Synthesis and absolute stereochemistry of an organo-palladium complex containing a P-chiral diphosphine ligand

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Abstract

The cationic palladium(II) complex containing ortho-metallated (R)-1-[1-(dimethylamino)ethyl]benzene and (1α, 4α, $5\alpha(S)$, $7R$)-[5-(diphenylphosphino)-2,3-dimethy-7-phenyl-7-phosphabicyclo[2.2.1]]-hept-2-ene was prepared by both the coordination of the diphosphine to the organopalladium unit and by the asymmetric Diels–Alder reaction between 1-phenyl-3,4-dimethylphosphole and diphenylvinylphosphine using the organopalladium unit as the reaction promoter. Compound $C_{36}H_{40}ClNO_4P_2Pd$ (−)-2, with $[\alpha]_D$ −39.0 (c = 1.0, $CHCl_3$), crystallizes in the monoclinic space group $P2_1$, with a = 10.538(4), b = 16.031(5), c = 10.709(4) Å, β = 100.20(3)°, V = 1781(1) Å³, Z = 2, D_c = 1.41 g cm⁻¹, μ(Cu K_α) = 60.5 cm⁻¹, $F(000)$ = 776. The structure refinement converged to R_1 = 0.033, wR_2 = 0.081 for 2905 independent observed reflections [$|F_0| > 4\sigma(|F_0|)$, $2\theta \le 126°$] and 387 parameters. The absolute stereochemistry of the phosphorus and the three carbon stereogenic centres in the diphosphine ligand were assigned unambiguously by both an R-factor test [R^+ = 0.033, R^- = 0.054] and the Flack parameter [x^+ = −0.02(2), x^- = +1.02(2)]. © 1997 Elsevier Science S.A.

Keywords: Palladium(II); Chiral diphosphine; Absolute stereochemistry; Crystal structure

1. Introduction

In 1994 we reported that the dichloro-bridged palladium complex containing the configurationally homogeneous ortho-metallated 1-[1-(dimethylamino)ethyl]naphthalene ligand is capable of promoting the asymmetric Diels–Alder reaction between 1-phenyl-3,4-dimethylphosphole and diphenylvinylphosphine (Scheme 1) [1]. Both enantiomeric forms of the corresponding rigid P-chiral diphosphine were obtained enantiospecifically as air-sensitive oils in high yields by using the appropriate forms of the naphthylamine auxiliary. Unfortunately, the absolute configurations of these new diphosphines were not assigned in our first report due to the fact that we could not produce single crystals of the intermediate palladium template complexes that cont. in the chiral naphthylamine auxiliary and the diphosphine ligand for X-ray structural analysis. Although these complexes are chemically stable and can

be readily crystallized from most solvent system, these crystals generally grow as hollow tubes and suffer from problems of rapid desolvation. Very recently, we established that simple ¹H ROESY NMR experiments can be used to assign the absolute stereochemistry of these template complexes in solution [2]. This NMR technique utilizes the unique stereochemical features of the ortho-metallated 1-[1-(dimethylamino)ethyl]naphthalene palladium unit as the internal reference. According to this solution NMR study, the diphosphine ligand (+)-1, which was produced when the R-naphthylamine auxiliary was used, was assigned the R absolute configuration at the bridged-head phosphorus stereogenic centre.

2. Results and discussion

In order to consolidate the above highly convenient and yet relatively new NMR assignment, we have reocoordinated the diphosphine (+)-1 to the analogous palladium complex containing the ortho-metallated (R)-1-[1-(dimethylamino)ethyl]benzene (Scheme 2). In contrast to its naphthylamine analogue, the resulting perchlorate

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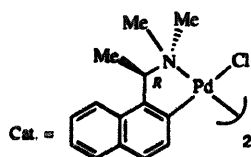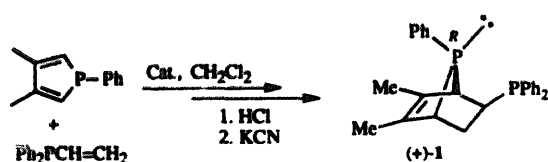
Scheme 1.

Scheme 2.

salt, (−)-2, was crystallized from acetone–diethyl ether as highly stable clear prisms which were suitable for the conventional absolute stereochemical determination via single crystal X-ray analysis.

The X-ray analysis of (−)-2 fully supports the stereochemical assignments derived from the ^{1}H ROESY NMR experiments [4]. The molecular structure is depicted in Fig. 1, while selected bond lengths and angles are listed in Table 1. The structural analysis confirms the absolute stereochemistries at the five chiral centres C(7), P(12), C(19), C(22) and C(23) to be *R, S, S, S* and *R* respectively. The apparent inversion of configuration that takes place at the phosphorus stereogenic centres when the diphosphine is coordinated to the metal is merely a consequence of the Cahn–Ingold–Prelog (CIP) sequence rules [3]. The coordination geometry is distorted square planar with angles at palladium ranging between 80.9(3) to 100.9(2) and 172.9(2) to
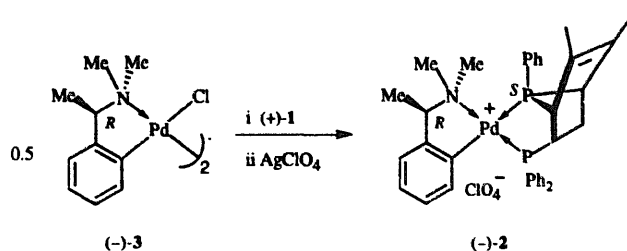
173.5(2)°, with the bite angles of both of the five-membered chelate rings being acute. There is a distinct tetrahedral distortion of the geometry at palladium, the ligand coordination planes being twisted by ca. 10° with respect to each other. The most marked feature of the palladium coordination is a 0.1 Å difference in the two Pd–P bond lengths, with the bond trans to carbon being 2.358(2) Å whilst that trans to nitrogen is 2.259(2) Å. This difference is accompanied by a surprising lengthening of the Pd–C bond to 2.059(8) Å, cf. a typical value of ca. 1.98 Å in related naphthylamine complexes [4]. The five-membered diphosphine chelate ring adopts a folded, δ conformation.

Despite the known preponderance for coordinated benzylamines to adopt both axial and equatorial conformations for the C(7) methyl group [5], here, only an axial geometry is observed. This is equivalent to observations for analogous, coordinated, naphthylamine species [6].

It should be noted, however, that the cationic complex (−)-2 can also be prepared directly from the
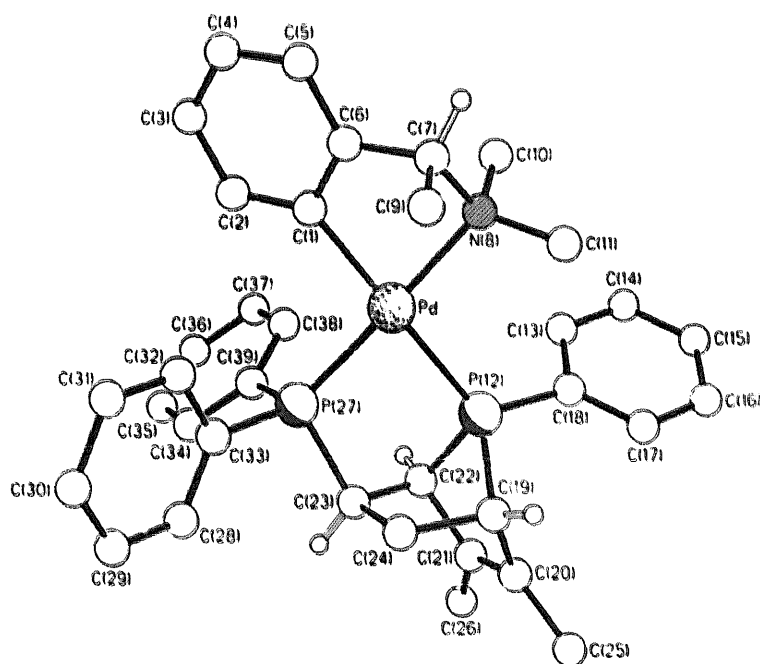

Fig. 1. The X-ray crystal structure of the cation in (−)-2, showing the *R, S, S, S* and *R* stereochemistries at the C(7), P(12), C(19), C(22) and C(23) centres respectively (50% probability ellipsoids).

Table 1
Selected bond lengths (Å) and angles (deg) for (−)-2

Pd–C(1)	2.059(8)	Pd–N(8)	2.152(6)
Pd–P(12)	2.358(2)	Pd–P(27)	2.259(2)
P(12)–C(18)	1.796(5)	P(12)–C(19)	1.842(9)
P(12)–C(22)	1.8_4(7)	P(27)–C(23)	1.825(8)
C(20)–C(21)	1.325(13)	C(23)–C(24)	1.572(11)
P(12)–Pd–P(27)	82.5(1)	N(8)–Pd–P(12)	100.9(2)
N(8)–Pd–P(27)	173.5(2)	C(1)–Pd–N(8)	80.9(3)
C(1)–Pd–P(12)	172.9(2)	C(1)–Pd–P(27)	96.4(2)
C(19)–P(12)–C(22)	80.9(4)	C(19)–P(12)–Pd	118.7(3)
C(22)–P(12)–Pd	107.1(3)	C(18)–P(12)–Pd	121.8(2)
C(23)–P(27)–Pd	105.5(3)	C(33)–P(27)–Pd	120.1(2)
C(39)–P(27)–Pd	113.1(2)	C(33)–P(27)–C(39)	108.1(3)
C(23)–C(22)–P(12)	97.1(5)	C(24)–C(19)–P(12)	99.1(6)
C(20)–C(19)–P(12)	102.9(6)	C(21)–C(22)–P(12)	104.9(6)
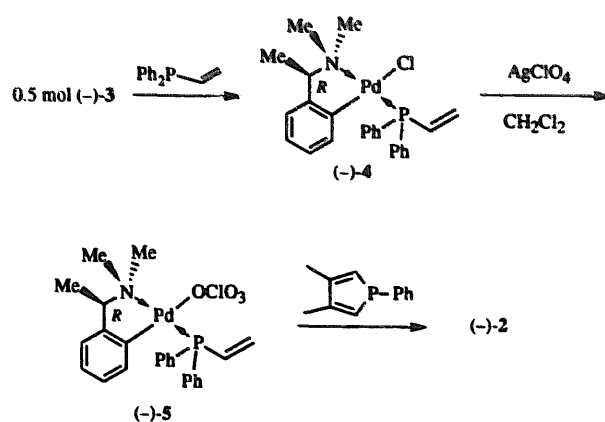
Scheme 3.

parallel palladium promoted asymmetric Diels–Alder reaction, as illustrated in Scheme 3, using (R)-benzylamine as the chiral auxiliary [9]. Thus the reaction between the dimeric species (−)-3 and diphenylphosphine gave the chloro complex (−)-4 61.8% isolated yield. The relatively strong chloro donor was subsequently replaced by a weakly bonded ligand [4] by the treatment of the neutral complex with silver perchlorate in dichloromethane. In all routine syntheses, the highly reactive perchlorato complex (−)-5 was not isolated and the dichloromethane solution containing the cationic complex was used directly for the Diels–Alder reaction

with dimethylphosphole. The cycloaddition reaction was completed in 3 h at room temperature to give the optically pure complex (−)-2 in 75% isolated yield.

It should be noted that in our earlier studies when the more expensive (R)-naphthylamine was used as the chiral auxiliary for the asymmetric synthesis of (−)-2, very similar yields, enantiomeric purities and reaction conditions were observed. Therefore, for the synthesis of the diphosphine ligand (+)-1, (R)-benzylamine is perhaps a more economical choice. However, the naphthylamine and the benzylamine palladium complexes show drastic differences in more stericially demanding processes. For example, while the naphth-

Table 2
Crystallographic data for (−)-2

Formula	[C₁₆H₄₀NP₂Pd] [ClO₄]
Molecular weight	754.48
Crystal system	monoclinic
Space group	$P2_1$
a (Å)	10.534(4)
b (Å)	16.031(5)
c (Å)	10.709(4)
α (deg)	90
β (deg)	100.20(3)
γ (deg)	90
T (K)	293(2)
V (Å³)	1780.5(11)
Z	2
D_{calc} (g cm⁻³)	1.407
$F(000)$	776
Crystal size (mm³)	0.20 × 0.13 × 0.12
Total observed data	3160
Total unique data	3077
No. of data used in refinement	2905
No. of refined parameters	387
λ, Å (Cu)	1.54178
μ, cm⁻¹	60.49
hkl limits	−12–12, −18–16, −12–12
R_1 [a]	0.033
wR_2 [b]	0.081

[a] $R_1 = \Sigma \|F_0| - |F_c\| / \Sigma |F_0|$.

[b] $wR2 = \sqrt{\left\{ \Sigma \left[w(F_0^2 - F_c^2) \right] / \Sigma \left[w(F_0^2)^2 \right] \right\}}$, $w^{-1} = \sigma^2(F_0^2) + (aP)^2 + bP$

ylamine complex promotes the analogous asymmetric Diels–Alder reaction between DMPP and phenyl-divinylphosphine efficiently to give the corresponding enantiomerically pure diphosphine that contains two phosphorus and three carbon stereogenic centres in 70% isolated yield [7], similar reactions involving the benzylamine complex do not produce any isolable product. Furthermore, the benzylamine complex decomposes in these stereochemically demanding processes but its naphthylamine counterpart remains intact throughout the reaction sequences. Hence, due to the superior stability [8] and the predictable stereochemistry [9], we routinely use the naphthylamine complex in our laboratory.

3. Experimental details

3.1. General

Reactions involving air-sensitive compounds were performed under a positive pressure of purified nitrogen. NMR spectra were recorded at 25°C on Brucker ACF 300 and AMX 500 spectrometers. Optical rotations were measured on the specified solutions in a 1 dm cell at 25°C with a Perkin-Elmer model 341 polarimeter. Elemental analyses were performed by the microanalytical Laboratory of the Department of Chemistry at the National University of Singapore. The enantiomerically pure form of bis(μ-chloro)bis[(R)-1-[1-(dimethylamino)ethyl]-2-naphthalenyl-C,N] dipalladium(II) dichloromethane solvate (–)-3 was prepared as previously described [10].

3.2. Preparation of the chloro complex (–)-4

A mixture of diphenylvinylphosphine (2.2 g) and (–)-3 (3.0 g) in dichloromethane (200 mL) was stirred at room temperature until all the reaction promoter had dissolved (ca. 1 h). The solvent was removed from the reaction mixture and the residue was recrystallized from ethanol-n-hexane mixture, forming beautiful yellow prisms (3.1 g, 61.8% yield); mp 104–105°C; $[\alpha]_D$ = 49.1° (c 1.1, CHCl$_3$). ^{31}P NMR (CDCl$_3$) δ 25.0(s); ^{1}H NMR (CDCl$_3$) δ 1.75 (d, 3H, $^3J_{HH}$ = 6.5 Hz, CHMe), 2.75 (d, 3H, $^4J_{PH}$ = 3.1 Hz, NMe), 2.83 (d, 3H, $^4J_{PH}$ = 2.1 Hz, NMe), 3.81 (qn, 1H, $^3J_{HH}$ = $^4J_{PH}$ = 6.4 Hz, CHMe), 5.29–5.42 (m, 1H, cis-PCCH), 5.96–6.13 (m, 1H, trans-PCCH), 6.40–6.44 (m, 1H, PCH), 6.80–7.80 (m, 14H, aromatics). Anal. Found: C, 57.4; H, 5.4; N, 2.8. C$_{24}$H$_{27}$ClNPPd. Calcd.: C, 57.4; H, 5.4; N, 2.8.

3.3. Preparation of chiral complex (–)-2 via the Diels–Alder approach

A solution of (–)-4 (1.0 g) in dichloromethane (100 mL) was stirred for 2 h in the presence of a solution of

silver perchlorate (0.4 g) in water (1 mL) to give the perchlorato complex. The colourless organic layer, after the removal of AgCl and dried (MgSO$_4$), was treated with DMPP (0.37 g) at room temperature for 3 h. The crude product was crystallized from acetone–diethyl ether in 75% yield; mp 136–138°C (dec); $[\alpha]_D$ – 39.0 (c = 1.0, CHCl$_3$); ^{31}P NMR (202 MHz, CDCl$_3$) δ 52.30 (d, $^3J_{PP}$ = 43.9 Hz), 117.05 (d, $^3J_{PP}$ = 43.9 Hz);

Table 3
Final coordinates and equivalent isotropic thermal parameters of the nonhydrogen atoms for compound (–)-2

Atom	x	y	z	$10^3 U_{eq}$	Occupancy
Pd	0.7526(1)	0.2996(1)	0.4765(1)	48(1)	
C(1)	0.7106(7)	0.2386(5)	0.6334(7)	51(2)	
C(2)	0.7218(8)	0.1558(6)	0.6683(9)	62(2)	
C(3)	0.6752(9)	0.1261(7)	0.7744(10)	78(3)	
C(4)	0.6170(9)	0.1805(8)	0.8460(10)	79(3)	
C(5)	0.6280(9)	0.2613(7)	0.8141(9)	73(3)	
C(6)	0.6490(6)	0.2914(8)	0.7063(6)	55(2)	
C(7)	0.6339(9)	0.3806(6)	0.6693(8)	68(2)	
N(8)	0.6109(6)	0.3844(4)	0.5256(6)	58(2)	
C(9)	0.7563(12)	0.4299(8)	0.7289(11)	102(4)	
C(10)	0.4785(8)	0.3521(7)	0.4787(8)	79(3)	
C(11)	0.6173(10)	0.4715(6)	0.479 5(9)	82(3)	
P(12)	0.7857(2)	0.3567(1)	0.2818(2)	53(1)	
C(13)	0.5410(5)	0.3532(3)	0.1493(5)	64(2)	
C(14)	0.4528(4)	0.3838(4)	0.0691(6)	79(3)	
C(15)	0.4387(6)	0.4600(4)	0.0084(6)	86(3)	
C(16)	0.5527(7)	0.5056(3)	0.0279(6)	93(4)	
C(17)	0.6609(5)	0.4749(3)	0.1080(6)	73(3)	
C(18)	0.6551(4)	0.3987(3)	0.1687(5)	56(2)	
C(19)	0.9366(8)	0.4134(6)	0.2770(8)	66(2)	
C(20)	0.9545(8)	– 0.4016(7)	0.1387(8)	67(2)	
C(21)	0.9218(8)	0.3245(7)	0.1013(8)	69(3)	
C(22)	0.8688(7)	0.2777(5)	0.2038(7)	53(2)	
C(23)	0.9819(7)	0.2618(5)	0.3160(7)	50(2)	
C(24)	1.0336(8)	0.3517(6)	0.3552(9)	61(2)	
C(25)	1.0218(11)	0.4679(9)	0.0758(11)	106(4)	
C(26)	0.9458(9)	0.2814(8)	– 0.0144(8)	84(4)	
P(27)	0.9155(2)	0.2149(1)	0.4458(2)	48(1)	
C(28)	1.1769(5)	0.1878(4)	0.5392(4)	70(2)	
C(29)	1.2840(4)	0.1781(4)	0.6346(5)	72(3)	
C(30)	1.2704(4)	0.1829(5)	0.7612(5)	72(3)	
C(31)	1.1497(5)	0.1975(5)	0.7923(4)	88(4)	
C(32)	1.0427(4)	0.2072(5)	0.6970(5)	78(3)	
C(33)	1.0563(4)	0.2023(4)	0.5704(4)	52(2)	
C(34)	0.9467(4)	0.0469(4)	0.3804(6)	68(2)	
C(35)	0.9003(6)	– 0.0305(3)	0.3350(6)	82(3)	
C(36)	0.7864(6)	– 0.0431(3)	0.2987(6)	80(3)	
C(37)	0.6830(4)	0.0217(4)	0.3078(6)	75(3)	
C(38)	0.7294(4)	0.0992(3)	0.3531(5)	59(2)	
C(39)	0.8613(5)	0.1117(3)	0.3894(5)	53(2)	
C(41)	0.3054(2)	0.1752(2)	0.2002(2)	72(1)	
O(41)	0.4087(12)	0.1372(10)	0.2786(14)	148(7)	0.67
O(42)	0.1901(10)	0.1294(7)	0.2055(17)	133(6)	0.67
O(43)	0.2887(12)	0.2564(6)	0.2527(12)	84(3)	0.67
O(44)	0.3277(18)	0.1820(8)	0.0757(9)	141(6)	0.67
O(41')	0.4154(19)	0.1775(16)	0.1361(24)	110(9)	0.33
O(42')	0.2530(23)	0.2558(11)	0.1976(23)	87(10)	0.33
O(43')	0.2140(21)	0.1200(14)	0.1292(23)	109(10)	0.33
O(44')	0.3482(29)	0.1440(19)	0.3207(18)	147(15)	0.33

U_{eq} = 1/3 of the trace of the orthogonalized U.

^{1}H NMR (500 MHz, CDCl$_3$) δ 1.40 (3H, s, C=CMe), 1.73 (3H, s, C=CMe), 1.81 (3H, d, CHMe, $^3J_{HH}$ = 6.4 Hz), 1.88 (1H, m, H$_{6,endo}$), 2.37 (1H, dd, H$_{6,exo}$, $^2J_{HH}$ = 13.2 Hz, $^3J_{PH}$ = 24.1 Hz), 2.52 (3H, d, NMe, $^3J_{PH}$ = 1.4 Hz), 2.55 (3H, dd, NMe, $^4J_{PH}$ =$^4J_{P'H}$ = 3.6 Hz), 2.79 (1H, s, H_4), 3.08 (1H, ddd, H_5, $^3J_{HH}$ =$^2J_{PH}$ = 8.6 Hz, $^3J_{P'H}$ = 41.0 Hz), 3.59 (1H, qn, CHMe, $^3J_{HH}$ =$^4J_{PH}$ = 6.4 Hz), 3.71 (1H, m, H_1), 6.56–8.23 (19H aromatics). Anal. Found: C, 57.5; H, 5.1; N, 1.9. C$_{36}$H$_{40}$ClNO$_4$P$_2$Pd. Calc.: C, 57.3; H, 5.3; N, 1.9.

3.4. Preparation of (−)-2 via the coordination approach

A fresh sample of (+)-1 (0. 1 g) in dichloromethane (20 mL) was stirred with a solution of (−)-3 (0. 1 g) in dichloromethane (20 mL). The resulting chloride salt was subsequently treated with stoichoimetric amount of silver perchlorate to give (−)-2 as its perchlorate salt. The physical properties of this material were identical to that obtained from the Diels–Alder synthesis.

3.5. X-ray structure determination of (−)-2

Crystal data and details on refinement are presented in Table 2. Final coordinates and equivalent isotropic thermal parameters are given in Table 3. A clear prism of dimensions 0.20 × 0.13 × 0.12 mm was used. 3077 independent reflections were measured on a Siemens P4/PC diffractometer with Cu K$_\alpha$ radiation (graphite monochromator) using ω-scans. The structure was solved by direct methods and all the major occupancy non-hydrogen atoms (disordered perchlorate) were refined anisotropically using full-matrix least-squares based on F^2 with absorption corrected data to give R_1 = 0.033, wR_2 = 0.081 for 2905 independent ob-

served reflections [|F_0| > 4σ(|F$_0$|), 2$\theta \leq$ 126°] and 387 parameters. The absolute stereochemistry was determined unambiguously by both the R-factor test [R^+ = 0.033, R^- = 0.054] and the Rack parameter [x^+ = 0.02(2), x^- = +1.02(2)].

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