

Robust and catalytically active mono- and bis-Pd-complexes of the 'Trost modular ligand'

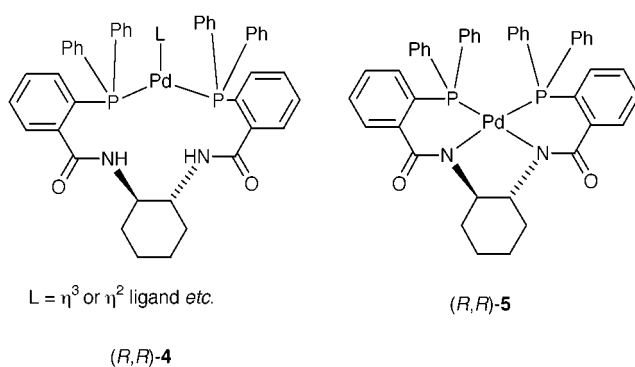
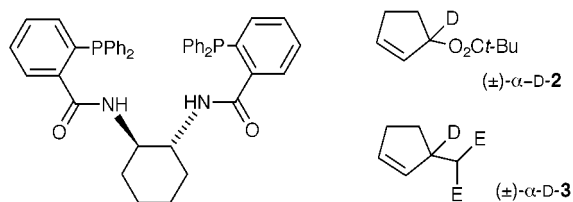
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A catalytically active, bimetallic Pd-allyl complex of the Trost modular ligand, for which X-ray crystallography reveals a tetradentate ('POPO') coordination mode, induces a memory effect in Pd-catalysed allylic alkylation.

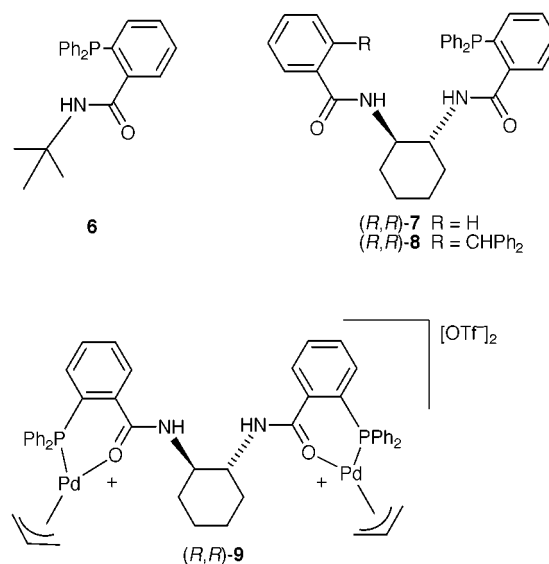
Asymmetric Pd-catalysed allylic alkylation¹ has recently enjoyed much attention and has undoubtedly joined the ranks of the 'benchmark reactions' by which new chiral ligands are tested and compared. Under the appropriate conditions, the modular ligand systems of Trost,² e.g. (*R,R*)-**1**, have proved to be remarkably enantioselective for a range of allylic alkylations, particularly the more demanding small cyclic substrates such as **2**→**3**.³



Knowledge of the mode(s) of coordination of **1** to palladium is essential in any mechanistic explanation of such high selectivities and it has generally been assumed that there is bidentate diphosphine chelation ('P,P') to Pd throughout the catalytic cycle[†] as in **4**.⁴ However, to date, there have been no reports of the isolation or *in situ* characterisation of catalytic intermediates—which are readily converted to catalytically inert **5**.⁵

In recent investigations⁶ of 'memory effects'⁷ in the Pd-catalysed conversion of **2** to **3**, we suggested that a (P,L)-complexation mode (L = non-P ligand) could be responsible for the memory effect with mismatched **2** and '[1-Pd]'. Powerful memory effects are sometimes observed with other (P,L) ligands^{6c,7c} and we noted that an amide carbonyl in **1** could act as 'L'. However, although we observed no memory effect with ligand **6**,^{6a} ligands **7** and **8** are reported to give low and reversed ees (as compared to **1**) in the reaction of **2**.⁴

These latter results have in fact been taken as evidence that P,P-bidentate coordination of **1** is essential and that amide



carbonyl coordination (P,O) is not important in the catalytically active species.⁸ Herein we describe air- and shelf-stable, catalytically active, Pd-complexes of **1**. We also show that P,O coordination of **1** can give rise to a highly active catalyst and a significant memory effect.

Non-complexed ligand **1** was crystallised from hot acetonitrile. The single crystal X-ray structure is presented in Fig. 1.† Notable is the latent tendency of **1** to present P and O donors on opposite faces of the elongated structure. Reaction of **1** with 1 equivalent of halide-free $[\text{Pd}(\text{allyl})(\text{MeCN})_2][\text{OTf}]$ in CH_2Cl_2 then evaporation gave a pale yellow powder. Combustion analysis and ES-MS§ were fully consistent with a complex of stoichiometry $[\text{Pd}(\text{allyl})(\mathbf{1})][\text{OTf}]$. However, despite many attempts at crystallisation, amorphous powders were always obtained and X-ray structural analysis remained elusive. Furthermore, ¹H and ¹³C NMR spectra (CD_2Cl_2 or 3:1 d_8 -THF- CD_2Cl_2 , 26 °C) were very broad and complicated. Nonetheless, all of the allyl-Pd signals disappeared rapidly on addition of a slight excess of $[\text{NaCH}(\text{CO}_2\text{Me})_2]$ and cleanly gave allyl- $\text{CH}(\text{CO}_2\text{Me})_2$ (> 95%, ¹H NMR).⁹

In the solid state, the mixture of complexes is air- and shelf-stable (for years) and serves as a very convenient pro-catalyst

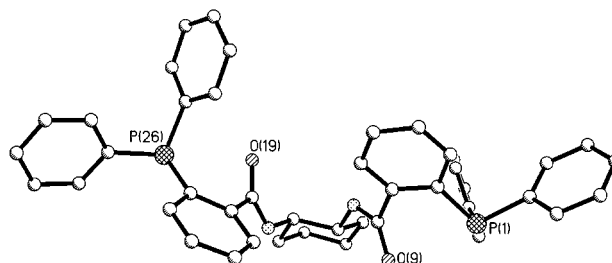


Fig. 1 The molecular structure of **1**. One and one half molecules occupy the unit cell. The half molecule and all hydrogens and solvent (MeCN) are omitted for clarity.

for asymmetric allylation of **2**.¶ Also, like the conventional 'Pd-**1**' catalysts generated *in situ* under chloride-free conditions,^{6b} the pro-catalyst mixture also effects powerful kinetic resolution with (*S*)-**2** reacting over twenty-fold faster than (*R*)-**2** with [NaCH(CO₂Me)₂] in THF.

When the ratio of Pd/**1** was raised (*i.e.* ≥1) evidence for P,O coordination was obtained. Thus, analytically pure [Pd₂(allyl)₂(**1**)][OTf]₂ **9** (mp 203 °C) was prepared as yellow-green prisms by addition of 2 equivalents of [Pd(allyl)(MeCN)₂][OTf] to **1** in CHCl₃ (99.9% yield on a 1.1 g scale). The single crystal X-ray structure of **9** which displays P,O-coordination to two Pd-allyl moieties is shown in Fig. 2.‡ This complex was also catalytically active and 2.5 mol% effected ≥90% conversion of α-[²H]-**2** to α,γ-[²H]-**3** in <60 s (22 °C, THF).|| Importantly, the P,O complexation mode induced a moderate α-memory effect: both enantiomers of substrate giving a *ca.* 57:43 (±1) ratio of α-[²H]-**3**/γ-[²H]-**3** [83–86% isolated yield after chromatography, ²H and ¹³C NMR analysis with (+)-Eu(hfc)₃] and a global enantioselectivity of *ca.* 2% ee (*R*).

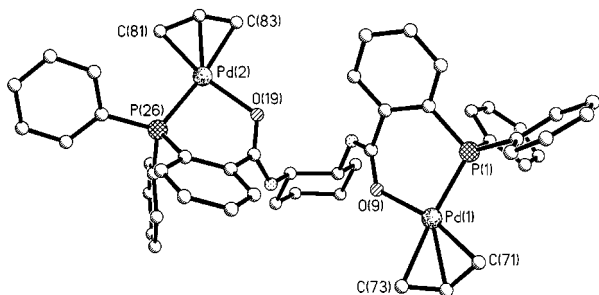


Fig. 2 The molecular structure of dication **9**. Hydrogens and triflate counter ions are omitted for clarity. Selected bond lengths (Å) and angles(°): Pd-P 2.279(2) 2.289(2), Pd-O 2.097(4), 2.109(4), Pd-C(71/81) 2.052(8)/2.086(7), Pd-C(73/83) 2.27(8)/2.191(7); P-Pd-O 89.90(11), 89.82(12), C-Pd-C 67.4(4), 69.5(3).

¹H, ¹³C and ³¹P NMR (CD₂Cl₂, 25 °C) of complex **9** indicated a single quasi-symmetrical species was present in solution (δ_P 24.8). Five unique π-allyl ¹H NMR signals with only one of the two allylic carbons *trans*-related to P (*J*_{CP} 27.3 Hz) indicated apparent allyl rotation was slow at the NMR time scale. Furthermore, the concentration independent 2.34 ppm downfield chemical shift of the N-H amide protons (δ 8.84) relative to free **1** confirmed the bis-(P,O)-complexation mode in solution. A moderate ion current corresponding to [Pd₂(allyl)₂(**1**)²⁺ (*m/z* 492) was observed on ES-MS analysis {a substantial proportion of the complex loses [Pd(allyl)]⁺ and [Pd(allyl)₂]⁺ (*m/z* 147 and 188) to give [Pd(allyl)(**1**)⁺]. When 1 equivalent of **1** was added, ³¹P NMR and ES-MS analysis indicated complete reaction of **1** and [Pd₂(allyl)₂(**1**)²⁺ to give [Pd(allyl)(**1**)⁺] suggesting a thermodynamically more favoured (P,P) binding mode in the latter species.⁹

In conclusion, reaction of **2** catalysed by the fully characterised complex **9** in which there is a bis-P,O-coordination mode (X-ray and NMR) proceeds with a significant α-memory effect in both manifolds (*R*- and *S*-**2**) and gives racemic **3**. However, with a Pd:**1** ratio of 1:1 a number of P,P-complexes are generated. These are active for *asymmetric* allylic alkylation with [NaCH(CO₂Me)₂], effect powerful kinetic resolution and,

consistent with earlier work, only demonstrate a memory effect with the mismatched enantiomer of **2**.^{6a}

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Notes and references

† To the best of our knowledge, published evidence for P,P-coordination of **1** is limited to the reaction of Pd₂(dba)₃·CHCl₃ with **1** (1/Pd = 2) which gives an AB ³¹P NMR spectrum (δ 24.9, 22.5; *J*_{PP} 14.6 Hz) and free **1** (δ –9) see ref. 4.

‡ *Crystal data*: for **1**: C_{68.46}H₆₀N_{4.23}O₃P₃, *M* = 1082.83, orthorhombic, space group *P*2₁2₁2, *a* = 17.8937(5), *b* = 31.1163(9), *c* = 10.8869(3) Å; *V* = 6061.7(3) Å³, *Z* = 4, μ = 0.147 mm⁻¹, *T* = 173(2) K. Data (38625 total, 13780 unique, *R*_{int} = 0.0753). Final *R*₁ = 0.0587 for all 7876 data with *F*² > 2σ(*F*²). For [Pd(C₃H₅)₂(**1**)₂][O₃SCF₃]₂ **9**: C₅₂H₅₀F₆N₂PdO₈P₂S₂, *M* = 1283.8, orthorhombic, space group *P*2₁2₁2₁, *a* = 16.9797(2), *b* = 17.594(3), *c* = 18.052(3) Å; *V* = 5392.7(14) Å³, *Z* = 4, μ = 0.878 mm⁻¹, *T* = 123(2) K. Data (40417 total, 12202 unique, *R*_{int} = 0.0470). Final *R*₁ = 0.051 for all 9638 data with *F*² > 2σ(*F*²). CCDC 182/1356. See <http://www.rsc.org/suppdata/cc/1999/1707/> for crystallographic data in .cif format.

§ The major ion current (>90%) corresponded to [Pd(allyl)(**1**)⁺ (*m/z* = 837), or oligomers, and there was no free **1**, reference **1**: [**1** + H]⁺, *m/z* = 691.

¶ In all literature reports, 'Pd-**1**' catalysts are generated *in situ* (1–1.5 equiv. **1** and Pd^{II} or Pd⁰). Identical results are obtained with [Pd(allyl)(**1**)][OTf] as pro-catalyst [adding chloride, if required, see ref. 6(b)].

|| The reaction mixture remained bright yellow (no palladium black) for up to 2 h after ≥98% consumption of substrate (<10 min), reinforcing the conclusion that **1** can function as a bis-bidentate ligand for Pd^{II} and Pd⁰.

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- Prior to (and after) addition of [NaCH(CO₂Me)₂] the ³¹P NMR spectrum indicated the presence of many complexes whose relative abundance were time-dependent. A much more complete and detailed report of our NMR, kinetic and other studies on this complex mixture will be published in due course.

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