Palladium (I) Dimers:

Precursor, Parasite, and Active Catalyst

Matt Bock Denmark Group Meeting 12 September 2023





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Palladium Dimers in Synthesis



Chem. Rev. 2022, 122, 16983-17027.; Molecules 2018, 23, 140; Angew. Chem. Int. Ed. 2021, 60, 3355-3366.

Ph₃P

Ph₂P

tBu-

0 ۰Pd

[Pd(µ-allyl)SIPr]2

- Pd-Pd bond

OMe

Pd-PtBu₃

SIP

MeO

PPh₃

∠PPh₃

Pd-Br

Br-Pd-Pd-Br

[Pd(dppm)(Br)]₂

JohnPhos Dimer

A Brief History of Palladium(I) Dimers



Coord. Chem. Rev. 2002, 231, 207-228; Angew. Chem. Int. Ed. 2021, 60, 3355-3366.

Outline

- I. Electronic Structure and Bonding of Pd(I) Dimers
- II. Synthetic Methods to Prepare Pd(I) Dimers
- III. Pd(I) Dimers: Precatalyst or Parasite?
- IV. Catalysis with Pd(I) Dimers

Not Covered:

- I. Palladium(I) Clusters
- II. Stoichiometric Transformations of [Pd(dppm)X]₂
- III. Stoichiometric Transformations of $Pd(\mu$ -allyl) Dimers
- IV. Catalytic Pd(I) Carbonylation Chemistry

Electronic Structure: Corner-Sharing Pd(I) Dimers



J. Am. Chem. Soc. 1975, 97, 1961-1962. Inorg. Chem. 1993, 32, 4271-4729.

Electronic Structure: Edge-Sharing Pd(I) Dimers





HF calculations show an interesting interaction is occupied Pd-Pd interaction is mediated by the ligands teraction: the total overlap population between the two metal atoms is practically equal to zero (0.03 e), which means that the Pd(I) atoms are practically not bonded to each other. To

J. Chem. Soc. Chem. Commun. 1981, 1077-1079.; Inorg. Chem. 1983, 4, 666-671.

Electronic Structure: µ-AllyI-Pd(I) Dimers



C(2) is positioned forward towards Pd coordination plane The phosphine ligands are positioned away from C(2)-H



 π -allyl Pd does not have interactions b and c; The termini of μ -Allyl-Pd(I) Dimers are unreactive

J. Am. Chem. Soc. 2011, 133, 3280-3283.; Chem. Soc. Rev. 2016, 45, 2871-2899.

What about Other Pd(I)-Dimers?



tBu tBu -Pd-PMe₃ Me₃P-Pd tBu^ftBu

Representative Bond lengths and angles Pd-Pd bond: 2.571 Å Pd-P-Pd angle: 67.0°

DFT calculations of $[Pd(PMe_3)(\mu - Pbu_2)]_2$ seems to suggest Pd-Pd bond is the result of $d(\sigma) - d(\sigma)$ interactions

J. Chem. Soc. Dalton Trans. 1996, 4313-4314; Inorg. Chem. 1987, 26, 4228-4231.; Inorg. Chem. 1999, 38, 4620-4625.

Synthetic Methods for Pd(I) Dimers



J. Chem. Soc. Dalton. Trans. **1996**, 4313-4314. *Organometallics* **2004**, *23*, 3931-3940, *J. Am. Chem. Soc.* **2006**, *128*, 898-904; *Organometallics* **2004**, *23*, 3931-3940. *J. Am. Chem. Soc.* **1978**, *100*, 6099-6106.; *Chem. Commun.* **2000**, 1689-1690.

Is Pd(I) Dimer Synthesis Really That Simple?



Data Science-Guided Synthesis for Pd(I) Dimers



Science 2021, 374, 1134-1140.

Data Science-Guided Synthesis for Pd(I) Dimers



Science **2021**, *374*, 1134-1140.

Data Science-Guided Synthesis for Pd(I) Dimers



D Experimental validation of representative examples (new Pd^(I) dimers - all of which are of bridged geometry)

Science 2021, 374, 1134-1140.

Pd(I) Dimers as Catalytic Precursors to Pd(0)



J. Am. Chem. Soc. 2017, 139, 5194-5200.; Angew. Chem. Int. Ed. 2002, 41, 4746-4748.;

Scope of [Pd(µ-Br)PR₃]₂-Catalyzed Transformations



Angew. Chem. Int. Ed. **2002**, *41*, 4746-4748.; J. Am. Chem. Soc. **2006**, *128*, 4976-4985.; J. Org. Chem. **2009**, *74*, 4005-4008. J. Org. Chem. **2013**, *78*, 8250-8266.; Org. Lett. **2012**, *14*, 3716-3719.

Determination of the Mechanism of Catalyst Activation



J. Am. Chem. Soc. 2012, 134, 606-612.

Determination of the Mechanism of Catalyst Activation

Dissociation Energies of Proposed Pathways

Dissociation Type	ΔG_{diss} (kcal/mol)
$Pd^{0}L_{2} \longrightarrow Pd^{0}L + L$	27.2
[Pd ^I LBr] ₂ → 2 Pd ^I LBr	24.8
$[Pd^{I}LBr]_{2} \rightarrow 2Pd^{II}LBr_{2} + Pd^{0}L$	38.1
$[Pd^{I}LBr]_{2} \longrightarrow 2 Pd^{II}Br_{2} + Pd^{0}L_{2}$	65.4
$[Pd^{I}LBr]_{2} \longrightarrow 2 LPd_{2}Br_{2} + L$	36.2

^aM06L(THF)//B3LYP/6-31+G(d) with SDD (for Pd)

Two takeaways:

- 1. Disproportionation in either direction is energetically prohibitive!
- 2. Pd(I) radical is energetically feasible but how the reductive process takes place is unclear



J. Am. Chem. Soc. 2012, 134, 606-612. Organometallics 2015, 34, 5191-5195.

Determination of the Mechanism of Catalyst Activation



J. Am. Chem. Soc. 2012, 134, 606-612. Organometallics 2015, 34, 5191-5195.

Beyond $[Pd(\mu-Br)PR_3]_2$: μ -AllyIPd(I) Dimers



when compared to their closely related π -allyl-Pd(II) No insight in method of activation or the active speciation

Organometallics 2004, 23, 3931-3940. Org Lett 2006, 8, 793-795. J. Org. Chem. 2009, 74, 8897-8900.

π-allyIPd(II) Monomers—An Insight into Catalysis

Colacot's Studies on the Mechanism of Activation



Similar slower rates observed with other ligated allyl/crotyl ligand pairs What is the origin of the slower rates?

Proposed Activation Pathways from Nolan's Original Work



J. Org. Chem. 2010, 75, 6477-6488. J Org Chem 2011, 76, 7918-7932. J. Org. Chem. 2015, 80, 6794-6813.

μ-allyIPd(I) Dimers: Precursor or Parasite?



J. Org. Chem. 2010, 75, 6477-6488. J Org Chem 2011, 76, 7918-7932. J. Org. Chem. 2015, 80, 6794-6813.

μ-allyIPd(I) Dimers: Precursor or Parasite?



For the monomers, formation of dimers were observed by NMR Sequestration of the monoligated Pd is likely

J. Am. Chem. Soc. 2014, 136, 7300-7316.



Low activity of allyl precatalyst appears to be due to sequestration of active Pd(0) to Pd(I)-dimer <u>On the formation of μ-allylPd(I) Dimers</u>



DFT supports these experimental findings

Summary Slide

On Pd2-µ-Br2 as a Precursor for Monoligated Pd(0)



Pd₂-µ-Br₂ acts as a reservoir for monoligated Pd(0) This happens most likely through a reductive pathway, though the actual mechanism is still unclear

On µ-allyIPd(I) Dimers as a Precursor for Monoligated Pd(0)



Organometallics 2004, 23, 3931-3940. Org Lett 2006, 8, 793-795. J. Org. Chem. 2009, 71, 8897-8900.

Pd(I) Dimer as the Active Catalyst: First Report





No observation of any Pd(II) intermediates. Additional control experiments suggest radical pathway not involved

Chem. Sci. 2013, 4, 4434-4439.

Introduction to Pd(I) Dimer-Catalysis



Chem. Sci. 2013, 4, 4431-4439.; For further kinetic studies, see: J. Org. Chem. 2014, 79, 12041-12046.

Introduction to Pd(I) Dimer-Catalysis



Chem. Sci. 2013, 4, 4431-4439.; For further kinetic studies, see: J. Org. Chem. 2014, 79, 12041-12046.

How to control Pd(I) dimer vs Pd(0)?



A Generalized Approach to Functionalization



be driven to completion?



Realization of a Catalytic Approach



Scope of Chalcogen Nucleophiles

Catalytic Trifluoromethylselenynation of Arenes



Angew. Chem. Int. Ed. **2015**, 54, 10322-10326; Angew. Chem. Int. Ed. **2018**, 57, 12425-12429.; Chem. Eur. J.**2019**, 25, 9419-9422. Angew. Chem. Int. Ed. **2019**, 58, 11395-11399.

What about Carbon-based Nucleophiles?



Organometallics **2015**, 34, 5191-5195. J. Am. Chem. Soc. **2012**, 134, 606-612.; Angew. Chem. Int. Ed. **2017**, 56, 1581-1585. Tetrahedron Lett. **2015**, 56, 554-557.; 31 Tetrahedron Lett. **2011**, 52, 6346-6348.

Site-Selective Couplings



What is the Active Catalyst: Monoligated Pd(0) or Pd(I)?

Addition Studies



Angew. Chem. Int. Ed. 2017, 56, 1581-1585.

Scope of Carbon Nucleophiles



 $Pd_2-\mu-I_2$ enables a variety of transformations that standard Pd(0) or Pd(II) precatalysts struggle to perform

Angew. Chem. Int. Ed. 2017, 56, 7078-7082.; Angew. Chem. Int. Ed. 2019, 58, 10179-10183.; Angew. Chem. Int. Ed. 2023, 62, e202211167

Modular Synthesis of Arenes



Not shown, but selective functionalization with OTf and Cl, Br and Cl are possible as well

Angew. Chem. Int. Ed. 2018, 57, 12573-12577.

Summary slide



Nuc = RMgCl, RZnCl, SCF₃, SeCF₃, SR, SeR, SP(O)(OR₁)(OR₂)

Takehome Messages

- Pd(I) dimers can react at the Pd(I) center!

 While reactivity as the Pd(I) dimer has been clearly demonstrated for chalogen-based nucleophiles, carbon nucleophiles may exist as either monomeric Pd(0) or dimeric Pd(I)

- Pd(I) catalysis is best used for installation of heteroatoms that are traditionally more challenging in Pd(0) catalysis

 This is because transmetalation/ligand substitution occurs after the rate determining step, oxidative addition

- Halogen-selective catalysis is possible by tuning the solvent alone

 It is unclear if this unique reactivity is because of the Pd(I) dimer or generation of a Highly active monomeric Pd(0) species.

Future Directions

Future Directions:

- 1. Whereas evidence for Pd(I)-dimers is clear for reactions with heteroatomic nucleophiles, less clear for carbon-based nucleophiles.
- 2. When Pd(I) species are catalytic precursors to monoligated Pd(0), what is the reduction mechanism which produces Pd(0) so easily? Seems to be highly reaction specific
- 3. More unique catalytic Pd(I)-Pd(I) reactivity!
 - 1. Lots of interesting stochiometric reactivity with carbonyls
 - 2. Wild C-C bond insertions with Pd(I) dimers (so many remarkable stoichiometric examples)



Leading References

Minireview 🖸 Open Access 💿 🛈

Catalysis with Palladium(I) Dimers

Dr. Christoph Fricke, Dr. Theresa Sperger, Marvin Mendel, Prof. Franziska Schoenebeck 🔀

Recent advances of dinuclear nickel- and palladium-complexes in homogeneous catalysis

Wentao Xu, Muzi Li, Liancheng Qiao and Jin Xie 💿 *

Review Dinuclear Nickel(I) and Palladium(I) Complexes for Highly Active Transformations of Organic Compounds

Takahiro Inatomi 🙆, Yuji Koga and Kouki Matsubara * 🙆

Dinuclear Pd^I complexes with bridging allyl and related ligands

Nilay Hazari* and Damian P. Hruszkewycz

Organopalladium complexes containing palladium-palladium bonds

Tetsuro Murahashi, Hideo Kurosawa*

Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565-0871, Japan Received 16 November 2001; received in revised form 28 March 2002 Angew. Chem. Int. Ed. 2021, 60, 3355-3366.

Chem. Commun. 2020, 56, 8524-8536.

Molecules 2018, 23, 140

Chem. Soc. Rev. 2016, 45, 2871-2899.

Coord. Chem. Rev. 2002, 231, 207-228

For a comprehensive review of approaches to monoligated Pd(0) checkout: *Chem. Rev.* **2022**, *122*, 16983-17027.