Development of the First P-Stereogenic PCP Pincer Ligands, Their Metallation by Palladium and Platinum, and Preliminary Catalysis[1])

by **B. Scott Williams**[a]), **Paulo Dani**[a])[2]), **Martin Lutz**[b]), **Anthony L. Spek***[b]), and **Gerard van Koten***[a])[3])

[a]) Department of Metal-Mediated Synthesis, Debye Institute, Universiteit Utrecht, Padualaan 8, 3584 CH, Utrecht, The Netherlands

[b]) Bijvoet Center for Biomolecular Research, Crystal and Structural Chemistry, Universiteit Utrecht, Padualaan 8, 3584 CH, Utrecht, The Netherlands

In memoriam Professor *Luigi M. Venanzi* for his pioneering work in organometallic chemistry, and in PCP-pincer chemistry in particular

The potentially tridentate P-stereogenic [P*CP*] ligands 1,3-{bis[(*tert*-butyl)(phenyl)phosphino]methyl}-benzene and 1,3-{bis[(*tert*-butyl)(phenyl) phosphino]methyl}-2-bromobenzene have been synthesized as the protected phosphine-borane adducts. Deprotection with a secondary amine affords the free phosphine ligand which can be metallated by Pd and Pt with standard metal synthons. Two of the resultant [P*CP*] metal complexes have been characterized by X-ray crystallography. The complexes exhibit a C_2 symmetric environment about the remaining binding site of the square-planar center, with *t*-Bu groups filling two quadrants of the open site. The Pd complexes can be converted by use of a Ag salt to the analogous aquo complex, which is catalytically active in the aldol condensation of methyl 2-isocyanoacetate and benzaldehyde. Preliminary results and comparisons with previously reported catalysts with more distal C-stereogenicity are presented.

Introduction. – Transition metal complexes of so-called 'pincer ligands' have found wide application in a variety of fields since this ligand type was first reported by *Moulton* and *Shaw* in 1976 [1]. The ligands can be abbreviated as '[ECE]' ligands, where E is the donating heteroatom. A number of early reactivity studies showed that the chemistry of square-planar late-transition-metal pincer complexes of this type is particularly rich ([2] and references therein). Subsequent studies have demonstrated the utility of such complexes in *Lewis* acid catalysis [2a][3], *Heck* reactions [4], *Kharasch* additions [5], catalytic dehydrogenation [6], transfer hydrogenation [7], and investigations of C–H and C–C oxidative addition reactions ([8] and references in [8a]).

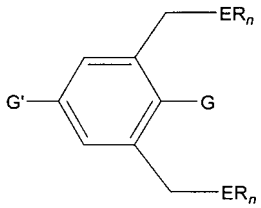
Recently, many efforts have been concentrated upon the immobilization of the catalytic systems upon recoverable supports, such as dendrimers [5c][9], highly symmetric organic frameworks [10], polymers [11], fullerenes [12], and solid supports [13]. Because of these advances in attachment of pincer ligands to recoverable supports, any new modification of the pincer framework or discovery of new patterns of reactivity can be applied in a straightforward manner to a practical catalytic process, in which the catalyst can be easily separated from the reaction medium, and thus the

---

[1]) This work was presented in part at OMCOS 11, Taipei, Republic of China, in July 2001.

[2]) Present Address: Avantium Technologies B. V., P. O. Box 2915, 1000 CX, Amsterdam, The Netherlands.

[3]) e-mail: g.vankoten@chem.uu.nl.

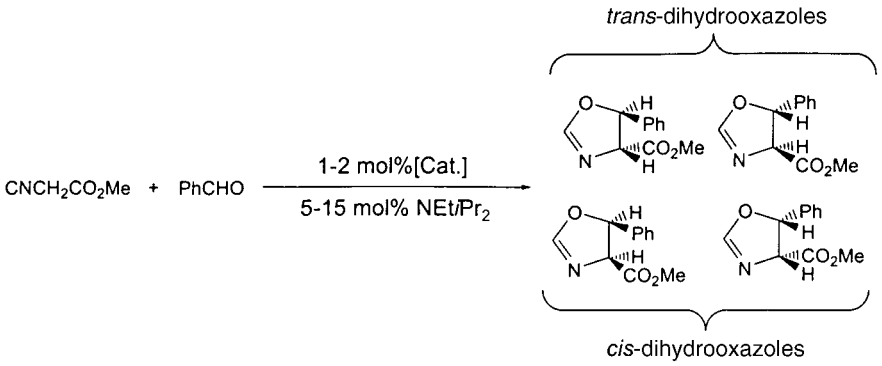


G, G' = H, halide, R

E = N, P; n = 2
E = O, S; n = 1

products of the reaction. For this reason, a major focus of the research in our laboratory is the development of the basic chemistry of pincer-supported organometallic catalysts. Despite the wide variety of catalytically active pincer complexes that have been reported, relatively few attempts have been made to explore enantioselective reactions with chiral versions of the pincer system [14][4]). We report herein the synthesis and procedures for the palladation and platination of a new type of [PCP] pincer ligand, as well as some initial results of the use of these complexes in a catalytic test reaction, namely the asymmetric aldol condensation of methyl 2-isocyanoacetate and benzaldehyde to form chiral dihydrooxazoles (*Scheme 1*).

Scheme 1. *The Aldol Condensation of Methyl 2-Isocyanoacetate and Benzaldehyde*

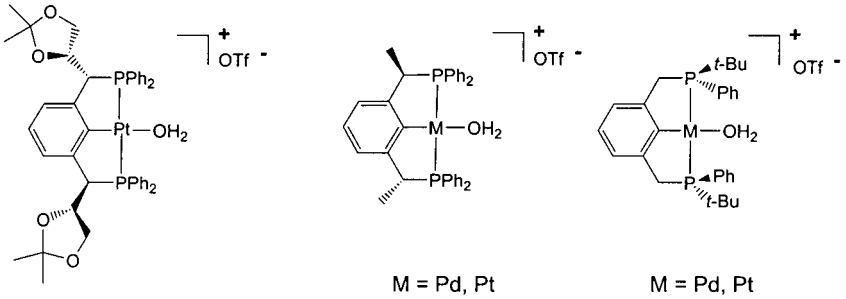


This asymmetric catalytic reaction was initially reported by *Hayashi*, *Ito*, and co-workers, who used a Au catalyst [15], and was also the subject of detailed further study by *Togni* and *Pastor* under similar conditions [16]. *Pregosin* and co-workers showed this reaction to be catalysed by Pd^{II} centres as well [17]. This reaction is interesting both because it is a potential route to β-hydroxy-amino acids, and because it involves the formation of a C–C bond with simultaneous creation of two chiral centres, resulting in

[4]) While not true pincer ligands in the strict sense as defined above, the tridentate ligands developed by *Richards et al.* ([14c] and references therein) as well as those of *Bergman*, *Tilley*, and co-workers [14d] are closely related, and should be kept in mind in discussions of this area.

four possible stereoisomers. It is thus a useful test reaction for exploring the chiral induction provided by new, chiral *Lewis* acid catalysts.

In 1994, *Venanzi* and co-workers prepared a Pt complex of a [PCP] ligand, in which the benzylic positions of the ligand had been modified to form stereogenic centres [14a]. This complex was found to be an active catalyst for the aforementioned aldol condensation. While the enantiomeric excesses and diastereoisomeric selectivities obtained were moderate for this [PCP]-Pt complex, it was clearly demonstrated that this sort of species was capable of chiral induction. More recently, *Zhang* and co-workers have prepared Pd and Pt complexes of a similar chiral [PCP] ligand, and tested their activities in the same aldol condensation [14b][5]). While selectivities remained modest, the synthetic approach used to synthesize the chiral ligand was considerably more straightforward than that of *Venanzi* and co-workers, thus increasing the potential usefulness of the system. In related studies, *Giménez* and *Swager* have prepared chiral [SCS]-Pd complexes in which the chirality is located on a tail attached to C(4) of the [SCS] aryl ring, although no significant chiral induction was observed with this catalyst [19].



Venanzi and co-workers *Zhang* and co-workers This work

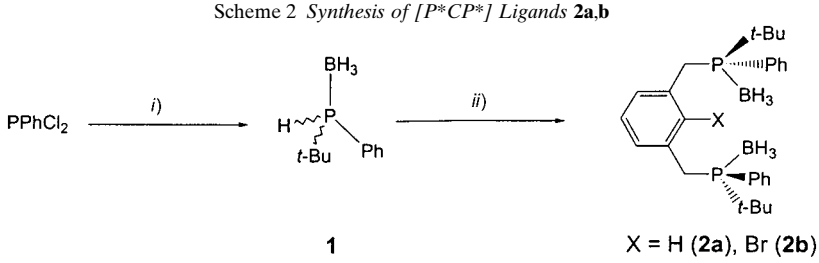
Since previous attempts to catalyse this reaction with pincer-supported metal complexes had centered upon complexes containing the chiral information at the benzylic C-atom, it seemed a logical approach to synthesize catalysts with the chiral information to be found at the P-atom itself, since the binding pocket of square-planar [PCP] complexes is quite deep, and thus the R-groups bound to the P-atom are in close proximity to a potential substrate. We therefore set out to prepare the C_2-symmetric complexes with sterically demanding R-groups.

Results and Discussion. – *Preparation of P-Stereogenic PCP Ligands [P*CP*].* The racemic monophosphorus compound *tert*-butyl(phenyl)phosphane-borane **1** was prepared in reasonable (67%) yield by a modification of the procedure of *Imamoto et al.* (*Scheme 2*) [20]. This secondary phosphine-borane can be deprotonated, as was shown by *Wolfe* and *Livinghouse*, by BuLi in Et_2O, in the presence of (−)-sparteine [21]. Warming this mixture to 30° for 1 h, followed by cooling and reaction with either 1,3-bis(bromomethyl)benzene or 1,3-bis(bromomethyl)-2-bromobenzene resulted in the formation of the terdentate [P*CP*] ligands **2a** and **2b**, respectively, in diastereoisomerically pure form (yields 53% purified and 99% crude, resp.).

---

5) This same ligand has also been used for catalytic dehydrogenation with a Ru catalyst (see [18]).

Scheme 2 *Synthesis of [P*CP*] Ligands* **2a**,**b**



1 X = H (**2a**), Br (**2b**)

i) 1) *t*-BuLi, Et_2O, −78°; 2) $LiAlH_4$, Filtration; 3) Me_2SBH_3. *ii*) 1) BuLi, (−)-sparteine, Et_2O, −78°; 2) 30°, 90 min; 3) di- or tribromoxylene, −78°.

The most striking spectral feature of these species is the sharp doublet (^3J(P,H) = 14 Hz in both cases) assigned to the *t*-Bu group. If the alkylation of the bromoxylenes is carried out in the absence of (−)-sparteine or in THF in place of Et_2O, a mixture of both diastereoisomers is obtained, in which the *t*-Bu *doublets* of both diastereoisomers are clearly separated in the ^{1}H-NMR spectrum. Presumably in the latter case, the THF coordinates strongly to the Li^+ cation, preventing sparteine complexation, thereby rendering the reaction completely nonstereoselective. The Me analogue of **2a**, 1,3-(PMePh(BH_3)CH_2)$_2C_6H_4$, can be prepared from PHMePh(BH_3) and 1,3-bis(bromomethyl)benzene, yet surprisingly, even when the reaction has been performed in Et_2O and in the presence of (−)-sparteine, an equimolar mixture of diastereoisomers has been obtained. This is presumably a result of the difference in steric congestion between the lithium methyl-phosphide-sparteine complex and the lithium *tert*-butyl-phosphide-sparteine complex.

Epimerization of Free Phosphine Centres. The phosphine–boranes **2a**,**b** can be deprotected with an excess of various types of amines [20][21][6]) to form the related phosphines **3a**,**b**, which are potential [P*CP*] ligand precursors (*Scheme 3*). Since the usefulness of these ligands is dependant upon their barrier to epimerization, a sample of **3a** was deprotected with Et_2NH, the volatiles were removed, and C_6D_6 was added *via* vacuum transfer. The epimerization of **3a** at 80° was monitored by ^{1}H-NMR in a *J. Young* NMR tube. A barrier of 28.1 ± 0.1 kcal/mol was determined for the loss of chiral purity[7]). Such an inversion barrier is actually rather low for phenyldialkyl phosphines [22], but sufficiently high that epimerization of metal catalysts derived from this ligand would not be a significant consideration, as quaternerization of the P-atom makes it configurationally stable[8]).

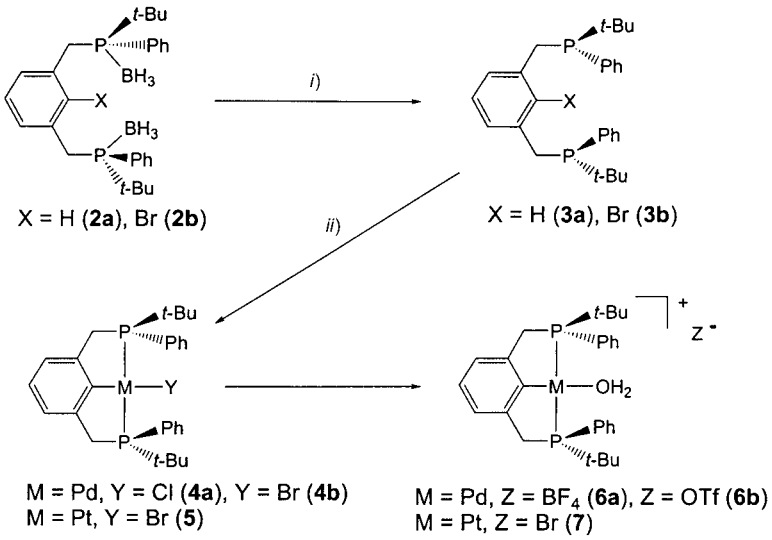
---

[6]) The most convenient methods have been the use of pyrrolidine (neat, 40°, *ca.* 12 h) or Et_2NH (50/50 mixture with THF, 55°, 1.5 h). The amine can be subsequently removed by evaporation. No sign of inversion has been observed under these relatively mild conditions, though epimerization becomes rapid at higher temperatures and over longer times (*vide infra*). In contrast to the report in [21], we have not been able to remove the amine-boranes by sublimation.

[7]) This barrier is for the *rac* to *meso* epimerization, and was determined by use of the *Eyring* equation. K_{eq}(375 K) = 0.33, thus the *rac* form is slightly more stable, so the barrier for *meso*-to-*rac* epimerization is 27.3 kcal/mol.

[8]) Assuming a very minimal metal–P bond energy of 17 kcal/mol ($k_{dissoc} > 1\ s^{-1}$ at 25°), this would provide a barrier > 40 kcal/mol to inversion ($k_{epim} < 5 \cdot 10^{-10}\ s^{-1}$ at 120°, $t_{1/2} > 40$ years; assuming entropy effects upon the epimerization rate are relatively minor).

Scheme 3. *Transition Metal Complexes of [P*CP*] Ligands*



i) HNR_2. *ii*) For **4a**: **3a** + $[Pd(MeCN)_4][BF_4]_2$ in MeCN, 60° followed by LiCl; for **4b**: **3b** + $Pd_2(dba)_3$ in C_6H_6, 22°, 12 h; for **5**: **3b** + $Pt_2(p\text{-tolyl})_4(\mu\text{-}SEt_2)_2$, C_6H_6, 55°, 5 min [23].

*Transition Metal Complexes of [P*CP*] Ligands.* Complexes of the form [P*CP*]MY (M = Pd, Y = Cl, (**4a**); M = Pd, Y = Br, (**4b**); M = Pt, Y = Br, (**5**)) can be formed by metallation of the deprotected ligands **3a** (for **4a**) or **3b** (for **4b** and **5**), from the appropriate organometallic precursors (*Scheme 3*). All of the complexes have been characterized by multinuclear (^1H, ^{13}C, ^{31}P) NMR and polarimetry, while **4a** and **5** were additionally characterized by X-ray crystallography.

Crystals of **4a** suitable for X-ray crystallography were obtained by crystallization from CH_2Cl_2/hexane, while those of **5** were obtained from toluene/pentane. Molecular plots of **4a** and **5** are shown in *Figs. 1* and *2*, and selected bond lengths, angles, and dihedral angles are given in the *Table*. Compound **4a** has approximate C_2 symmetry, while compound **5** crystallizes with two molecules in the asymmetric unit, which both have an exact, crystallographic C_2 symmetry. The dihedral angle of the aryl plane and the coordination plane is 14.46(10)° in **4a**, and 9.81(6)° and 10.01(6)° in **5**. The most interesting feature of these crystal structures is the fact that the *t*-Bu groups of the phosphine are oriented out and away from the ligand in the direction of the halide, whereas the Ph groups of the phosphine are held nearly perpendicular to the square plane of the complex (88.18(11)° and 93.01(11)° for the two Cl–P–Pd–C (*ipso*)torsion angles in **4a**). This effect is less pronounced in the Pt structure, in which the same torsion angles of the Ph groups are reduced to 78.07(7)° and 84.89(6)°.

When the complexes (especially that of Pd, **4a**) are viewed along the halogen-metal axis, two of the four quadrants are occupied by *t*-Bu groups, while two are relatively empty due to the distance of the Ph groups. This creates a deep chiral pocket around the halogen, which could potentially have a strong chiral induction in reactions in which a substrate is bound in the position occupied by the halogen. *Cross et al.* have named this

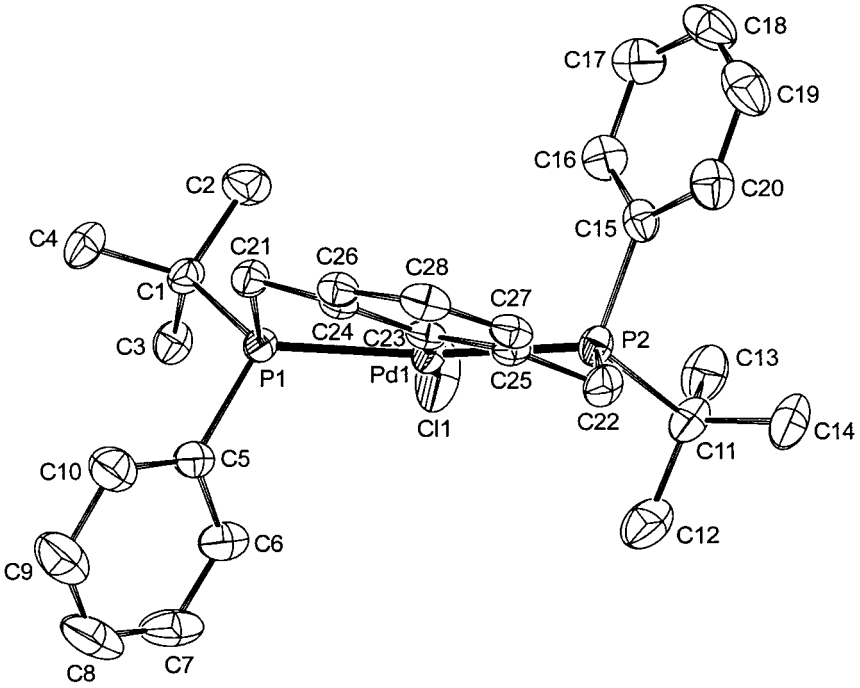


Fig. 1. *Displacement ellipsoid plot of* **4a** (50% probability). H-Atoms omitted for clarity.

a 'staggered' configuration in their analysis of pincer and pincer-type ligand structures [24]. The contrasting situation, or 'eclipsed' form, would place all four phosphine substituents evenly distanced from the square plane of the metal, thus placing large bulky groups in all four quadrants, which would be expected to give much less selectivity, and to dramatically slow the rate of catalysis.

Reaction of complexes **4** and **5** with AgZ in wet acetone affords the corresponding cationic aqua complexes **6** and **7** (M = Pd, Z = BF_4, **6a**; M = Pd, Z = OTf, **6b**; M = Pt, Z = OTf, **7**). Complex **6b** has been synthesized on a preparative scale (452 mg, 95%) and fully characterized by elemental analysis, multinuclear NMR (^{1}H, ^{31}P), and polarimetry. Since we were interested in the application of these catalysts to the aldol condensation of $CNCH_2CO_2Me$ with aldehydes, $CNCH_2CO_2Me$ was added to **6b** to form the isocyanate adduct **8**, which was spectroscopically (^{1}H-, ^{13}C-NMR; IR) characterized. The change in ν_{CN} ($\Delta\nu = 56\ cm^{-1}$) between free $CNCH_2CO_2Me$ and **8** indicates that the isocyanate is bound through the isocyanate C-atom.

Chiral Aldol Condensation Reaction. The complexes **6a**,**b** are active catalysts in the aldol condensation of methyl 2-isocyanoacetate with benzaldehyde. The product of this reaction, methyl 4,5-dihydro-5-phenyl-1,3-oxazoline-4-carboxylate exists in four isomeric forms: two (*E*)-enantiomers and two (*Z*)-enantiomers. Previous work by the groups of *Venanzi* and *Zhang* has demonstrated that the reaction has some enantioselectivity when performed with catalysts in which the chiral information is located at the benzyl C-atom of the [PCP]-Pt and -Pd catalysts (see *Introduction*)

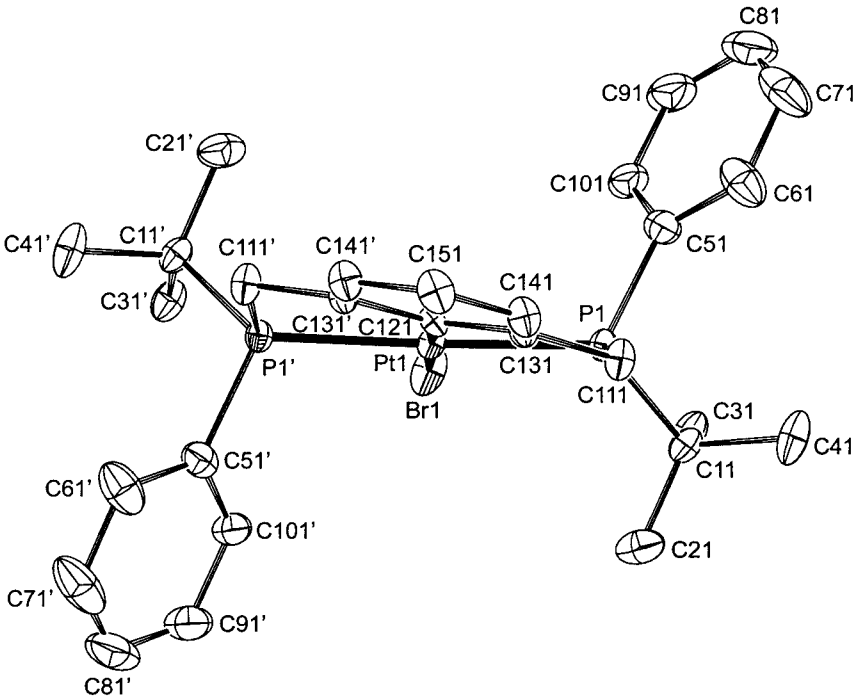


Fig. 2. *Displacement ellipsoid plot of the first independent molecule of* **5** (50% probability). H-Atoms omitted for clarity. Symmetry operation: $1-x, y, -z$.

Table. *Selected Bond Lengths, Angles, and Torsion Angles for* **4a** *and* **5**

	4a		**5**	
Bond lengths [Å]	Pd–Cl	2.3571(12)	Pt–Br	2.5430(4)
	Pd–C(23)	2.011(3)	Pt′–Br′	2.5442(4)
	Pd–P(1)	2.2975(8)	Pt–C(121)	2.021(3)
	Pd–P(2)	2.2947(8)	Pt′–C(122)	2.016(3)
			Pt–P	2.2926(5)
			Pt′–P′	2.2928(6)
Bond Angles [°]	Cl–Pd–P(1)	99.55(3)	Br–Pt–P	96.73(1)
	Cl–Pd–P(2)	96.34(3)	Br′–Pt′–P′	97.16(1)
	C(23)–Pt–P(1)	82.22(8)	C(121)–Pt–P	83.27(1)
	C(23)–Pt–P(2)	81.86(8)	C(122)–Pt′–P′	82.84(1)
Dihedral Angles [°]	Cl–Pd–P(1)–C(1)	– 40.21(10)	Br–Pt–P–C(11)	– 48.94(9)
	Cl–Pd–P(2)–C(11)	– 36.00(14)	Br′–Pt′–P′–C(12)	– 43.84(9)
	Cl–Pd–P(1)–C(5)	88.19(13)	Br–Pt–P–C(51)	78.07(7)
	Cl–Pd–P(2)–C(15)	93.01(13)	Br′–Pt′–P′–C(52)	84.90(7)

[14a,b]. (*E*/*Z*)-Ratios of 70/30 and 78/22, and *e.e.* values of 65% and 24% were reported for the (*E*)-isomers, respectively. In both cases, the chirality of these complexes was located on the benzylic C-atom of the [PCP] ligand.

We anticipated that moving the chiral site closer to the substrate binding pocket by the synthesis of a P-chiral version of the [PCP] ligand would increase the enantio- and

diastereoselectivity of the reaction. Indeed, for the Pd complexes **6**, the diastereoisomeric ratio was found to be higher, yielding 94–98% (*E*)-product. However, the enantiomeric excess was never found to be higher than 11%. Variations of the concentration of catalyst, aldehyde, and *Hünig*'s base did not appreciably affect the enantioselectivity, nor did changing the reaction solvent from CH_2Cl_2 to THF or toluene. Use of the isocyanate adduct **8**, under anhydrous conditions also showed no appreciable enantioselectivity. In contrast to the experience of *Venanzi* and co-workers [14a], we found the Pt analogue **7** of our catalyst to be slower than the blank reaction that occurs in the absence of transition metal catalyst. This is presumably due to the greater steric bulk about the open site of our catalyst relative to that of *Venanzi* and co-workers.

It is perhaps not surprising that our [P*CP*] catalyst displays a lower enantioselectivity than that of the Au catalyst of *Hayashi* and co-workers [15], as the selectivity of the latter has been ascribed to a H-bonding interaction with a pendant amino group, which is lacking in the Pd/Pt system. However, it is striking that the enantioselectivity is not higher than that of the other [PCP]-Pd/Pt-pincer systems discussed above in which the chirality is more distant from the active site of the catalyst. Further investigation of other reactions of these [P*CP*] catalysts will be necessary before nonspeculative explanations can be advanced, and these are underway in our laboratory.

Conclusions. – The wide use and versatility of pincer ligands in catalysis, and especially advances in macromolecular pincer catalysts that can be recycled with high efficiency by current and developing techniques, makes the development of new pincer-based systems a very attractive field of catalyst development. To date, pincer-based systems have shown poor to moderate enantioselectivities in catalytic reactions that result in chiral products. We have shown that it is possible to prepare enantiomerically pure transition metal pincer complexes with chirality at the P-atoms themselves which are directly bonded to the transition metal. An initial test reaction between methyl 2-isocyanoacetate and benzaldehyde did not generate high enantiomeric excesses, though this does not preclude the possibility of enantioselectivity in other reactions. We are currently involved in the use of these ligands with other metals and catalytic reactions, as well as the synthesis of related P-stereogenic pincer ligands in order to find systems in which our techniques for recoverable catalyst synthesis can be applied to useful asymmetric transformations.

This material is based upon work supported by the *North Atlantic Treaty Organization* (*NATO*) under a grant awarded in the year 2000 (to B. S. W.). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of *NATO*. *A. L. S.* and *M. L.* acknowledge funding from the *Council for the Chemical Sciences of the Dutch Organization for Scientific Research* (*CW-NWO*) and *P. D.* acknowledges funding from the *Conselho Nacional de Desenvolvimento Cientifico e Tecnológico* of Brazil. *B. S. W.* would like to thank *H. P. Dijkstra* and Dr. *S. Medici* for helpful discussions.

Experimental Part

General. Unless otherwise noted, all transformations were carried out under N_2, by standard *Schlenk* techniques, or under vacuum. Recrystallizations were performed under ambient atmosphere, either at r.t. or $-30°$. Both protio- and deutero-solvents were purified by standard methods in reactions run under N_2. Et_2NH and pyrrolidine were degassed before use. 1,3-Bis(bromomethyl)-2-bromobenzene [25] and $Pt_2(p\text{-tolyl})_4(\mu$-

$SEt_2)_2$ [23] were prepared according to published literature procedures. Other reagents, unless specified, were used as received from commercial suppliers or prepared by inorganic synthesis procedures. Enantiomeric excesses in catalytic reactions were determined by chiral HPLC, while diastereoisomeric ratios were determined by NMR.

*Preparation of (*tert-*Butyl)(phenyl)phosphine–borane* (**1**). This preparation is a variant upon that published by *Imamoto* and co-workers [20]. In a typical experiment, a flame-dried *Schlenk* flask was charged with a stir bar, $PPhCl_2$ (5.80 g, 32.4 mmol), and dry ether (100 ml). The reaction vessel was cooled to $-78°$ and *t*-BuLi (1.5M soln. in pentane, 28 ml, 42 mmol) was added dropwise *via* syringe over the course of 0.5 h. The mixture was allowed to stir at $-78°$ for 1.5 h, after which the temp. was raised to r.t. over the course of another 1.5 h. The temp. was subsequently reduced to $-41°$, and $LiAlH_4$ (1.43 g, 37.6 mmol) was added in a single portion. The cooling bath was removed, and the mixture filtered through *Celite* on sintered glass under N_2. The solids were washed with dry ether (2×20 ml) and borane dimethyl sulphide complex (16.2 ml, 94%, 158 mmol) was added *via* syringe at 0°. This was allowed to stir for 0.5 h at r.t. before being carefully poured onto a mixture of ice (100 g) and 4M HCl (50 ml). The org. layer was separated and the aq. layer washed twice with ether (2×50 ml). The combined org. layers were washed with H_2O (50 ml) and brine (50 ml) before being dried ($MgSO_4$) and filtered. The crude product was dissolved in CH_2Cl_2 (100 ml) and filtered through silica to give a heavy oil upon evaporation of the CH_2Cl_2 (3.90 g, 67%).

*Synthesis of (*S,S*) 1,3-(P(BH$_3$)(*t*Bu)(Ph)CH$_2$)$_2$(C$_6$H$_4$)* (**2a**) and (S,S) *1,3-(P(BH$_3$)(tBu)(Ph)CH$_2$)$_2$(2-Br)C$_6$H$_3$* (**2b**). This preparation was derived from the method of sparteine resolution described by *Wolfe* and *Livinghouse* [21]. **2a** and **2b** were prepared by identical methods from **1** and either 1,3-bis(bromomethyl) benzene (**2a**) or 1,3-bis(bromomethyl)-2-bromobenzene (**2b**). The synthesis and characterization of **2a** is given here. Phosphine–borane **1** (3.90 g, 21.7 mmol) was placed in a *Schlenk* flask with a stirbar, (−)-sparteine (7 ml, 29 mmol) and ether (80 ml). The temp. was lowered to $-78°$, and BuLi (1.6M soln. in pentane, 16.7 ml, 8.8 mmol) was added dropwise via syringe. *We have noticed that it is essential to have more (−)-sparteine than BuLi present in order to ensure the formation of only one isomer*. Within minutes, a voluminous white precipitate had formed. After 0.5 h, the cooling bath was removed, and the reaction allowed to come to r.t. over the course of 0.5 h. The reaction was placed in a warm water bath (*ca.* 30°) for 1.5 h in order to allow the sparteine-lithium-phosphide complex to form the desired isomer. Subsequently, the temp. was reduced to $-78°$ and 1,3-bis(bromomethyl)benzene was added, and the reaction warmed to $-20°$ over the course of 2 h before being placed in the freezer ($-30°$) overnight. The reaction was poured into toluene (100 ml), CH_2Cl_2 (200 ml), and 3% H_2SO_4 (200 ml), the org. layer separated, and the aq. layer extracted thrice with CH_2Cl_2 (100, 100, and 50 ml). The combined org. fractions were reduced to 150 ml, and washed (aq. Na_2CO_3, 50 ml) and brine (50 ml). The solvents were evaporated, the product passed through silica in CH_2Cl_2, and subsequently precipitated with hexane (2.09 g, 42%, 2 crops). $[\alpha]_D^{23} = +106$ ($c = 0.21$, $CHCl_3$). ^{1}H-NMR ($CDCl_3$): 1.11 (*d*, ^3J(P,H) = 13.8, 22 H (includes some intensity from broad BH_3 signal), P–*t*-Bu); 3.2–3.5 (8 line ABX pattern, 4 H, diastereoisotopic P–CH_2); 6.9–7.0 (*m*, H–C(3), H–C(4), and H–C(5) of central aryl ring); 7.18 (*s*, H–C(1) of central aryl ring); 7.3–7.5 (*m*, 6 H, *m*- and *p*-signals of P–Ph); 7.75 (*t*, ^3J(P,H)(H,H) = 8.1, 4 H, *o*-signals of P–Ph). ^{13}C-NMR ($CDCl_3$): 25.8 (CMe_3); 27.0, 30.0 (2*d*, $J = 30.0$, P–CMe_3 and P–CH_2); 126.0 (*d*, ^1J(P,C) = 47, P–*C*(*ipso*)); 127.9 (arom.); 128.2 (*d*, ^3J(P,C) = 9, P–*C*(*meta*)); 128.8 (arom.); 131.2 (arom.); 132.7 (arom.); 133.9 (*d*, ^2J(P,C) = 7, P–*C*(*ortho*)). ^{31}P-NMR ($CDCl_3$): 34 (br. *q*). Anal. calc. for $C_{28}H_{42}B_2P_2$ (462.21): C 72.76, H 9.16, P 13.40; found: C 72.52, H 9.08, P 13.46.

Compound **2b** was isolated only in crude form (3.22 g, 99%) and thus characterized spectroscopically: $[\alpha]_D^{23} = +136$ ($c = 1.01$, CH_2Cl_2). ^{1}H-NMR ($CDCl_3$): 1.11 (*d*, ^3J(P,H) = 13.8, 22 H (includes some intensity from broad BH_3 signal), P–*t*-Bu); 3.2–3.5 (8 line ABX pattern, 4 H, diastereoisotopic P–CH_2); 6.9–7.0 (*m*, 3 H, H–C(3), H–C(4), and H–C(5) of central aryl ring); 7.3–7.5 (*m*, 6 H, *m*- and *p*-signals of P–Ph); 7.75 (*t*, ^3J(P,H)(H,H) = 8.1, 4 H, *o*-signals of P–Ph). ^{13}C-NMR ($CDCl_3$): 25.9 (CMe_3); 27.5, 30.5 (2*d*, $J = 30.0$, P–CMe_3 and P–CH_2); 126.0 (*d*, ^1J(P,C) = 47, P–*C*(*ipso*)); 126.6 (arom.); 128.6 (*d*, ^3J(P,C) = 9, P–*C*(*meta*); 129.1 (*t*, $J = 6.1$, *C*–Br); 129.7 (arom.); 131.6 (*d*, ^4J(P,C) = ~2, P–*C*(*para*); 134.2 (*d*, ^2J(P,C) = 7, P–*C*(*ortho*)); 134.6 (arom). ^{31}P-NMR ($CDCl_3$): 34 (br. *q*).

*Deprotection of Phosphine–Boranes to form 1,3-{Bis[(*tert-*butyl)(phenyl)phosphino]methyl}benzene and 1,3-{Bis[*tert-*butyl(phenyl)phosphino]methyl}-2-bromobenzene* (**3a**,**b**): The phosphine–boranes **2a**,**b** were deprotected by heating in neat pyrrolidine (40°, 12 h) or 50/50 (*v*/*v*) mixture of THF and Et_2NH (55°, 1.5 h) to afford the free phosphines **3a**,**b**, respectively (^{31}P-NMR: 8.5 (for **3a**), 8.1 (for **3b**)). The volatiles were removed under vacuum and the free phosphines directly used in metallation reactions without further purification.

*Preparation of {(*S,S*)-1,3-{Bis[(*tert-*butyl)(phenyl)phosphino]methyl}phenyl}chloropalladium* (**4a**): Freshly deprotected **3a** (from 585 mg, 1.35 mmol of **2a**) was dissolved in MeCN, and was allowed to react with

$[Pd(MeCN)_4][BF_4]_2$ (680 mg, 1.5 mmol) over the course of 12 h, after which a large quantity of palladium black had formed. LiCl (200 mg, 7.5 mmol) in wet acetone was added to the soln., and after 1 h, the solvents were removed *in vacuo* and the product extracted from the solids with CH_2Cl_2. A brown impurity was removed by THF/ether precipitation, and the product was isolated by precipitation from ether/EtOH in two crops (118 mg, 15% (unoptimized)). $[\alpha]_D^{23} = -129$ ($c = 0.21$, $CHCl_3$). ^{1}H-NMR ($CDCl_3$): 1.30 (t, ^3J(P,H) = 7.7, 2 *t*-Bu); 3.62 (br. *m*, 2 P–CH_2); 6.88 (t, 7.2, H–C(4) of central aryl ring); 7.05 (d, $J = 7.5$, H–C(3), H–C(5) of central aryl ring); 7.42 (br. *m*, 6 H, *m*- and *p*-signals of P–Ph); 8.07 (br. *m*, 4 H, *o*-signal of P–Ph). ^{13}C-NMR ($CDCl_3$): 26.9 (C*Me*); 33.3, 35.6 (2t, $J = 11, 5$, P–CMe_3, P–CH_2); 123.3 (t, $J = 11$, arom.); 125.6 (arom.); 128.5 (arom.); 129.9 (t, $J = 16$, arom.); 130.7 (arom.); 134.3 (t, $J = 3$, arom.); 148.1 (t, $J = 0$, arom.); 158.2 (arom.). ^{31}P-NMR ($CDCl_3$): 53.2. Anal. calc. for $C_{28}H_{35}ClP_2Pd$ (575.41): C 58.45, H 6.16; found: C 58.39, H 6.07.

*Preparation of {(*S,S*)-1,3-{Bis[(*tert*-butyl)(phenyl)phosphino]methyl}phenyl}bromopalladium* (**4b**): Freshly deprotected **3a** (from 3.06 g, 5.66 mmol of **2a**) was dissolved in benzene, and was allowed to react with $Pd_2(dba)_3 \cdot CHCl_3$ (2.75 g, 2.66 mmol) over the course of 12 h. The product was filtered through silica in ether. Subsequently, the product was purified by column chromatography (silica, CH_2Cl_2) and crystallization from acetone/hexane at $-30°$ (680 mg, 19% (unoptimized) as **4b** $\cdot$ 1/3(C_2H_6O)). The crystals were washed thrice with hexane. ^{1}H-NMR ($CDCl_3$): 1.35 (t, ^3J(P,H) = 7.6, 2, *t*-Bu); 3.63 (br. *m*, 2 P–CH_2); 6.85 (t, $J = 7.4$, H–C(4) of central aryl ring); 7.03 (d, $J = 7.4$, H–C(3), H–C(5) of central aryl ring); 7.41 (br. *m*, 6 H, *m*- and *p*-signals for P–Ph); 8.05 (br. *m*, 4 H, *o*-signal for P–Ph). ^{13}C-NMR ($CDCl_3$): 27.0 (CMe_3); 33.6, 35.6 (2t, $J = 12$, P–CMe_3 and P–CH_2); 123.3 (t, $J = 10$, arom.); 125.6 (arom.); 128.5 (arom.); 129.7 (t, $J = 20$, arom.); 130.6 (arom.); 134.3 (arom.); 147.6 (3t, $J = 10$, arom.). ^{31}P-NMR ($CDCl_3$): 54.0. Anal. calc. for $C_{28}H_{35}BrP_2Pd$ (619.76): C 54.43, H 5.49, P 10.03; found: C 54.26, H 5.38, P 10.03.

*Preparation of {(*S,S*)-1,3-{Bis[(*tert*-butyl)(phenyl)phosphino]methyl}phenyl}bromoplatinum* (**5**): Freshly deprotected [P*C(Br)P*] (**3b**, from 930 mg of **2b**, 1.7 mmol) was suspended in benzene with $Pt_2(p\text{-tolyl})_4(\mu\text{-}SEt_2)_2$ (800 mg, 0.86 mmol). The soln. was placed in a water bath at 55°. After 1 min, the ^{31}P-NMR spectrum of the crude mixture (unlocked, unreferenced) showed primarily signals for the product, **7**, ($\delta = 50.0$, ^1J(Pt,P) = 2895 Hz), a small amount of starting material ($\delta = 8.2$), and a small amount of an intermediate, putatively assigned as the mono-phosphine-coordinated species *cis*-Pt(*p*-tolyl)$_2$(SEt_2)(κ^1-**3b**) ($\delta = 21.7$, ^1J(Pt,P) ~ 1700 Hz; $\delta = 8.8$). After 5 min at 55°, only the product was visible by ^{31}P-NMR spectroscopy. The volatiles were removed under vacuum. The product was passed through a column of silica gel (40 cm) in CH_2Cl_2 and crystallized from toluene/pentane (0.599 g, 49% in two crops). $[\alpha]_D^{23} = -51$ ($c = 1.04$, CH_2Cl_2). ^{1}H-NMR ($CDCl_3$): 1.42 (t, ^3J(P,H) = 7.7, 2 *t*-Bu); 3.65 (br. *m*, 2 P–CH_2); 6.98 (t, $J = 7.2$, H–C(4) of central aryl ring); 7.09 (d, with Pt satellites, ^3J(H,H) = 7.5, ^4J(H,Pt) = 21, H–C(3), H–C(5) of central aryl ring); 7.43 (br. *m*, 6 H, *m*- and *p*-signals for P–Ph); 8.14 (br. *m*, 4 H, *o*-signal or P–Ph). ^{13}C-NMR ($CDCl_3$): 27.3 (CMe_3); 33.6, 36.2 (2t, with Pt satellites, J(P,C) = 15, ^2J(Pt,C) = 59 (33.6); J(P,C) = 16, ^2J(Pt,C) = 105 (36.2); P–CMe_3 and P–CH_2); 123.6 (t with Pt satellites, J(P,C) = 8, J(Pt,C) = 39, arom.); 124.9 (arom.); 128.5 (t, $J = 5$, arom.); 130.8 (arom.); 134.4 (t, $J = 11$, arom.); 146.4 (arom.); 148.1 (arom.). ^{31}P-NMR ($CDCl_3$): 49.9 (s, with Pt satellites, ^1J(Pt,P) = 2900).

Crystal-Structure Determinations: X-Ray intensities were measured on a *Nonius KappaCCD* diffractometer with rotating anode ($\lambda = 0.71073$ Å) at a temp. of 150(2) K. The structures were solved with automated *Patterson* methods (DIRDIF 97) [26] and refined with SHELXL97 [27] against F^2 of all reflections. Molecular illustration, structure checking, and calculations were performed with the PLATON [28] package.

Crystal-Structure Determination of **4a**: X-Ray-quality crystals of **4a** were grown from a mixture of CH_2Cl_2/hexane at r.t. by slow evaporation. $C_{28}H_{35}ClP_2Pd$, $Fw = 575.35$, colorless needle, $0.45 \times 0.06 \times 0.06$ mm^3, hexagonal, $P6_3$ (No. 173), $a = b = 20.3046(2)$, $c = 11.6707(1)$ Å, $V = 4166.93(7)$ Å^3, $Z = 6$, $\rho = 1.376$ g/cm^3. 81498 reflections were measured. 6380 reflections were unique ($R_{int} = 0.066$). 5431 reflections were observed [$I > 2\sigma(I)$]. The θ range was 1.16–27.47° with indices hkl −26/26, −26/26, −15/15. The absorption correction was based on multiple measured reflections (program PLATON [28] routine MULABS, $\mu = 0.89$ mm^{-1}, 0.91–0.96 transmission). Non-H-atoms were refined freely with anisotropic displacement parameters. H-atoms were refined as rigid groups. 295 refined parameters, 1 restraint. *R*-values [obs. refl.]: $R1 = 0.0292$, $wR2 = 0.0566$. *R*-values [all refl.]: $R1 = 0.0429$, $wR2 = 0.0605$. $GoF = 1.022$. *Flack* x-parameter −0.05(2) [29]. Residual electron density between −0.49 and 0.65 e/Å^3.

Crystal-Structure Determination of **5**: Crystals of **5** suitable for X-ray-diffraction study were grown from toluene/pentane. $C_{28}H_{35}BrP_2Pt$, $Fw = 708.50$, colorless block, $0.33 \times 0.15 \times 0.15$ mm^3, monoclinic, $C2$ (No. 5), $a = 15.5173(1)$, $b = 13.0548(1)$, $c = 15.3827(1)$ Å, $\beta = 118.7775(3)°$, $V = 2731.29(3)$ Å^3, $Z = 4$, $\rho = 1.723$ g/cm^3. 60576 reflections were measured. 16878 reflections were unique ($R_{int} = 0.033$). 15320 reflections were observed [$I > 2\sigma(I)$]. The θ range was 1.51–40.23° with indices hkl −28/27, −23/23, −27/27. An analytical absorption correction was applied (program PLATON [28], routine ABST, $\mu = 6.73$ mm^{-1}, 0.34–0.65 transmission). The

structure contains two independent molecules in the asymmetric unit, which both are located on a twofold axis. Non-H-atoms were refined freely with anisotropic displacement parameters. The H-atoms of Me at C(21) and C(22) were refined freely with isotropic displacement parameters; all other H-atoms were refined as rigid groups. 321 refined parameters, 49 restraints. *R*-values [obs. refl.]: $R1 = 0.0243$, $wR2 = 0.0466$. *R*-values [all refl.]: $R1 = 0.0302$, $wR2 = 0.0481$. $GoF = 1.031$. *Flack* x-parameter $-0.004(3)$ [29]. Residual electron density was between -2.16 and 0.90 e/Å^3.

Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the *Cambridge Crystallographic Data Centre* as supplementary publication no. CCDC 169317 (**4a**) and 169318 (**5**). Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ UK, (fax: +44 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk).

*Preparation of Aqua Complexes Aqua[(*S,S*)-1,3-{bis[(*tert*-butyl)(phenyl)phosphino]methyl}phenyl]palladium Tetrafluoroborate* (**6a**), *Trifluoroacetate* (**6b**) *and Aqua[(*S,S*)-1,3-{bis[(*tert*-butyl)(phenyl)phosphino]methyl}phenyl]platinum Bromide* (**7**): As all three aqua complexes were prepared by the same method, that for **6b** is given as typical. On the benchtop, a sample of [PCP]PdBr (**4b**) (430 mg, 0.67 mmol) was dissolved in wet acetone. AgOTf (176 mg, 0.68 mmol) was added, which resulted in an off-white precipitate. After 1 h, the sample was filtered through *Celite* on glass wool and precipitated with hexane as a microcrystalline white powder to form the product with one acetone molecule of crystallization (452 mg, 95%). $[\alpha]_D^{23} = -13.5$ ($c = 1.04$, CH_2Cl_2). ^{1}H-NMR (C_6D_6): 1.2 ppm (br., 2 *t*-Bu); 1.54 (6 H, acetone); 3.0 (4 H, P–CH_2); 3.4–4.8 (Pd–OH_2); 7 (aryl signals); 7.1–8.2 (P–Ph signals). Aryl region not integratable due to C_6D_5H and overlap. Anal. calc. for $C_{29}H_{37}F_3O_4P_2PdS \cdot (C_3H_6O)$ (765.11): C 50.23, H 5.66, P 8.10; found: C 49.99, H 5.55, P 8.20.

For **7**: $[\alpha]_D^{23} = -57$ ($c = 0.76$, CH_2Cl_2).

Isolation of Pd Isocyanate Complex (**8**): On the benchtop, [[PCP]Pd(OH_2)][OTf] (108.3 mg, 0.14 mmol) was dissolved in acetone, to which methyl 2-isocyanoacetate (14 µl, 0.15 mmol) was added. The solvent was evaporated, and the product precipitated from THF/hexane (84.1 mg, 75%). $[\alpha]_D^{23} = -34$ ($c = 0.23$, CH_2Cl_2). IR: 1758 cm^{-1} (C=O), 2219 cm^{-1} (C≡N). ^{1}H-NMR ($CDCl_3$): 1.27 (*t*, ^3J(P,H) = 8.1, 2 *t*-Bu); 3.8 (br. *m*, 2 P–CH_2); 3.87 (*s*, O*Me*); 5.21 (*s*, CNCH_2); 7.03 (*t*, $J = 7$, H–C(4) of central aryl ring); 7.13 (*d*, $J = 7.5$, H–C(3), H–C(5) of central aryl ring); 7.52 (br. *m*, 6 H, H–C(3), H–C(4), H–C(5) of P–Ph); 7.73 (br. *m*, 4 H, H–C(2), H–C(6) of P–Ph). ^{13}C-NMR ($CDCl_3$): 26.6 (C*Me*$_3$); 33.0, 36.5 (2*t*, $J = 12$, P–*C*Me$_2$, P–*C*H$_2$); 47.3 (*s*, CN*C*H$_2$); 53.8 (*s*, O*Me*); 123.7 (*t*, $J = 10$, arom.); 127.3 (*t*, $J = 10$, arom.); 127.9 (*t*, $J = 20$, arom.); 129.5 (arom.); 131.9 (arom.); 133.9 (arom.); 148.4 (*t*, $J = 10$, arom.); 162.8 (*s*, Pd–*C*N); 164.4 (*s*, *C*=O). ^{31}P-NMR ($CDCl_3$) = 71.0. We have been unable to obtain a satisfactory elemental analysis of compound **8**, presumably due to loss of isonitrile ligand under high vacuum conditions.

Typical Catalytic Experiment for Aldol Condensation: A 20-ml vial was charged sequentially with [[PCP]Pd(OH_2)][BF_4] (**6a**) (0.016 mmol, 1 mol-%), 5 ml of CH_2Cl_2 (distilled from CaH_2), isonitrile (145 µl, 1.60 mmol, 100 mol-%), benzaldehyde (162 µl, 1.59 mmol, 100 mol-%, *Hünig*'s base (28 µl, 0.16 mmol, 10 mol-%), and mesitylene (223 µl, 1.60 mmol, 100 mol-%). The reaction was monitored by occasionally removing a 100-µl aliquot, evaporation of the volatiles under a slow stream of N_2, and dissolution in $CDCl_3$ for NMR spectroscopy.

REFERENCES

[1] C. L. Moulton, B. L. Shaw, *J. Chem. Soc., Dalton Trans.* **1976**, 1020.

[2] a) M. Rietveld, D. M. Grove, G. van Koten, *New J. Chem.* **1997**, *21*, 751; b) G. van Koten, *Pure Appl. Chem.* **1989**, *61*, 1681.

[3] F. Gorla, L. M. Venanzi, A. Albinati, *Organometallics* **1994**, *13*, 43.

[4] M. Ohff, A. Ohff, M. E. van der Boom, D. Milstein, *J. Am. Chem. Soc.* **1997**, *119*, 11697.

[5] a) D. M. Grove, G. van Koten, A. H. M. Verschuuren, *J. Mol. Catal.* **1988**, *45*, 169; b) D. M. Grove, A. H. M. Verschuuren, G. van Koten, J. A. M. van Beek, *J. Organomet. Chem.* **1989**, *372*, C1; c) A. Kleij, R. A. Gossage, R. J. M. Klein Gebbink, N. Brinkmann, E. J. Reijerse, U. Kragl, M. Lutz, A. L. Spek, G. van Koten, *J. Am. Chem. Soc.* **2000**, *122*, 12112.

[6] M. Gupta, C. Hagen, R. J. Flescher, W. C. Kaska, C. M. Jensen, *Chem. Commun.* **1996**, 2083; M. Gupta, W. C. Kaska, C. M. Jensen, *Chem. Commun.* **1997**, 461; W. W. Xu, G. P. Rosini, M. Gupta, C. M. Jensen, W. C. Kaska, K. Krogh-Jespersen, A. S. Goldman, *Chem. Commun.* **1997**, 2273; F. Liu, E. B. Pak, B. Singh, C. M. Jensen, A. S. Goldman, *J. Am. Chem. Soc.* **1999**, *121*, 4086.

[7] P. Dani, T. Karlen, R. A. Gossage, S. Gladiali, G. van Koten, *Angew. Chem., Int. Ed.* **2000**, *39*, 743.

[8] B. Rybtchinski, D. Milstein, *Angew. Chem., Int. Ed*. **1999**, *38*, 870; M. Kanzelberger, B. Singh, M. Czerw, K. Krogh-Jespersen, A. S. Goldman, *J. Am. Chem. Soc*. **2000**, *122*, 11017.
[9] J. W. J. Knapen, A. W. van der Made, J. C. de Wilde, P. W. N. M. van Leeuwen, P. Wijkens, D. M. Grove, G. van Koten, *Nature* **1994**, *372*, 659; R. A. Gossage, L. A. van de Kuil, G. van Koten, *Acc. Chem. Res.* **1998**, *31*, 423.
[10] H. P. Dijkstra, P. Steenwinkel, D. M. Grove, M. Lutz, A. L. Spek, G. van Koten, *Angew. Chem., Int. Ed*. **1999**, *38*, 2186; H. P. Dijkstra, M. D. Meijer, J. Patel, R. Kreiter, G. P. M. van Klink, M. Lutz, A. L. Spek, A. J. Canty, G. van Koten, *Organometallics* **2001**, *20*, 3159.
[11] L. A. van de Kuil, D. M. Grove, J. W. Zwikker, L. W. Jenneskens, W. Drenth, G. van Koten, *Chem. Mater*. **1994**, *6*, 1675.
[12] M. D. Meijer, N. Ronde, D. Vogt, G. P. M. van Klink, G. van Koten, *Organometallics* **2001**, *20*, 3993.
[13] C. Patmamanoharan, P. Wijkens, D. M. Grove, A. P. Philipse, *Langmuir* **1996**, *12*, 4372; C. Bezemer, R. J. M. Klein Gebbink, G. van Koten, submitted for publication.
[14] a) F. Gorla, T. Togni, L. M. Venanzi, A. Albertini, F. Lianza, *Organometallics* **1994**, *13*, 1607; b) J. M. Longmire, X. Zhang, M. Shang, *Organometallics* **1998**, *17*, 4374; c) M. A. Stark, G. Jones, C. J. Richards, *Organometallics* **2000**, *19*, 1282; d) M. Gerisch, J. R. Krumper, R. G. Bergman, T. D. Tilley, *J. Am. Chem. Soc*. **2001**, *123*, 5818.
[15] Y. Ito, M. Sawamura, T. Hayashi, *J. Am. Chem. Soc*. **1986**, *108*, 6405.
[16] A. Togni, S. D. Pastor, *J. Org. Chem*. **1990**, *55*, 1649.
[17] R. Nesper, P. S. Pregosin, K. Püntener, M. Wörle, *Helv. Chim. Acta* **1993**, *76*, 2239; R. Nesper, P. S. Pregosin, K. Püntener, M. Wörle, A. Albinati, *J. Organomet. Chem*. **1996**, *507*, 85.
[18] P. Dani, M. Albrecht, G. P. M. van Klink, G. van Koten, *Organometallics* **2000**, *19*, 4468.
[19] R. Giménez, T. M. Swager, *J. Mol. Catal.*, *A* **2001**, *166*, 265.
[20] T. Imamoto, T. Oshiki, T. Onozawa, T. Kusomoto, K. Sato, *J. Am. Chem. Soc*. **1990**, *112*, 5244.
[21] B. Wolfe, T. Livinghouse, *J. Am. Chem. Soc*. **1998**, *120*, 5116.
[22] R. D. Baechler, K. Mislow, *J. Am. Chem. Soc*. **1970**, *92*, 3090.
[23] A. J. Canty, J. Patel, B. W. Skelton, A. H. White, *J. Organomet. Chem*. **2000**, *599*, 195.
[24] R. J. Cross, A. R. Kennedy, K. W. Muir, *J. Organomet. Chem*. **1995**, *487*, 227.
[25] L. A. van de Kuil, H. Luitjes, D. M. Grove, J. W. Zwikker, J. G. M. van der Linden, A. M. Roelofsen, L. W. Jenneskens, W. Drenth, G. van Koten, *Organometallics* **1994**, *13*, 468.
[26] P. T. Beurskens, G. Admiraal, G. Beurskens, W. P. Bosman, S. Garcia-Granda, R. O. Gould, J. M. M. Smits, C. Smykalla, DIRDIF 97 program system, 'Technical Report of the Crystallography Laboratory', University of Nijmegen, The Netherlands, 1997.
[27] G. M. Sheldrick, SHELXL-97 program for crystal-structure refinement, University of Göttingen, Germany, 1997.
[28] A. L. Spek, PLATON, multipurpose crystallographic tool, Utrecht University, The Netherlands, 2000.
[29] H. D. Flack, *Acta Crystallogr., Sect. A* **1983**, *39*, 876.

Received August 29, 2001