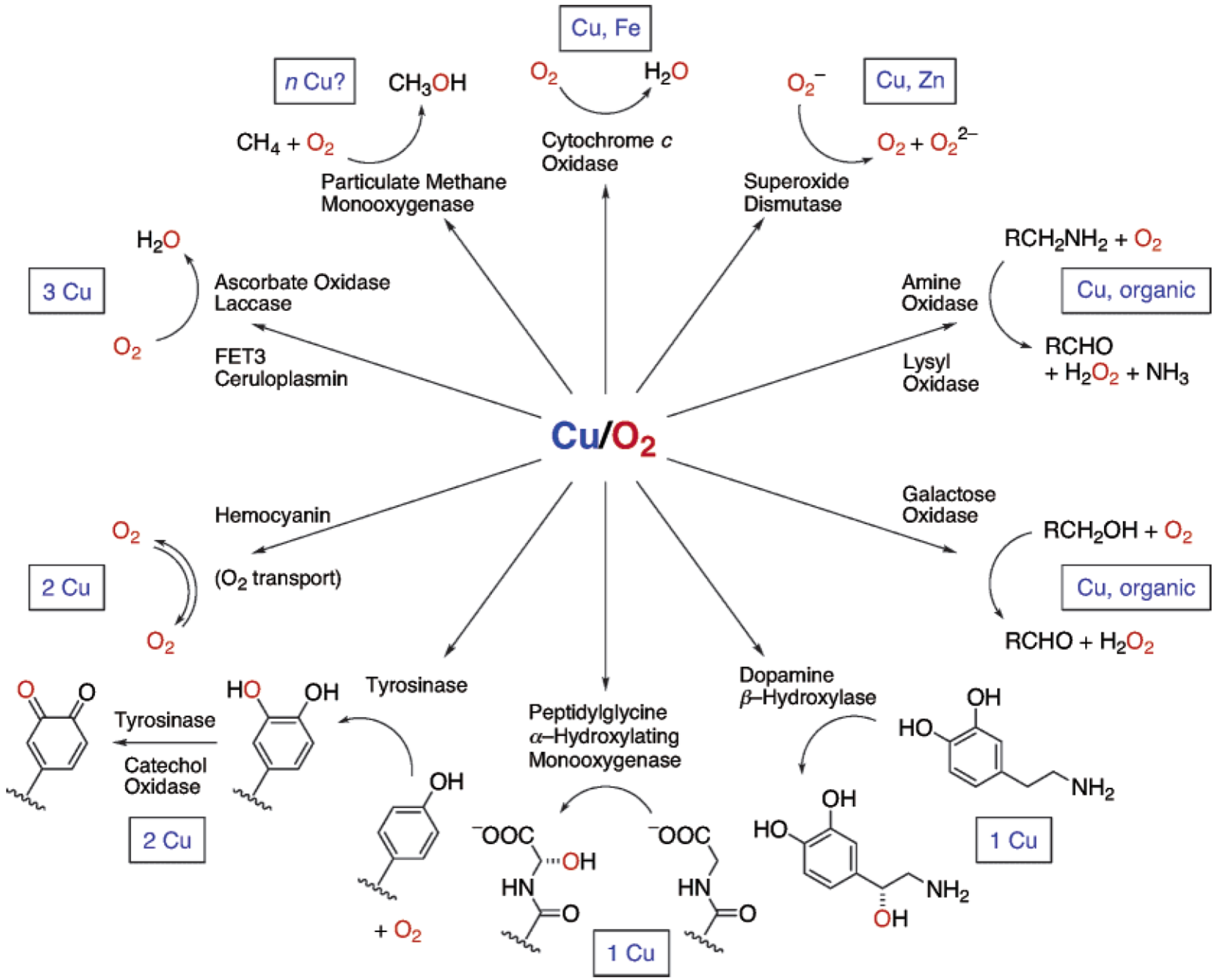
# Synthetic Dioxygen-Copper Complexes
## ~ Toward Dioxygen Activation ~

Literature Seminar

2011. 04.13.

Y. Kimura (D2)

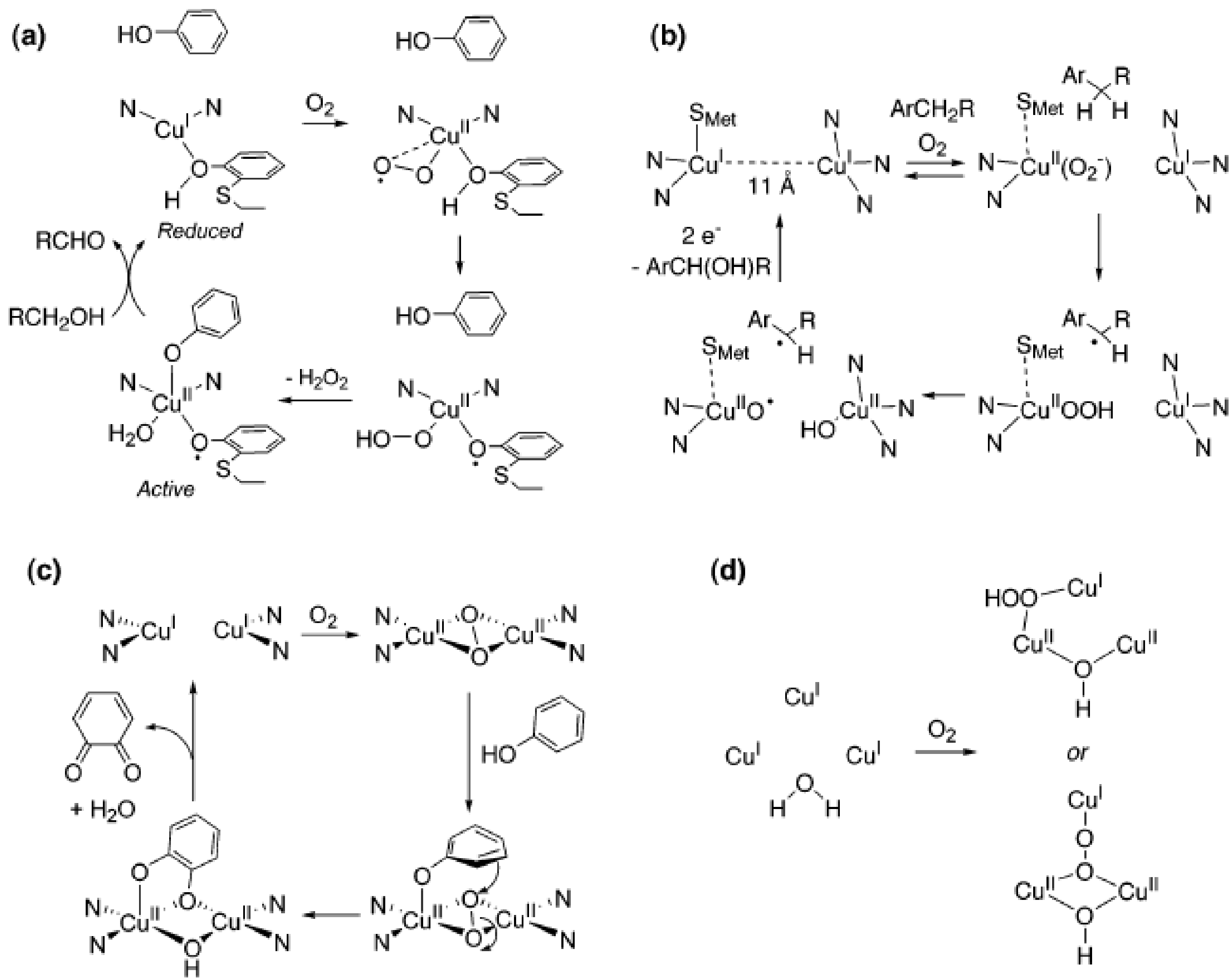
# Introduction 1




Selected Cu enzymes and proteins that activate $O_2$

T. D. P. Stack *et al.*
*Chem. Rev.* **2004**, *104*, 1013

# Introduction 2



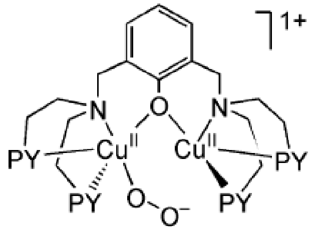

Aspects of the mechanisms proposed for several copper enzymes

W. B. Tolman *et al.*
*Chem. Rev.* **2004**, *104, 1047*

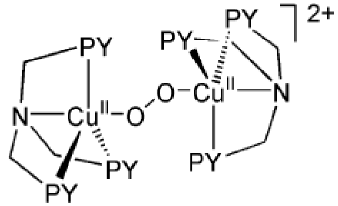
# Today's Topic

## [1] Reactivity Comparisons of $Cu_2$-$O_2$ Complexes

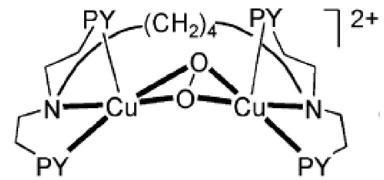
K. D. Karlin *JACS* 1991, *113*, 5322




$[Cu_2(XYLO^-)(O_2)]^+$




$[\{(TMPA)Cu\}_2(O_2)]^{2+}$

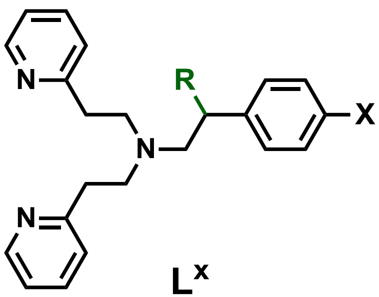



$[Cu_2(N4)(O_2)]^{2+}$

***Structure and Reactivity***

## [2] Intramolecular Benzylic Hydroxylation

S. Itoh *JACS* 1998, *120*, 2890
S. Itoh *ACIE* 2000, *39*, 398

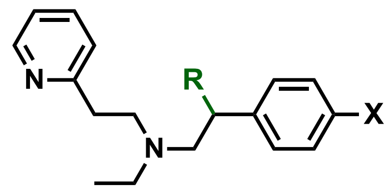



$L^x$

**R = H**

$Cu^I/O_2$
***Ligand Oxidation***

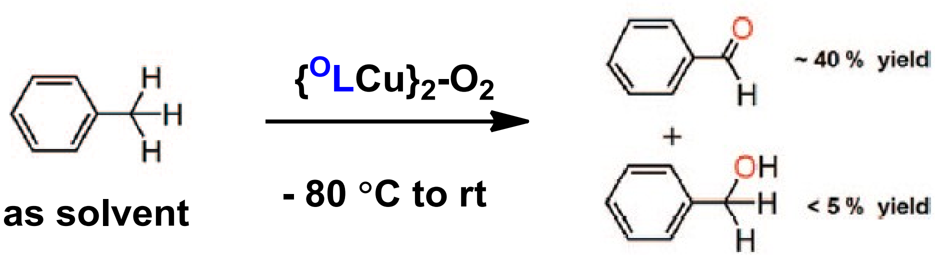
**R = OH**

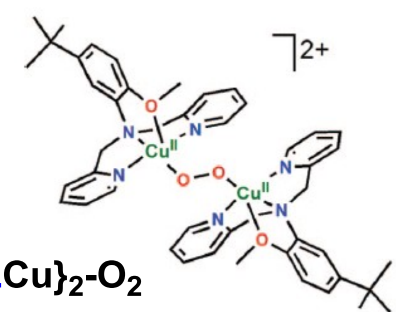



$L'^x$

## [3] Aliphatic C-H Oxidation of Exogenous Substrate

K. D. Karlin *JACS* 2009, *131*, 3230



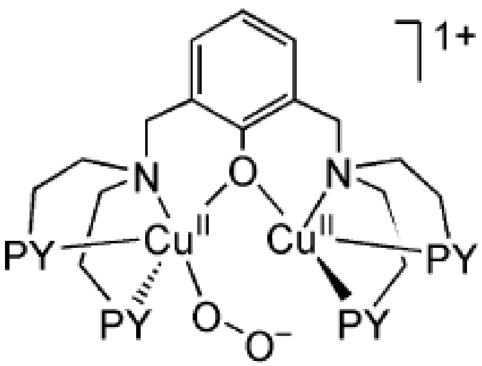

$\{^OLCu\}_2$-$O_2$

# [1] Reactivity Comparisons of $Cu_2$-$O_2$ Complexes

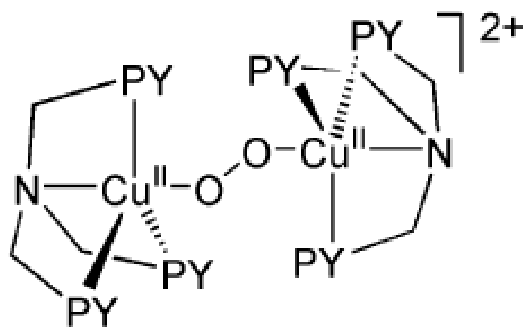
**Reactivity Pattern and Comparisons in Three Classes of Synthetic Copper-Dioxygen {$Cu_2$-$O_2$} Complexes: Implication for Structure and Biological elevance**

**K. D. Karlin *et al.***
***JACS* 1991, *113*, 5322**

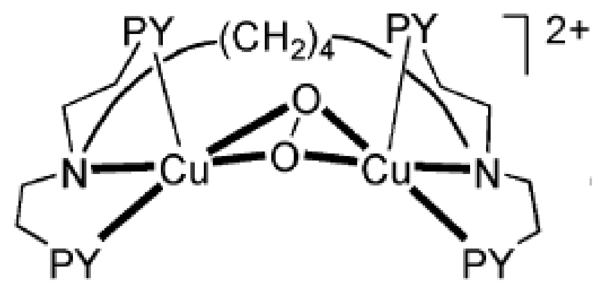
***Relationships between Structure and Reactivity ??***




$[Cu_2(XYLO^-)(O_2)]^+$



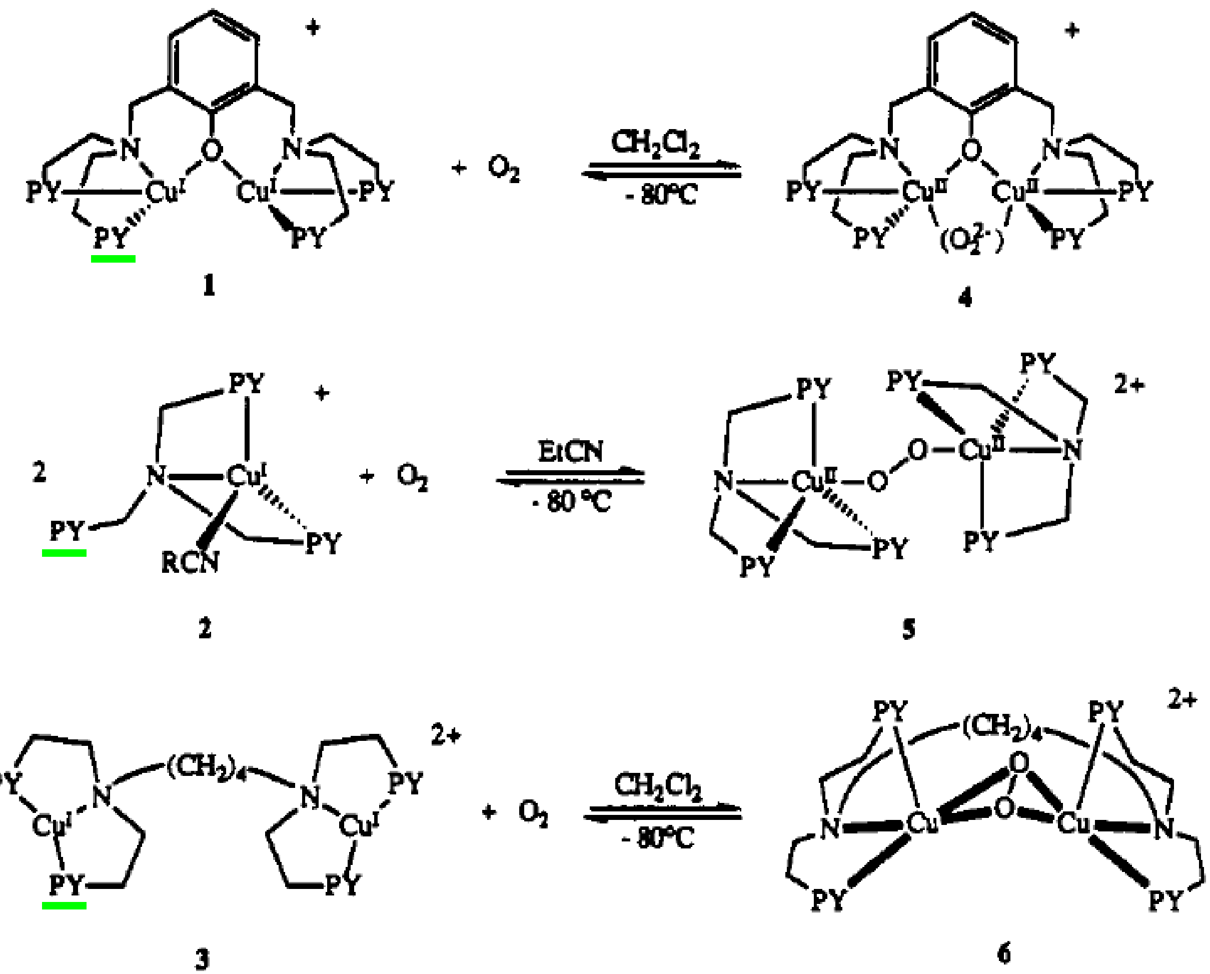

$[\{(TMPA)Cu\}_2(O_2)]^{2+}$




$[Cu_2(N4)(O_2)]^{2+}$

# $Cu_2$-$O_2$ Complex Types: Endo-on and Side-on

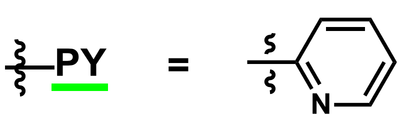
**Scheme I**




$[Cu^{II}_2(XYLO^-)(O_2)]^+$

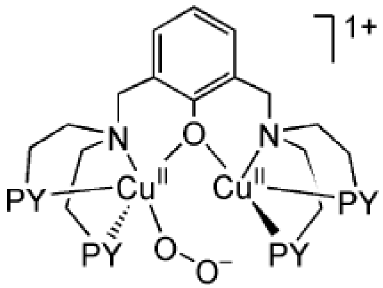
$[\{(CuTMPA)\}_2(O_2)_2]^{2+}$

$[Cu_2(N_4)(O_2)]^{2+}$



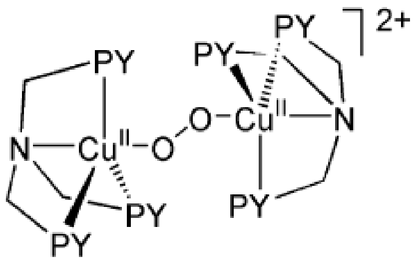

***How do they react ?***

# Reaction with $PPh_3$




$[Cu_2(XYLO^-)(O_2)]^+$

$$[Cu^{II}_2(XYLO^-)(O_2)]^+ + 2\ PPh_3 \xrightarrow[CH_2Cl_2,\ -80\ °C]{Ar} [Cu^{II}_2(XYLO^-)(PPh_3)_2]^+ + O_2$$




$[\{(TMPA)Cu\}_2(O_2)]^{2+}$

$$[\{(CuTMPA)\}_2(O_2)_2]^{2+} + 2\ PPh_3 \xrightarrow[EtCN,\ -80\ °C]{Ar} 2\ [\{Cu(TMPA)(PPh)_3]^{2+} + O_2$$

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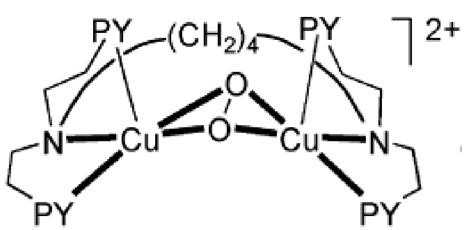
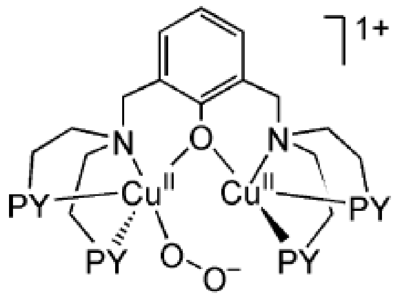


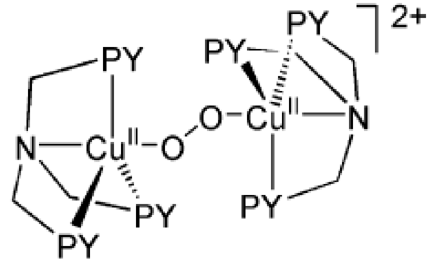

$[Cu_2(N4)(O_2)]^{2+}$

$$[Cu_2(N_4)(O_2)]^{2+} + 4\ PPh_3 \xrightarrow[CH_2Cl_2,\ -80\ °C \Rightarrow rt]{Ar} [Cu_2(N_4)(PPh_3)_2]^{2+} + 2\ PPh_3{=}O$$

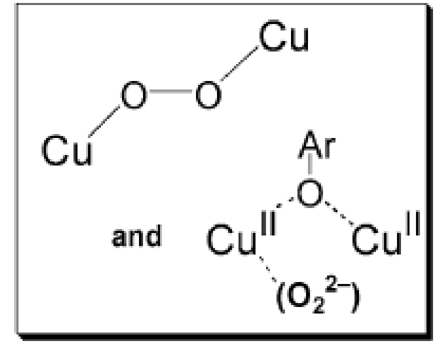
# Reactivity of Endo-on Peroxo Complexes




$[Cu_2(XYLO^-)(O_2)]^+$




$[\{(TMPA)Cu\}_2(O_2)]^{2+}$




**endo on-peroxo**

(a) $\xrightarrow{PPh_3}$ $O_2$ + Cu(I)-$PPh_3$ complex

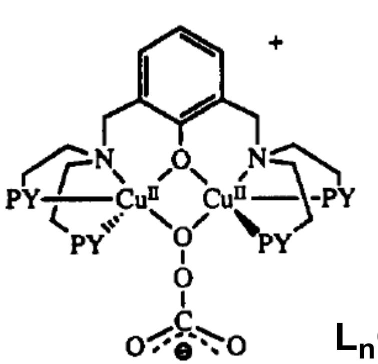
(b) $\xrightarrow{H^+}$ $\{L_nCu_2^{II}(OOH)\}$ $\xrightarrow{H^+}$ $H_2O_2$

(c) $\xrightarrow{RC(O)^+}$ $\{L_nCu_2^{II}O_2C(O)R\}$

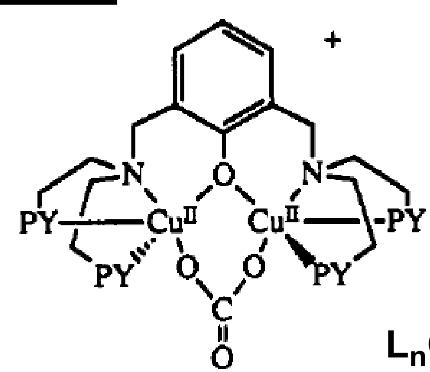
(d) $\xrightarrow{CO_2}$ $\{L_nCu_2^{II}O_2CO\}$ $\longrightarrow$ $\{L_nCu_2^{II}CO_3\}$

(e) $\xrightarrow{PhOH}$ $PhO^-$ + $\{L_nCu_2^{II}(OOH)\}$

**Basic/Nucleophilic Peroxide**

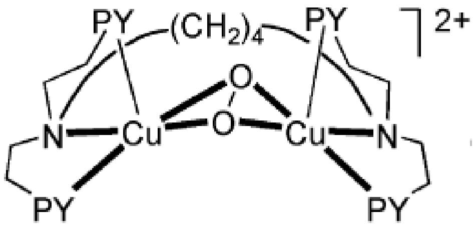



$L_nCu_2^{II}O_2CO_2$

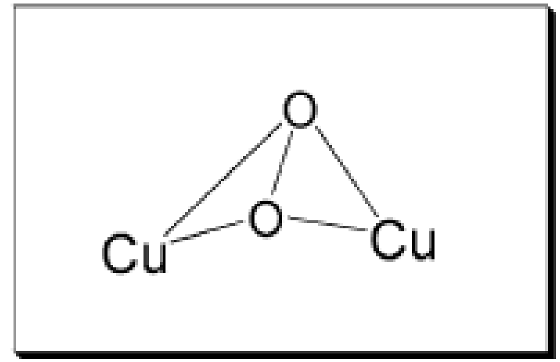



$L_nCu_2^{II}CO_3$

# Reactivity of Side-on Peroxo complex (1)




$[Cu_2(N4)(O_2)]^{2+}$




**side on-peroxo**

(a) $\xrightarrow{PPh_3}$ ⟶ $\{(Nn)Cu_2^{I}(PPh_3)_2\}$ + $O{=}PPh_3$

(b) $\xrightarrow{H^+}$ *No reaction*

(c) $\xrightarrow{RC(O)^+}$ *No reaction*

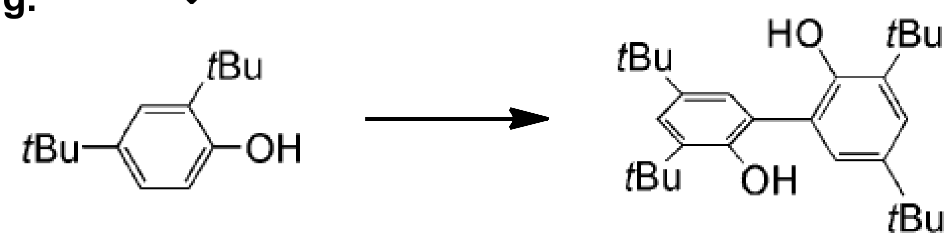
(d) $\xrightarrow{CO_2}$ *No reaction*

(e) $\xrightarrow{PhOH}$ PhO· + Cu(II) Complex(es)

PhO· ⟶ radical coupling products

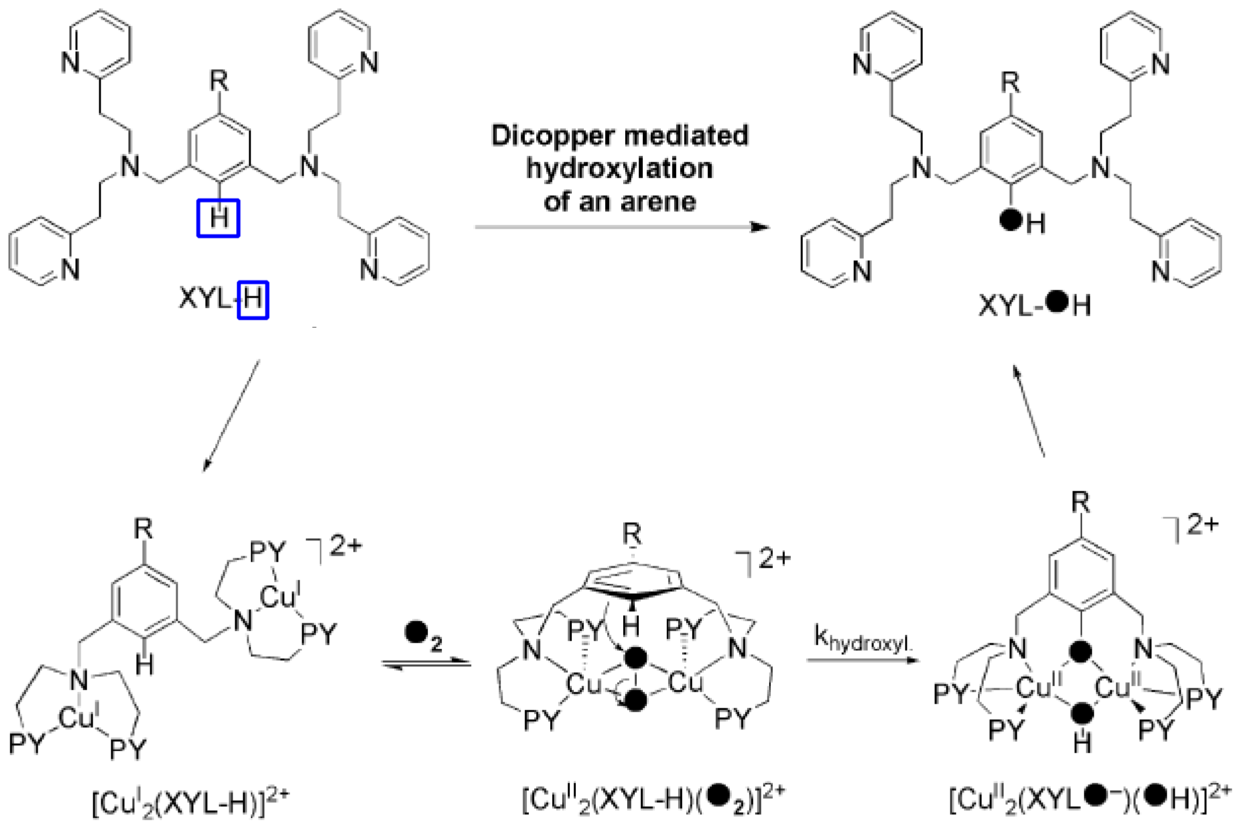
**Non Basic/Electrophilic Peroxide**

**e.g.**



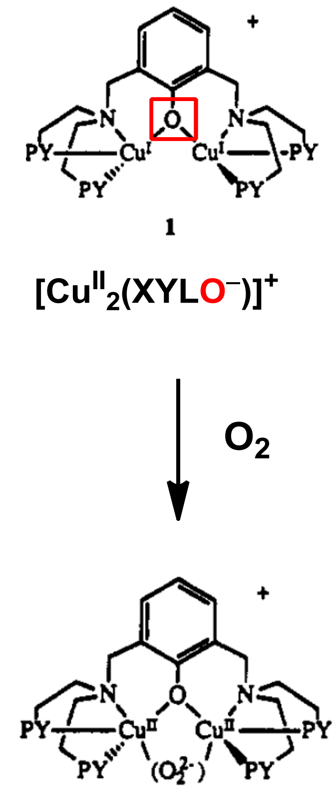

**EPR spectroscopy**
**=> presence of organic radical**
**(most likely phenoxy radical)**

# Reactivity of Side-on Peroxo Complexes (2)




**side on-peroxo**

*cf.*



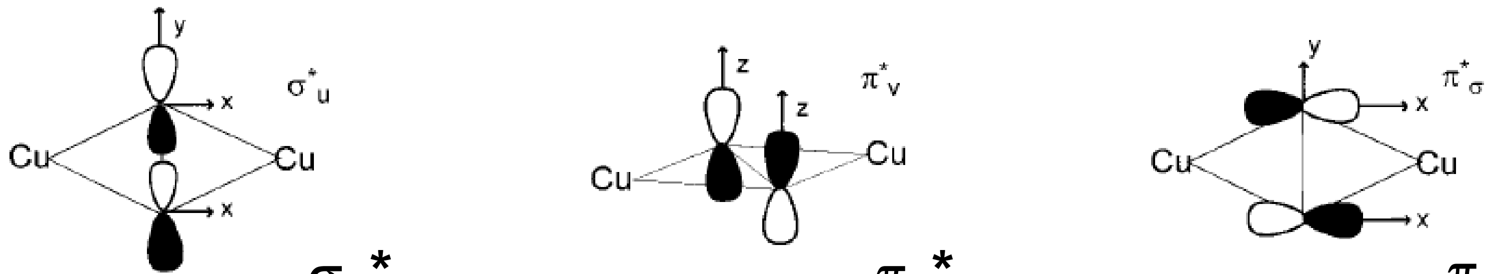

**endo on-peroxo**

- **R = electron-donating: $k_{hydroxyl}$ increases**
- **No KIE observed**
- **NIH shift type 1,2-rearrangement (Me instead of H)**

⟹ **via electrophilic attack**

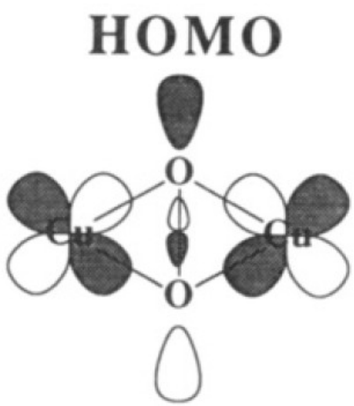
**K. D. Karlin *JACS* 1984, *106*, 2121**

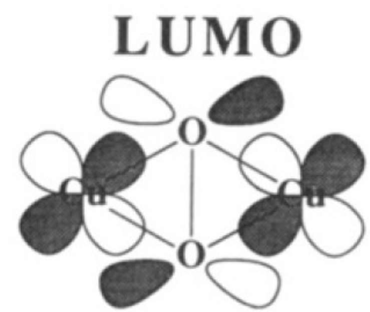
# Explanation for the Different Reactivity (1)




$\sigma_u^*$ $\pi_v^*$ $\pi_\sigma^*$

**HOMO and LOMO level of side-on $\mu$-$\eta^2$:$\eta^2$-peroxo dimer**




**mixing $\sigma^*$ into the HOMO**

⇩

**weakens O-O bond for cleavage**

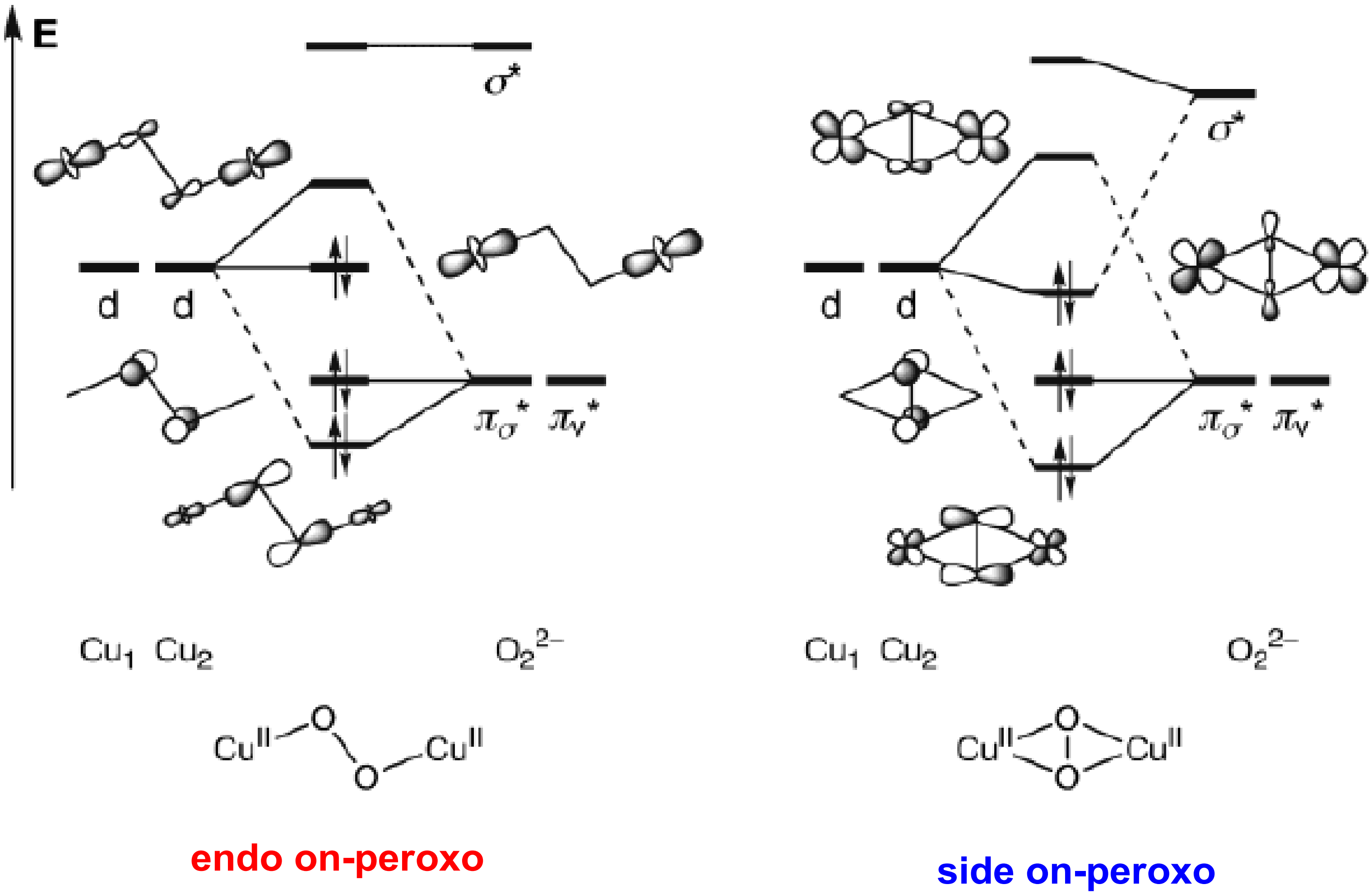
**mixing $\pi_\sigma^*$ into the LUMO**

⇩

**donates electron density to Cu**
**increases peroxide's electrophilicity**

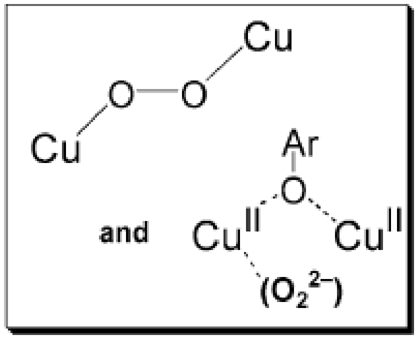
**E. I. Solomon *et al. JACS* 1991 *113*, 3246**

# Explanation for the Different Reactivity (2)



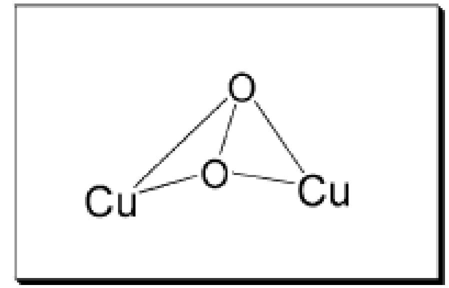

D. P. Stack *et al.*
*Chem. Rev.* 2004, *104* 1013

# Endo-on vs Side-on: Decisive Factor



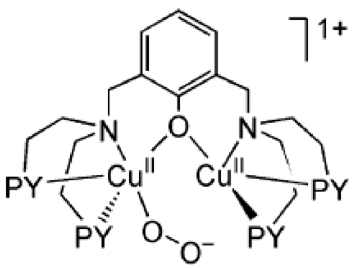

**Denticity is the most decisive factor**

**T. D. P. Stack *et al.* *Chem. Rev.* 2004, *104,* 1013**

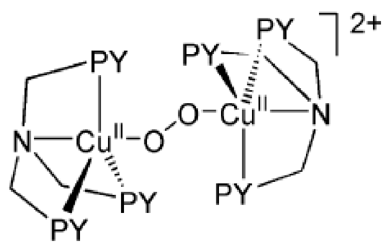



**endo on-peroxo**

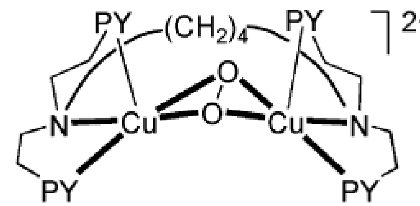
**side on-peroxo**




$[Cu_2(XYLO^-)(O_2)]^+$




$[\{(TMPA)Cu\}_2(O_2)]^{2+}$




$[Cu_2(N4)(O_2)]^{2+}$

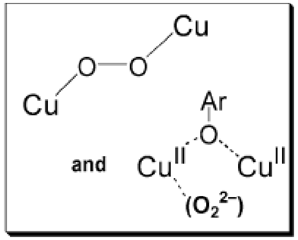
⇓

**Basic/Nucleophilic Peroxide**

⇓

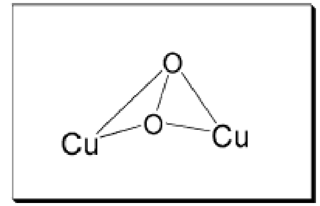
**Non Basic/Electrophilic Peroxide**

# Endo-on vs Side-on: Key Factor for Small Molecule Activation ?




**Basic/ Nucleophilic Peroxide**

**endo on-peroxo**




**Non Basic/ Electrophilic Peroxide**

**side on-peroxo**

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**In the case of $N_2$ activation chemistry...**

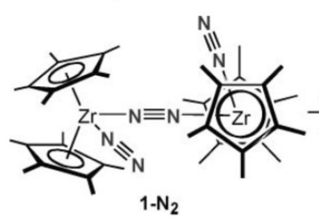
**Ref. Kimura's Lit. Seminar (20100421)**

J. E. Bercaw et al. *J. Am. Chem. Soc.* **1974**, *96*, 6229

$$2\ Cp^*_2ZrCl_2 + 4\ Na(Hg) \xrightarrow{1\ atm\ N_2} (Cp^*_2Zr)(N_2)_3 + 4\ NaCl$$

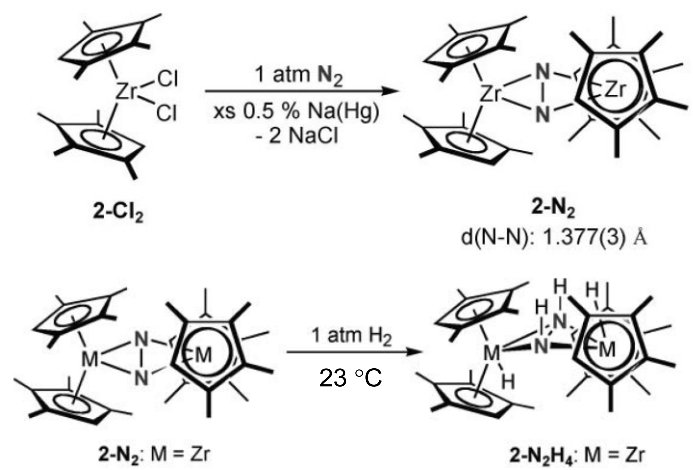
||

**No $N_2$ reducition**
**$N_2$ dissociation** ← $H_2$




**end-on**
**Zr-$N_2$** ⟹ **reductively inert**

P. J. Chirik et al. *Nature* **2004**, *427*, 527

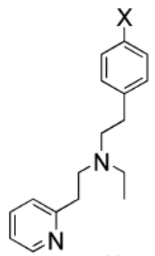



**side-on**
**Zr-$N_2$** ⟹ **$N_2$ reduced under mild conditons**

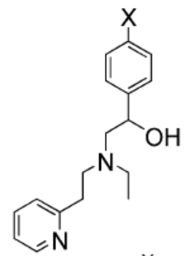
# [2] Intramolecular Benzylic Hydroxylation

**Aliphatic Hydroxylation by a Bis(μ-oxo)dicopper(III) Complex**

Itoh *et al.*
*ACIE* 2000, *39*, 398




$L^X$




$L_{OH}^X$

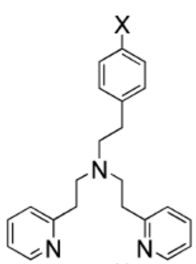
$2\ Cu^I\ (L^x) + O_2 \longrightarrow L_{OH}^x + Cu^{II}$ product

$2\ Cu^I\ (L'^x) + O_2 \longrightarrow L_{OH}'^x + Cu^{II}$ product

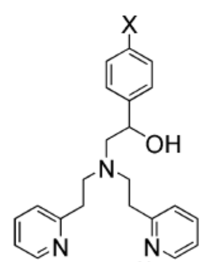
⇒ *Different Rate-Determining Step*

⇓

*Elucidation of Actual Active Species*




$L'^X$




$L_{OH}'^X$

**Mechanistic Studies of Aliphatic Ligand Hydroxylation of a Copper Complex by Dioxygen: A Model Reaction for Copper Monooxygenases**

Itoh *et al.*
*JACS* 1998, *120*, 2890

# $L^x$: $O_2$ Binding Mode

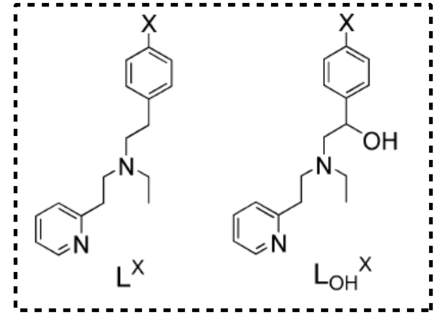
2 $Cu^I$ ($L^x$) → ($O_2$, acetone, - 90 °C) [ $Cu_2^{II}(L^x)_2$-$O_2$ ] → (- 78 °C to rt) $L_{OH}^x$ + $Cu^{II}$ product

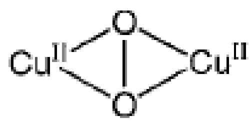
46% (max 50%)

||

[$Cu^I(L^x)$MeCN]$PF_6$

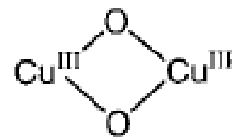
↑ $O_2$ binding mode??



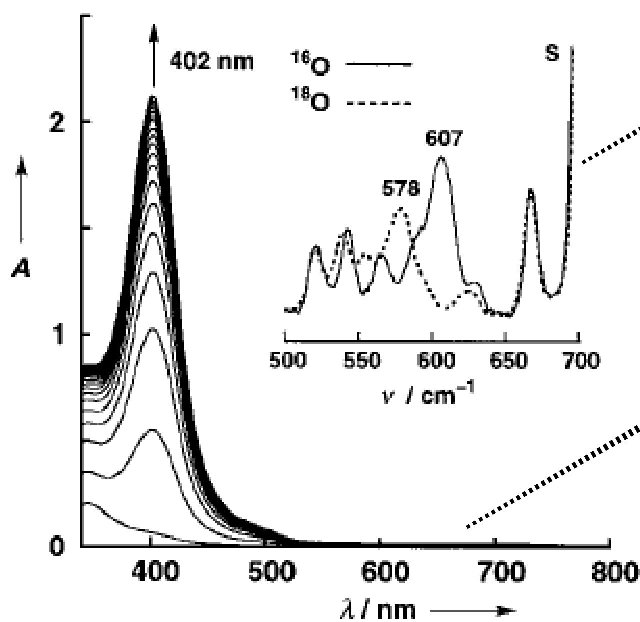




μ–η²:η²-peroxo

or




bis(μ-oxo)dicopper




resonance Raman

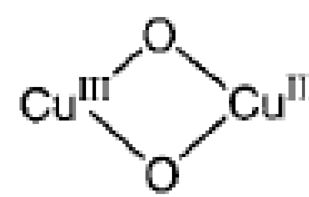
Cu-O, O-O vibration mode

UV-Vis

oxygen to copper charge transfer

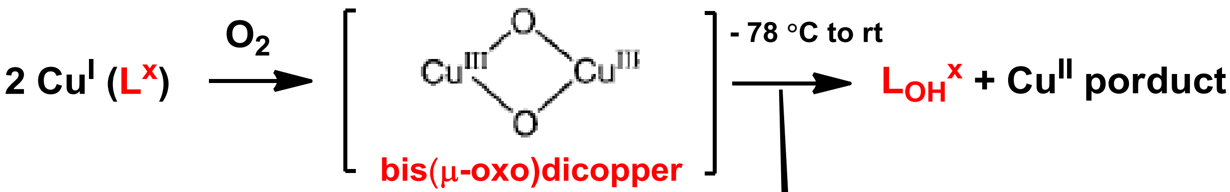
$Cu_2^{II}(L^x)_2$-$O_2$

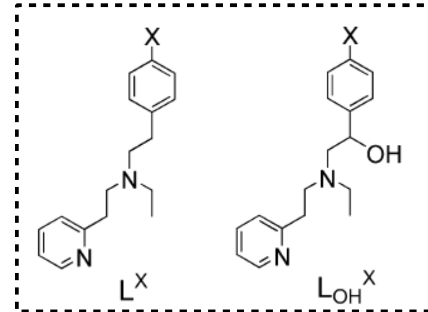
||

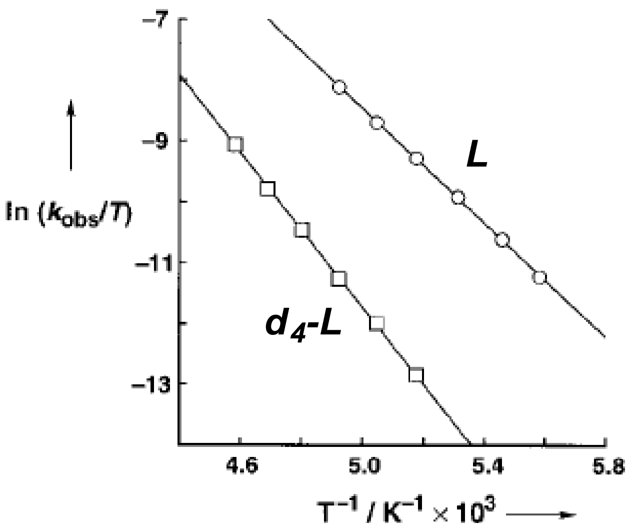


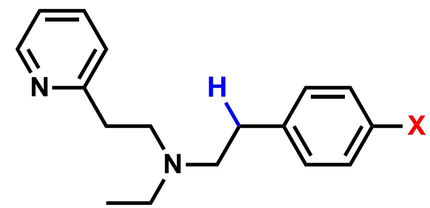

bis(μ-oxo)dicopper

# $L^x$: Hydroxylation



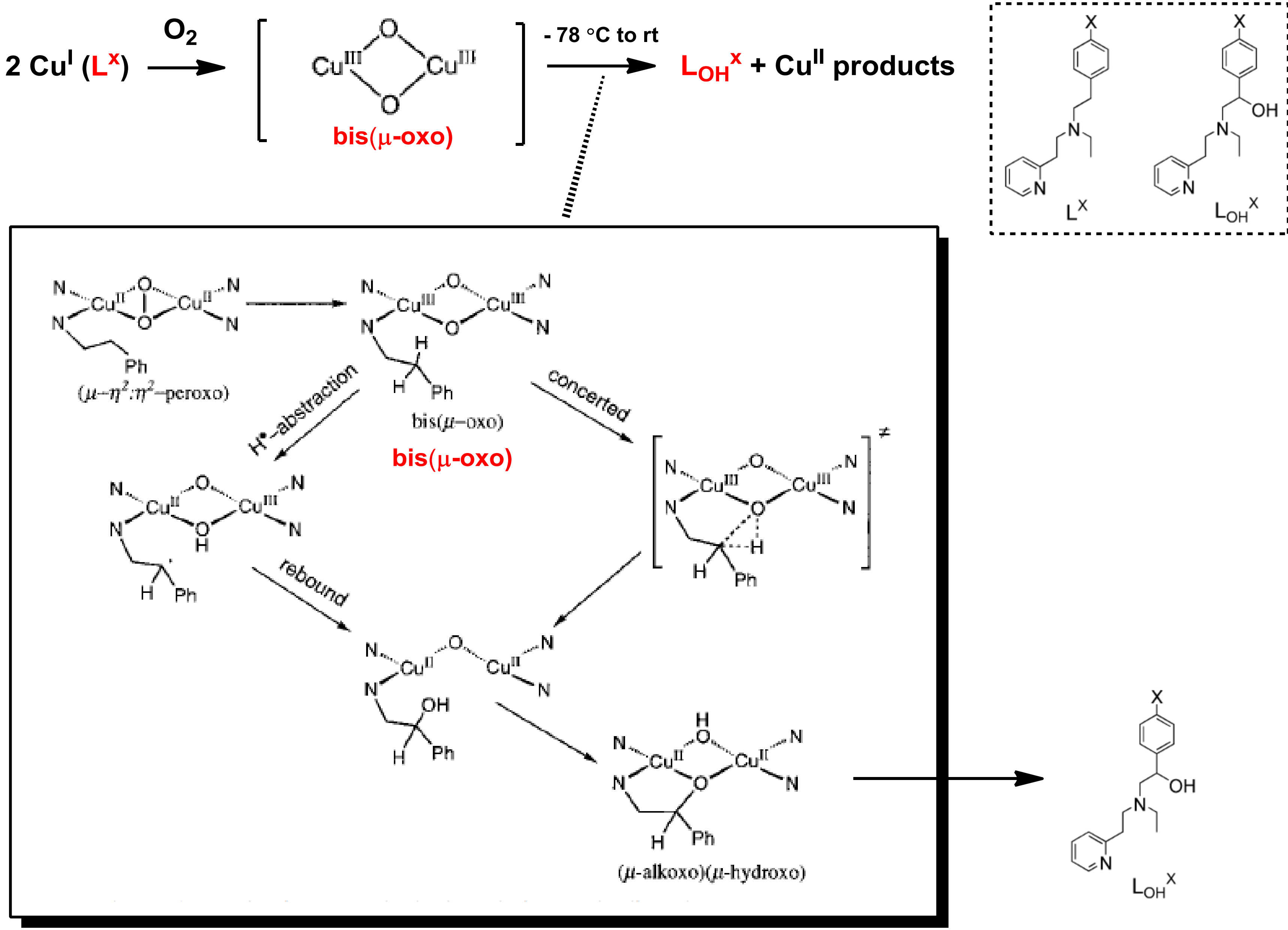




- rate: first-order kinetics
- Eyring plot: $\Delta S^{\ddagger} = -73\ JK^{-1}mol^{-1}$
- KIE: $k_H/k_D = 35$ (– 80 °C)

- Hammett analysis ($k_{obs}$ vs $\sigma^+$)
  $\rho = -1.48$
  [ $-5<\rho<-2$: benzylic carbocation
  $-1.5<\rho<0$: H atom abstraction
  from benzylic position ]

=> intramolecular rate-deteming H atom abstraction and
rebound of a copper-bound OH group

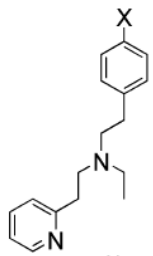
# $L^x$: Hydroxylation Mechanism



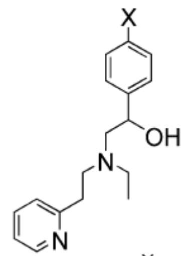
# [2] Intramolecular Benzylic Hydroxylation

**Aliphatic Hydroxylation by a Bis(μ-oxo)dicopper(III) Complex**

Itoh *et al.*
*ACIE* 2000, *39*, 398



$L^X$



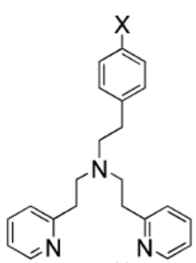
$L_{OH}^X$

$2\ Cu^I\ (L^x) + O_2 \longrightarrow L_{OH}^x + Cu^{II}$ product

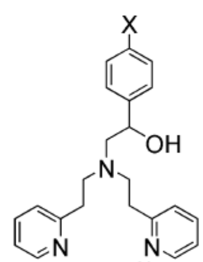
$2\ Cu^I\ (L'^x) + O_2 \longrightarrow L_{OH}'^x + Cu^{II}$ product

*Different Rate-Determining Step*

*Elucidation of Actual Active Species*



$L'^X$



$L_{OH}'^X$

**Mechanistic Studies of Aliphatic Ligand Hydroxylation of a Copper Complex by Dioxygen: A Model Reaction for Copper Monooxygenases**

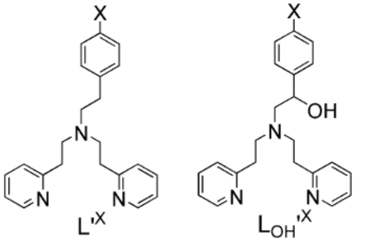
Itoh *et al.*
*JACS* 1998, *120*, 2890

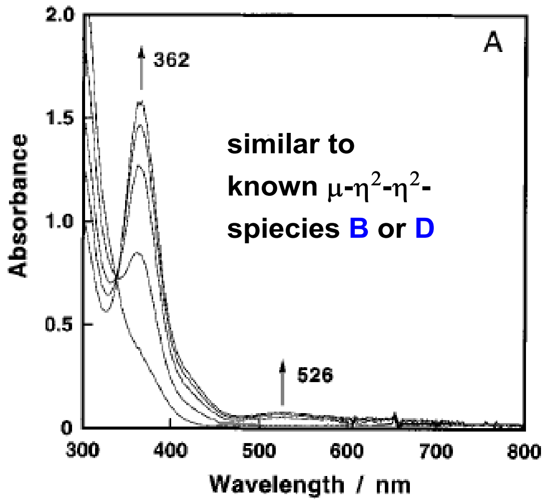
# L'x: $O_2$ Binding Mode

2 $Cu^I$ (L'x) ‖ [Cu(L'x)]$PF_6$ —$O_2$, DCM, - 78 °C→ [$Cu_2^{II}$(L'x)$_2$-$O_2$] —- 78 °C => rt→ $L_{OH}$'x + $Cu^{II}$ porduct

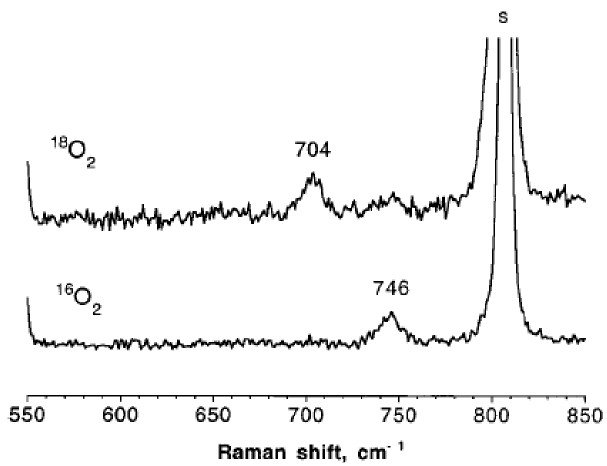
47% (max 50%)

$O_2$ binding mode??

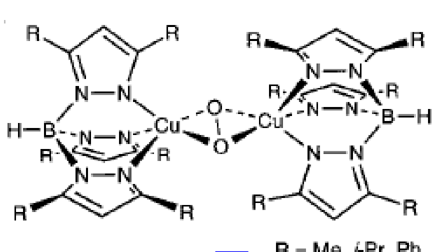



UV-vis

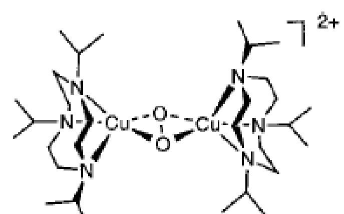



rRaman




B

Kitajima, Moro-oka et al.
*JACS* 1989 *111* 8975



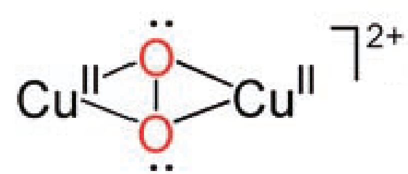

D (μ–$\eta^2$:$\eta^2$)

Kitajima, Moro-oka et al.
*JACS* 1994 *116* 9785

⟹

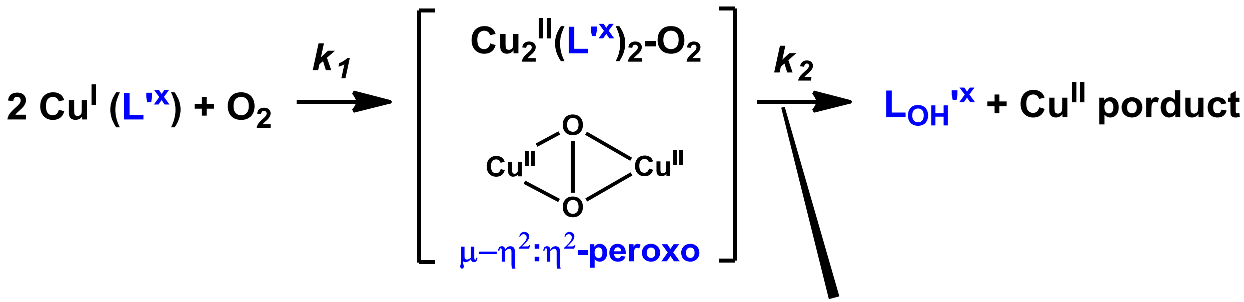
[$Cu_2^{II}$(L'x)$_2$-$O_2$]

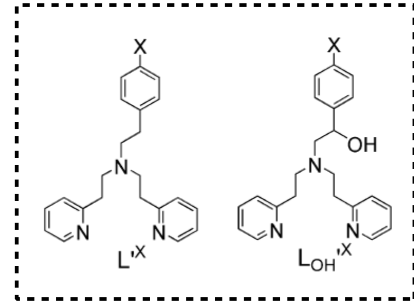
≡

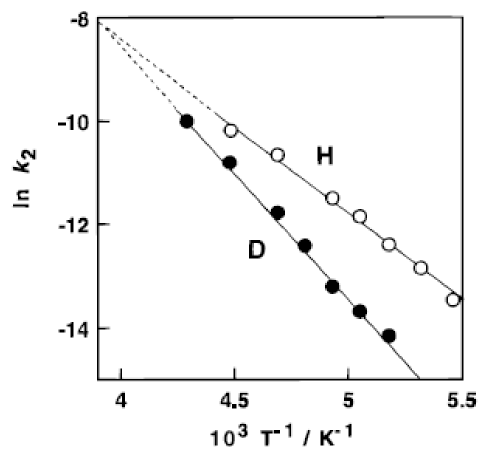



μ–$\eta^2$:$\eta^2$-peroxo

# L'x: Benzylic Hydroxylation




**Eyring plot: $\Delta S^{\ddagger} = -155\ JK^{-1}mol^{-1}$**

**=> highly constrained TS for RDS**

**KIE: $k_H/k_D$ = 1.8 (– 40 °C )**

**=> very small (as "normal" H abs.)**

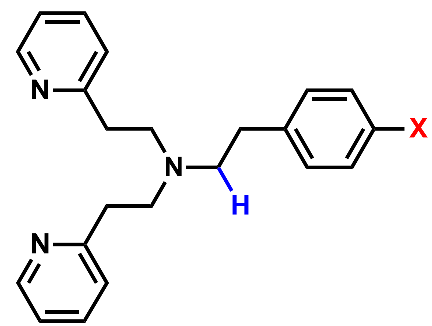



**Table 2.** *p*-Substituent Effects on the Formation and Decay Rate Constants ($k_1$ and $k_2$) of the $\mu$-$\eta^2$:$\eta^2$-Peroxodicopper(II) Complex at −80 °C[a]

| run | X (ligand) | solvent | $\lambda_{max}$ | $k_1$ ($M^{-1}\ s^{-1}$) | $10^4 k_2$ ($s^{-1}$) |
|---|---|---|---|---|---|
| 1 | $CH_3$ (1b) | $CH_3OH$ | 360 | 0.39 | 3.1 |
| 2 | H (1a) | $CH_3OH$ | 362 | 2.0 | 3.1 |
| 3 | Cl (1c) | $CH_3OH$ | 362 | 4.1 | 3.7 |
| 4 | H (1a) | acetone | 362 | 1.8 | 4.8 |
| 5 | $NO_2$ (1d) | acetone | 362 | 7.1 | 5.1 |

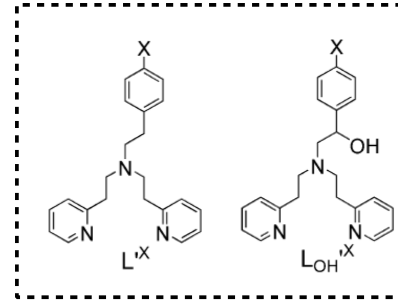
[a] Counteranion: $PF_6^-$.

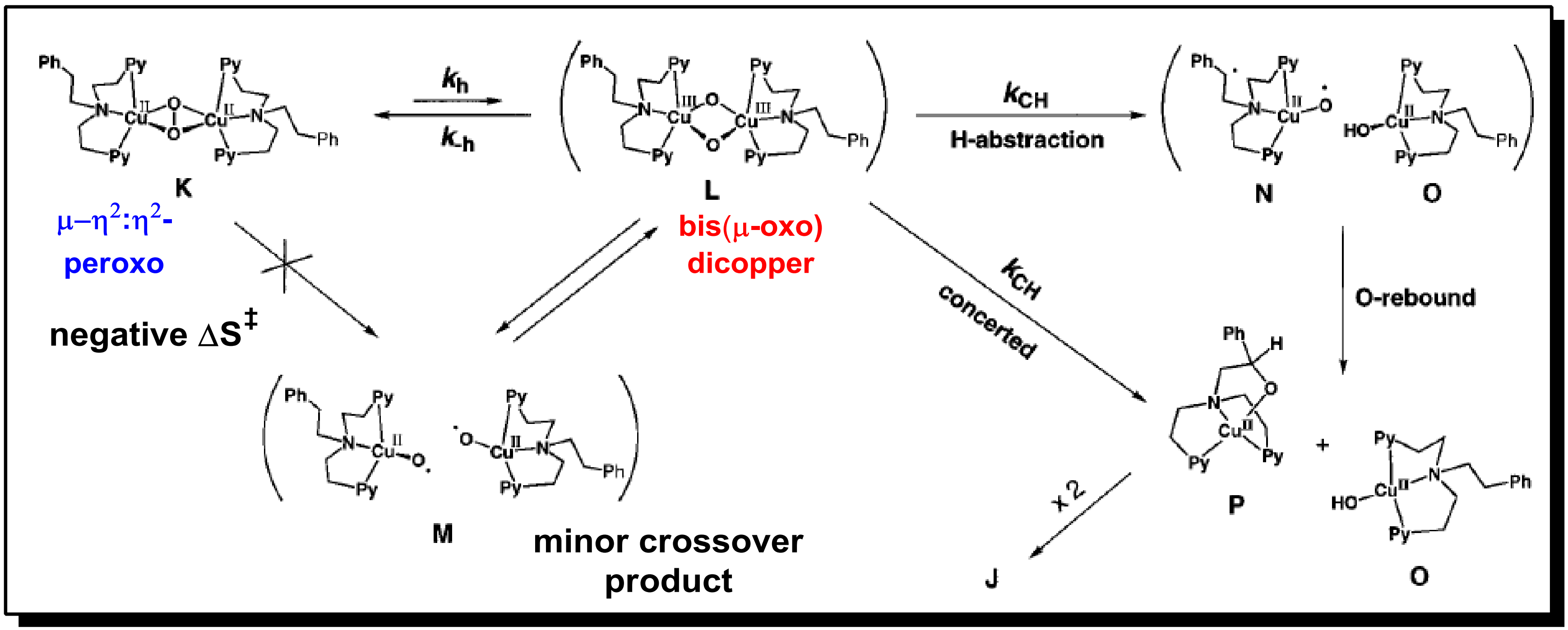
***p*-substituents:**
**little effect on the ligand hydroxylation**

**=> benzylic hydrogen transfer is not involved in RDS ??**

# L'x:Hydroxylation Mechanism

$2\ Cu^I(L'^x) + O_2 \xrightarrow{k_1} [Cu_2^{II}(L'^x)_2\text{-}O_2]\ (\mathbf{K}) \xrightarrow{k_2} L_{OH}'^x + Cu^{II}$ porduct




**if O-O cleav. is solely RDS => KIE = 1**

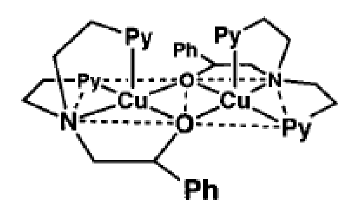
**if $k_h << k_{-h} \sim k_{CH}$**

$\Longrightarrow k_2 = k_h k_{CH}/(k_{-h} + k_{CH})$

**non deuterated: $k_{CH} >> k_{-h}$**

**deuterated: $k_{-h} \sim k_{CH}$**

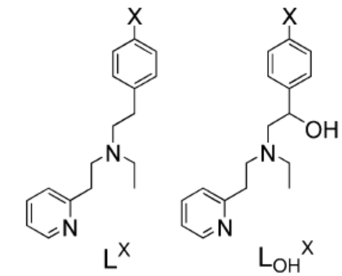
$\Longrightarrow$ **KIE $\neq$ 1**

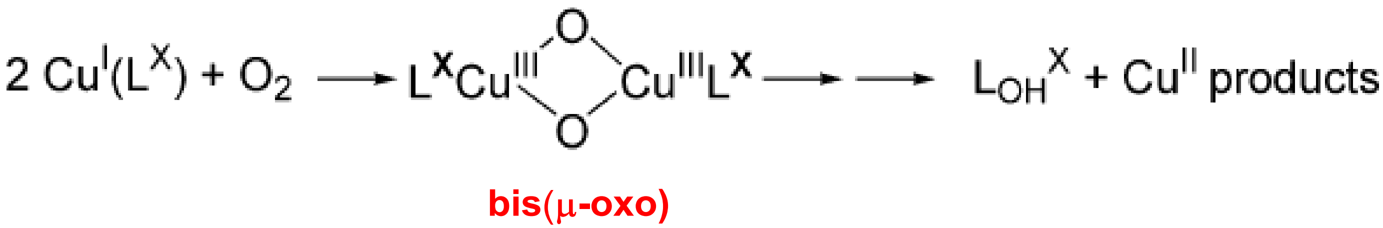



**J**

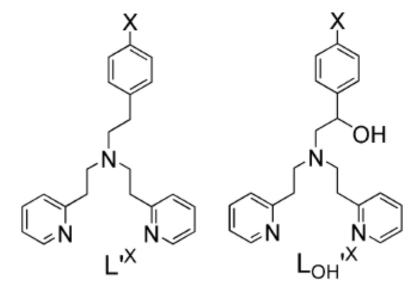
# Intramolecular Benzylic Hydroxylation: Summary

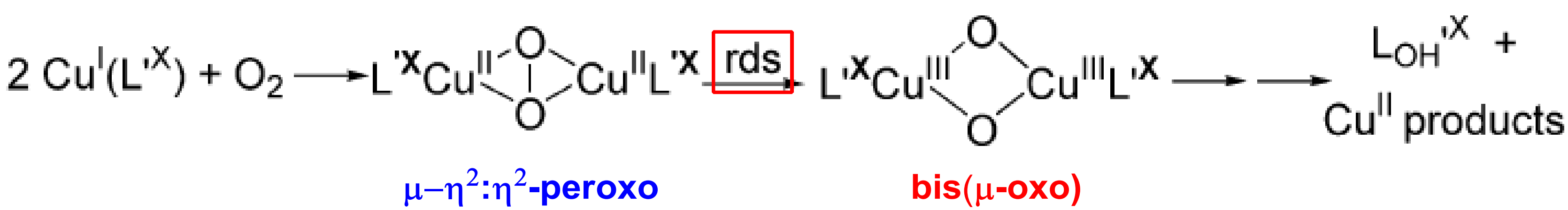
**Itoh *et al.* *ACIE* 2000 *39* 398**



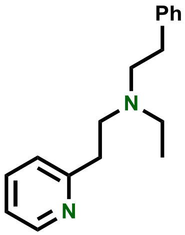




**Itoh *et al.* *JACS* 1998 *120* 2890**



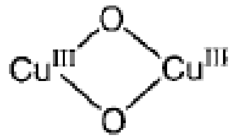



# Ligand Denticity and $O_2$ Binding Mode




$L^x$

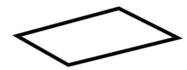
**bidentate**



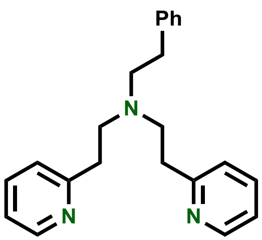

**bis(μ-oxo)**

**Cu(III) $d^8$**

**square-planar**

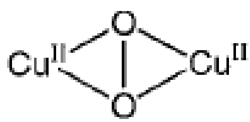


**T. D. P. Stack *et al.* *Chem Rev*. 2004, *104,* 1013**




$L'^x$

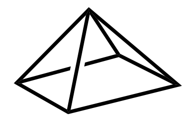
**tridentate**




**$\mu$–$\eta^2$:$\eta^2$-peroxo**

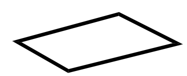
**Cu(II) $d^9$**

**square-pyramidal**



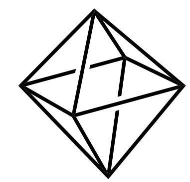
**or**

**square-planar**



**Jahn-Teller effect**

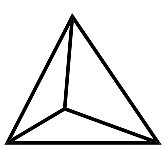
**geometrical flexibility**



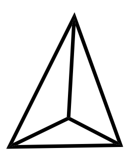
**octahedral**

---

**cf.**



**tetrahedral**

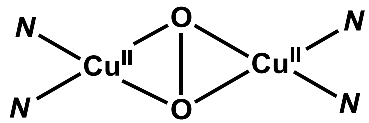


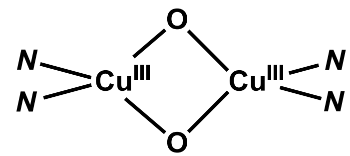
**trigonal monopyramidal**

**Cu(I) $d^{10}$**

**relatively indifferent to coordination topology**
**dominated by steric factor and structural constrain**
**commonly tetrahedral of trigonal monopyramidal**

# Peroxo vs μ-oxo: General Tendency

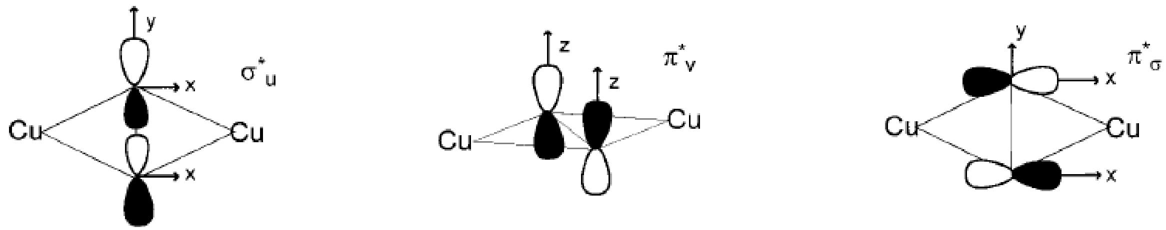


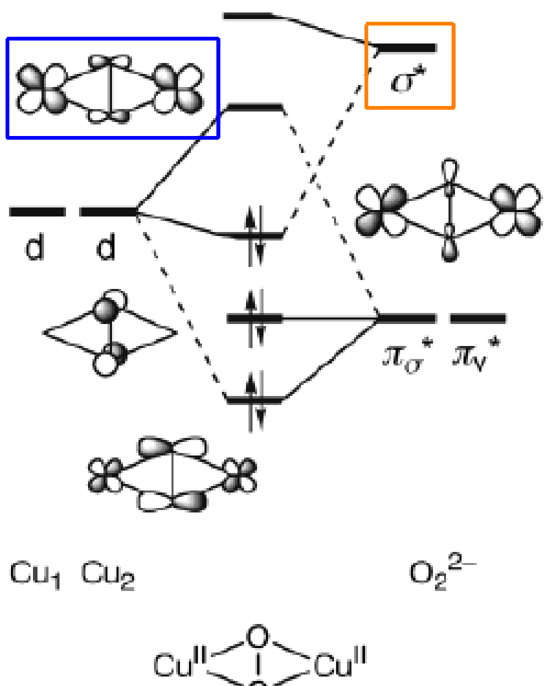




| **General Tendency** NOT Always Hold True | **$\mu$–$\eta^2$:$\eta^2$-peroxo** | **bis($\mu$-oxo)** | **key factor** |
|---|---|---|---|
| **Ligand Denticity** | **tridententate** | **didentate** | **coordination field & oxidation state** |
| **Ligand Steric Hindrance** | **more bulky** | **less bulky** | **Cu-Cu length** |
| ***N*-Cu-*N* Angle** | **less acute** | **more acute** | **O-Cu-O angle** |
| **Type of *N*-Donor** | **pyridyl-N (less $e^-$-donating)** | **alkyl amine (more $e^-$-donating)** | **stabilization of higher oxidation state** |

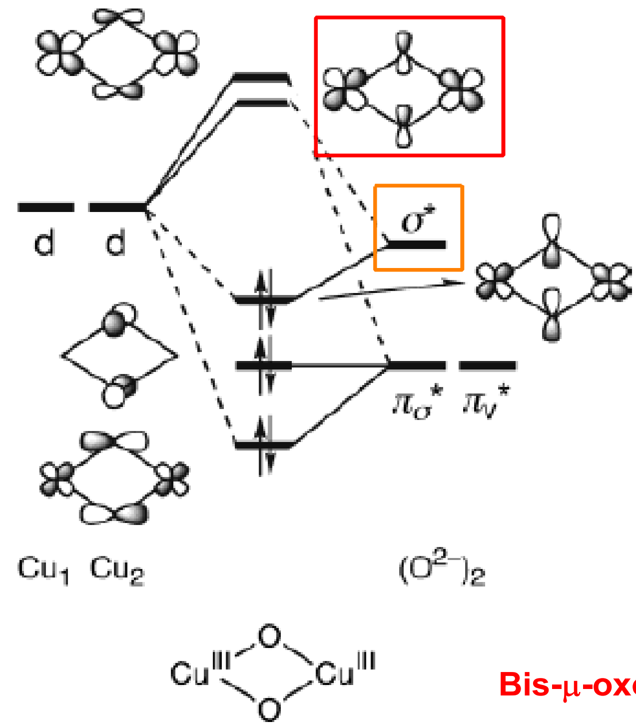

K. D. Karlin *et al. Adv. Inorg. Chem.* 2006, *58*, 131
T. D. P. Stack. *et al. Chem. Rev.* 2004, *104*, 1013

# Explanation for Different Reactivity (1)




μ–η2:η2–peroxo

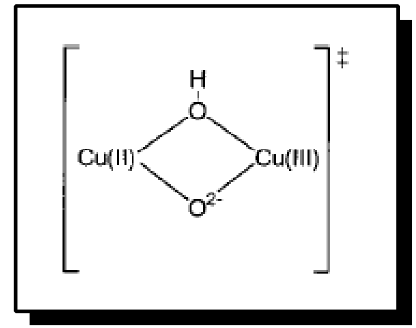


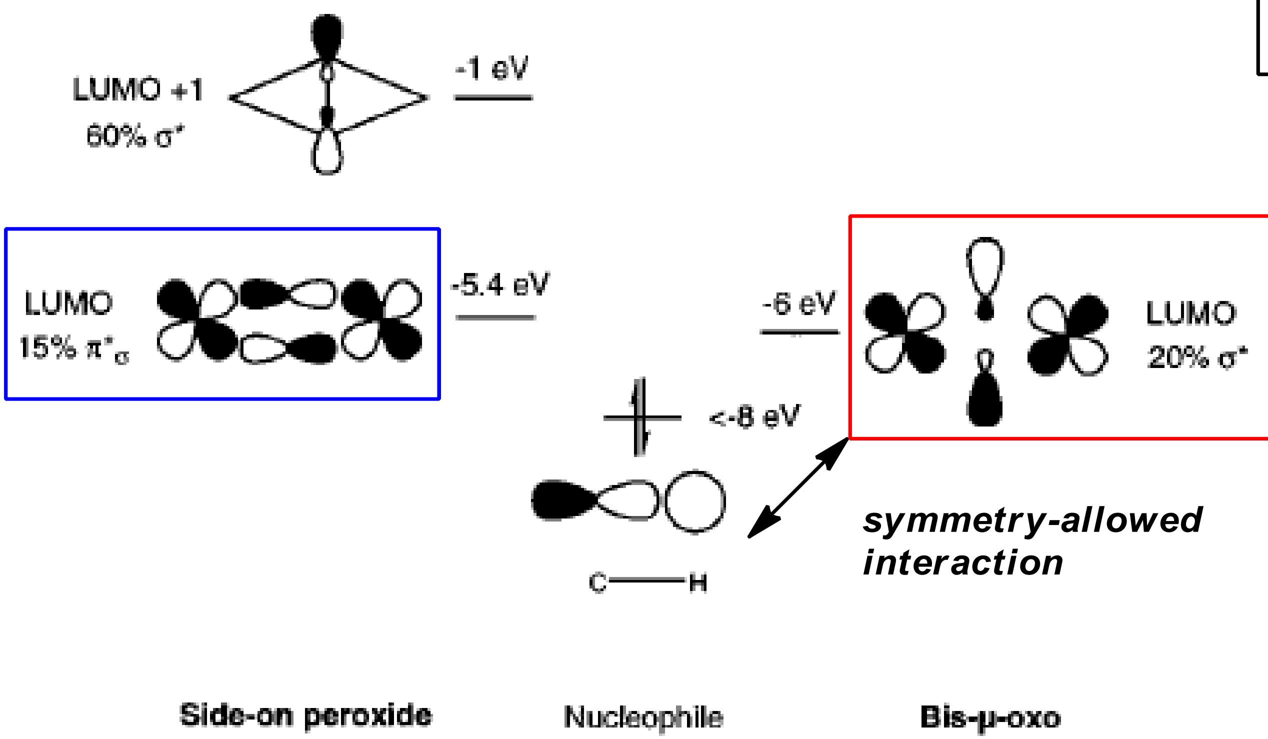

Bis-μ-oxo

E. I. Solomon. *et al. JACS* 1999, *121*, 1870
T. D. P. Stack. *et al. Chem. Rev.* 2004, *104*, 1013

E. I. Solomon. *et al. J. Inorg. Biochem.* 2002*, 88,* 368

# Explanation for Different Reactivity (2)



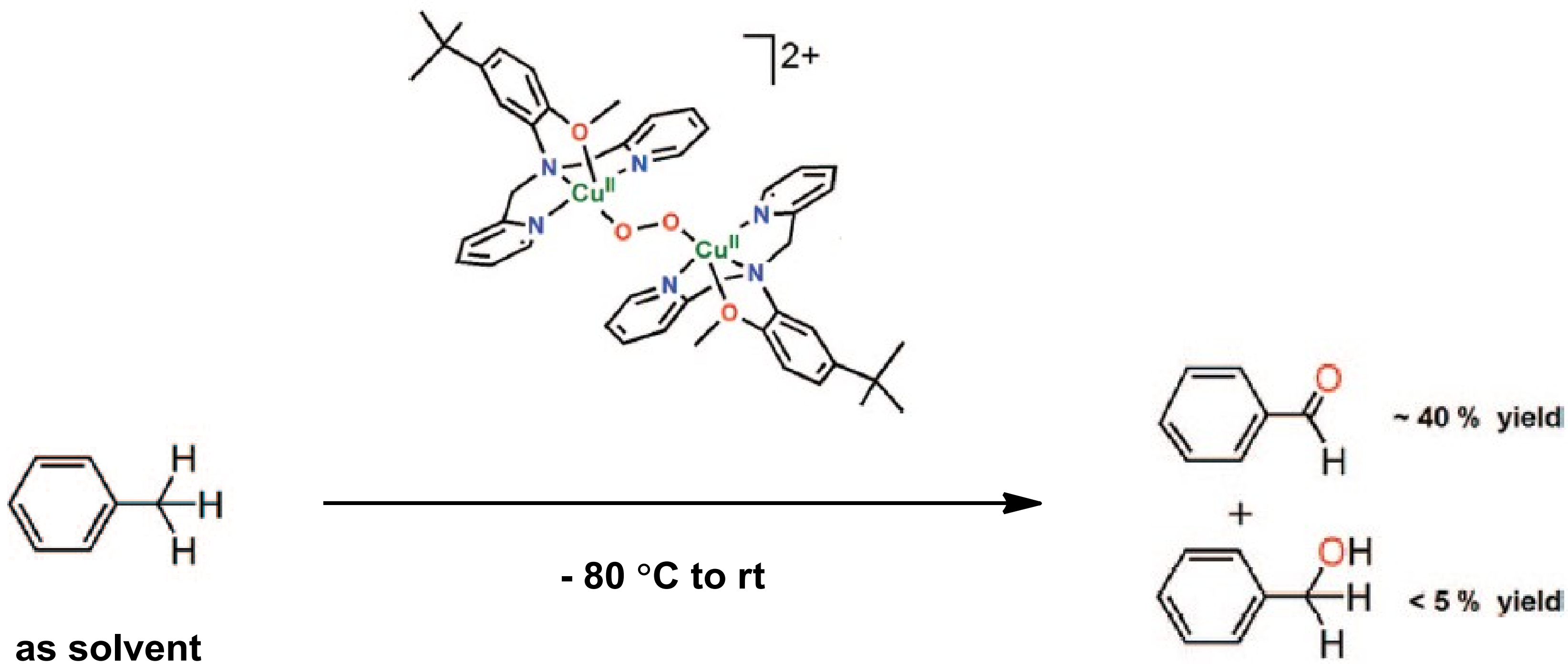

**E. I. Solomon et *al.* *JACS* 1999 *121* 1870**

**(Discussion based on Franck-Condon barrier: E. I. Solomon et al. *JACS* 1999 *121* 10332)**

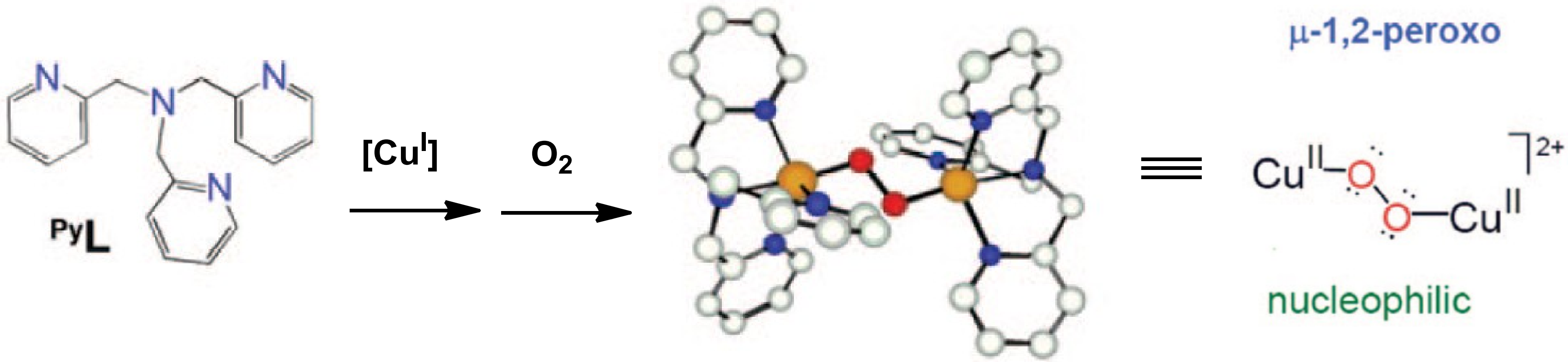
# [3] Aliphatic C-H Oxidation of Exogenous Substrate

**Toluene and Ethylbenzene Aliphatic C-H Bond Oxidations Initiated by a Dicopper(II)-μ-1,2-peroxo Complex**

D. Karlin *et al.*
*JACS* 2009 *131* 3230



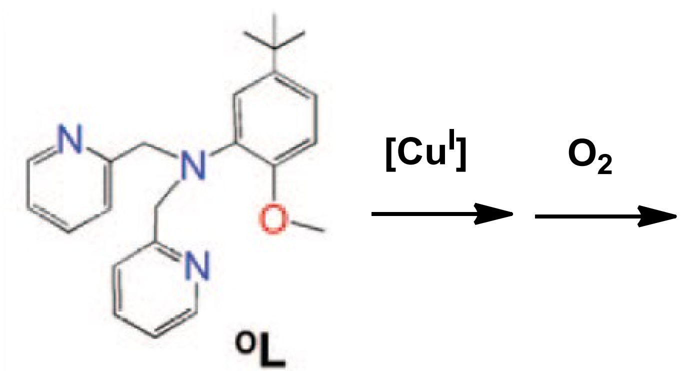
# Modification of Classical $^{Py}L$ Ligand: $^{O}L$




**tetradentate (N$_4$)**

**{$^{Py}$LCu$^{II}$}$_2$-O$_2$**

***"oxidatively inert"***



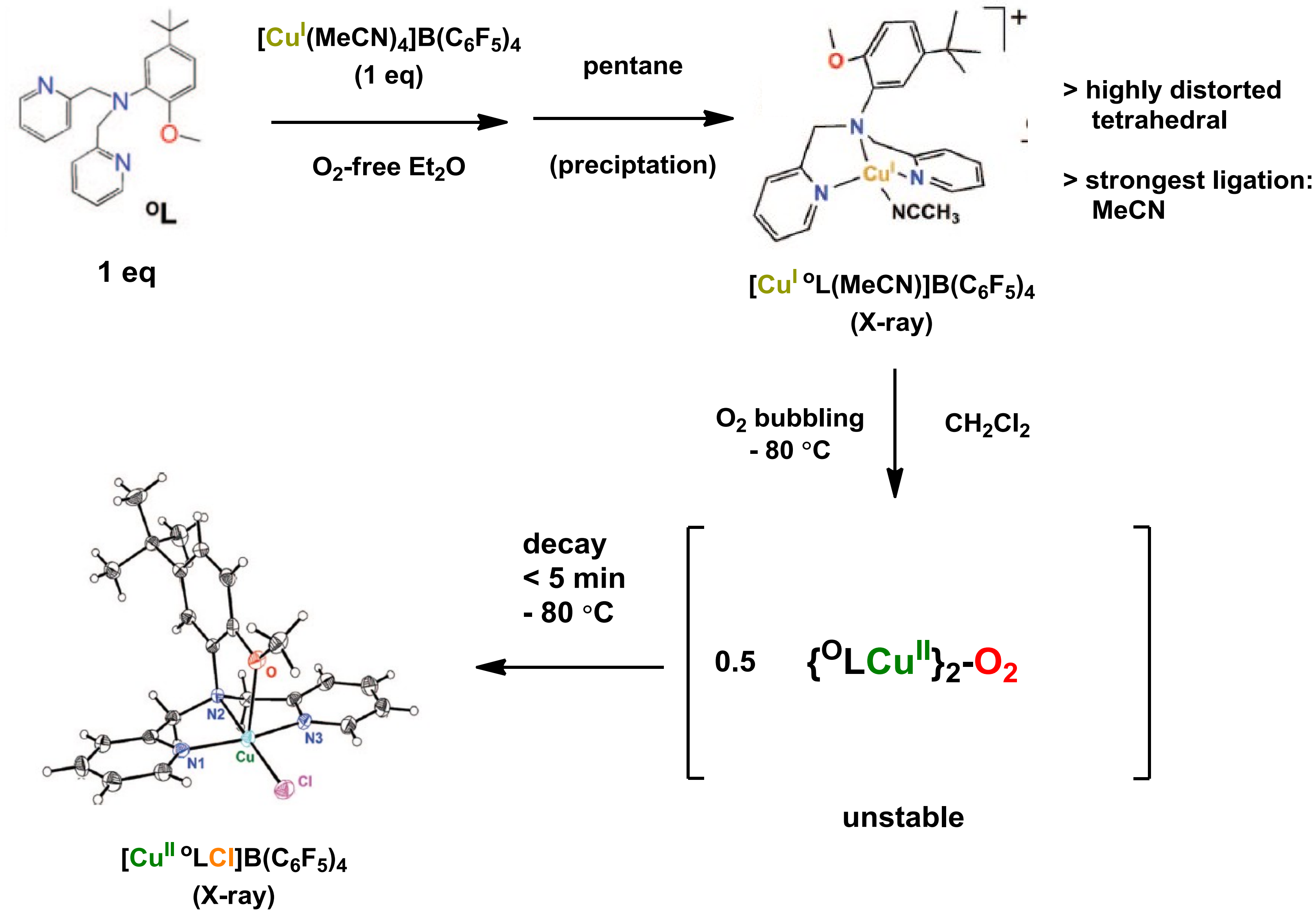

# ?

**> $O_2$-binding mode ??**

**> Reactivity??**

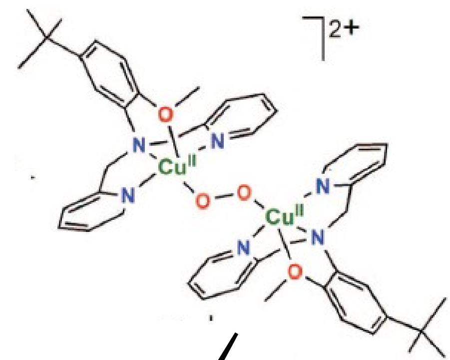
**tetradendate (N$_3$O)**

# Preparation of $\{^{O}LCu\}_2$-$O_2$ Complex



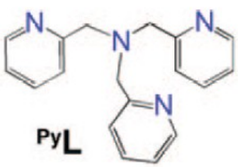
# Speculated Structure of $\{^{O}LCu\}_2$-$O_2$ Complex

$\{^{O}LCu^{II}\}_2$-$O_2$ =

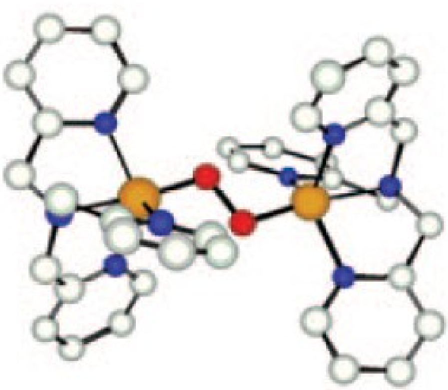



**Speculated Structure**
**$Cu^{II}_2$-*end on*-peroxide**
**(also supported by r-Raman)**

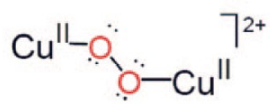
**Similar UV-Visible Spectroscopy**




**$^{Py}L$**

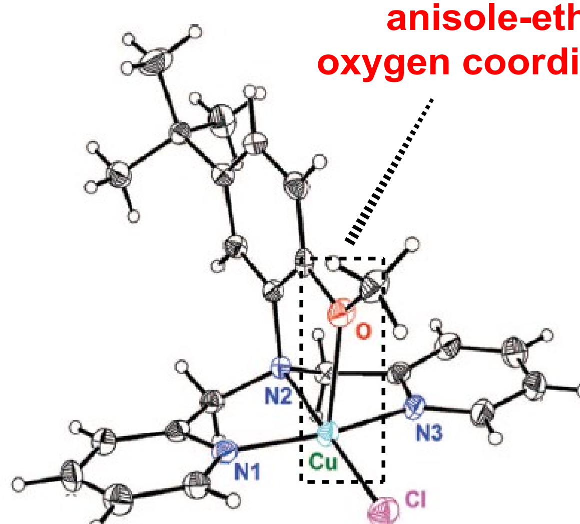


≡



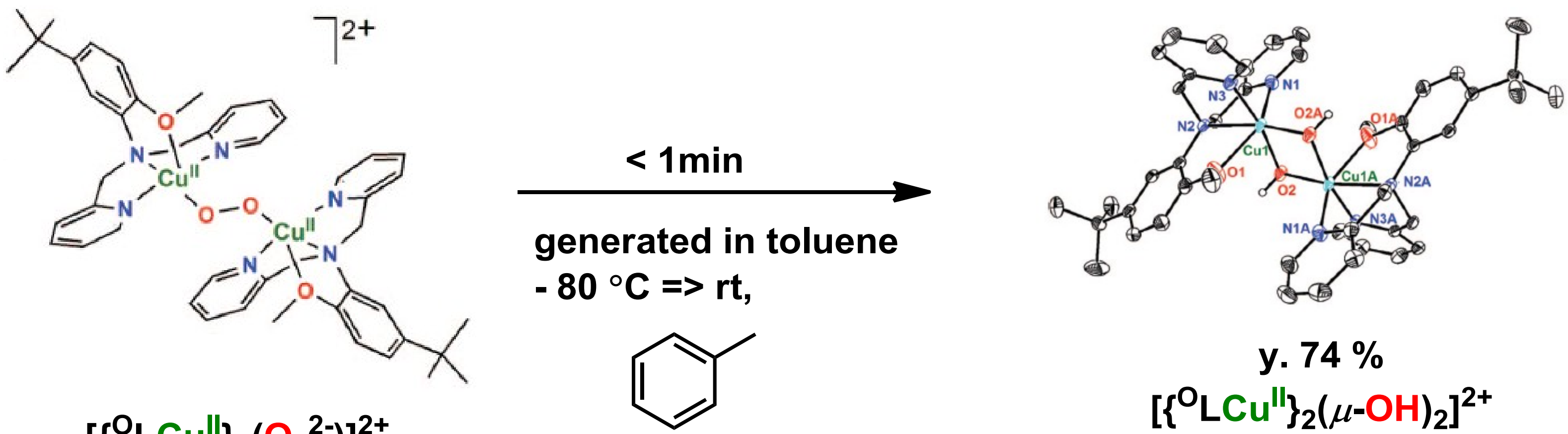

**$[\{^{Py}LCu^{II}\}_2(O_2^{2-})]^{2+}$ (X-ray)**
**$Cu^{II}_2$-*end on*-peroxide**

**anisole-ether oxygen coordination**




**$[Cu^{II}\ ^{o}LCl]B(C_6F_5)_4$ (X-ray)**

# Toluene Oxidation with $\{^{O}LCu\}_2$-$O_2$ Complex

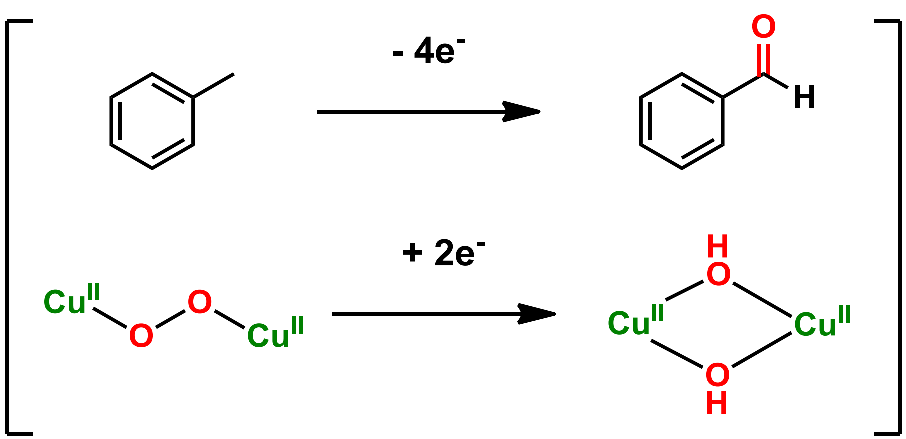


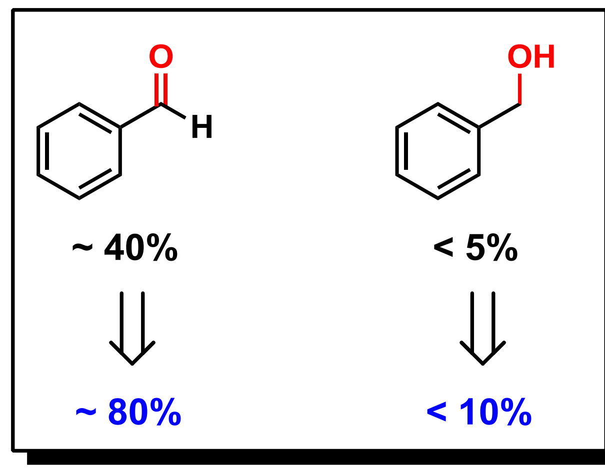

$[\{^{O}LCu^{II}\}_2(O_2^{2-})]^{2+}$

Cu$^{II}_2$-*end on*-peroxide

$[\{^{O}LCu^{II}\}_2(\mu\text{-}OH)_2]^{2+}$

\+

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$[\{^{Py}LCu^{II}\}_2(O_2^{2-})]^{2+}$

Cu$^{II}_2$-*end on*-peroxide

in toluene ⟹

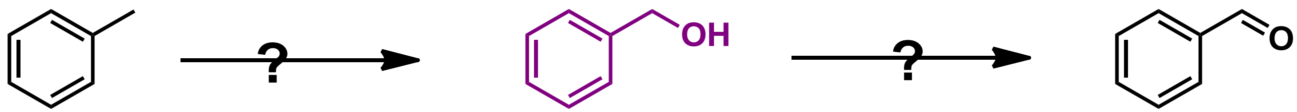
much more stable

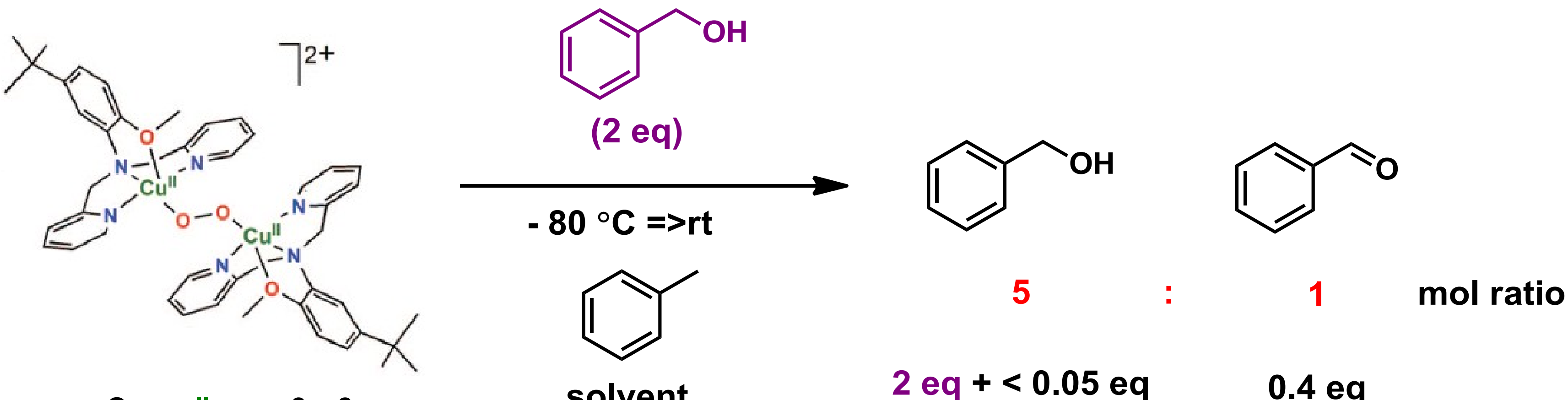
decomp. over 1 week at rt

< 10% benzaldehyde generated

# Toluene Oxidation: Mechanistic Study

- **Oxidation via benzyl alcohol ??**




$[\{^{O}LCu^{II}\}_2(O_2^{2-})]^{2+}$

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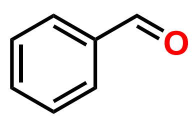
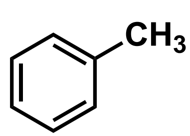
- **Other Control Experiments**

  - **$^{18}O_2$-labeling experiments:**

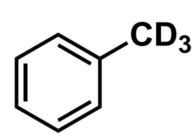



**O atom in aldehyde is derived from** $[\{^{O}LCu^{II}\}_2(O_2^{2-})]^{2+}$

  - **kinetic isotope effect**




**vs**

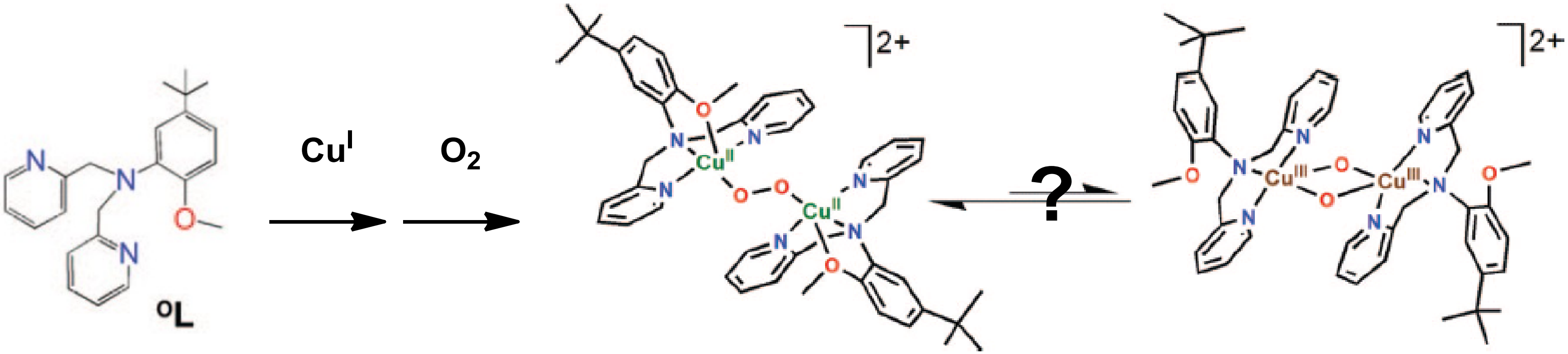



$k_H/k_D = 7.5$

⇓

**hydrogen abstraction ??**

# Possible Active Species and New $^{Bz}L$ Ligand




**tetradentate ($N_3O$)**
**or**
**tridentate ($N_3$) ??**

**tetradentate**

**$Cu^{II}_2$-*end on*-peroxide**

**tridentate**

**$Cu^{III}_2$–bis–μ–oxo**

**toluene oxidation**
**via H abstraction??**

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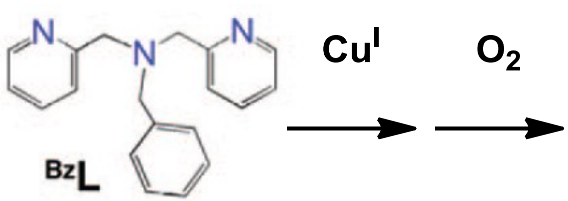


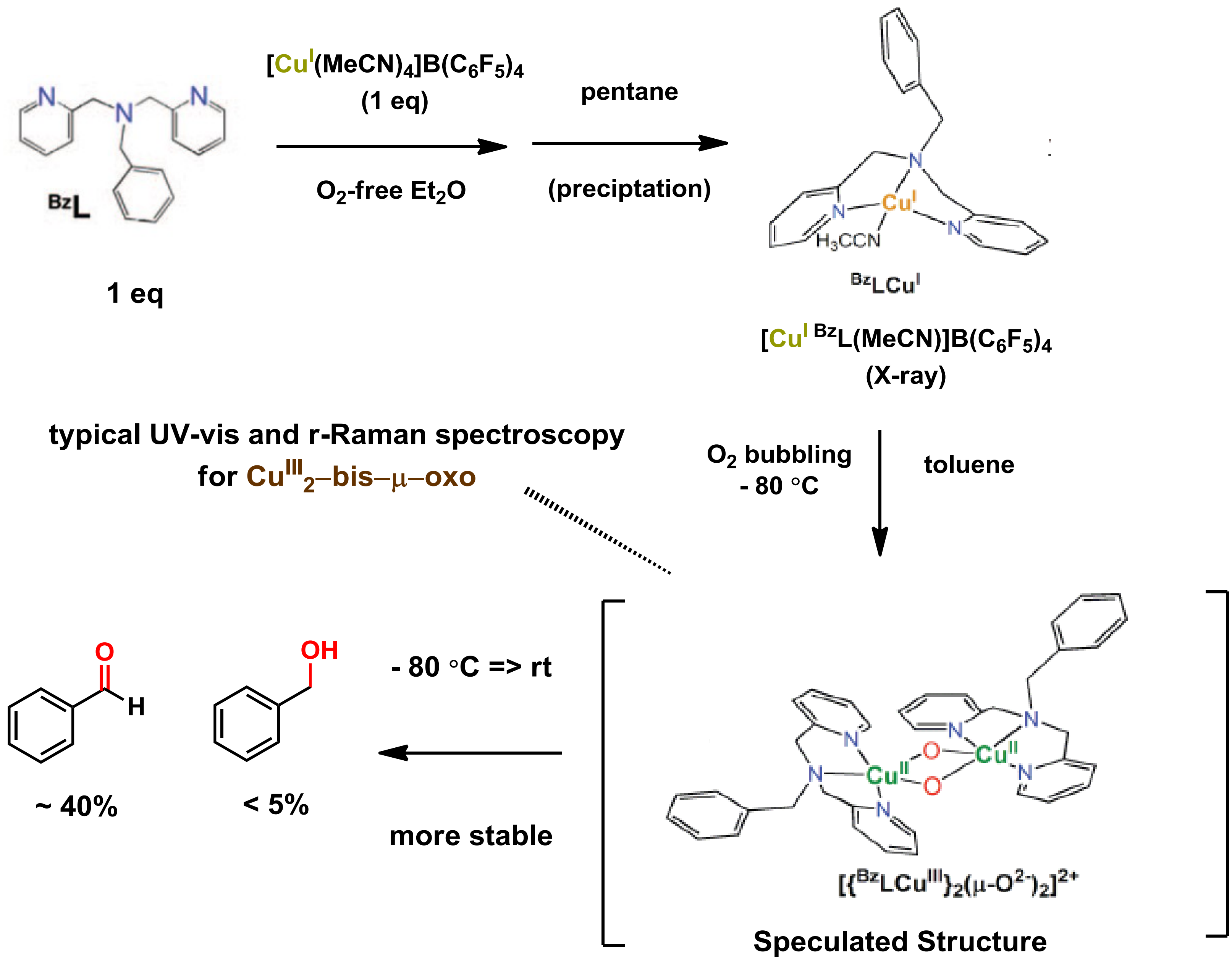

**$Cu_2$ - $O_2$**
**complex**

**$O_2$-binding mode??**

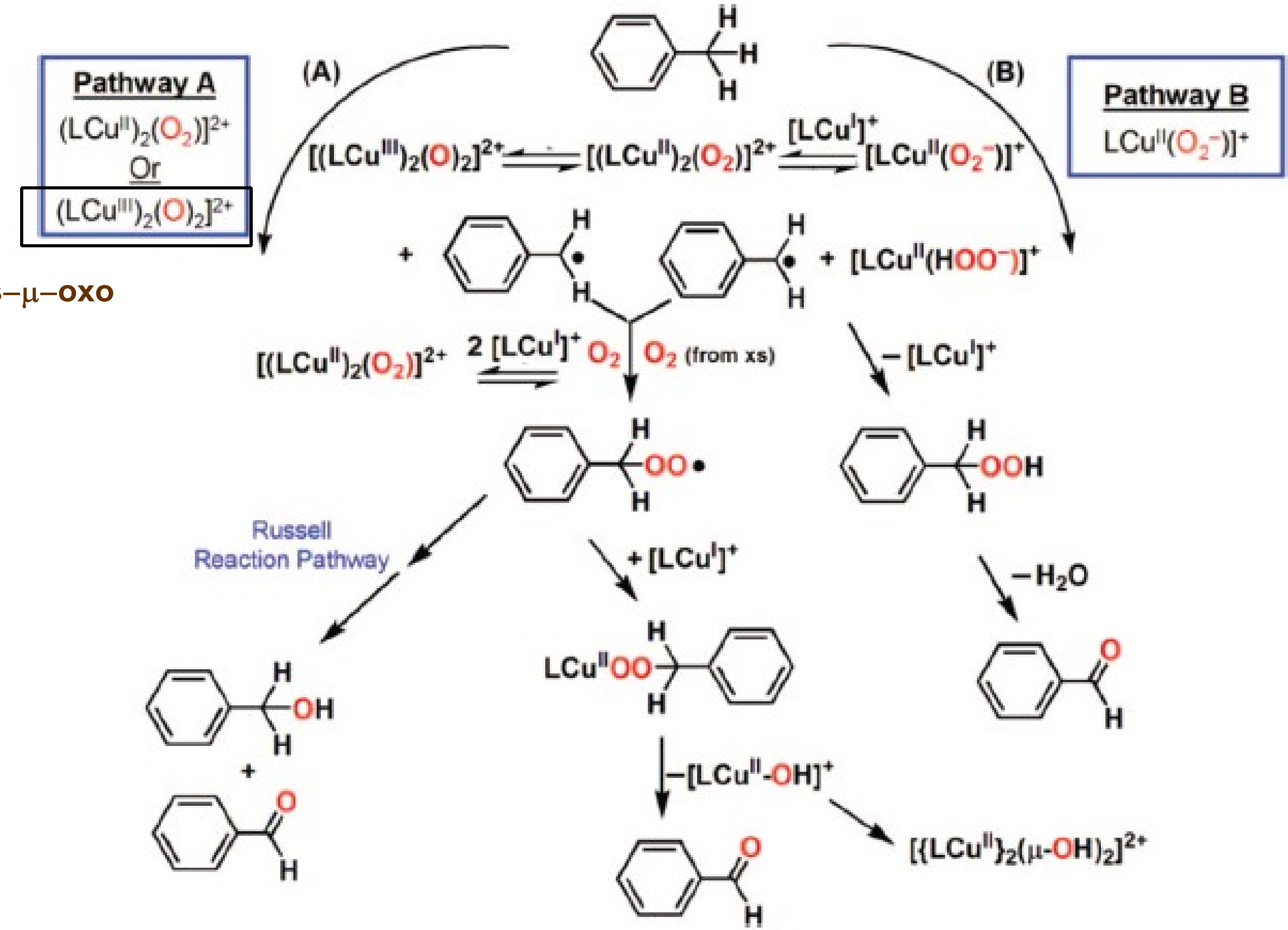
**Reactivity toward toluene??**

**tridentate ($N_3$)**

# Toluene Oxidation with $^{Bz}LCu_2$-$O_2$ Complex

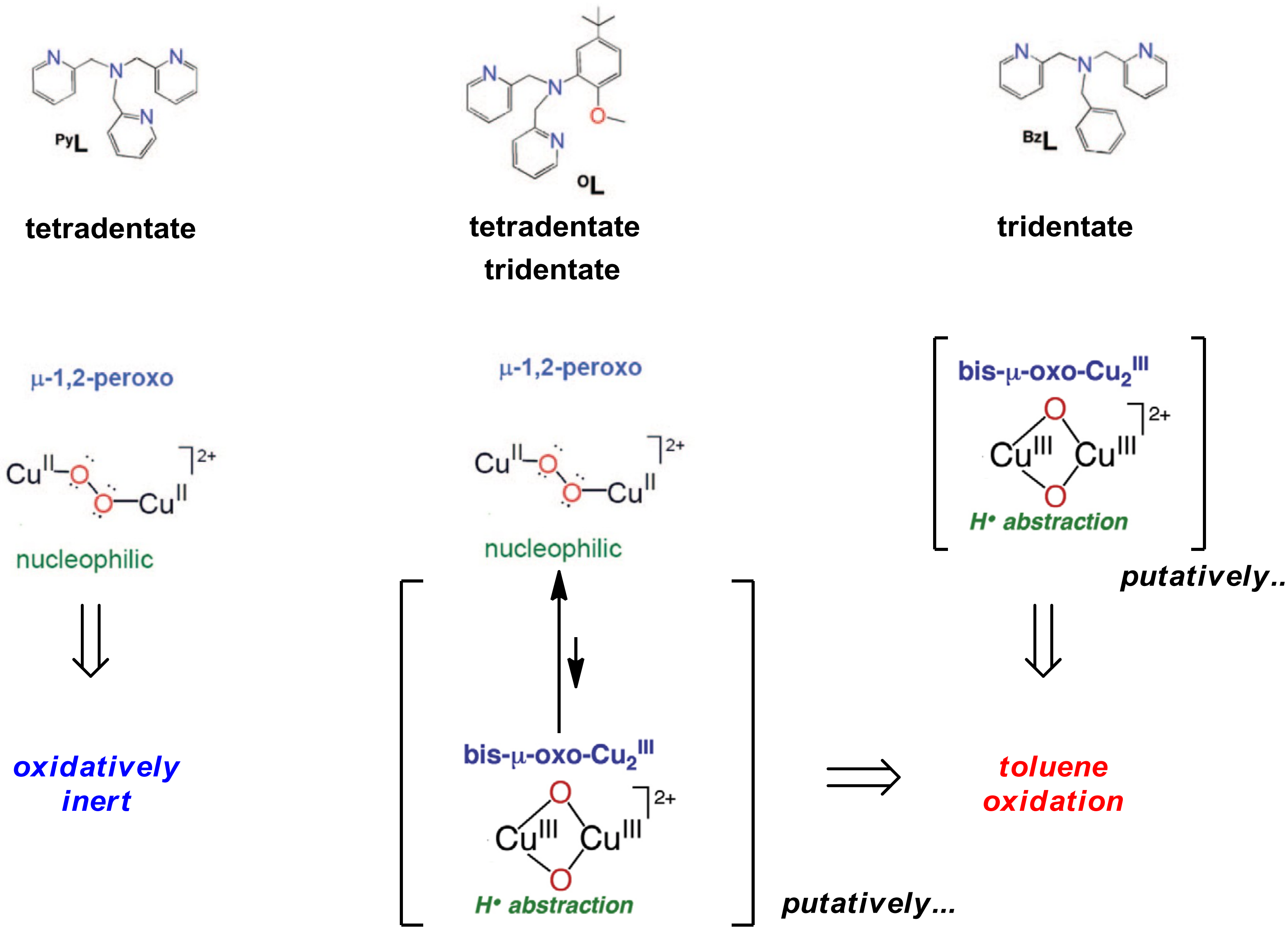


# Toluene Oxidation: Mechanism

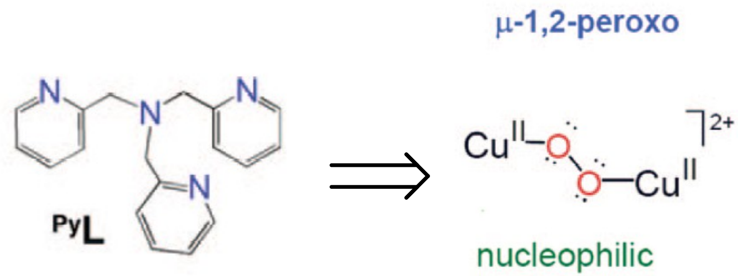



**$Cu^{III}_2$–bis–μ–oxo**

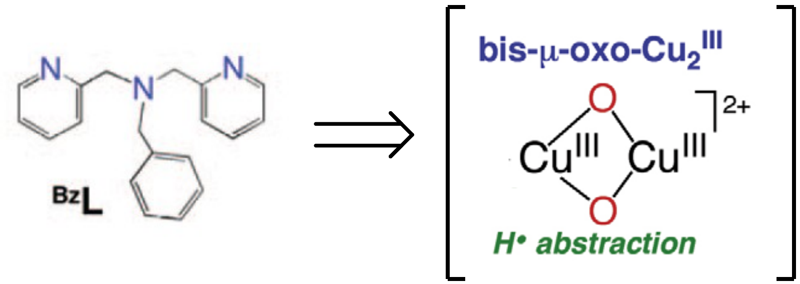
# Summary of Toluene Oxidation: $^{Py}L$, $^{O}L$, and $^{Bz}L$



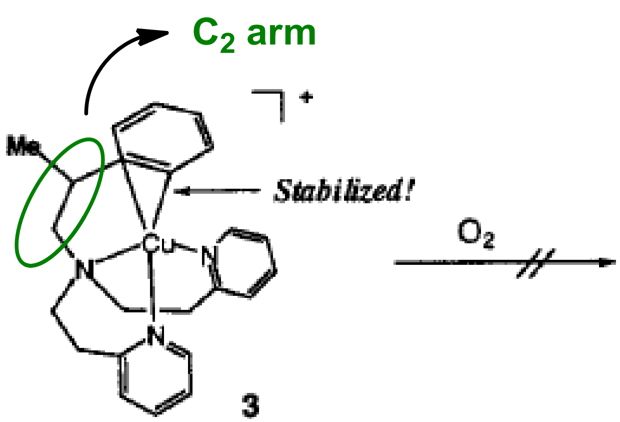
# Comparison of $^{Py}L$ and $^{Bz}L$




**tetradentate** ***"oxidatively inert"***




**tridentate** ***putatively...***

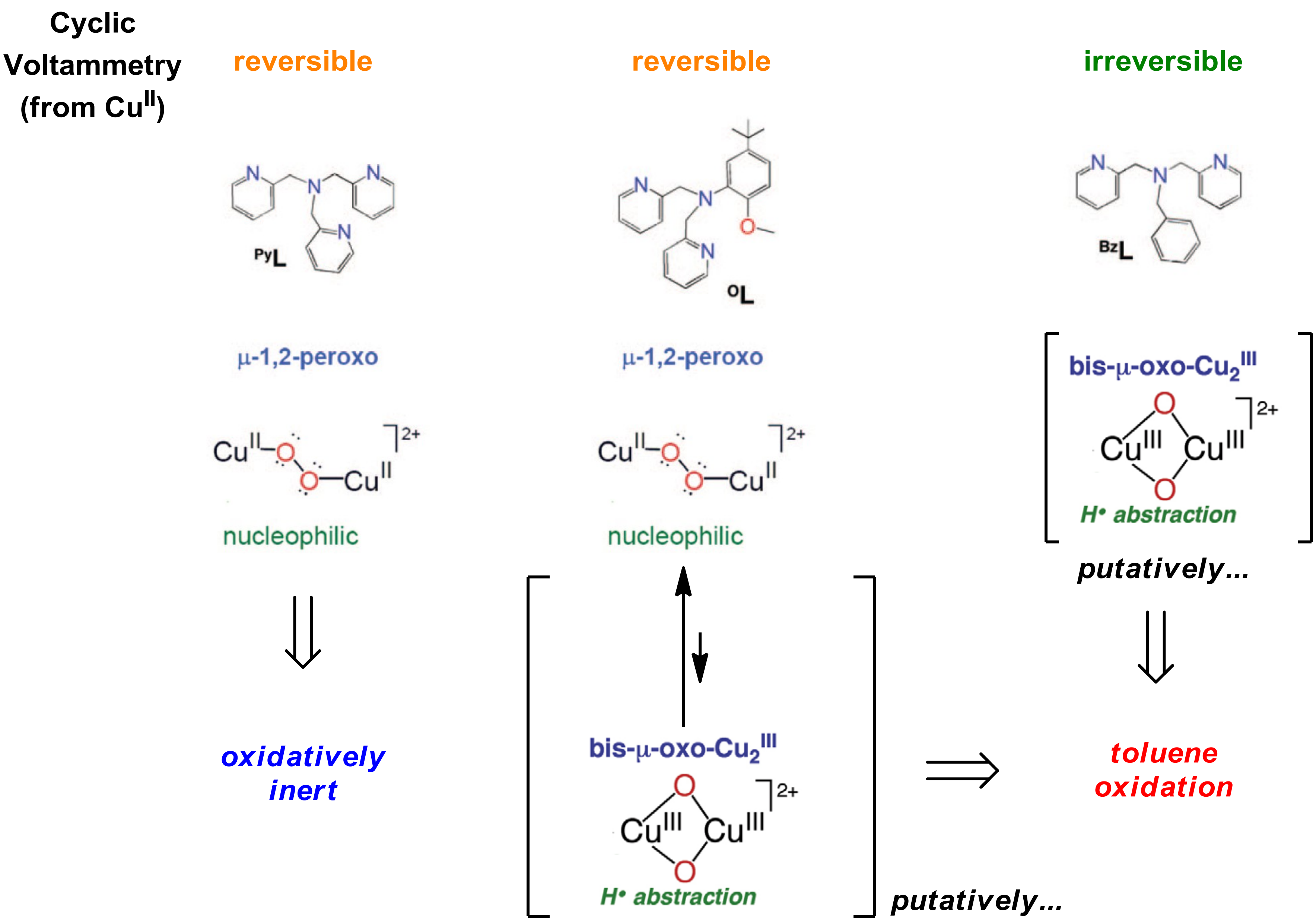



**unproductive π-d interaction**

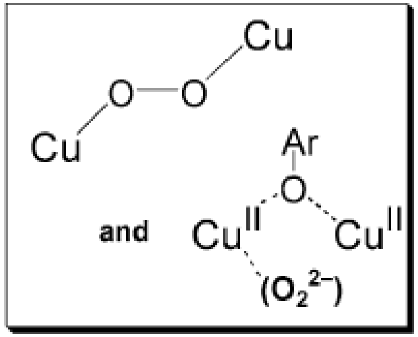
**S. Itoh *et al.***
***Inorg. Chem.* 2001, *40*, 6604**

- **Denticity**
  **tridentate => side-on complex**
- **Short arm ($C_1$)**
  **acute *N*-Cu-*N* angle => μ-oxo**
  **no benzylic hydroxylation**
  **no unproductive π-d interaction**

# Comparison of $^{O}L$ and $^{Bz}L$

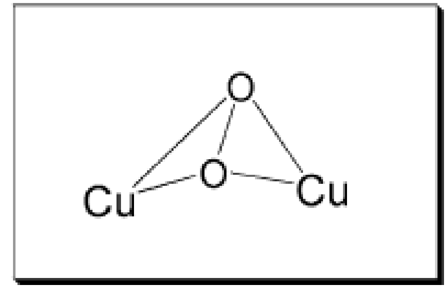


# Summary 1: End-on vs Side-on




**Denticity is the most decisive factor**

T. D. P. Stack *et al.* *Chem. Rev.* 2004, *104,* 1013

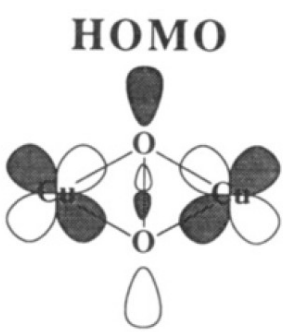



**endo on-peroxo**

**Basic/Nucleophilic Peroxide**

**side on-peroxo**

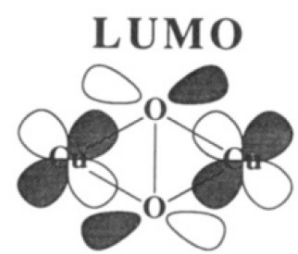
**Non Basic/Electrophilic Peroxide**




**mixing $\sigma^*$ into the HOMO**

⇩

**weakens O-O bond for cleavage**



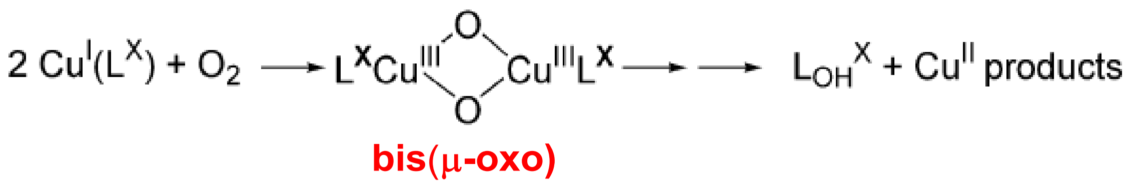

**mixing $\pi_\sigma^*$ into the LUMO**

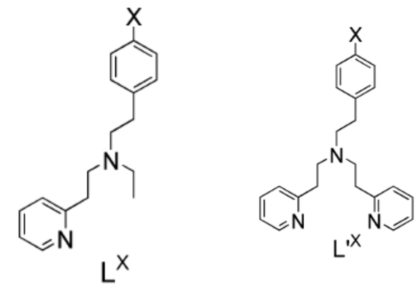
⇩

**donates electron density to Cu increases peroxide's electrophilicity**

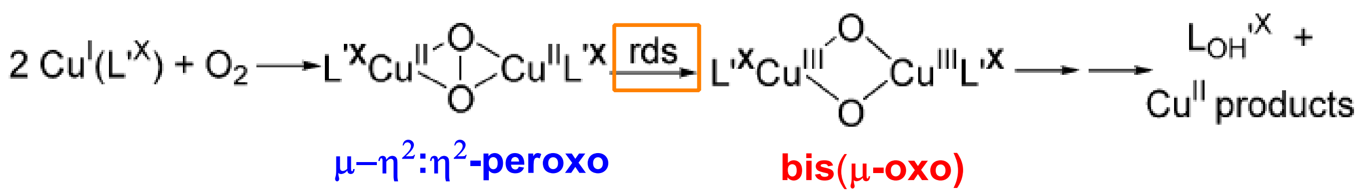
# Summary 2: Intramolecular Benzylic Oxidation

**Itoh *et al.* *ACIE* 2000 *39* 398**




**Itoh *et al.* *JACS* 1998 *120* 2890**

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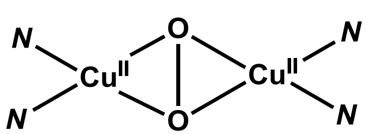
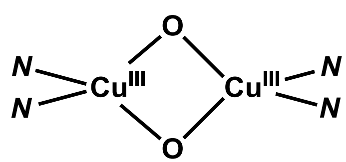



vs




$\mu$–$\eta^2$:$\eta^2$**-peroxo** — **aromatic hydroxylation**

**bis($\mu$-oxo)** — **H abstraction**

**<u>Controlling Factor</u>**

| | |
|---|---|
| **Ligand Denticity** | ***N*-Cu-*N* Angle** |
| **Ligand Steric Hindrance** | **Type of *N*-Donor** |
| | **etc.** |

# Summary 3: Toluene Oxidation