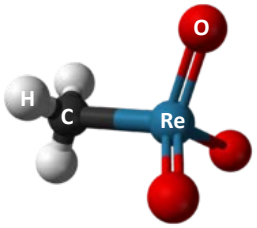
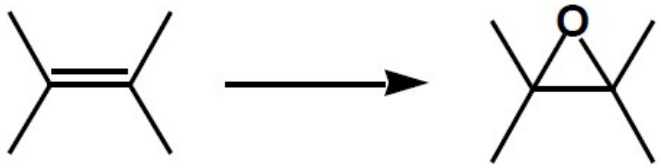
# Elucidating the precise role of water in olefin epoxidation catalyzed by methyltrioxorhenium

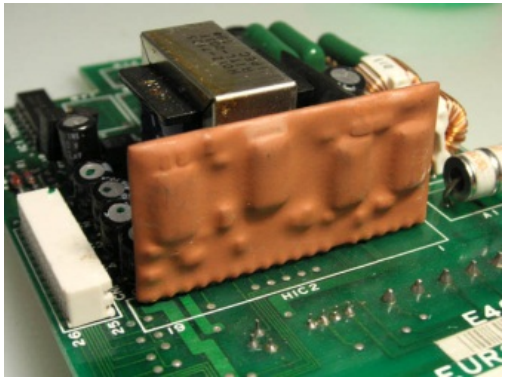



Bryan Goldsmith, Taeho Hwang, Stefan Seritan
Baron Peters, Susannah L. Scott

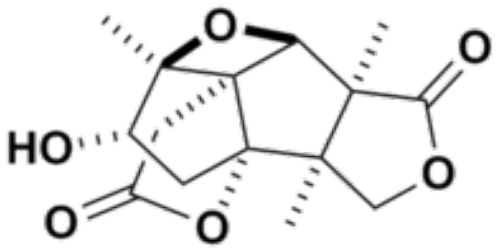
CHEMICAL ENGINEERING
UC SANTA BARBARA

# Olefin epoxidation plays a key role in chemical industry

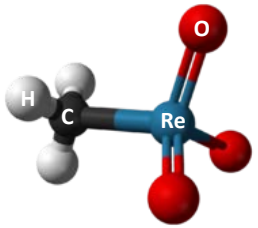






# Methyltrioxorhenium is an active epoxidation catalyst




First organometallic Re oxide synthesized

by Beattie and Jones *Inorg. Chem.* **1979**, *18*

First example of epoxidation

W.A. Herrmann, R.W. Fischer, D.W. Marz, Angew. Chem. Int. Ed. Engl. 30 (1991) 1638–1641.

Activated by $H_2O_2$

Versatile

Stable

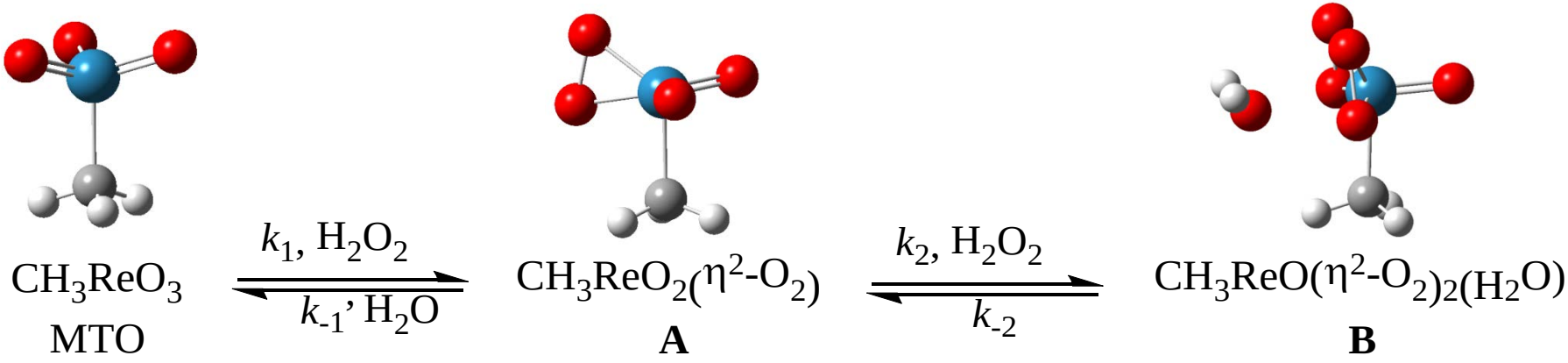
G.S. Owens et al. / Catalysis Today 55 (2000) 31

Table 1. MTO-catalyzed epoxidation of olefins with $H_2O_2$.

| | olefin | $T$ [°C] | $t$ [h] | product | yield [%] [a] |
|---|---|---|---|---|---|
| a) | propene | −10 | 12 | propenoxide | 50* [b] |
| | | | | 1,2-propanediol | 50* [b] |
| b) | 2-butene | −10 | 6 | 2,3-butanediol | 100* [b] |
| c) | *cis*-2-pentene | 25 | 3 | 2,3-pentanediol | 10* |
| | | | | *cis*-2,3-epoxypentane | 90* |
| d) | 2,3-dimethyl-2-butene | 25 | 1 | 2,3-dimethyl-2,3-butanediol | 75 |
| e) | *trans*-4-octene | 25 | 2 | *trans*-4,5-epoxyoctane | 95 |
| f) | cyclohexene | 82 | 0.1 | *trans*-1,2-cyclohexanediol | 97* |
| | | 10 | 5 | 1,2-epoxycyclohexane | 90 |
| g) | 4-vinylcyclo-hexene | 15 | 2 | 1,2-epoxy-4-vinyl-cyclohexane | 50 |
| | | | | 1,2-dihydroxy-4-vinylcyclo-hexane | 40 |
| h) | 1-methylcyclo-hexene | 25 | 2 | 1-methyl-1,2-cyclohexanediol | 70 |
| i) | 1,4-cyclohexa-diene | 70 | 3 | 1,2,4,5-tetrahydroxycyclohexane | 92 |
| k) | *cis,cis*-1,5-cyclo-octadiene | 0 | 1.5 | 5,6-epoxycyclooctene | 80 |
| l) | cyclododecene | 25 | 1 | 1,2-epoxycyclododecane | 100* |
| m) | β-pinene | 5 | 0.1 | β-pinene oxide | 40* |
| | | | | β-pinane-1,2-diol | 50* |
| n) | methyl oleate | 25 | 24 | methyl 9,10-dihydroxy-octadecanate | 92 |
| o) | allyl alcohol | 25 | 10 | 2,3-epoxy-1-propanol | 90 |
| p) | crotylaldehyde | 25 | 24 | 2,3-epoxybutaneal | 60 |
| q) | 1,4-naphtho-quinone | 70 | 18 | 2,3-epoxy-1,4-naphthoquinone | 64* |
| r) | pentafluoro-phenylethene | 25 | 24 | 1,2-epoxy(pentafluoro-phenyl)ethane | 38 |

And many, many more

# Methyltrioxorhenium is readily activated by $H_2O_2$

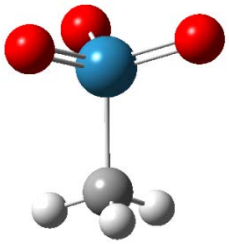




Espenson, J. H. *Chem. Comm.* 1999, 479

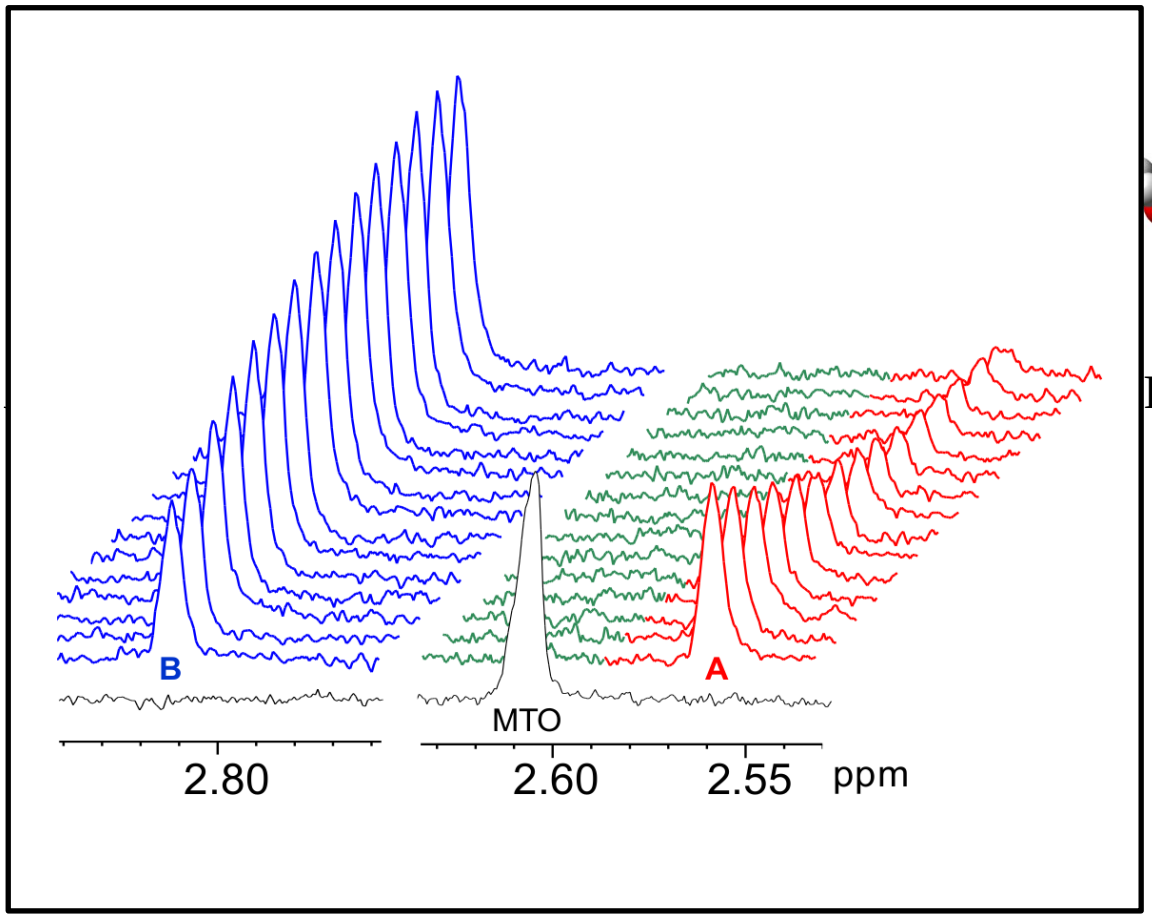
Herrmann, W. A. and Fischer, R. W.; Correia, J. D. G. *J. Mol. Catal.* 1994, *94*

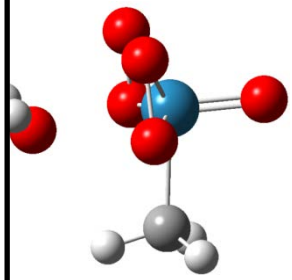
# Methyltrioxorhenium is readily activated by $H_2O_2$



$CH_3ReO_3$

MTO



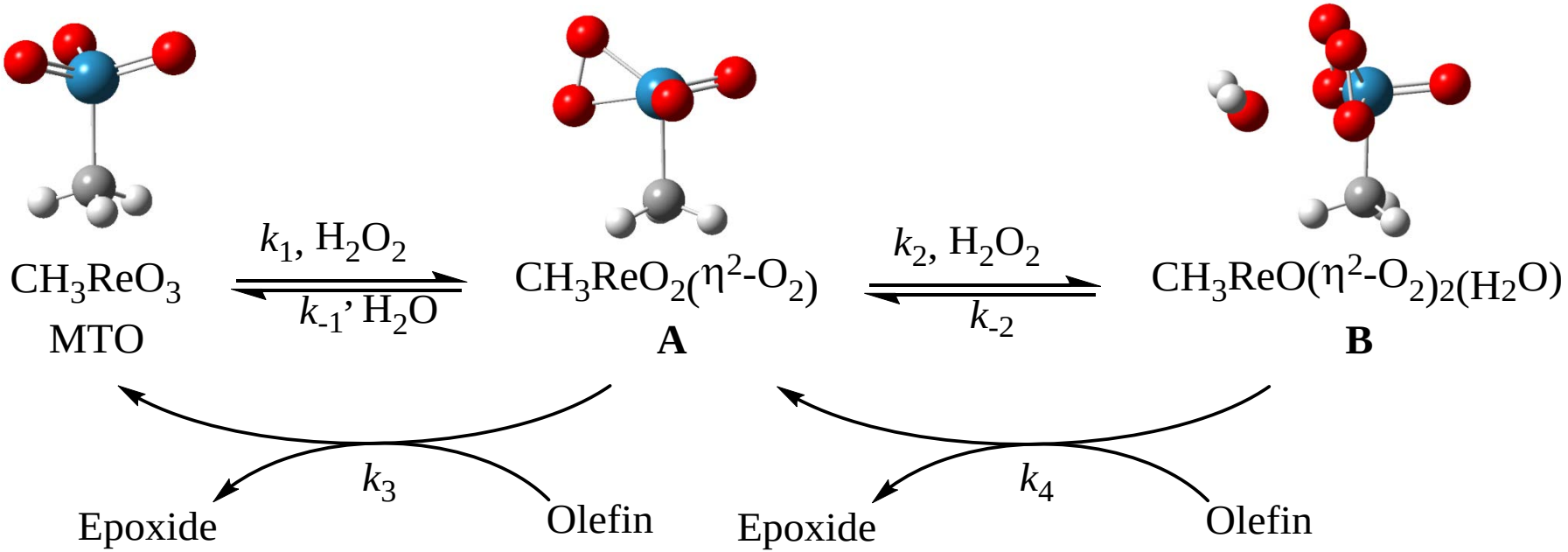



$ReO(\eta^2\text{-}O_2)_2(H_2O)$

**B**

T. Hwang,* B. R. Goldsmith,* B. Peters, and S. L. Scott, Inorg. Chem. 52, 13904 (2013)

# The epoxidation of olefins is catalyzed efficiently by MTO

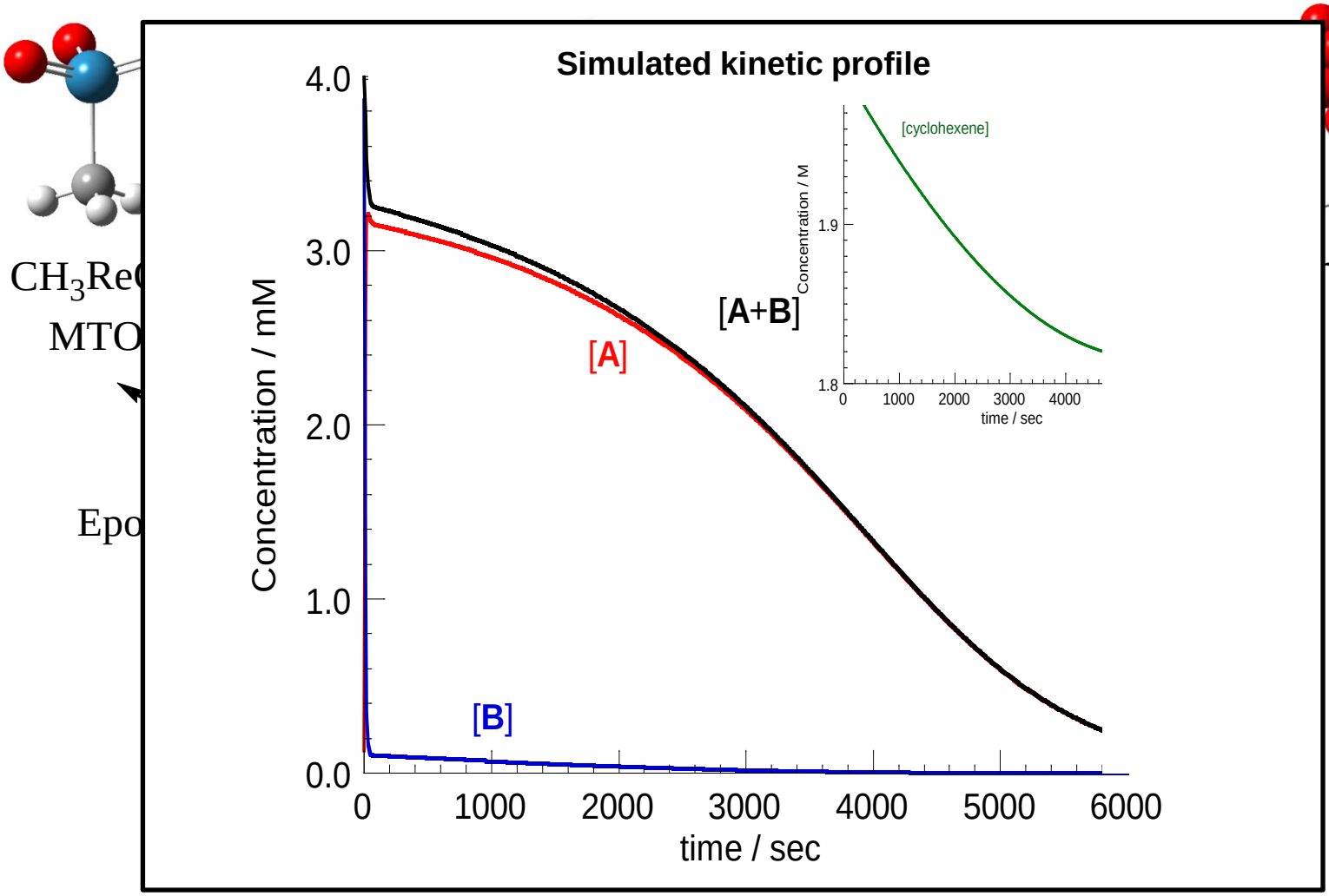




Espenson, J. H. *Chem. Comm.* 1999, 479

Herrmann, W. A. and Fischer, R. W.; Correia, J. D. G. *J. Mol. Catal.* 1994, *94*

# The epoxidation of olefins is catalyzed efficiently by MTO



# Water accelerates the epoxidation process

| | **A**+$C_6H_6$ | | **B**+$C_6H_6$ | |
|---|---|---|---|---|
| | $k_3 \times 10^2$ ($M^{-1}$ $s^{-1}$) | | $k_4 \times 10^2$ | |
| | $CH_3CN$ | $CH_3CN/H_2O$ | $CH_3CN$ | $CH_3CN/H_2O$ |
| Styrene | 0.20 | - | 1.5 | 11 |
| β–methylstyrene | 2.1 | 51 | 5.2 | 22 |
| α-methylstyrene | 4.5 | - | 4.5 | 47 |
| cyclohexene | 3.1 | - | 22 | 106 |

Gregory S. Owens, Armando Durazo, and Mahdi M. Abu-Omar Chem. Eur. J. 2002, 8, No. 13

Ahmad M. Al-Ajlouni and James H. Espenson *J. Am. Chem. SOC. 1995,117,* 9243-9250

# Towards elucidating the precise role of water during olefin epoxidation

but also

1) obtain accurate kinetics for the complexation of MTO with $H_2O_2$
2) reconcile kinetic discrepancies between theory and experiment
3) benchmarking of computational methods for Re system

Experimental

neglected reversibility of reaction and water dependence

Computational

reported ΔH are positive[2]

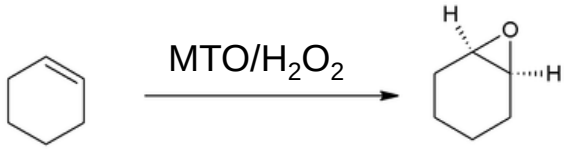
$\Delta H^{\ddagger}_{theory}$ don't agree with experiment

$\Delta H^{\ddagger}_{theory}$ ~ 100 kJ $mol^{-1}$

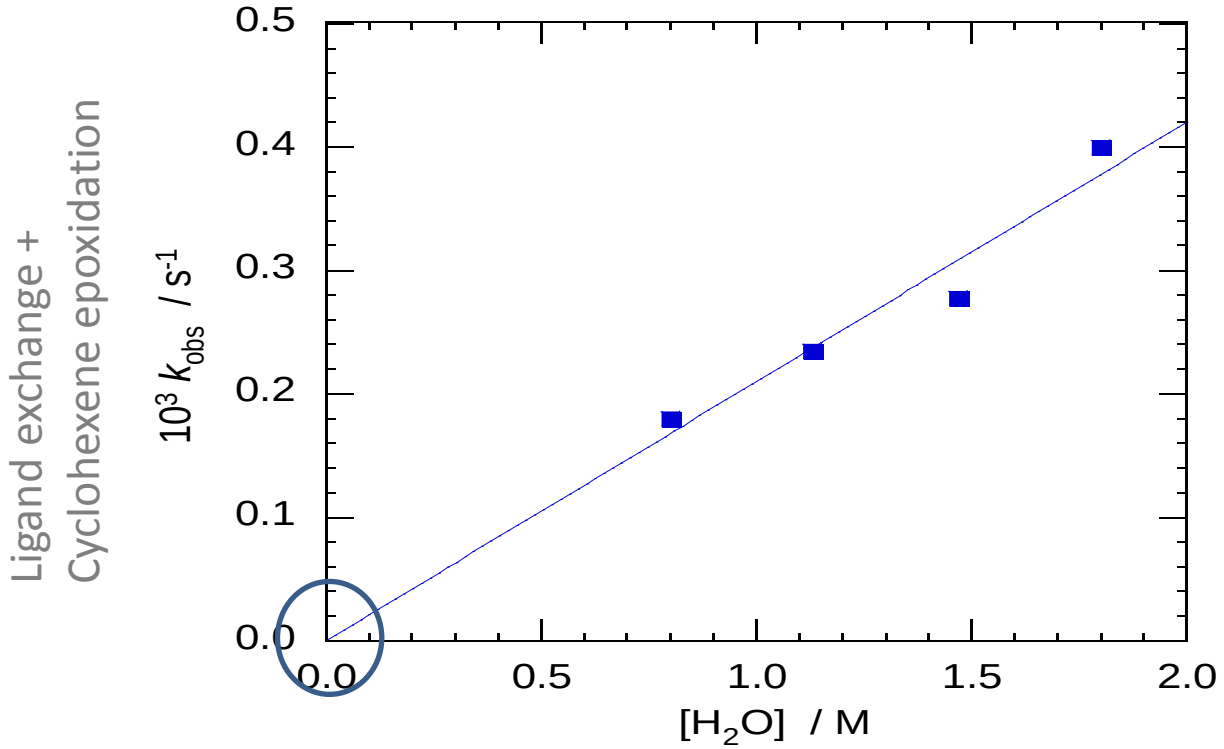
$\Delta H^{\ddagger}_{experiment}$ ~ 25 kJ $mol^{-1}$

Wang, W. D. and Espenson, J. H. *Inorg. Chem.* **1997**, *36*
Gonzales, J. et al. *J. Am. Chem. Soc.* **2007**, *129*

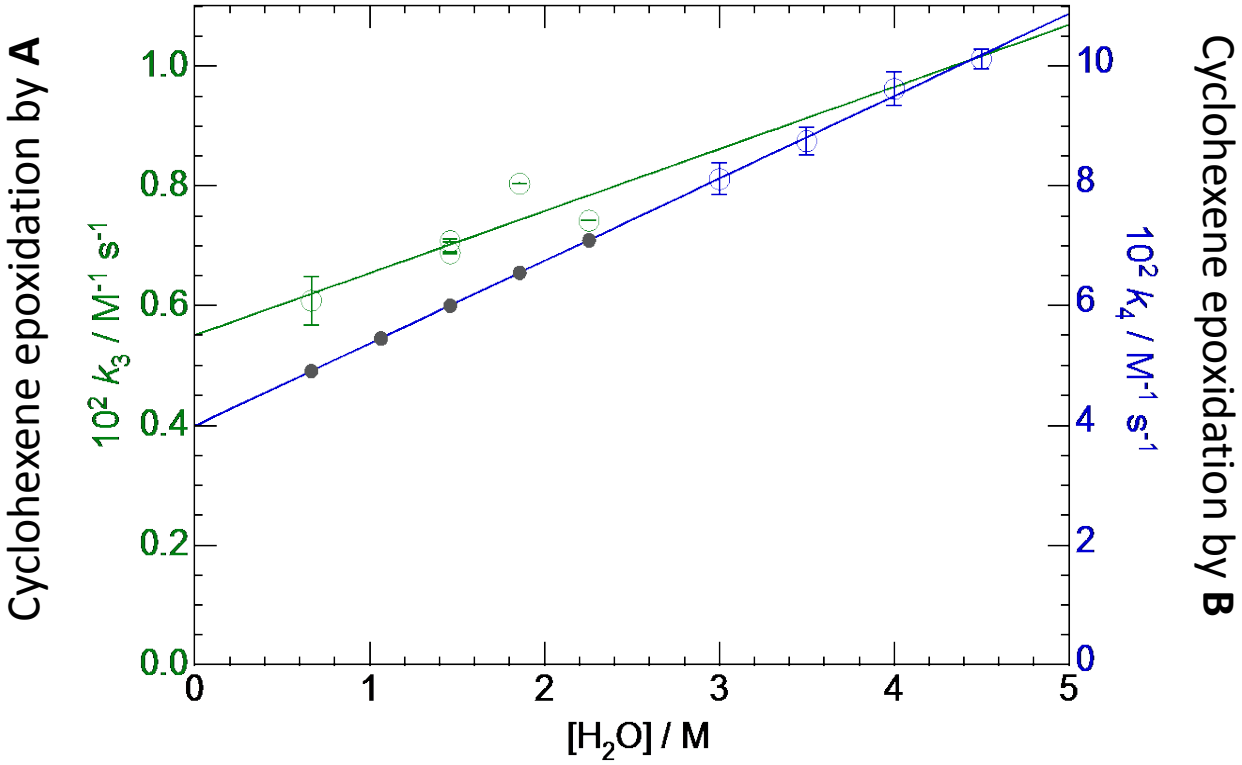
# No significant water-independent pathway during cyclohexene epoxidation by **A** and **B**

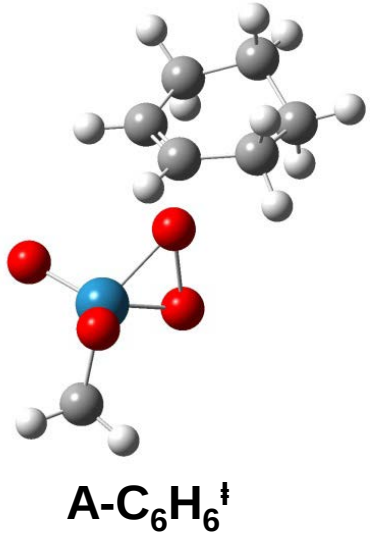



$[cyclohexene]_0 >> [H_2O_2]_0 >> [Re]_T$

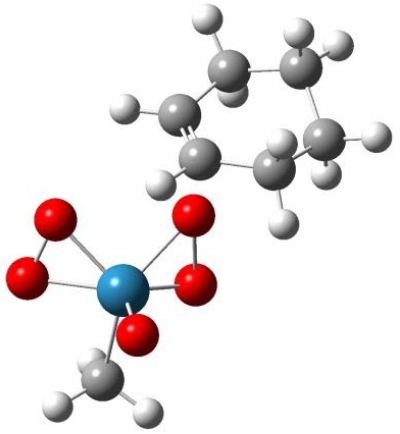


# Water dependence on cyclohexene epoxidation is weaker



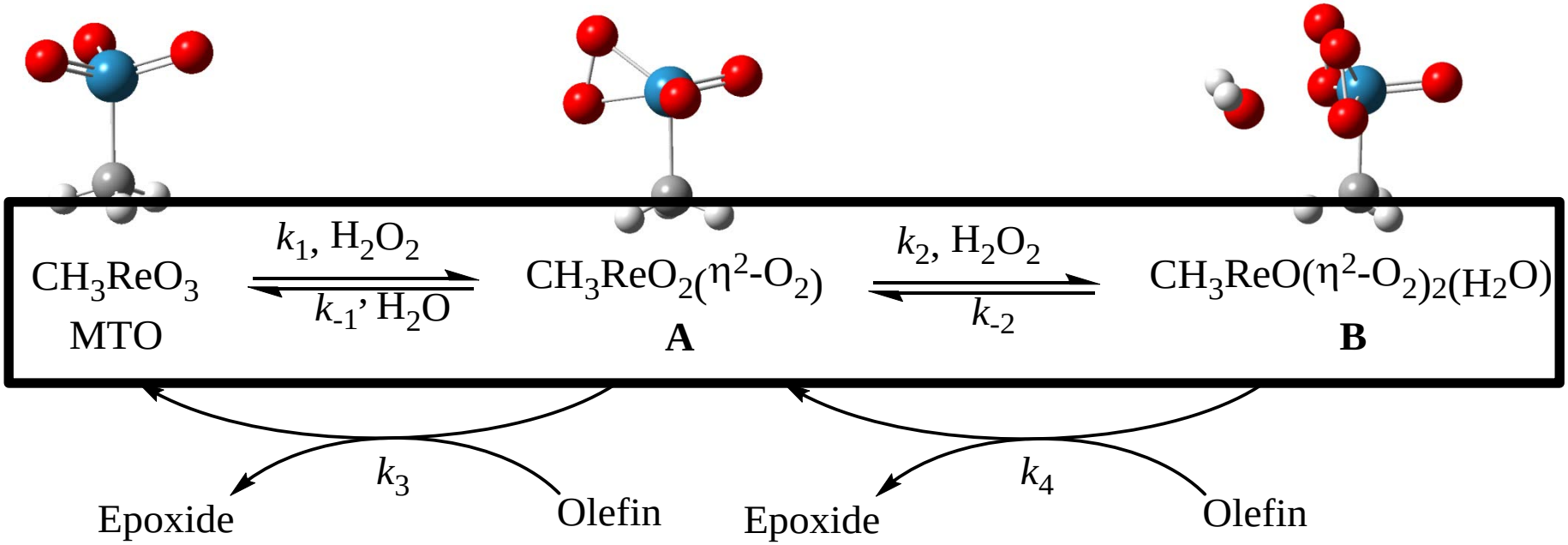
A-$C_6H_6^{\ddagger}$



B-$C_6H_6^{\ddagger}$

Infer water dependence comes primarily from ligand exchange

# Water dependence may originate from catalyst-regeneration step

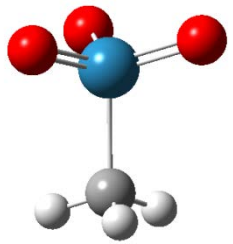



[$H_2O$] mainly influences the formation of species **A** and **B** from MTO and $H_2O_2$, which can effectively increase in the epoxidation rate.

# Modeling procedure

Cluster model

ωB97X-D/aug;def2-TZVP



Solvent corrected

conducting polarized continuum model (acetonitrile)

Parabolic barrier Tunneling correction

$\Gamma = (\hbar|\omega_{\ddagger}|/(2k_BT))/\sin[\hbar|\omega_{\ddagger}|/(2k_BT)]$

Free energies

$$H_{gas} = H_{trans} + H_{rot} + H_{vib}$$

$$S_{gas} = S_{trans} + S_{rot} + S_{vib}$$

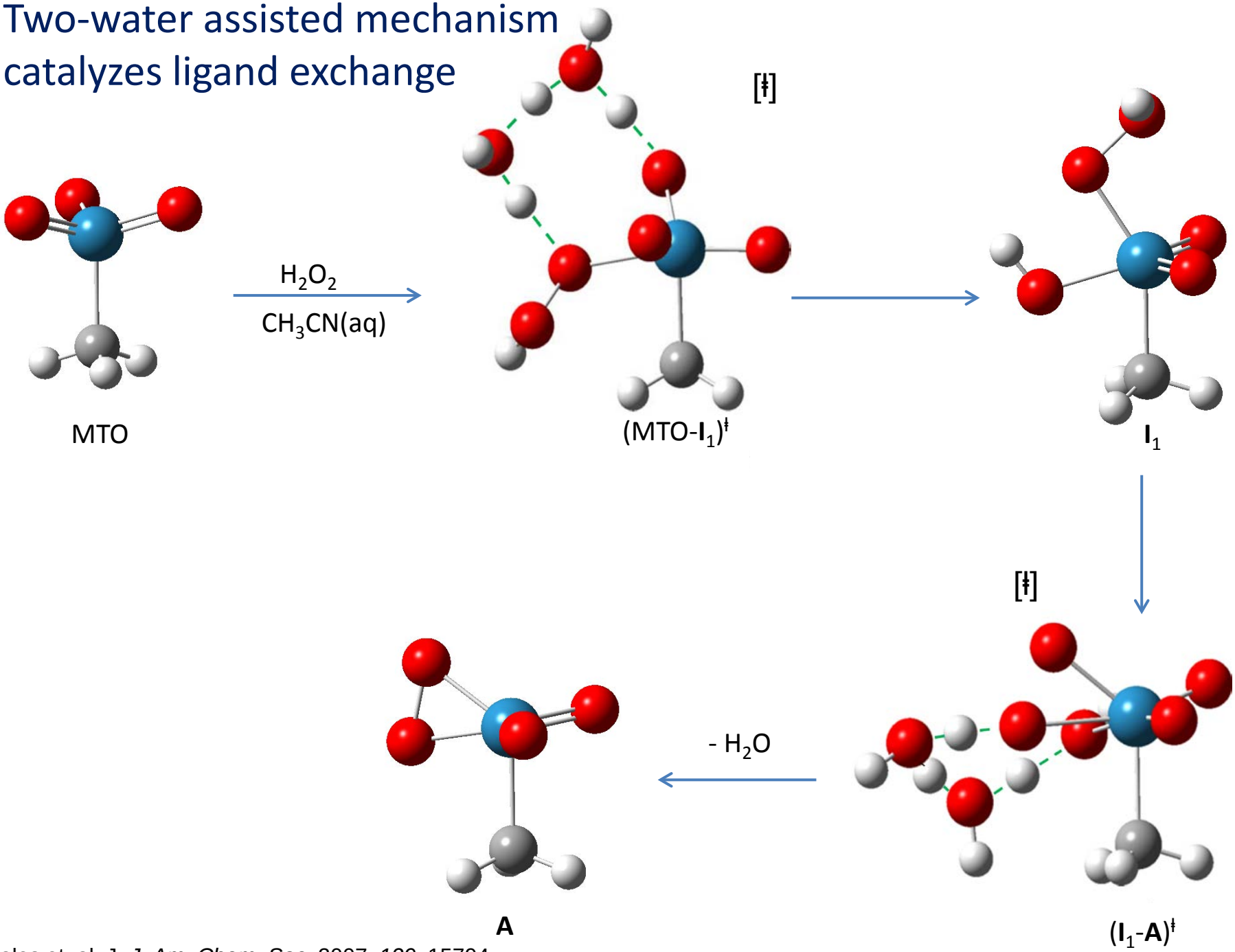
$$S_{acetonitrile} = S_{gas} + \Delta S_{Wertz} = S_{gas} + \left(-12.21\left(\frac{\text{kcal}}{\text{mol}}\right) - 0.23\left(\frac{\text{kcal}}{\text{mol}}\right)\left(S_{gas} - 12.21\left(\frac{\text{kcal}}{\text{mol}}\right)\right) + 5.87\left(\frac{\text{kcal}}{\text{mol}}\right)\right)$$

$$G_{s,CPCM} = \left(V_{B.O} + H_{gas} - T(S_{gas} + \Delta S_{Wertz})\right) + \Delta G_{soln} \qquad \text{Rate Constant} = k = \Gamma \frac{k_b T}{h} e^{-\frac{\Delta G^{\ddagger}}{k_b T}}$$

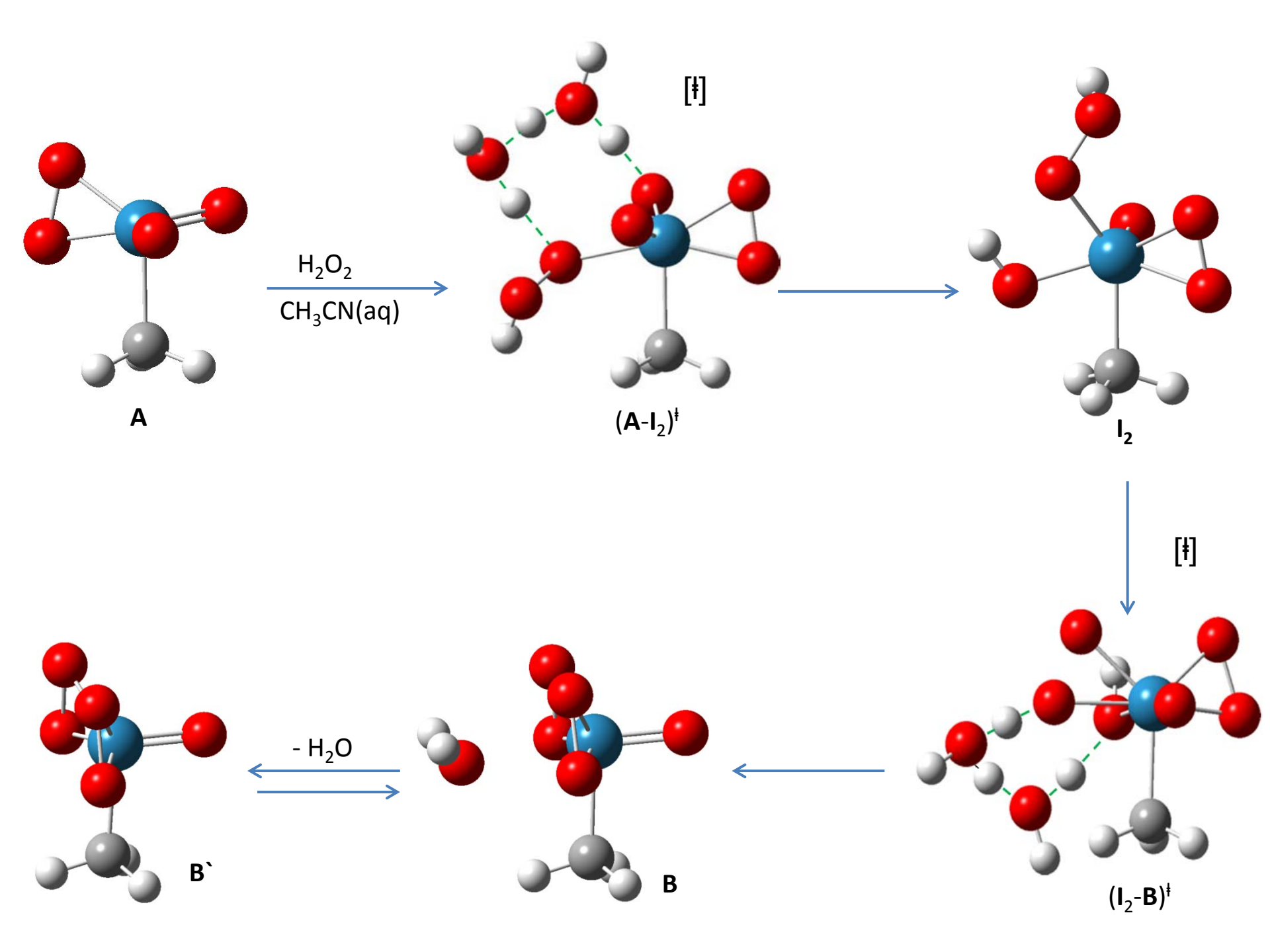
Jensen, F. Introduction to Computational Chemistry, 2nd Ed.; Wiley: Chichester, 2007.

Wertz, D. H. J. Am. Chem. Soc. 1980, 102, 5316.

# Two-water assisted mechanism catalyzes ligand exchange



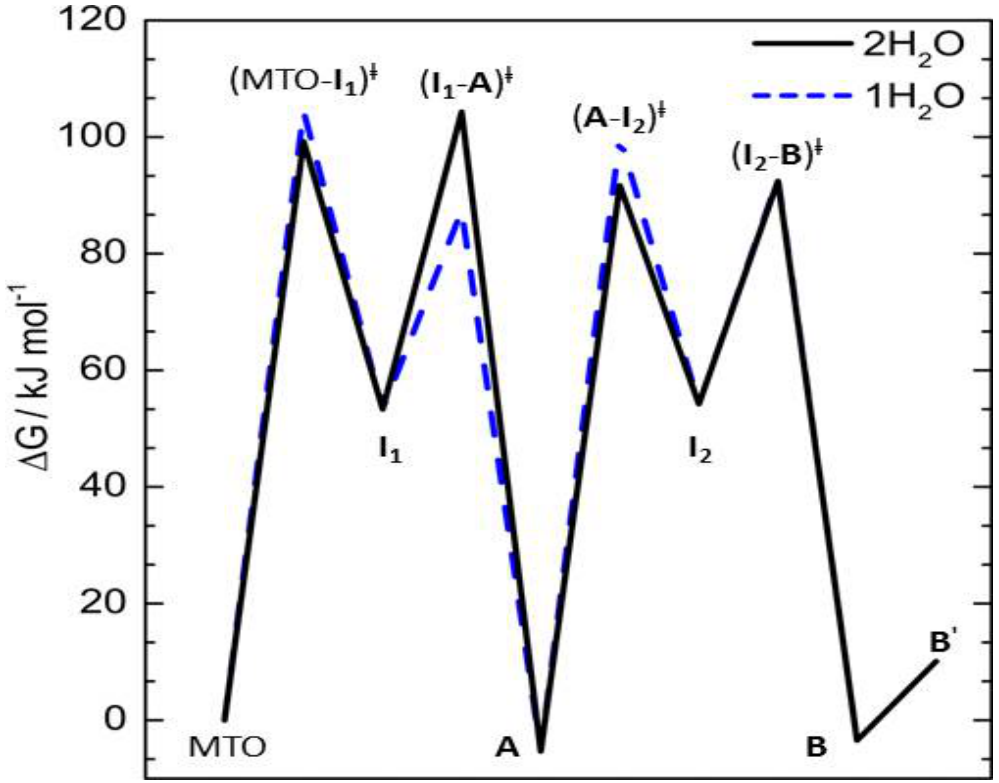

Gonzales et. al, J. *J. Am. Chem. Soc.* 2007, *129*, 15794


[ǂ]
$H_2O_2$
$CH_3CN(aq)$
A
$(A\text{-}I_2)^{ǂ}$
$I_2$
[ǂ]
$(I_2\text{-}B)^{ǂ}$
B
- $H_2O$
B`

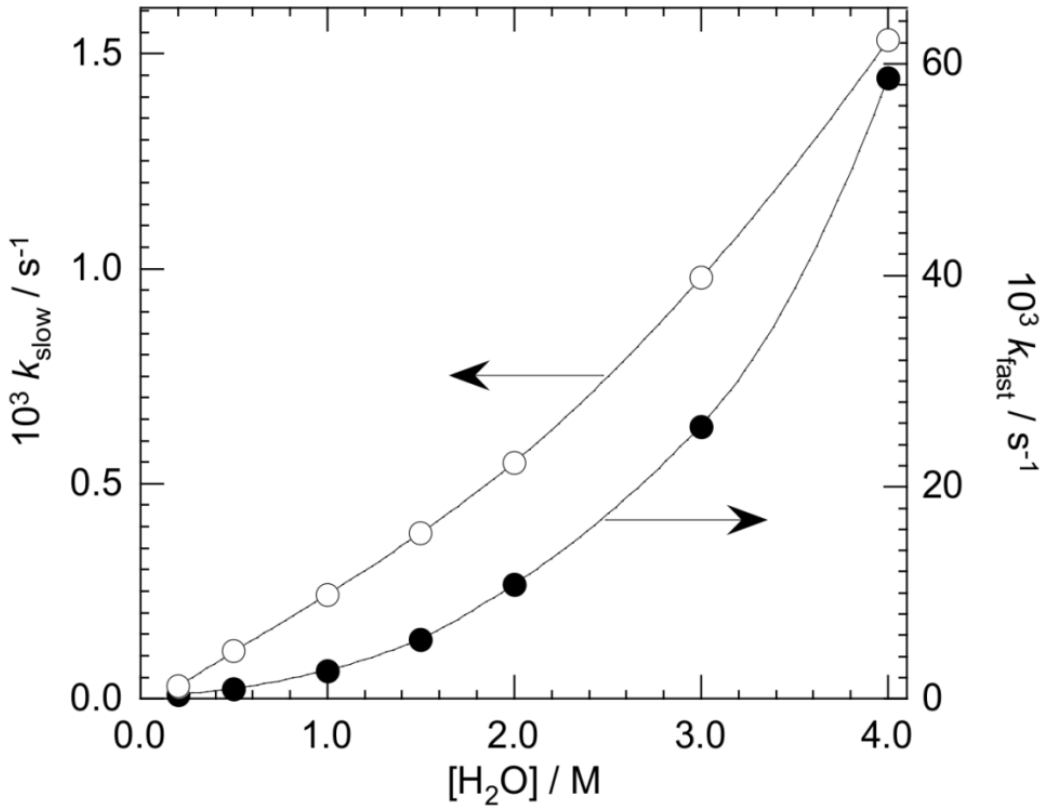
# Two-water assisted mechanism catalyzes ligand exchange

$$CH_3ReO_3 \underset{k_{-1},\ H_2O}{\overset{k_1,\ H_2O_2}{\rightleftharpoons}} CH_3ReO_2(\eta^2\text{-}O_2) \underset{k_{-2}}{\overset{k_2,\ H_2O_2}{\rightleftharpoons}} CH_3ReO(\eta^2\text{-}O_2)_2(H_2O)$$

MTO **A** **B**



# Experiments support computational finding of a water supported mechanism



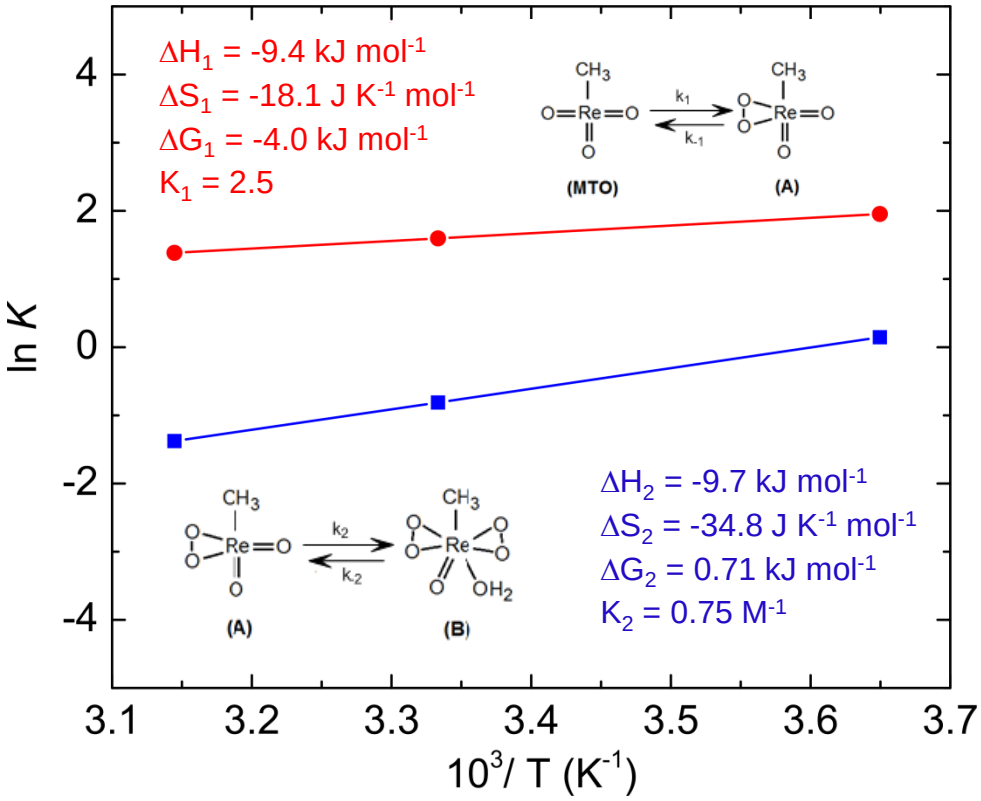

$k_{fast}$ and $k_{slow}$ from UV-Vis measurements

T. Hwang,* B. R. Goldsmith,* B. Peters, and S. L. Scott, Inorg. Chem. 52, 13904 (2013)

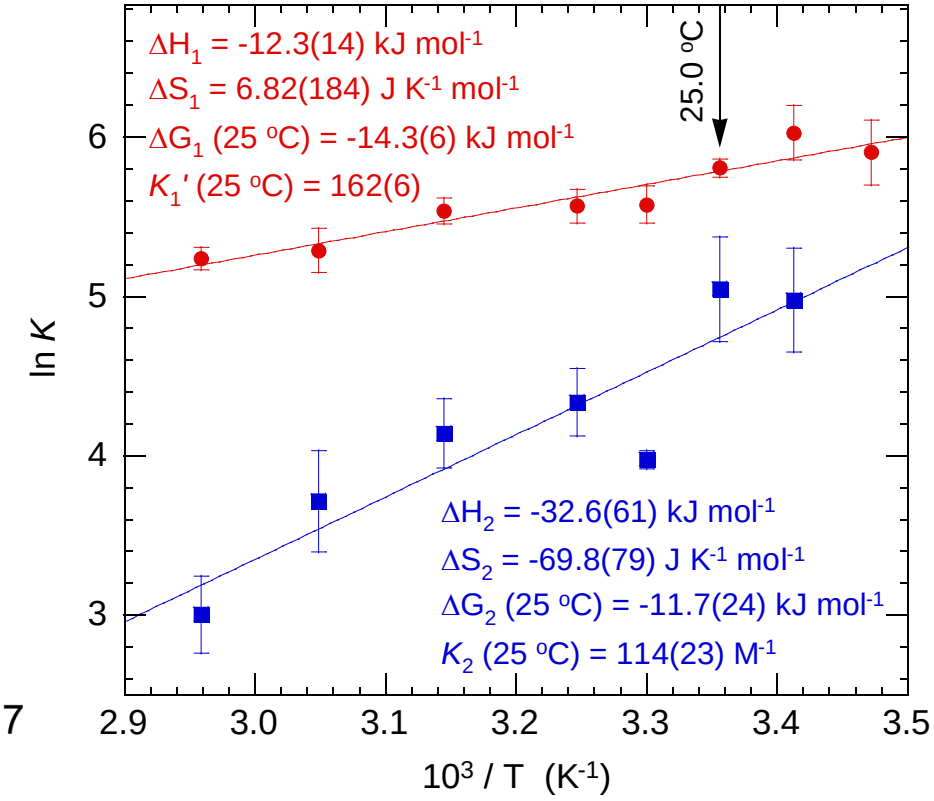
# Computed & experimental thermodynamic parameters are in relative agreement

$$\ln K = -\frac{\Delta H}{R\,T} + \frac{\Delta S}{R}$$

Computation



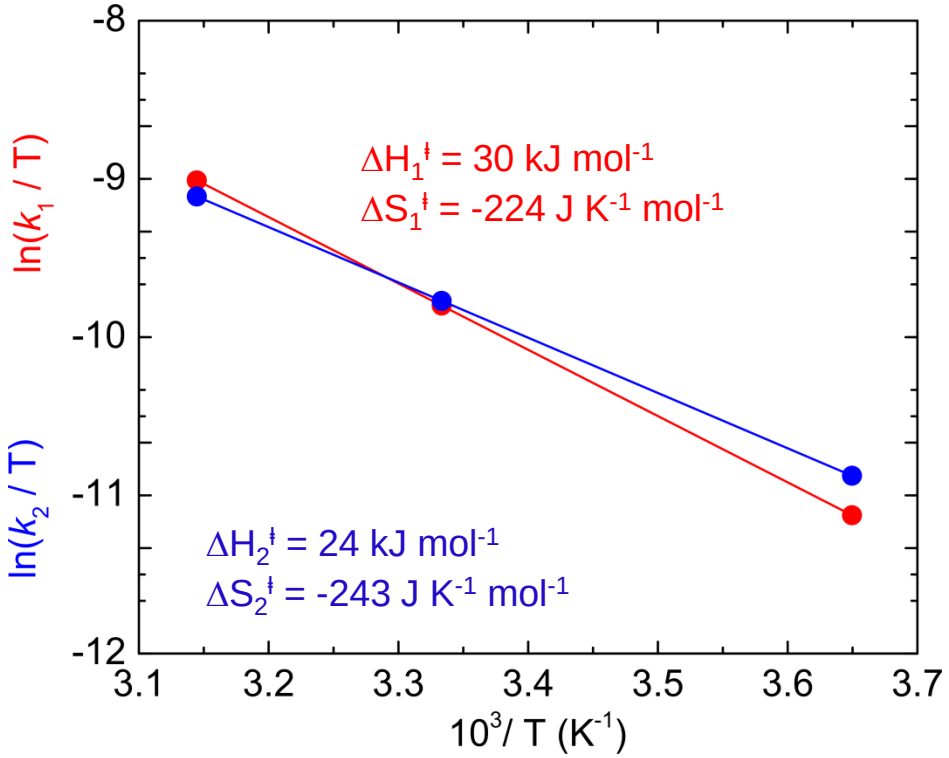

Experimental



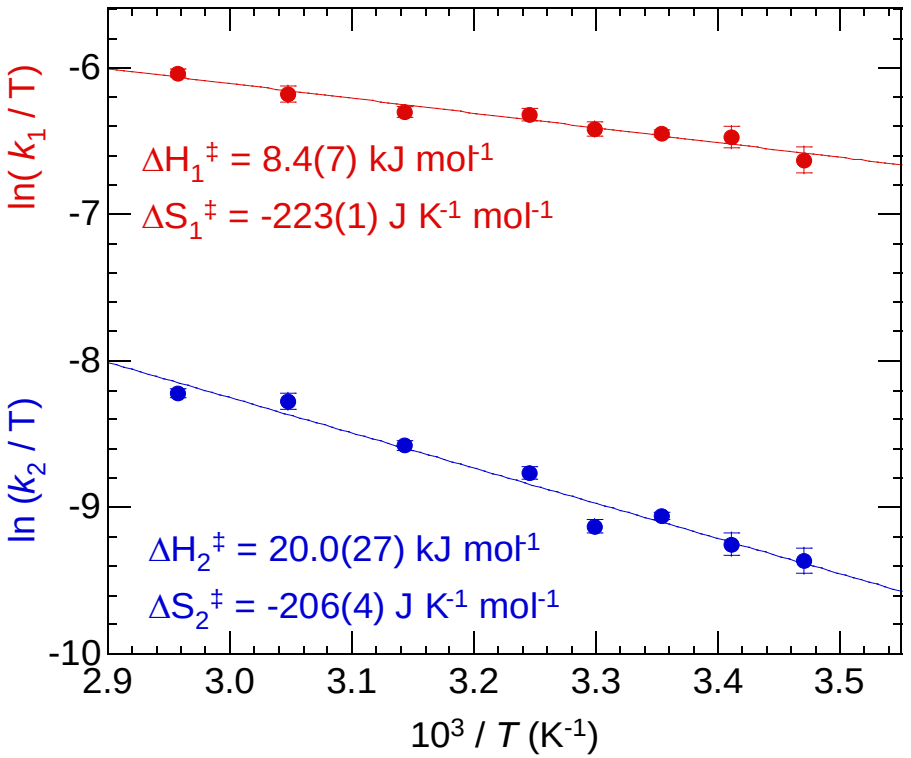
# Computed & experimental activation parameters are in agreement

$$\ln\left(\frac{k\,h}{T\,k_B}\right) = -\frac{\Delta H^{\ddagger}}{R\,T} + \frac{\Delta S^{\ddagger}}{R}$$

Computed (2 water-mechanism)

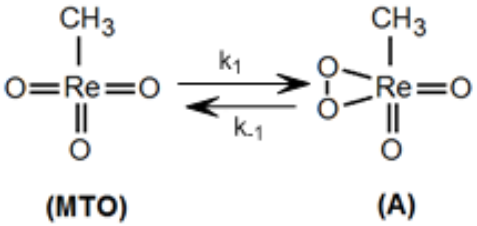


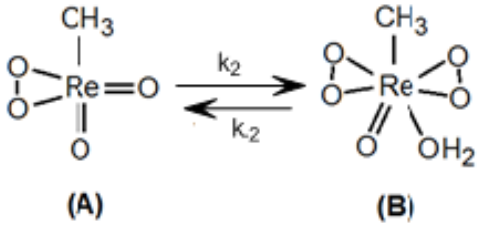

Experimental




$$k_1^{\,w} = \frac{k_{MTO\to I_1}\,k_{I_1\to A}}{k_{I_1\to MTO} + k_{I_1\to A}} \qquad k_2^{\,w} = \frac{k_{A\to I_2}\,k_{I_2\to B}}{k_{I_2\to A} + k_{I_2\to B}}$$

# Two water-assisted mechanism predicts parameters in better agreement with experiment than one water-assisted mechanism



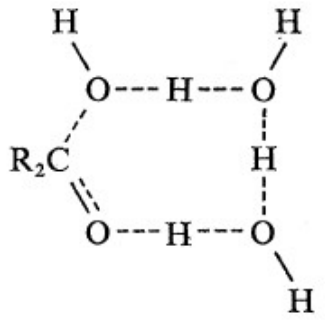




| Parameter | Exp. | $1H_2O$ | $2H_2O$ |
|---|---|---|---|
| $\Delta H_1^{\ddagger}$ | 8.38 | 53 | 30 |
| $\Delta S_1^{\ddagger}$ | -223 | -163 | -224 |
| $\Delta G_1^{\ddagger}$ | 74.9 | 102 | 96 |
| $\Delta H_{-1}^{\ddagger}$ | 20.7 | 63 | 39 |
| $\Delta S_{-1}^{\ddagger}$ | -230 | -150 | -217 |
| $\Delta G_{-1}^{\ddagger}$ | 89.3 | 108 | 104 |

| Parameter | Exp. | $1H_2O$ | $2H_2O$ |
|---|---|---|---|
| $\Delta H_2^{\ddagger}$ | 20.0 | 52 | 24 |
| $\Delta S_2^{\ddagger}$ | -206 | -173 | -243 |
| $\Delta G_2^{\ddagger}$ | 81.5 | 104 | 96 |
| $\Delta H_{-2}^{\ddagger}$ | 52.8 | 71 | 49 |
| $\Delta S_{-2}^{\ddagger}$ | -136 | -88 | -153 |
| $\Delta G_{-2}^{\ddagger}$ | 93.2 | 97 | 94 |

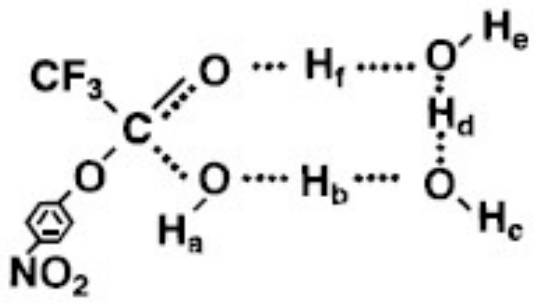
$\Delta G$ and $\Delta H$ : kJ/mol
$\Delta S$ : J $K^{-1}$ $mol^{-1}$

# Do we really have a two water-assisted mechanism?




Proc. R. Soc. Lond. A 1971 325

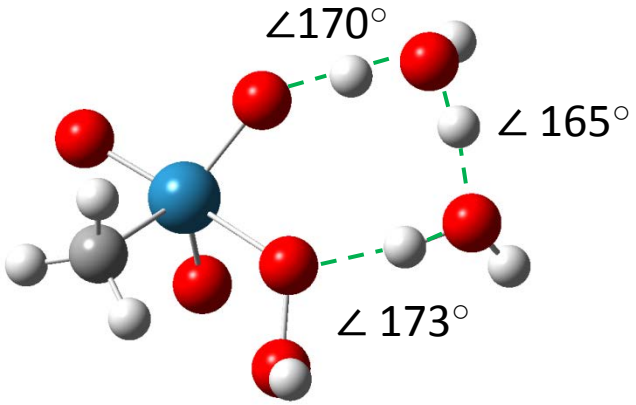
J. Am. Chem. Soc., 117, 15, 1995



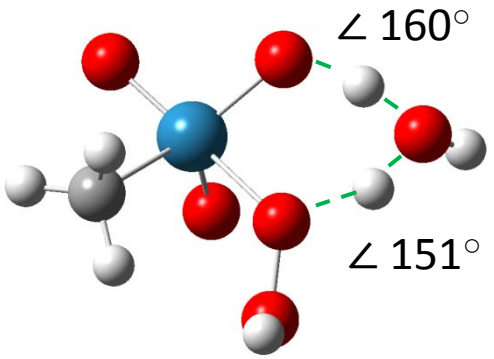

J. Org. Chem., 63, 18, 1998

"linearity of hydrogen bonds formed in the TS balances the entropic disadvantage of bringing four molecules together."

8 membered ring



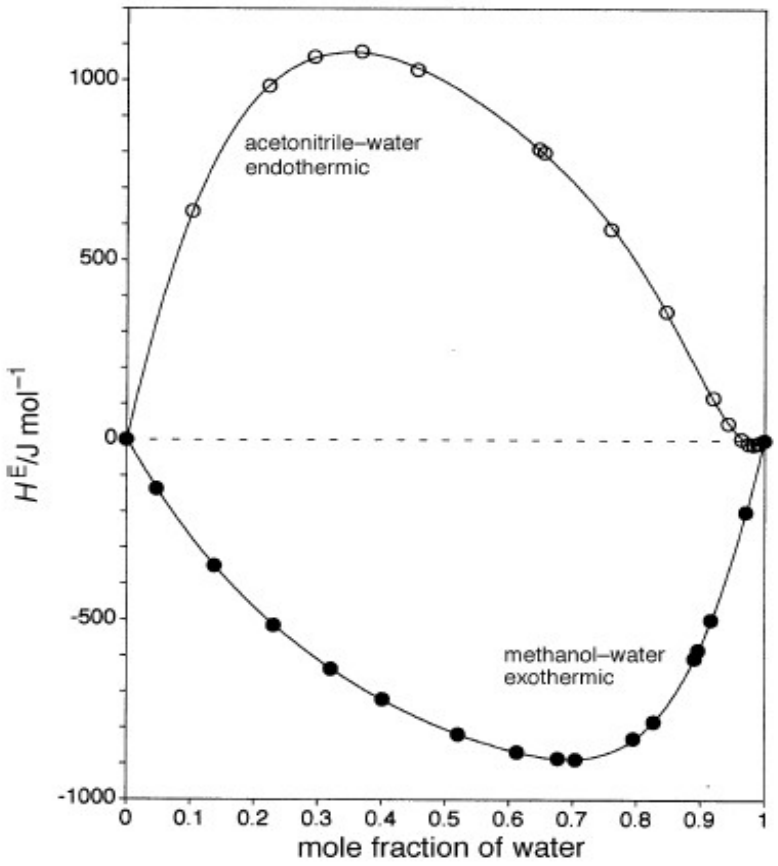

6 membered ring

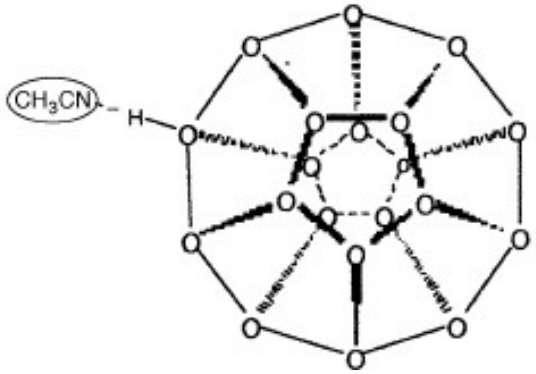


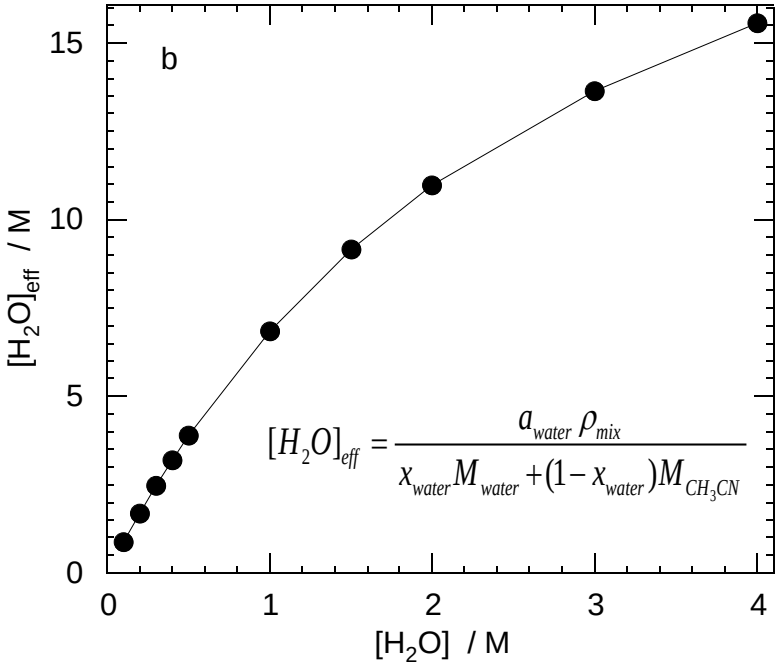

R. Gandour Tetrahedron. Lett. 15,3 1974, 295

P. A. Kollman and L. C. Allen, *Chem. Rev., 72,* 283 (1972).

# Water-acetonitrile mixtures are very non-ideal



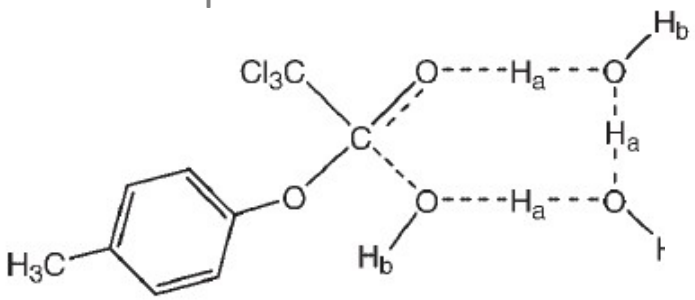




Wakisaka J. Chem. Soc., Faraday Trans., 1998, 94

# Discerning the reaction order based on water activity

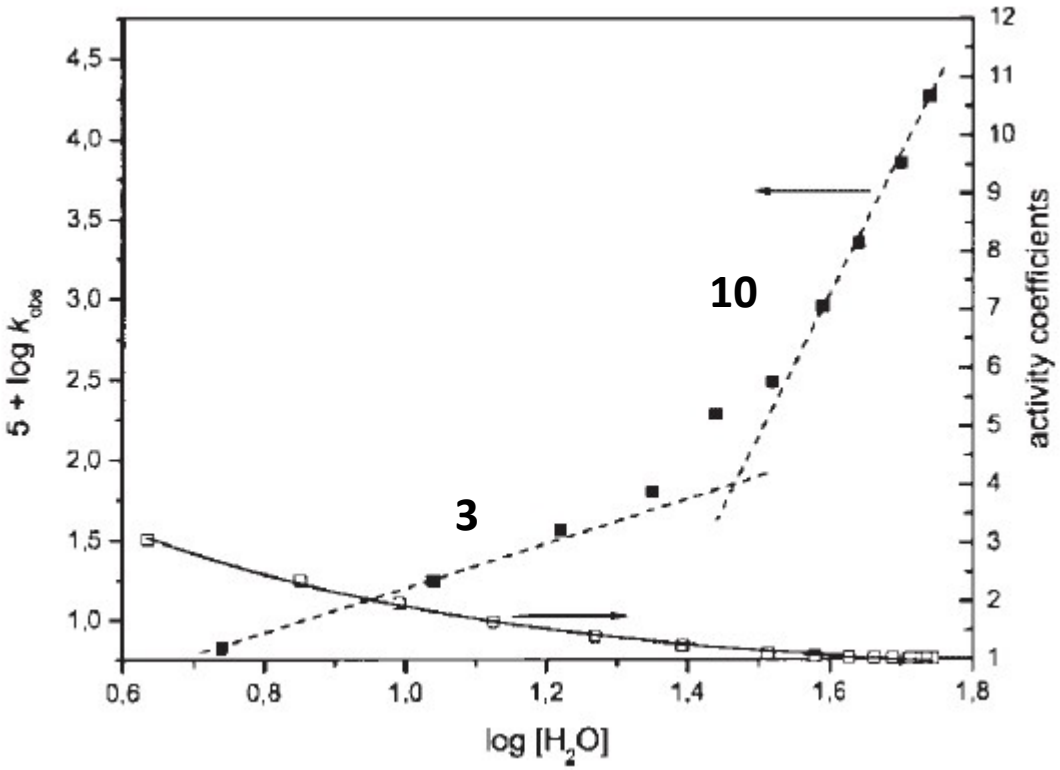
An example




$$k_{obs} = k_1[H_2O]^x$$

$$\log k_{obs} = \log k_1 + x\log[H_2O]$$

Hydrolysis of p-methylphenyl trichloroacetate in aqueous acetonitrile

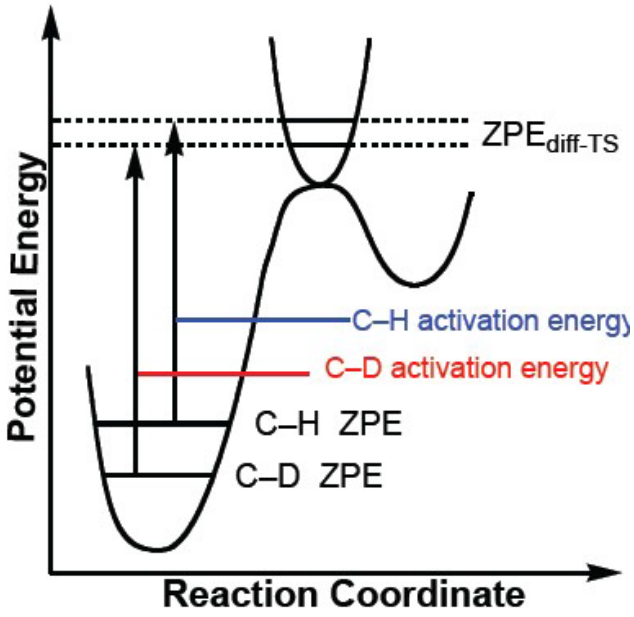


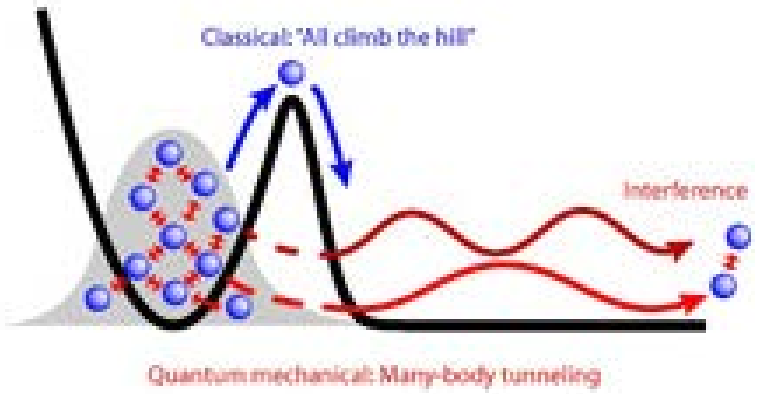

What to do..

Local effective water concentration
vs. average effective water concentration

C. Frasson et al. J. Phys. Org. Chem. 2006; 19: 143–147

# Perform proton inventory experiments: based on kinetic isotope effects




$E_V = 1/2h\nu$

Isotopes changes
- tunneling
- internal excitations
- minimum energy path
- location of the transition state

$$\nu = \frac{1}{2\pi}\sqrt{\frac{k}{m_r}} \qquad m_r = \frac{m_1 m_2}{m_1 + m_2}$$

$$\frac{k_H}{k_D} = \exp^{\frac{\Delta G^D - \Delta G^H}{k_B T}}$$

# Computed KIE on free energy barriers and tunneling

| Parameter | $2H_2O$ | $2D_2O$ [b] |
|---|---|---|
| $\Delta G_1^{\ddagger}$ | 96 | 100 |
| $\Delta G_{-1}^{\ddagger}$ | 104 | 107 |
| $\Delta G_2^{\ddagger}$ | 96 | 101 |
| $\Delta G_{-2}^{\ddagger}$ | 94 | 96 |

Normal primary kinetic isotope effects

KIE effects on tunneling

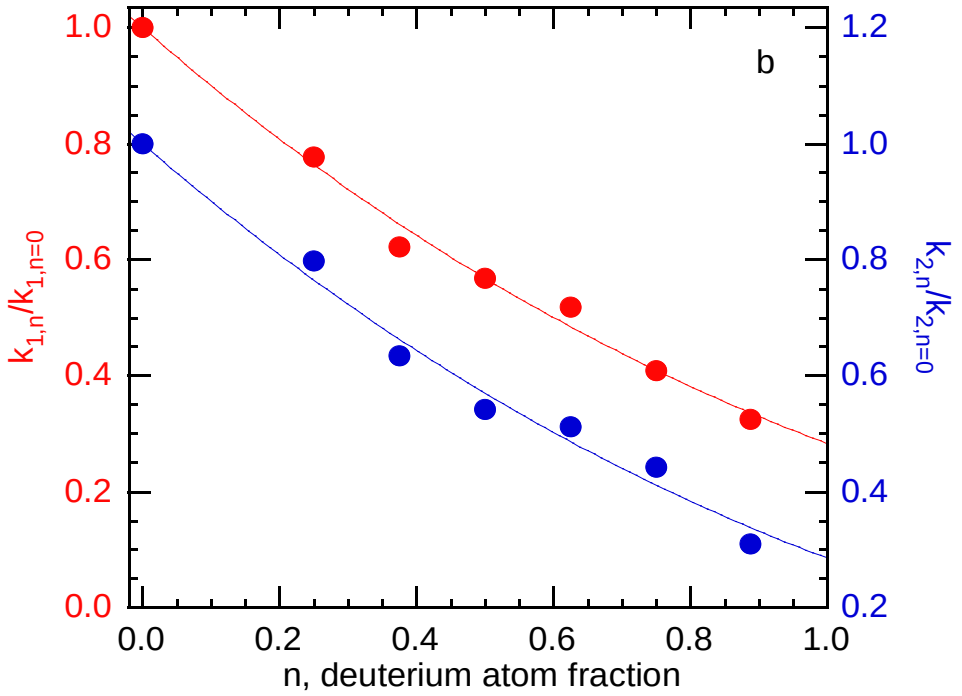
| | $1H_2O/1D_2O$ | | $2H_2O/ 2D_2O$ | |
|---|---|---|---|---|
| Species | $\lvert\omega_{\ddagger}\rvert/cm^{-1}$ | Γ | $\lvert\omega_{\ddagger}\rvert/cm^{-1}$ | Γ |
| $(MTO\text{-}I_1)^{\ddagger}$ | 680/529 | 1.65/1.33 | 353/296 | 1.13/1.09 |
| $(A\text{-}I_2)^{\ddagger}$ | 334/281 | 1.08/1.08 | 251/216 | 1.06/1.05 |

$$\Gamma = (\hbar|\omega_{\ddagger}|/(2k_BT))/\sin[\hbar|\omega_{\ddagger}|/(2k_BT)]$$

# Proton inventory supports two water assisted mechanism

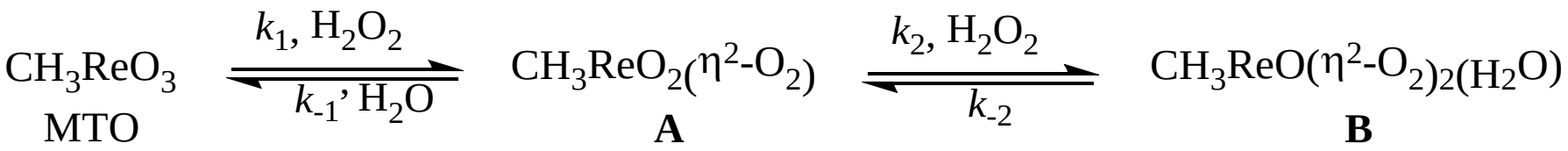
$$k_n = k_0 \frac{\prod_i^{\ddagger}(1-n+n\phi_i^*)}{\prod_j^{RS}(1-n+n\phi_j)} \qquad \phi = \frac{(x_D / x_H)_{solute}}{(x_D / x_H)_{solvent}}$$

$$k_n / k_0 = (1-n+n\phi^*_{H_2O_2})(1-n+n\phi^*_{H_2O})^m = (1-n+n\phi^*)^{m+1}$$




| | Calculated [a] | | Experimental Best fits |
|---|---|---|---|
| | $1H_2O/D_2O$ | $2H_2O/D_2O$ | |
| $\varphi_1$ | 0.41 | **0.63** | **0.66** |
| $\varphi_2$ | 0.43 | **0.56** | **0.66** |

*Manuscript in preparation*




| Parameter | Calculated [a] | | Experimental [b] |
|---|---|---|---|
| | *1 $H_2O/D_2O$* | *2 $H_2O/D_2O$* | |
| $k^w_1$ ($M^{-1}$ $s^{-1}$) | 8.98 x $10^{-6}$ | 8.37 x $10^{-5}$ | 1.02 |
| $k^D_1$ ($M^{-1}$ $s^{-1}$) | 1.48 x $10^{-6}$ | 2.12 x $10^{-5}$ | 0.29 [c] |
| $k^w_2$ ($M^{-1}$ $s^{-1}$) | 3.98 x $10^{-6}$ | 8.75 x $10^{-5}$ | 6.6 x $10^{-2}$ |
| $k^D_2$ ($M^{-1}$ $s^{-1}$) | 7.40 x $10^{-7}$ | 1.51 x $10^{-5}$ | 1.8 x $10^{-2}$ [c] |

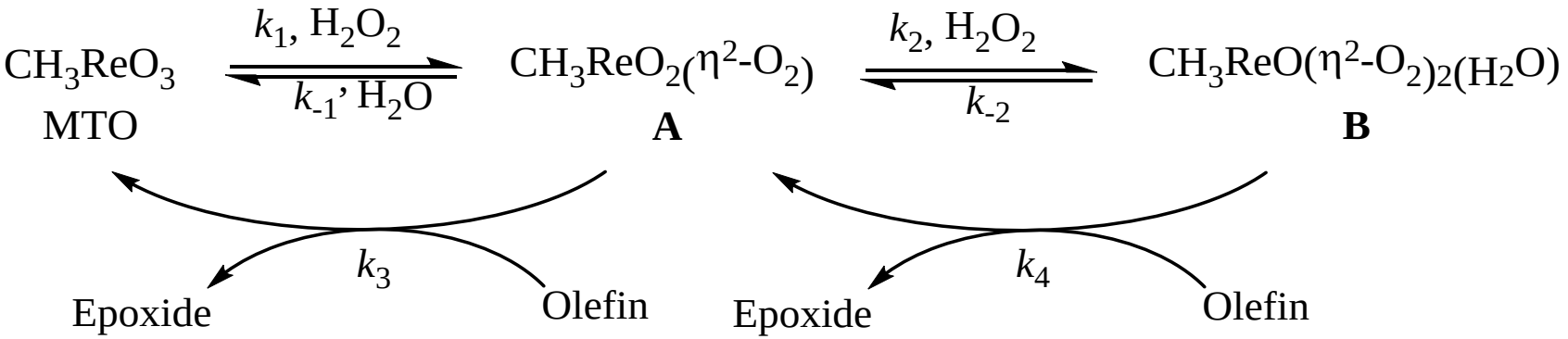
Pseudo-second order

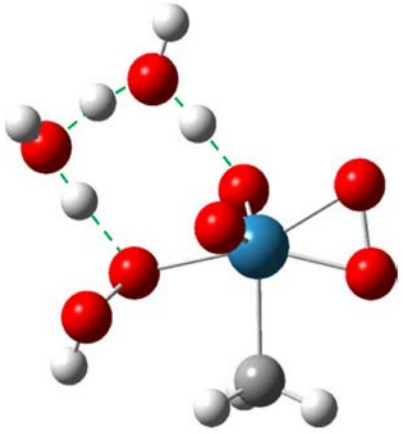
$$\frac{d[A]}{dt} = k_1^{w}[MTO][H_2O_2] - (k_{-1}^{w}[H_2O] + k_2[H_2O_2] + k_3[alk])[A] + (k_{-2}^{w} + k_4[alk])[B]$$

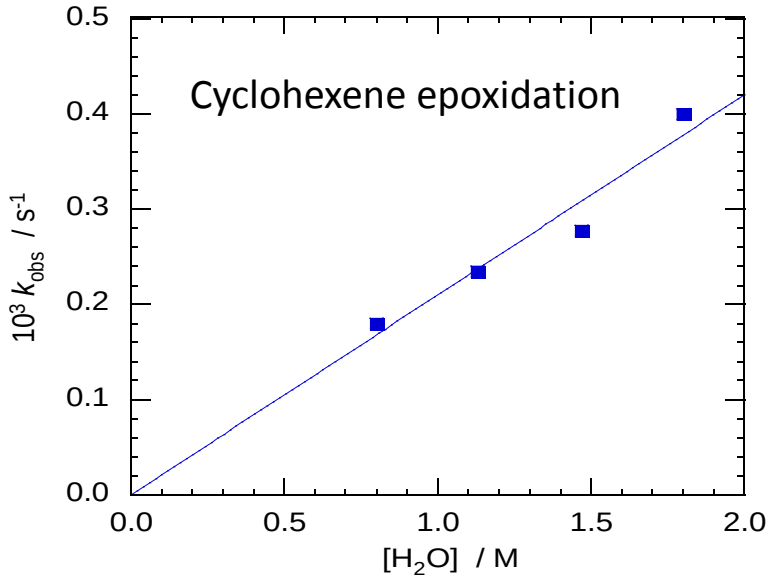
$$\frac{d[B]}{dt} = k_2^{w}[H_2O_2][A] - (k_{-2}^{w} + k_4[alk])[B]$$

$$\frac{d[epoxide]}{dt} = (k_3[A] + k_4[B])[alk]$$

# Experiments and computation support two water-assisted mechanism






Water may play important role for other transition metal reactions involving hydrogen shift steps
Tetramolecular reactions may be more prevalent in solution than normally appreciated

# Questions?

Acknowledgements
Prof. Baron Peters
Prof. Susannah Scott
Dr. Taeho Hwang
Stefan Seritan