Oxidative Addition to the Carbon-Sulfur Bond

Everything (more than?) you ever want to know about C—S oxidative addition

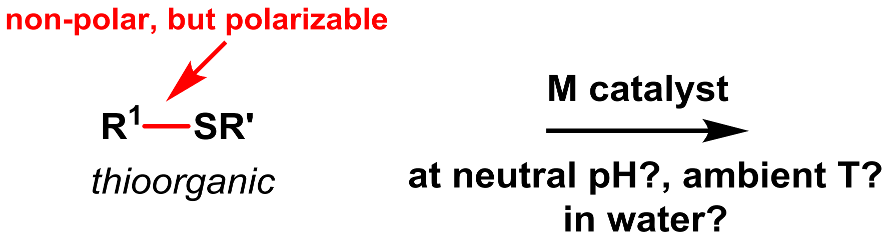
A descriptive survey.

Why Study C—S Oxidative Addition?

Primarily because of interest in the hydrodesulfurization of fossil fuels

Liebeskind Group interest: Achieving high chemoselectivity in complex molecular systems through desulfitative catalysis

Tactic: Explore selective metal-catalyzed reactions at the non-polar, but polarizable C—S bond, both man-made and native, in the presence of C—O, C—N, C—X, N-H, and O-H functional groups, at or near neutral pH, at or near ambient temperature, and in relevant solvent/buffer systems.



non-polar, but polarizable

$$R^1\text{—}SR' \xrightarrow{\text{M catalyst}}$$

thioorganic

at neutral pH?, ambient T?
in water?

Selective, metal-tuned, room temperature reactions in the presence of:

O- and N-functional groups

C-halogen bonds

OH and NH residues

water and biological buffers

Discrete C—S Oxidative Additions

Various aspects of the C—S oxidative addition have been extensively studied. Most studies were driven by interests in the hydrodesulfurization of fossil fuels where the reductive removal of sulfur containing compounds is important.

This lecture is restricted (primarily) to examples where the oxidative addition product $L_nM—SR$ has been isolated and characterized.

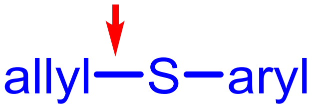
Low-valent Metals Explored	**C—S Substrates Examined**
Ni, Pd, Pt	Allylic and benzylic C—S.
Co, Rh, Ir	Alkenyl thio ether C—S.
Fe, Ru, Os	Aromatic C—S.
Mo, W	S-Heteroaromatic C—S.
Mn, Re	Thiol esters C—S.
Zr	Alkyl thio ethers C—S.

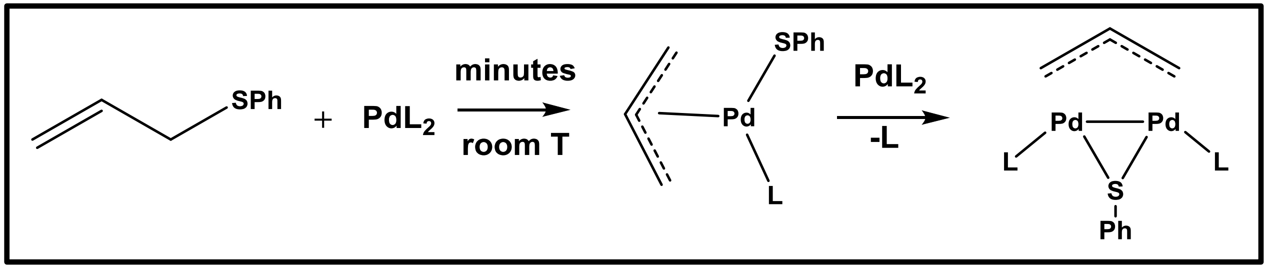
A Recent Descriptive Review of C—S Activation: Wang, He, Yu, *Chem. Soc. Rev*., **2013**, *42*, 599.

Studies of Allylic C—S Substrates

Allylic Thio Ether Substrates

Earliest Examples: Allyl Phenyl Sulfide With Pd(0) Complexes



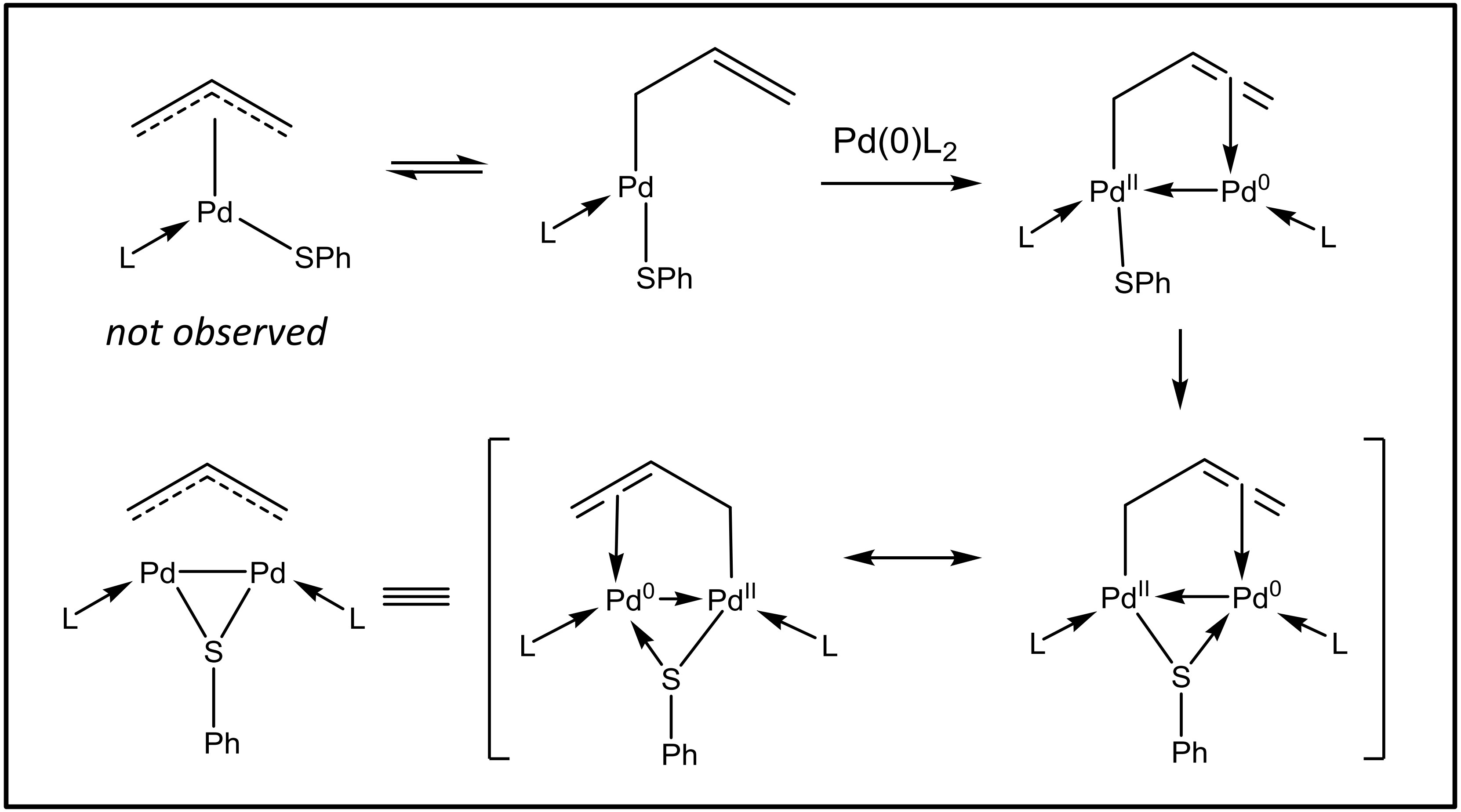


A subtle influence of the ligand was observed:
Reaction occurs when L = P(C_6H_{11})$_3$, P(t-Bu)$_3$, and PMe$_3$, **but not PPh$_3$**

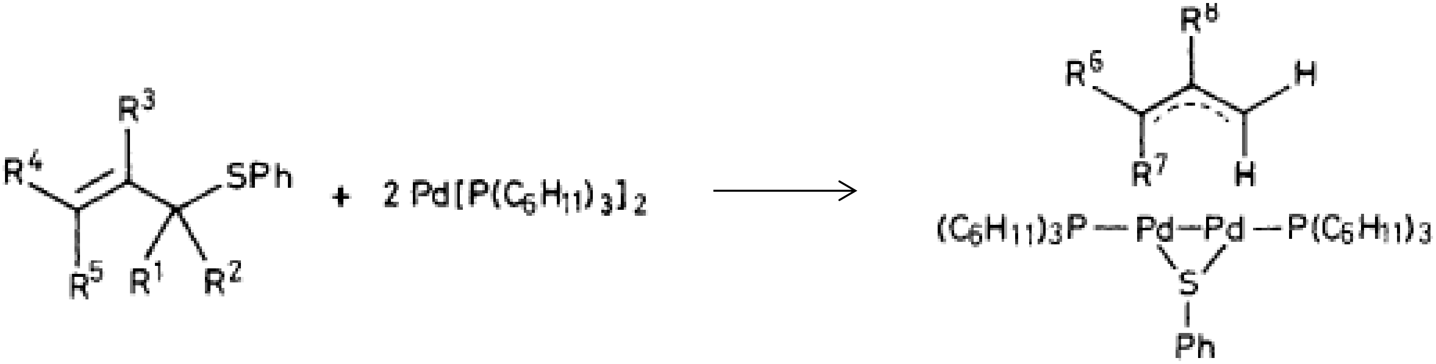
- Reactions of allyl phenyl sulfide with alkyl phosphines are completed instantly at room temperature to yield $Pd_2(\mu\text{-}C_3H_5)(\mu\text{-SPh})L_2$.
- The product complexes are composed of an initially formed oxidative addition product $Pd(\eta^3\text{-}C_3H_5)(SPh)L_2$ with a second equivalent of PdL, or PdL_2.
- Attempts to isolate the presumed initial intermediate $Pd(\eta^3\text{-}C_3H_5)$-(SPh)L-type complex failed.

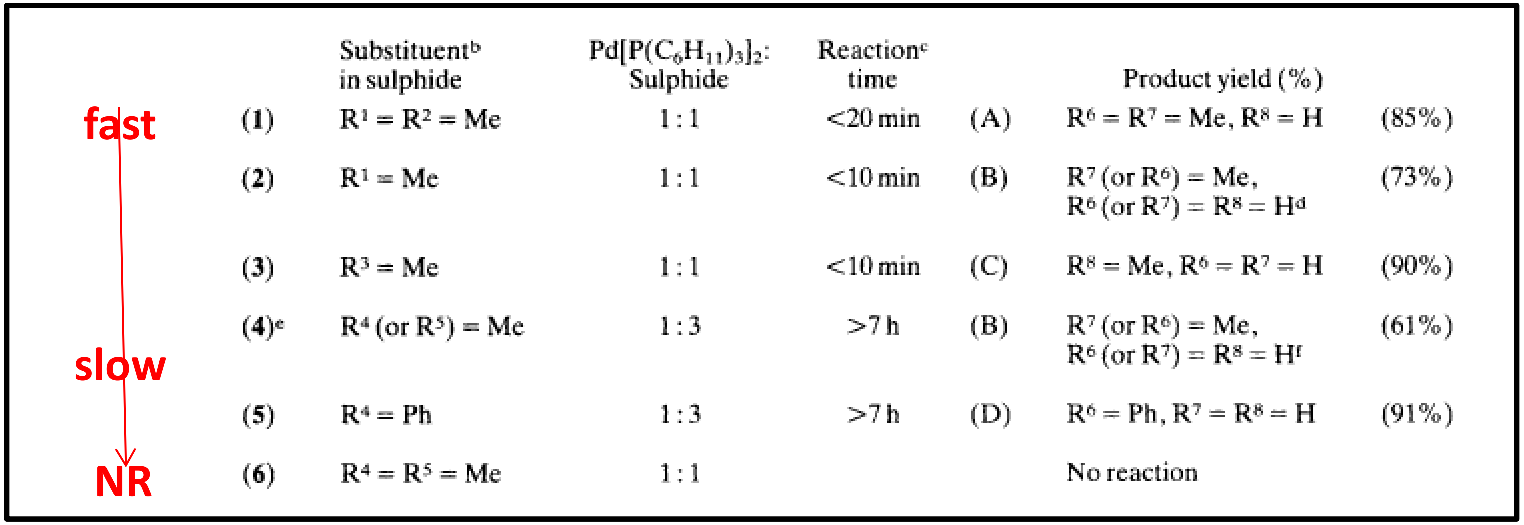
Yamamoto, Aklimoto , Saito, Yamamoto *Organometallics* **1986**, *5*, 1559. Osakada, Chiba, Nakamura, Yamamoto, Yamamoto, *J. Chem. Soc., Chem. Commun.* **1986**, 1589. Osakada, Chiba, Nakamura, Yamamoto, Yamamoto, *Organometallics* **1989**, *8*,2602-2605. Osakada, Ozawa, Yamamoto, *J. Organomet. Chem.* **1990**, *399*, 341.

How Might the Di-Pd-Allyl Form?



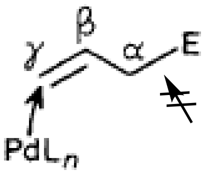
Possible S_N2' Mechanism for OA





		Substituent[b] in sulphide	$Pd[P(C_6H_{11})_3]_2$: Sulphide	Reaction[c] time		Product yield (%)	
fast	(1)	$R^1 = R^2 = Me$	1:1	<20 min	(A)	$R^6 = R^7 = Me, R^8 = H$	(85%)
	(2)	$R^1 = Me$	1:1	<10 min	(B)	R^7 (or R^6) = Me, R^6 (or R^7) = R^8 = H[d]	(73%)
	(3)	$R^3 = Me$	1:1	<10 min	(C)	$R^8 = Me, R^6 = R^7 = H$	(90%)
	(4)[e]	R^4 (or R^5) = Me	1:3	>7 h	(B)	R^7 (or R^6) = Me, R^6 (or R^7) = R^8 = H[f]	(61%)
slow	(5)	$R^4 = Ph$	1:3	>7 h	(D)	$R^6 = Ph, R^7 = R^8 = H$	(91%)
NR	(6)	$R^4 = R^5 = Me$	1:1			No reaction	

Variation of the reaction rate with the allylic substitution pattern suggests a C—S oxidative addition mechanism by direct S_N2'attack of Pd(0).



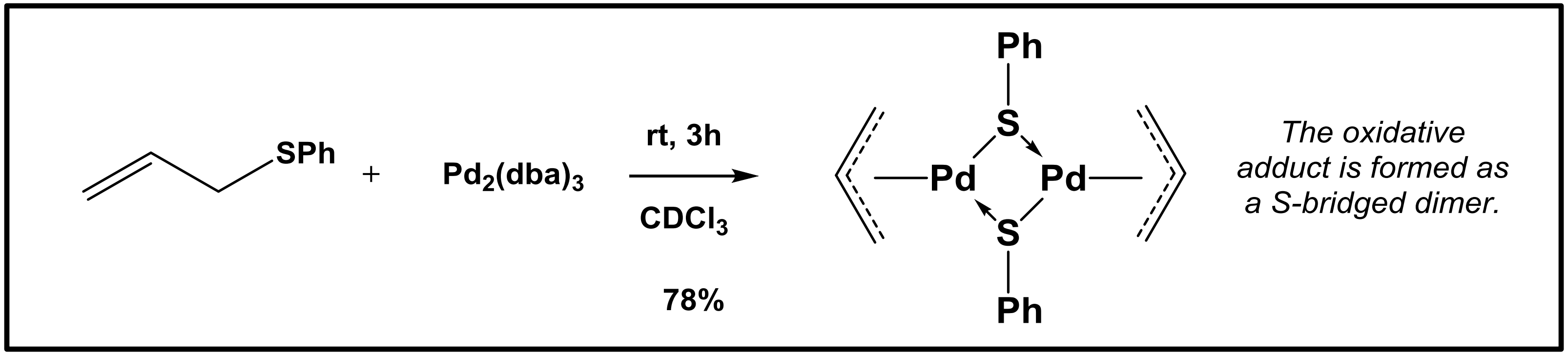
Kurosawa Mechanistic Study

C—S Oxidative Addition by Pd in the Absence of Phosphine Ligands

Miyauchi, Watanabe, Kuniyasu, Kurosawa, *Organometallics* **1995**, *14*, 5450-5453

Yamamoto and coworkers showed that allylic sulfides react with Pd(0)-**trialkyl**phosphine complexes to give di-Pd π-allylic complexes.

Kurosawa and coworkers provided definitive evidence for formation of a first-formed allylpalladium(II) thiolate intermediate and explained the behavior of different phosphines in the Yamamoto chemistry.



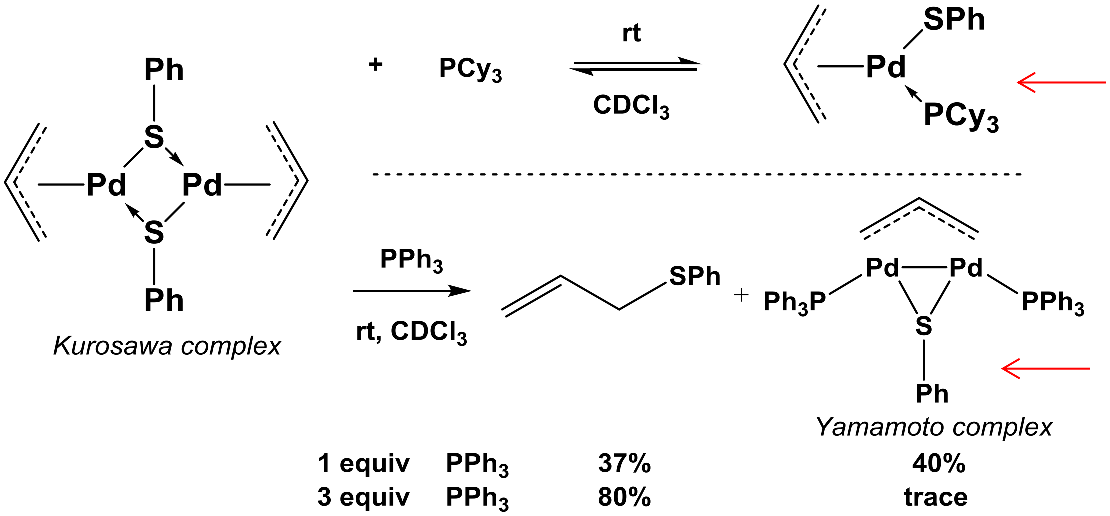
The oxidative adduct is formed as a S-bridged dimer.

The oxidative addition intermediate is stable in the absence of phosphine ligands.
None of the Yamamoto di-Pd allyl complex is formed.

Reaction with Phosphines

- **Yamamoto**: No reaction of $CH_2=CH-CH_2SPh$ takes place in the case of Pd-PPh_3, but the di-Pd allyl forms through an apparent oxidative addition in the case of basic alkyl phosphines, R = Cy, R = t-Bu, and R = Me.
- **Kurosawa**: Pd(0)-olefin complexes generate the product of direct oxidative addition, and not the di-Pd allyl complex.

Kurosawa used his isolated oxidative addition complex generated from the $Pd_2(dba)_3$ reagent to explore reaction behavior in the presence of different phosphines.



Kurosawa complex

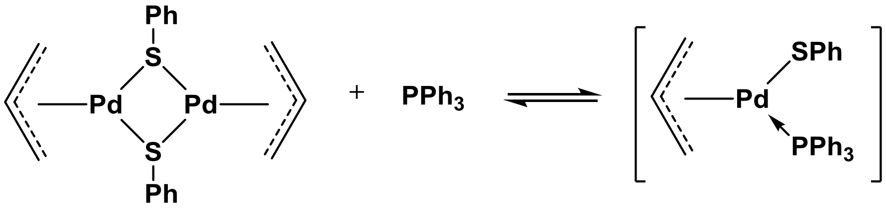
Yamamoto complex

Reaction with a basic phosphine
With a basic alkyl phosphine, the thiolate bridge is broken and a new **monomeric** product is formed reversibly. T**he monomer is stable to further reaction.**

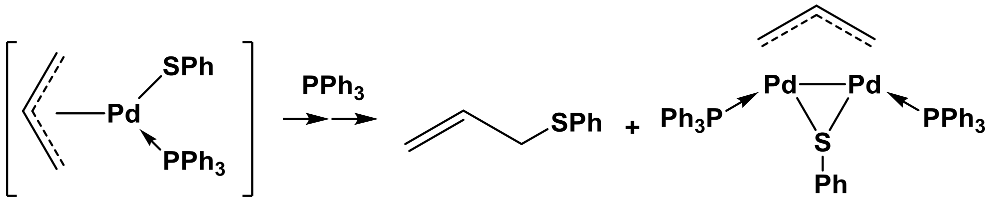
Reaction with a non-basic phosphine
With PPh_3 C—S reductive elimination is observed along with formation of the Yamamoto bridging di-Pd allyl. However, with excess PPh_3 reductive elimination to the allyl sulfide is fully favored.

An Explanation

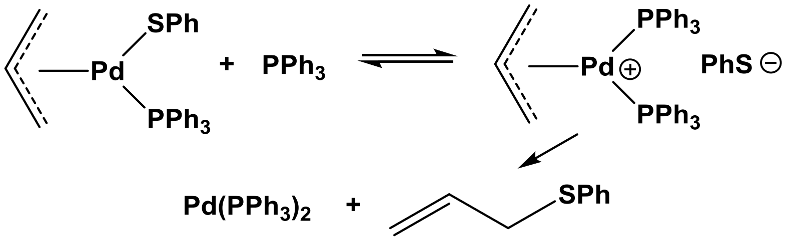
- The initial oxidative addition product forms and then reacts reversibly with 1 equiv of PPh_3 to break its S-bridge to form *transiently* a PPh_3-coordinated complex, analogous to the stable complexes generated with **alkyl** phosphine.



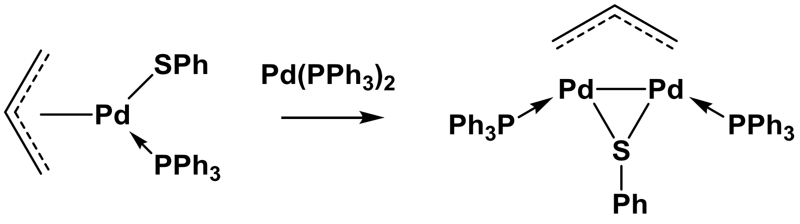
- The unstable adduct (transiently observed by NMR) disappears to give a mixture of the Yamamoto di-Pd allyl complex along with CH_2=$CHCH_zSPh$ by reductive elimination.



The initial oxidative adduct is stable with respect to direct C—S reductive elimination. **However**, in the presence of traces of free PPh_3, C-S bond formation occurs readily via an ionic intermediate $[Pd(\eta^3\text{-}CH_2CH\text{-}CH_2)(PPh_3)_2]^+ PhS^-$.

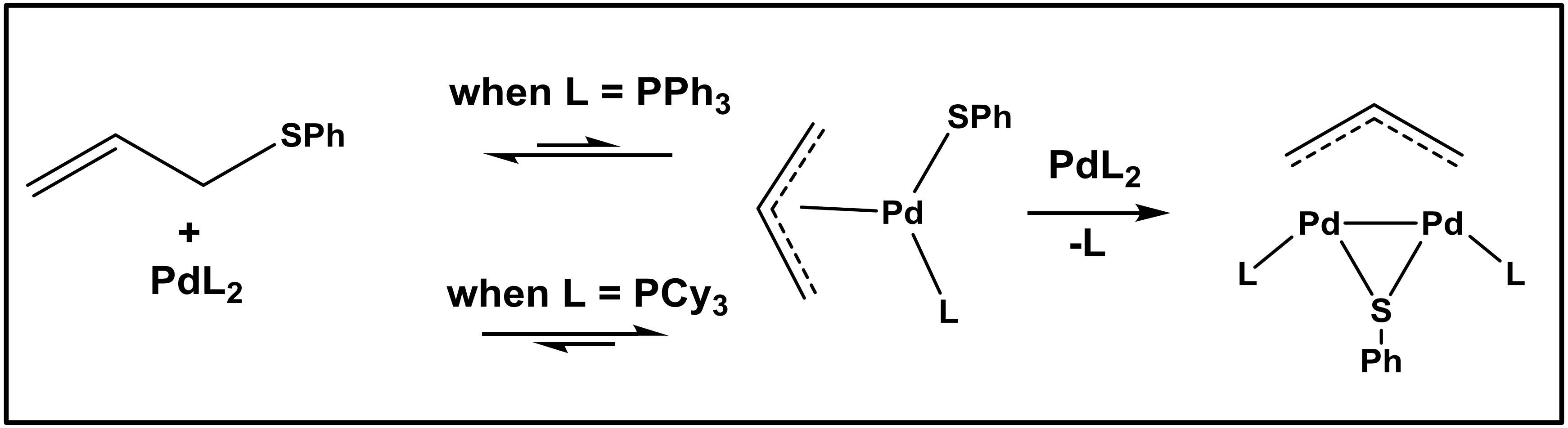


The collapse of the ionic intermediate gives allyl phenyl sulfide and $Pd(PPh_3)_2$. The latter Pd(0) complex would then react rapidly with remaining unchanged $[Pd(\eta^3\text{-}CH_2CHCH_2)(SPh)]$ to form the Pd-Pd-bonded allyl product.



Ox-Add—Red-Elim Reversibility

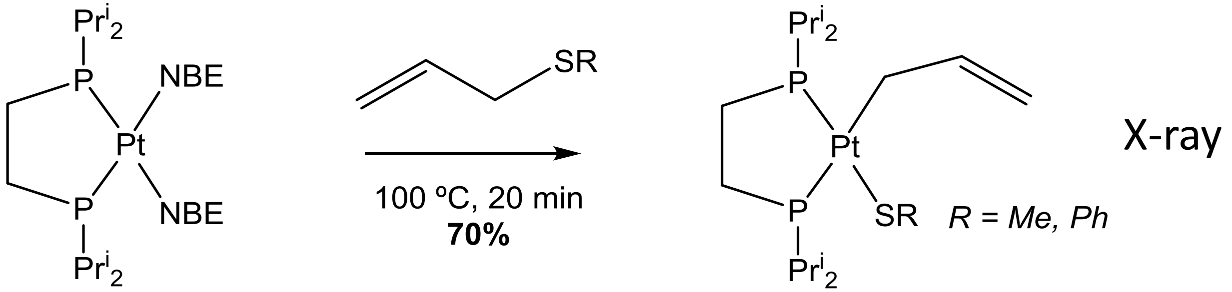
- Overall, the position of the equilibrium of CH_2=$CHCH_zSPh$ and PdL_n ↔ Pd(η^3-C_3H_5)(SPh)L_m must be highly ligand dependent.
- The equilibrium is in favor of the Pd(0) side when L = PPh_3 and $P(OMe)_3$.
- On the other hand, the Pd(II) side is more stable when L = $PCy_{3.}$



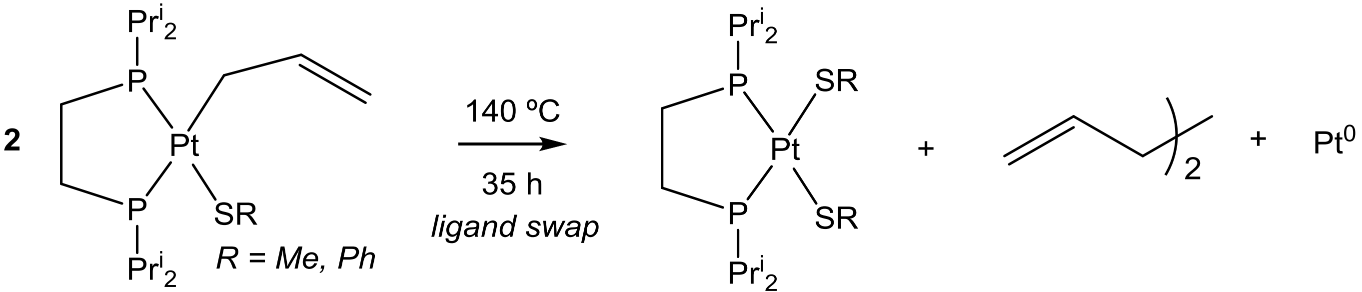
Allylic Sulfide OA with Pt

Platinum is useful in model studies because:
(a) it has readily accessible and easily tuned complexes and
(b) it is the most kinetically inert element of the Ni/Pd/Pt triad
(c) it can model catalytic reactions undergone by the lighter and more labile elements.

At 100 °C in 20 min: (dippe)Pt(NBE)$_2$ reacts with excess allyl methyl/phenyl sulfide.

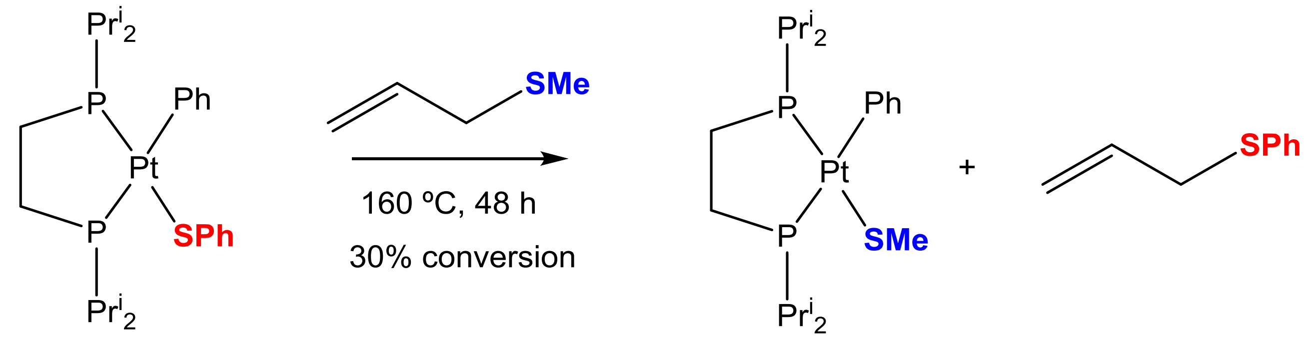


At 140 °C after extended periods: ligand scrambling and reductive elimination take place.



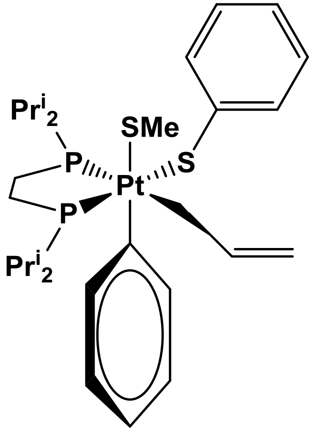
Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D. *Polyhedron* **2013**, *58*, 99–105.

A Pt(II) to Pt(IV) C—S Oxid-Addn?



Reaction of allyl methyl sulfide with the allyl thiophenyl complex at 160 °C for 2 d.

Authors suggest that data are consistent with an octahedral Pt(IV) intermediate that then suffers *selective* reductive elimination to form allyl phenyl sulfide and the observed Pt complex.



Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D. *Polyhedron* **2013**, *58*, 99–105.

Other Allylic C—S Oxidative Additions

Allyl Phenyl Thio Ether With Ru(0) Complexes

Planas, J. G.; Hirano, M.; Komiya, S. *Chemistry Letters* **1998**, 123–124. Planas, J. G.; Marumo, T.; Ichikawa, Y.; Hirano, M.; Komiya, S. *Journal of Molecular Catalysis A*: Chemical **1999**, *147*, 137–154.

Allyl phenyl sulfide reacts with the Ru complex, Ru(cod)(cot)/Pme in the presence of 2 equiv of the BIDENTATE LIGAND 1,2-bis(diethylphosphino)ethane (depe) at room temperature to generate the cationic (η^3-allyl)ruthenium(II) complexes, $[Ru(\eta^3\text{-}C_3H_5)(depe)_2]^+ [RY]^-$ [RY = PhS, MeS] as yellow or brown oils in good yield. No mechanistic studies were reported.

Allyl Phenyl Thio Ether With Rh-H Complexes

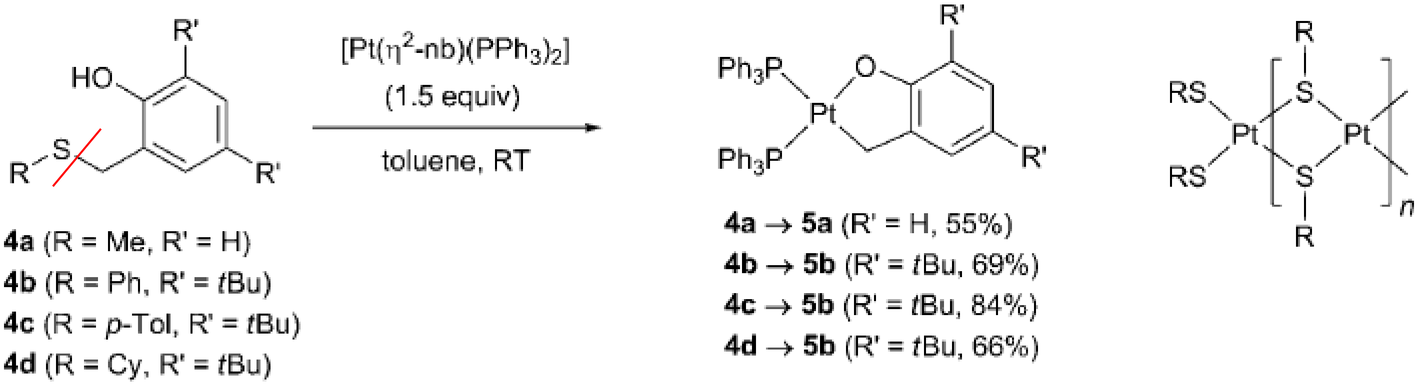
Kohtaro Osakada, Keizo Matsumoto, Takakazu Yamamoto, and Akio Yamamoto, *Organometallics* **1986**, *4*, 857-862.

Several allyl aryl sulfides ($RCH{=}CR'CH_2SC_6H_4R''$, R'' = p-CH,, o-CH_3, p-OCH_3, p-F, and p-CF_3) undergo C-S bond cleavage reactions with $RhH(PPh_3)_4$ to give very high yields of propylene accompanied by formation of complexes formulated as $[Rh(p\text{-}SC_6H_4R)\text{-} (PPh_3)_2]_2$. Bond cleavage between the aryl group and sulfur atom does not occur. Experimental evidence suggests a hydrometalation-β-elimination mechanism

Benzylic C—S Oxidative Addition

Not Much is Known

From Nakata, N. N.; Furukawa, N. N.; Toda, T. T.; Ishii, A. A. *Angew. Chem. Int. Ed* **2010**, *49*, 5784–5787.

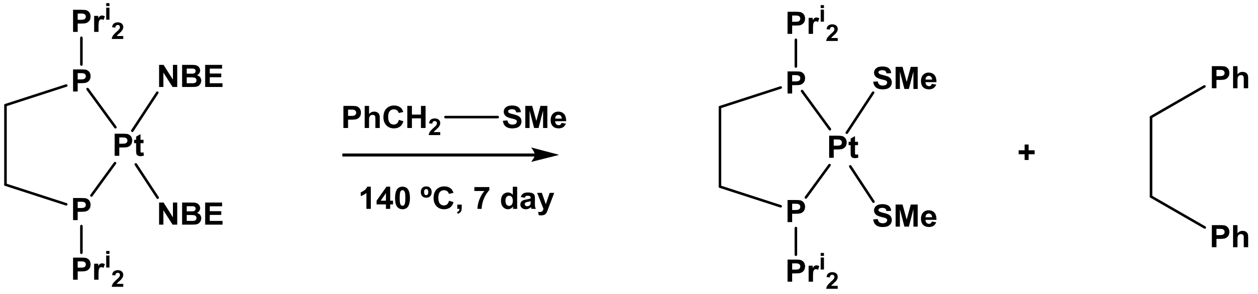


4a (R = Me, R' = H)
4b (R = Ph, R' = *t*Bu)
4c (R = *p*-Tol, R' = *t*Bu)
4d (R = Cy, R' = *t*Bu)

4a → **5a** (R' = H, 55%)
4b → **5b** (R' = *t*Bu, 69%)
4c → **5b** (R' = *t*Bu, 84%)
4d → **5b** (R' = *t*Bu, 66%)

Also, from Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D. *Polyhedron* **2013**, *58*, 99–105.

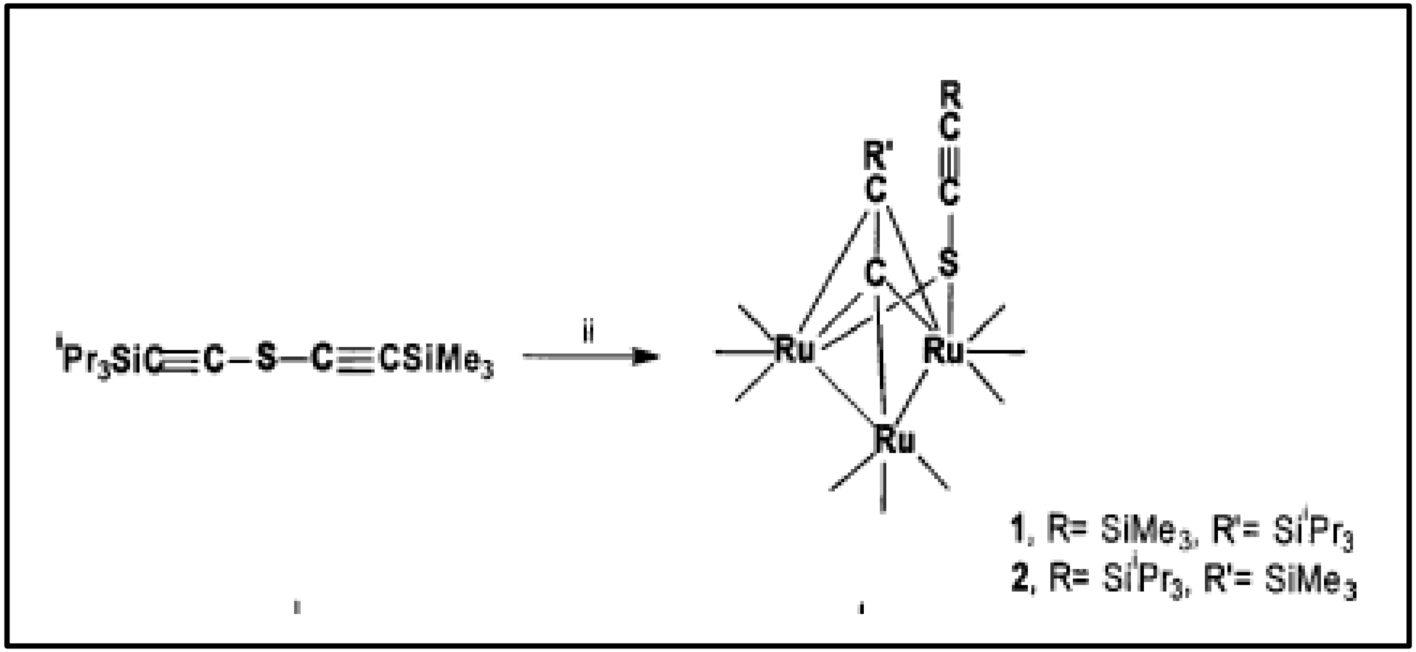
Reaction of Pt^0 with excess benzyl methyl sulfide in C_6H_6 at 140 °C yielded a complicated reaction mixture .
(dippe)Pt(SMe)(CH_2Ph) was **not** identified, but sub-stoichiometric bibenzyl was observed.
Suggested: (dippe)Pt(SMe)(CH_2Ph) was an intermediate.



Alkynyl C—S Oxidative Addition

Not Much is Known

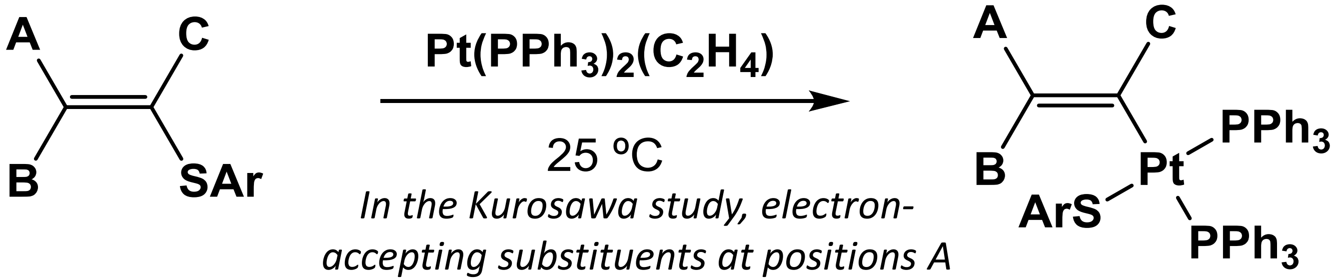
Alcalde, M. I.; Delgado, E.; Donnadieu, B.; Hernandez, E.; Martin, M. P.; Zamora, F. *J. Organomet. Chem.* **2004**, *689*, 552–556.



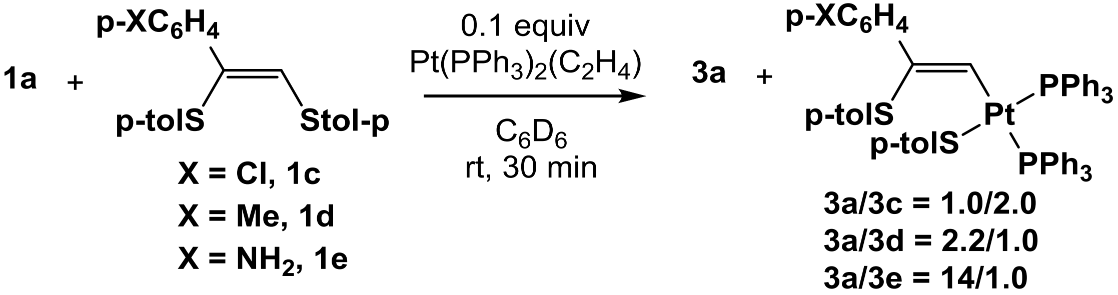
Studies of Alkenyl C—S Substrates

Alkenyl C—S Bond Oxid-Add

Kuniyasu, H. H.; Ohtaka, A.; Nakazono, T.; Kinomoto, M.; Kurosawa, H.
J. Am. Chem. Soc. **2000**, *122*, 2375–2376.



In the Kurosawa study, electron-accepting substituents at positions A and B (but not C) were necessary in order to achieve the OA.



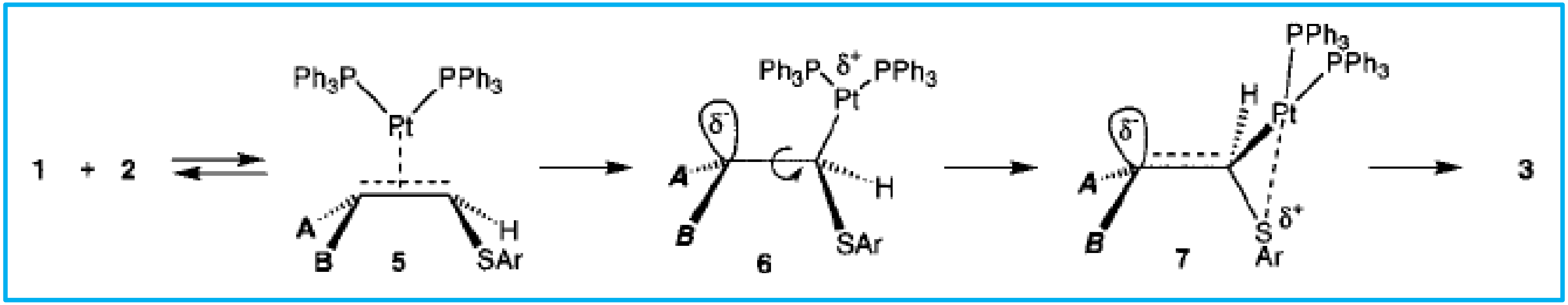
X = Cl, 1c
X = Me, 1d
X = NH_2, 1e

3a/3c = 1.0/2.0
3a/3d = 2.2/1.0
3a/3e = 14/1.0

Electron-withdrawing substituents influenced the rate of the OA; X = Cl reacted about 2.0 times faster than X = H. X = H reacted about 2.2 times faster than X = Me and 14 times faster than X = NH_2.

Example: (Z)-1,2-bis(p-tolylthio)styrene (1a) with $Pt(PPh_3)_2(C_2H_4)$ at 25 °C in benzene provided the product cis-Pt[(Z)-C(H)=C(Stol-p)(Ph)](Stol-p)$(PPh_3)_2$ in 78% isolated yield. At 50 °C in the presence of PPh_3 the kinetically formed *cis* isomer isomerizes to the *trans* isomer.

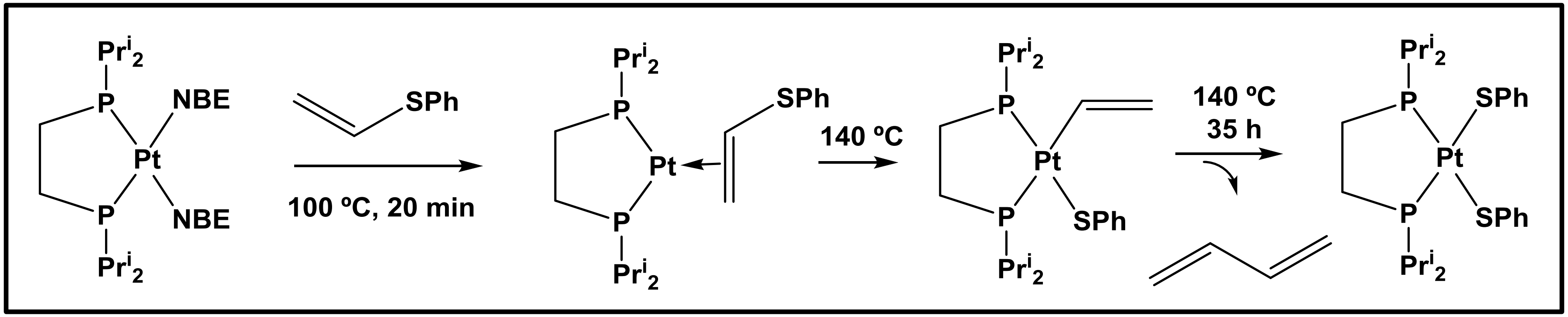
Kurosawa Mechanism for Oxid-Add



- A π-complex forms first - backbonding rehydridizes the alkene carbon atoms.
- The Pt(0) then distorts toward the sterically less hindered terminal vinyl carbon.
- The zwitterionic species possesses anionic charge at the β-carbon; the charge is stabilized by electron-accepting substituents at A and B (electron-withdrawing group in Ar at **A** accelerates the reaction).
- Minimum rotation about the C-C bond directs the anionic lobe coplanar with the C-S antibonding orbital (antiperiplanar to the breaking C—S bond).
- The SAr- group would be pushed out and migrate onto the Pt atom giving the product.
- During the process, the two PPh$_3$s on Pt remain *cis* coordinated and the stereochemistry of substituents on the vinyl group is retained.

Pt Oxidative Addition is General

Jones and coworkers: demonstrated oxidative addition of Pt(0) to less activated vinyl sulfides using a higher reaction temperature. The oxidative addition reaction is therefore general. The intermediate alkene π-complex was observed by Jones.



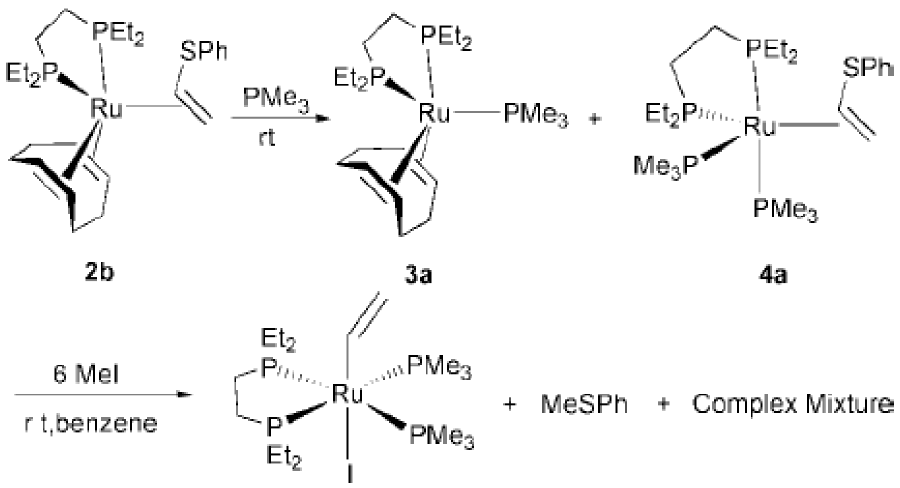
Treatment of (dippe)Pt(NBE)$_2$ with excess phenyl vinyl sulfide in benzene or p-xylene at 100 °C for 20 min afforded the π-complex (dippe)Pt(η^2-CH_2CHSPh). Further reaction of the π-complex occurs upon heating to 140 °C. First, the OA vinyl thiolate complex is observed, then the bis-thiolate is generated. Butadiene was identified as the organic product.

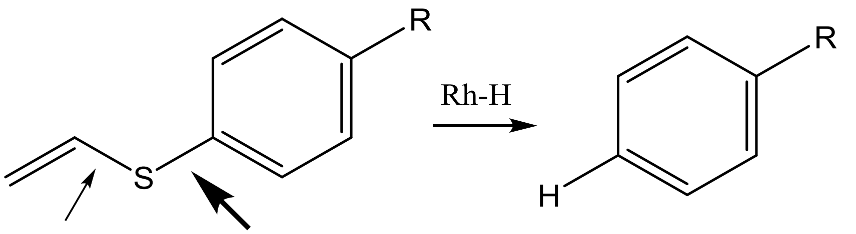
Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D.
Polyhedron **2013**, *58*, 99–105.

Other Vinyl Sulfide Oxid-Add Refs

Ruthenium: Planas, J. G.; Marumo, T.; Ichikawa, Y.; Hirano, M.; Komiya, S. *J. Chem. Soc., Dalton Trans.* **2000**, 2613–2625.

Kohtaro Osakada, Keizo Matsumoto, Takakazu Yamamoto, and Akio Yamamoto, *Organometallics* **1986**, *4*, 857-862.





In contrast to observations using Pt, Rh (as Rh-H) selects for the aryl carbon-sulfur bond in an aryl vinyl thioether.

The authors provide no explanation.

The authors provide no explanation.

Studies of Aryl C—S Substrates

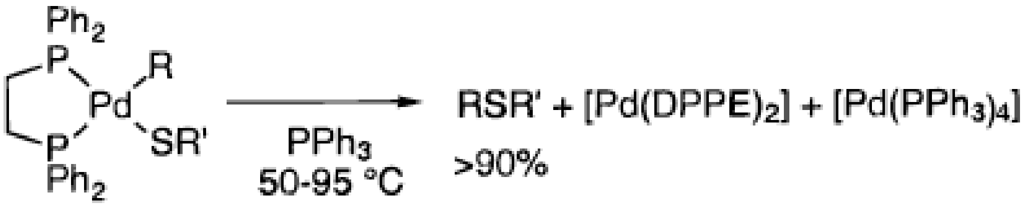
The easy reversibility of oxidative addition using Ni and Pd is relevant.

C—S Reductive Elimination Study

The C—S oxidative addition is readily reversible with metals like Pd and Ni. This forms the basis of many synthetic reactions.

The C—S reductive elimination at Pd has been studied by Hartwig and coworkers:

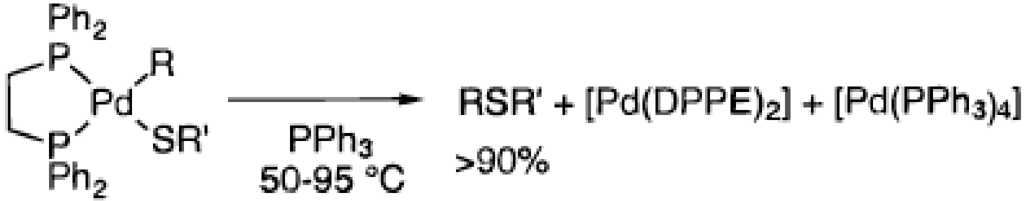
Mann, G.; Baranano, D.; Hartwig, J. F.; Rheingold, A. L.; Guzei, I. A.
J. Am. Chem. Soc. **1998**, *120*, 9205-9219.



Investigation: palladium thiolato complexes [(L)Pd(R)(SR’)],
R is a methyl, alkenyl, aryl, or alkynyl ligand. R’ is an aryl or alkyl group.

When exposed to PPh_3 all thiolato complexes undergo carbon-sulfur bond-forming reductive elimination in high yields.

Relative Rates of C—S Red-Elim

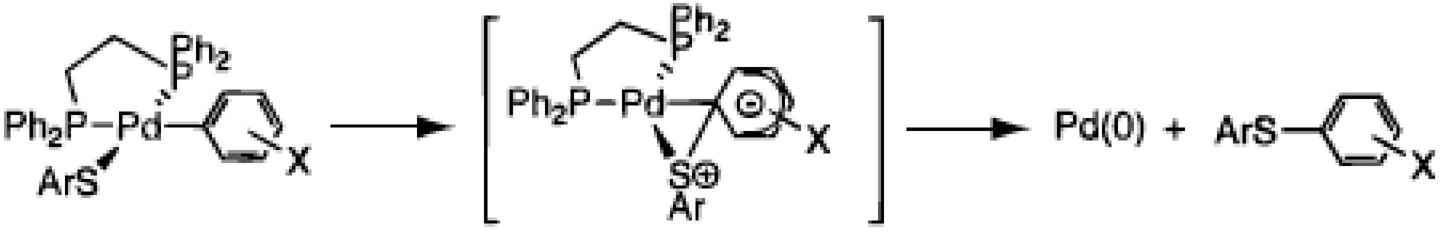


RE fastest: forming alkenyl alkyl sulfides and aryl alkyl sulfides.
RE slower: forming alkynyl alkyl sulfides.
RE slowest: forming dialkyl sulfides.

Thus relative rates for C—S RE follows carbon hybridization: $sp^2 > sp \gg sp^3$.

The C—S RE of both saturated and unsaturated hydrocarbyl groups is *intramolecular and concerted*.

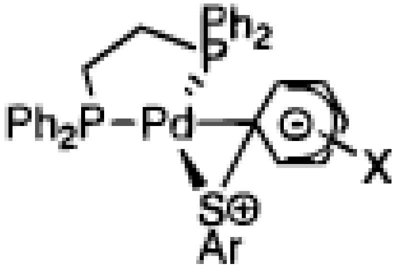
The RE is the fastest when the aryl group attached to Pd is electron deficient and the arene thiolate is electron rich: suggests a reductive elimination mechanism in which the thiolate acts as a nucleophile and the aryl group an electrophile.



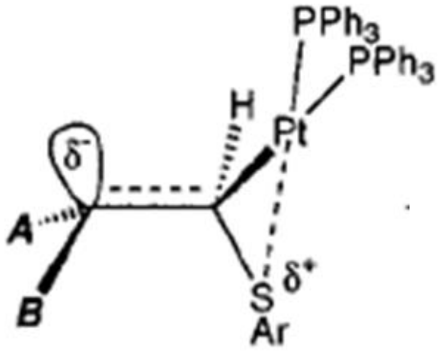
OA-RE. Microscopic Reversibility

Compare the Hartwig and coworkers Pd^{II} C—S reductive elimination mechanism to the Pt^0 C—S oxidative addition mechanism reported by Kurosawa and coworkers.

Hartwig: an electron-withdrawing group in C_6H_4X promoted RE, an observation that is consistent with a transition state *in which the thiolate acts as a nucleophile and the aryl group an electrophile.*
Kurosawa: similar electronic effects stabilize the transition state of the OA of the alkenyl C-S bond to Pt(0).



Hartwig
reductive elimination mechanism



Kurosawa
oxidative addition mechanism

These observations are consistent with the principle of microscopic reversibility.

Reversible C—S Oxidative Addition: Ni

Kohtaro Osakada, Meguru Maeda, Yoshiyuki Nakamura, Takakazu Yamamoto, and Akio Yamamoto, *J. Chem. Soc., Chem. Commun.* **1986**, 442–443.

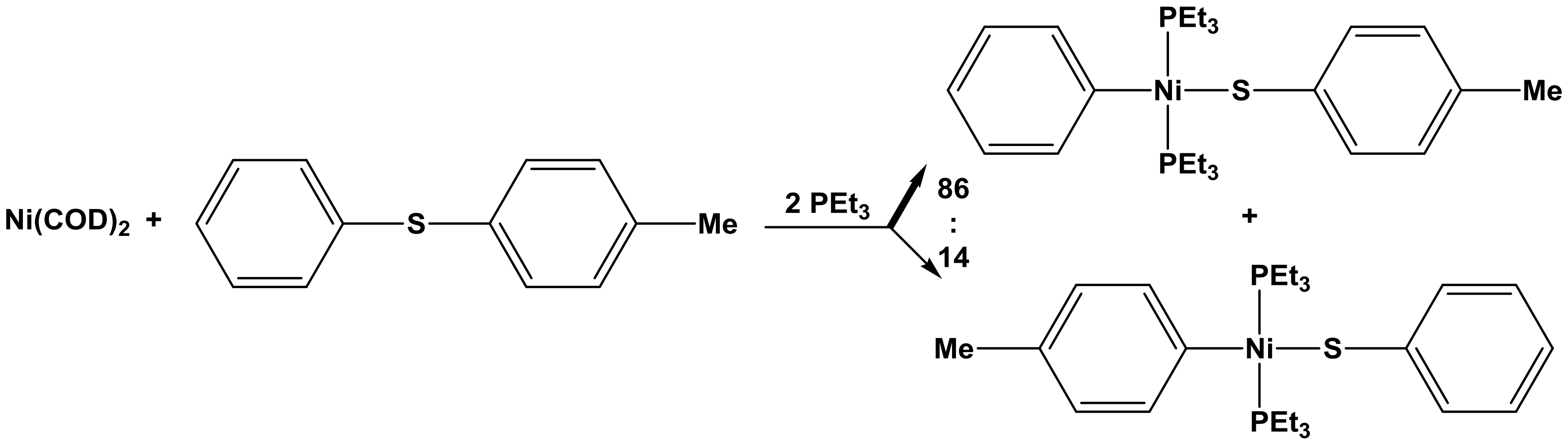
Reversible Oxidative Addition and Reductive Elimination of Diaryl Sulphide by Ni^0

Yamamoto and coworkers showed that the C—S bond in diphenyl sulphide is readily cleaved upon treatment with $Ni(COD)_2$ generating a phenyl(benzenethiolato)Ni(II) complex. Addition of triethylphosphine provides an isolable complex.

$$\mathbf{Ni(COD)_2} \quad + \quad \mathbf{Ph—S—Ph} \xrightarrow{2\ PEt_3} \mathbf{Ph\text{-}Ni(SPh)(PEt_3)_2} \quad + \quad \mathbf{2\ COD}$$

Subtle Selectivity of C—S Cleavage

In reactions of unsymmetrical diaryl sulphides, selective oxidative addition at the less electron-rich C—S bond is observed.



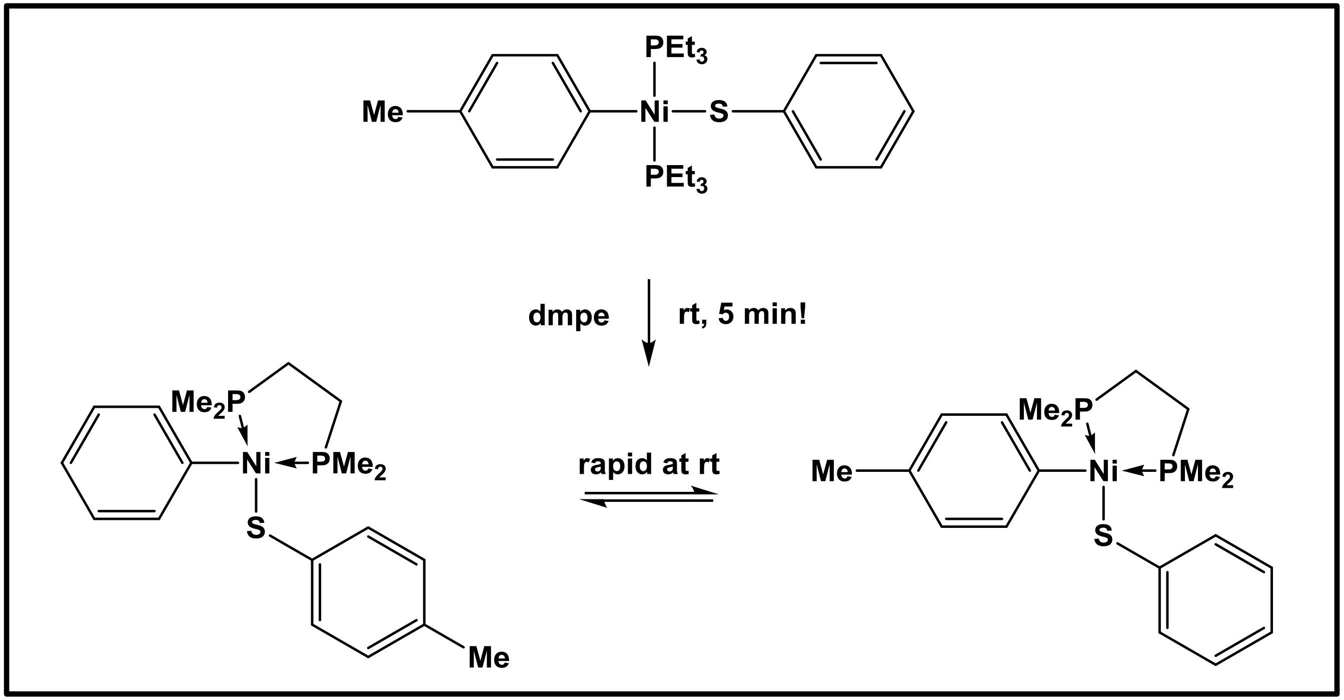
Oxidative addition by Ni at the less electron-rich C—S bond is favored.

REVERSIBILITY: At 60 °C the system equilibrates to a 1:1 mixture within 25 h, presumably through a reversible reductive elimination-oxidative addition.

Rapid and Reversible Oxid-Addn

Yamamoto used a chelating ligand (dmpe) to enhance reaction rates. Mutual exchange of the two newly generated *cis* complexes is very rapid on the NMR time scale at rt. Broadened peaks are observed.

Only at -40 °C is the exchange (the reversible reaction) sufficiently slow that both complexes can be observed in the NMR spectrum.

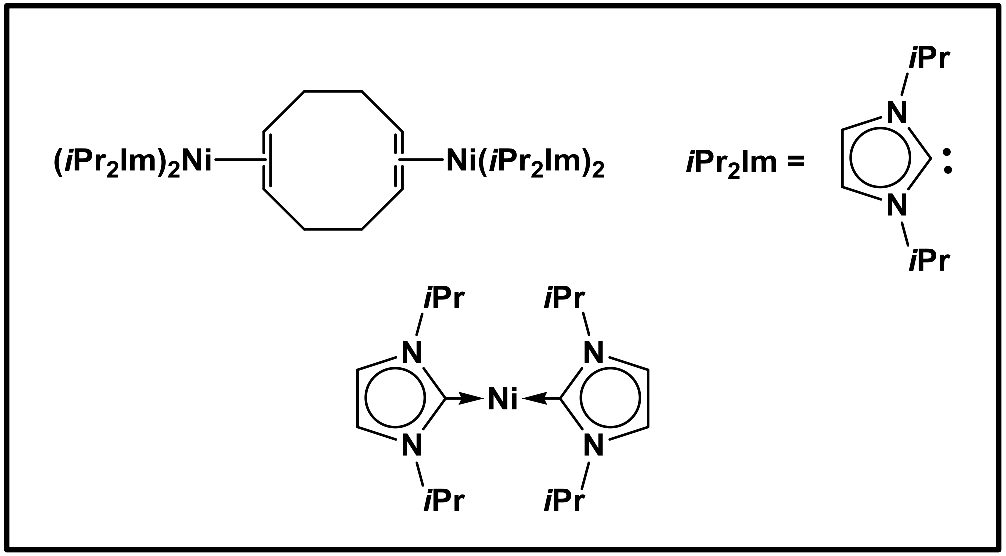


Ni(NHC)$_2$ and C—S Oxid-Add

Schaub, T.; Backes, M.; Plietzsch, O.; Radius, U. *Dalton Trans* **2009**, 7071–7079.

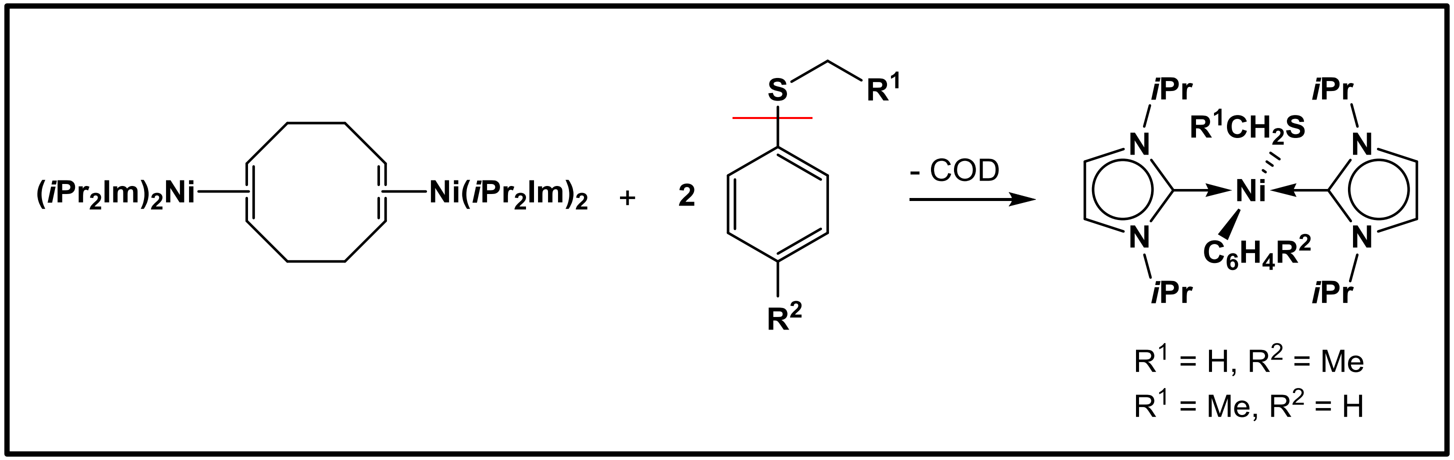
- Radius and coworkers have studied the compound [$Ni_2(iPr_2Im)_4(COD)$] (iPr_2Im = 1,3-di-(isopropyl)-imidazol-2-ylidene) as a source for the very electron-rich nickel(0) biscarbene fragment {$Ni(iPr_2Im)_2$}.

- The complex {$Ni(iPr_2Im)_2$} usually shows a much higher reactivity compared to the widely studied phosphine analogues. It easily cleaves C—C, C—F, and C—S bonds.



Ni(NHC)$_2$ and C—S Oxid-Add

Schaub, T.; Backes, M.; Plietzsch, O.; Radius, U. *Dalton Trans* **2009**, 7071–7079.



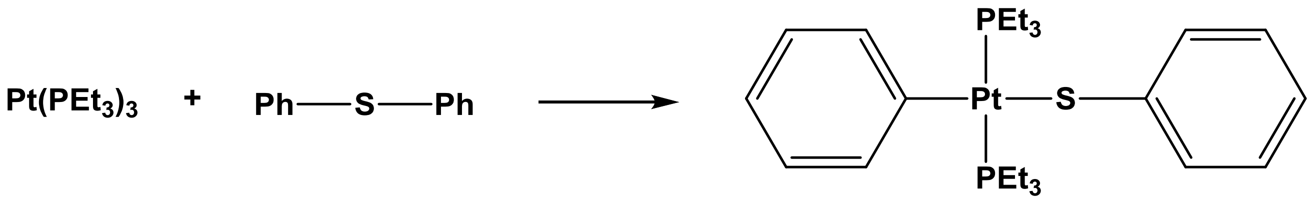
Room temp reaction of [$Ni_2(iPrIm)_4(COD)$] with methyl p-tolyl sulfide and ethyl phenyl sulfide causes cleavage of the aryl C–S bond to afford the oxidative addition complexes: isolated in 50–65% yields as yellow, diamagnetic and relatively air stable powders.

Is there a potential role for complexes like $Ni^0(NHC)_2$ or $(dmpe)Ni^0$ in desulfitative catalysis?

Aryl Sulfide Oxidative Addition with Pt

Han, L. B.; Choi, N.; Tanaka, M. *J. Am. Chem. Soc.* **1997**, *119*, 1795–1796.

Tanaka: a study of $Pt(PEt_3)_3$ oxidative addition to Te, Se, and S organics.
C-X oxidative addition reactivity decreases in the order C-Te > C-Se > C-S



rt, 24 h, no reaction
50 ºC, 24 h, <3%
110 ºC, 6 h, 76%

At room temperature after 24 h, Ph_2S + $Pt(PEt_3)_3$: no reaction.

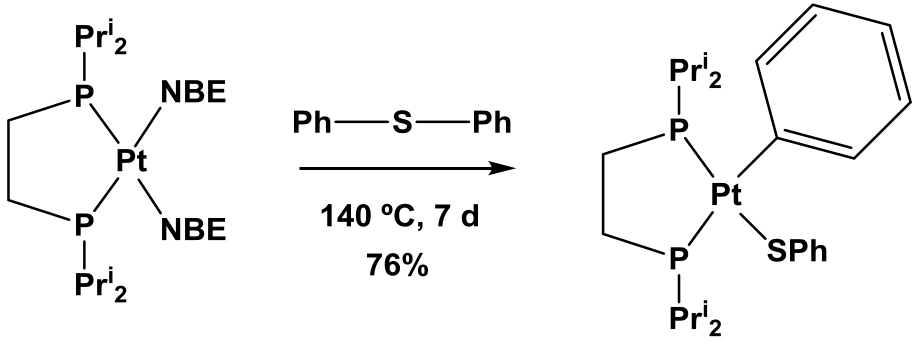
At 50 °C after 24 h: traces of *trans* $PtPh(PhS)(PEt_3)_2$ (<3%).

At 110 °C after 6 h: oxidative addition complex forms as off-white crystals in 76% yield.s

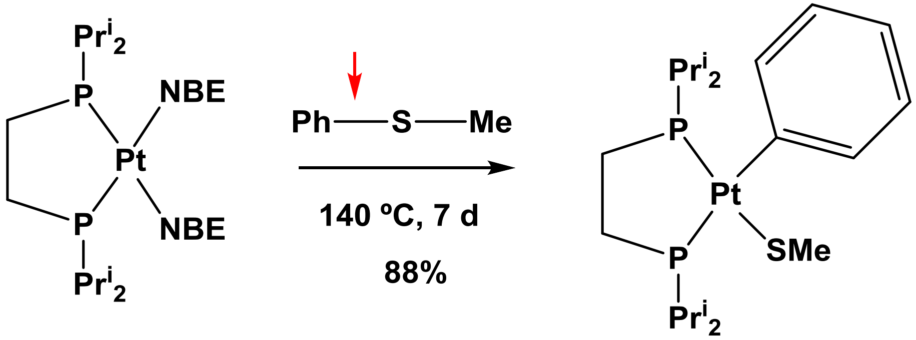
Aryl Sulfide Oxidative Addition with Pt

Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D.
Polyhedron **2013**, *58*, 99–105.

(dippe)Pt(NBE)$_2$ with excess diphenyl sulfide in p-xylene at 140 °C for 7 d.

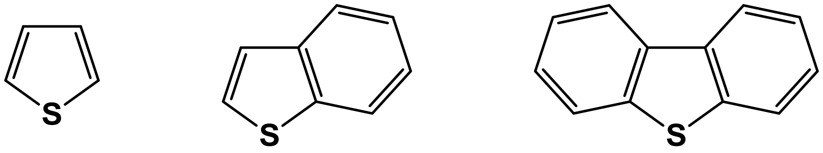


(dippe)Pt(NBE)$_2$ with excess methyl phenyl sulfide in p-xylene at 140 °C for 7 d. Reaction only at the aryl C—S bond.



Thiophenes, Benzothiophenes, Dibenzothiophenes

Extensively studied because of their relevance to the hydrodesulfurization of fossil fuels.



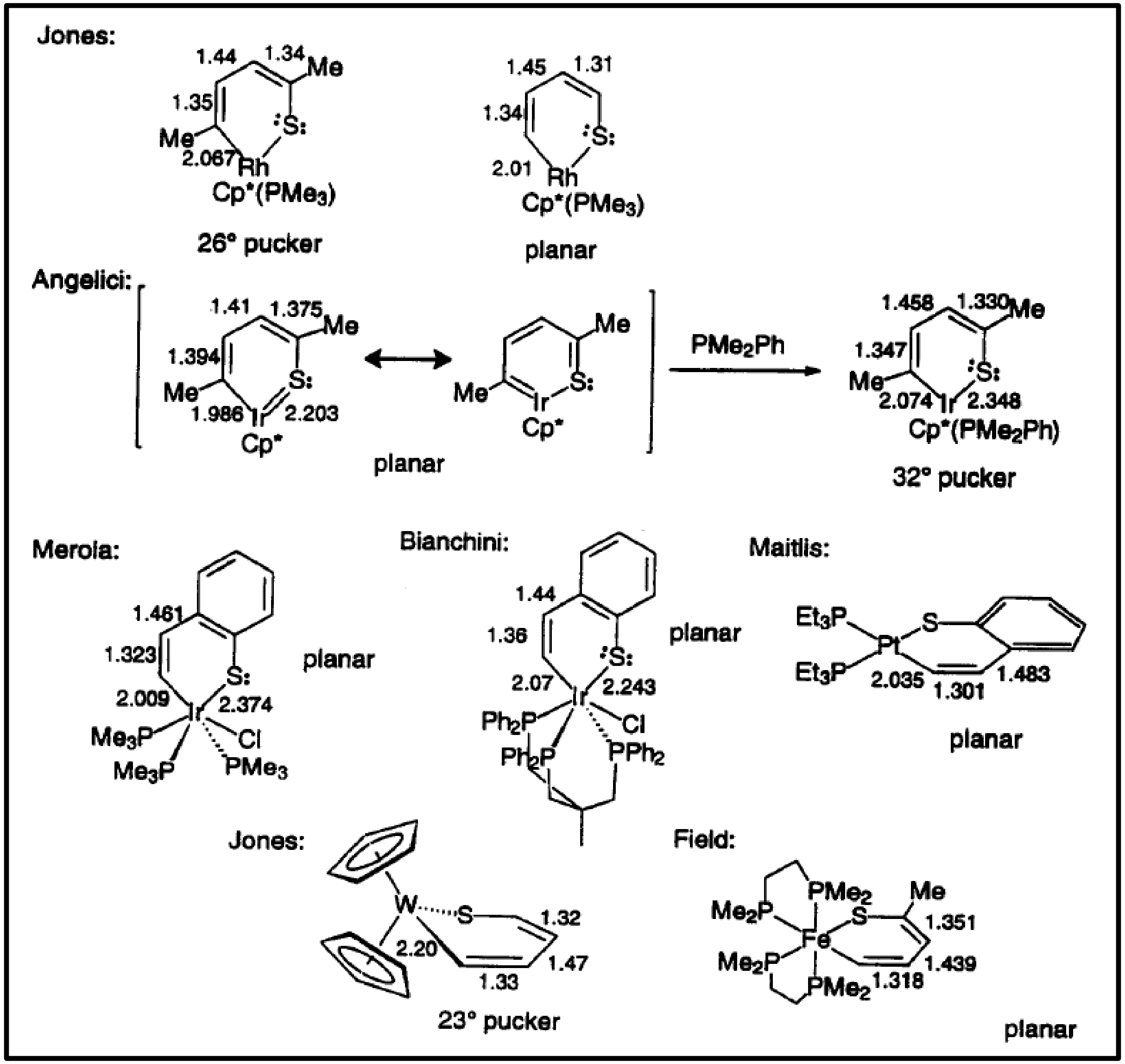
Thiophene, Benzothiophene, and Dibenzothiophene

- There is much interest in the reactions that occur in metal-promoted removal of sulfur (hydrodesulfurization, HDS) during the pretreatment of fossil fuels (e.g., crude oil) prior to refining.
- HDS removes undesirable impurities, such as sulfur-containing molecules.
- This prevents poisoning of the reforming catalysts, produces sulfur-free fuels, and is practiced on a vast scale using a sulfided metal catalyst (e.g., Co-Mo on alumina) at high temperature.
- Heterocycles such as thiophenes (T), benzo[b]thiophenes (BT), and dibenzo[b,d]thiophenes (DBT) present problems as they occur in substantial amounts, particularly in heavier crudes, and are rather resistant to normal HDS techniques.

Weisser, O.; Landa, S. Sulphide Catalysts, Their Properties and Applications; Pergamon: Oxford, **1973**.

Angelici, R. J. *Acc. Chem. Res*. **1988**, 21, 387; *Organometallics* **2001**, *20*, 1259.

Ni, Pt, Co, Rh, Ir, Ni, Fe, Ru, Mo, W, Mn, etc!



Many Researchers.
Many Metals.
Many Complexes.

Leading Reviews:

Angelici, R. J. *Organometallics* **2001**, *20*, 1259–1275.

W.D. Jones, D.A. Vicic, R.M. Chin, J.H. Roache, A.W. Myers, *Polyhedron* 16 (1997) 3115

Some More Recent Studies

Nickel: *J Am Chem Soc* **2009**, *131*, 4120–4126. *Dalton Trans* **2009**, 7071–7079; *Organometallics* **2004**, *23*, 4534–4536.

Platinum: *Organometallics* **2011**, *30*, 4578–4588; *Organometallics* **2011**, *30*, 1637–1645; *Inorg. Chem* **2008**, *47*, 4596–4604.

Rhodium: *Organometallics* **2010**, *29*, 4923–4931; *Inorg. Chem* **2008**, *47*, 10889–10894; *Organometallics* **2008**, *27*, 3666–3670.

Iridium: *J. Organometal. Chem.* **2008**, *693*, 3197–3200.

Molybdenum: *Organometallics* **2010**, *29*, 448–462; *J. Am. Chem. Soc.* **2008**, *130*, 16187.

Tungsten: *Chem. Commun.* **2001**, 1506–1507.

Manganese: *Organometallics* **2002**, *21*, 1262–1270.

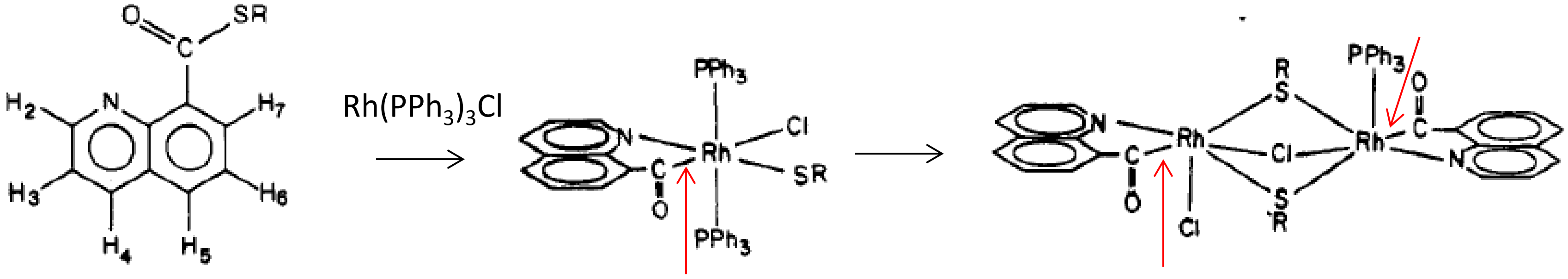
Rhenium: *J. Am. Chem. Soc.* **2005**, *127*, 10436–10447.

Thiol Ester C—S Oxid-Addn

Thiol Ester C—S Oxidative Addn: Rh

Shaver, A.; Uhm, H. L.; Singleton, E.; Liles, D. C. *Inorg. Chem.* **1989**, *28*, 847–851.

Compounds la-e react with $Rh(PPh_3)_3Cl$ in refluxing toluene to give a change in color of the solution from red to yellow and precipitation of the series of yellow thiol ester oxidative addition complexes.



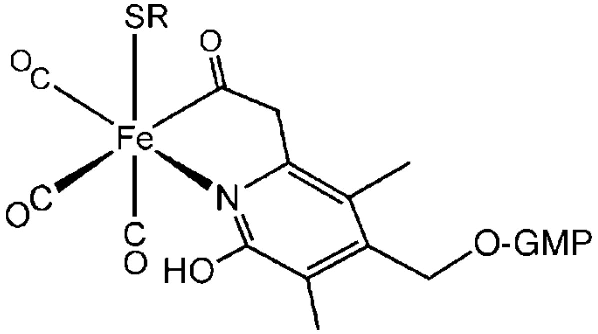
1a, $R = CH_2CH_2CH_2CH_3$
b, $R = CH_2Ph$
c, $R = CHMe_2$
d, $R = Ph$
e, $R = 4\text{-}C_6H_4Me$

Thiol Ester Oxidative Addition: Fe

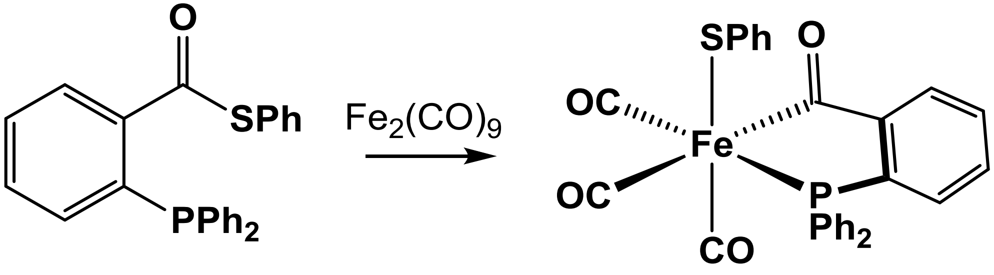
One of the great surprises in bioinorganic chemistry was the discovery of the iron carbonyl sites in the [NiFe]- and the [FeFe]-hydrogenases. A third hydrogenase, Hmd (methylene-tetrahydromethanopterin dehydrogenase), formerly thought to be “metal-free,” was shown to also contain a single iron carbonyl center.

Rauchfuss Model: $Ph_2PC_6H_4$-2-C(O)SPh reacts with $Fe_2(CO)_9$ to give $[Ph_2PC_6H_4C(O)]Fe(SPh)(CO)$, a model for the CO-inhibited active site of the enzyme Hmd. This species reversibly decarbonylates to give a diiron derivative.

Structure of the CO-inhibited active site of Hmd



Rauchfuss Model

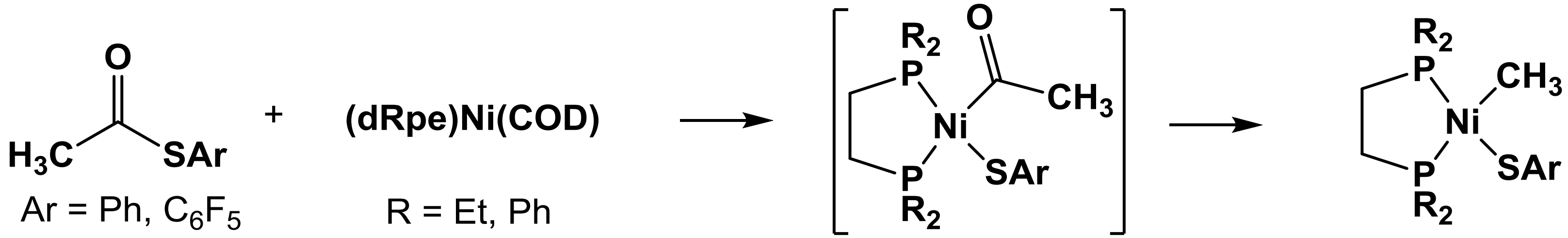


Royer, A. M.; Rauchfuss, T. B.; Gray, D. L. *Organometallics* **2009**, *28*, 3618–3620.

Thiol Ester Oxidative Addition: Ni

Of relevance to various metalloenzymatic processes: Ariyananda, P. W. G.; Kieber-Emmons, M. T.; Yap, G. P. A.; Riordan, C. G. *Dalton Trans* **2009**, 4359–4359.

The thiol esters MeC(O)SC_6F_5 and MeC(O)SPh react with (dRpe)Ni(COD) (R = Ph; R = Et) to produce the corresponding methylnickel thiolates in variable yields.



R = Ph, Ar = Ph
R = Ph, Ar = C_6F_5
R = Et, Ar = Ph
R = Et, Ar = C_6F_5

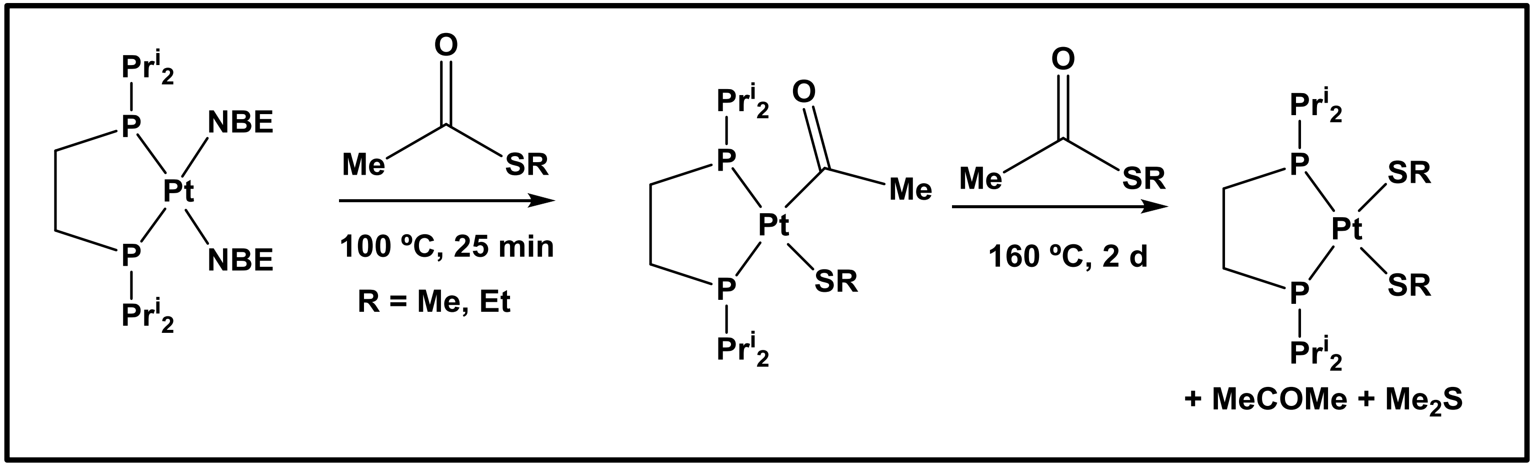
The more electron rich (dppe)Ni fragment facilities the oxidative addition by stabilizing the Ni(II) state. The C_6F_5 substituent of the thioester renders the C–S bond more susceptible to cleavage. Low temperature reaction revealed the initial formation of the acylnickel thiolates which decarbonylated to the more stable alkylnickel thiolates.

Thiol Esters: Pt

Studied by the groups of Kambe and Jones.

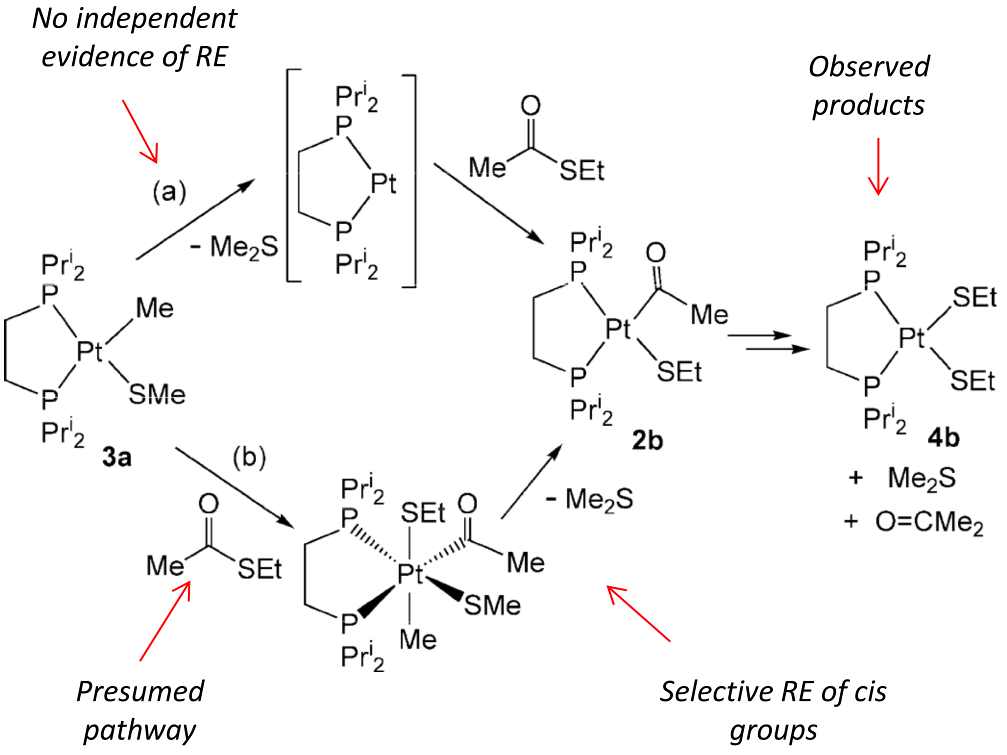
Minami, Y.; Kato, T.; Kuniyasu, H.; Terao, J.; Kambe, N. *Organometallics* **2006**, *25*, 2949–2959. Kambe studied the reaction of $Pt(PPh_3)_3(C_2H_4)$ with α,β-unsaturated thioesters. The authors suggest a reversible oxidative addition

Kundu, S.; Brennessel, W. W.; Jones, W. D. *Organometallics* **2011**, *30*, 5147–5154. Jones and coworkers report the C—S bond activation of both cyclic and acyclic thioesters using $(dippe)Pt(NBE)_2$. *An interesting double oxidative addition through a Pt^{IV} intermediate is proposed to be involved in the reaction mechanism.*

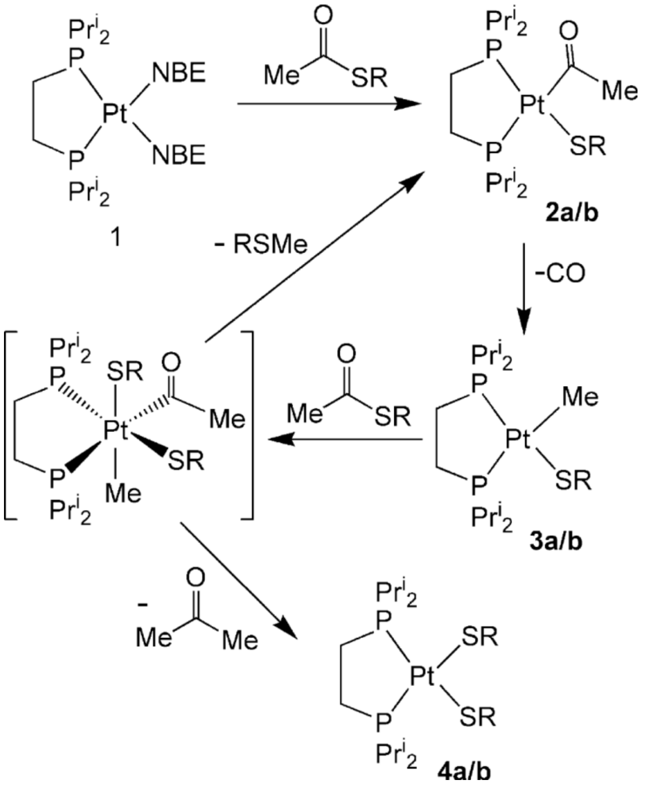


Jones: Cross Over Experiment

Cross-Over Experiments.
Pt—SMe to Pt—SEt



Proposed Mechanism of the
C—S OA of Thiol Esters by Pt



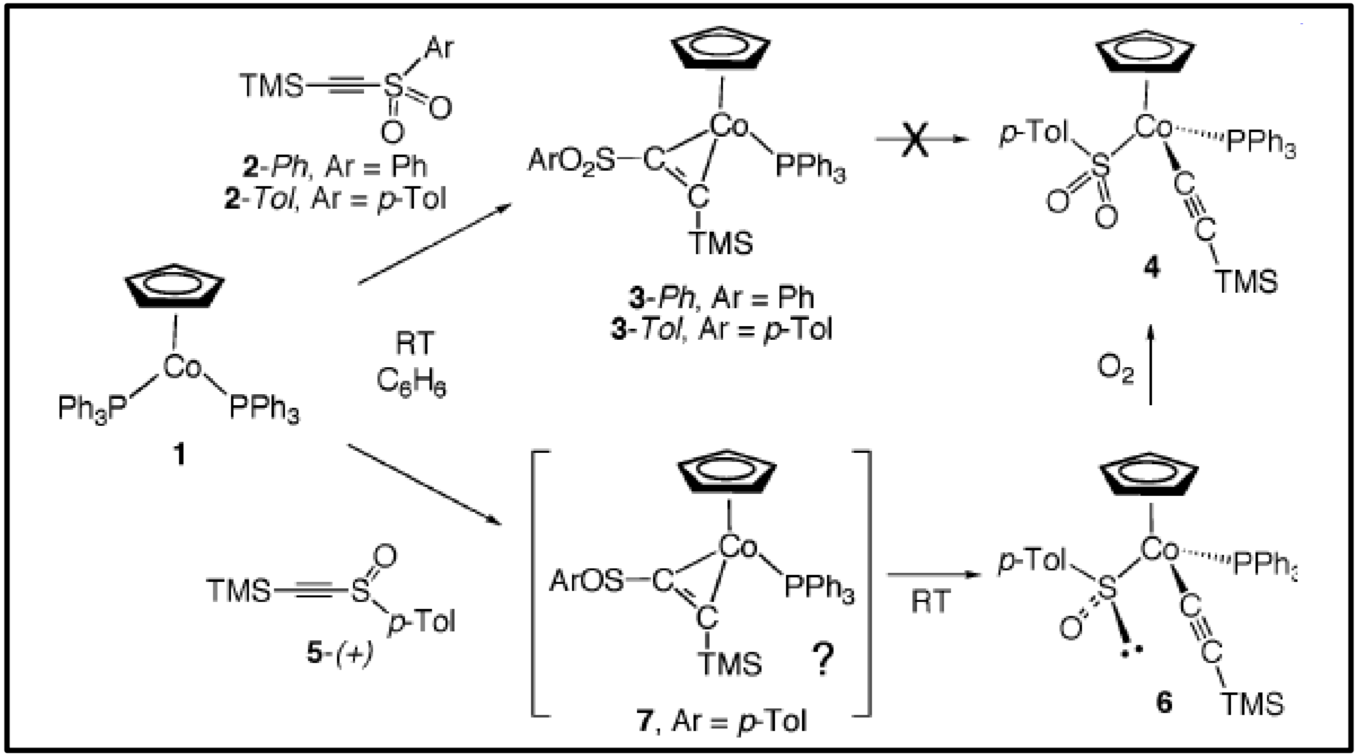
OA of the thioester to the [Pt^0(dippe)] generates an acyl platinum thiolate; -CO gives a methylplatinum thiolate.
A 2nd thioester then reacts with the methylplatinum to form a 6-coordinate Pt^{IV} intermediate.
C-C RE generates acetone a Pt dithiolate; C-S RE generates Me_2S and a new acylPt thiolate.

Sulfoxide C—S Oxidative Addition

Sulfoxide C—S Oxid-Addn: Co

O'Connor, J. M. J.; Bunker, K. D. K.; Rheingold, A. L. A.; Zakharov, L. L.
J. Am. Chem. Soc. **2005**, *127*, 4180–4181.

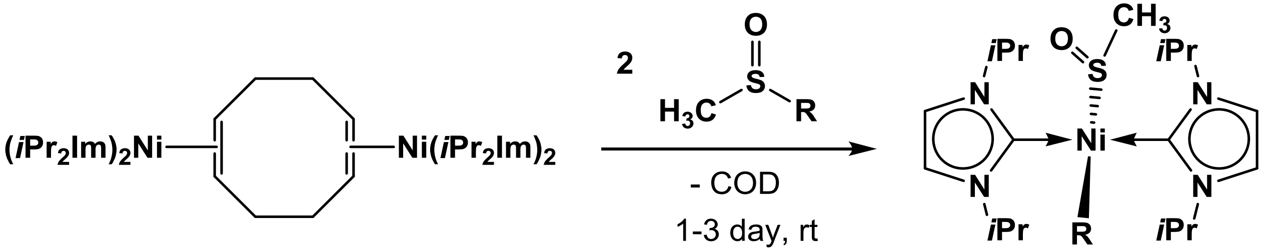
(η^5-C_5H_5)Co(PPh_2) + alkynyl **sulfone** at rt → η^2-alkyne complex, 75-80% yield. No evidence for OA.
In contrast, (η^5-C_5H_5)Co(PPh_2) + alkynyl **sulfoxide** → C(sp)–S oxidative addition (72%).
Coordination (at S?) prior to oxidative addition may be important.



Sulfoxide C—S OA with Ni(NHC)

Schaub, T.; Backes, M.; Radius, U. *Chemical Communications* **2007**, 2037–2039.

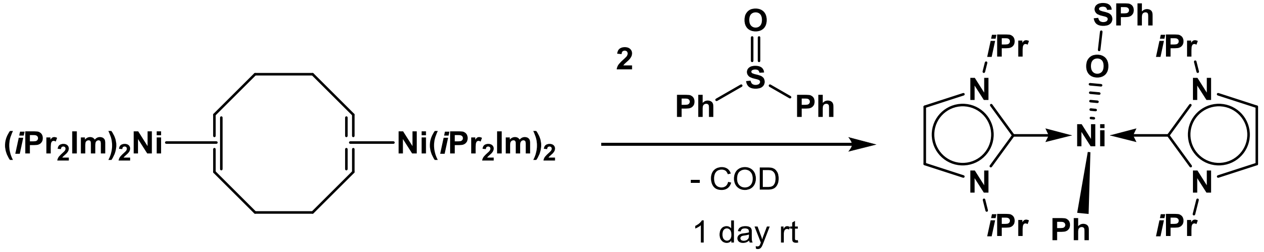
$Ni_2(NHC)_4(COD)$ reacts with two equivalents of dimethyl sulfoxide (DMSO) or phenyl methyl sulfoxide (PMSO) in toluene at rt to give good yields of products of sp^3-C–S(O) bond cleavage (DMSO) and sp^2-C–S(O) bond cleavage (PMSO) as stable yellow solids.



R = Me, Ph

Note that Ph-S cleavage is selected over Me-S cleavage

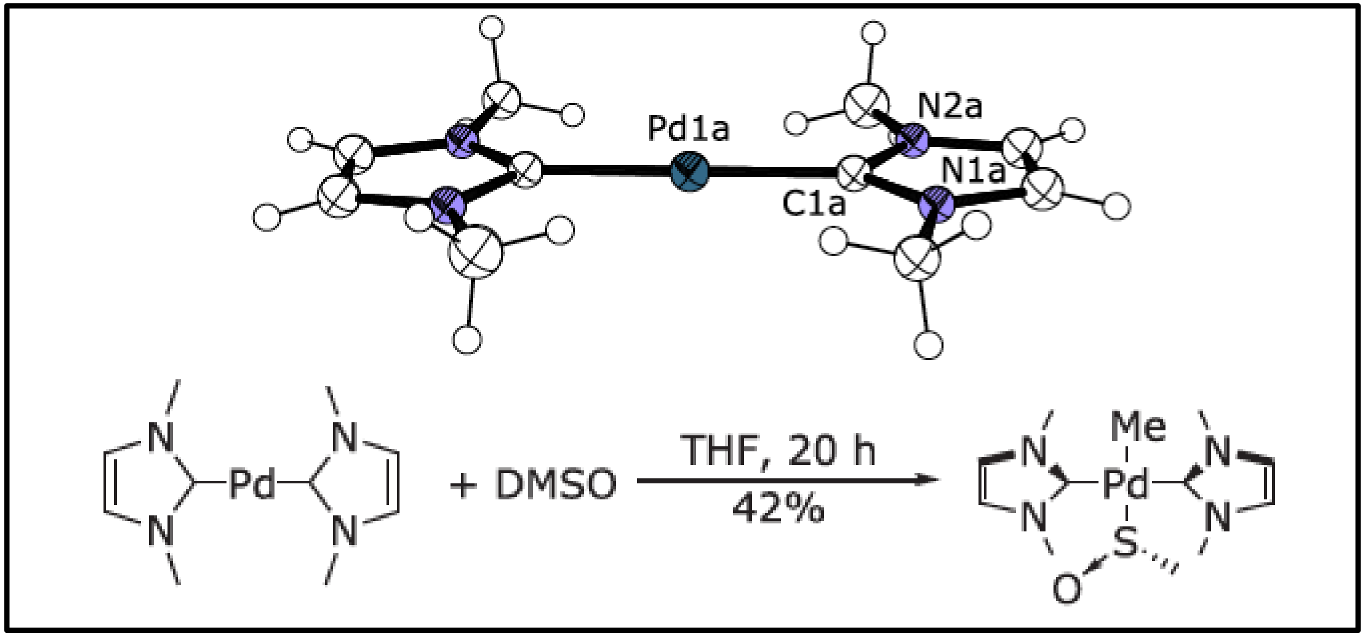
Ph_2SO and $Ni_2(NHC)_4(COD)$ afford $[Ni(iPr_2Im)_2(Ph)(OSPh)]$, an S→O linkage isomer product in which the phenyl sulfinyl ligand is bound via the oxygen atom to the nickel atom.



Compare Radius (2007, Ni NHC) to Lee (2011, Pd NHC)

E. Lee, D. V. Yandulov *J. Organomet. Chem*. 696 (**2011**) 4095-4103

Yandulov described the synthesis and reaction chemistry of an interesting sterically unhindered Pd^0(NHC)$_2$ complex. The study includes C—S oxidative addition along with extensive computational analyses.



Aliphatic C—S Oxidative Addition

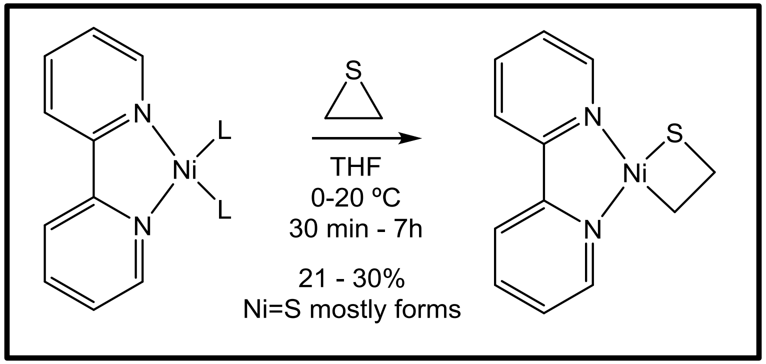
Most are Special Cases

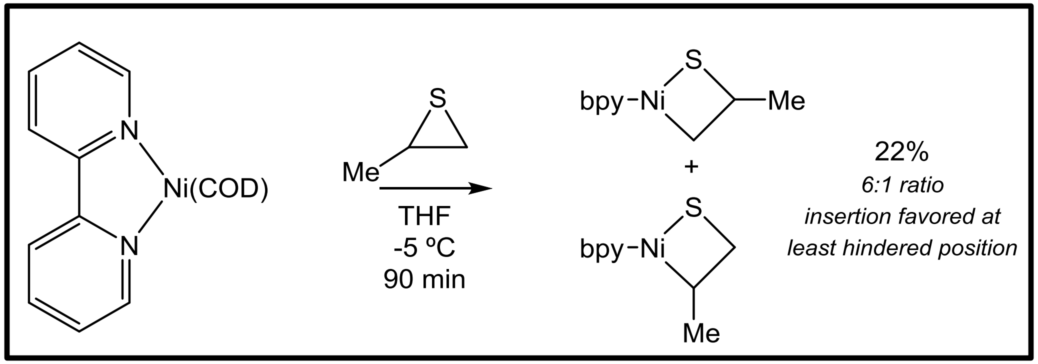
Strained Rings, Chelates

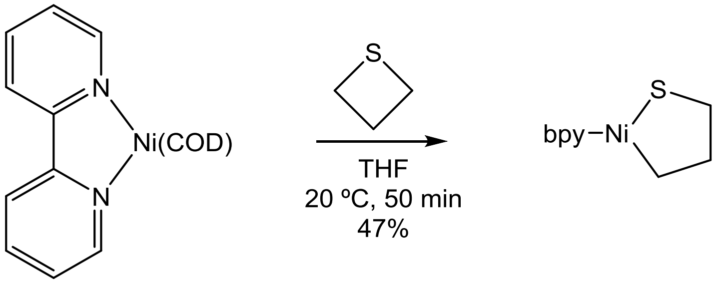
A Few Intriguing Examples

Aliphatic C—S OA

Matsunaga, P. T.; Hillhouse, G. L. *ACIE* **1994**, *33*, 1748–1749.







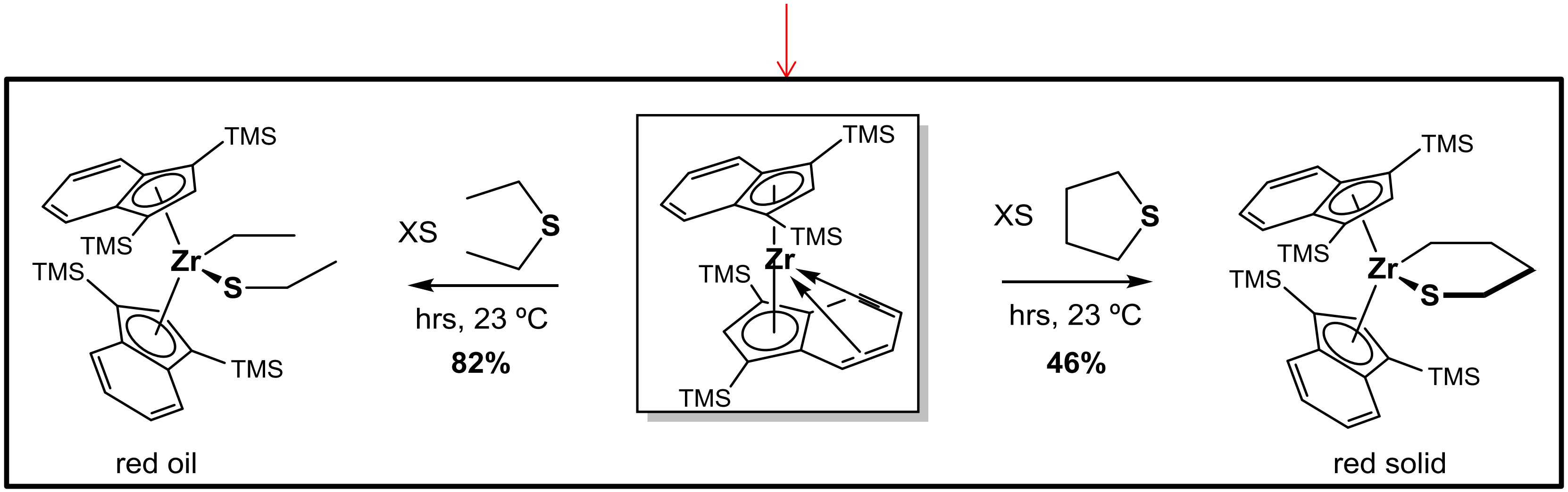
No oxidative addition to tetrahydrothiophene.

(Adams and coworkers studied Ru and Os clusters with strained S-containing rings: *Organometallics* **1992**, *11*, 2281–2289; 2016–2024; 1460–1465.)

An Early Metal C—S Oxid-Addn: Zr

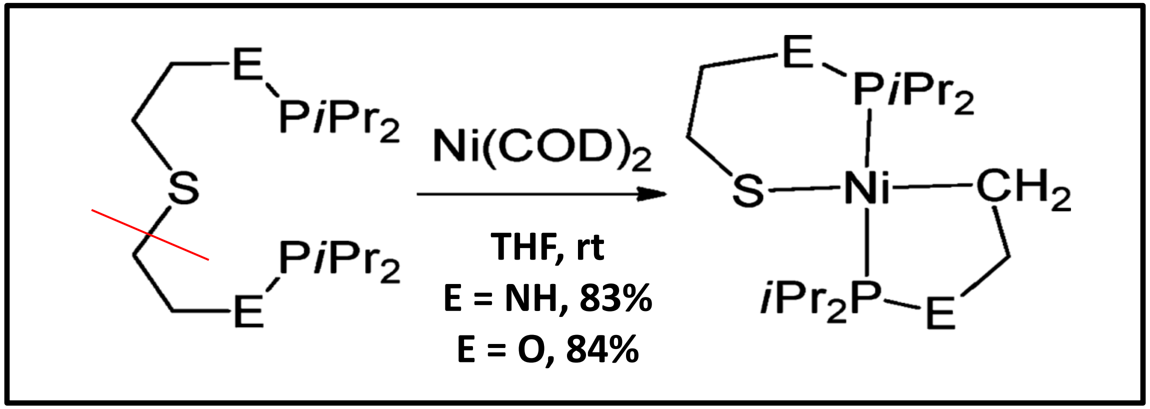
Bradley, C. A.; Veiros, L. F.; Chirik, P. J. *Organometallics* **2007**, 26, 3191–3200.

Bulky η^9,η^5-bis(indenyl)zirconium sandwich complexes have allowed the study of fundamental coordination chemistry at a reduced zirconium center. While one of the indenyl rings adopts unusual η^9 hapticity in the ground state, rapid interconversion of η^9 and η^5 coordination modes at ambient temperature in solution.



Proximity-Driven Oxid-Addn to C(sp^3)-S

Sgro, M. J.; Stephan, D. W. *Organometallics* **2012**, 31, 1584–1587.
A facile C-sp^3—S oxidative addition by Ni(0) is described. The oxidative adducts result upon binding the precursor ligand to Ni(0) followed by oxidative addition of the S−C bonds.



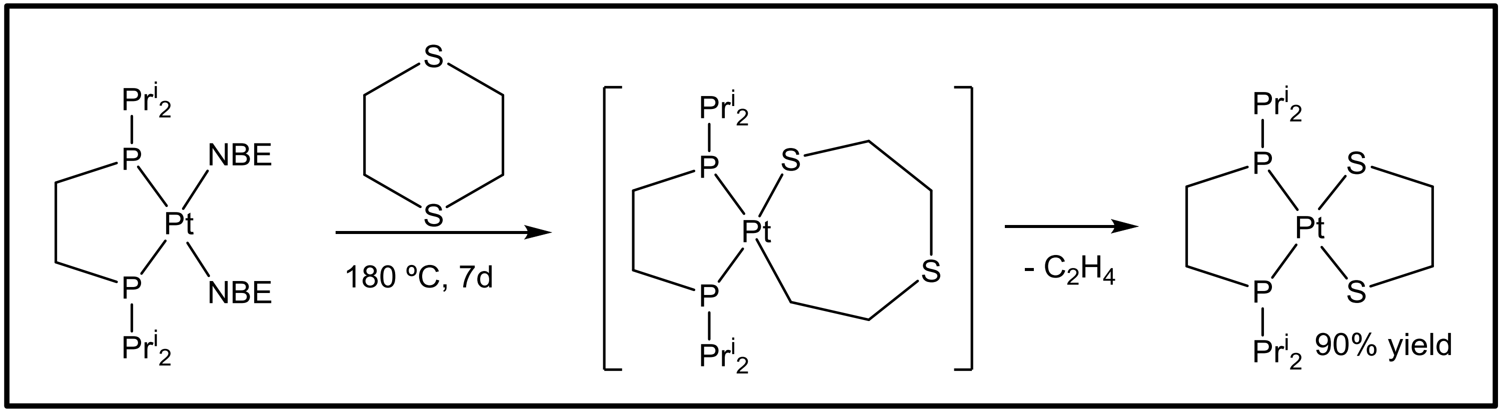
The initial interaction of the ligand with Ni(0) favors an approximately *trans* binding of phosphines, a geometry that enforces the proximity of the C—S bond to Ni(0). This factor, and the very electron-rich nature of the Ni(0) center, induce oxidative addition of the S−C bond.

Subsequent isomerization is required to generate the trans-phosphine disposition observed.

An related and interesting very facile and reversible C—N oxidative addition is also described.

And Platinum, of Course.

Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D.
Polyhedron **2013**, *58*, 99–105.



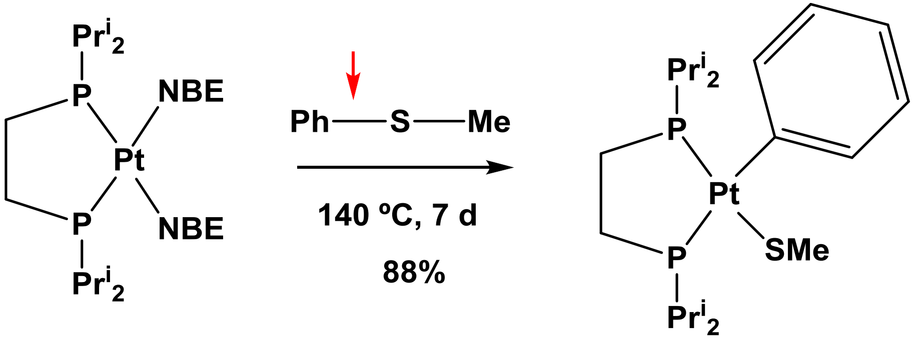
- Reaction of (dippe)$Pt^0(NBE)_2$ with excess dithiane in mesitylene at 180 °C gave complete conversion of the starting material after 7 days furnishing (dippe)Pt(k^2-SCH_2CH_2S) in 90% yield.
- The presence of ethylene in the reaction mixture suggests formation of the C—S oxidative addition product that then suffers a β-elimination to the observed products.

Compare $PhSCH_3$ to $PhSCF_3$

Kundu, S.; Snyder, B. E. R.; Walsh, A. P.; Brennessel, W. W.; Jones, W. D.
Polyhedron **2013**, *58*, 99–105.

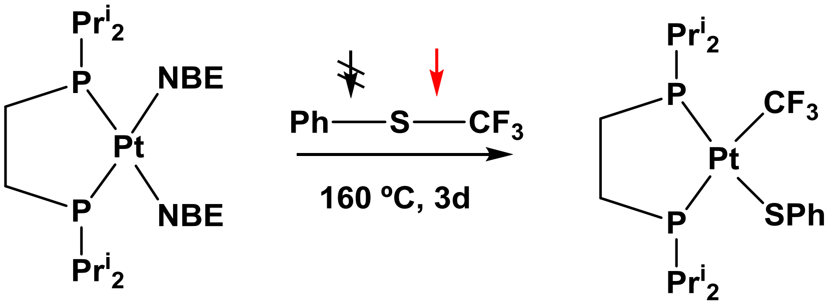
Recall…

(dippe)Pt(NBE)$_2$ with excess methyl phenyl sulfide in p-xylene at 140 °C for 7 d. Only reacts at aryl C—S bond.



Compare…

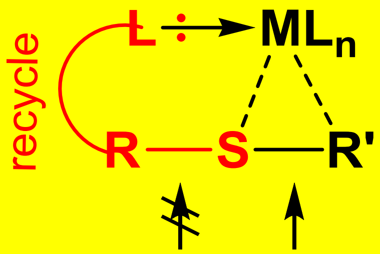
(dippe)Pt(NBE)$_2$ with excess phenyl trifluoromethyl sulfide in mesitylene at 160 °C after 3 d gave (in low yld) what appears to be (dippe)Pt(SPh)(CF_3), and not (dippe)Pt(SCF_3)(Ph).



Looking Ahead

Although C—S oxidative addition has been extensively investigated, most studies relate to the hydrodesulfurization of fossil fuels. From the perspective of utilizing C—S oxidative addition in highly selective synthesis, much remains to be learned.

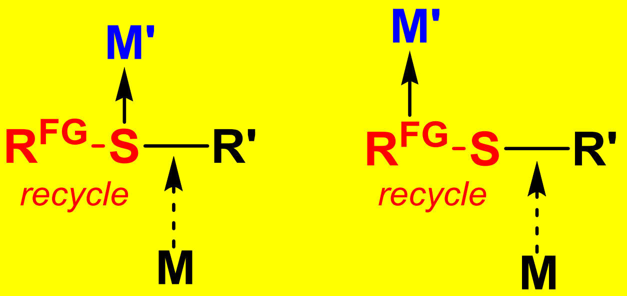
<u>We understand little about directing effects:</u>



where R' = sp, sp^2, sp^3 carbon

directing effects → sp, sp^2, and sp^3 oxidative addition

<u>We understand little about cooperative effects:</u>



*use a co-catalytic **M'** to enhance the desired oxidative addition*

Can a functionalized (recyclable) S-pendant influence the site of oxidative addition and the synthetic outcome of the reaction?

Can a second co-catalyst **M'** in conjugation with a functionalized thiolate cooperatively influence the oxidative addition?