Available online at www.sciencedirect.com
SCIENCE DIRECT®
Tetrahedron: *Asymmetry* 15 (2004) 3519–3529
Tetrahedron: *Asymmetry*

Enantiomerically pure disulfides: key compounds in the kinetic resolution of chiral P^{III}-derivatives with stereogenic phosphorus

Wieslawa Perlikowska,[a] Maryse Gouygou,[b] Marian Mikolajczyk[a,*] and Jean-Claude Daran[b,*]

[a]*Centre of Molecular and Macromolecular Studies, Polish Academy of Sciences, Sienkiewicza 112, 90-363 Lodz, Poland*
[b]*Laboratoire de Chimie de Coordination du CNRS, 205 Route de Narbonne, 31077 Toulouse Cedex 4, France*

Received 27 July 2004; accepted 6 September 2004

Abstract—Enantiomerically pure disulfides were reacted with various chiral P^{III}-derivatives with stereogenic phosphorus such as tertiary phosphines, halogenophosphines, phosphinite and phosphole under kinetic resolution conditions to afford enantiomerically enriched phosphine oxides or sulfides with ee values up to 50%. Enantiomeric excess rose to 70% under dynamic kinetic resolution conditions in the case of *tert*-butylphenylchlorophosphine.

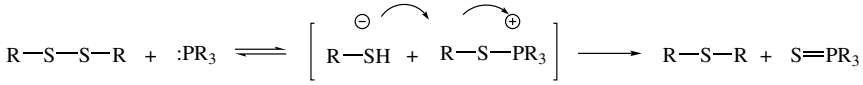
1. Introduction

Enantiopure phosphine transition metal complexes play an important role in asymmetric synthesis.[1] Although most of the chiral ligands used are bidentate diphosphines, a limited number of monodentate chiral phosphine ligands[2] proved to be efficient auxiliaries in catalytic asymmetric induction processes. Indeed, for some reactions both reactivities and/or selectivities displayed by diphosphines are lower than with monophosphines.[3] In recent years, increasing attention has also been directed to chiral monophosphites,[4] monophosphonites[5] and monophosphoramidites.[6]

In connection with our continued work on the design and synthesis of new chiral phosphine ligands with applications in asymmetric catalysis,[7] we decided to explore a new versatile method for obtaining enantiomerically pure chiral phosphines and other trivalent phosphorus derivatives. Our attention was focused on the kinetic resolution of racemic P^{III}-compounds, which can take place in the reaction with enantiomerically pure disulfides.

Although the sulfurization of phosphines by disulfides has been reported[8] (Scheme 1), the asymmetric version of this reaction has never been described. Therefore, we investigated the asymmetric sulfurization reaction of P-stereogenic phosphines with enantiomerically pure disulfides as a way for the synthesis of enantiomerically enriched phosphines sulfides, which in turn can be converted into the desired phosphines by known stereoselective methods.[9]

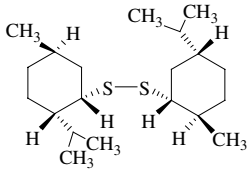
Our initial studies were carried out on a few configurationally stable phosphines using enantiomerically pure disulfides *R*–S–S–R** such as bis-thiophosphoryl **2** and bis-phosphoryl **5** disulfide compounds (Fig. 1) under kinetic resolution conditions.[10] As an extension of this study, our attention was focused on the synthesis



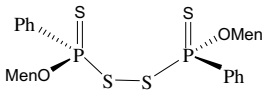
Scheme 1.

* Corresponding authors. E-mail: daran@lcc-toulouse.fr

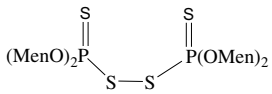
0957-4166/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetasy.2004.09.014



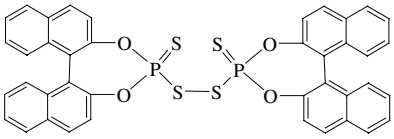
(+)-(*RSS*)-**1**



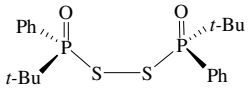
(+)-(*S,S*)-**2**



(-)-(*RRS*)-**3**



(-)-(*R,R*)-**4**



(+)-(*R,R*)-**5**

Figure 1. View of the enantiomerically pure disulfides **1**–**5**.

of new disulfides **1**, **3** and **4** containing chiral alkyl, alkoxy or aryloxy groups (menthyl, menthoxy, binaphthoxy) (Fig. 1) and their use for the resolution of various configurationally stable and unstable P-chiral phosphines **6**.

Herein, we report the results of our work on the kinetic resolution and/or kinetic dynamic resolution of various racemic, P-stereogenic trivalent phosphorus compounds such as tertiary phosphines **6a**–**d**, halogenophosphines **6e**–**f**, phosphinite **6g** and phosphole **9**. The synthesis and characterization of the enantiomerically pure disulfides **1** and **3**–**5** are also described.

2. Results and discussion

2.1. Synthesis of enantiomerically pure disulfides 1–5

The enantiomerically pure (−)-(*S,S*)-bis-(menthoxylphenylphosphinothioyl)disulfide **2** was prepared according to the published procedure.[11] For disulfides **1** and **3**–**5**, the method used was based on the oxidative coupling reaction of the corresponding thioacid derivatives.

The oxidation by iodine, under two-phase conditions ($CHCl_3/H_2O$), of the enantiomerically pure (+)-(*RSS*)-

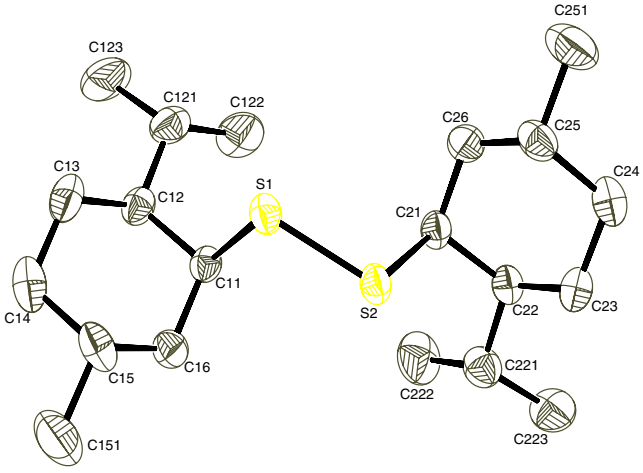
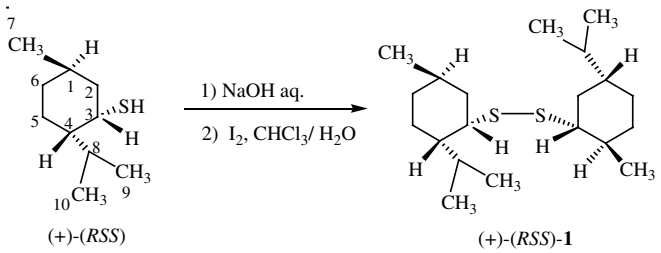
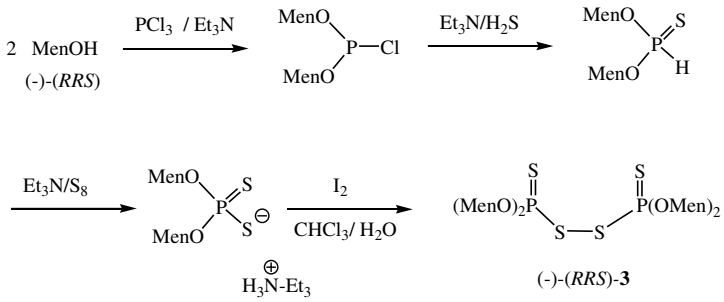


Figure 2. Molecular view of (+)-(*RSS*)-**1** with atom labelling scheme. Ellipsoids are drawn at the 30% probability level. Selected bond distances (Å) and bond angles (°): S1–C11 1.8487(12); S2–C21 1.8466(12); S1–S2 2.0273(5); C11–S1–S2 102.90(4); C21–S2–S1 103.04(4).



(+)-(*RSS*) (+)-(*RSS*)-**1**

Scheme 2.



Scheme 3.

neomenthanethiol, prepared according to the literature,[12] gave in 83% yield the enantiomerically pure (+)-(*RSS*)-bis-neomenthyl disulfide **1** (Scheme 2). This compound was characterized by ^{1}H, ^{13}C NMR spectroscopy and mass spectrometry with its crystal structure determined by X-ray diffraction analysis (Fig. 2). It crystallized in the enantiomorphous space group $P6_1$. The absolute configuration was deduced from the refinement of the Flack parameter and confirmed with the synthetic pathway used. The two cyclohexyl rings have a chair conformation as observed in the related bis-(2-(*N*,*N*-dimethylamino)cyclohexyl)disulfide[13] with the torsion angle C(11), S(1), S(2), C(21) being 87.2°. This value is slightly larger than the value of 82.6° found in bis-(2-(*N*,*N*-dimethylamino)cyclohexyl)disulfide as mentioned above.[13] The S–S bond length, 2.0273(5) Å, is within the usual range of values observed for disulfide compounds.[14]

(−)-Bis-[(*RRS*)-dimenthoxyphosphorothionyl]disulfide **3** was obtained in four steps starting from (−)-(*RRS*)-menthol (Scheme 3). In the first step, menthol was reacted with phosphorus trichloride in the presence of triethylamine to give the corresponding chlorophosphinite. In the second step, treatment of the latter with hydrogen sulfide in the presence of triethylamine led to the corresponding thiophosphite, which gave in the next step upon treatment with elemental sulfur in the presence of triethylamine, the triethylammonium salt of phosphorodithioic acid. Next, the oxidation of this thioacid salt by iodine afforded in the last step the desired disulfide **3** in 68% yield. This compound was characterized by ^{31}P, ^{1}H, ^{13}C NMR spectroscopy and mass spectrometry. Its structure was confirmed by X-ray diffraction analysis (Fig. 3). The disulfide **3** crystallized in the orthorhombic noncentrosymmetric

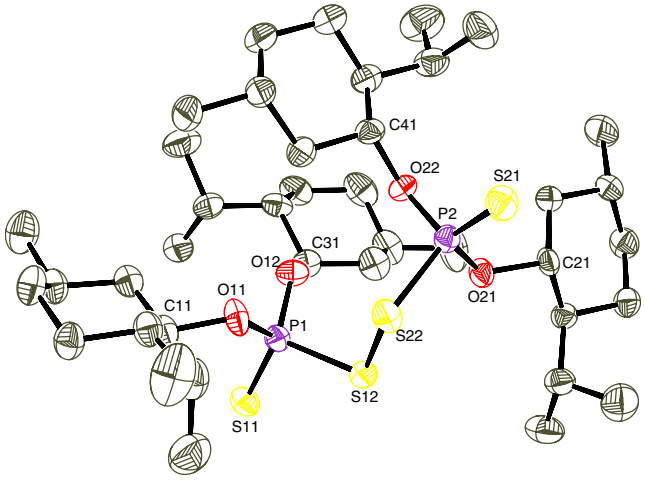
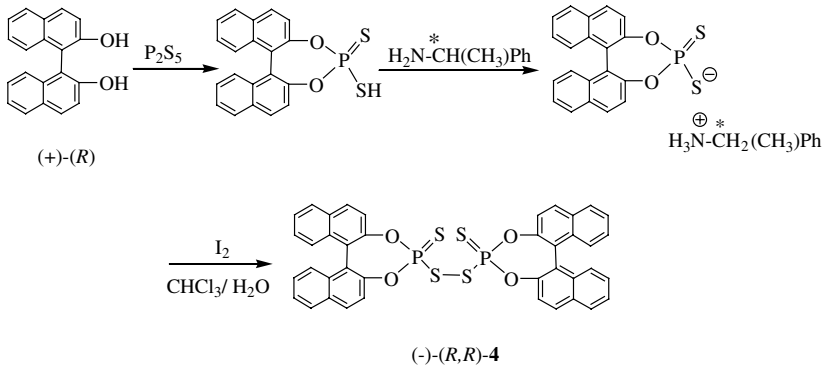
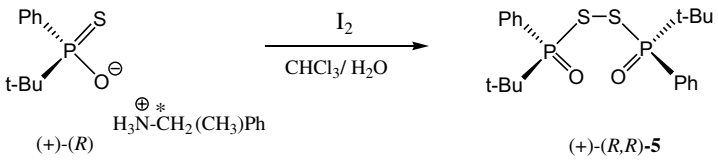


Figure 3. Molecular view of (−)-(*RRS*)-**3** with atom labelling scheme. Ellipsoids are drawn at the 30% probability level. Selected bond distances (Å) and bond angles (°): P1–S11 1.9222(11); P1–S12 2.0895(11); P1–O11 1.571(2); P1–O12 1.567(2); P2–S21 1.9220(11); P2–S22 2.0973(11); P2–O21 1.561(2); P2–O22 1.583(2); S12–S22 2.0615(12); P1–S12–S22 105.90(5); P2–S22–S21 108.13(5).



Scheme 4.



Scheme 5.

space group $P2_12_12_1$. There was only one enantiomer in the crystal and the absolute configuration deduced from the refinement of the Flack parameter agreed with the synthetic pathway used. The geometry of the P_2S_4 framework is closely related to the compounds having phosphoryl groups and adopting a *syn–syn* conformation.[14] However, the torsion angle P(1), S(1), S(2), P(2) of 119.8° is much larger than the 93.7° reported for the sulfur derivatives. This difference may be related to the larger S–S contact, 3.43 Å, as compared to the S–O contact of 3.02 Å.

The enantiomerically pure (−)-(*R*,*R*)-bis-(1,1-di-2-naphthoxyphosphinothioyl)disulfide **4** was prepared by the oxidation of 1,1-bis-2-naphthoxyphosphinodithioic acid obtained according to the literature[15] from the (+)-(*R*)-1,1′-bis-2-naphthol (Scheme 4). This compound, obtained in 75% yield, was characterized by ^{31}P, ^{1}H, ^{13}C NMR spectroscopy and mass spectrometry.

Finally, the two-phase ($CHCl_3/H_2O$) oxidation by iodine of the enantiomerically pure (−)-α-phenylethylammonium salt of the (+)-(*R*)-*tert*-butylphenylphosphinothioic acid[16] gave the enantiomerically pure (+)-(*R*,*R*)-bis-(*tert*-butylphenylphosphinoyl)disulfide **5** (Scheme 5). This compound was characterized by ^{31}P and ^{1}H NMR spectroscopy and its stereostructure was confirmed by X-ray diffraction analysis (Fig. 4).[10]

2.2. Kinetic resolution of the P-chiral tertiary phosphines 6a–d

The reactivity of the five enantiomerically pure disulfides **1**–**5** was tested under kinetic resolution conditions towards various racemic P-stereogenic phosphines **6a**–**d**, prepared via known methods starting from chlorophosphine.[17]

Disulfide **1** did not react with phosphines **6a**–**c** in dichloromethane solution at room temperature, or under reflux.

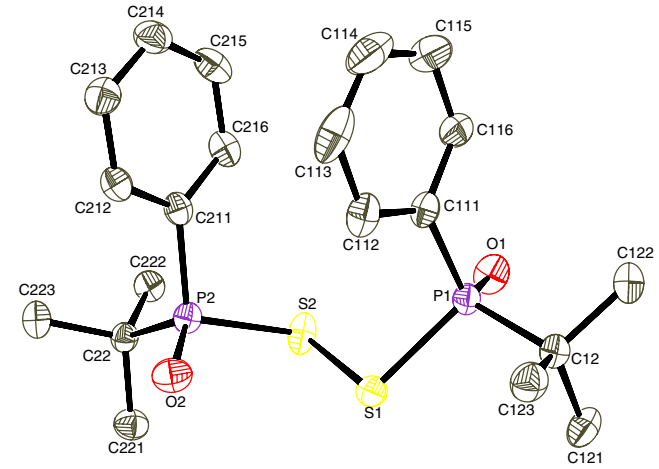
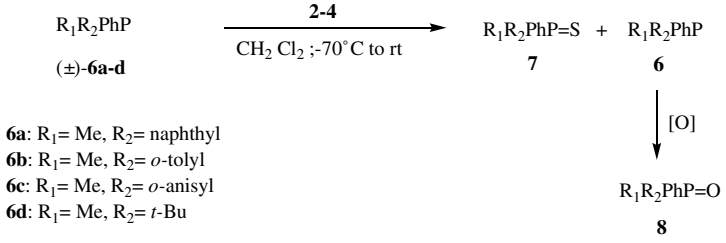


Figure 4. Molecular view of (+)-(*R*,*R*)-**5** with atom labelling scheme. Ellipsoids are drawn at the 30% probability level. Selected bond distances (Å) and bond angles (°): P1–S1 2.1113(6); P1–O1 1.4758(14); P1–C12 1.8382(18); P1–C111 1.7939(18); P2–S2 2.1357(7); P2–O2 1.4755(13); P2–C22 1.8341(18); P2–C211 1.8056(18); S1–S2 2.0495(7); P1–S1–S2 97.12(3); P2–S2–S1 100.66(3).

In contrast, the reaction with disulfides **2**–**4** proceeded rapidly in dichloromethane solution, even at low temperatures (−40 °C), as evidenced by ^{31}P NMR. When racemic phosphines **6a**–**d** were treated with half-molar amounts of disulfides, the reaction led, as expected, to an equimolar mixture of optically active phosphine sulfides **7a**–**d** and unreacted starting phosphines (Scheme 6). The remaining phosphines were oxidized to the corresponding oxides **8a**–**d** by oxidation with air. Both phosphine sulfides and phosphine oxides, isolated after typical work-up and separation by column chromatography, exhibited low enantiomeric purity[18] (0–28%) (Table 1). The best results were obtained with phosphines **6a** and **6b**.

The formation of optically active phosphine sulfides **7a**–**d**, from the reaction of the disulfide **2**–**4** with racemic



Scheme 6.

Table 1. Absolute configurations and enantiomeric excesses of phosphine sulfides **7** and phosphine oxides **8** determined by specific rotation

Phosphines	Reaction with **2**	Reaction with **3**	Reaction with **4**
6a			
R^1 = Me	(−)-(*S*)-**7a**[12a], $[\alpha]_D = -33.5$ ($CHCl_3$), ee = 26%	(−)-(*S*)-**7a**, $[\alpha]_D = -25.2$ ($CHCl_3$), ee = 19.5%	(−)-(*S*)-**7a**, $[\alpha]_D = -29.5$ ($CHCl_3$), ee = 23%
R^2 = α-naphthyl	(−)-(*R*)-**8a**[12b], $[\alpha]_D = -5.2$ (MeOH), ee = 26%	(−)-(*R*)-**8a**, $[\alpha]_D = -4.0$ (MeOH), ee = 20%	(−)-(*R*)-**8a**, $[\alpha]_D = -3.8$ (MeOH), ee = 19%
6b			
R^1 = Me	(−)-**7b**, $[\alpha]_D = -2.2$ ($CHCl_3$)	(−)-**7b**, $[\alpha]_D = -2.1$ ($CHCl_3$)	(+)-**7b**, $[\alpha]_D = +6.8$ ($CHCl_3$)
R^2 = *o*-tolyl	(−)-(*S*)-**8b**[12c], $[\alpha]_D = -8.9$ ($CHCl_3$), ee = 28%	(−)-(*S*)-**8b**, $[\alpha]_D = -4.8$ ($CHCl_3$), ee = 15%	(−)-(*S*)-**8b**, $[\alpha]_D = -7.5$ ($CHCl_3$), ee = 23.5%
6c			
R^1 = Me	(+)-(*R*)-**7c**[12d], $[\alpha]_D = +0.8$ (MeOH), ee = 10%	(+)-(*R*)-**7c**, $[\alpha]_D = +0.7$ (MeOH), ee = 9%	(+)-(*R*)-**7c**, $[\alpha]_D = +0.9$ (MeOH), ee = 11%
R^2 = *o*-anisyl	(−)-(*S*)-**8c**[12e], $[\alpha]_D = -3.2$ (MeOH), ee = 12%	(−)-(*S*)-**8c**, $[\alpha]_D = -2.7$ (MeOH), ee = 10%	(−)-(*S*)-**8c**, $[\alpha]_D = -2.7$ (MeOH), ee = 10%
6d			
R^1 = Me	**7d**, ee = 0%	(−)-(*S*)-**7d**[12e], $[\alpha]_D = -136$ ($CHCl_3$), ee = 26%	(+)-(*R*)-**7d**, $[\alpha]_D = +4.2$ ($CHCl_3$), ee = 8.2%
R^2 = *t*-butyl		(+)-(*R*)-**8d**[12f], $[\alpha]_D = +3.6$ (C_6H_6), ee = 24%	(−)-(*S*)-**8d**, $[\alpha]_D = -0.8$ (C_6H_6), ee = 5.8%

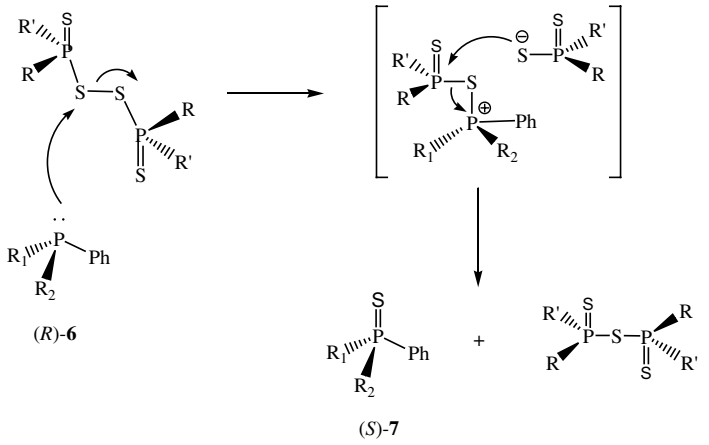
phosphine **6a–d**, proceeds by a classical mechanism, which involves in the first step a nucleophilic attack of the phosphine at the sulfur atom of the disulfide. Afterwards, the thiophosphonium salt intermediate undergoes decomposition to the final products, that is, **7** and trithioanhydride (Scheme 7).

Better enantioselectivities were obtained in the reaction of enantiopure disulfide **5** (Scheme 8) with phosphines **6a–d** used in a 1:2 ratio (Table 2). In these cases, the reactions afforded instead of phosphine sulfides optically active phosphine oxides **8a–d**, and unreacted starting phosphines.[19] The addition of elemental sulfur to this mixture resulted in the conversion of the remaining phosphines into the corresponding optically active phosphine sulfides **7a–d** (Scheme 8). The absolute configurations, specific rotations and ee values are reported in Table 2. According to these results, phosphines **6a–d** with an (*R*)-configuration reacted faster with the disulfide (+)-(*R*,*R*)-**5**. Their conversion into phosphine oxides **8a–d** can be explained by the mechanism shown in Scheme 9. As in the case of disulfides **2–4**, the first step proceeded in the same way by a preferential nucleophilic attack of (*R*)-**6** at sulfur in (*R*,*R*)-**5** leading to the first phosphonium intermediate (Scheme 9). Two different pathways can be postulated for the second step. The first involves an intramolecular thiolo–thiono isomerization with retention of configuration at the phosphonium phosphorus atom leading, after decomposition, to the formation of (−)-(*S*)-**8** and dithioanhydride. The second pathway proceeds with an inversion of configuration at the phosphonium centre as a result of intermolecular nucleophilic substitution. As all of these phosphine oxides were obtained with an (*S*)-configuration, meaning the first mechanism to be the most likely.

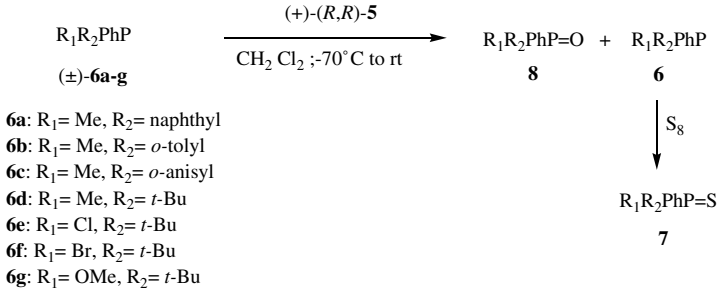
2.3. Kinetic resolution of the P-chiral halogenophosphines 6e–f and the *O*-methyl *tert*-butylphosphinite 6g

2.3.1. Kinetic resolution conditions. Our attention was next focused on the kinetic resolution of P-chiral halogenophosphines **6e** and **6f** and methoxyphosphinite **6g**. The enantiomerically enriched halogenophosphines[20] and phosphinite would be useful in the synthesis of new classes of monophosphine ligands with a P-stereogenic atom.[21] Disulfide **5**, which seems to be the better resolving agent was used in these experiments.

The reaction of chlorophosphine **6e** with disulfide **5** under kinetic resolution conditions afforded (+)-(*S*)-*tert*-butylphenylphosphinoyl chloride **8e** and (−)-(*R*)-*tert*-butylphenylphosphinothionyl chloride **7e** obtained after sulfurization of the unreacted chlorophosphine **6e** (Scheme 8). The enantiomeric excess of the oxide compound **8e** was 50% whereas the sulfur compound **7e** was only obtained with 28% ee (Table 2). This lower ee value is probably due to a partial racemization of the unreacted chlorophosphine **6e** caused by trace amounts of the chloride anion[18j,22] present in the reaction mixture. This isomerization appears to be faster than the reaction of the chlorophosphine **6e** with the disulfide **5**.



Scheme 7.



Scheme 8.

Table 2. Absolute configurations and enantiomeric excesses of phosphine sulfides **7** and phosphine oxides **8** determined by specific rotation

Phosphines	Reaction with **5**
6a	
R^1 = Me	(+)-(*S*)-**8a**, $[\alpha]_D$ = +7.0 (MeOH), ee = 35%
R^2 = α-naphthyl	(+)-(*R*)-**7a**, $[\alpha]_D$ = +45.1 ($CHCl_3$), ee = 33%
6b	
R^1 = Me	(−)-(*S*)-**8b**, $[\alpha]_D$ = −8.3 ($CHCl_3$), ee = 26%
R^2 = *o*-tolyl	(+)-**7b**, $[\alpha]_D$ = +13.5 ($CHCl_3$)
6c	
R^1 = Me	(−)-(*S*)-**8c**, $[\alpha]_D$ = −0.9 (MeOH), ee = 3.5%
R^2 = *o*-anisyl	**7c**, $[\alpha]_D$ = 0.0 (MeOH)
6d	
R^1 = Me	(−)-(*S*)-**8d**, $[\alpha]_D$ = −5.85 (C_6H_6), ee = 39%
R^2 = *t*-butyl	(+)-(*R*)-**7d**, $[\alpha]_D$ = +7.1 ($CHCl_3$), ee = 14%
6e	
R^1 = Cl	(−)-(*S*)-**8e**$^{(12h)}$, $[\alpha]_D$ = −24.9 (C_6H_6), ee = 50%
R^2 = *t*-butyl	(−)-(*R*)-**7e**$^{(12i)}$, $[\alpha]_D$ = −2.8 (C_6H_6), ee = 28%
6f	
R^1 = Br	(−)-(*S*)-**8f**$^{(12k)}$, $[\alpha]_D$ = −12.0 ($CHCl_3$), ee = 26%
R^2 = *t*-butyl	(+)-(*R*)-**7f**$^{(12l)}$, $[\alpha]_D$ = +4.3 ($CHCl_3$), ee = 24.4%
6g	
R^1 = OMe	(+)-(*R*)-**8g**$^{(12l)}$, $[\alpha]_D$ = +14.2 ($CHCl_3$), ee = 21%
R^2 = *t*-butyl	(−)-(*R*)-**7g**$^{(12m)}$, $[\alpha]_D$ = −6.6 (C_6H_6), ee = 19%

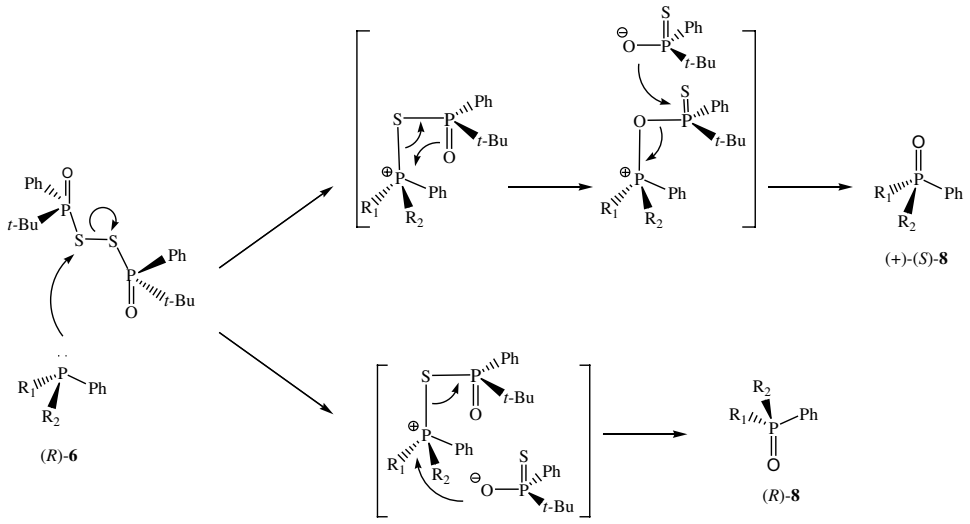
In contrast, when racemic bromophosphine **6f** was used under the same conditions, the enantiomeric purities of oxide **8f** (26%) and the sulfide **7f** (24%) were lower (Table 2). As the ee values are roughly the same in this case, the racemization process, due to a bromide–bromide exchange, is probably slower than the reaction of disulfide **5** with bromophosphine **6f**.

In the last experiment, the kinetic resolution of methoxyphosphinite **6g** was examined. Unfortunately, the optically active phosphinate **8g** (21%) and phosphinothionate **7g** (19%) were obtained with moderate enantioselectivities (Table 2).

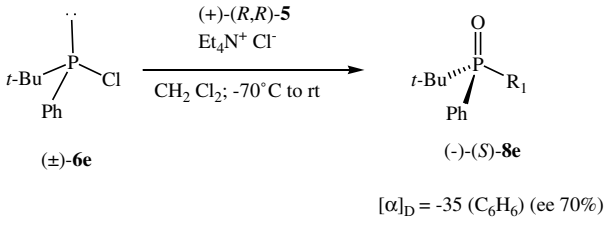
2.3.2. Kinetic dynamic resolution conditions. As mentioned above, the racemization of chlorophosphine **6e** was faster than the reaction with the disulfide **5**. This observation prompted us to perform the reaction under dynamic kinetic resolution conditions in the presence of chloride ions.

This was accomplished by reacting racemic phosphine **6e** with one equivalent of disulfide (+)-(*R*,*R*)-**5** in the presence of $Et_4N^+Cl^-$ in dichloromethane solution. Under these conditions, (−)-(*S*)-phosphinoylchloride **8e** was obtained with a high enantiomeric excess of 70% (Scheme 10).

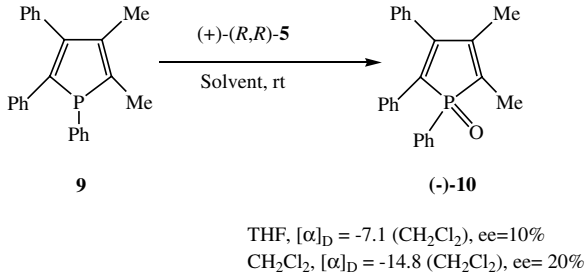
2.3.3. Kinetic dynamic resolution of the P-chiral phosphole. Encouraged by these results, we attempted to extend our study to the resolution of chiral phospholes under kinetic dynamic resolution conditions. Chiral



Scheme 9.



Scheme 10.



Scheme 11.

phospholes, which are stereolabile phosphines in solution at room temperature due to a low pyramidal inversion barrier[23] of the phosphorus, are good candidates for the dynamic kinetic resolution.

Initially, the resolution of 2,3-dimethyl-4,5-diphenyl-1-phenylphosphole[24] **9** was investigated under similar conditions (Scheme 11). When at room temperature using either dichloromethane or tetrahydrofurane as solvent, the reaction occurred with low enantioselectivities (10–20%). The best result was obtained using CH_2Cl_2 as solvent (20%). These low enantioselectivities are probably due to the slow isomerization of the two enantiomers of phosphole **9** with respect to their rate of reaction with disulfide **5**.

3. Conclusion

We have shown that enantiomerically pure disulfides are key compounds in the kinetic resolution of P-stereogenic phosphines and other trivalent P-compounds. These compounds allowed the obtention of various enantiomerically enriched P-stereogenic phosphoryl and thiophosphoryl compounds.

Among the enantiomerically pure disulfides used, (+)-(*R*,*R*)-bis-(*tert*-butylphenylphosphinoyl)disulfide **5** proved to be the best resolving agent, especially for the resolution of chlorophosphine **6e** under kinetic dynamic conditions. The enantiomerically enriched chlorophosphine obtained as oxide derivative (ee 70%) can be easily used for the synthesis of new functionalized P-chirogenic compounds and then easily converted into the corresponding P^{III}-compounds by a known stereoselective method.[25] Further studies are currently in progress in order to improve and generalize this method of resolution.

4. Experimental

4.1. General

All moisture sensitive reactions were carried under an inert atmosphere of dry argon by using Schlenk glassware and vacuum line techniques. Solvents were freshly distilled from standard drying agents. ^{1}H,$^{31}P\{^{1}H\}$- and $^{13}C\{^{1}H,^{31}P\}$-NMR spectra were recorded on a Bruker AM 250 spectrometer operating at 250, 101 and 63 MHz, respectively. Chemical shifts are reported in parts per million (ppm) relative to Me_4Si (^{1}H and ^{13}C) or 85% H_3PO_4 (^{31}P). Mass spectra were obtained with a Finnigan MAT 95 spectrometer for HRMS (FAB) and a Mermag R10-10 instrument for DCI. All optical rotation measurements were done on a Perkin–Elmer MC 241 photopolarimeter. Column chromatography was performed using Merck silica gel (70–230 mesh).

The enantiomerically pure (−)-(*S*,*S*)-bis-(menthoxylphenylphosphinothioyl)disulfide **2** was prepared as described in the literature.[11] The (+)-neomenthanethiol was prepared according to a published procedure.[8] The (−)-α-phenyl-ethylammonium salt of (+)-(*R*)-*tert*-butylphenylphosphinothioic acid was prepared according to the method described by Harger.[16] Phenylnaphthylmethylphosphine **6a**, phenyl-*o*-tolylmethylphosphine **6b** and phenyl-*o*-anisylmethylphosphine **6c** were prepared by known methods.[17a,b] Phenyl-*t*-butylmethylphosphine **6d**, phenyl-*t*-butylchlorophosphine **6e**, phenyl-*t*-butylbromophosphine **6f** and *o*-methylphenyl-*t*-butylphosphinite **6g** were obtained via general methods starting from phenyldichloro- or phenyldibromophosphine.[17a,b] 2,3-Dimethyl-4,5-diphenyl-1-phenylphosphole **9** was prepared according to the published procedure.[24]

4.2. Syntheses

4.2.1. (+)-(*RSS*)-Bis-neomenthyl disulfide 1. To a solution of (+)-neomenthanethiol (3.61 g, 0.021 mol) in 40 mL of benzene were added a 20% aq solution of NaOH (0.92 g, 0.023 mol) and 2.67 g of I_2 (0.0105 mol). The mixture was stirred at room temperature for 48 h. After separation, the aqueous phase was extracted with CH_2Cl_2 (3 × 15 mL). The combined organic extracts were then washed with an aq solution of $Na_2S_2O_3$, then with water and finally dried over $MgSO_4$. Evaporation of the solvent gave 3.3 g (83%) of crude disulfide **1**. Suitable crystals for X-ray analysis were obtained by slow evaporation of an ethanol solution. Mp 55–56 °C, $[\alpha]_D^{20}$ = +371.3 (*c* 1.1, $CHCl_3$). ^{1}H NMR ($CDCl_3$): δ = 0.80 (m, 4H, H-5a, H-6a), 0.87 (d, *J* = 7.0 Hz, 6H, H-9), 0.89 (d, *J* = 6.5 Hz, 6H, H-7), 0.97 (d, *J* = 7.0 Hz, 6H, H-10), 1.01 (m, 2H, H-2a), 1.15 (m, 2H, H-4a), 1.29 (m, 2H, H-1a), 1.56 (m, 4H, H-5e, H-6e), 2.01 (m, 2H, H-2e), 2.39 (m, 2H, H-8), 3.22 (m, 2H, H-3e). ^{13}C NMR ($CDCl_3$): δ = 20.6 (C-9), 21.2 (C-10), 22.2 (C-7), 25.9 (C-5), 26.2 (C-8), 29.9 (C-1), 35.5 (C-6), 39.7 (C-2), 48.7 (C-4), 52.5 (C-3). For the numeration of the atoms in the menthyl part, see Scheme 2. MS (DCI, NH_3); *m*/*z* (%): 343 (100) [MH^+].

4.2.2. (−)-Bis-[(*RRS*)-dimenthoxyphosphorothionyl]disulfide 3. To a solution of (−)-(*RRS*)-menthol (15.6 g, 0.1 mol) in dry toluene (150 mL) and Et_3N (14 mL, 0.1 mol), was added dropwise PCl_3 (5.8 mL 0.066 mol). The reaction mixture was stirred at room temperature for 4 h and then cooled at −10 °C. Et_3N (7 mL, 0.05 mol) was added and H_2S (0.2 mol) passed over this reaction mixture at −10 °C. This mixture was allowed to warm to room temperature, stirred overnight, washed with water (30 mL) and finally dried over $MgSO_4$. After evaporation of the solvent, the crude compound was purified by column chromatography on silica gel using pentane/diethyl ether mixture as eluent (99/1) to yield 19.0 g (77%) of dimenthyl thiophosphite. This compound was characterized only by ^{31}P NMR spectroscopy before use in the next step. ^{31}P NMR ($CDCl_3$): δ 67.05 ppm.

To a solution of this compound (18.7 g, 0.05 mol) in a dry hexane (200 mL) and toluene (40 mL) mixture at room temperature were added Et_3N (7 mL 0.05 mol) and elemental sulfur (2.25 g, 0.07 mol). After 2 days of stirring at room temperature, the insoluble pure triethylammonium salt of dimenthylphosphinodithioic acid was filtrated off. This compound (20.8 g, yield: 82%), obtained in a pure form, was characterized before using in the next step. Mp 115–116 °C. $[\alpha]_D$ = −47.7 (*c* 0.95, $CHCl_3$). ^{31}P NMR ($CDCl_3$): δ = 107.64 ppm. ^{1}H NMR ($CDCl_3$): δ = 0.83 (d, *J* = 6.75 Hz, 6H, H-7), 0.87 (d, *J* = 6.44 Hz, 12H, H-9, H-10), 1.02–2.55 (m, 12H, H-5, H-8, H-1, H-6, H-4, H-2), 1.38 (t, *J* = 7.3 Hz, 9H, CH_3 amine), 3.25 (q, *J* = 7.2 Hz, 6H, CH_2 amine), 4.20 (m, 2H, H-3). ^{13}C NMR ($CDCl_3$): δ = 8.55 (CH_3 amine), 16.60 (C-10), 21.38 (C-9), 22.25 (C-7), 23.01 (C-5), 25.10 (C-8), 31.64 (C-1), 34.55 (C-6), 43.23 (C-2), 45.94 (CH_2 amine), 48.73 and 48.89 (d, J^3 = 8 Hz, C-4), 77.69 and 77.86 (d, J^2 = 8.5 Hz, C-3). HRMS (FAB) calcd for $C_{20}H_{38}PO_2S_2^-$ 405.2036, obsd 405.2051.

To a solution of this salt (10.14 g, 0.02 mol) in chloroform (150 mL) were added H_2O (150 mL) and then I_2 (2.54 g, 0.01 mol). The reaction mixture was stirred at room temperature for 3 h. After separation, the organic phase was washed with an aq solution of $Na_2S_2O_3$, then with water and finally dried over $MgSO_4$. Crude disulfide **3**, obtained after evaporation of the solvent, was purified by column chromatography on silica gel using a pentane/dichloromethane (75/25) mixture as eluent to yield 6.5 g (80%) of compound **3**. Crystals suitable for X-ray analysis were obtained by slow concentration of an ethanol solution. Mp 92–93 °C. $[\alpha]_D$ = −11.4 (*c* 2.25, CH_2Cl_2). ^{31}P NMR ($CDCl_3$): δ = 81.92 ppm. ^{1}H NMR ($CDCl_3$): δ = 0.82 (d, *J* = 6.81 Hz, 12H, H-7), 0.92 (d, *J* = 7.33 Hz, 24H, H-9, H-10), 1.10–2.43 (m, 36H, H-5, H-8, H-1, H-6, H-2, H-4), 4.42 (m, 4H, H-3). ^{13}C NMR ($CDCl_3$): δ = 15.74 (C-10), 15.91 (C-10), 20.96 (C-9), 21.18 (C-9), 21.94 (C-7), 22.11 (C-7), 22.63 (C-5), 22.81 (C-5), 25.16 (C-8), 25.32 (C-8), 31.62 (C-1), 34.02 (C-6), 41.56 (C-2), 42.94 (C-2), 48.23 (d, J^3 = 7.7 Hz, C-4), 48.38 (d, J^3 = 7.7 Hz, C-4), 81.22 (d, J^2 = 10.2 Hz, C-3), 81.43 (d, J^2 = 10.2 Hz, C-3), 81.71 (d, J^2 = 8.6 Hz, C-3), 81.88 (d, J^2 = 8.6 Hz, C-3). MS (FAB) 405.3 (M).

4.2.3. (−)-(*R*,*R*)-Bis-(1,1-di-2-naphthoxyphosphinothioyl)-disulfide 4. A mixture of (+)-(*R*)-1,1-bis-(2-naphthol) (5.72 g, 0.02 mol) and phosphorus pentasulfide (2.22 g, 0.01 mol) was refluxed in dry toluene (50 mL) for 24 h. The evaporation of toluene led to 7.4 g (97%) of crude compound, which was characterized by ^{31}P NMR spectroscopy and used without purification. ^{31}P NMR ($CDCl_3$): δ = 97.78 ppm.

To a solution of this crude compound in dry CH_2Cl_2 (70 mL) was added (−)-(*S*)-1-phenylethyl amine (2.55 mL, 0.02 mol). The reaction mixture was stirred at room temperature for 2 h, after which dry hexane (80 mL) was added and the suspension filtered to give 9.32 g (93%) of white crystals of the phenylethylammonium salt of the 1,1-bis-(2-naphthoxy)-phosphinodithioic acid. Mp 245–246 °C. $[\alpha]_D$ = −401.7 (*c* 2.3, MeOH). ^{31}P NMR (CD_3OD): δ = 133.78 ppm. ^{1}H

NMR (CD_3OD): $\delta = 1.52$ (d, $J = 6.89$ Hz, 3H, CH_3 amine), 4.36 (q, $J = 6.87$ Hz, 1H, CH amine), 4.88 (s, 3H, NH_3 amine), 7.20–7.57 (m, 13H, Ar), 7.98–8.03 (m, 4H, Ar). ^{13}C NMR (CD_3OD): $\delta = 20.66$ (CH_3 amine), 52.31 (CH amine), 124.18 (Ar), 125.95 (Ar), 126.93 (Ar), 127.62 (Ar), 127.83 (Ar), 129.47 (Ar), 130.03 (Ar), 130.17 (Ar), 130.68 (Ar), 132.78 (Ar), 133.88 (Ar), 139.38 (Ar), 150.65 (Ar), 150.91 (Ar). HRMS (FAB) calcd for $C_{20}H_{12}PO_2S_2^-$ 379.0024, obsd 379.0016.

To a solution of this salt in a mixture of chloroform (80 mL) and dichloromethane (60 mL), were added H_2O (90 mL) and I_2 (1.28 g, 0.005 mol). This reaction mixture was then stirred at room temperature for 2 h. After separation, the organic phase was washed with an aq solution of $Na_2S_2O_3$, then with water, dried over $MgSO_4$ and finally evaporated in vacuo. The crude compound was recrystallized from an hexane/dichloromethane (55/45) mixture to give 3.0 g (79%) of disulfide **4**. Mp 198–199 °C. $[\alpha]_D = -480.2$ (c 1.0, CH_2Cl_2). ^{31}P NMR ($CDCl_3$): $\delta = 103.58$ ppm. ^1H NMR ($CDCl_3$): $\delta = 7.26$–7.73 (m, 16H, Ar), 7.80–8.29 (m, 8H, Ar). HRMS (FAB) calcd for $C_{40}H_{25}P_2O_4S_4$ 759.0082, obsd 759.0111.

4.2.4. (+)-(*R*,*R*)-Bis-(*tert*-butylphenylphosphinoyl)disulfide 5. To a solution of the (−)-α-phenylethylammonium salt of the (+)-(*R*)-*tert*-butylphenylphosphinothioic acid (6.3 g, 0.0188 mol) in a benzene (10 mL) and chloroform (35 mL) mixture, were added 35 mL of H_2O and 2.39 g of I_2 (0.0094 mol). This reaction mixture was stirred at room temperature overnight. After separation, the organic phase was washed with an aq solution of $Na_2S_2O_3$, then with water and finally dried over $MgSO_4$. Evaporation of the solvent gave 3.3 g (82.5%) of crude disulfide **5**. Suitable crystals for X-ray analysis were obtained by slow evaporation of a diethyl ether solution. Mp 152–154 °C. $[\alpha]_D^{20} = +183.8$ (c 0.77, C_6H_6). ^{31}P NMR ($CDCl_3$): $\delta = 68.4$. ^1H NMR ($CDCl_3$): $\delta = 1.14$ (d, $J_{H-P} = 17.3$ Hz, 18H, *t*-Bu), 7.14–7.64 (m, 10H, Ph).

4.2.5. General procedure for the reaction with disulfide 2–4. To a solution of phosphine **6** (0.52 mmol) in dry CH_2Cl_2 (10 mL) was added dropwise a solution of the disulfide (0.26 mmol) in CH_2Cl_2 (3 mL) at −70 °C. The reaction mixture was stirred for 1 h at −70 °C and then allowed to warm to room temperature after which it was stirred overnight. The ^{31}P NMR analysis of the reaction mixture indicated a mixture of phosphine sulfide **7** and phosphine **6** in a 1:1 ratio. This crude mixture was then oxidized by air, washed with a 5% aq solution of $NaHCO_3$, H_2O and finally dried over $MgSO_4$. Evaporation of the solvent gave a crude product, which corresponded to a mixture of phosphine sulfide **7** and phosphine oxide **8** in a 1:1 ratio as evidenced by ^{31}P NMR analysis. This mixture was separated by column chromatography using as eluent first a pentane/dichloromethane (1/1) mixture and then dichloromethane for the phosphine sulfides **7** and then acetone for the phosphine oxides **8**. Yield: 80–90% after column chromatography.

Compound **6a**: ^{31}P NMR ($CDCl_3$): $\delta = -37.1$ ppm. **7a**: ^{31}P NMR ($CDCl_3$): $\delta = 34.5$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.38$ (d, $J_{P-H} = 13$ Hz, 3H, CH_3), 7.25–8.35 (m, 12H, Ar). **8a**: ^{31}P NMR ($CDCl_3$): $\delta = 32.3$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.10$ (d, $J_{P-H} = 13.2$ Hz, 3H, CH_3), 7.26–8.4 (m, 12H, Ar). **6b**: ^{31}P NMR ($CDCl_3$): $\delta = -36.1$ ppm. **7b**: ^{31}P NMR ($CDCl_3$): $\delta = 34.8$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.26$ (d, $J_{P-H} = 13$ Hz, 3H, CH_3), 2.27 (s, 3H, *o*-CH_3), 7.2–7.78 (m, 9H, Ar). **8b** ^{31}P NMR ($CDCl_3$): $\delta = 31.8$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.01$ (d, $J_{P-H} = 13$ Hz, 3H, CH_3), 2.34 (s, 3H, *o*-CH_3), 7.17–7.67 (m, 9H, Ar). **6c**: ^{31}P NMR ($CDCl_3$): $\delta = -36.51$ ppm. **7c**: ^{31}P NMR ($CDCl_3$): $\delta = 35.5$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.34$ (d, $J_{P-H} = 14$ Hz, 3H, CH_3), 3.64 (s, 3H, *o*-OMe), 6.80–8.30 (m, 9H, Ar). **8c**: ^{31}P NMR ($CDCl_3$): $\delta = 28.7$ ppm; ^1H NMR ($CDCl_3$): $\delta = 2.03$ (d, $J_{P-H} = 14$ Hz, 3H, CH_3), 3.67 (s, 3H, *o*-OMe), 6.80–8.00 (m, 9H, Ar). **6d**: ^{31}P NMR ($CDCl_3$): $\delta = -10.01$ ppm. **7d**: ^{31}P NMR ($CDCl_3$): $\delta = 56.25$ ppm; ^1H NMR ($CDCl_3$): δ 1.15 (d, $J_{H-P} = 16.5$ Hz, 9H, *t*-Bu), 1.98 (d, $J_{H-P} = 12.28$ Hz, 3H, CH_3), 7.42–7.5 (m, 3H, Ph), 7.81–7.92 (m, 2H, Ph). **8d**: ^{31}P NMR ($CDCl_3$): $\delta = 47.89$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.10$ (d, $J_{H-P} = 14.8$ Hz, 9H, *t*-Bu), 1.70 (d, $J_{H-P} = 12.1$ Hz, 3H, CH_3), 7.40–7.48 (m, 3H, Ph), 7.64–7.72 (m, 2H, Ph).

4.2.6. General procedure for the reaction with disulfide 5. To a solution of phosphine **6a–g** (0.0005 mol) in dry dichloromethane (10 mL) was added dropwise a solution of disulfide **5** (0.00025 mol) in dichloromethane (3 mL) at −70 °C. The reaction mixture was stirred for 1 h at −70 °C and then allowed to warm to room temperature after which it was stirred overnight. The ^{31}P NMR analysis of the reaction mixture indicated a mixture of phosphine oxide **8** and phosphine **6** in a 1:1 ratio. Elemental sulfur (2 equiv) was then added and the mixture stirred for 2 h. This reaction mixture was then washed with a 5% aq solution of $NaHCO_3$, H_2O and finally dried over $MgSO_4$. Evaporation of the solvent gave a crude product corresponding to a mixture of phosphine oxide **8** and phosphine sulfide **7** in a 1:1 ratio as evidenced by ^{31}P NMR analysis. This mixture was separated by column chromatography and analyzed as described above.

Compound **6e**: ^{31}P NMR ($CDCl_3$): $\delta = 107.13$ ppm. **7e**: ^{31}P NMR ($CDCl_3$): $\delta = 114.92$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.26$ (d, $J_{H-P} = 20.5$ Hz, 9H, *t*-Bu), 7.53–7.98 (m, 3H, Ph), 8.00–8.06 (m, 2H, Ph). **8e**: ^{31}P NMR ($CDCl_3$): $\delta = 72.7$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.22$ (d, $J_{H-P} = 18.9$ Hz, 9H, *t*-Bu), 7.33–7.58 (m, 3H, Ph), 7.66–7.88 (m, 2H, Ph). **6f**: ^{31}P NMR ($CDCl_3$): $\delta = 104.26$ ppm. **7f**: ^{31}P NMR ($CDCl_3$): $\delta = 107.6$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.25$ (d, $J_{H-P} = 21.2$ Hz, 9H, *t*-Bu), 7.44–7.55 (m, 3H, Ph), 7.99–8.10 (m, 2H, Ph). **8f**: ^{31}P NMR ($CDCl_3$): $\delta = 73.15$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.24$ (d, $J_{H-P} = 19.76$ Hz, 9H, *t*-Bu), 7.49–7.92 (m, 5H, Ph). **6g**: ^{31}P NMR ($CDCl_3$): $\delta = 134.8$ ppm. **7g**: ^{31}P NMR ($CDCl_3$): $\delta = 108.09$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.14$ (d, $J_{H-P} = 17.4$ Hz, 9H, *t*-Bu), 3.66 (d, $J_{H-P} = 12.9$ Hz, 3H, CH_3), 7.40–7.85 (m, 5H, Ph). **8g**: ^{31}P NMR ($CDCl_3$): $\delta = 47.34$ ppm; ^1H NMR ($CDCl_3$):

$\delta = 1.12$ (d, $J_{H-P} = 16.5$ Hz, 9H, *t*-Bu), 3.21 (d, $J_{H-P} = 12.8$ Hz, 3H, CH_3), 7.35–7.75 (m, 5H, Ph).

4.2.7. Kinetic dynamic resolution of the chlorophosphine 6e. To a solution of chlorophosphine **6e** (0.6 g, 0.003 mol) and tetraethylammonium chloride (0.1 g, 0.0006 mol) (20% equiv) in dry CH_2Cl_2 (15 mL) at −70 °C was added a solution of disulfide **5** (1.3 g, 0.003 mol) in dry CH_2Cl_2 (3 mL). The reaction mixture was stirred for 18 h at −70 °C and then allowed to warm to room temperature. The ^{31}P NMR analysis of the reaction mixture indicated the complete disappearance of the starting chlorophosphine. This reaction mixture was washed with an 5% aq solution of $NaHCO_3$, H_2O and finally dried over $MgSO_4$. Evaporation of the solvent gave a crude product, which was purified by column chromatography using a pentane/dichloromethane (35/65) mixture as eluent. Yield: 0.52 g (80%), $[\alpha]_D = -35$ (*c* 3.5, C_6H_6), ee 70%.

4.2.8. Kinetic dynamic resolution of the phosphole 9. To a solution of phosphole **9** (0.04 g, 0.0001176 mol) in dry solvent (THF or CH_2Cl_2, 5 mL) was added a solution of disulfide **5** (0.05 g, 0.0001176 mol) in dry solvent (THF or CH_2Cl_2, 5 mL). The reaction mixture was stirred for 2 days at room temperature and then washed with a 5% aq solution of $NaHCO_3$, water and finally dried over $MgSO_4$. Evaporation of the solvent gave the crude product, which was purified by column chromatography using a dichloromethane/acetone (95/5) mixture as eluent. Yield: 0.039 g (93%); ^{31}P NMR ($CDCl_3$): $\delta = 46.1$ ppm; ^1H NMR ($CDCl_3$): $\delta = 1.75$ (s, 3H, CH_3), 1.92 (d, $J_{H-P} = 12$ Hz, 3H, CH_3), 6.98–7.33 (m, 15H, Ph).

5. X-ray structural analyses of compounds 1 and 3

Single crystals of compounds (+)-(*RSS*)-**1** and (−)-(*RRS*)-**3** were mounted under inert perfluoropolyether at the tip of glass fibre and cooled in the cryostream of the diffractometer. Both data were collected on a Stoe IPDS diffractometer operating with monochromatic Mo K_α radiation ($\lambda = 0.71073$).

The structures were solved by direct methods (SIR97[26]) and refined by least-squares procedures on *F* using CRYSTALS.[27] All H atoms were introduced in calculations with idealized positions [*d*(CH) = 1.0 Å] and treated as riding models. The weighting scheme used in the last refinement cycles was $w = w'[1-\{\Delta F/6\sigma(F_o)\}^2]^2$ where $w' = 1/\sum_1^n A_r T_r(x)$ with three coefficients A_r for the Chebyshev polynomial $A_r T_r(x)$, where *x* was $F_c/F_c(\max)$.[28] Models reached convergence with $R = \sum(||F_o|-|F_c||)/\sigma(|F_o|)$ and $Rw = [\sum w(|F_o|-|F_c|)^2/\sum w(F_o)^2]^{1/2}$. Final refinements allowed the fraction contribution of the inverted enantiomer to vary,[29] the Flack parameter quoted being the refined value of this contribution. Crystallographic details of the structure determination of **1** and **3** are summarized below:

Compound (+)-(*RSS*)-**1**. Empirical formula $C_{20}H_{38}S_2$; formula weight 342.64; crystal system: hexagonal; space group $P6_1$, $a = b = 13.1746(12)$ Å, $c = 21.505(2)$ Å; $\alpha = \beta = 90°$, $\gamma = 120°$; volume 3232.5(5) Å^3, $Z = 6$; calculated density (g cm^{-3}) 1.056; absorption coefficient (mm^{-1}) 0.245; reflections collected/unique 25,365/4177 [*R*(int) = 0.0264]; data/restraints/parameters 3883/1/201; goodness-of-fit on F_o 1.039; final *R* indices [$I > 2s(I)$]:*a* $R_1 = 0.0263$, $Rw = 0.0289$; absolute structure parameter 0.02(4); largest diff. peak and hole (e Å^{-3}) 0.18 and −0.14.

Compound (−)-(*RRS*)-**3**. Empirical formula $C_{40}H_{76}O_4P_2S_4$; formula weight 811.19; crystal system: orthorhombic; space group $P2_12_12_1$, $a = 10.7178(8)$ Å, $b = 14.6438(18)$ Å, $c = 30.226(2)$ Å; $\alpha = \beta = \gamma = 90°$; volume 4744.0(8) Å^3, $Z = 4$; calculated density (g cm^{-3}) 1.136; absorption coefficient (mm^{-1}) 0.302; reflections collected/unique 37,557/9137 [*R*(int) = 0.0784]; data/restraints/parameters 4911/1/452; goodness-of-fit on F_o 1.127; final *R* indices [$I > 2s(I)$]:*a* $R_1 = 0.0304$, $Rw = 0.0335$; absolute structure parameter 0.00(6); Largest diff. peak and hole (e Å^{-3}) 0.33 and −0.43.

$$^aR_1 = \sum(||F_o| - |F_c||)\Big/\sum |F_o|;$$

$$Rw = \left\{\sum[w(||F_o| - |F_c||)^2\Big/\sum w(F_o)^2]\right\}^{1/2}$$

Crystallographic data (excluding structure factors) for the structures herein have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 224397 and 224398. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 (0)1223 336033; deposit@ccdc.cam.ac.uk).

Acknowledgements

We acknowledge the CNRS and DESMOL for financial support.

References

1. (a) Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; John Wiley and Sons: New York, 1994; (b) *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: Berlin, 1999; (c) *Catalytic Asymmetric Synthesis*, 2nd ed.; Ojima, I., Ed.; VCH: Weinheim, 2000.
2. (a) For selected examples of monophosphine ligands, see: Knowles, W. S.; Sabacky, M. J.; Vineyard, B. D. *J. Chem. Soc., Chem. Commun.* **1972**, 10; (b) Ogasawara, M.; Yoshida, K.; Hayashi, T. *Organometallics* **2001**, *20*, 1014–1019; (c) Marinetti, A.; Carmichael, D. *Chem. Rev.* **2002**, *102*, 201–230; (d) Guillen, F.; Rivar, M.; Toffano, M.; Legros, J.-Y.; Daran, J.-C.; Fiaud, J.-C. *Tetrahedron* **2002**, *58*, 5895–5904; (e) Sava, X.; Marinetti, A.; Ricard, L.; Mathey, F. *Eur. J. Inorg. Chem.* **2002**, 1657–1665.
3. (a) Lagasse, F.; Kagan, H. B. *Chem. Pharm. Bull.* **2000**, *48*, 315–324; (b) Hayashi, T. *J. Organometal. Chem.* **1999**, *576*, 195–202; (c) Komorav, I. V.; Börner, A. *Angew. Chem., Int. Ed.* **2001**, *40*, 1197–1200.
4. (a) Reetz, M. T.; Mehler, G. *Angew. Chem., Int. Ed.* **2000**, *39*, 3889–3890; (b) Chen, W.; Xia, J. *Tetrahedron Lett.*

2001, *42*, 2897–2899; (c) Hannen, P.; Militzer, H.-C.; Vogel, E. M.; Rampf, F. A. *Chem. Commun.* **2003**, 2210–2211.
5. (a) Claver, C.; Fernandez, E.; Gillon, A.; Heslop, K.; Hyett, D. J.; Martorell, A.; Orpen, A. G.; Pringle, P. G. *Chem. Commun.* **2000**, 961–962; (b) Reetz, M. T.; Shell, T.; Meiswinkel, A.; Mehler, G. *Angew. Chem., Int. Ed.* **2003**, *42*, 790–793.
6. (a) Jia, X.; Guo, R.; Li, X.; Yao, X.; Chan, A. S. C. *Tetrahedron Lett.* **2002**, *42*, 5541–5544; (b) Vander Berg, M.; Minnaard, A. J.; Haak, R. M.; Leeman, M.; Schudde, E. P.; Meetsma, A.; Feringa, B. L.; Hyett, D.; Henderickx, H. J. W.; Boogers, J. A. F.; DeVries, J. G. *Adv. Synth. Catal.* **2003**, *345*, 308–323; (c) Tissot-Crosset, K.; Polet, D.; Alexakis, A. *Angew. Chem., Int. Ed.* **2004**, *43*, 2426–2428.
7. (a) Tissot, O.; Gouygou, M.; Dallemer, F.; Daran, J.-C.; Balavoine, G. G. A. *Angew. Chem., Int. Ed.* **2001**, 1076–1078; (b) Tissot, O.; Gouygou, M.; Dallemer, F.; Daran, J.-C.; Balavoine, G. G. A. *Eur. J. Inorg. Chem.* **2001**, 2385–2389; (c) Hydrio, J.; Gouygou, M.; Dallemer, F.; Daran, J.-C.; Balavoine, G. G. A. *Tetrahedron: Asymmetry* **2002**, *13*, 1097–1102.
8. Saegusa, T.; Kobayashi, S.; Ito, Y.; Yasuda, N. *J. Am. Chem. Soc.* **1968**, *90*, 4181–4182.
9. For a stereoselective desulfurization method, see: (a) Omelanczuk, J.; Perlikowska, W.; Mikolajczyk, M. *J. Chem. Soc., Chem. Commun.* **1980**, *9*, 24–25; (b) Omelanczuk, J.; Mikolajczyk, M. *Tetrahedron Lett.* **1984**, *25*, 2493–2496.
10. Perlikowska, W.; Gouygou, M.; Daran, J.-C.; Balavoine, G. G. A.; Mikolajczyk, M. *Tetrahedron Lett.* **2001**, *42*, 7841–7845.
11. Lopusinski, A.; Luczak, L.; Michalski, J.; Koziol, A. E.; Gdaniec, M. *J. Chem. Soc., Chem. Commun.* **1991**, 889–890.
12. Mikolajczyk, M.; Perlikowska, W.; Omelanczuk, J. *Synthesis* **1987**, *9*, 1009–1012.
13. Kochetkov, M. A.; Kuz'min, V. S.; Sadovnikov, S. V.; Sitnikov, V. B.; Sosnov, A. V.; Fokin, E. A. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1998**, 1802–1807.
14. Knopik, P.; Luczak, L.; Potrzebowski, M. J.; Michalski, J.; Blaszczyk, J.; Wieczorek, M. W. *J. Chem. Soc., Dalton Trans.* **1993**, 2749–2758.
15. Gong, B.-Q.; Chen, W.-Y.; Hu, B.-F. *Phosphorus Sulfur Silicon* **1991**, *57*, 87–94.
16. Harger, M. J. P. *J. Chem. Soc., Perkin Trans. 2* **1978**, 326–331.
17. (a) Yoshikuni, T.; Bailar, J. C. *Inorg. Chem.* **1982**, *21*, 2129–2133; (b) Singh, S.; Nicholas, K. M. *J. Chem. Soc., Chem. Commun.* **1998**, *9*, 149–150.
18. The enantiomeric purity was calculated on the following literature data: (a) for **7a**: $[\alpha]_D = +129$ ($CHCl_3$), Kawashima, T.; Kojima, S.; Inamoto, N. *Chem. Lett.* **1989**, 849–852; (b) for **8a**: $[\alpha]_D = -19.8$ (MeOH), Luckenbach, R. *Phosphorus* **1972**, *1*, 223–228; (c) for **8b**: $[\alpha]_D = +31.8$ ($CHCl_3$), Chodkiewicz, W.; Jore, D.; Pierrat, A.; Wodzki, W. *J. Organomet. Chem.* **1979**, *174*, C21–C23; (d) for **7c**: $[\alpha]_D = -7.9$ (MeOH), Corey, E. J.; Chen, Z.; Tanoury, G. J. *J. Am. Chem. Soc.* **1993**, *115*, 11000–11001; (e) for **8c**: $[\alpha]_D = +29.5$ (MeOH), Vineyard, B. D.; Knowles, V. S.; Sabacky, M. J.; Bachmann, G. L.; Weinkauff, D. *J. Am. Chem. Soc.* **1977**, *99*, 5946–5952; (f) for **7d**: $[\alpha]_D = +52.1$ ($CHCl_3$), Kawashima, T.; Kojima, S.; Inamoto, N. *Chem. Lett.* **1989**, 849–852; (g) for **8d**: $[\alpha]_D = -10.2$ (C_6H_6) (ee 68%), Michalski, J.; Skrzypczynski, Z. *J. Organomet. Chem.* **1975**, *97*, C31–C32; (h) for **7e**: $[\alpha]_D = +8.0$ (C_6H_6) (ee 76.5%), Omelanczuk, J.; Micholajczyk, M. *J. Chem. Soc., Chem. Commun.* **1994**, 2223–2224; (i) for **8e**: $[\alpha]_D = +49.8$ (C_6H_6), Luckenbach, R.; Bechtolsheimer, H.-H. *Z. Naturforsch. B.* **1977**, *32B*, 584587; (j) for **7f**: $[\alpha]_D = +14.2$ ($CHCl_3$), Omelanczuk, J.; Mikolajczyk, M. *J. Chem. Soc., Chem. Commun.* **1994**, 2223–2224; (k) for **8f**: $[\alpha]_D = -46.2$ ($CHCl_3$), Haynes, R. K.; Wai-Lam, W.; Williams, I. D.; Yeung, L.-L. *Chem. Eur. J.* **1997**, *3*, 2052–2057; (l) for **8g:** $[\alpha]_D = -51.5$ ($CHCl_3$) (ee 76%), Drabowicz, J.; Lyzwa, P.; Omelanczuk, J. *Tetrahedron: Asymmetry* **1999**, *10*, 2757–2763; (m) for **7g**: $[\alpha]_D = +34.9$ (C_6H_6), Omelanczuk, J.; Mikolajczyk, M. *J. Am. Chem. Soc.* **1979**, *101*, 7292–7295, The enantiomeric excesses were also determined by ^1H NMR method using (−)-(*S*)-*t*-butylphenylphosphinothioic acid as the chiral solvating agent in the case of compounds **8a**–**e**. The ee values obtained in this way are in good agreement (±1.5%) with the calculated ones.
19. For mechanistic features (intermediates, steps, rearrangements) of the reaction of achiral bis-(phosphinoyl)disulfides with achiral three-coordinate phosphorus compound, see: Krawczyk, E.; Skowrońska, A.; Michalski, J. *J. Chem. Soc., Perkin Trans. 1* **1994**, *9*, 89–99.
20. Only the partially enantiomerically enriched *tert*-butylchlorophosphine has been described to date; see: Omelanczuk, J. *J. Chem. Soc., Chem. Commun.* **1992**, 1718–1719. Highly enantiomerically enriched chlorophosphines were available as borane derivatives, see: Bauduin, C.; Moulin, D.; Kaloun, E. B.; Darcel, C.; Jugé, S. *J. Org. Chem.* **2003**, *68*, 4293–4301.
21. For pertinent reviews on the stereochemistry of single nucleophilic displacement at the P-chirogenic phosphinous derivatives, see (a) Pietrusiewicz, K. M.; Zablocka, M. *Chem. Rev.* **1994**, *94*, 1375–1411; (b) Kolodiazhnyi, O. I. *Tetrahedron: Asymmetry* **1998**, *9*, 1279–1332.
22. Humbel, S.; Bertrand, C.; Darcel, C.; Bauduin, C.; Jugé, S. *Inorg. Chem.* **2003**, *42*, 420–427.
23. Egan, W.; Tang, R.; Zon, G.; Mislow, K. *J. Am. Chem. Soc.* **1971**, *93*, 6205–6215.
24. Hydrio, J.; Gouygou, M.; Dallemer, F.; Daran, J.-C.; Balavoine, G. G. A. *J. Organomet. Chem.* **2000**, *595*, 261–267.
25. For stereoselective reduction of phosphine oxides, see: Imamoto, T.; Kihuchi, S.; Miura, T.; Wada, Y. *Org. Lett.* **2001**, *3*, 87–90.
26. Altomare, A.; Burla, M. C.; Camalli, M.; Cascarano, G. L.; Giacovazzo, C.; Guagliardi, A.; Moliterni, A. G. G.; Polidori, G.; Spagn, R. SIR97 a program for automatic solution of crystal structures by direct methods. *J. Appl. Cryst.* **1999**, *32*, 115–119.
27. Watkin, D. J.; Prout, C. K.; Carruthers, J. R.; Betteridge, P. W. *CRYSTALS Issue 12*; Chemical Crystallography Laboratory: University of Oxford, Oxford, 2003.
28. Prince, E. *Mathematical Techniques in Crystallography*; Springer: Berlin, 1982.
29. (a) Bernardinelli, G.; Flack, H. D. *Acta Crystallogr.* **1985**, *A41*, 500–511; (b) Flack, H. D. *Acta Crystallogr.* **1983**, *A39*, 876–881.