

The First Examples of Enantiomerically Pure Diphosphane Dioxides— (*R_P*,*R_P*)- and (*S_P*,*S_P*)-1,2-Di-*tert*-butyl-1,2-diphenyldiphosphane 1,2-Dioxides, and (*R_P*)- and (*S_P*)-1-*tert*-Butyl-1,2,2-triphenyldiphosphane 1,2-Dioxides

Richard K. Haynes,* William Wai-Lun Lam, Ian D. Williams and Lam-Lung Yeung

Abstract: Whereas oxidative dimerization of each of the lithiated reagents (*R_P*)- and (*S_P*)-*tert*-butylphenylphosphane oxides **1** Li and **2** Li by means of oxygen in THF at low temperature led cleanly to *meso*-1,2-di-*tert*-butyl-1,2-diphenyldiphosphane dioxide (**3**), the respective nucleophilic substitution reactions of **1** Li and **2** Li with the (*R_P*)- and (*S_P*)-*tert*-butylphenylphosphinic bromides (**4** and **6**) in THF under

argon led to the corresponding (*S_P*,*S_P*)- and (*R_P*,*R_P*)-1,2-di-*tert*-butyl-1,2-diphenyldiphosphane dioxides (**5** and **7**) in

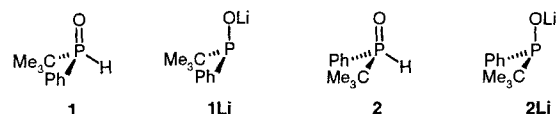
good yields, together with the *meso*-diphosphane dioxide **3**. The structures of **3** and **5** were established by X-ray crystallography. Similarly, the reaction of lithiated (*R_P*)-phosphane oxide **1** Li with diphenylphosphinic bromide (**8**) or of achiral lithiated diphenylphosphane oxide **10** Li with (*R_P*)-*tert*-butylphenylphosphinic bromide (**4**) provided (*S_P*)-*tert*-butyltriphenyldiphosphane dioxide (**9**).

Keywords

asymmetric synthesis • chiral ligands • P ligands • permutational isomerization • phosphane oxides

Introduction

We have developed a large-scale, practical route to each of the enantiomerically pure, secondary (*R_P*)- and (*S_P*)-phosphane oxides **1** and **2**. An important observation that enhances the value



of these reagents is that the configuration is strictly maintained during lithiation with butyllithium or LDA in THF to provide the lithiated (*R_P*)- and (*S_P*)-phosphane oxides **1** Li and **2** Li, respectively.^[1–3] Although **1** Li has also been prepared previously by Se–Li exchange on (benzylseleno)-*tert*-butylphenylphosphane oxide, this route is less accessible.^[4] Lithiated methylphenylphosphane oxide, prepared by reductive cleavage of an *O*-menthyl group in a menthyl phosphinate, has also been reported to be configurationally stable.^[5]

Reactions of the lithiated phosphane oxides **1** Li and **2** Li with electrophiles such as alkylating agents, aldehydes and α,β -unsaturated carbonyl compounds proceed smoothly at low tempera-

ture without loss of configurational integrity.^[1, 2] When prochiral carbonyl compounds are used, diastereoselection is usually good; if this is not the case, the diastereomers are generally readily separated by flash chromatography.^[2] The resulting functionalized tertiary phosphane oxides, with chirality at phosphorus, are promising chiral ligands for a series of catalysed asymmetric reactions.^[6]

To extend the range of ligand types for asymmetric catalysis, we considered preparing the hitherto unreported enantiomerically pure *P*-chiral diphosphane dioxides by oxidatively coupling the lithiated phosphane oxides **1** Li and **2** Li. These have the potential to act as ligands for main-group and high-valent transition metals for catalysed asymmetric reactions, especially under aqueous conditions.

To our knowledge, direct oxidative coupling of phosphinyl anions has not been used previously to prepare diphosphane dioxides. Only one, albeit unusual, example of oxidative coupling of anionic phosphorus has been reported in the case of diphenylphosphide.^[7] A second example involves coupling of diphenylphosphinyl radicals formed thermally.^[8] However, by analogy with the oxidative coupling of carbanions, including *P*-chiral α -phosphoryl anions,^[9] oxidative coupling was expected to be facile for the lithiated phosphane oxides **1** Li and **2** Li. In addition, early literature reports indicate that radicals derived from optically pure phosphinates and phosphinothioates are configurationally stable.^[10, 11] Thus, it was expected that this property would be displayed by the *P*-centred radicals formed upon oxidation of the lithiated phosphane oxides **1** Li and **2** Li.

A variety of methods have been used to prepare achiral or racemic diphosphane dioxides.^[8, 12–15] The most flexible in-

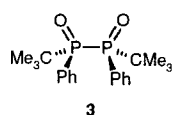
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volves an unusual reaction of dichlorophosphanes with Grignard reagents to provide diphosphanes, which are then converted into symmetrically substituted diphosphane dioxides by oxidative workup. Thus, treatment of *tert*-butyldichlorophosphane with 2,2-dimethylpropylmagnesium chloride and oxidative workup provided racemic 1,2-di-*tert*-butyl-1,2-bis(2,2-dimethylpropyl)diphosphane 1,2-dioxide, which has been thoroughly characterized.^[14, 15] However, enantiomerically pure, symmetrically substituted diphosphane dioxides are unknown, and it is clear that they cannot be prepared by this Grignard method. Also, to our knowledge, no unsymmetrically substituted diphosphane dioxides, let alone enantiomerically pure examples, have hitherto been reported.

It is the aim of this work to develop general routes to enantiomerically pure, symmetrically and unsymmetrically substituted diphosphane dioxides for future applications as ligands in asymmetric catalysis. We start by focussing on the oxidative dimerization of the lithiated phosphane oxides **1** Li and **2** Li. We then examine heterolytic methods for preparing diphosphane dioxides, based on nucleophilic substitutions.

Results and Discussion

Oxidative Dimerization: The lithiated (*R_p*)-phosphane oxide **1** Li was obtained from the enantiopure (*R_p*)-phosphane oxide **1** and butyllithium in THF under nitrogen at -78°C .^[3] Treatment of the solution with copper(II) chloride as oxidant failed to give the coupled product; instead, *tert*-butylphenylphosphinic chloride was obtained. However, by replacing the nitrogen with an oxygen



3

atmosphere, **1** Li was cleanly converted into the diphosphane dioxide **3** (65% yield, prisms, m.p. $202\text{--}204^{\circ}\text{C}$). Unexpectedly, however, this was shown unambiguously to be the *meso* compound by means of X-ray crystallography (Figure 1; Table 1, see Experimental Section).

The X-ray structural determination reveals a P–P bond length of $2.244(2)\text{ \AA}$ with a crystallographic inversion centre at its mid-point. The bond is thus slightly shorter than that of racemic 1,2-di-*tert*-butyl-1,2-bis(2,2-dimethylpropyl)diphosphane 1,2-dioxide ($2.288\text{ \AA}$).^[14] The P–O bond length of $1.491\text{ \AA}$ is typical for this type of bond. The orientation of substituents about the P–P bond is *anti*, as reflected by the inversion symmetry of the P–P linkage; the torsion angles for O1–P1–P1'–O1', C1–P1–P1'–C1' and C10–P1–P1'–C10' (crystallographic numbering, Figure 1) are 180° . The unit cell also contains a molecule of water positioned on a twofold axis of symmetry of the crystal structure; it forms two hydrogen bonds to the phosphane oxide oxygen atoms of different molecules (O1w–H1w...O1 $2.785\text{ \AA}$).

The exclusive formation of the *meso* compound from **1** Li is intriguing. It indicates that, contrary to expectations raised by the literature,^[10, 11] inversion takes place in the radical **1**[•] to give the enantiomeric radical **2**[•] and that reaction occurs exclusively between the enantiomeric radicals. For a neutral species, complexation by Li^+ will not be significant and, presumably, dipolar repulsion between the reactants therefore becomes impor-

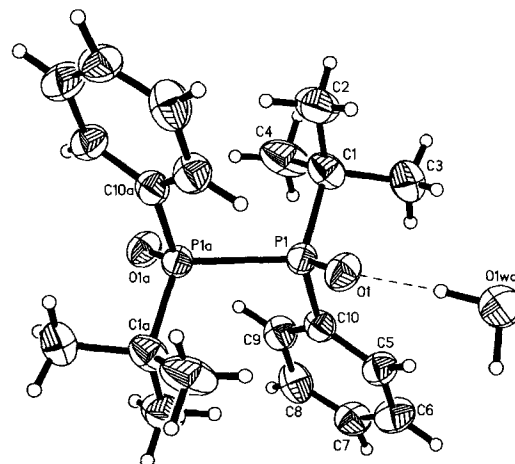
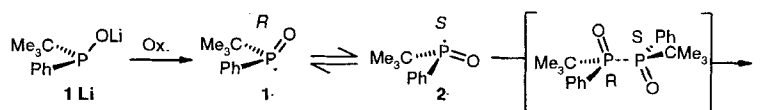


Figure 1. Crystal structure of **3**.

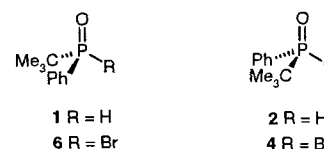
tant. Thus, dipolar repulsion places the P–O bonds of the reacting enantiomeric radicals in an *antiperiplanar* relationship with respect to the incipient P–P bond and consequently the phenyl and *tert*-butyl groups in a *gauche* relationship (Scheme 1). If radicals of the same configuration were to react, one of the *gauche* interactions would involve two *tert*-butyl substituents, and the resulting transition state would be of higher energy.



Scheme 1. Radical dimerization.

Nucleophilic Substitution: The unexpected failure of the oxidative coupling led us to focus upon the direct nucleophilic substitution of halide in the (*R_p*)- and (*S_p*)-*tert*-butylphenylphosphinic bromides **4** and **6** by the lithiated (*R_p*)- and (*S_p*)-phosphane oxides **1** Li and **2** Li, reactions which have no literature analogy.

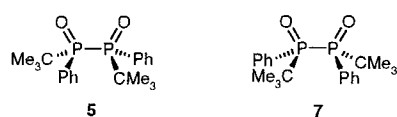
Treatment of (*S_p*)-phosphane oxide **2** in dichloromethane with *N*-bromosuccinimide at 0°C gave crystalline (*R_p*)-phosphinic bromide **4** (95% yield, $[\alpha]_{\text{D}}^{23} = +44.1$ ($c = 0.56$, CHCl_3); $[\alpha]_{\text{D}}^{23} = +52.0$ ($c = 0.45$, C_6H_6)). Similarly, (*R_p*)-phosphane oxide **1** was converted into (*S_p*)-phosphinic bromide **6** ($[\alpha]_{\text{D}}^{22} = -46.2$ ($c = 0.73$, CHCl_3), $[\alpha]_{\text{D}}^{22} = -55.6$ ($c = 0.73$, C_6H_6)).



Enantiomeric purities of $\geq 99\%$ were established by ^1H NMR assay as previously described, by addition of (*S_p*)- and (*R_p*)-*tert*-butylphenylphosphinothioic acid.^[1, 2] Our preparation of **4** is based on that developed by Krawiecka and co-workers,^[16] who used carbon tetrachloride as solvent; they quoted a value of $[\alpha]_{\text{D}} = +49.91$ ($c = 0.0107$, C_6H_6) with an *ee* $\geq 74\%$, established by chemical correlation. Under these conditions, we

found that traces of the corresponding phosphinic chloride were also formed; the use of dichloromethane avoids this problem. We previously prepared **4** by treatment of **2Li** in THF with bromine or 1,2-dibromoethane at -78°C and found $[\alpha]_{\text{D}}^{21} = +31.3$ ($c = 0.26$, CHCl_3);^[2] the *ee*, measured by the NMR assay method, was also $\geq 99\%$.^[11] However, we found this procedure to be very sensitive to the purity of the electrophile and the reaction temperature.^[17]

Lithiated (*R_p*)-phosphane oxide **1Li** (0.5 mmol) in THF under nitrogen was treated with (*R_p*)-phosphinic bromide **4** (1 equiv) in THF at -78°C . After 10 hours, a 2:1 mixture of two diphosphane dioxides was obtained (78% overall yield), which were readily separated by flash chromatography. The minor component was the *meso* compound **3**, and the major was the (*S_p*,*S_p*)-diphosphane dioxide **5** (prisms, m.p. $180\text{--}182^{\circ}\text{C}$, $[\alpha]_{\text{D}}^{20} = +71$ ($c = 0.05$, CHCl_3)). Similarly, (*S_p*)-phosphinic bromide **6** reacted with lithiated (*S_p*)-phosphane oxide **2Li** to provide (*R_p*,*R_p*)-diphosphane dioxide **7** (prisms, m.p. $181\text{--}182^{\circ}\text{C}$,



$[\alpha]_{\text{D}}^{20} = -70$ ($c = 0.05$, CHCl_3)) and **3** (2:1 mixture, 78% overall yield).^[18] Optical purities of $\geq 99.6\%$ were established for **5** and **7** by ^1H NMR assay at 400 MHz as previously described, by addition of (*S_p*)- and (*R_p*)-*tert*-butylphenylphosphinothioic acids.^[11]

The absolute configurations of **5** and **7** were confirmed by X-ray crystallographic analysis of the former (Figure 2; Table 1, see Experimental Section),^[12] and through consideration of the stereochemistry of the nucleophilic substitution reactions at the phosphinic bromides, as discussed below.

The (*S_p*,*S_p*) compound **5** has a P–P bond length of $2.274(1)\text{ \AA}$, slightly longer than that in the *meso* compound **3**, although shorter than the $2.288\text{ \AA}$ observed for racemic 1,2-di-*tert*-butyl-1,2-bis(2,2-dimethylpropyl)diphosphane 1,2-dioxide.^[13] The P–O bond lengths of 1.490 and $1.493(2)\text{ \AA}$

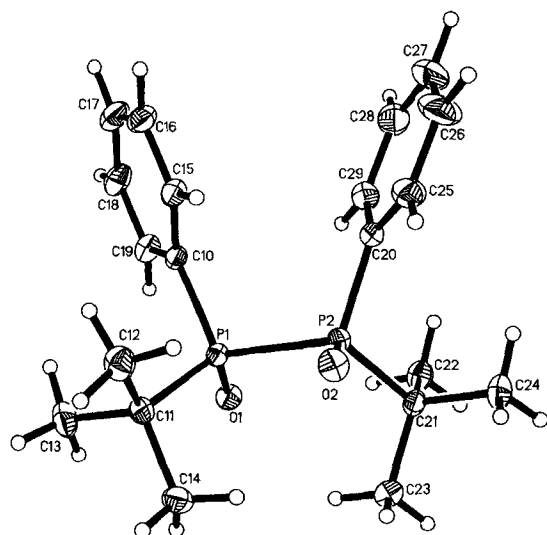


Figure 2. Crystal structure of **5**.

are very similar to that in compound **3**. The orientation of the substituents about the P–P bond in **5** is essentially eclipsed, with a C10–P1–P2–C20 (crystallographic numbering, Figure 2) torsion angle of -16.5° , and O1–P1–P2–C21 and C11–P1–P2–O2 torsion angles of -9.5° . Thus, the two phenyl groups are eclipsed, and each oxygen is in an eclipsed conformation with a *tert*-butyl group. This arrangement contrasts with the *anti* orientations adopted by the *tert*-butyl, phenyl and oxygen substituents in the *meso* compound.

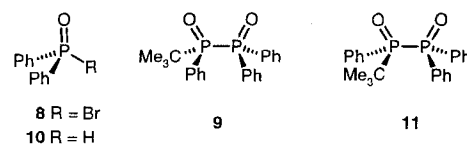
The optimization of the gas-phase geometries of **3** and **5** by using MM⁺ with the Polak-Ribiere algorithm on Hyperchem 5 (Hypercube, Gainsville, FA) with default parameters gives a minimum energy of $46.6\text{ kcal mol}^{-1}$ for the *meso* compound **3**, with an O–P–P–O torsion angle of 179.4° , and of $44.3\text{ kcal mol}^{-1}$ for (*S_p*,*S_p*) compound **5**, with a C10–P1–P2–C20 torsion angle of -7.5° and O1–P1–P2–C21 torsion angle of -15.3° . Clearly the ground-state energies do not provide any indication of the preferential formation of (*S_p*,*S_p*) and (*R_p*,*R_p*) compounds **5** and **7** over *meso* compound **3**.

Whilst we have succeeded in obtaining the enantiomeric diphosphane dioxides, the formation of *meso* diphosphane dioxide **3** as a by-product in the nucleophilic substitution reactions is most intriguing. A number of possible explanations may be considered.

Degenerate bromine–lithium exchange between **1Li** and (*R_p*)-phosphinic bromide **4** would produce **2Li** and (*S_p*)-phosphinic bromide **6**; nucleophilic substitution involving **1Li** and **6** or **2Li** and **4** could then in principle provide **3**. The implicit assumption here is that the bromine–lithium exchange must be slow, and that the nucleophilic reactions between **1Li** and **6** (or **2Li** and **4**) to produce *meso* **3** is fast compared to the reaction between **1Li** and **4** to give (*S_p*,*S_p*)-diphosphane dioxide **5**; this is a most unlikely scenario. It is important to note that *not even a trace* of the (*R_p*,*R_p*)-diphosphane dioxide **7** could be detected amongst the products from the reaction of **1Li** with **4**, or of the (*S_p*,*S_p*)-diphosphane dioxide **5** from reaction of **2Li** with **6**.

Alternatively, electron transfer between **1Li** and (*R_p*)-phosphinic bromide **4** could provide the secondary phosphane oxide radical **1'** (Scheme 1) and phosphinic bromide radical ion **4'**[–], which could be transformed into the neutral radical **2'** after extrusion of bromide; reaction between the radicals (cf. Scheme 1) would then produce *meso* compound **3**. *S_{RN}1* processes have indeed been recorded for reactions of potassium diphenylphosphide, albeit under specific conditions, and coupled products have been isolated.^[19]

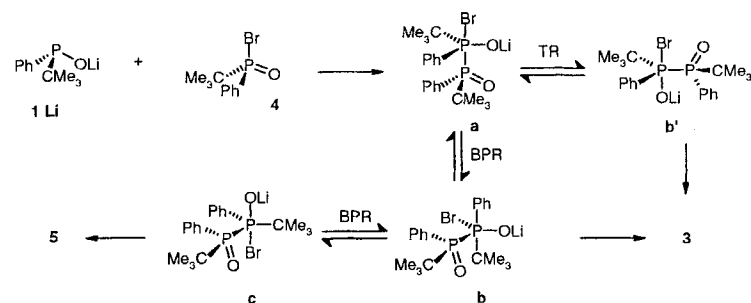
In the following we demonstrate that both the processes described above are unlikely. Achiral diphenylphosphinic bromide **8** was prepared from lithiated diphenylphosphane oxide (**10Li**) and bromine. Lithiated (*R_p*)-phosphane oxide **1Li** was then treated with phosphinic bromide **8** to provide *enantiomerically pure* (*S_p*)-diphosphane dioxide **9** (48% yield, $[\alpha]_{\text{D}}^{21} = +27.2$ ($c = 0.05$, CHCl_3)). Conversely, **10Li** was treated with (*R_p*)-



phosphinic bromide **4** to give again *enantiomerically pure* (S_P)-diphosphane dioxide **9**. Similarly, **10Li** reacted with (S_P)-phosphinic bromide **6** to give (R_P)-diphosphane dioxide **11** (58% yield, $[\alpha]_D^{21} = -26.8$ ($c = 0.38$, CHCl_3)).

Were bromine–lithium exchange or the $S_{RN}1$ mechanism to operate between the *P*-chiral and *P*-achiral phosphinyl anions and phosphinic bromides, we would obtain *partially or totally racemized* products, in addition to symmetrically coupled products. No such products were observed. Whilst bromine–lithium exchange is no longer degenerate in the reaction between **1Li** and **8** to form **8Li** and **6**, it is likely to be exothermic since a weaker base is produced. Thus, bromine–lithium exchange or $S_{RN}1$ processes can be excluded. In addition, the nucleophilic substitution by lithiated diphenylphosphide oxide **10Li** at phosphinic bromides **4** and **6** leading to products **9** and **11**, respectively, has unequivocally been demonstrated to proceed with clean inversion of configuration at phosphorus. Hence, the same is true for the reactions of lithiated (R_P)- and (S_P)-*tert*-butylphenylphosphane oxides **1Li** and **2Li** with **4** and **6** to produce **5** and **7**.

The formation of *meso* compound **3** in the reactions of **1Li** and **2Li** with phosphinic bromides **4** and **6** is probably due to permutational isomerization, either Berry pseudorotation (BPR) or turnstile rotation (TR), in the pentacoordinate intermediates of the nucleophilic substitution (Scheme 2).^[20] Back-side attack of **1Li** at phosphinic bromide **4** will provide the pentacoordinate intermediate **a**. As a result of a stereoelectronic



Scheme 2. Permutational isomerization in the reaction of **1Li** with **4**.

effect ensuring that the bromine is apical and the stereochemical preference for *tert*-butyl to be equatorial,^[20–22] the pentacoordinate intermediate **a** preferentially collapses to provide the (S_P, S_P) compound **5** without undergoing permutational isomerization. However, one BPR can transform **a** to **b** in which the large *tert*-butylphenylphosphane oxide group becomes equatorial.^[20–22] Extrusion of bromide from **b** provides *meso* compound **3**.^[23] Alternatively, a TR^[20] within **a** provides intermediate **b'**, which can also collapse to the *meso* compound; formation of **b'** with the bulky *tert*-butyl and *tert*-butylphenylphosphane oxide group both equatorial may be especially favoured.^[24]

In the sterically less demanding reactions involving the diphenylphosphane oxides, configurational integrity of the products is fully maintained; elimination of apical bromine is faster than permutational isomerism. In this context, it should be noted that reaction of **1Li** with phosphinic bromide **4** or **2Li** with phosphinic bromide **6** on a 0.5 mmol scale requires ten

hours reaction time at -78°C , whereas reaction of lithiated diphenylphosphane oxide **10Li** with phosphinic bromide **4** on the same scale requires two hours for completion.

Conclusion

A method has been described for the facile synthesis of novel symmetrically and unsymmetrically substituted diphosphane dioxides in enantiomerically pure form. Whilst the current investigation has focussed on secondary phosphane oxides bearing phenyl and *tert*-butyl ligands, it clearly provides the basis for extension to other substitution patterns. In addition, the prospect has been opened up for the coupling *P*-chiral secondary phosphane oxides with *S*-chiral reagents such as sulfinyl halides to provide the unknown sulfinyl phosphane oxides containing a P–S linkage with chirality at both phosphorus and sulfur.

The properties of the enantiomerically pure symmetrically and unsymmetrically substituted diphosphane dioxides as chiral ligands for asymmetric catalysis will be reported elsewhere.

Experimental Section

General: Melting points were determined in a capillary tube and are uncorrected. IR spectra were recorded for thin films on NaCl plates by using a Perkin-Elmer 16PC FTIR spectrometer. ^1H (400 MHz, 300 MHz), ^{13}C (100 MHz, 75 MHz) and ^{31}P (161 MHz) NMR spectra were recorded on a JOEL FX-400 and Bruker ARX-300 spectrometers with CDCl_3 as solvent unless otherwise stated. ^{31}P NMR spectra were referenced with trimethylphosphite ($\delta_P = 140.0$). Optical activities were recorded on a Perkin Elmer 241 polarimeter, and enantiomeric purities were determined by means of ^1H NMR spectra with added (R_P)- and (S_P)-*tert*-butylphenyl-phosphinothioic acids in CDCl_3 , as previously described.^[11]

Materials: (R_P)- and (S_P)-*tert*-butylphenylphosphane oxides **1** and **2** were prepared as previously described.^[11]

X-Ray Crystallography: Details of crystal structure determination for compounds **3** and **5** are given in Table 1. Data was collected on a Siemens P4-RA four-circle diffractometer with MoK_α radiation ($\lambda = 0.71073 \text{ \AA}$) and a precisely oriented graphite crystal monochromator. Structure solution and refinement were carried out by direct methods with SHELXTL-PLUS (G. W. Sheldrick, Siemens Analytical Instruments, 1992).

The absolute configuration of the diphosphane dioxide **5** was established as (S_P, S_P) by refinement of a free variable which multiplied all $\Delta f''$ imaginary components of the atomic scattering factors. This refined to a value of 1.1 (0.2) indicating the correct enantiomorph,^[23] and the Flack parameter refined to a value close to zero, $-0.05(10)$,^[24] confirming this assignment.

Whilst structure solution and refinement for **5** proceeded smoothly, the structure of the *meso* compound **3**, although solved initially with success, only refined to an *R* value of ca. 0.15. At this point, “ghost” peaks could be discerned for the phosphorus and several other non-hydrogen atoms. These were successfully incorporated as a minor component of a twin-disorder with site occupancies of 0.22. Eventually peaks for all non-hydrogen atoms of the minor component were located and refined isotropically with bond distance restraints. Through this approach, the final *R* value decreased to a more respectable 0.047 (0.060 for all data), with commensurately better esd’s for structural parameters and a clear final difference Fourier map showing no electron density peaks or holes $>0.20 \text{ e \AA}^{-3}$.

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data

Table 1. Summary of the crystallographic data for diphosphane dioxides **3** and **5**.

	3	5
empirical formula	C ₂₀ H ₂₈ O ₂ P ₂ ·H ₂ O	C ₂₀ H ₂₈ O ₂ P ₂
colour: habit	colourless bars	colourless prisms
crystal size (mm)	0.5 × 0.2 × 0.15	0.4 × 0.3 × 0.3
crystal system	monoclinic	orthorhombic
space group	C2/c	P2 ₁ 2 ₁ 2 ₁
unit cell dimensions		
<i>a</i> (Å)	15.437(3)	9.734(2)
<i>b</i> (Å)	9.516(2)	10.645(3)
<i>c</i> (Å)	14.360(3)	19.019(5)
β (°)	100.80(3)	
<i>V</i> (Å ³)	2072.1(7)	1972.4(14)
<i>Z</i>	4	4
<i>M_r</i>	380.4	362.4
ρ_{calc} (Mg m ⁻³)	1.219	1.231
absorp. coeff. (mm ⁻¹)	0.225	0.232
<i>F</i> (000)	816	776
<i>T</i> (K)	298	199
2θ range (°)	3.0–55.0	3.0–55.0
scan type: speed (° min ⁻¹)	ω ; 4.00–60.00 in ω	$2\theta - \theta$; 3.00–60.00 in ω
scan range ω (°)	0.80	0.80 + $K\alpha$ separation
reflins collected	1706	2745
independent reflns	1636 ($R_{\text{int}} = 2.15\%$)	2645 ($R_{\text{int}} = 1.64\%$)
observed reflns	1326 ($F > 4.0\sigma(F)$)	2516 ($F > 4.0\sigma(F)$)
absolute structure		$\eta = 1.1(2)$
weighting scheme	$w^{-1} = \sigma^2(F) + 0.0003F^2$	$w^{-1} = \sigma^2(F) + 0.0002F^2$
no. parameters refined	167	219
final <i>R</i> indices (obs. data) (%)	<i>R</i> = 4.71, <i>wR</i> = 5.84	<i>R</i> = 3.19, <i>wR</i> = 4.17
<i>R</i> indices (all data) (%)	<i>R</i> = 6.01, <i>wR</i> = 7.67	<i>R</i> = 3.41, <i>wR</i> = 4.30
goodness of fit	1.97	1.63
largest and mean Δ/σ	1.908, 0.135	
data-to-parameter ratio	7.9:1	11.5:1
largest diff. peak/hole (e Å ⁻³)	0.19/–0.19	0.33/–0.26

Centre as supplementary publication no. CCDC-100555. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB21EZ, UK (Fax: Int. code + (1223) 336-033; e-mail: deposit@chemcrs.cam.ac.uk).

(*R_p*)-tert-Butylphenylphosphinic bromide (4): (*S*)-tert-Butylphenylphosphane oxide (**2**) (331 mg, 1.82 mmol) in CH₂Cl₂ (9.0 mL) was added dropwise to *N*-bromosuccinimide (323 mg, 1 mmol) in CH₂Cl₂ (9.0 mL) at 0 °C under nitrogen. The resulting solution was stirred for 2 d. The mixture was concentrated under reduced pressure. Flash chromatography (SiO₂; ethyl acetate/hexanes 30:70) of the residue followed by concentration of the eluate gave needles (450 mg, 95%). $[\alpha]_D^{25} = +44.1$ ($c = 0.56$, CHCl₃); $[\alpha]_D^{25} = +52.0$ ($c = 0.45$, C₆H₆); m.p. 81–83 °C [ref. [16]; $[\alpha]_D = +49.91$ ($c = 0.0107$, C₆H₆)]. ¹H NMR (400 MHz): $\delta = 7.86$ –7.92 (2H, m, Ar-H), 7.57–7.62 (1H, m, Ar-H), 7.49–7.54 (2H, m, Ar-H), 1.27 (9H, d, *J* = 19.53 Hz). ³¹P NMR (161 MHz): $\delta = 29.90$. ee ≥ 99% (established by ¹H NMR assay as previously described.^{11,21} by addition of (*S_p*)- and (*R_p*)-tert-butylphenylphosphinothioic acid).

(*S_p*)-tert-Butylphenylphosphinic bromide (6) was similarly obtained from (*R*)-tert-butylphenylphosphane oxide (**1**), ee ≥ 99%, needles m.p. 81–83 °C. ¹H NMR (400 MHz): $\delta = 7.86$ –7.92 (2H, m, Ar-H), 7.57–7.62 (1H, m, Ar-H), 7.49–7.54 (2H, m, Ar-H), 1.27 (9H, d, *J* = 19.53 Hz). ³¹P NMR (161 MHz): $\delta = 29.90$. MS: *m/z* (CI): 261 (*M*⁺ + 1, 65%). C₁₀H₁₄BrOP calcd C 46.00, H 5.40; found C 46.23, H 5.44. $[\alpha]_D^{22} = -46.2$ ($c = 0.73$, CHCl₃), $[\alpha]_D^{22} = -55.6$ ($c = 0.73$, C₆H₆).

Diphenylphosphinic bromide (8): Diphenylphosphane oxide (125 mg, 1.00 mmol) in tetrahydrofuran (5 mL) at –78 °C under nitrogen was treated dropwise with *n*-butyllithium. After 10 min, bromine (50 μ L, 1.1 mmol) was added dropwise. The solution was stirred for a further 1 h with warming to room temperature. The reaction mixture was quenched with saturated aqueous ammonium chloride solution and extracted with diethyl ether (2 × 20 mL). The extracts were washed with 5% aqueous sodium bisulfite solution (10 mL), dried (MgSO₄) and concentrated under reduced pressure. Flash chromatography (ethyl acetate/hexanes 50:50) gave the phosphinic bromide **8** as needles (137 mg, 49%), m.p. 100–101 °C, from ethyl acetate.

¹H NMR (400 MHz): $\delta = 7.79$ –7.83 (4H, m, Ar-H), 7.44–7.53 (6H, m, Ar-H). ³¹P NMR (161 MHz): $\delta = 78.4$. MS: *m/z* (CI): 282 (*M*⁺ + 1, 65%). C₁₂H₁₀BrOP calcd C 51.28, H 3.59; found C 51.51, H 3.62.

(*R_p*,*R_p*)-1,2-Di-tert-butyl-1,2-diphenyldiphosphane 1,2-dioxide (7) and meso-1,2-Di-tert-butyl-1,2-diphenyldiphosphane 1,2-dioxide (3): *n*-Butyllithium was added dropwise to (*S*)-tert-butylphenylphosphane oxide (**2**) (91 mg, 0.5 mmol) in THF (3.0 mL) at –78 °C under nitrogen. The solution was stirred for 10 min and then treated with (*S*)-tert-butylphenylphosphinic bromide **6** (131 mg, 0.5 mmol) in THF (3.0 mL). The reaction mixture was stirred for a further 10 h at –78 °C, and then quenched with saturated NH₄Cl solution, warmed to RT and extracted with diethyl ether. The combined ether extracts were washed with brine, dried and concentrated in vacuo. Flash chromatography (SiO₂; ethyl acetate/hexanes) of the residue afforded two products: first **3** and then **7** in a 1:2 ratio (141 mg, 78% overall yield).

3: prisms, m.p. 202–204 °C. ¹H NMR (400 MHz): $\delta = 8.33$ (2H, brs, Ar-H), 8.12 (2H, brs, Ar-H), 7.45–7.59 (6H, br, Ar-H), 0.97 (18H, d, *J* = 16.12 Hz, Me₃C). ³¹P NMR (161 MHz): $\delta = 48.9$. MS: *m/z* (CI): 363 (*M*⁺ + 1, 4%), 306 (*M*⁺ + 1 – Me₃C), 250 (*M*⁺ + 2 – 2 Me₃C), 228 (*M*⁺ – Me₃C – Ph). C₂₀H₂₈O₂P₂ calcd C 66.29, H 7.79; found C 66.42, H 7.80.

7: prisms, m.p. 181–182 °C. ¹H NMR (400 MHz): $\delta = 7.44$ –7.76 (10H, brm, Ar-H), 1.39 (18H, d, *J* = 16.60 Hz, Me₃C). ³¹P NMR (161 MHz): $\delta = 48.9$. MS: *m/z* (EI): 362 (*M*⁺, 4%), 306 (*M*⁺ – Me₃C), 250 (*M*⁺ – 2 Me₃C), 228 (*M*⁺ – Me₃C – Ph). C₂₀H₂₈O₂P₂ calcd C 66.29, H 7.79; found C 66.36, H 7.79. $[\alpha]_D^{20} = -70$ ($c = 0.05$, CHCl₃).

(*S_p*,*S_p*)-1,2-Di-tert-butyl-1,2-diphenyldiphosphane 1,2-dioxides (5) was obtained as described above and on the same scale starting with phosphane oxides **1** and **4**. Products **5** and **3** were obtained in a ratio of 2:1 (78% overall yield). **5:** m.p. 180–182 °C. ¹H NMR (400 MHz): $\delta = 7.44$ –7.76 (10H, brm, Ar-H), 1.39 (18H, d, *J* = 16.60 Hz, Me₃C). ³¹P NMR (161 MHz): $\delta = 48.9$. MS: *m/z* (EI): 362 (*M*⁺, 5%), 306 (*M*⁺ – Me₃C), 228 (*M*⁺ – Me₃C – Ph). $[\alpha]_D^{20} = +71$ ($c = 0.05$, CHCl₃).

(*S_p*)-1-tert-Butyl-1,2,2-triphenyldiphosphane 1,2-dioxide (9): *n*-Butyllithium was added dropwise to (*R*)-tert-butylphenylphosphane oxide (**1**) (91 mg, 0.5 mmol) in THF at –78 °C under nitrogen. After 10 min, diphenylphosphinic bromide **8** (102 mg, 0.5 mmol) in THF was added, and the solution was stirred for a further 3 h at –78 °C. It was then quenched with saturated NH₄Cl solution, and the mixture was extracted with diethyl ether. The combined ether extracts were washed with brine, dried and concentrated under vacuum. Flash chromatography (SiO₂; ethyl acetate/hexanes 60:40) of the residue afforded **9** (58% yield) as needles, m.p. 140–144 °C, from ethyl acetate. ¹H NMR (400 MHz): $\delta = 7.46$ –7.86 (15H, brm, Ar-H), 1.42 (9H, d, *J* = 15.42 Hz, Me₃C). ³¹P NMR (161 MHz): $\delta = 48.5$ (d, *J* = 60.4 Hz), 49.3 (d, *J* = 60.4 Hz). MS: *m/z* (CI): 383 (*M*⁺ + 1, 50%), 326 (*M*⁺ + 1 – Me₃C); (EI) 382 (*M*⁺, 3%). C₂₂H₂₄O₂P₂ calcd C 69.10, H 6.33; found C 69.23, H 6.35. $[\alpha]_D^{25} = +27.2$ ($c = 0.40$, CHCl₃).

(*R_p*)-1-tert-Butyl-1,2,2-triphenyldiphosphane 1,2-dioxide (11): *n*-Butyllithium (0.42 mL, 1.05 mmol, 2.5M in hexanes) was added to diphenylphosphane oxide (**10**) (202 mg, 1.0 mmol) in THF (6 mL) at –78 °C under nitrogen. The resulting solution was stirred for 10 min and then treated with (*S_p*)-tert-butylphenylphosphinic bromide (**6**) (262 mg, 1.0 mmol) in THF (6 mL). The solution was stirred for a further 2 h at –78 °C and then quenched with saturated aqueous ammonium chloride solution at this temperature. After warming, the mixture was extracted with diethyl ether. The combined ether extracts were washed with brine, dried and concentrated under reduced pressure. Flash chromatography (ethyl acetate/hexanes 60:40) afforded **11** (222 mg, 58%) as needles, m.p. 140–144 °C, from ethyl acetate. ¹H NMR (400 MHz): $\delta = 7.46$ –7.80 (15H, brm, Ar-H), 1.45 (9H, d, *J* = 15.64 Hz, Me₃C). ³¹P NMR (161 MHz): $\delta = 48.5$ (d, *J* = 60.4 Hz), 49.3 (d, *J* = 60.4 Hz). MS: *m/z* (CI): 383 (*M*⁺ + 1, 50%), 326 (*M*⁺ + 1 – Me₃C). C₂₂H₂₄O₂P₂ calcd C 69.10, H 6.33; found C 69.20, H 6.36. $[\alpha]_D^{21} = -26.8$ ($c = 0.38$, CHCl₃).

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