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Enantiopure Encaged Verkade's Superbases: Synthesis, Chiroptical Properties, and Use as Chiral Derivatizing Agent

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Abstract: Verkade's superbases, entrapped in the cavity of enantiopure hemicryptophane cages have been synthesized with enantiomeric excess (*ee*) superior to 98%. Their absolute configuration has been determined by using electronic circular dichroism (ECD) spectroscopy. These enantiopure encaged superbases turned out to be efficient chiral derivatizing agents for chiral azides, underlining that the chirality of the cycloveratrylene (CTV) macrocycle induces different magnetic and chemical environments around the phosphazide functions.

INTRODUCTION

Pro-azaphosphatranes **1** (Chart 1), also named Verkade's superbases, were discovered in 1989 by J. G. Verkade.[1] These species are highly basic with a pK_a around 32 in CH_3CN.[2] In contrast with phosphazene bases (Schwesinger's bases), protonation occurs on the phosphorus atom of the pro-azaphosphatrane. The high pK_a value was attributed to the high stability of its conjugated acid, the azaphosphatrane cation. Pro-azaphosphatranes have been extensively used as basic and nucleophilic catalysts in many transformations, providing high yields of the desired compounds under mild conditions while avoiding most of the side reactions encountered with other systems.[3,4] New aspects of pro-azaphosphatranes have recently been developed. J. G. Verkade reported their use as ligands for palladium-catalyzed reactions, for instance in Suzuki coupling or Hartwig-Buchwald reaction.[5] J.Y. Yang et al. nicely pursued this study by complexing other metals like Ni and Rh to pro-azaphosphatranes and investigated the stereoelectronic properties of this ligand.[6] In link with this research, our group described the synthesis and structures of Verkade's superbase-gold complexes.[7] Another elegant application of Verkade superbases is their use as Lewis base to create "reversed frustrated Lewis acid/base" or true frustrated Lewis pairs (FLP) systems.[8,9] Alternatively, our group studied the behavior of Verkade's superbases in the confined space of hemicryptophanes,[10] which are chiral host molecules built from a cyclotriveratrylene unit bound to another C_3-symmetry group.[11] The confinement was found to simultaneously increase the thermodynamic basicity of the pro-azaphosphatrane and decrease the rate of proton transfer. When tested as catalyst in a Diels-Alder basico-catalyzed reaction, the encaged Verkade's superbase led to an improvement of the diastereoselectivity, when compared to its model compound that is devoid of cavity.[12] The endohedral functionalization of the cage also allowed building FLP system benefiting from the strong isolation of the Lewis basic and acid partners induced by the cavity.[13]
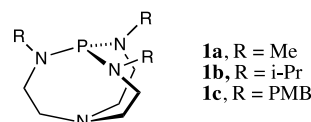

Chart 1 Structure of Verkade's superbases (PMB = *p*-methoxybenzyl).

Herein, we wish to report on the synthesis of the first Verkade's superbase encaged in enantiopure covalent cages. The absolute configuration was assigned by ECD spectroscopy, and these encapsulated pro-azaphosphatranes were found to act as efficient chiral derivatizing agents for chiral azides.

MATERIALS AND METHODS

General

All commercial reagents and starting materials were used directly as received without further purification. All dry solvents were purified prior to use through standard procedures or obtained from a solvent drying system (MB-SPS-800). All the reactions were carried out under an atmosphere of argon, unless otherwise noted. Flash column chromatography was performed using silica gel 60 (230-400 mesh). Thin-layer chromatography

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was performed on aluminum-coated plates with silica gel 60 F$_{254}$ and was visualized with a UV lamp or by staining with potassium permanganate. NMR spectra were recorded at either 300 or 400 MHz on BRUKER Avance III nanobay spectrometers. Chemical shifts δ are reported in ppm and coupling constants J in Hz. ECD and UV spectra were measured on a JASCO J-815 spectrometer equipped with a JASCO Peltier cell holder PTC-423 to maintain the temperature at 25.0 ± 0.2 °C. High-resolution mass spectra (HRMS) were performed at Spectropole Analysis Service of Aix Marseille University. Enantiopure hemicryptophanes (*P*)-**2** and (*M*)-**2** were synthesized according to our previous reported procedure.[14]

Synthesis of enantiopure caged azaphosphatranes (*P*)-3 and (*M*)-3. In an ice-bath cooled round-bottom flask, bis(dimethylamino)chlorophosphine (0.154 mL, 1.0 mmol, 1.0 equiv) was dissolved in acetonitrile (6 mL), to which a solution of hemicryptophane (*P*)-**2** or (*M*)-**2** (952 mg, 1 mmol, 1.0 equiv) in acetonitrile (15 mL) was then added drop-wise. The reaction mixture was vigorously stirred at 0 °C for 0.5 h. The mixture was then brought to room temperature overnight. The solvent was then removed under vacuum and the residue was purified on silica gel by flash chromatography (CH$_2$Cl$_2$/MeOH; 15/2) to give pure azaphosphatrane (*P*)-**3** or (*M*)-**3** as a white solid (884 mg, 87%). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.32 (s, 3H), 6.97 (s, 3H), 6.15 (d, J = 8.27 Hz, 6H), 6.01 (d, J = 8.27 Hz), 4.82-4.93 (m, 3H), 4.89 (d, J = 13.6 Hz, 3H), 4.45 (d, [1]J$_{P-H}$ = 491 Hz, 1H, P-H), 4.42-4.19 (m, 9H), 3.87-3.74 (m, 3H), 3.64 (d, J = 13.5 Hz, 3H), 3.57 (s, 9H), 3.36 – 3.47 (m, 3H), 3.31-3.17 (m, 9H), 2.68 - 2.76 (m, 3H); ^{13}C NMR (400 MHz, CDCl$_3$) δ 158.27, 147.20, 146.45, 132.03, 131.71, 131.31, 129.01, 114.95, 114.61, 112.74, 70.23, 65.65, 55.12, 50.38, 47.63, 42.54, 36.80; ^{31}P NMR (121 MHz, CDCl$_3$) δ -31.98. These data are consistent with those reported in the literature.[15] (+)-(*P*)-**3**: $[\alpha]_D^{25}$ = + 73 (c 0.1, CH$_2$Cl$_2$)
(-)-(*M*)-**3**: $[\alpha]_D^{25}$ = - 74 (c 0.1, CH$_2$Cl$_2$)

Synthesis of enantiopure caged proazaphosphatranes (*P*)-4 and (*M*)-4. Under an atmosphere of argon, in a flame-dried Schlenk flask, azaphosphatrane (*P*)-**3** or (*M*)-**3** (350 mg, 0.35 mmol, 1.0 equiv) was dissolved in dried THF (2 mL), t-BuOK (98 mg, 0.875 mmol, 2.5 equiv) was then added, and the reaction mixture was stirred at room temperature for 2 h. The solvent was removed under vacuum, and toluene (5 mL) was added. The reaction mixture was stirred for another 0.5 h, and then the suspension was filtered under argon through a two-necked fritted glass funnel. The filtrate was recovered and the solvent was removed under vacuum to give enantiopure proazaphosphatrane (*P*)-**4** or (*M*)-**4** as a white solid (200 mg, 58%). ^{1}H NMR (300 MHz, Toluene-d$_8$) δ 7.31 (s, 3H), 7.04 (d, J = 6.6 Hz, 6H), 6.91 (s, 3H), 6.73 (d, J = 8.5 Hz, 6H), 4.80 (d, J = 13.6 Hz, 3H), 4.27 – 4.11 (m, 12H), 4.10 – 3.93 (m, 6H), 3.84 – 3.71 (m, 3H), 3.69 (s, 9H), 3.60 (d, J = 13.2 Hz, 3H), 3.15 – 2.99 (m, 3H), 2.99 – 2.90 (m, 6H), 2.88 – 2.74 (m, 3H); ^{31}P NMR (121 MHz, Toluene-d$_8$) δ 121.29; ^{13}C NMR (400 MHz, CDCl$_3$) δ 157.35, 149.68, 147.27, 134.13, 133.57, 132.03, 128.56, 118.57, 115.13, 114.82, 68.78, 67.26, 54.83, 54.41, 52.42, 48.83, 36.15. These data are in agreement with those reported in the literature for the racemic mixture.[10]
(+)-(*P*)-**4**: $[\alpha]_D^{25}$ = + 78 (c 0.1, CH$_2$Cl$_2$)
(-)-(*M*)-**4**: $[\alpha]_D^{25}$ = - 76 (c 0.1, CH$_2$Cl$_2$)

Procedure for the synthesis of 2-azido-1-isopropyl-4-methylcyclohexane (6).[16]

2-isopropyl-5-methylcyclohexyl methanesulfonate. To a solution of racemic menthol (12.8 mmol) in dichloromethane (50 mL) was added NEt$_3$ (2.7 mL, 19 mmol). The mixture was stirred for 1 h, then it was brought to 0 °C, and a solution of methanesulfonyl chloride (MsCl) (1.5 mL, 19 mmol) in dichloromethane was added dropwise. Then the reaction mixture was warmed to room temperature and kept stirring for another 2 hours until the reaction completed monitored by TLC. The reaction was quenched with saturated NH$_4$Cl solution (50 mL). The mixture was extracted by dichloromethane (3 × 50 mL). Organic phases were collected and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated to give the crude product which was purified by silica gel column chromatography (petroleum ether: ethyl acetate = 20:1) to give pure 2-isopropyl-5-methylcyclohexyl methanesulfonate as a colorless oil, 2.85 g, 95% yield. ^{1}H NMR (400 MHz, CDCl$_3$) δ 4.57 (td, J = 10.9, 4.6 Hz, 1H), 3.02 (s, 3H), 2.37 – 2.21 (m, 1H), 2.14 – 2.02 (m, 1H), 1.79 – 1.65 (m, 2H), 1.58 – 1.38 (m, 2H), 1.36 – 1.20 (m, 1H), 1.16 – 1.01 (m, 1H), 0.95 (dd, J = 6.8, 3.4 Hz, 6H), 0.93 – 0.87 (m, 1H), 0.85 (d, J = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 83.37, 77.21, 47.46, 42.25, 39.11, 33.78, 31.64, 25.83, 23.15, 21.83, 20.79, 15.70.[16]

2-azido-1-isopropyl-4-methylcyclohexane (6).[16] To a solution of racemic 2-isopropyl-5-methylcyclohexyl methanesulfonate (13.3 mmol) in DMF (50 mL) was added NaN$_3$ (80 mmol). The mixture was stirred at 80 °C for 48 h. And then DMF was evaporated under vacuum, 100 mL of water was added, and the mixture was extracted by dichloromethane (3 × 50 mL). Organic phases were collected and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated to give the crude product which was purified by silica gel column chromatography (petroleum ether: ethyl acetate = 10:1) to give pure 2-azido-1-isopropyl-4-methylcyclohexane (**6**) as a colorless oil, 603 mg, 25% yield. ^{1}H NMR (400 MHz, CDCl$_3$) δ 3.99 (q, J = 3.3 Hz, 1H), 2.08 – 1.98 (m, 1H), 1.80 – 1.63 (m, 3H), 1.60 – 1.46 (m, 1H), 1.31 – 1.11 (m, 2H), 0.99 – 0.82 (m, 11H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 60.54, 47.39, 38.95, 34.85, 29.48, 26.51, 24.89, 22.14, 20.86, 20.64. HRMS (ESI-TOF) m/z: calcd for C$_{10}$H$_{19}$N$_3$Ag$^+$ [M+Ag]$^+$, 288.0624; found 288.0623.[16]

Procedure for the synthesis of (1-azido-2-methoxyethyl)benzene (7).[17]

2-methoxy-1-phenylethan-1-ol. To a solution of 2-methoxy-1-phenylethan-1-one (10 mmol) in 50 mL methanol was added gradually NaBH$_4$ (20 mmol) at 0 °C, then reaction mixture was brought to room temperature and kept stirring for another 2 hours until the reaction completed monitored by TLC. Then solvent was removed under vacuum, 50 mL water was added and extracted by EtOAc (3 × 50 mL). Organic phases were collected and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated to give the crude product which was purified by silica gel column chromatography (petroleum ether: ethyl acetate = 5:1) to give pure 2-methoxy-1-phenylethan-1-ol as a colorless oil, 1.3g, 86% yield. ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.49 – 7.24 (m, 5H), 4.92 (dd, J = 8.9, 2.8 Hz, 1H), 3.69 – 3.36 (m, 5H), 3.04 – 2.88 (m, 1H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 140.34, 128.38, 127.81, 126.14, 78.22, 72.63, 59.00. HRMS (ESI-TOF) m/z: calcd for C$_9$H$_{12}$O$_2$Na$^+$ [M+Na]$^+$, 175.0730; found 175.0731.[17]

(1-bromo-2-methoxyethyl)benzene. To a solution of 2-methoxy-1-phenylethan-1-ol (6.6 mmol) in 50 mL chloroform was added gradually PBr$_3$ (10 mmol) at 0 °C, then reaction mixture was brought to room temperature and kept stirring for another 2 hours until the reaction completed monitored by TLC. Then the reaction was quenched by adding saturated K$_2$CO$_3$ (50 mL). The mixture was extracted by chloroform (3 × 50 mL). Organic phases were collected and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated to give the crude product which was purified by silica gel column chromatography (petroleum ether:

ethyl acetate = 10:1) to give pure (1-bromo-2-methoxyethyl)benzene as a colorless oil, 965 mg, 68% yield. ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.39 – 7.13 (m, 5H), 4.98 (t, J = 7.0 Hz, 1H), 3.92 – 3.71 (m, 2H), 3.30 (s, 3H). ^{13}C NMR (75 MHz, CDCl$_3$) δ 139.11, 128.75, 128.71, 127.84, 76.86, 58.97, 51.64. HRMS (ESI-TOF) m/z: calcd for C$_9$H$_{15}$NOBr$^+$ [M+NH$_4$]$^+$, 232.0332; found 232.0330.[17]

(1-azido-2-methoxyethyl)benzene (7). To a solution of (1-bromo-2-methoxyethyl)benzene (6.53 mmol) in 50 mL DMF was added gradually NaN$_3$ (9.8 mmol), then the reaction mixture was heated at 80 °C overnight until the reaction completed monitored by TLC. Then 100 mL of water was added and extracted by chloroform (3 × 50 mL). Organic phases were collected and dried over anhydrous Na$_2$SO$_4$, filtered and concentrated to give the crude product which was purified by silica gel column chromatography (petroleum ether: ethyl acetate = 20:1) to give pure (1-azido-2-methoxyethyl)benzene (7) as a colorless oil, 856 mg, 74% yield. ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.39 – 7.20 (m, 5H), 4.62 (t, J = 6.4 Hz, 1H), 3.53 (d, J = 6.7 Hz, 2H), 3.34 (s, 3H). ^{13}C NMR (75 MHz, CDCl$_3$) δ 136.71, 128.78, 128.48, 127.05, 76.45, 65.14, 59.11. HRMS (ESI-TOF) m/z: calcd for C$_9$H$_{11}$N$_3$ONa$^+$ [M+Na]$^+$, 200.0794; found 200.0794.[17]

General procedure for reactions of enantiopure caged proazaphosphatrane (*M*)-4 with chiral azides 6 and 7. Under an atmosphere of argon, to a solution of (*M*)-4 (0.05 mmol) in toluene in a flame-dried Schlenk tube was added azide compound **6** or **7** (0.05 mmol). The mixture was stirred at 50 °C overnight. The solvent was evaporated under vacuum and the residue was dissolved in CDCl$_3$ for NMR analysis.[17]

RESULTS AND DISCUSSION

Synthesis of enantiomerically pure encaged Verkade's superbases

The synthesis of the first enantiopure hemicryptophanes was described in 2005 by J. Crassous and J.-P. Dutasta,[18] and more recently we reported a convenient large-scale synthesis of these supramolecular structures.[14] Enantiopure hemicryptophanes (*P*)-**2** and (*M*)-**2** were thus synthesized in four steps following our previous reported procedure (Scheme S1, Supporting Information).[14] The corresponding azaphosphatranes (*P*)-**3** and (*M*)-**3** were then obtained by reaction of respectively (*P*)-**2** and (*M*)-**2** with (Me$_2$N)$_2$PCl in acetonitrile at room temperature overnight (Scheme 1). Our previously reported synthesis of the two enantiomers (*P*)-**3** and (*M*)-**3** is of limited utility here due to the tedious optical resolution of the racemate **3** by chiral HPLC. Chromatography on these species required a solvent mixture in the mobile phase that degraded the stationary phase, leading to very low product recovery from the process.[15] In the present report, we chose to resolve the racemate of the key CTV intermediate **5** (Scheme 1 and Scheme S1), which can be effectively done on a large-scale. In this manner, enriched (*P*)-**3** and (*M*)-**3** can be obtained at the hundred mg scale. As CTV units can racemize before the ring closure of the cage (the energy barrier of racemization of CTV compound being around 112kJ.mol^{-1} at 298 K),[14] the enantiomeric purity of these compounds was checked by adding chiral hexacoordinated phosphorus TRISPHAT anion (Tris(tetrachlorobenzenediolato)phosphate(V) anion, Figure 1).[15,19] This anion presents a right-handed or left-handed propeller geometry of Δ or Λ configurations respectively, and is a useful chiral solvating agent (CSA) for the NMR discrimination of

enantiomers of chiral cationic and certain neutral organometallic species. In a typical experiment, 1.0 equivalent of [cinchonidinium][Δ-TRISPHAT] was added to a solution of [(*M*)-**3**][Cl$^-$], [(*P*)-**3**][Cl$^-$] or *rac*-**3** in CDCl$_3$. The resulting ^{31}P NMR spectra displayed respectively one signal at −30.82 ppm, one signal at −31.63 ppm and two signals at −30.74 and −31.63 ppm (Figure 1), giving rise to an enantiomeric excess (ee) superior to 98% for both enantiomers [(−)-(*P*)-**3**][Cl$^-$] and [(+)-(*M*)-**3**][Cl$^-$]. Azaphosphatranes (*M*)-**3** and (*P*)-**3** were then deprotonated with *t*-BuOK in THF, affording the enantiopure encaged Verkade's superbases (*M*)-**4** and (*P*)-**4** with 58% yield (Scheme 1). It can be highlighted that the synthesis of a Verkade's superbase, confined in an enantiopure cavity is, to the best of our knowledge unprecedented.
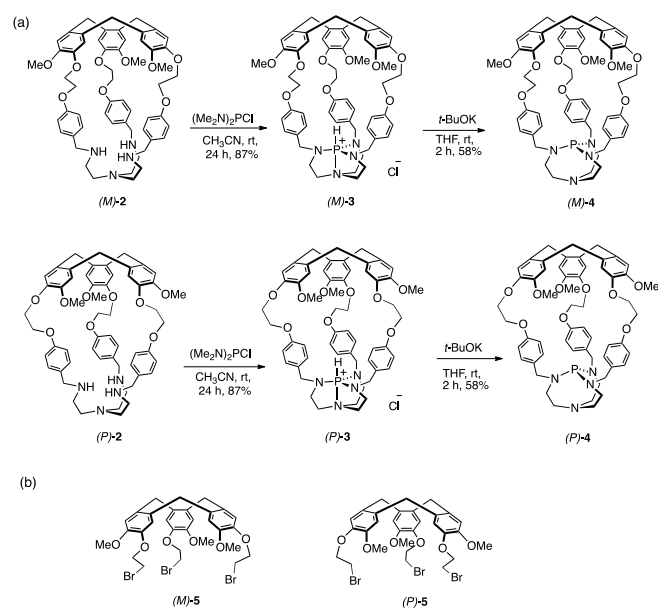
Scheme 1 (a) Synthesis of enantiomerically pure encaged Verkade's superbases (*P*)-**4** and (*M*)-**4**. (b) the CTV **5** that has been resolved on gram scale.[14]
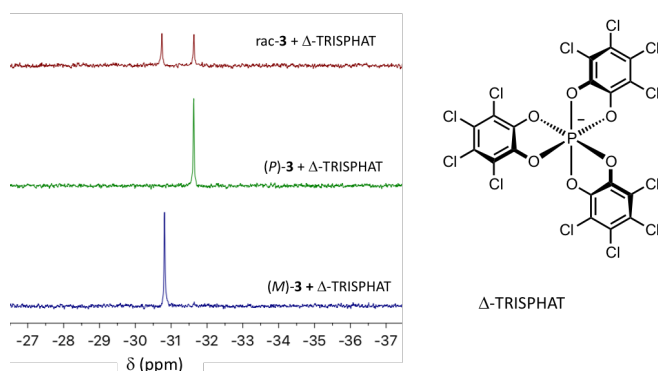

Figure 1 ^{31}P NMR spectra (CDCl$_3$, 298 K, 121.5 MHz) of hemicryptophane *rac*-**3** and the enantiomers (−)-(*P*)-**3** and (+)-(*M*)-**3** in the presence of 1 equiv. of [cinchonidinium][Δ−TRISPHAT].

Assignment of the absolute configuration

The ECD spectra of both enantiomers of **4** were recorded in CH_2Cl_2 at 293 K (Figure 2). As previously observed with cyclotriveratrylene, cryptophane, and hemicryptophane derivatives, the ^1L_a band of the spectra (230 to 270 nm) is poorly sensitive to substituents and allows for the assignment of the absolute configuration of the CTV moiety.[20] A characteristic positive-negative bisignate (from low to high energies) is observed in the ECD spectrum of (+)-**4** at around 250 nm, which can be attributed to the *P* configuration, whereas the *M* configuration was assigned to the (−)-**4** enantiomer, which exhibits a negative-positive bisignate (Figure 2).
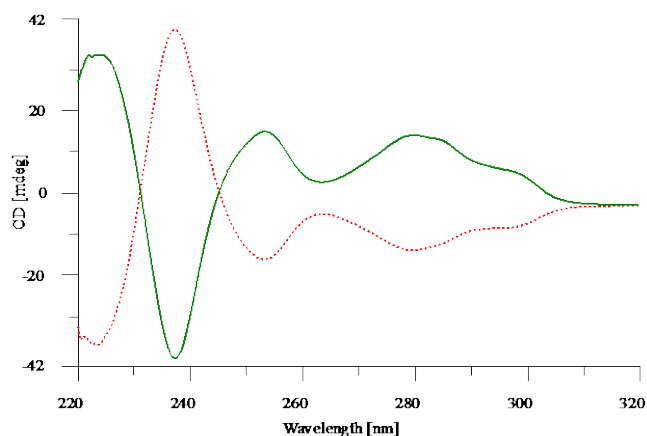

Figure 2 ECD spectra of enantiomerically pure encaged Verkade's superbases (+)-(*P*)-**4** (red) and (−)-(*M*)-**4** (green) in CH_2Cl_2 at 293 K.

Use of enantiopure encaged Verkade's superbase as chiral derivatizing agent for chiral azides

In 2000, J. G. Verkade demonstrated that enantiopure proazaphosphatranes could be used as chiral derivatizing agents for chiral azides.[17] As a follow-up of this work, we thus carried out the reaction of the enantiopure encapsulated Verkade's superbase (*M*)-**4** with two different racemic chiral azides *rac*-**6** or *rac*-**7**, in toluene at 50 °C overnight to afford the corresponding encapsulated phosphazide diastereomers (*1S,2R,5S*)-(*M*)-**8** and (*1R,2S,5R*)-(*M*)-**8** and (*S*)-(*M*)-**9** and (*R*)-(*M*)-**9** (Scheme 3). An excellent diastereomeric peak separation of around 98 Hz was observed in the ^1H-decoupled ^{31}P NMR spectra of both species (Figure 3), allowing for an accurate quantitative determination of the diastereomeric ratios. If the ^{31}P NMR revealed only two sets of signals, the ^1H NMR was much more complicated, probably because of the expected C_1 symmetry of each diastereomer (Figures S12 and S14). Although no diastereomeric ratio was reached when the azides derivatives were used in excess, these results underline that once covalently bound to the phosphorus of the encaged Verkade's superbase, the two enantiomers of a chiral molecule are in strongly different magnetic and chemical environments even if the inherently chiral CTV unit is remote from the phosphorus center.
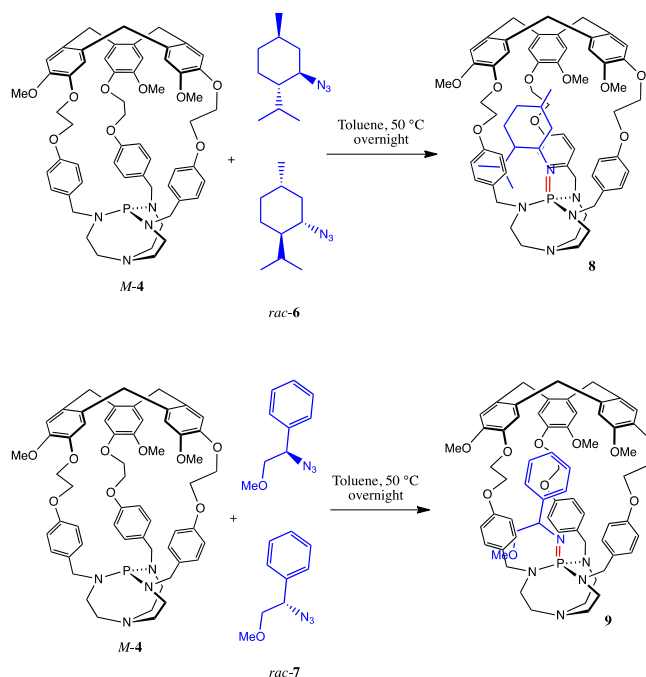
Scheme 3 Synthesis of encapsulated phosphazides 8 and 9.

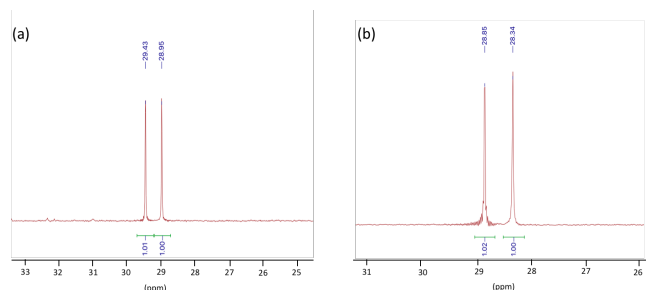

Figure 3 ^1H-decoupled ^{31}P NMR spectra ($CDCl_3$, 298 K, 162 MHz) of encaged phosphazides (a) **8** and (b) **9**.

Conclusions

In conclusion, we have described the unprecedented synthesis of enantiopure encaged Verkade's superbases. Our synthetic pathway provides the desired compounds in six steps from vanillyl alcohol with an overall yield of 6%. The assignment of the absolute configuration has been achieved by comparison of ECD spectra of enantiopure (*M*)-**4** and (*P*)-**4** with other CTV derivatives. Moreover, these compounds could act as efficient chiral derivatizing agents when reacting with racemic azides, leading to encapsulated chiral phosphazides.

Supporting information

Additional supporting information, including ^{1}H, ^{13}C, ^{31}P NMR of **3**, **4**; ^{1}H, ^{13}C NMR of **6**, **7**, ^{1}H, ^{31}P NMR of **8** and **9**; UV and CD spectra of **2**, **3** and **4** can be found in the online version of this article at the publisher's website.

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Graphical Abstract