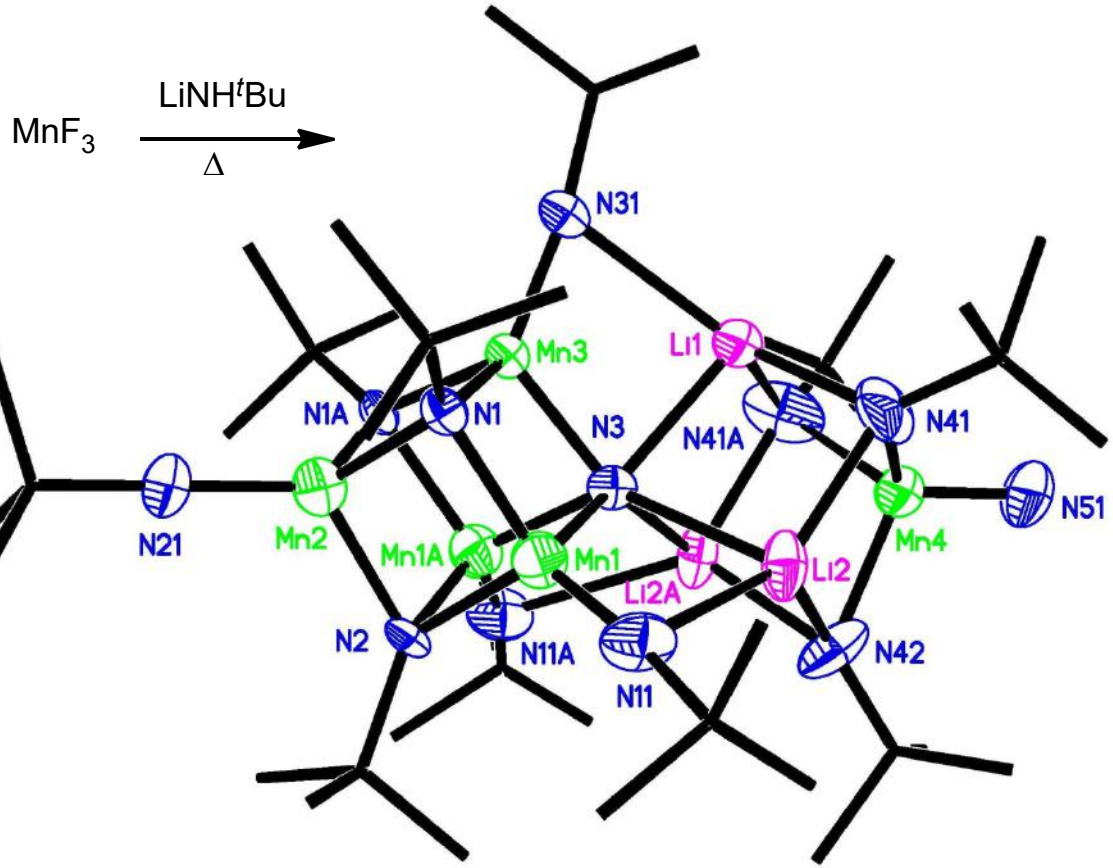
- Our approach: lower-coordinate clusters with minimal chelation.
- Imide as a surrogate of oxide to control cluster geometry
  - Isolobal
  - Charge
  - Heteroatom size
  - Sterically and electronically tunable R-group
- This motifs may show O-based biomimetic chemistry, or show biomimetic chemistry via the oxene-nitrene analogy (below)

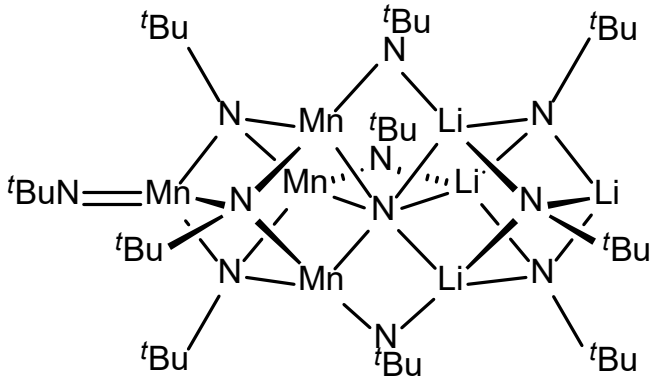


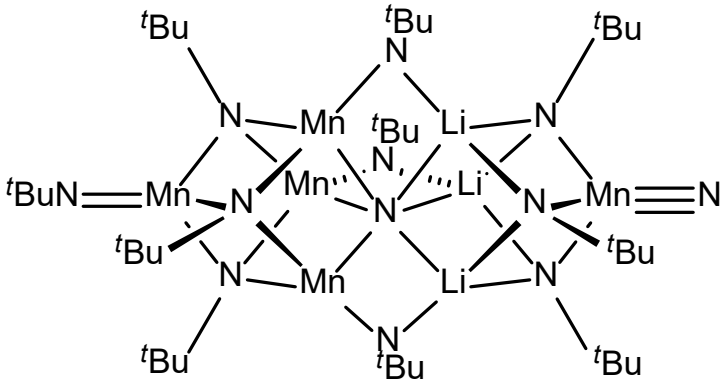
OH_2	OH^-	O^{2-}	HO—OH	O=O
RNH_2	RNH^-	RN^{2-}	RHN—NHR	RN=NR
(water/amine)	(hydroxide/amide)	(oxide/imide)	(peroxide/hydrazine)	(dioxygen/diazene)

Heterocubane with pendant Mn

- Prepared by a simple metathesis reaction, involving somewhat chaotic redox chemistry, giving the two shown products in a 9:1 ratio (top:bottom)







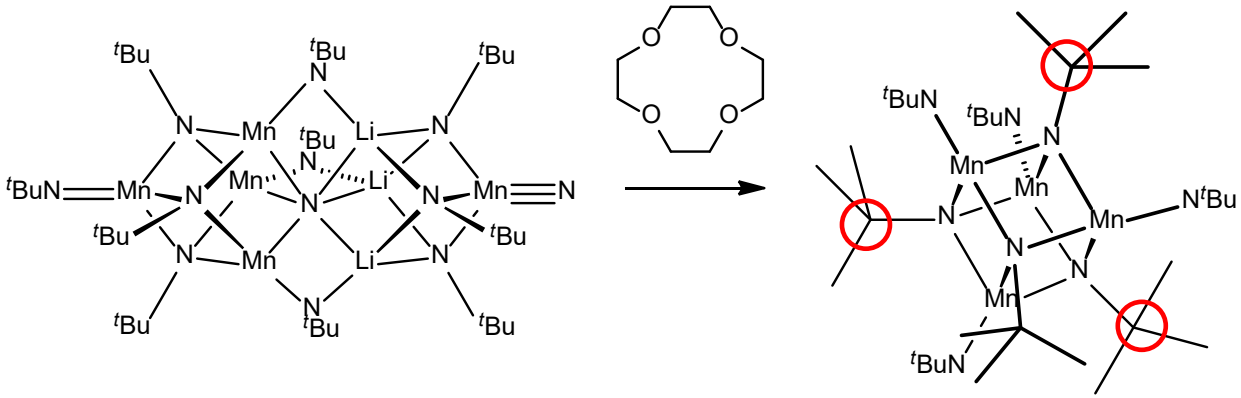
Vaddypally, S.; Kondaveeti, S. K.; Zdilla, M. J. *Inorg. Chem.* **2012**, *51*, 3950.

Removal of Li from dicubane

- To improve relevance to the OEC, we sought to remove the L ion (and replace with Ca). We can remove Li^+ using crown either.
- Crystallographic problem: Non-positive displacement parameters on three carbons. This means the computer "thinks" these are heavy atoms, which is hard to explain.
- More on this later.

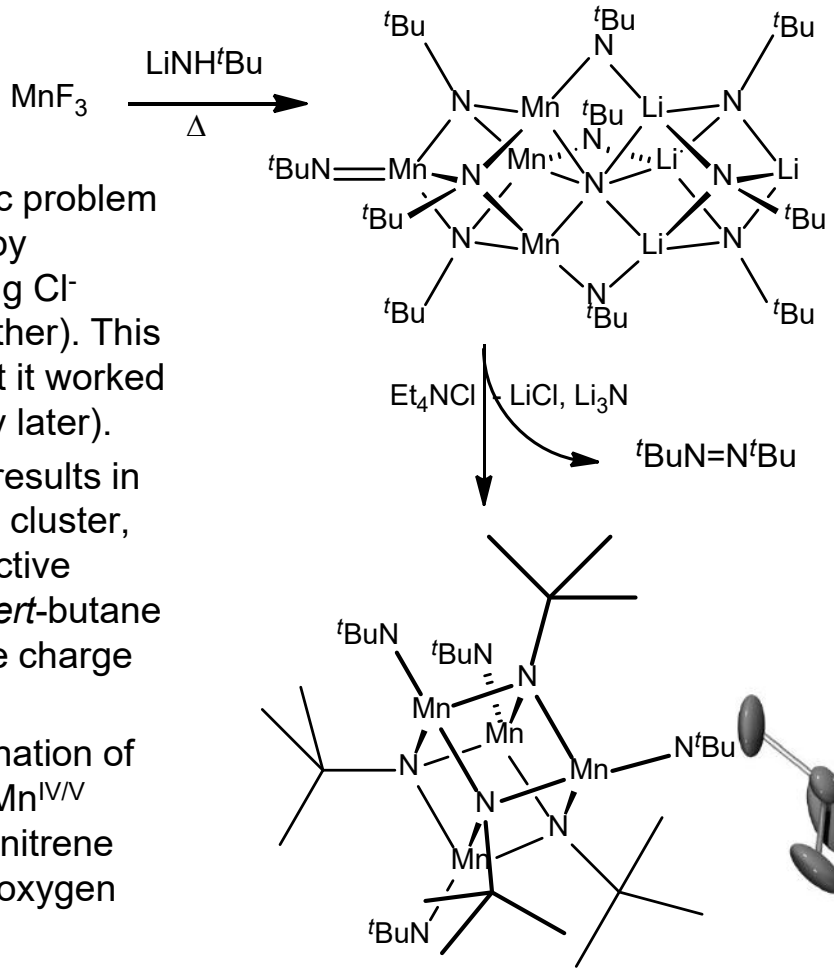
Shiva Vaddypally

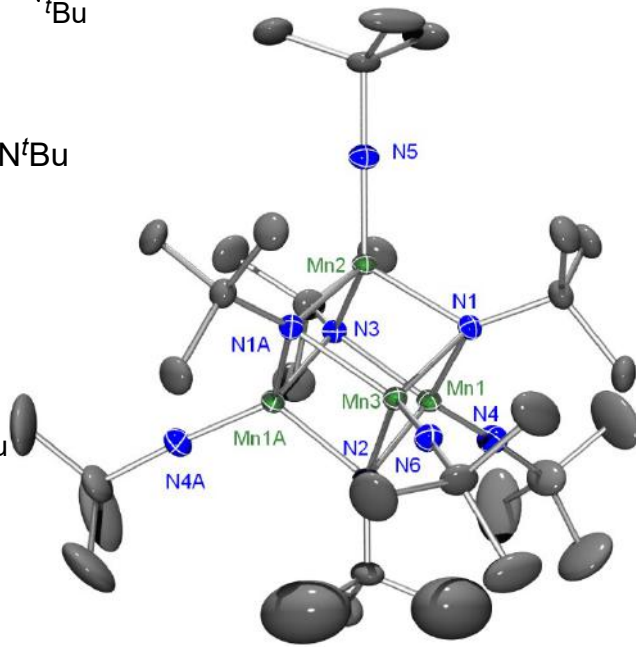
Sandeep (Sunny) Kondaveeti



Mn-Li heterodicubane

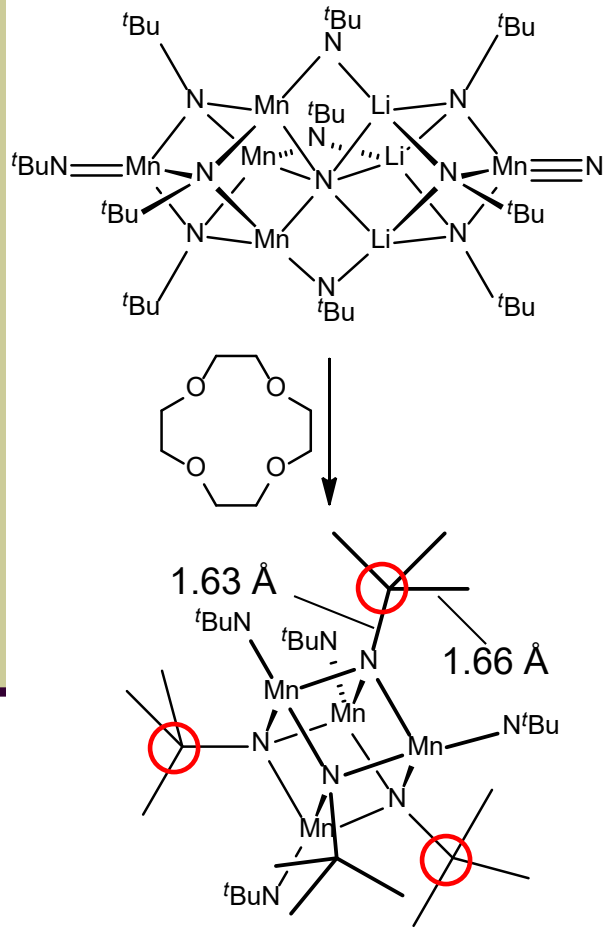
- The crystallographic problem was circumvented by precipitating Li^+using Cl^- (instead of crown ether). This made no sense, but it worked (we will explain why later).
- The removal of Li^+ results in an unstable anionic cluster, which triggers reductive elimination of azo-*tert*-butane to alleviate negative charge buildup on imide.
- The reductive elimination of ^{t}BuN=N^{t}Bu from a $Mn^{IV/V}$ cubane cluster is a nitrene analog of the OEC oxygen evlolution reaction



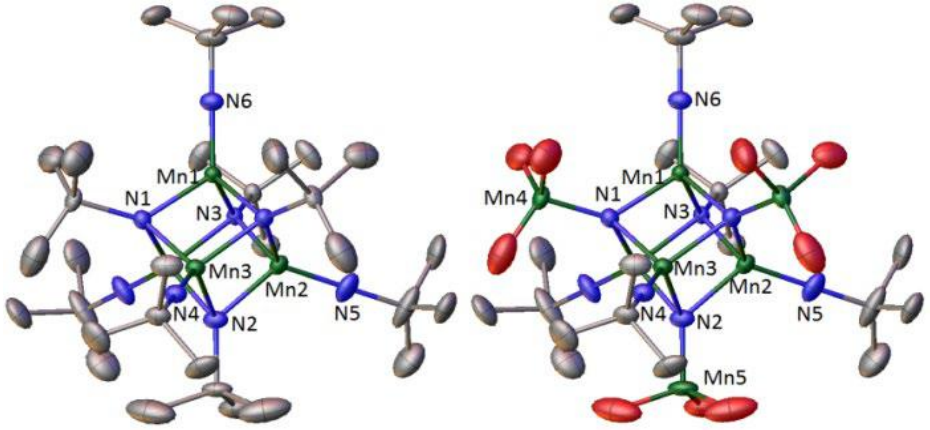


Vaddypally, S., et al. *Chem. Commun.*, **2014**, *50*, 1061.
Vaddypally, S., et al. *Inorg. Chem*. **2017**, *56*, 3733.

Removal of Li from dicubane with crown ether: What happened?



- Considering further the non-positive displacement parameters when crown ether was used
- We also noticed long bond lengths similar to permanganate. This is clearly not just a *tert*-butyl group.
- Structure modeled as a disordered mixture of *tert*-butyl imido ligands and nitridotrioxomanganese(VII) metalloligands gave an excellent crystallographic model.

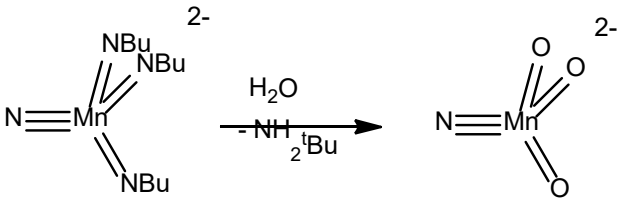


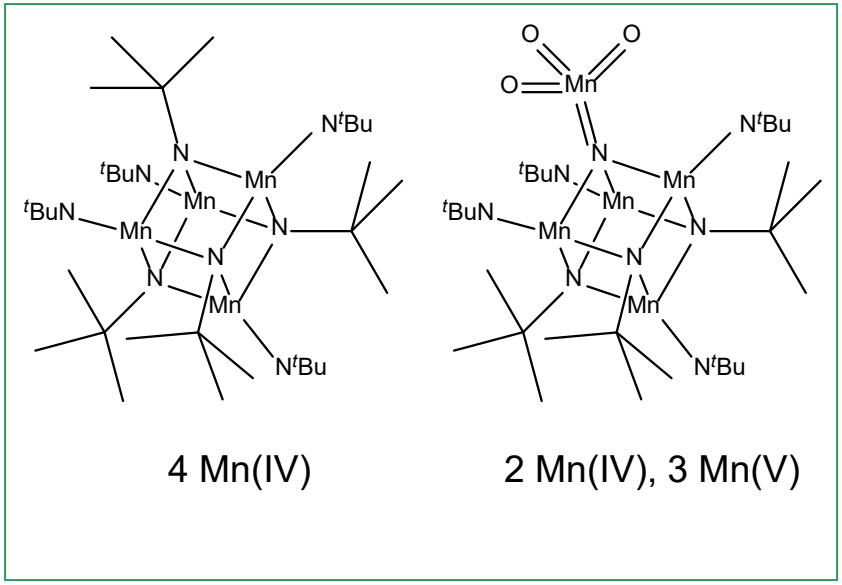
R_1 = 2.84%

Vaddypally, et al. *J. Am. Chem. Soc.* **2017**, *139*, 4675

How did this happen? Where did oxygen come from?

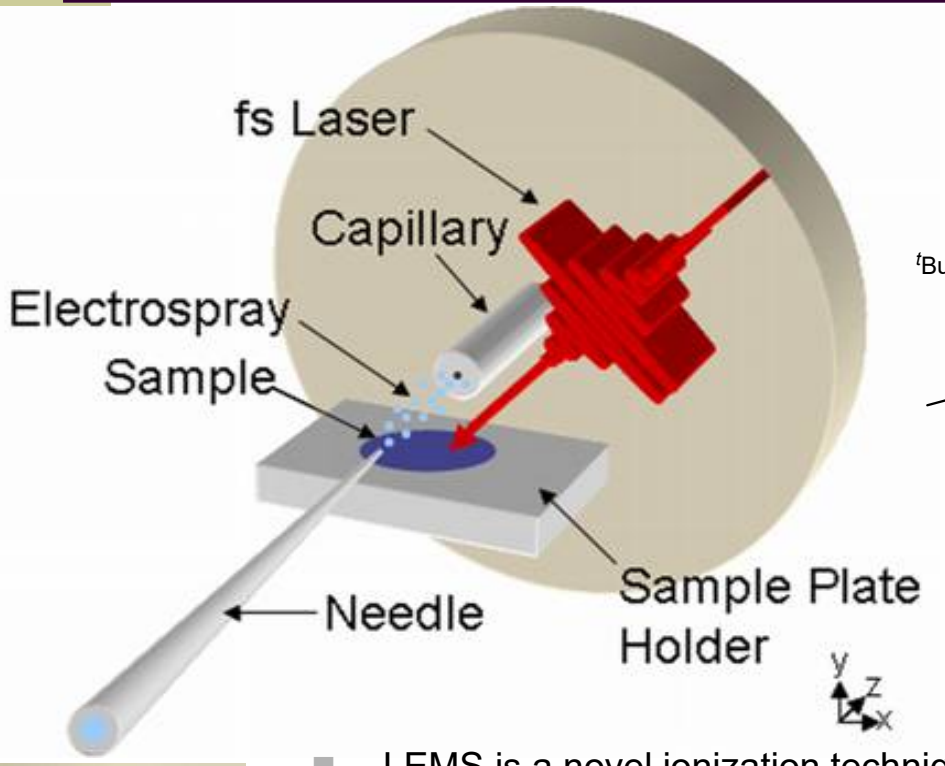
- Li removed by crown ethers (wet).
- Protolysis of tert-butyl amide fragement of parent cluster gives MnO_3N^{2-}
- MnO_3N^{2-} structurallly comparable to *tert*-butyl, and incorporates randomly.
- Majority of the material is all-*t*-butyl (90%), and a single metalloligand (10%). Other species with several metalloligands are only present in traces.

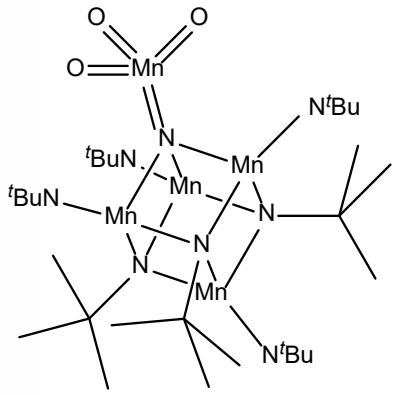




Vaddypally, et al. *J. Am. Chem. Soc*. **2017**, *139*, 4675

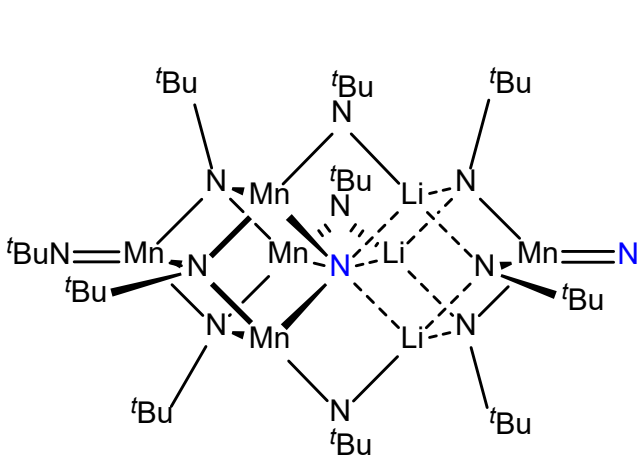
Laser Electrospray Mass Spectroscopy – LEMS for detection of metalloligand cluster



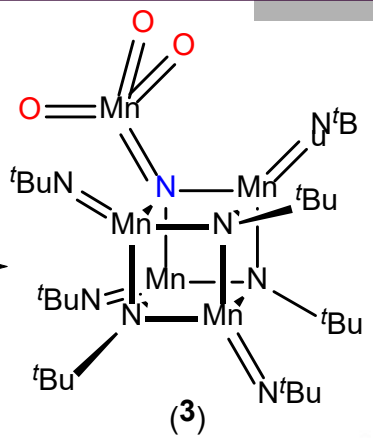


- LEMS is a novel ionization technique that uses a femtosecond laser to non-destructively vaporize a sample and deposit it onto the surface of charged electrospray droplets.
- Ideal for nonplar molecules that are insoluble in normal electrospray solvents.

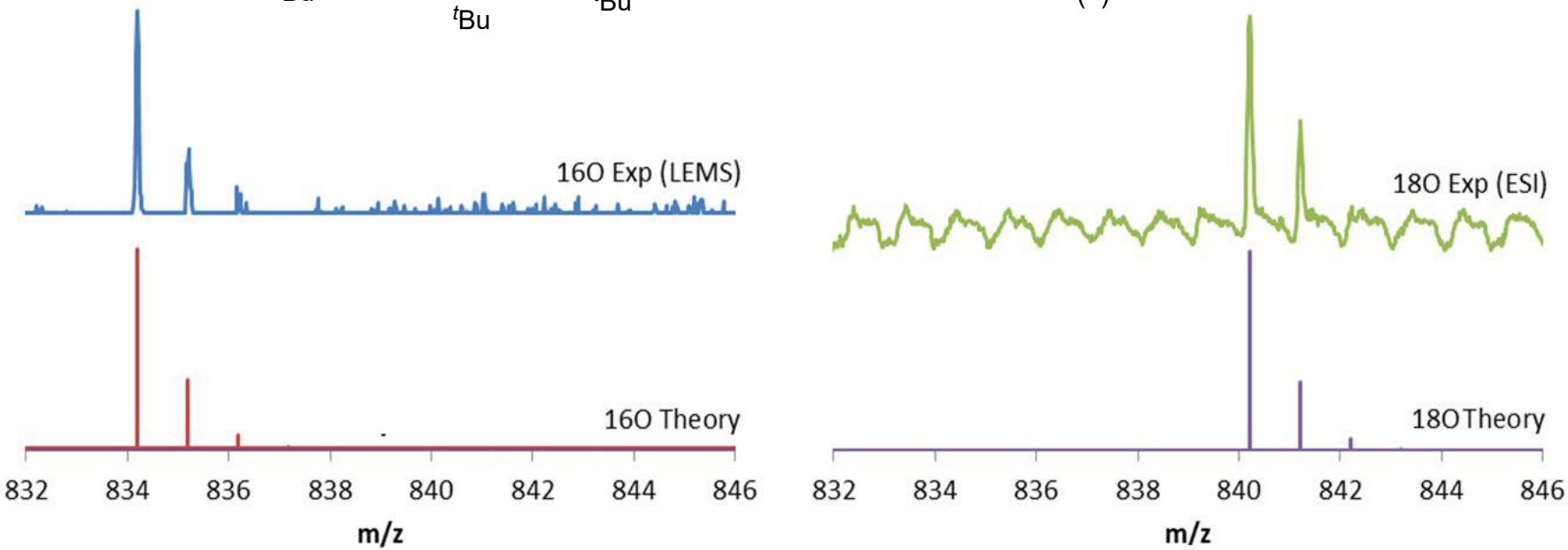
Isotopic labelling with ^{18}O confirms water is the source of O



12-crown-4
$H_2{}^{18}O$



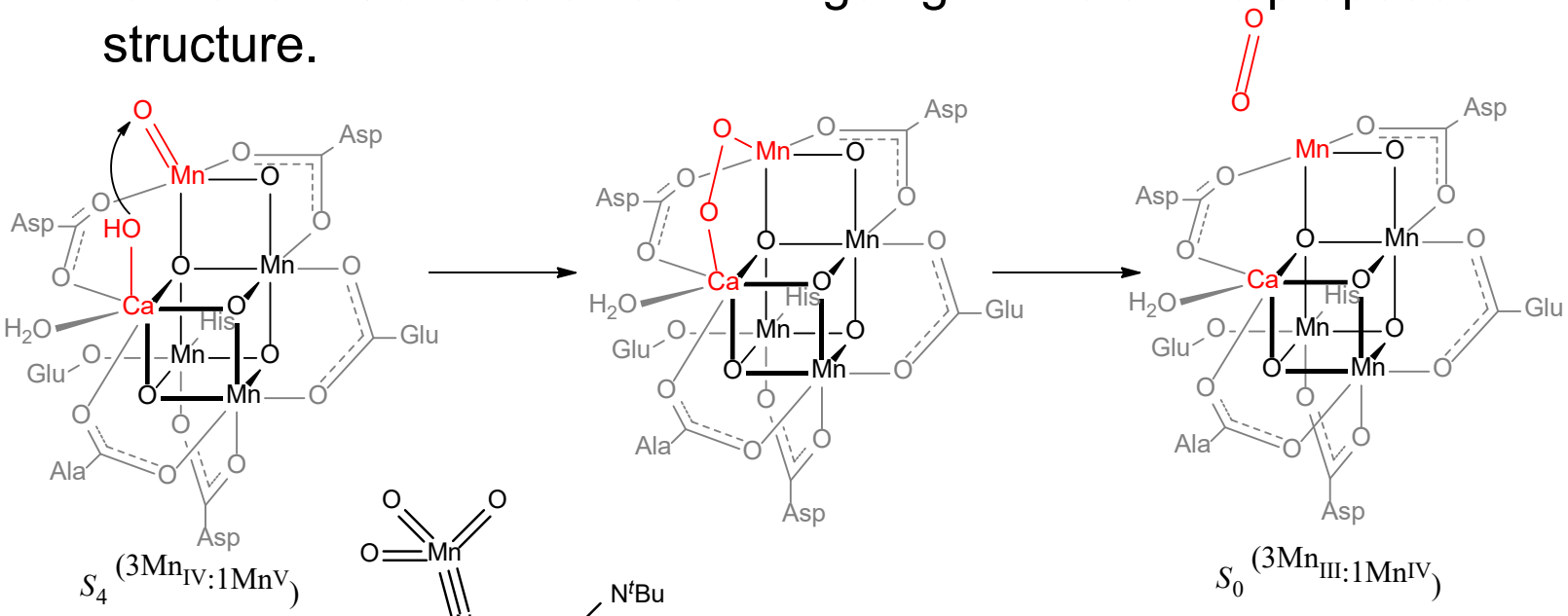
(**3**)



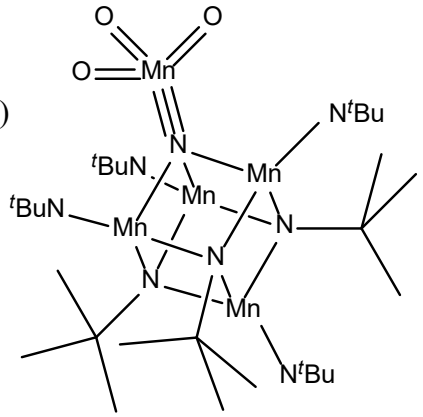
Vaddypally, et al. *J. Am. Chem. Soc*. **2017**, *139*, 4675

S_4 state as a high-valent Mn=O

- Nucleophilic attack by Ca-bound hydroxide on high-valent Mn-O at dangler Mn is a popular mechanistic proposal for O-O bond formation. Our cluster is an intriguing mimic of this proposed structure.



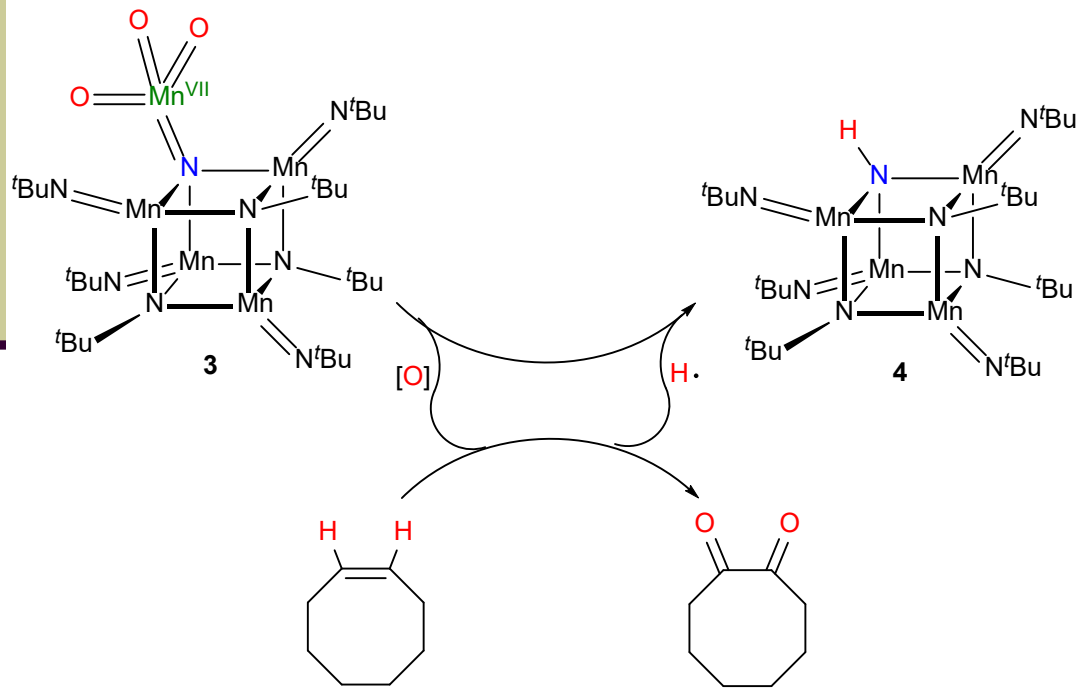
S_4 $(3Mn^{IV}:1Mn^{V})$ S_0 $(3Mn^{III}:1Mn^{IV})$

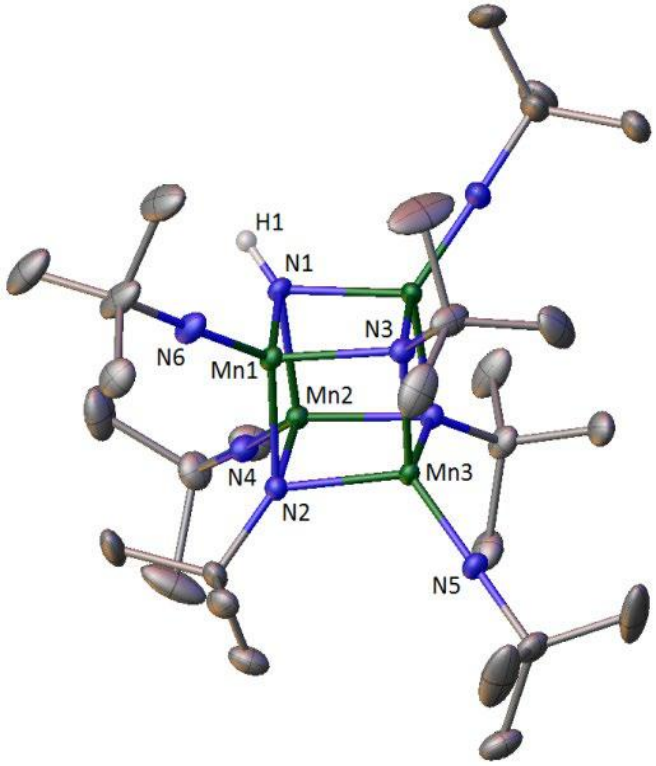


J. P. McEvoy, G. W. Brudvig. *Phys. Chem. Chem. Phys.* **2004**, *6*, 4754

Reactivity of the Pendant Mn=O

- “Dangler” oxygens do not oxidize water to give detectable oxygens in our experiments, but they do react with olefins quantitatively to give deoxygenated products (permanganate-like reactivity).
- Oxygen is transferred from the cluster to the substrate.
- Hydrogen atom is transferred from the stubstrate to the cluster.

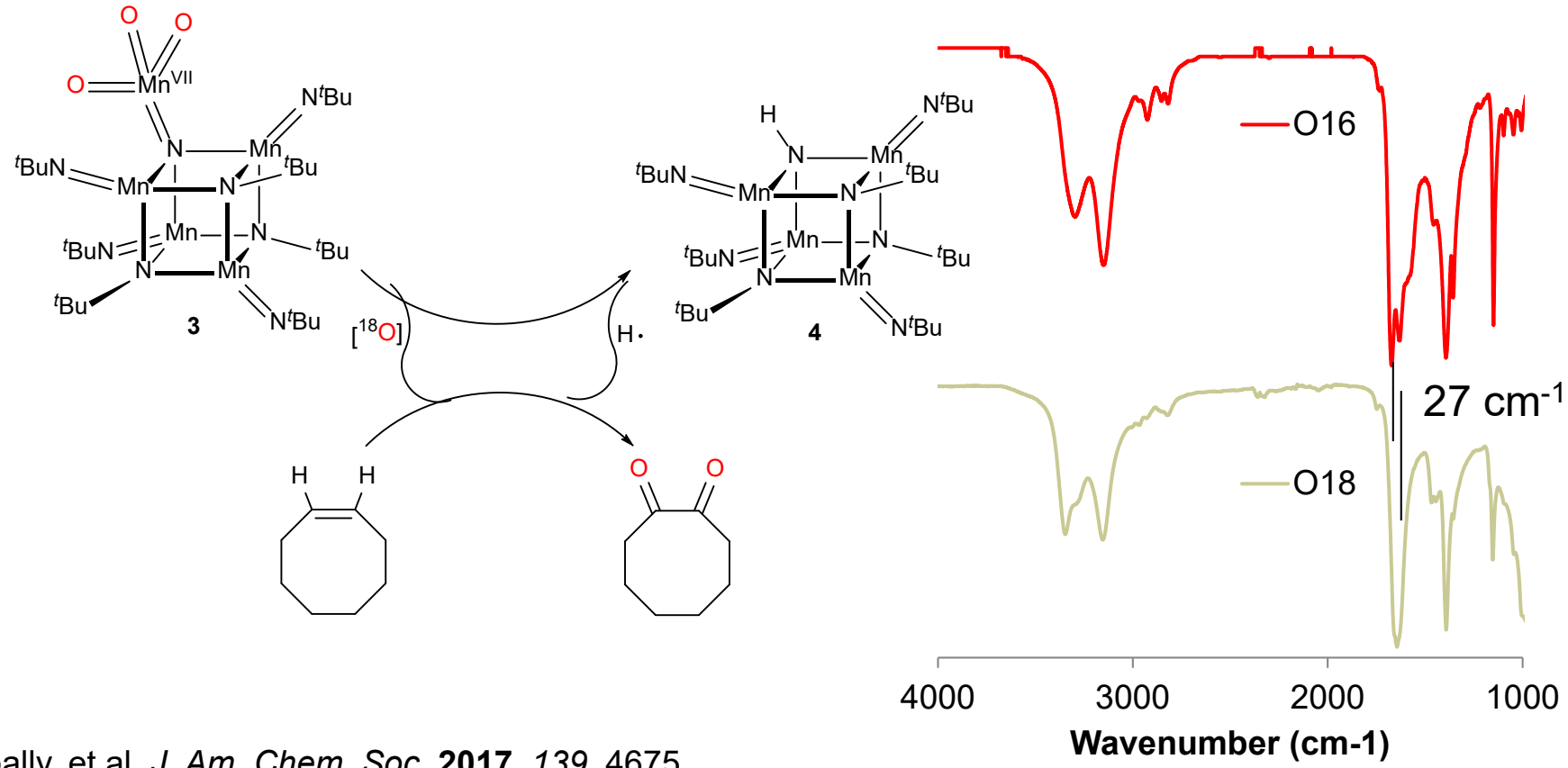




Vaddypally, et al. *J. Am. Chem. Soc*. **2017**, *139*, 4675

Reactivity of the Pendant Mn=O – Isotopic labelling

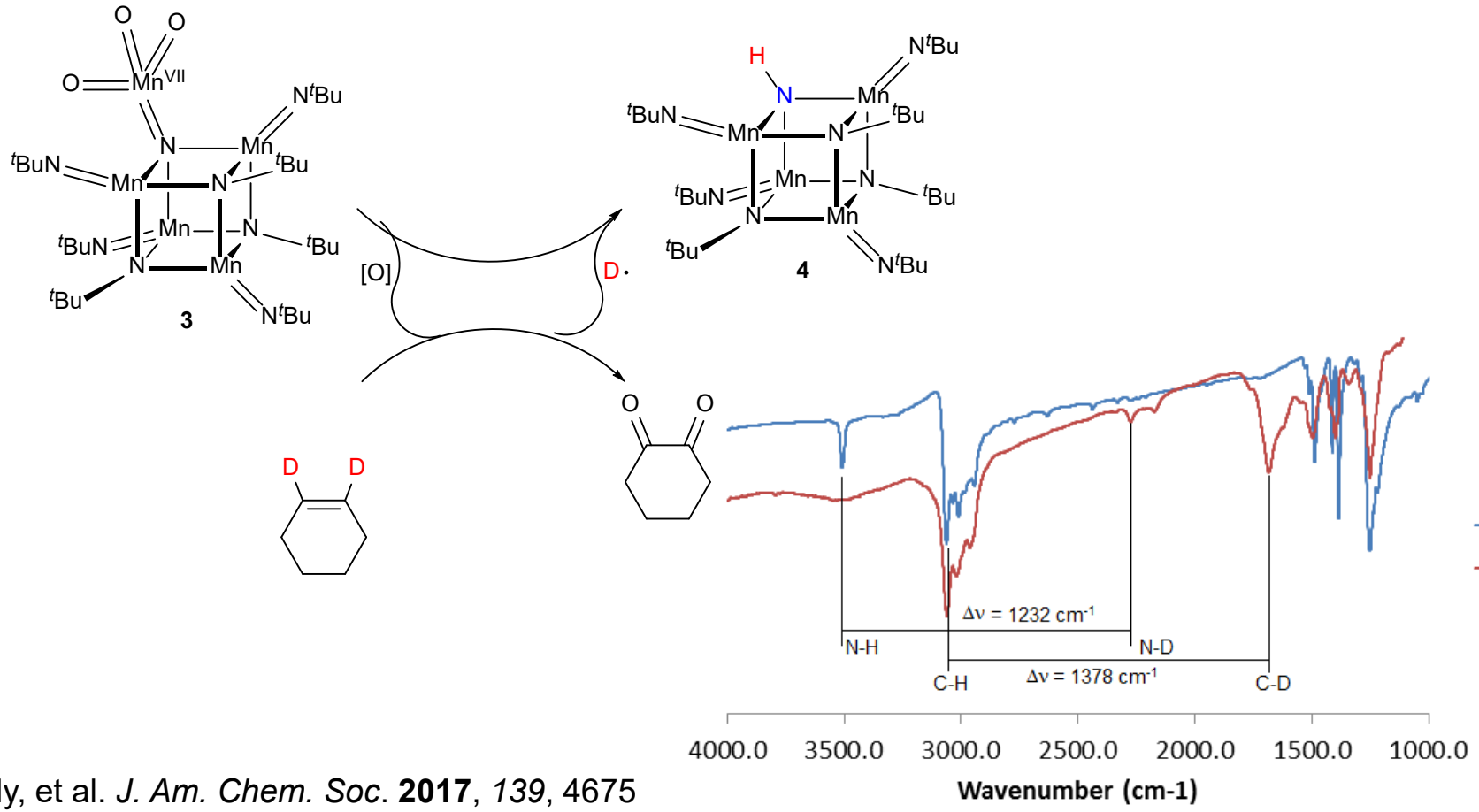
- Isotopic ^{18}O labelling shows transfer of cluster oxygen to the substrate ketone product.



Vaddypally, et al. *J. Am. Chem. Soc.* **2017**, *139*, 4675

Reactivity of the Pendant Mn=O – Isotopic labelling

- ^{2}D isotopic labelling illustrates transfer of substrate hydrogen atom to the cubane cluster



Vaddypally, et al. *J. Am. Chem. Soc.* **2017**, *139*, 4675

Concluding statements

- Lower-coordinate, unchelated manganese clusters show significant reactivity (though no water oxidation…yet).
- Future tests will try to "stack the deck" in favor of the nucleophilic attack mechanism to test its plausibility.
  - Reduce the Mn^{VII} cubane with dangler oxygen to a more bio-relevant Mn^{V}
  - Test reactivity with OH^- and H_2O to see if $O_2$is formed
- Such experiments—fail or succeed—may shed light on the plausibility of the nucleophilic attack hypothesis.

The Zdilla Lab at Temple University

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Jacob Dewey
Alex Byrne

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