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# Protodesilylation of 2,6-Disubstituted Silyphosphinines. Experimental and Theoretical Study

Matthias Blug, Olivier Piechaczyk, Marie Fustier,
Nicolas Mézailles, and Pascal Le Floch*

*Laboratoire Hétéroéléments et Coordination, Ecole Polytechnique, CNRS, Palaiseau, France*

*pascal.lefloch@polytechnique.edu*

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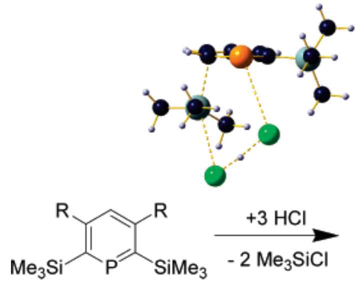
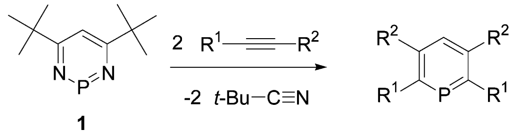


2,6-Disilylphosphinines react with HCl in ethereal solution to cleanly yield the corresponding 2,6-unsubstituted derivatives. DFT calculations allowed rationalization of the mechanism of this protodesilylation.

Phosphinines[1−3] are one of the most important classes of phosphorus aromatic heterocycles with phospholes[4] and their anionic derivatives. Due to their very specific electronic properties, that strongly differ from that of classical phosphines and related nitrogen heterocycles, they have found applications as ligands in coordination chemistry for the stabilization of highly reduced complexes[5,6] and in homogeneous catalysis such as the hydroformylation process of olefins.[7−12] More recently they also proved to be well adapted for the growing and stabilization of metallic nanoparticles.[13,14] However, from these last studies it appeared that the substitution scheme of the ring plays a crucial role on the coordinating ability of the ligand as well as on the solubility of the resulting nanomaterials. The most interesting performances in terms of particle size and shape were obtained with 3,5-disubstituted derivatives. Though many synthetic approaches toward functional phosphinines have been devised, most of these studies focused on the elaboration of 2,6-disubstituted derivatives and methods providing a convenient access toward 3,5-disubstituted compounds have been much less studied. In most cases, these approaches rely on multistep procedures that are specific from the nature of the functional groups grafted at the 3 and 5 positions.[15−23] A few years ago we reported a synthetic strategy, which allows the synthesis of tetrafunctional derivatives. Polyfunctional compounds,[24−27] polydentate ligands,[28,29] and phosphorus macrocycles[30−33] could be easily prepared from disubstituted alkynes and 1,3,2-diazaphosphinine **1** through a cycloaddition/cycloreversion sequence which is depicted in Scheme 1.

**SCHEME 1**



However this process could not be successfully extended toward the synthesis of disubstituted derivatives with terminal

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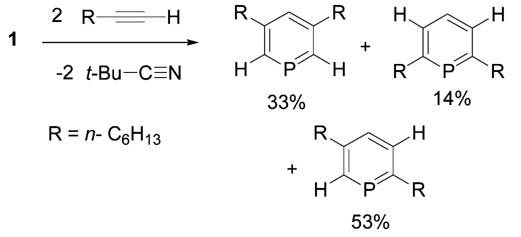
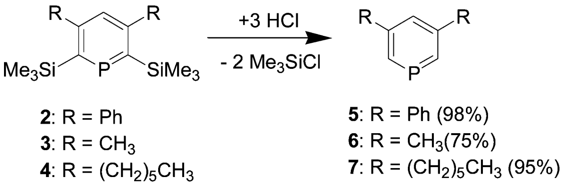
**SCHEME 2**



**SCHEME 3**



alkynes since in most cases cycloadditions did not proceed regioselectively. Thus, for example, reaction of **1** with 1-octyne yields a mixture of the three possible isomers, the 2,5-disubstituted derivative being predominant (Scheme 2).

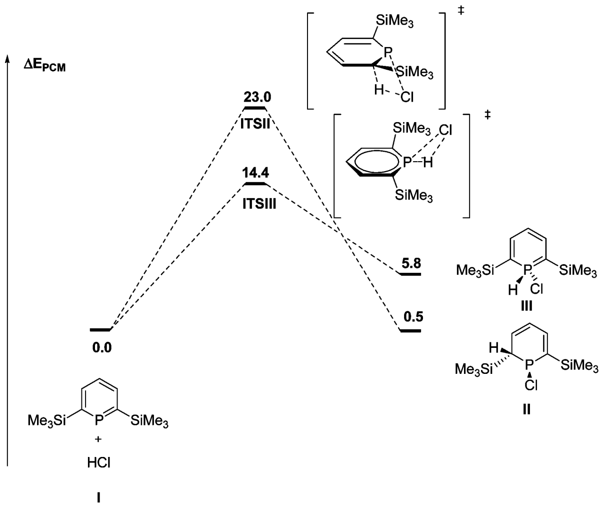
In order to devise a convenient route toward 3,5-disubstituted phosphinines, we decided to investigate the protodesilylation of 2,6-disilylphosphinines, which are produced regiospecifically when silylalkynes are employed as partners in these cyloaddition/cycloreversion sequences. Herein we wish to report on theses results as well as on a theoretical study which shed some light on this protodesilylation process.

The synthesis of 3,5-disubstituted phosphinines bearing alkyl or phenyl substituents **5**−**7** was achieved by a highly regioselective method, employing a two-step strategy. In the first step the trimethylsilyl group was used as a directing group in the Diels−Alder reaction sequence leading selectively to 2,6-di(trimethylsilyl)-substituted phosphinines **2**−**4**. Then we found that the protodesilylation of these compounds could be simply driven to completion upon reaction with a slight excess (1,5 equiv per $SiMe_3$) of 2 M HCl in ethereal solution (Scheme 3).

Monitoring of the reaction by $^{31}P$ NMR spectroscopy allowed two interesting observations. During the synthesis of **7**, formation of a monosilyl compound was evidenced by the appearance of a signal at $\delta = 238$ ppm showing a characteristic coupling constant $^2J(H-P)$ of 62.9 Hz. A second intermediate, which does not exhibit a measurable coupling constant with the phosphorus nucleus, was also detected in the crude reaction mixture at $\delta = 86$ ppm. This chemical shift, which is not in the usual range for the phosphorus atom of phosphinines (phosphinines usually appear at low field between 180 and 250 ppm depending on the substitution scheme), indicates that during the process the aromaticity of the ring is disrupted.

Compounds **5**−**7** were then isolated by evaporation of the solvent, excess HCl, and $Me_3SiCl$ and were characterized by means of NMR spectroscopy and high-resolution mass spectrometry. The $^1H$ NMR spectra of the 2,6-unsubstituted compounds show a very characteristic coupling between the protons in the 2 and 6 position and the phosphorus atom with a large $^2J(P-H)$ coupling constant of about 40 Hz. Note that the chemical shift of the H4 hydrogen atom was also found to be strongly dependent on the substitution scheme (between 7.9 ppm (R=Ph) and 6.8 ppm (R=Me)), as usually observed in other substituted phosphinines. To get further insights on the mechanism of this protodesilylation process, DFT calculations were carried out with the 2,6-di(trimethylsilyl)phosphinine **I** as model.

**SCHEME 4**



Combination of the B3LYP functional with the 6-31+G* was used for structure optimizations, and the polarized continuum model (PCM) at the B3LYP/6-311+G** level of theory was used for energy calculations. The first point concerns the addition of HCl to phosphinine **I**. Two pathways were envisioned.

Indeed, this addition might occur either via a 1,2-addition leading to the 1-P-chloro-1,2-dehydrophosphinine **II** or through an oxidative addition to the phosphorus atom leading to the $\lambda^5$-phosphinine **III** (see Scheme 4). In both transition states, the hydrogen−phosphorus or hydrogen−carbon bonds are rather short and quite close to their final distances, while the phosphorus−chloride bonds are still pretty long (Figure 1). Thus the energy of these transition states should be directly related to the protonation energy at the phosphorus atom or at the α-position. Accordingly, the transition state leading to the $\lambda^5$-phosphinine **III** is lower in energy than the transition state leading to the phosphine **II** ($\Delta E^{\ddagger}_{I\_TS\_III} = 14.4$ kcal·mol$^{-1}$ vs $\Delta E^{\ddagger}_{I\_TS\_II} = 23.0$ kcal·mol$^{-1}$) which corresponds to a higher proton affinity at the phosphorus atom than at the α-carbon atom (211.1 kcal·mol$^{-1}$ vs 207.5 kcal·mol$^{-1}$).[34] It should also be noted that the addition of HCl leading to the $\lambda^5$-phosphinine **III** does not adopt a $C_{2v}$ symmetry, as was previously observed in the case of the addition of $H_2$ to the parent phosphinine $C_5H_5P$.[35]

Since **II** and **III** are both close in energy and kinetically accessible, the elimination process of $Me_3SiCl$ from each species had to be calculated. In order to allow for the elimination of $Me_3SiCl$ from **II** to form the monosilylated phosphine $C_5H_4$-$PSiMe_3$, the trimethysilyl and the chlorine substituents have to adopt a cis stereochemistry.

The inversion of the phosphorus atom in **II** to form its diastereomer **V** was thus investigated, prior to the elimination process. As can be seen in Scheme 5, the direct isomerization requires a significant activation energy ($\Delta E^{\ddagger}_{\mathbf{II\_TS\_V}} = 47.7$ kcal·mol$^{-1}$) not accessible under the experimental conditions. A second pathway which relies on the addition of a second molecule of HCl onto chlorophosphine **II** was considered. This

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(34) PA = ($\Delta E_{el} + \Delta E_{ZPE} + 5/2RT$), see: Pham-Tran, N.; Bouchoux, G.; Delaere, D.; Nguyen, M. T. *J. Phys. Chem. A* **2005**, *109*, 2957−2963.

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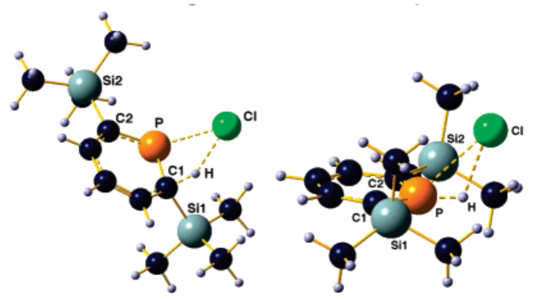
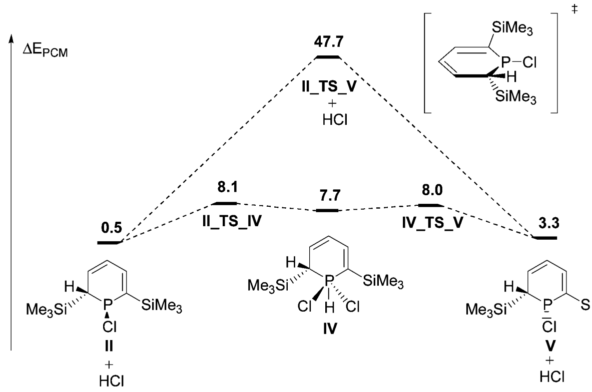


**FIGURE 1.** View of **I_TS_II** (left picture). Significant bond lengths in Å, angles in deg: C1−P: 1.812, C2−P: 1.754, C1−H: 1.187, P−Cl: 3.032, H−Cl: 1.941, C1−P−C2: 103.4. View of **I_TS_III** (right picture): C1−P: 1.712, C2−P: 1.712, P−H: 1.410, P−Cl: 2.984, H−Cl: 2.168, C1−P−C2: 114.4.

**SCHEME 5**



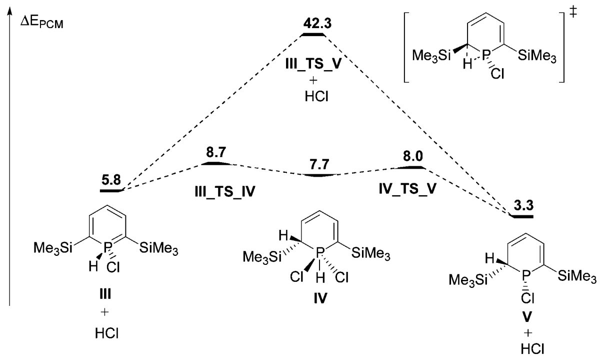
addition was found to be endothermic ($\Delta E_{\mathbf{II\_IV}} = 7.2$ kcal·mol$^{-1}$) and requires a rather low activation energy ($\Delta E^{\ddagger}_{\mathbf{II\_TS\_IV}} = 7.6$ kcal·mol$^{-1}$).

As expected, the energetic profile of the subsequent elimination step form **II** to form **V** is very comparable to the energetic profile of the addition step ($\Delta E_{\mathbf{IV\_V}} = -4.4$ kcal·mol$^{-1}$, $\Delta E^{\ddagger}_{\mathbf{IV\_TS\_V}} = 0.3$ kcal·mol$^{-1}$). Interestingly, we found that compound **IV** can also be obtained from the reaction of a second molecule of HCl onto the $\lambda^5$-phosphinine **III**. As can be seen in Scheme 5, this reaction is slightly endothermic ($\Delta E_{\mathbf{III\_TS\_IV}} = 1.9$ kcal·mol$^{-1}$) and requires a lower activation energy ($\Delta E^{\ddagger}_{\mathbf{III\_TS\_IV}} = 3.0$ kcal·mol$^{-1}$). The elimination of HCl which yields chlorophosphine **V** has been discussed above. To be exhaustive, a mechanism relying on the 1,2-sigmatropic shift of one hydrogen atom from the phosphorus atom to the α-carbon atom was also computed. As reported for the parent $\lambda^5$-phosphinine $C_5H_5P{-}H_2$, this rearrangement requires a very important activation energy ($\Delta E^{\ddagger}_{\mathbf{III\_TS\_V}} = 36.5$ kcal·mol$^{-1}$) and may not occur under the experimental conditions used (see Scheme 6).

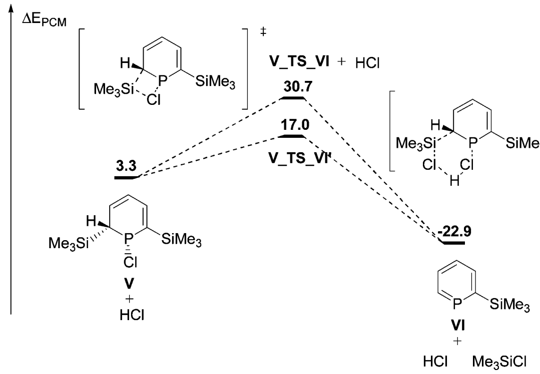
Having rationalized the formation of compound **V** we then turned our attention to the elimination of $Me_3SiCl$ which provides the monosilylated phosphinine **VI**, an observable intermediate in the reaction. The direct syn-elimination of trimethylsilyl chloride was computed, but the corresponding four-center transition state was found to be relatively high in energy ($\Delta E^{\ddagger}_{\mathbf{V\_TS\_VI}} = 27.4$ kcal·mol$^{-1}$). A more convincing alternative was found by considering the involvement of a second molecule of HCl.

A more accessible 6-center transition state was located ($\Delta E^{\ddagger}_{\mathbf{V\_TS\_VI}} = 13.7$ kcal·mol$^{-1}$). This last step is highly exothermic ($\Delta E_{\mathbf{V\_TS\_VI}} = -19.4$ kcal·mol$^{-1}$) and yields **VI** (Scheme 7). The calculated pathway is fully consistent with the fact that an intermediate at 86 ppm in $^{31}$P NMR is observed. DFT calculations of the $^{31}$P NMR shift for **II** and **V** show chemical shifts of 100 and 106 ppm, respectively, which are in the usual range of chemical shifts of chlorophosphine derivatives.

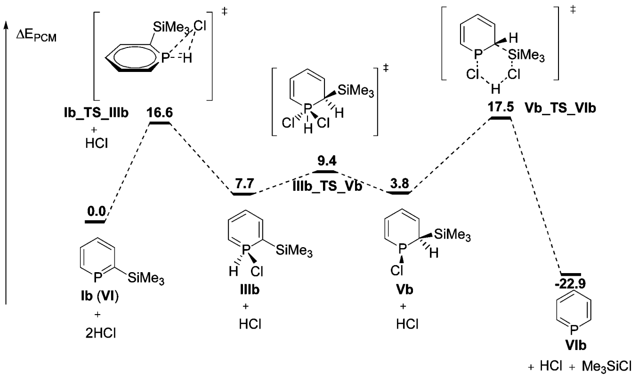
**SCHEME 6**



**SCHEME 7**



**SCHEME 8**



An analogous reaction scheme was computed for the formation of the bis-desilylated compound. As expected, the energetic pathway is similar. The main difference with the elimination of the first trimethylsilyl moiety lies in the fact that we observe, for the second elimination, the simultaneous addition−elimination of HCl for the isomerization of **IIIb** into **Vb** (Scheme 8).[36]

Note that the mechanism suggested by our calculations is consistent with the experiments conducted by Hunter et al. on

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(36) The appearance/disappearance of reaction barriers with a substitution scheme change was also observed by Bickelhaupt et al. in recent studies, see: Van Bochove, M. A.; Swart, M.; Bickelhaupt, F. M. *J Am. Chem. Soc.* **2006**, *128*, 10738−10744.

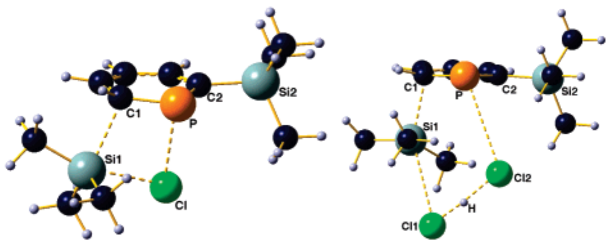
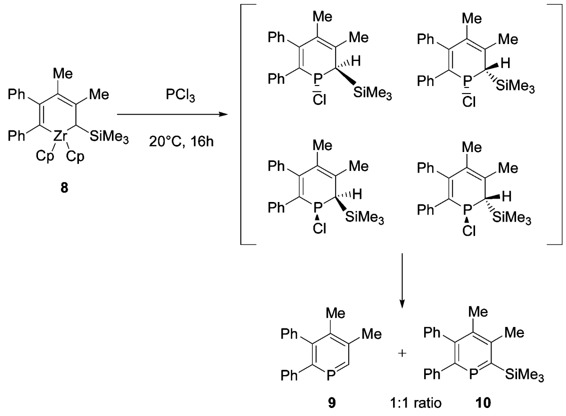


**FIGURE 2.** View of **V_TS_VI** (left picture). Significant bond distances in Å, angles in deg: C1−H: 1.089, C1−Si1: 2.475, C1−P: 1.784, C2−P: 1.763, P−Cl: 2.698, Si1−Cl: 2.596; C1−Si1−Cl: 76.8. View of **V_TS_VI′** (right picture): C1−H: 1.091, C1−Si1: 2.453, C1−P: 1.775, C2−P: 1.751, P−Cl2: 4.015; Si1−Cl1: 3.507; C1−Si1−Cl1: 151.4.

**SCHEME 9**



the formation of the 2,3-diphenyl-4,5-dimethylphosphinine **9** and the 2-trimethylsilyl-3,4-dimethyl-5,6-diphenylphosphinine **10**, in a 1:1 ratio, from the reaction of the zirconacycle **8** with $PCl_3$.[37] This ratio might be explained by the fact that the reaction of the zirconium complex yields the four possible diastereomers of 1-P-chloro-1,2-dehydrophoshinine in a statistical ratio. These diastereomers might then undergo either the elimination of HCl (which corresponds to **II_TS_I** in our model) or an elimination of $Me_3SiCl$ (**V_TS_VI′**) according to their stereochemistry leading to two phosphinines in a 1:1 ratio (Scheme 9). In conclusion, we have shown that 2,6-unsubstitued phosphinines can be easily produced in high yields from the simple reaction of HCl with readily available 2,6-di(trimethylsilyl)phosphinine derivatives. This straightforward route yields access to various 3,5-difunctionalized derivatives whose synthesis was somewhat tedious. Contrary to what could be expected, the mechanism of this protodesilylation process does not rely on a simple addition elimination sequence. Rather, as shown by DFT calculations, it involves the formation of intermediates bearing a hypervalent phosphorus center, such as in **IV**. The readily accessible hypervalent state of the P center allows a low energetic reaction path for this transformation, from either compounds **II** or **III**. This mechanism, involving dihalogeno-$\lambda^5$-phosphinines, is reminiscent of the one proposed for the α-bromination of 2-halogeno-phosphinines.[38]

## Experimental Section

**Typical Protodesilylation Procedure.** A 2 M solution of HCl in $Et_2O$ (3 mL, 6 mmol) was added to a solution of **2** (785 mg, 2 mmol) in $Et_2O$ (20 mL). The reaction mixture was stirred for 30 min at 25 °C. **5** was obtained pure by evaporation of the volatiles. Yield: 486 mg (1.96 mmol, 98%).

**Computational Details.** DFT calculations were carried out using the Gaussian 03W set of programs,[39] with the B3LYP[40−42] functional. Geometry optimizations were computed using the 6-31+G(d) basis set and completed by single point calculations using the PCM method[43−46] with the 6-311+G(d,p) basis set considering $Et_2O$ as solvent. Transition states were characterized by one imaginary frequency and checked by IRC calculations. NMR calculations use the GIAO method.[47]

**Acknowledgment.** The CNRS, the Ecole Polytechnique, and the IDRIS (for computer time, project no. 081616) are thanked for supporting this work.

**Supporting Information Available:** Experimental procedures and characterization data of compounds **4**−**7** and computed theoretical structures data (geometries, frequencies, and PCM energies). This material is available free of charge via the Internet at http://pubs.acs.org.

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