Synthesis and Structure of Enantiomerically Pure Platinum Complexes of Phosphino-oxazolines and Their Use in Asymmetric Catalysis

A. John Blacker,[†] Matthew L. Clarke,[‡] Michael S. Loft,[§] Mary F. Mahon,[‡] and Jonathan M. J. Williams*[,‡]

Zeneca, Huddersfield Works, Leeds Road, Huddersfield HD2 1FF, U.K., Department of Chemistry, University of Bath, Claverton Down, Bath BA2 7AY, U.K., and Glaxo-Wellcome, DC1, Temple Hill, Dartford DA1 5AH, U.K.

Received March 15, 1999

Novel organoplatinum complexes of the enantiomerically pure P, N ligand, (4*S*)-2-(2-(diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline, have been synthesized and shown to act as Lewis acids. These complexes consist of the bidentate P, N ligand, an achiral organic ligand, and a solvent ligand that can be readily displaced by organic substrates. The solvent ligand is situated cis to the nitrogen donor and, as such, is in a "chiral pocket" created by the oxazoline ring. The complexes are readily prepared from the well-known, and versatile, precursors (COD)PtR_2 and are obtained as single isomers. Two of the complexes have had their structures elucidated by X-ray crystallography. The cationic complexes were shown to be enantioselective catalysts in the Michael reaction of α-cyano carboxylates with methyl vinyl ketone.

Introduction

The use of enantiomerically pure metal complexes in catalysis is widespread and of considerable importance.[1] There are now many examples of metal catalyzed reactions which provide very high selectivity. The majority of these reactions utilize substrates which can chelate to the metal center.[2] If a substrate chelates to a metal center, it cannot rotate freely, thus making the job of the chiral ligands that bit easier. Substrates that contain only one donor group are more challenging, and consequently there are fewer examples of successful asymmetric reactions in the literature.

To address this problem, several research groups have prepared C_2 symmetric, tridentate chiral ligands such as the "pybox" ligands in Figure 1.[3] These ligands have seen use in a number of asymmetric reactions, with varying degrees of success.[4] As a rationale for their selectivity, the vacant coordination site can be described as being at the center of a grid, in which two quadrants are blocked off by the chiral ligand (Figure 1). This controls the position of the coordinated substrate and/or the approach of the incoming reactant.

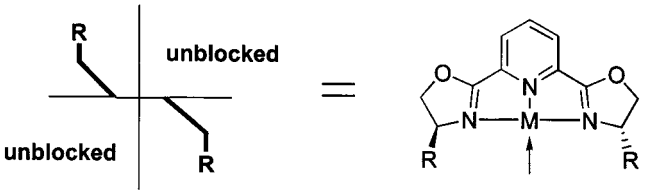


Figure 1.

As an alternative to this, we wanted to study complexes which had three out of four quadrants blocked out by the ligand architecture. We considered the use of cationic platinum complexes containing an enantiopure phosphinooxazoline ligand and an achiral, organic ligand as potential catalysts.

Organoplatinum complexes of enantiopure diphosphines have already been shown to be catalysts for enantioselective epoxidation of unfunctionalized alkenes.[5] We envisaged that complexes of this type would provide a highly controlled environment around the vacant coordination site, perhaps similar to that shown in the schematic of Figure 2. It was thought in particular that complexes of this shape might provide the ideal chiral environment for a terminal alkene.

As there are many readily available organoplatinum precursors to the desired compounds, an advantage to this design is the potential for easy modification of the

[†] Zeneca Huddersfield Works.
[‡] University of Bath.
[§] Glaxo-Wellcome.

(1) (a) Ojima, I. *Catalytic asymmetric syntheses*; VCH Publishers: New York, 1993. (b) Narasaka, K. *Synthesis* **1991**, 1.

(2) For some examples, see: (a) Evans, D. A.; Burgey, C. S.; Paras, N. A.; Vojkovsky, T.; Tregay, S. A. *J. Am. Chem. Soc.* **1998**, *120*, 5824. (b) Evans, D. A.; Murry, J. A.; Koxloski, M. C.; *J. Am. Chem. Soc.* **1996**, *118*, 5814. (c) Corey, E. J.; Ishihara, K. *Tetrahedron Lett.* **1992**, *33*, 6807. (d) Brown, J. M. *Chem. Br.* **1989**, 276. (e) Koenig, K. E. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic: New York, 1985; Vol. 5, p 71. (f) Halpern, J. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic: New York, 1985; Vol. 5, p 41. (g) Hayashi, T.; Kawamura, N.; Ito, Y. *J. Am. Chem. Soc.* **1987**, *109*, 7876.

(3) Nishiyama, H.; Kondo, M.; Nakamura, T.; Itoh, K. *Organometallics* **1991**, *10*, 500.

(4) (a) Hydrosilation: see ref 4. (b) Diels Alder: Evans, D. A.; Murry, J. A.; Von Matt, P.; Norcross, R. D.; Miller, S. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 798. (c) Mukaiyama Aldol reaction: Evans, D. A.; Murry, J. A.; Kozlowski, M. C. *J. Am. Chem. Soc.* **1996**, *118*, 5814. (d) Cyclopropanation: Gupta, A. D.; Bhuniya, D.; Singh, V. K. *Tetrahedron* **1994**, *50*, 13725. (e) Nishiyama, H.; Itoh, Y.; Matsumoto, H.; Park, B. B.; Itoh, K. *J. Am. Chem. Soc.* **1994**, *116*, 2223. (f) Aldol reaction of isocyanoacetates: *J. Organomet. Chem.* **1996**, *507*, 85.

(5) (a) Zanardo, A.; Michelin, R. A.; Pinna, F.; Strukul, G. *Inorg. Chem*, **1988**, *27*, 1966. (b) Sinigalia, R.; Michelin, R. A.; Pinna, F.; Strukul, G.; *Organometallics* **1987**, *6*, 728.

10.1021/om990186e CCC: $18.00
Publication on Web 06/29/1999

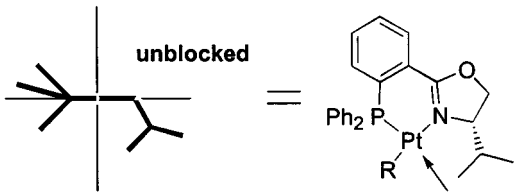
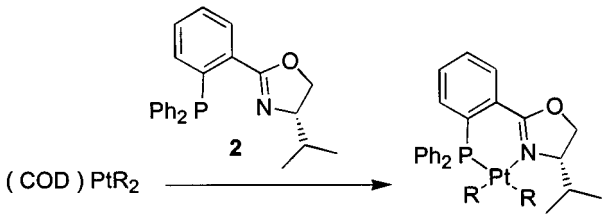


Figure 2.

Scheme 1



1a: R=Me **3a: R=Me; yield = 98%**

1b: R=Ph **3b: R=Ph; yield = 65%**

organic ligand. Complexes could be tailored to suit the electronic and steric requirements of a given reaction. Phosphinooxazoline ligands (shown in Figure 2) were chosen in particular because they direct their chirality toward the vacant coordination site and because they have given remarkable results in a range of other catalytic reactions.[6]

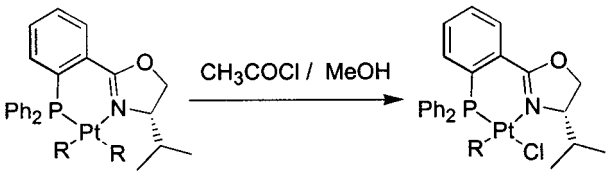
We report here on the synthesis, structure, and reactivity of several novel platinum complexes of the enantiopure ligand, (4*S*)-2-(2-(diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline (from now on abbreviated as (*S*)-P^N).

Results and Discussion

Platinum complexes of (4*S*)-2-(2-(Diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline [(*S*)-P^N]. The dimethyl and diphenyl derivatives **3a** and **3b** were prepared by ligand displacement reactions (Scheme 1) from readily available (COD)PtR_2.[7] The ^{31}P NMR spectra of these two compounds showed the characteristic small coupling constants ($^1J_{P-Pt}$ = 1972 and 1849 Hz, respectively) associated with strongly bound trans ligands.[8]

It was hoped that the selective cleavage of the Pt−C bond trans to phosphorus could be achieved. This would enable the vacant coordination site to be generated in the chiral pocket created by the oxazoline ring. Indeed, the addition of 1.1 equiv of HCl (generated by methanolysis of acetyl chloride) gives single isomers of compounds **4a** and **4b** (Scheme 2). Phosphorus−platinum coupling constants (**4a**, ^1J = 4703 Hz; **4b**, ^1J = 4637 Hz) are consistent with the chloride ligand being trans to phosphorus. This complete selectivity is easily explained as phosphines show increased trans effect (and trans influence) relative to nitrogen donors.

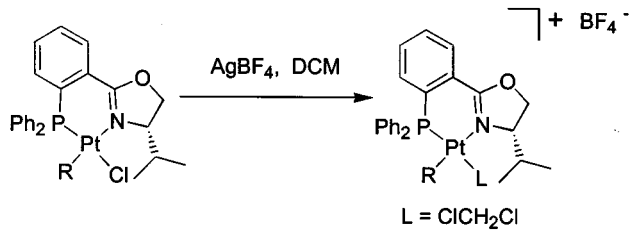
Scheme 2



3a: R=Me **4a: R=Me: yield = 81%**

3b: R=Ph **4b: R=Ph: yield = 89%**

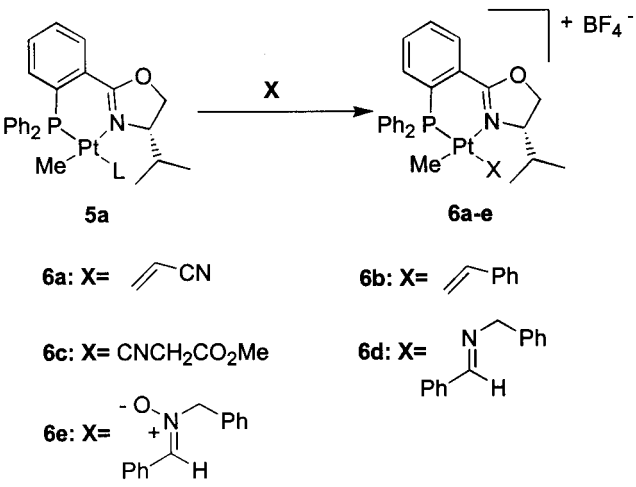
Scheme 3



4a: R=Me **5a: R=Me: yield = 78%**

4b: R=Ph **5b: R=Ph: yield = 79%**

Scheme 4



Addition of 1 equiv of $AgBF_4$ to compounds **4a** and **4b** generates the cationic compounds **5a** and **5b** (Scheme 3). ^{31}P and ^1H NMR spectroscopy of **5a** show the DCM ligand to be weakly bound, with the protons deshielded by the cationic platinum center. In the case of **5b**, the complex isolated was always impure and was therefore not fully characterized. However, the spectroscopic data obtained confirmed a number of important features: that chloride abstraction had taken place, giving a cationic compound which contained weakly bound ligands. It seems most likely that we obtained a mixture of the desired DCM solvento complex and an aquo complex.

By way of finding out more about the vacant coordination site, [(*S*)-P^N)Pt(Me)CH_2Cl_2]BF_4, (**5a**) was allowed to react with the organic ligands shown in Scheme 4. The ^{31}P and ^1H NMR spectra were then recorded, and compared to ^1H NMR spectra of the free organic substrates. The results are summarized in Table 1.

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(8) (a) Allen, F. H.; Pidcock, A. *J. Chem. Soc. A* **1968**, 2700. (b) Hopton, F. J.; Rest, A. J.; Rosevear, D. J.; Stone, F. G. A. *J. Chem. Soc. A* **1966**, 1326.

Table 1. Comparison of Selected NMR Data for Free Organic Ligands and Their Metal Complexes Formed on Addition to [(*S*)-P^N)Pt(Me)CH_2Cl_2]BF_4 (5a)

complex	δ_H (free substrate)	δ_H (coord substrate)	δ_P ($^1J_{P-Pt}$, Hz)
5a	5.30	5.5	8.47 (5255)
6a	5.66, 6.08, 6.23	6.33, 6.53, 6.71	10.21 (4746)
6b	5.90, 5.84, 5.36	no change	8.47 (5255)
6c	3.82, 4.24	3.83, br, 4.73, br	17.57 (3424)
6d	4.75, 8.32	5.04, 9.51, 10.0	11.19 (4114) 12.12 (4145)
6e	8.40	many new peaks	11.49 (4350) 4.91 (3884) 7.89 (4919) + others

When acrylonitrile was added to a solution of **5a**, a new complex formed in which the alkene protons are deshielded by the platinum cation. The smaller coupling constant, $^1J_{P-Pt}$, of the acrylonitrile complex, **6a**, when compared to the DCM complex, **5a** (4746 Hz vs 5255 Hz), reflects the stronger interaction between the platinum cation and the acrylonitrile. A similar situation arose in the case of the methyl isocyanoacetate complex, **6c**. It appears that styrene, **b**, does not interact with the platinum cation to any great extent. (It was expected that formation of an η^2 alkene compound could be detectable by both ^1H and ^{31}P NMR.) The case of the imine, **6d**, is somewhat more complicated. Quantitative formation of two new platinum complexes takes place. One of these can be assigned as the platinum−imine cation. The other compound present is suggested to be a benzylamine complex, formed by hydrolysis of the imine by adventitious water. Inspection of the ^1H NMR spectrum reveals the characteristic proton resonance of benzaldehyde. On addition of a nitrone to complex **5a**, the NMR spectra reveal a number of new platinum complexes being formed. It seems that the nitrone decomposes in the presence of the platinum cations. We therefore felt confidant that the cationic complexes would act as Lewis acids, although alkene activation did not seem likely.

Crystal Structure of Complex 3b. Single crystals of [(*S*)-P^N]$PtPh_2$ (**3b**) were obtained from DCM/petroleum ether (60/80) after standing at room temperature overnight. An ORTEP view of the structure is shown in Figure 3, along with selected bond lengths and angles in Table 2. The structure shows some deviation from idealized square planar geometry. The bite angle of the bidentate ligand N(1)−Pt(1)−P(1) is 85.7(3)°. In the crystal structure of [(*S*)-P^N]$PtCl_2$ (to be discussed elsewhere), this bite angle is 90°.

This contraction probably opens out the coordination sphere to accommodate the two phenyl ligands. The angle between the diphenylphosphino moiety and the phenyl group coordinated cis to it [C(22)−Pt(1)−P(1) = 96.8(4)°] is large, hence reducing interactions between phosphino−aryl and platinum−aryl rings. This is not the case with the phenyl ring cis to the oxazoline moiety; C(28) and N(1) are relatively close together [C(28)−Pt(1)−N(1) = 88.6(4)°]. This is possible because the phenyl ring relieves any steric clashes by orientating itself above the plane of the molecule [C(28)−Pt(1)−P(1) = 171.8(4)°] [with respect to the isopropyl group C(34)−C(35)−C(36)].

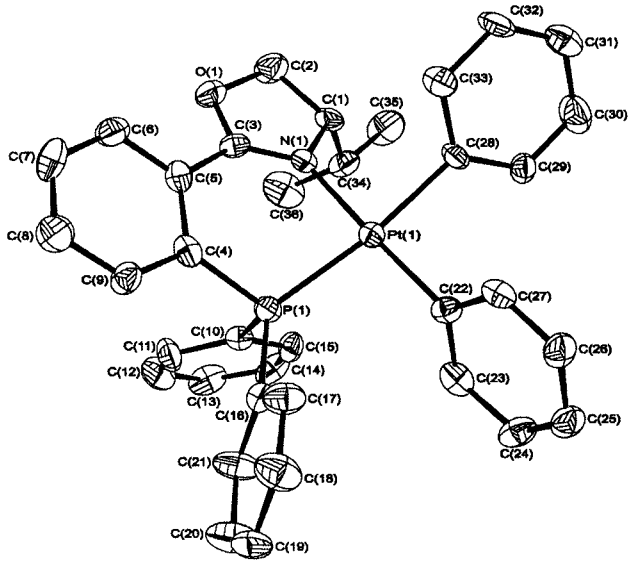


Figure 3. Molecular structure of **3b**.

Table 2. Selected Bond Lengths (Å) and Angles (deg) for [(*S*)-P^N]$PtPh_2$ (3b)

Pt−C(22)	2.006(13)	N(1)−C(3)	1.30(2)
Pt−C(28)	2.050(12)	N(1)−C(1)	1.49(2)
Pt−N(1)	2.086(11)	O(1)−C(3)	1.36(2)
Pt−P(1)	2.289(3)	O(1)−C(2)	1.45(2)
P(1)−C(4)	1.813(14)	C(1)−C(34)	1.51(2)
P(1)−C(16)	1.824(14)	C(1)−C(2)	1.52(2)
P(1)−C(10)	1.825(11)	C(3)−C(5)	1.47(2)
C(10)−P(1)−Pt	116.5(4)	N(1)−C(1)−C(2)	102.8(12)
C(3)−N(1)−C(1)	107.6(12)	C(34)−C(1)−C(2)	114.0(14)
C(3)−N(1)−Pt	129.6(10)	O(1)−C(2)−C(1)	104.7(12)
C(1)−N(1)−Pt	122.8(8)	N(1)−C(3)−O(1)	115.6(13)
C(3)−O(1)−C(2)	107.0(11)	N(1)−C(3)−C(5)	128.3(13)
N(1)−C(1)−C(34)	112.2(11)	O(1)−C(3)−C(5)	116.1(12)

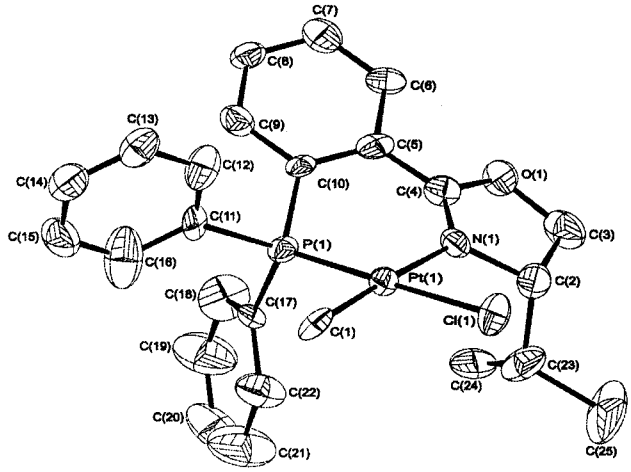


Figure 4. Molecular structure of **4a**.

This significant deviation is a manifestation of the chiral center at C(1) and is one of several effects throughout the structure brought about by this single chiral carbon atom; the ligand and platinum form a six-membered chelate ring which is puckered, with all three carbon atoms residing above the plane of the complex.

As has been found with a crystal structure of a palladium complex of this ligand,[9] the phenyl groups from the diphenylphosphino moiety adopt a face-on/

(9) Sprinz, J.; Kiefer, M.; Helmchen, G.; Reggelin, M.; Huttner, G.; Walter, O.; Zsolnai, L. *Tetrahedron Lett.* **1994**, *35*, 1523.

Table 3. Selected Bond Lengths (Å) and Angles (deg) for [(*S*)-P^N]Pt(Me)Cl (4a)

Pt−C(1)	2.12(2)	P(1)−C(10)	1.80(2)
Pt−N(1)	2.13(2)	P(1)−C(11)	1.85(2)
Pt−P(1)	2.181(4)	N(1)−C(4)	1.28(3)
Pt−Cl(1)	2.352(5)	N(1)−C(2)	1.55(3)
P−C(17)	1.792(14)		
C(1)−Pt−N(1)	177.3(7)	P(1)−Pt−Cl(1)	178.4(8)
C(1)−Pt−P(1)	94.1(7)	C(17)−P(1)−Pt	115.8(5)
N(1)−Pt−P(1)	87.8(7)	C(10)−P(1)−Pt	112.1(6)
C(1)−Pt−Cl(1)	87.5(7)	C(11)−P(1)−Pt	115.7(9)
N(1)−Pt−Cl(1)	90.7(7)		

edge-on conformation. (The edge-on phenyl group is below the plane of the complex.) This ligand can therefore transmit chiral information from both sides of the ligand.

Crystal Structure of Complex 4a. Single crystals of {(4*S*)-2-(2-(diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline}chloro(methyl)platinum(II) (**4a**) were grown from DCM/petrol (60/80). However, as revealed by elemental analyses and the electron density map from the diffraction experiments, the crystals contained petroleum ether. These disordered solvent molecules hampered the solution of the structure (further details are described in the experimental section).

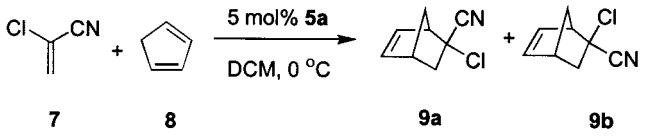
As a result of this, the structural parameters have relatively large standard deviations. Although no quantitative data can be obtained from the bond lengths, the overall structural features are not invalidated (Table 3).

The structure does confirm NMR data which assigned the chlorine atom as being trans to the phosphorus atom. The conformation of the phosphinooxazoline ligand is very similar to that in the diphenyl complex, allthough the bite angle of the ligand is slightly larger [N(1)−Pt(1)−P(1) = 87.8(7)°]. The complex shows less deviation from square planar geometry compared to complex **3b**. The chlorine atom is not forced up and away from the isopropyl group [P(1)−Pt(1)−Cl(1) = 178.4(8)°], and the methyl and chlorine groups do not push each other apart [C(1)−Pt(1)−Cl(1) = 87.5(7)°]. The structure does show the bulk features outlined in Figure 2: The achiral organic ligand and the chiral oxazoline are situated as desired and should exert an influence at this site.

Enantioselective Catalysis. The complexes **5a** and **5b** were tested as catalysts for enantioselective epoxidation of terminal alkenes (using HO_2Na or H_2O_2 as oxidant),[5] and in the 1,3-dipolar cycloaddition of terminal alkenes,[10] but sadly did not show any activity. As the complexes definitely did bind, and withdrew electron density from, nitrile functionalities, we tested the catalysts in the reactions below.

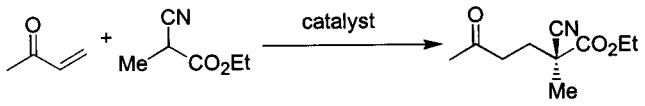
An enantioselective version of the Diels−Alder reaction of acrylonitrile derivatives would be a very useful process, as the nitrile group is readily transformed into other functionalities. In the case of substrate **7**, the cyano and chloro groups can be simply converted to a carbonyl group, and it therefore acts as a useful ketene equivalent.[11]

Scheme 5



7 8 9a 9b

Scheme 6



10 11 12

We found that 5 mol % of complex **5a** would catalyze the reaction shown to give high conversion to **9a** and **9b** as a 7:1 mixture of endo and exo isomers (Scheme 5). NMR spectroscopy reveals that the endo-2-chloro isomer is favored (as is the case with the uncatalyzed reaction (4:1 mixture).[11c] The enantioselectivity of the process could be estimated by GC[12] and was always found to be low (ca. 10% enantiomeric excess (ee)) under a variety of conditions. As a result of this, no further testing was carried out. This is the first time, to the best of our knowledge, that the use of an enantiopure Lewis acid has been evaluated in this reaction and the first instance of platinum catalyzing a reaction of this type. Clearly further studies are required.

The cationic complexes were then tested as catalysts in the asymmetric Michael reaction of α-cyano carboxylates (Scheme 6). This reaction was first studied by Ito and co-workers.[13] They found that in the presence of 1 mol % of $Rh(H)CO(PPh_3)_3$ and an enantiopure, trans chelating ligand high yields and high enantioselectivities (81% ee for the substrate shown) were achieved. The high selectivities obtained using their ligand were in contrast to those obtained using "standard" chiral diphosphines. It has also been shown that this reaction proceeds in the presence of a palladium catalyst and a catalytic amount of base to give the desired product (74% yield; 34% ee).[14] We wished to find out if organoplatinum cations would catalyze this reaction.

We were pleased to find that the methyl substituted platinum compound **5a** was quite a good catalyst, 1 mol % of **5a** giving essentially complete conversion (by thin layer chromatography (TLC)) in 16 h. Enantioselectivity, however, is rather low. Changing the solvent to toluene gave a small increase in ee. The results obtained are shown in Table 4. In contrast, the phenyl substituted compound **5b** was a much less active catalyst, with the reactions still not reaching completion even after long reaction times. This catalyst was also less enantioselective (17% ee vs 25% ee). Although the ee's obtained are relatively poor, they do suggest that changing the achiral, organic substituent could be used

(10) (a) Brunig, I.; Grashey, R.; Hauck, H.; Huisgen, R.; Seidl, H. *Org. Synth.* **1973**, 5, 1124. (b) Gothelf, K. V.; Jorgensen, K. A. *Chem. Rev.* **1998**, *98*, 863.

(11) (a) Freeman, P. K.; Balls, D. M.; Brown, D. J. *J. Org. Chem.* **1968**, *33*, 2211. (b) Evans, D. A.; Scott, W. L.; Truesdale, L. K. *Tetrahedron Lett.* **1972**, *2*, 121. (c) Yates, P.; Kronus, J. D. *Can. J. Chem.* **1984**, *62*, 1751.

(12) Determined by GC using a Supelco BETA-DEX 120 fused silica capilliary column. Conditions were set up such that both starting material and endo and exo isomers of the product could be detected. Another injection under modified conditions allowed the detection of both enantiomers of the major isomer, allthough full base-line resolution could not be obtained.

(13) Sawamura, M.; Hamashima, H.; Ito, Y. *Tetrahedron* **1994**, *50*, 4439.

(14) Stark, M. A.; Richards, C. J. *Tetrahedron Lett.* **1997**, *38*, 5881.

Table 4. Asymmetric Michael Reaction of 10 and 11 Using the New Platinum Complexes as Catalysts

catalyst[a]	solvent	reacn time (h)	yield[b]	e.e.[c] (configuration)[d]
5a (5 mol %)	DCM	16	88%	16% (*R*)
5a	DCM	40	78%	17% (*R*)
5a	toluene	16	81%	23% (*R*)
5a[e]	toluene	16	84%	25% (*R*)
5b	DCM	23	56%	17% (*R*)
5b	toluene	55	56%	17% (*R*)

[a] All reactions, ran at 20 °C using 1 mol % Pt catalyst, 10 mol % $^{i}Pr_2EtN$, 1 equiv of nitrile, 1.5 equiv of methyl vinyl ketone (unless described otherwise). [b] Isolated yields by column chromatography. [c] Determined by HPLC using Chiracel OD column. [d] Determined by optical rotation. [e] Methyl vinyl ketone added as a solution in 3 mL of toluene via a syringe pump over 10 h.

to fine tune the catalyst structure, without the need to prepare alternative enantiomerically pure ligands.

Conclusions and Further Work

The synthesis of several new organoplatinum complexes of the enantiopure P, N ligand (4*S*)-2-(2-(diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline has been achieved. Crystal structure studies, along with spectroscopic evidence, have shown the complexes to have the desired shape and coordination environment. They show Lewis acidity to nitrile functionalities and are, to the best of our knowledge, the first platinum complexes to be shown to catalyze the reactions described.

Although no highly enantioselective reactions have been realized, the design of the complexes is such that new derivatives could be prepared using similar syntheses to those described here.

Experimental Section

General Procedures. All reactions were carried out under an atmosphere of nitrogen, while all work up and purification procedures were carried out in air, unless stated otherwise. Solvents were of HPLC grade and were used as received unless otherwise stated. Where a solvent is described as dry, it was freshly distilled from an appropiate drying agent. Elemental analyses were conducted on a Carbo Erba Stametazione EA1506 Analyzer. ^1H, ^{13}C, and ^{31}P NMR spectra were recorded using a JEOL GX400 instrument. Crystal structures were obtained using a CAD 4 automatic four circle diffractometer. Commercially available reagents were used without any purification. $(COD)PtI_2$, $(COD)PtMe_2$, $(COD)PtPh_2$,[7] and (4*S*)-2-(2-(diphenylphosphino)phenyl)-4-isopropyl-1,3-oxazoline[15] were prepared as described in the literature.

[(*S*)-P^N] $PtMe_2$, (3a). A solution of ligand **2** (196 mg, 0.584 mmol) in dry toluene (6 mL) was slowly added over 6 h to a stirred solution of dimethyl(1,5-cyclooctadiene)platinum(II) (218 mg, 0.584 mmol) in dry toluene (6 mL) at 50 °C. The reaction was stirred at 50 °C for a further 10 h after addition was complete.

The reaction was then cooled to room temperature, and the solvent and most of the cyclooctadiene are removed in vacuo at 40 °C. The yellow crystals that have formed are washed with cold abs. EtOH, (2 × 4 mL) using a syringe. The washed crystals are dissolved in DCM, filtered, and dried in vacuo (yield: 0.346 g, 0.578 mmol, 98%). Anal. Calcd for $C_{26}H_{30}NOPPt$: C, 52.17; H, 5.05; N, 2.34. Found: C, 52.19; H, 5.03; N, 2.16. $[\alpha]_D^{20} = +143.1°$ ($c = 1.16$, $CHCl_3$). IR (υ_{max}/cm^{-1}) 1622, 1435, 1366, 1237, 1105, 1098, 1055, 747, 695. ^{31}P NMR (161.7MHz; $CDCl_3$): δ 21.294 ($^1J_{P-Pt} = 1972$ Hz). ^1H NMR (400 MHz; $CDCl_3$): δ 0.04 (3H, d, $^3J = 7.0$ Hz, $[CH(CH_3)_2]$), 0.51 (3H, d, $^3J_{H-P} = 7.63$ Hz, $^2J_{H-Pt} = 87.14$ Hz, $[CH_3-Pt-N]$), 0.61 (3H, d, $^3J_{H-P} = 7.63$ Hz, $^2J_{H-Pt} = 68.1$ Hz, $[CH_3-Pt-P]$), 0.82 (3H, d, $^3J = 7.3$ Hz, $[CH(CH_3)_2]$), 2.5 (1H, m, $[CH(CH_3)_2]$), 4.24 (2H, m, $[CH_2O]$), 4.88 (1H, m, [*CH*N]), 6.9−8.0 (14 H, m, Ar*H*).

[(*S*)-P^N] $PtPh_2$ (3b). To a stirred solution of diphenyl-(1,5-cyclooctadiene)platinum(II), (0.609 g, 1.33 mmol) in dry toluene (40 mL) was added a toluene solution of [(*S*)-P^N] (0.493 g, 1.32 mmol in 9.2 mL of solvent) over a period of 12 h via a syringe pump. This was left stirring 16 h to yield a clear yellow solution. Solvent was removed in vacuo to give a yellow slurry.

This was then dissolved in the minimum amount of DCM. Petrol (60/80) was added until the solution started to go cloudy. This was left to crystallize into yellow prisms suitable for a crystal structure determination (yield: 617 mg, 0.854 mmol, 65%). (Anal. Calcd for $C_{36}H_{34}NOPPt$: C, 59.8; H, 4.74; N, 1.94. Found: C, 59.6; H, 4.76; N, 1.92. $[\alpha]_D^{20} = +22.6°$ ($c = 2.35$, $CHCl_3$). IR (υ_{max}/cm^{-1}): 3046, 1634, 1570, 1248, 1097, 1055, 1024, 955, 739, 694. ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 18.23 ($^1J_{P-Pt} = 1849$). ^1H NMR (400 MHz; $CDCl_3$): δ 0.27 (3H, d, $J = 7$ Hz, CH_3), 0.71 (3H, d, $J = 7$ Hz, CH_3), 2.65 (1H, m, $CH(CH_3)_2$), 4.20 (1H, m, *CH*N), 4.40 (2H, m, CH_2O), 6.75 (3H, m, Ar*H*), 7.10 (1H, m, Ar*H*), 7.2−7.9 (17H, m, Ar*H*), 8.05 (2H, m, Ar*H*), 8.35 (1H, m, Ar*H*).

[(*S*)-P^N] Pt(Me)Cl (4a). To a stirred solution of [(*S*)-P^N] $PtMe_2$ (**3a**) (0.320 g, 0.535 mmol) in dry methanol (2.3 mL) and dry DCM (3.5 mL) was added acetyl chloride (0.040 mL, 0.044 g, 0.562 mmol). This is stirred for 2 h. The volume of solvent was then reduced to ca. 0.3 mL in vacuo. The yellow precipitate was washed with hexane (2 × 1 mL) and collected using a Buchner funnel. This powder was then dissolved in DCM and filtered. Solvent was then removed from the filtrate and the yellow powder dried in vacuo to give the desired product (yield: 0.268 g, 0.433 mmol, 81%). Recrystallization from DCM/petroleum ether gives crystals suitable for X-ray diffraction. These single crystals contained some residual petroleum, as revealed by analysis and the X-ray study. Anal. Calcd for $C_{25}H_{27}ClNOPPt$: C, 48.51; H, 4.40; N, 2.26. Found: C, 45.7; H, 4.21; N, 2.14. A week later these crystals collapsed to a yellow powder, which was almost analytically pure. Found: C, 47.9; H, 4.35; N, 2.24. $[\alpha]_D^{20} = +123°$. IR (υ_{max}/cm^{-1}): 1733, 1628, 1242, 1100, 953, 730, 696. ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 12.71 ($^1J_{P-Pt} = 4702.5$ Hz). ^1H NMR (400 MHz; $CDCl_3$): δ 0.07 (3H, d, $^3J = 6.7$ Hz, $[CH(CH_3)_2]$), 0.52 3H, d, $^3J_{H-P} = 3.4$ Hz, $^2J_{H-Pt} = 72.6$ Hz, (CH_3-Pt-N)), 0.83 (3H, d, $^3J = 7.3$ Hz, $[CH(CH_3)_2]$), 2.74 (1H, m, $(CH(CH_3)_2)$), 4.45 (2H, m, (CH_2O)), 5.50 (1H, m, (*CH*N)), 7.0−8.3 (14H, m, Ar*H*).

[(*S*)-P^N] Pt(Ph)Cl (4b). To a stirred solution of [(*S*)-P^N] $PtPh_2$ (**3b**) (0.178 g, 0.246 mmol) in dry methanol (1.3 mL) and dry DCM (2.5 mL) was added acetyl chloride (0.019 mL, 0.266 mmol). This was stirred for 30 min. The resultant pale yellow solution was filtered. The filtate had solvent removed and was dried under high vacumn (yield: 150 mg, 0.202 mmol, 89%). Anal. Calcd for $C_{30}ClH_{29}NOPPt$: C, 52.9; H, 4.29; N, 2.06. Found: C, 53.1; H, 4.65; N, 1.83. $[\alpha]_D^{20} = +51.4°$ ($c = 1.4$, $CHCl_3$). IR (υ_{max}/cm^{-1}): 1734, 1625, 1570, 1243, 1099, 730, 694. ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 8.1 ($^1J_{P-Pt} = 4637$ Hz). ^1H NMR (400 MHz, $CDCl_3$): δ 0.11 (3H, d, $J = 6.7$, $CH(CH_3)_2$), 0.70 (3H, d, $J = 6.7$, $CH(CH_3)_2$), 2.5 (1H, m, $CH(CH_3)_2$), 4.22 (2H, m, CH_2O), 5.55 (1H, m, *CH*N), 6.35 (3H, m, Ar*H*), 6.73 (2H, m, Ar*H*), 6.80−7.5 (11H, m, Ar*H*), 7.70 (2H, m, Ar*H*), 7.95 (1H, m, Ar*H*).

[((*S*)-P^N)Pt(Me)CH_2Cl_2] BF_4 (5a). To a stirred solution of [(*S*)-P^N] Pt(Me)Cl (**4a**) (0.176 g, 0.285 mmol) in dry DCM was added silver tetrafluoroborate, (0.056 g, 0.287 mmol) in one portion. The flask was then flushed with nitrogen and stirred in the dark for an hour. The resulting suspension was then filtered under nitrogen using a filter cannula. The

(15) Allen, J. V.; Dawson, G. J.; Frost, C. G.; Williams, J. M. J.; Coote, S. J. *Tetrahedron* **1994**, *50*, 799.

solution obtained had the solvent removed and was dried under high vacumn (yield: 0.167 g, 0.221 mmol, 78%). Anal. $C_{26}H_{29}BCl_2F_4NOPPt$: C, 41.37; H, 3.88; N, 1.86. Found: C, 41.9; H, 4.20; N, 1.87. $[\alpha]_D^{20} = 80.0°$ ($c = 1.56$, $CHCl_3$). IR (υ_{max}/cm^{-1}): 3363, 2287, 1631, 1584, 1567, 1258, 1101, 1063, 998, 955, 732, 693. ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 8.46 ($^1J_{P-Pt}$ = 5263 Hz). ^{1}H NMR (400 MHz; $CDCl_3$): δ 0.20 (3H, d, ^3J = 6.7 Hz, [CH*Me*$_2$]), 0.341 (3H, s, ^2J = 63.2 Hz, [C*H*$_3$−Pt−P]), 0.80 (3H, d, ^3J = 7.0 Hz, [CH*Me*$_2$]), 2.32 (1H, m, [C*H*Me$_2$]), 4.34 (1H, dd, ^3J = 9.0 Hz, 4.3 Hz, [C*H*O]), 4.60 (t, ^3J = 9.0 Hz, [C*H*O]), 4.80 (1H, m, [C*H*N]), 5.61 (s, br, 2H, [coord DCM]), 7.0−8.2 (14H, m, [Ar*H*]).

[((*S*)-P^N) Pt(Ph)CH$_2$Cl$_2$] BF$_4$ (5b). To a stirred solution of [(*S*)-P^N] Pt(Ph)Cl (0.119 g, 0.175 mmol) in dry DCM (6 mL) was added silver tetrafluoroborate (0.034 g, 0.175 mmol) in one portion. The flask was then flushed with nitrogen and stirred in the dark for an hour. The resulting suspension was then filtered through a pad of Celite. The solution obtained had the solvent removed and was dried under high vacumn (yield: 0.113 g, 0.138 mmol, 79%). MS (FAB): 645.1647 (M − BF_4·CH_2Cl_2)$^+$ req.s 645.1634. ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 3.89 (^1J = 5198 Hz)). ^{1}H NMR (400 MHz; $CDCl_3$): δ 0.34 (3H, d, ^3J = 6.7 Hz, [CH*Me*$_2$]), 0.85 (3H, d, ^3J = 6.9 Hz, [CH*Me*$_2$]), 2.33 (1H, m, [C*H*Me$_2$]), 4.40 (1H, m, [C*H*O]), 4.78 (2H, m, [C*H*O and C*H*N]), 5.8 (1H, br, s, [coord DCM?]), 6.6−8.4 (ArH).

Impurities (c. 30% wrt major product): ^{31}P NMR (161.7 MHz; $CDCl_3$): δ 5.14 (^1J = 5075 Hz)). ^{1}H NMR (400 MHz; $CDCl_3$): δ 0.10 (d, 6.7 Hz), 0.74 (d, 6.7 Hz), 1.70 (s, br), 2.46 (m), 4.03 (m), 4.35 (m), 6.4−8.2 (m, ArH).

General Procedure for Compounds 6a−e. To a flask containing **5a** (10 mg, 0.013 mmol) was added a solution of organic ligands **a**−**e** (0.016 mmol, 1.2 equiv in 0.5 mL of $CDCl_3$). The resulting solution was then added via a syringe to an NMR tube and the NMR spectrum measured. Selected resonances are noted in Table 3.

General Procedure for Diels−Alder Reactions. To an evacuated round-bottomed flask containing **5a** (25 mg, 0.0331 mmol) and a stirring bead was added DCM (2.5 mL) and 2-chloroacrylonitrile (58 mg, 0.662 mmol). This flask was then flushed with nitrogen. Cyclopentadiene (0.220 g, 3.31 mmol) was then added. This reaction vessel was then stirred at a given temperature (25, 0, or −15 °C) until the reaction had gone to completion. The progress of the reaction was followed by GC. The ENDO/EXO ratio and the enantioselectivity were also determined by GC.[12] When the reaction was complete, DCM (4 mL) was added, and the reaction mixture was filtered through a pad of silica. The resultant solution had its solvent removed to give a colorless oil which solidified on standing. The major isomer was identified as *endo*-2-chlorobicyclo[2.2.1]-hept-5-ene-2-(*exo*)-carbonitrile by comparison of its NMR spectra with the literature.[11c] MS (CI$^+$): 154.0 (MH$^+$). ^{1}H NMR (400 MHz) (major *endo*-2-chloro isomer): δ 1.70 (1H, dd, ^3J = 13.1, 3.1 Hz, [HC*H*CCN]), 1.71 (2H, br, s, [C*H*$_2$]), 2,70 (1H, dd, ^3J = 13.1, 3.7 Hz, [*H*CHCCN]), 3.09 (1H, br, s, [C*H*CH$_2$ (bridgehead)]), 3.49 (1H, br, s, [C*H*CH$_2$ (bridgehead)]), 6.11 (1H, dd, ^3J = 5.7, 3.1, [=C*H*]), 6.41 (1H, dd, ^3J = 5.7, 3.1, [=C*H*]). ^{13}C NMR (67.80 MHz): δ 42.86 ([−*C*H−(bridgehead)]), 45.67 ([−*C*H$_2$−]), 48.51 ([−*C*H$_2$−]), 55.35 ([−*C*H− (bridgehead)]), 56.1 ([*C*(Cl)CN]), 121.4 ([−CN]), 131.97 ([=CH]), 139.38 ([=CH]).

Ethyl 2-Cyanopropionate (11). A more efficient synthesis of compounds of this type has been published,[16] but the following synthesis is also convenient. The reaction was only run once, and hence the yield is not optimized. A solution of sodium ethoxide (9.024 g, 0.133 mol) in ethanol (60 mL) was added dropwise, via an addition funnel, to a stirring solution of ethyl cyanoacetate (15 g, 14.11 mL, 0.133 mol) in ethanol (60 mL). Once addition was complete, the reaction was cooled to 0 °C. Methyl iodide (19.63 g, 8.611 mL, 0.138 mol) was carefully added via a syringe, and the reaction was stirred for 2 h. Solvent was removed from the reaction flask, and the residue was extracted with ether (100 mL) and washed with water (2 × 100 mL). The organic extract was dried ($MgSO_4$) and filtered. The solvent was removed from the filtrate. The crude material was purified by column chromatography using 30% ether/petroleum ether as eluent (yield: 37%). MS (CI$^+$): 128.0 (MH$^+$). IR (υ_{max}/cm^{-1}): 3475, 2988, 2949, 2912, 2253, 1747, 1458, 1383, 1369, 1300, 1270, 1200, 1110, 1034, 862. ^{1}H NMR (270 MHz): δ 1.33 (3H, t, ^3J = 7.1 Hz, [CH$_2$C*H*$_3$]), 1.60 (3H, d, ^3J = 7.3 Hz, [CHC*H*$_3$]), 3.57 (1H, q, ^3J = 7.3 Hz, [C*H*CH$_3$]), 4.27, 2H, q, ^3J = 7.1 Hz, [C*H*$_2$CH$_3$]). ^{13}C NMR (67.80 MHz): δ 166.44 ([−*C*O$_2$−]), 117.29 ([−*C*N]), 62.73 ([*C*H$_2$CH$_3$]), 31.412, [CH*C*H$_3$]), 13.816 ([CH$_2$*C*H$_3$]).

General Procedure for Asymmetric Michael Reactions. To an evacuated one-necked round-bottomed flask containing **5a** (7.6 mg, 0.01 mmol) and a stirring bead was added a solution of ethyl cyanopropionate (0.127 g, 1 mmol) in dry solvent (4 mL). This flask was then flushed with nitrogen. Hunigs base (0.017 mL, 13 mg, 0.1 mmol) and methyl vinyl ketone (0.125 mL, 0.105 g, 1.5 mmol) were then syringed into the flask (on some occasions methyl vinyl ketone was added as a solution in 3 mL of solvent using a syringe pump at its slowest setting). The reaction was then stirred at room temp. Reaction progress was assessed by TLC. (The product has an R_F of 0.2 in 30% ether/petrol; $KMnO_4$ dip). When the reaction is complete, solvent (and excess methyl vinyl ketone) is removed in vacuo, and the pure product is obtained after column chromatography using 30% ether/petrol as eluent (yields are given in the table). The compound was identified by comparison of its NMR data with literature values.[13] ^{1}H NMR (400 MHz): δ 1.34 (3H, t, ^3J = 7.1 Hz, [CH$_2$C*H*$_3$]), 1.61 (3H, s, [NC−C−C*H*$_3$]), 2.0−2.3 (2H, m, [CH$_2$−C*H*$_2$−C−]), 2.19 (3H, s, [C*H*$_3$−CO]), 2.5−2.8 (2H, m, [C(O)−C*H*$_2$−]), 4.27 (2H, q, ^3J = 7.1 Hz, [C*H*$_2$CH$_3$]), ^{13}C NMR (67.8 MHz): δ 13.90, 23.43, 29.90, 31.46, 39.12, 43.02, 62.87, 119.46, 168.79. 205.74. MS (CI$^+$): 198.1 (MH$^+$).

Table 5. Crystal Data and Structure Refinement for [(*S*)-P^N] PtPh$_2$ (3b)

emp formula	$C_{36}H_{34}NOPPt$
fw	722.70
temp	293(2) K
wavelength	0.709 30 Å
cryst syst	monoclinic
space group	$P2_1$
unit cell dimens	a = 9.388(1) Å b = 16.113(2) Å c = 10.045(1) Å β = 90.31(1)°
vol	1519.5(3) Å^3
Z	2
density (calcd)	1.580 mg/m^3
abs coeff	4.699 mm^{-1}
F(000)	716
cryst size	0.25 × 0.25 × 0.2 mm
θ range for data collecn	2.02−23.92°
index ranges	$-10 \le h \le +10$; $0 \le k \le +18$; $0 \le l \le +11$
reflcs collecd	2486
independent reflcns	2486 [R(int) = 0.0000]
abs corr	DIFABS
max and min transm	1.00 and 0.496
refinement method	full-matrix least squares on F^2
data/restraints/params	2486/1/365
goodness-of-fit on F^2	1.016
final R indices [$I > 2\sigma(I)$]	R1 = 0.0326, wR2 = 0.0690
R indices (all data)	R1 = 0.0486, wR2 = 0.0757
abs structure param	0.01(2)
largest diff peak and hole	1.133 and −1.058 e Å^{-3}
weighting scheme	calc $w = 1/[\sigma^2(F_o^2) + (0.0462P)^2 + 0.0000P]$, where $P = (F_o^2 + 2F_c^2)/3$.
extincn coeff	0.0000(3)
extincn expression	$F_c^* = kF_c[1 + 0.001F_c^2\lambda^3/\sin(2\theta)]^{-1/4}$

(16) Albarella, J. P. *J. Org. Chem.* **1977**, *42*, 2009.

X-ray Crystal Structure Determination of [(*S*)-P^N]PtPh$_2$ (3b). A crystal of approximate dimensions 0.25 × 0.25 × 0.2 mm was used for data collection. (Table 5). *Crystal data.* $C_{36}H_{34}NOPPt$, M = 722.70, monoclinic, a = 9.388(1) Å, b = 16.113(2) Å, c = 10.045(1) Å, β = 90.31(1)°, U = 1519.5(3) Å^3, space group $P2_1$, Z = 2, D_c = 1.580 g cm^{-3}, μ(Mo Kα) = 4.699 mm^{-1}, F(000) = 716. Crystallographic measurements were made at 293(2) *K* on a CAD4 automatic four-circle diffractometer in the range 2.02 < θ <23.92°. Data (2486 reflections) were corrected for Lorentz and polarization effects and also for absorption.[17] (maximum and minimum absorption corrections, 1.00, 0.496 respectively). In the final least squares cycles all atoms were allowed to vibrate anisotropically. Hydrogen atoms were included at calculated positions where relevant. The solution of the structure (SHELX86)[18] and refinement (SHELX93)[19] converged to a conventional [i.e. based on 2099 F^2 data with $F_o > 4\sigma(F_o)$] R1 = 0.0326 and wR2 = 0.0690. Goodness of fit = 1.016. The maximum and minimum residual densities were 1.133 and −1.058 e Å^{-3}, respectively. The asymmetric unit (shown in Figure 3), along with the labeling scheme used was produced using ORTEX.[20] Final fractional atomic coordinates and isotropic thermal parameters, bond distances, and angles are given in the Supporting Information.

X-ray Crystal Structure Determination of [(*S*)-P^N]Pt(Me)Cl (4a). A crystal of approximate dimensions 0.25 × 0.25 × 0.25 mm was used for data collection (Table 6). *Crystal data.* $C_{28.10}H_{27}ClNOPPt$, M = 656.22, monoclinic, a = 9.697(3) Å, b = 9.740(2) Å, c = 14.739(4) Å, α = 90°, β = 101.75(3)°, γ = 90°, U = 1362.9(6) Å^3, space group $P2_1$, Z = 2, D_c = 1.599 g cm^{-3}, μ(Mo Kα) = 5.324 mm^{-1}, F(000) = 641. Crystallographic measurements were made at 293(2) *K* on a CAD4 automatic four-circle diffractometer in the range 2.14 < θ < 23.92°. Data (2266 reflections) were corrected for Lorentz and polarization effects and also for absorption[17] (maximum and minimum absorption corrections, 1.000, 0.327, respectively).

In the final least squares cycles all atoms were allowed to vibrate anisotropically. Hydrogen atoms were included at calculated positions where relevant.

Despite reasonable *R* factors, this is not a high-quality crystal structure. However, no problems were evident prior to, or during, the data collection procedure. The refinement was partially hampered by a fragment of disordered solvent in the asymmetric unit, which could not be successfully modeled. Eventually, peaks in this area of the electron density map were treated as partial carbon atoms which were isotropically refined.

Phenyl rings were refined as rigid hexagons, primarily because of shift/estimated standard duration values pertaining to the ring containing carbons C(17)−C(22). In particular, the positions of carbons C(18) and C(19) did not converge as well as expected in the absence of any restraints. This was surprising as crystal quality was good, and the data collection procedure was trouble free. Smearing of the electron density in the proximity of C(18) and C(19) was evident in early difference Fourier maps, prior to any correction for absorption. In fact, the program used for refinement of this structure suggested that these carbon positions should be split between two sites which were not structurally meaningful. Hence, this strategy was abandoned.

However, it is reasonable to suggest that there is probably some minor disorder within this phenyl ring, given the larger than average thermal parameters of the atoms therein.

The solution of the structure (SHELX86)[18] and refinement (SHELX93)[19] converged to a conventional [i.e. based on 1773 F^2 data with $F_o > 4\sigma(F_o)$] R1 = 0.0461 and wR2 = 0.1283. Goodness of fit = 1.070. The maximum and minimum residual densities were 1.012 and −0.757 e Å^{-3}, respectively. The asymmetric unit (shown in Figure 4), along with the labeling scheme used was produced using ORTEX.[20] Final fractional atomic coordinates and isotropic thermal parameters, bond distances, and angles are given in the Supporting Information.

Table 6. Crystal Data and Structure Refinement for [(*S*)-P^N)Pt(Me)Cl (4a)

emp formula	$C_{28.10}H_{27}ClNOPPt$
fw	656.22
temp	293(2) K
wavelength	0.709 30 Å
cryst system	monoclinic
space group	$P2_1$
unit cell dimens	a = 9.697(3) Å b = 9.740(2) Å c = 14.739(4) Å β = 101.75(3)°
vol	1362.9(6) Å^3
Z	2
density (calcd)	1.599 mg/m^3
abs coeff	5.324 mm^{-1}
F(000)	641
cryst size	0.25 × 0.25 × 0.25 mm
θ range for data collecn	2.14−23.92°
index ranges	$-11 \le h \le +10$; $0 \le k \le +11$; $0 \le l \le +16$
reflcns collected	2266
independent reflcns	2266 [R(int) = 0.0000]
abs corr	DIFABS
max and min transm	1.000 and 0.327
refinement method	full-matrix least squares on F^2
data/restraints/params	2262/1/236
goodness-of-fit on F^2	1.070
final R indices [$I > 2\sigma(I)$]	R1 = 0.0461, wR2 = 0.1283
R indices (all data)	R1 = 0.0690, wR2 = 0.1473
abs structure param	−0.01(3)
largest diff peak and hole	1.012 and −0.757 e Å^{-3}
weighting scheme	calc $w = 1/[\sigma^2(F_o^2) + (0.0880P)^2 + 0.9764P]$, where $P = (F_o^2 + 2F_c^2)/3$

Acknowledgment. Thanks to the Link Asymmetric synthesis program, Glaxo-Wellcome, and Zeneca for financial support.

Supporting Information Available: Tables giving final refined atomic coordinates, thermal parameters, bond distances and angles for crystal structures **3b** and **4a** are available free of charge via the Internet at http://pubs.acs.org.

OM990186E

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