

# Homo- and Heterobimetallic Precursor Catalysts for the Heck Reaction, and a Proposal for a General Catalytic Cooperativity Index

Nathan D. Jones, Brian R. James\*

Department of Chemistry, University of British Columbia, Vancouver, Canada V6T 1Z1  
Fax: (+1)-604-822-2847, e-mail: brj@chem.ubc.ca

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This paper is dedicated to Roger Sheldon on the occasion of his 60th birthday; one of us (BRJ) has known Roger for one half-life, and in 1974 he led a Dutch soccer side to a memorable 4-4 tie against my international side.

**Abstract:** Homo- ( $\text{Pd}_2$ ) and heterobimetallic ( $\text{PtPd}$ ) complexes supported by a  $P,P$ -bridging, bis( $P,N$ -chelating) coordination mode of the potentially hexadentate ligand 1,1-bis[di(*o*-*N,N*-dimethylanilyl)phosphino]methane (dmapm) are effective catalyst precursors for the aerobic Heck coupling of iodobenzene and styrene at 100 °C in DMF/ $\text{H}_2\text{O}$  solution containing  $\text{K}_2\text{CO}_3$ . This medium allows for trivial separation of the *trans*-stilbene product which precipitates after the reaction mixture is cooled. The bimetallic precursors are more active than predicted from the sum of the activities of complexes chosen to mimic their mono-metallic “half units,” suggesting some degree of intermetallic cooperativity during the

reaction. A non-linear dependence of initial rate on catalyst concentration implies, however, that the complexes do not remain intact, and may be involved in dissociative equilibria with non-dmapm containing monometallic components that are more active species for the Heck coupling. The complexes are slowly degraded by oxidation at a phosphorus centre. A general index for quantifying the degree of intermetallic cooperativity during a catalytic cycle is proposed and its utility and limitations are discussed.

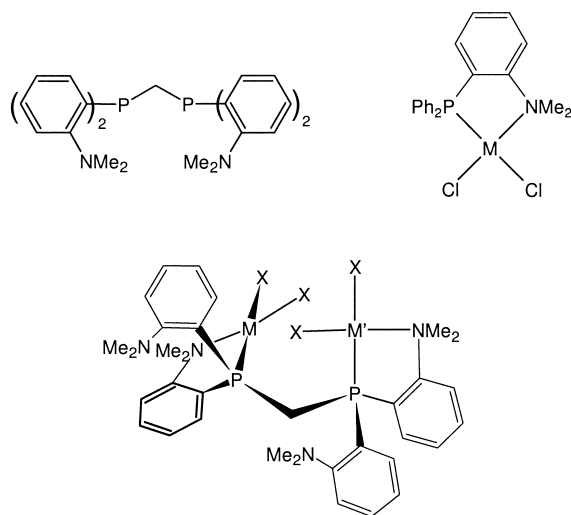
**Keywords:** bimetallic; cooperativity; Heck reaction (aqueous, aerobic); homogeneous; palladium; phosphine (anilyl); platinum; thermomorphic

## Introduction

The Pd-catalysed Heck coupling of aryl halides and olefins is an important method for the formation of C–C bonds and, since its introduction in 1968,<sup>[1]</sup> has been the subject of intensive research,<sup>[2]</sup> including some recent kinetic/mechanistic work.<sup>[3,4]</sup> Much work has focused on improving the efficiency and scope of the reaction by tailoring the Pd catalyst and by varying reaction conditions (solvent, temperature, base, additives).

The first use of Pd-phosphine complexes for vinylic hydrogen substitution reactions was by Dieck and Heck in 1974.<sup>[5]</sup> Although the catalysts are frequently generated *in situ* [e.g., from  $\text{Pd}(\text{OAc})_2$  and a monodentate tertiary phosphine],<sup>[6–9]</sup> many preformed catalysts are now being reported, including complexes of chelating  $P,P$ -,<sup>[10]</sup>  $P,C$ -,<sup>[11,12]</sup>  $P,C,P$ -,<sup>[13]</sup>  $S,C,S$ -,<sup>[14]</sup> and  $P,N$ -donor<sup>[15]</sup> ligands. In general, these chelated compounds demonstrate higher catalytic activities and lifetimes than their predecessors (which typically required a 1–5 mol % loading) and turnover numbers as high as  $10^6$  have been observed.<sup>[12]</sup>

We have interests in the synthesis and coordination chemistry of  $P,N$ -donor ligands and of the catalytic properties of their complexes.<sup>[16]</sup> Thus, the appearance of Pd catalyst precursors bearing  $P,N$ -ligands, and the fact that the Heck and related reactions can be conducted in water (in the presence of a quaternary ammonium salt),<sup>[17]</sup> or in mixtures of polar organic solvents (e.g., DMF, THF, *i*-PrOH, nitriles) and water using Pd complexes of sulphonated<sup>[18]</sup> or of guanidinium phosphines,<sup>[19]</sup> prompted us to investigate the use of anilyldiphosphine complexes recently developed in our laboratory (*vide infra*) as catalyst precursors for aqueous, aerobic Heck reactions. The results presented here provide a suitable contribution dedicated to Roger Sheldon, who amongst others has championed the use of water as a solvent in homogeneous catalysis.<sup>[20]</sup> We were further motivated by the observation of Bankston et al. that in an intramolecular Heck cyclisation of crotyl ethers, the use of  $\text{RhCl}(\text{PPh}_3)_3$  in combination with  $\text{Pd}(\text{OAc})_2$  yielded a system in which the rate of formation of, and selectivity for, the endocyclic form of the bicyclic ether products were significantly enhanced as compared to the use of  $\text{Pd}(\text{OAc})_2$  alone.<sup>[21]</sup>



**Figure 1.** The ligand dmamp (top left) and the general form of its Group 10 bimetallic complexes (bottom, X = halide). The bimetallic complexes tested as Heck catalyst precursors were  $M = M' = Pd$ ,  $X = Cl$  (**1**) and  $M = Pt$ ,  $M' = Pd$ ,  $X = Cl$  (**2**). The complexes  $MCl_2(PMA)$  [top right;  $M = Pd$  (**3**),  $Pt$  (**4**)] were used as monometallic mimics of the coordination environments of the individual metal centres in **1** and **2**.

the two metals were considered to interact synergistically to mediate the intramolecular coupling, although no concrete proof or mechanism was presented.

The strong tendency for  $-CH_2-$  tethered bisphosphines to bridge metal centres,<sup>[22]</sup> combined with the possibility of five-membered  $P,N$ -chelate ring formation, made us realise that the ligand 1,1-bis[di(*o*-*N,N*-dimethylaniliny)]phosphino]methane (dmamp)<sup>[23]</sup> would give access to homo- and heterobimetallic Group 10 complexes of the general form illustrated in Figure 1. Use of these complexes as Heck catalysts allows, in principle, for the assessment of the catalytic effects of a second metal centre, not supplied simply as a separate additive, but as an integral component of a bimetallic catalyst that puts two metal centres in close juxtaposition. Acetate-bridged  $Pd_2$  complexes have been used as catalysts for the Heck reaction, but these fragment under the reaction conditions<sup>[4,11]</sup> to form monometallic com-

plexes that are believed to be the active species. Bimetallic catalysts that stay intact permit intramolecular, intermetallic cooperativity.

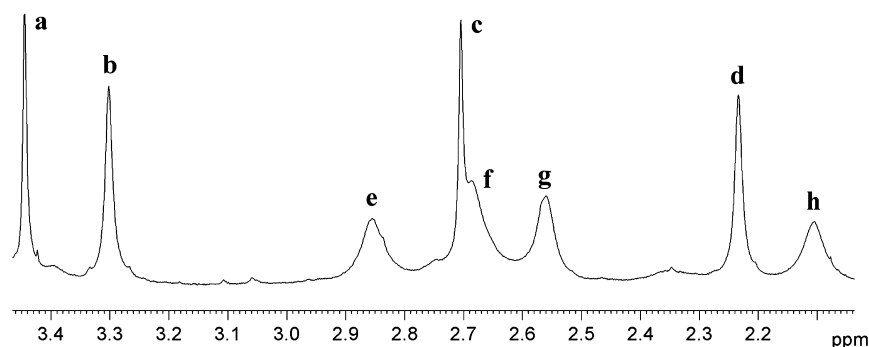
The bimetallic complexes  $MPdCl_4(dmamp)$  [ $M = Pd$  (**1**),  $Pt$  (**2**)] were thus assayed as catalyst precursors for the production of *cis*- and *trans*-stilbene by Heck coupling of iodobenzene and styrene in aqueous DMF solutions. The monometallic compounds  $MCl_2(PMA)$ <sup>[24]</sup> [see Figure 1;  $PMA = Ph_2P-o-C_6H_4NMe_2$ ;  $M = Pd$  (**3**),  $Pt$  (**4**)] were also tested. These were chosen so that their steric and electronic properties would mimic closely the “half units” of the bimetallic complexes; a baseline activity for each of the metals was needed in order to assess whether cooperative effects were a factor during the catalysed reactions. This approach has been adopted previously by Stanley and coworkers in the analysis of hydroformylations catalysed by dirhodium complexes.<sup>[25]</sup> The simple salts  $MCl_2$  were also used as Heck catalytic precursors.

## Results and Discussion

### Synthesis and NMR Characterisation of **1** and **2**

The dmamp ligand provides a convenient scaffold for the synthesis of homo- and heterobimetallic complexes of the Group 10 metals *via* a  $P,P$ -bridging, bis( $P,N$ -chelating) coordination mode. Thus,  $PdCl_2(dmamp)$  reacts with either *trans*- $PdCl_2(PhCN)_2$  in  $CH_2Cl_2$  at r.t. or with  $K_2PtCl_4$  in  $EtOH/H_2O$  at 70 °C to form **1** and **2**, respectively. The mixed-metal complex **2** could not be made by reaction of  $PdCl_2(dmamp)$  with either  $PtCl_2(cod)$  or *cis*- $PtCl_2(MeCN)_2$ , nor could it be made “oppositely” by reaction of  $PtCl_2(dmamp)$  with  $PdCl_2(PhCN)_2$ .

Both **1** and **2** give rise to singlets (and associated “Pt-satellites” in the case of **2**) in their  $^{31}P$  NMR spectra; no 2-bond PP coupling is observed. In addition, although both of the P-atoms in the static structures are chiral, no diastereomers are observed in either the  $^{31}P$  or  $^1H$  NMR spectra. The  $NCH_3$  region of the  $^1H$  NMR spectrum of **2** (Figure 2) contains 8 distinct resonances, each corre-

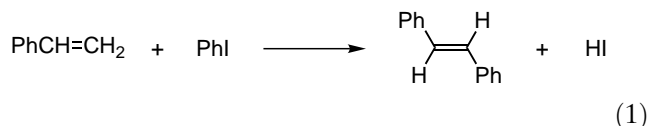


**Figure 2.** The  $NCH_3$  region of the  $^1H$  NMR spectrum of **2**.

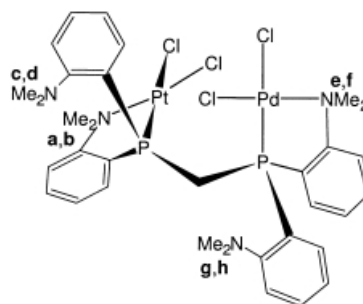
sponding to 3 protons, representing diastereotopic methyl groups associated with both the bound and free N-atoms on the Pt and Pd “sides” of the molecule. The peaks can be classified into two groups of four based on their sharp, or slightly broad shapes, the latter implying an exchange process in the molecule. Assuming that the broader peaks are due to the NCH<sub>3</sub> protons associated with the more labile Pd “side” of the molecule, we have assigned the peaks in Figure 2 according to the scheme in Figure 3. A <sup>1</sup>H 2D EXSY measurement of **2** reveals, however, that the free and bound N-atoms are in chemical exchange, even those manifested by sharp peaks in the 1D <sup>1</sup>H NMR spectrum. The EXSY spectrum demonstrates that methyl group **a** (Figure 3) is in exchange with **c**, **b** with **d**, **e** with **h**, and finally **f** with **g**. Furthermore, the spectrum shows that there is no exchange between the N-atoms associated with opposite “sides” of the molecule, i.e., between groups **a–d** and **e–h**. Exchange phenomena must lead to non-observation of chirality at the coordinated P-atoms.

### Heck Catalysis

Complexes **1–3** were effective catalyst precursors for the synthesis of *trans*-stilbene by the aerobic Heck coupling of PhI and styrene in aqueous DMF with K<sub>2</sub>CO<sub>3</sub> as base (Equation 1); **4** was completely inactive under these conditions.



Aqueous DMF/K<sub>2</sub>CO<sub>3</sub> has been used previously in the Pd-catalysed  $\alpha$ -arylation of vinyl ethers as an alternative to the use of expensive Tl and Ag additives (which give rise to the active, cationic Pd species),<sup>[26]</sup> but in the Heck coupling reported here, this choice of reaction medium also allows for facile separation of product and catalyst. Although DMF and H<sub>2</sub>O are miscible in all proportions,



**Figure 3.** Assignment of the peaks in Figure 2.

the reaction mixture consists of 2 phases at r.t. because of the presence of the various components. However, at 100 °C, the phases became miscible, and the solution was homogeneous by visual inspection. The *trans*-stilbene product precipitated on allowing the reaction mixture to cool; *cis*-stilbene, a liquid at r.t., was only produced to the extent of ~ 1% and remained in solution, while 1,1-diphenylethylene was not observed. The so-called “thermomorphic” method, i.e., the technique of using temperature to bring reactants and catalyst into the same phase as well as to separate product and catalyst post-reaction, has been used to great effect by Bergbreiter et al. in Heck reactions catalysed by Pd-centres bound to soluble polymers.<sup>[27]</sup>

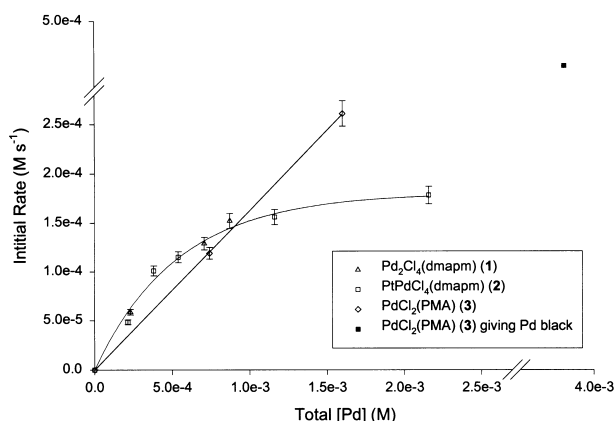
The initial rates and turnover frequencies (TOFs) for mono- and bimetal-catalysed Heck coupling reactions are given in Table 1. The initial TOFs imply that the bimetallic catalysts are more active than would be predicted from the sum of the activities of their selected, corresponding monometallic “half units.” The TOFs also show that the catalysis is likely to be mediated by Pd only, given that (i) **1** is almost exactly twice as active as **2**, and (ii) **4** is completely inactive. Comparing TOFs in this concentration regime is considered valid because catalyst loading studies (*vide infra*) show the reaction to be first-order in Pd up to ~ 5 × 10<sup>−4</sup> M. The catalytic systems are considered to be homogeneous as judged by the “Hg test”;<sup>[28]</sup> addition of 0.05 mL of Hg after 30 min to reactions under standard conditions had no effect of the reaction rates. Colloidal or heterogeneously cata-

**Table 1.** Initial rates and TOFs for the Heck coupling of PhI (0.4 M) and styrene (0.4 M) at 100 °C in DMF/H<sub>2</sub>O (3 : 2 by vol.) with K<sub>2</sub>CO<sub>3</sub> (0.4 M) as base.

Catalyst	Concentration (M, × 10 <sup>4</sup> )	Initial rate <sup>[a]</sup> (M s <sup>−1</sup> , × 10 <sup>5</sup> )	Initial TOF <sup>[b]</sup> (s <sup>−1</sup> , × 10 <sup>3</sup> )
<b>4</b> , PtCl <sub>2</sub> (PMA)	7.00	0	0
<b>3</b> , PdCl <sub>2</sub> (PMA)	7.41	11.9 ± 0.6	161 ± 8
<b>1</b> , Pd <sub>2</sub> Cl <sub>4</sub> (dmapm)	1.15	5.87 ± 0.3	510 ± 26
<b>2</b> , PtPdCl <sub>4</sub> (dmapm)	2.14	4.85 ± 0.2	227 ± 11
	3.80	10.1 ± 0.5	266 ± 13

<sup>[a]</sup> Measured over the first 30 min of reaction time.

<sup>[b]</sup> Mol product per mol catalyst per second.



**Figure 4.** Variation of initial rate of the Heck coupling of PhI and styrene with total Pd concentration for reactions catalysed by **1–3** at 100 °C in H<sub>2</sub>O/DMF with K<sub>2</sub>CO<sub>3</sub> base.

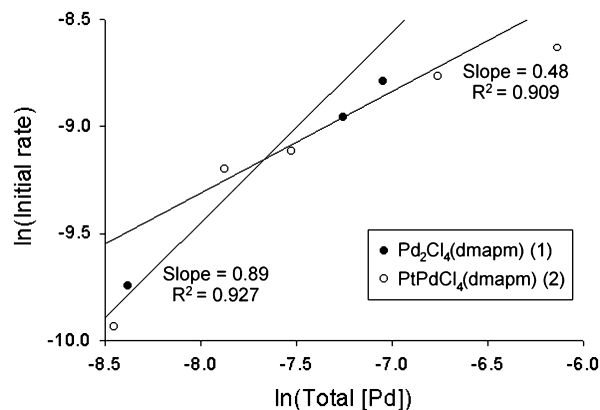
lysed Pt(0) and Pd(0) metal systems are typically strongly inhibited *via* formation of inactive Hg-alloys. Moreover, catalyst loading studies (see below) point to monometallic rather than polymetallic, colloidal species as the active catalysts.

### Catalyst Loading

The variation of initial rate of the Heck coupling of PhI and styrene catalysed by **1–3** with total Pd concentration is shown in Figure 4. If, during catalysis, the bimetallic complexes **1** and **2** fragment completely or if no fragmentation at all occurs, then the rate should show a first-order dependence on the catalyst concentration. If, however, an equilibrium between bimetallic and monometallic species is established and, if the reaction is catalysed by one or both of the smaller fragments, then the rate should show a first-order dependence on catalyst concentration at lower concentrations (in which the bimetallic complex is almost completely fragmented into its constituent pieces) decreasing to a half-order dependence in the higher concentration regime (when the majority of complexes in solution remains almost completely undissociated).

When **3** is used as the catalyst, the initial rate shows a first-order dependence on total [Pd] at least up to  $1.6 \times 10^{-3}$  M; at higher concentrations, Pd metal precipitates immediately on addition of K<sub>2</sub>CO<sub>3</sub>, and the initial rate shows a corresponding non-linear dependence on catalyst loading. No metal precipitation was observed using the bimetallic complexes.

The dependence of the initial rate of the bimetallic catalysed reactions on total [Pd] is first-order up to  $\sim 5 \times 10^{-4}$  M, when the similarly active bimetallic catalysts **1** and **2** are slightly more active than **3**. These observations suggest that both **1** and **2** precursors give rise to the same active species.

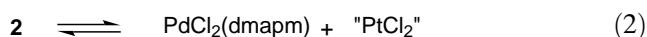


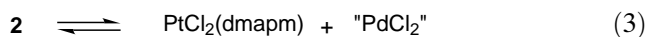
**Figure 5.** Plot of ln (Initial rate) vs. ln (Total [Pd]) for the Heck coupling of PhI and styrene catalysed by the bimetallic complexes **1** and **2** showing a rough first- to half-order transition from low to high total [Pd]. The highest concentration point has been omitted from this analysis.

Shown in Figure 5 is a plot of ln (Initial rate) vs. ln (Total [Pd]) for the Heck coupling catalysed by **1** and **2**. The plot, broken into low and high [Pd] regimes, shows an approximately first- to half-order transition. At higher [Pd], the bimetallic catalysts are substantially less active than **3**, pointing to a dearth of active, monometallic species in solutions of **1** and **2** under these conditions. The observations suggest that an equilibrium between bi- and monometallic complexes is established for both **1** and **2**, and that the catalysis results, in fact, mainly from monometallic species. At higher Pd concentration ( $> 1.5 \times 10^{-3}$  M), the dependence on total [Pd] is  $< \frac{1}{2}$  order, indicating the possible formation of inactive Pd colloids/clusters.

Kinetic data for the Heck coupling of *p*-bromobenzaldehyde and butyl acrylate using a palladacycle catalyst similarly reveal a catalytic cycle that incorporates an active monomer-inactive dimer equilibrium.<sup>[4]</sup> Such catalytic reaction systems are increasingly common. For example, in the chiral amino alcohol-promoted asymmetric alkylation of aldehydes with zinc dialkyl, the enantiomeric purity of the product is much higher than that of the chiral promoter, and the rate of enantioselective catalysis decreases markedly with decreasing enantiopurity of the promoter. These effects have been rationalised in terms of the reversible homo- and heterochiral dimerisation of the zinc amino alkoxide catalysts.<sup>[29]</sup> A related treatment has been applied to the Sharpless epoxidation.<sup>[30]</sup>

Ignoring oxidation of the dmapm ligand (*vide infra*), two possible dissociation equilibria exist for the heterobimetallic complex **2** (Equations 2 and 3).





In order to assess which of the two equilibria predominates,  $\text{PdCl}_2(\text{dmampm})$  was used as a catalyst precursor for the Heck reaction at a concentration of  $4.0 \times 10^{-4} \text{ M}$ . This gave an initial rate of  $2.2 \times 10^{-5} \text{ M s}^{-1}$ ,  $\sim 10$  times less than predicted by linear extrapolation of the curve due to **1** and **2** at low concentration in Figure 4 ( $\sim 2 \times 10^{-4} \text{ M s}^{-1}$ ). This is consistent with equilibrium (3) being dominant and with the catalysis proceeding via a derivative of  $\text{PdCl}_2$ . In principle, equilibria (2) and (3) should be verifiable by NMR spectroscopy, but satisfactory spectra for **2** (and **1**) under pseudo-catalytic conditions could not be obtained.

The following experiment suggests perhaps that equilibrium (3) dominates but that (2) is also operative. A mixture of DMF (1 mL) and  $\text{H}_2\text{O}$  (1 mL) containing equimolar **2** and 1,2-bis(diphenylphosphino)ethane (dppe) was heated to  $100^\circ\text{C}$  in air for 4.5 h. The solvent was removed under vacuum and the residue analysed by NMR spectroscopy. The major product was  $\text{PdCl}_2(\text{dppe})$ ;<sup>[31]</sup> if it is assumed that dppe reacts preferentially with  $\text{MCl}_2$ , this results reflects the predominance of equilibrium (3). In order of decreasing abundance, the other products were:  $\text{PtCl}_2(\text{dppe})$ ;<sup>[32]</sup> which is accessed presumably by equilibrium (2), unreacted **2**,  $[\text{Pt}(\text{dppe})_2]\text{Cl}_2$ ,<sup>[33]</sup> dmampm and  $\text{PtCl}_2(\text{dmampm})$ .<sup>[34]</sup>

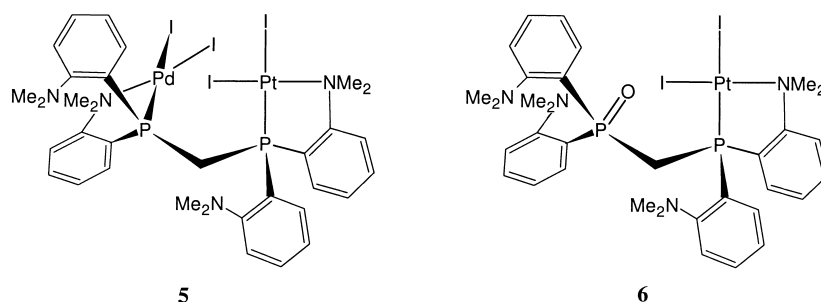
Given that equilibrium (3) is likely to predominate and, assuming that  $\text{PtCl}_2(\text{dmampm})$  does not contribute to the catalysis (a likely prediction in light of inactivity of **4** and  $\text{PtCl}_2$ ), the overall catalysis results most probably from a " $\text{PdCl}_2$ " species, or a derivative  $\text{Pd}^0$  compound, that may incorporate any of DMF,  $\text{H}_2\text{O}/\text{OH}^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{I}^-$  or styrene as ligands. Of note, the Heck coupling of iodobenzene derivatives and styrene has been shown to occur in predominantly aqueous medium in the presence of  $\text{Pd}(\text{OAc})_2$  without any added ancillary ligands.<sup>[35]</sup>

The initial TOF for a  $\text{PdCl}_2$ -catalysed Heck reaction between PhI and styrene under the conditions used in

this work was  $\sim 0.05 \text{ s}^{-1}$ , significantly lower than expected from the data of Table 1 (and Figure 4) if a "simple" derivative of  $\text{PdCl}_2$  were the active species in the bimetal-catalysed reactions. In this experiment,  $\text{PdCl}_2$  was dissolved in the reaction mixture at  $100^\circ\text{C}$  prior to addition of aqueous  $\text{K}_2\text{CO}_3$ . Metallic Pd deposited during the course of the reaction from the resulting blood red solution, pointing to the fact that the catalytic cycles involving the homo- and heterobimetallic complexes **1** and **2** and that involving  $\text{PdCl}_2$  differ. The former is homogeneous while in the latter significant precipitation of Pd metal occurs. In addition, the bimetallic catalytic precursors are more active than simple monometallic derivatives of  $\text{PdCl}_2$ , perhaps because of the possibility for dimer recombination during the cycle which prevents the precipitation of metal. Another possible explanation for the lower activity of  $\text{PdCl}_2$  compared to that of **1** and **2** is that the last two may rapidly generate catalytically active monomeric, halide-ligated  $\text{Pd}(0)$  species, while  $\text{PdCl}_2$  is polymeric and converts comparatively slowly to such monomers; Heck catalysis *via* such  $\text{Pd}(0)$  monomers has been substantiated by others.<sup>[17,36]</sup> The non-linear kinetic dependence on  $[\text{Pd}]$  would then be attributed to less aggregation, at lower  $[\text{Pd}]$ , of the  $\text{Pd}(0)$  species to clusters and ultimately Pd black. The P-N ligand may also play a role in suppressing formation of the Pd black, without being bound to the metal in the catalytic cycle.

### Oxidative Degradation

Subsequent to an unsuccessful attempt to follow by NMR spectroscopy a Heck reaction catalysed by **2**, orange-brown crystals deposited from a mixture of DMF/ $\text{D}_2\text{O}$  containing PhI and styrene that had been heated to  $80^\circ\text{C}$  for 0.5 h in air and then left for 2 d at r.t. These were submitted for X-ray crystallographic analysis and, although the structure did not refine sufficiently for publication standards, the essential molecular structures of the two constituent complexes were established. Present in the unit cell were the compounds  $\text{PtPdI}_4(\text{dmampm})$  (**5**) and  $\text{PtI}_2(P,N\text{-dmampmO})$  (**6**)



**Figure 6.** Complexes present in the unit cell of crystals isolated subsequent to an NMR-scale Heck coupling of PhI and styrene in DMF/ $\text{D}_2\text{O}$  at  $80^\circ\text{C}$ .

(Figure 6), and one solvate molecule of both DMF and D<sub>2</sub>O. The iodide in these complexes results from the HI generated stoichiometrically in the Heck reaction (Equation 1), and at high concentration will replace the chloride of the precursor complex; **5** is indeed the iodide derivative of **2**, while **6** is a monophosphine oxide derivative, solely a Pt fragment.

The crystallographic results show that the bimetallic catalyst can also decompose/dissociate via a redox route, but whether this is significant during the catalysis is unknown. The most plausible pathway for the formation of **6** is by attack of OH<sup>−</sup> on the iodo-analogue of **2** with concomitant formation of Pd<sup>0</sup> and a proton; such generation of Pd<sup>0</sup> and phosphine oxide from Pd<sup>II</sup>-phosphine complexes during catalytic transformations of aryl halides is well documented.<sup>[37,38]</sup> A less likely and more speculative path involves reaction of OH<sup>−</sup> with PtCl<sub>2</sub>(dmapm), generated by equilibrium (2), to give an intermediate such as "Pt(dmapmO)" which is transformed in a subsequent step(s) to give **6** (e.g., by double oxidative addition of PhI followed by reductive elimination of biphenyl). Of note, even under the high temperature, strong base conditions of the reaction, a significant proportion of the catalyst survived intact (based on the composition of the isolated crystals).

### A Cooperativity Index Proposal

Cooperative effects between adjacent metal centres in complexes containing two or more bridged metal ions are now established for a variety of homogeneous, catalytic transformations and continue to attract attention. The majority of these systems employ homobimetallic catalyst precursors. Representative examples include bimetallic catalysts for phosphoester hydrolysis (Co<sub>2</sub>,<sup>[39]</sup> Cu<sub>2</sub>,<sup>[40,41]</sup> Zn<sub>2</sub>,<sup>[42]</sup>), nitrile hydration (Ni<sub>2</sub>,<sup>[43,44]</sup> Pd<sub>2</sub>,<sup>[45]</sup>), hydroformylation (Rh<sub>2</sub>,<sup>[25,46–48]</sup> Ru<sub>2</sub>,<sup>[49]</sup>), alkene<sup>[50]</sup> and alkyne<sup>[51]</sup> hydrogenation (Ir<sub>2</sub>), and asymmetric epoxide ring-opening (Cr<sub>2</sub>).<sup>[52]</sup> In addition, cooperative effects between two different metal centres have been invoked but not proven to be operative in the catalytic hydrogenation of cyclohexene (RuIr<sup>[53]</sup>) and in hydroformylations (RhPd<sup>[49]</sup>).

Given the increasing number of presumed cooperative effects during catalysis, we now propose a general index for the degree of cooperativity between metal centres in a polymetallic assembly. This index serves as a kinetic complement to the well-established Hill coefficient for thermodynamic cooperativity.<sup>[54]</sup>

Assuming no intramolecular, intermetallic interactions, the predicted total activity,  $A_p$ , of a polymetallic catalyst of  $n$  metal centres is given by Equation 4, where  $A_i$  is the measured activity of the monometallic complex that most closely mimics the steric and electronic attributes of the  $i$ th metal centre. By activity, any reasonable observable should suffice, e.g., initial rate,

TOF or % conversion in a given time. The average activity,  $\bar{A}$ , is then given by Equation 5.

$$A_p = \sum_{i=1}^n A_i \quad (4)$$

$$\bar{A} = \frac{A_p}{n} \quad (5)$$

If the observed activity of the polymetallic complex is  $A_o$ , then Equation 6 defines one possibility for an index of cooperativity,  $a$ .

$$a = \frac{A_o - A_p}{\bar{A}} \quad (6)$$

This index is sensible in that impeding effects result in  $a$  values less than zero, while completely non-interacting centres give  $a = 0$ , and cooperative effects yield positive  $a$  values. If  $a = 0$ , cluster catalysis is not ruled out. In this case, catalysis may proceed at only one centre in the complex, or at multiple non-interacting centres. Conversely, the cluster may be fragmenting. In general, the index corresponds to a number of "virtual" metal centres, i.e., the number of centres of average catalytic activity the polymetallic complex appears to possess beyond its real number,  $n$ .

Of particular relevance to these ideas is the work of Jacobsen and coworkers who have been able to distinguish kinetically between inter- and intramolecular pathways in the catalytic asymmetric ring-opening of cyclopentene oxide by Cr(salen)-type dimers. These dimers are linked by tethers of varying lengths, and for each of these an effective reactive concentration of the two salen units has been determined by the ratio of  $k_{\text{intra}}/k_{\text{inter}}$ .<sup>[52]</sup> This method is akin to the cooperativity index proposed here, and is an exact treatment for reactions which necessarily involve two metal centres, even if they are not held in proximity by a bridging ligand. The  $a$  index is appropriate for reactions which occur readily at one active site and which may or may not benefit by the juxtaposition of other sites.

The  $a$  values for the bimetallic catalysts used here are calculated from initial TOFs. The observed activities ( $A_o$ ) for **1** and **2** are taken to be the initial TOFs given in Table 1; the calculations of  $a$  for each of the bimetallic complexes are outlined in Table 2.  $A_p$  values are determined by summing the appropriate initial TOFs of reactions catalysed by **3** and **4**.

Even though the loading studies suggest that the major catalytic cycle involves a monometallic active species,  $a$  indices are consistent with a mechanism involving intramolecular, intermetallic cooperativity: **1** and **2** act as if each possessed an additional metal centre

**Table 2.** Calculation of cooperativity indices ( $a$ ) for bimetallic catalysts.

	<b>1</b>	<b>2</b>
$A_O$	$0.510 \pm 0.026$	$0.247 \pm 0.012$
$A_P$	$0.322 \pm 0.016$	$0.161 \pm 0.008$
$\bar{A} = A_P/2$	$0.161 \pm 0.008$	$0.081 \pm 0.004$
$a = (A_O - A_P)/\bar{A}$	$1.17 \pm 0.32$	$1.06 \pm 0.30$

of average catalytic activity. This discrepancy may be rationalised by considering some of the limitations of the cooperativity index. In addition to the possibility of a true cooperative mechanism operating in a parallel, minor cycle involving bimetallic catalysts, the positive  $a$  values may also be accounted for by other factors that include: (i) dimerisation that may prevent Pd metal precipitation during the cycle, hence maintaining a higher overall [Pd], and (ii) an inappropriate choice of the monometallic “half-units” **3** and **4** (which may not mimic accurately enough the coordination sphere of each of the constituent metal centres in **1** and **2**) may make the predicted activity,  $A_P$ , too small; i.e., the assumption of Equation 4 may be too simple. Future versions of the index may provide a better description by incorporating a factor that accounts for differences between the properties of metal centres in real polymetallic catalysts and those of their idealised monometallic mimics:  $\bar{A}$  would become  $\omega_{\bar{A}}$ , where  $\omega$  is a vector of coefficients.

It is also apparent that the  $a$  indices for **1** and **2** are identical within error, pointing once more to the same active species generated by each catalyst precursor.

As a comparison, the  $a$  values for the bimetallic Rh hydroformylation catalysts  $[\text{Rh}_2(\text{nbd})_2(\text{rac-et, ph-P4})][\text{BF}_4]_2$  and  $[\text{Rh}_2(\text{nbd})_2(\text{meso-et, ph-P4})][\text{BF}_4]_2$  reported by Stanley's group are 422 and 34, respectively; the ligand nomenclature is given in ref.<sup>[25]</sup>

It should be noted that the index  $a$  is based solely on kinetic data at a single catalyst concentration (i.e., it assumes that the reaction is first-order in catalyst) and may lead to the conclusion that a cooperative mechanism is at work whereas studies of the rate dependence on catalyst loading may prove otherwise.

Notwithstanding the fact that the Heck reaction studied here may be catalysed mainly by a derivative of  $\text{PdCl}_2$  and not by a bimetallic assembly, we feel that the  $a$  index outlined above will be of general utility in establishing a scale for the extent of intermetallic cooperativity in reactions catalysed by polymetallic complexes.

## Conclusions

Although the  $\text{dmapm}$  ligand gives ready access to the homo- and heterobimetallic complexes **1** and **2** that are

active catalyst precursors in the aqueous, aerobic Heck coupling of PhI and styrene, kinetic data imply that these complexes dissociate in to active, monometallic catalysts; a derivative of  $\text{PdCl}_2$  or a monomeric, halide-ligated, anionic  $\text{Pd}(0)$  species is suggested as the most likely active species. The observation that **1** and **2** give rise to slightly more active catalysts than those whose activities are predicted by the sum the activities of their monometallic “halves” is difficult to explain, based on equilibria (2) and (3), suggested by the kinetic data that implicate a  $\text{PdCl}_2$ -based catalyst. The iodo analogue of **2** and a Pt-phosphine monoxide derivative were identified as oxidative degradation products in solutions following a Heck reaction catalysed by precursor **2**. In retrospect, the  $\text{dmapm}$  ligand is largely incidental to the catalysis, and in some ways the system resembles recent work from our group showing that the active hydrogen transfer catalyst within a  $\text{NiBr}_2(\text{PPh}_{3-n}\text{py}_n)_2$  system, where  $\text{py} = 2\text{-pyridyl}$ , is in fact derived from simply  $\text{NiBr}_2$ !<sup>[55,56]</sup>

A cooperativity index, that should be generally applicable to systems where polymetallic catalysts are implicated, is proposed, and its limitations are discussed.

## Experimental Section

### General

Unless otherwise noted, synthetic procedures were performed using standard Schlenk techniques under an atmosphere of dry Ar or  $\text{N}_2$ . 1,1-Bis[di(*o*-*N,N*-dimethylaniliny)phosphino]methane ( $\text{dmapm}$ ),<sup>[23]</sup> diphenylphosphino-*N,N*-dimethylaniline (PMA),<sup>[24]</sup>  $\text{MCl}_2(\text{PMA})$  ( $\text{M} = \text{Pt}, \text{Pd}$ )<sup>[24]</sup> and *trans*- $\text{PdCl}_2(\text{PhCN})_2$ <sup>[57]</sup> were made according to literature procedures. The synthesis and coordination chemistry of monometallic Pt and Pd complexes of  $\text{dmapm}$ <sup>[34]</sup> will be published elsewhere. All other reagents were purchased from commercial sources and, with the exception of styrene that was passed through a short alumina column, were used as supplied. Solvents were dried over the appropriate agents and distilled under  $\text{N}_2$  prior to use.

NMR spectra were recorded in  $\text{CDCl}_3$  solution at 300 K on an AV300 (121.49 MHz for  $^{31}\text{P}$ ) spectrometer. Residual solvent proton ( $^1\text{H}$ , relative to external  $\text{SiMe}_4$   $\delta$  0.00) and external  $\text{P}(\text{OMe})_3$  ( $^{31}\text{P}\{^1\text{H}\}$ ,  $\delta$  141.00 vs. external 85% aq.  $\text{H}_3\text{PO}_4$ ) were used as references. Downfield shifts were taken as positive; s = singlet, d = doublet, t = triplet, m = multiplet, br = broad, p = pseudo. All  $J$  values are given in Hz. Gas chromatographic analyses of Heck reaction mixtures were conducted using a Hewlett Packard 5890A gas chromatograph equipped with a 25 m  $\times$  0.32 mm HP17 column and an  $\text{H}_2$ /air flame ionisation detector (FID). He was used as the carrier gas. UV-vis spectra were recorded on a Hewlett Packard 8452A diode array spectrophotometer and are reported as  $\lambda_{\text{max}}$  ( $\pm 2$  nm) [ $\epsilon$  ( $\text{M}^{-1} \text{cm}^{-1}$ )]. Elemental analyses were conducted in the UBC Chemistry Department by Peter Borda using a Carlo Erba 1108 analyzer.

## Syntheses

**PdCl<sub>2</sub>(dmapm), 1:** To a combination of *trans*-PdCl<sub>2</sub>(PhCN)<sub>2</sub> (110 mg, 0.29 mmol) and dmapm (82 mg, 0.15 mmol) was added CH<sub>2</sub>Cl<sub>2</sub> (5 mL). The initially orange solution turned yellow within a few seconds. After the solution was stirred for 5 min, the volume was reduced under vacuum to ~ 1 mL, and Et<sub>2</sub>O (20 mL) was added to give a yellow powder. This was isolated by filtration, washed with Et<sub>2</sub>O (3 × 3 mL) and dried under vacuum; yield: 110 mg (78%). Anal. calcd. for C<sub>33</sub>H<sub>42</sub>N<sub>4</sub>Cl<sub>4</sub>P<sub>2</sub>Pd<sub>2</sub>: C 43.5, H 4.7, N 6.2%; found: C 43.8, H 4.6, N 6.0%. UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ = 354 nm [3050]. <sup>1</sup>H NMR: δ = 2.31 (s, 12H, NCH<sub>3</sub>), 2.78 (s, 6H, NCH<sub>3</sub>), 3.28 (s, 6H, NCH<sub>3</sub>), 4.97 (t, 2H, CH<sub>2</sub>, <sup>2</sup>J<sub>HP</sub> = 17.1), 7.40 (br m, 6H, Ar), 7.65 (br m, 4H, Ar), 7.80 (br m, 2H, Ar), 8.52 (br m, 2H, Ar), 8.74 (br m, 2H, Ar). <sup>31</sup>P{<sup>1</sup>H} NMR: δ = 34.8 (s).

**PtPdCl<sub>2</sub>(dmapm), 2:** A mixture of EtOH (10 mL) and H<sub>2</sub>O (4 mL) containing K<sub>2</sub>PtCl<sub>4</sub> (25 mg, 0.060 mmol) and PdCl<sub>2</sub>(dmapm) (42 mg, 0.057 mmol) was heated to 70 °C for 1.5 h during which time a beige precipitate formed. The solvent was removed under vacuum and the residue was dried thoroughly before being taken up in CH<sub>2</sub>Cl<sub>2</sub> (10 mL). The slurry was filtered through a mixture of Celite 545 and MgSO<sub>4</sub> and reduced to ~ 1 mL. Addition of Et<sub>2</sub>O (10 mL) gave the product as a beige powder that was collected by filtration, washed with Et<sub>2</sub>O (3 × 3 mL) and dried under vacuum; yield: 39 mg (69%). Anal. calcd. for C<sub>33</sub>H<sub>42</sub>N<sub>4</sub>Cl<sub>4</sub>P<sub>2</sub>PdPt: C 39.6, H 4.2, N 5.6%; found: C 39.9, H 4.3, N 5.4%. UV-vis (CH<sub>2</sub>Cl<sub>2</sub>): λ = 352 nm [2000]. <sup>1</sup>H NMR: δ = 2.10 (s, 3H, NCH<sub>3</sub>), 2.23 (s, 3H, NCH<sub>3</sub>), 2.56 (s, 3H, NCH<sub>3</sub>), 2.69 (s, 3H, NCH<sub>3</sub>), 2.70 (s, 3H, NCH<sub>3</sub>), 2.85 (s, 3H, NCH<sub>3</sub>), 3.30 (s, 3H, NCH<sub>3</sub>), 3.44 (s, 3H, NCH<sub>3</sub>), 4.74 (pdt, 1H, CH<sub>2</sub>, <sup>2</sup>J<sub>HH</sub> = 19.2, <sup>2</sup>J<sub>HP</sub> = 27.7), 5.27 (pdt, 1H, CH<sub>2</sub>, <sup>2</sup>J<sub>HH</sub> = 19.2, <sup>2</sup>J<sub>HP</sub> = 26.6), 7.39 (m, 6H, Ar), 7.60 (m, 5H, Ar), 7.85 (pt, 1H, Ar), 8.30 (m, 1H, Ar), 8.43 (m, 1H, Ar), 8.85 (m, 1H, Ar), 9.21 (m, 1H, Ar). <sup>31</sup>P{<sup>1</sup>H} NMR: δ = 11.8 (s, <sup>1</sup>J<sub>Pt</sub> = 3980), 30.7 (s). Neither two-bond PP nor three-bond coupling of either the CH<sub>2</sub> or NCH<sub>3</sub> protons with Pt was observed.

## Heck Catalysis

The catalyst precursor (ca. 1–2 μmol) was dissolved in a stock DMF solution containing 1.00 M PhI and 1.00 M styrene (2 mL). This was diluted by the addition of DMF (1 mL) and preheated to 100 °C in a 20 mL three-necked, round-bottom flask fitted with a condenser. Over the course of about 30 s, a 1.00 M stock solution of K<sub>2</sub>CO<sub>3</sub> in H<sub>2</sub>O (2 mL) was added. The beginning of this addition marked zero time. The temperature was maintained at 100 °C throughout the reaction. No precautions were taken to exclude O<sub>2</sub>. When the reaction solution is cooled to room temperature (r.t.) during the catalysis, the stilbene product precipitates and can be isolated by simple filtration. Aliquots of the reaction mixture (0.1 mL) were withdrawn at 10 min intervals and diluted by addition to CH<sub>2</sub>Cl<sub>2</sub> (1 mL) at r.t. The CH<sub>2</sub>Cl<sub>2</sub> solution (0.1 μL) was then analysed by GC in order to determine the extent of reaction, by comparing the relative peak areas for PhI and *cis*- and *trans*-stilbene. Analysis of solutions containing known concentrations of PhI and *trans*-stilbene showed that a weighting factor of 2.3 needed to be applied to the area of the PhI peak to compensate for its lower response factor at the FID. The styrene peak was not used in the analysis because of its overlap with the tail of the DMF peak.

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