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Diastereoselective Synthesis of Bulky, Strongly Nucleophilic, and Configurationally Stable *P*-Stereogenic Tricyclic Phosphines

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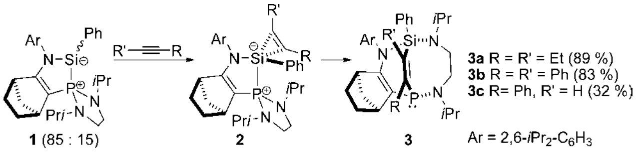
Abstract: A very simple, one-step highly diastereoselective synthesis of bulky, configurationally and air-stable *P*-chiral tricyclic phosphines **3**, showing an exceptionally strong nucleophilic character, has been developed. This method involves the reaction of the stable phosphonium sila-ylide **1** with aryl- and alkyl-substituted acetylene derivatives. Starting from commercially available chiral (*R*,*S*)-(+)-*endo*-2-norborneol, the corresponding enantiomerically pure phosphines were obtained with excellent enantioselectivities (ee ≥ 99%) and high chemical yields.

Chiral phosphines are essential ligands for asymmetric transition metal-catalyzed transformations. Among them, *P*-chiral phosphines such as DIPAMP were landmark discoveries at an early stage in the history of asymmetric catalysis[1] yet planar- and backbone-chiral phosphines are the most commonly employed ligands today.[2] This is largely ascribed not only to the dearth of efficient methods[3] for the preparation of enantioenriched *P*-stereogenic phosphines but also to their potential racemization.[4] A solution is the use of rigid bicyclic phosphines with a bridgehead chiral phosphorus center, implying a fixed *P*-chirality. With this strategy, the synthesis of the bis-phosphanorbornadienyl BIPNOR has been recently described.[5] In addition to the traditional synthesis of *P*-chiral phosphines by resolution or chiral auxiliary-based routes, nowadays several new efficient enantioselective synthetic methods *via* asymmetric metal-catalyzed approaches[6] and *via* the enantioselective deprotonations of dimethylphosphine-BH_3 complexes using chiral bases[7] are under development. However, a simple and straightforward synthetic method for the preparation of tricyclic *P*-stereogenic phosphines is missing. Here, we present a one-step diastereoselective synthesis of the bulky configurationally and air-stable *P*-chiral tricyclic phosphines **3** showing an exceptionally strong nucleophilic character.

Scheme 1. Reaction of Phosphonium Sila-Ylide **1** with Acetylenic Derivatives



Recently, Tamao et al have reported the synthesis of cyclic phosphines by reaction of a transient phosphonium sila-ylide with diphenylacetylene.[8] However, this synthetic way is limited due to the instability of the sila-ylide used and the relatively harsh experimental conditions. Since we have described an easy access to a new class of stable phosphonium sila-ylide **1**[9] with a nucleophilic silylenoid character,[10] we decided to use it as a precursor for the synthesis of new tricyclic phosphines. The racemic phosphonium sila-ylide **1** (mixture of two diastereomers, 85:15) cleanly reacts at room temperature with acetylenic derivatives to give the corresponding tricyclic phosphines *rac*-**3a**−**c** which have been isolated as spectroscopically pure products by crystallization (Scheme 1). The structure of **3b** was confirmed by an X-ray diffraction analysis clearly showing the tricyclic structure with an insertion of the acetylenic moiety into the Si−P bond, and the migration of one amino group from the phosphorus to silicon atoms (Figure 1). Interestingly, in all cases, only one diastereomer was obtained, clearly indicating the occurrence of dynamic kinetic resolutions. In the case of phenylacetylene, the reaction is completely regioselective, with the formation of the diastereomer with the phenyl group on the vinyl bridge in α-position relative to phosphorus atom. In contrast to the transient ammonium sila-ylides[11] or stable silylenes,[12] no insertion reaction of the Si(II) center into terminal acetylene C−H bond has been observed.

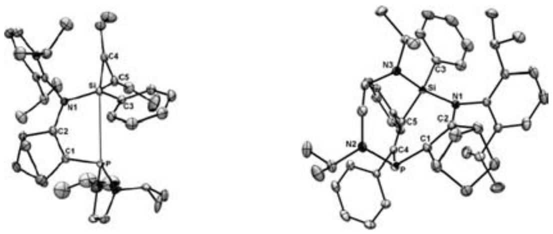


Figure 1. Molecular structures of **2a** and **3b**. Thermal ellipsoids represent 30% probability. H atoms are omitted for clarity. Selected bond lengths [Å] and angles [deg] **2a**: Si−C3 1.8615(18), Si−C5 1.7955(18), Si−C4 1.8051(18), Si−N1 1.7518(14), Si−P 3.2324 (7), C4−C5 1.348(3), N1−Si−C5 124.70(8), C3−Si−C5 122.09(8), N1−Si−C3 112.09(7); **3b**: P−C1 1.796(2), P−C4 1.873(2), P−N2 1.6960(19), N1−C2 1.406(3), C1−C2 1.354(3), N2−P−C1 100.98(10), N2−P−C4 102.81(9), C1−P−C4 111.08(10).

In the presence of an excess amount of diethylacetylene (20 equiv), a pentacoordinate silirene **2a** was detected by ^{31}P NMR spectroscopy ($\delta = 71.3$ ppm) as only one diastereomer. This hypervalent silicon derivative slowly transforms into the corresponding phosphine **3a** ($\delta = 42.9$ ppm). The formation of silirene **2a**, which presents a characteristic high-field resonance in ^{29}Si NMR spectroscopy ($\delta = -99.7$ ppm, $J_{SiP} = 29.9$ Hz), clearly demonstrates that the first step of the reaction is a [2 + 1] cycloaddition typical for transient silylenes.[13] In the case of diphenylacetylene we were unable to detect any intermediate.

Silirene **2a** was isolated as colorless crystals from a saturated Et_2O solution at −30 °C and unambiguously characterized by an

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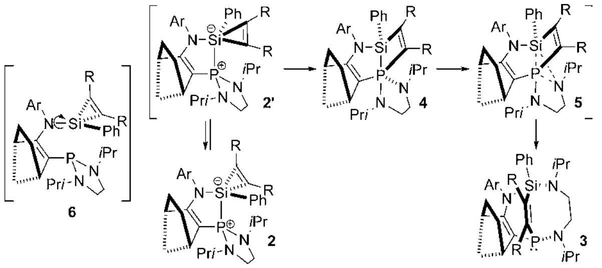
X-ray diffraction analysis. The molecular structure of **2a** shows a strongly distorted P,C-apical trigonal bipyramidal geometry (TBP) around the pentacoordinate silicon atom incorporated in a three-membered ring. It presents a long apical Si−P bond distance (3.232 Å) compared with the much shorter distance observed for the related oxasilirane derivative (2.491 Å) (Figure 1).[11] In contrast, the sum of equatorial bond angles around the silicon atom (358°) is close to the ideal value for a TBP geometry (360°).

The mechanism of the reaction is probably similar to that previously proposed by Tamao,[8] with an initial [2 + 1] cycloaddition reaction which is an irreversible process. Then the ring expansion of the first formed silirene **2**, via a 1,2-migration of the vinyl carbanion from silicon to phosphorus, would lead to the transient phosphorane **4** (Scheme 2). In the case of aryl-substituted acetylene derivatives, the negative charge in the transition state delocalizes through the π-system of the migrating fragment, and consequently, the energy barrier for such rearrangements is lower. This is in good agreement with the rapid evolution of the transient hypervalent silirene **2b**, which was not detected, and with the regioselectivity observed with phenylacetylene.

Scheme 2. Dynamic Kinetic Resolution in the Ring Expansion of Silirene **2**



The migration of the amino group from P to Si center, with the valence reduction of the P atom (P^{V} to P^{III}), can be rationalized by a ligand-coupling reaction within the hypervalent phosphorane **4**[8,14] (Scheme 2). Taking into account the structure of **3a** (Figure 1), the migration should occur on the less hindered side of the molecule as depicted in Scheme 2. This requires the formation of **4**, as an intermediate with the vinyl bridge at the more hindered side, resulting from the ring expansion of silirene isomer **2′**. The isomerization of hypervalent silirene **2** would involve the P−Si bond dissociation and a rotation around the Si−N bond axis in the resulting silirene **6**.[10]

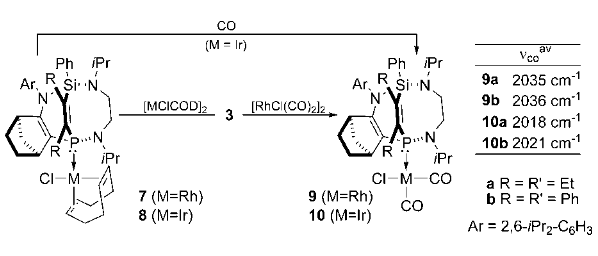


Figure 2. Synthesis of Rh(I) and Ir(I) dicarbonyl complexes **9**, **10** and average values of CO-stretching frequencies.

The molecular structure of **3b** indicates that the P−C1 bond (1.796 Å) is substantially shorter than the single P−C4 bond (1.873 Å), suggesting a strong π-electron donation of the enamine function. Therefore, an enhanced nucleophilic character of phosphines **3** was expected, and in order to evaluate their donor ability the Rh(I) and Ir(I) dicarbonyl complexes **9** and **10** were prepared by reaction of **3a**,**b** with $[RhCl(CO)_2]_2$ and $[IrClCOD]_2$ respectively. In the case of Ir(I) complex, the first formed complex **8** was easily transform into the corresponding dicarbonyl derivative **10** just by bubbling carbon monoxide. The infrared spectra of **9** and **10** show the characteristic CO stretching frequencies with an average values of 2035−2036 cm^{-1} for Rh(I) and 2018−2021 cm^{-1} for Ir(I) complexes (Figure 2). These data suggest that phosphines **3** have a donor capability similar to *N*-heterocyclic carbenes (Rh: 2036−2060, Ir: 2021−2030 cm^{-1})[15] and surpass other phosphines (Rh: 2043−2051 cm^{-1}, Ir: 2028−2043 cm^{-1}).[16] In spite of this strong nucleophilic character, phosphines **3** are perfectly air-stable in the solid state for months, and even in oxygen-bubbled $CHCl_3$ solution no decomposition was observed for two days.

The enantiomerically pure phosphine (***R,S,R*$_P$,*S*$_{Si}$)-3a,b** ($[\alpha]^{22}_D$ = +15.2° for **3a** and +6.7° for **3b**, ee ≥ 99%) was obtained from the two diasereoisomers of chiral ylides (***R,S,R*$_{Si}$)-1** and (***R,S,S*$_{Si}$)-1** readily synthesized from commercially available chiral (*R*,*S*)-(+)-*endo*-2-norborneol. The phosphine exhibits remarkable configurational and thermal stabilities since after heating at 150 °C for 1 day, no appreciable degradation was observed and the enantiopurity was unchanged.

In summary we have reported an original straightforward diastereoselective method for the preparation of *P*-chiral phosphines by the reaction of phosphonium sila-ylide **1** with aryl- and alkyl-substituted acetylene derivatives. Interestingly, the reaction proceeds *via* a [2 + 1] cycloaddition, due to the silylenoid character of **1**, leading to a hypervalent transient silirene **2**, which is the key intermediate for an efficient dynamic kinetic resolution. By taking into account the importance of the combination of enhanced steric-nucleophilic ligand properties closely related to the creation of highly robust and reactive transition-metal catalysts as it is well demonstrated by NHCs ligands,[17] the new strongly robust, bulky and nucleophilic *P*-chiral phosphines **3** would allow not only to realize asymmetric catalytic reactions but also to gain more efficiency in catalysis.

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Supporting Information Available: Experimental details for the synthesis and spectroscopic data of **2a**, **3**, (***R,S,R*$_P$,*S*$_{Si}$)-3a,b**, **7**, **8**, **9**, and **10**. This material is available free of charge via the Internet at http://pubs.acs.org.

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