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Brief Communication

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Reductions of Phosphine Oxides and Sulfides by Perchlorosilanes: Evidence for the Involvement of Donor-Stabilized Dichlorosilylene

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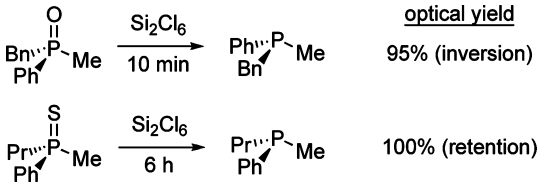
Supporting Information

ABSTRACT: Hexachlorodisilane reduces phosphine oxides and sulfides to the corresponding phosphines with opposite stereoselectivities. Through quantum mechanical calculations, a new mechanistic picture is reported that explains these stereoselectivities. Phosphine oxides are shown to react via conventional phosphorane intermediates, but phosphine sulfides follow a dramatically different mechanism involving donor-stabilized $SiCl_2$.

One of the classic protection strategies for phosphines consists of oxidation to a P═O or P═S derivative, followed by reduction with a chlorosilane.[1] The pioneering work of Mislow[2,3] provided highly stereoselective methods for the deprotection of *P*-chiral phosphine oxides and sulfides by Si_2Cl_6. The excellent optical yields obtained from acyclic[4] oxide or sulfide precursors are illustrated in Scheme 1. However, one

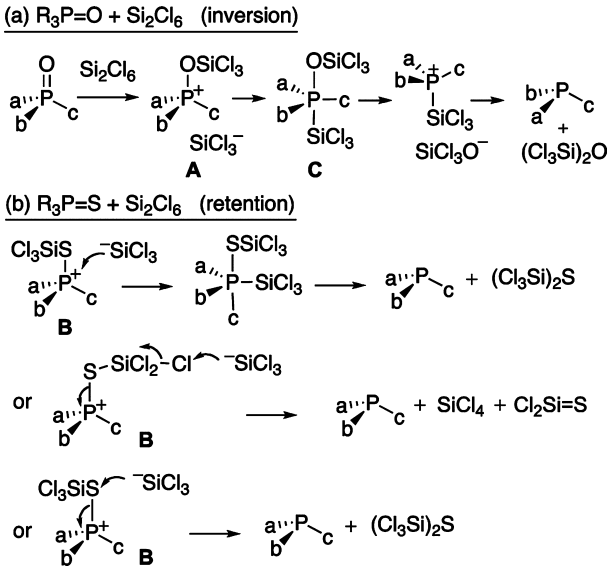
Scheme 1. Stereoselectivities of Reductions of Phosphine Oxides and Sulfides by Si_2Cl_6 (Benzene, 70−80 °C), Reported by Mislow[2,3]



feature of these reductions has never been understood: acyclic phosphine oxides are reduced with inversion of configuration, while sulfides are reduced with retention. Scarce mechanistic information is available about these reductions. Experimental studies are hampered by the complex decomposition reactions that Si_2Cl_6 undergoes in the presence of even catalytic quantities of nucleophiles.[5,6] Quantum mechanical calculations at the B3LYP, B3LYP-D, and SCS-MP2 levels, reported here, reveal a new mechanistic picture that explains these stereoselectivities for the first time. Donor-stabilized dichlorosilylene[7,8] is found to play an important role in the reductions of phosphine sulfides.

Mislow proposed that phosphine oxides and sulfides react with Si_2Cl_6 by the mechanisms shown in Scheme 2.[2,3] Nucleophilic attack on Si_2Cl_6 by the oxide or sulfide generates the phosphonium salts **A** and **B**. In the oxide-derived salt (**A**), the $SiCl_3^-$ counterion displaces $OSiCl_3^-$ in a backside manner, with inversion, via an intermediate phosphorane (**C**). The phosphine is then liberated by O−Si attack and P−Si cleavage. For the sulfide-derived phosphonium salt (**B**), backside attack

Scheme 2. Previously Proposed Mechanisms for the Reductions of Phosphine Oxides and Sulfides by Si_2Cl_6[2,3]



apparently cannot operate. Three stereoretentive possibilities were suggested: (i) frontside attack at phosphorus, (ii) attack at chlorine, and (iii) attack at sulfur. Mislow recognized, however, that it is unclear why backside attack should not occur. Reactions of nucleophiles with closely related phosphonium ions [e.g., alkaline hydrolysis of $R_3P(SR')^+$] do proceed with clean inversion.[3]

The unexpected reversal of stereoselectivity is addressed here by means of density functional theory and ab initio calculations[9,10] on the reductions of Me_3P═O and Me_3P═S by Si_2Cl_6. The potential energy surfaces were explored initially at the B3LYP/6-31G(d) level.[11] Single-point energies were

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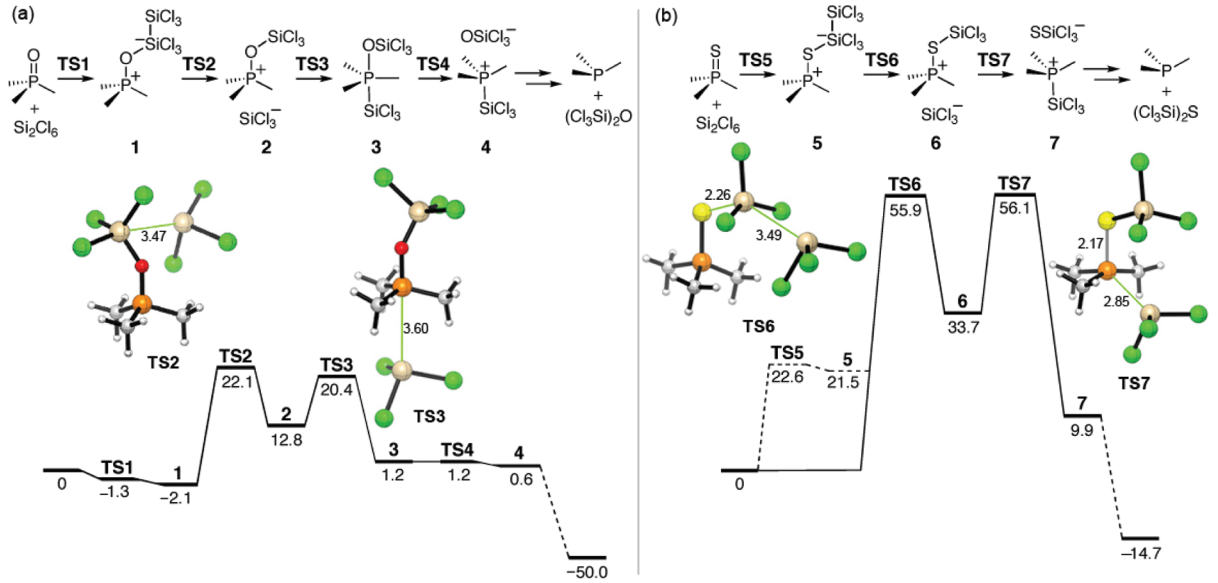

Figure 1. Free-energy profiles for reduction of $Me_3P{=}O$ and $Me_3P{=}S$ by Si_2Cl_6 in benzene via backside attack of $SiCl_3^-$ on phosphonium ions $Me_3P(ESiCl_3)^+$ (E = O, S). ΔG (kcal/mol) reported at the SCS-MP2/6-311+G(d,p)//B3LYP/6-31G(d) level including CPCM [B3LYP/6-31G(d)] solvation corrections. Bond lengths in angstroms.

then calculated at the SCS-MP2/6-311+G(d,p) level[12] and used in conjunction with solvation corrections (in benzene) obtained from CPCM calculations.[13] Dispersion-corrected DFT energies were also computed with B3LYP-D.[14] The DFT calculations yield the same mechanistic conclusions as the SCS-MP2 data reported below.

In Figure 1a is shown the free energy surface for the reaction of $Me_3P{=}O$ with Si_2Cl_6 in benzene, according to the mechanism in Scheme 2a.

This sequence of transformations, beginning with formation of the $Me_3P{=}O{\cdots}Si_2Cl_6$ adduct **1**, leads straightforwardly to the phosphine with inversion of configuration. The rate-limiting step (**TS2**) is the cleavage of the Si−Si bond in the initial adduct. The Si−Si cleavage generates the phosphonium salt **2** with a $\Delta G^{\ddagger}$ of 22.1 kcal/mol. Subsequent backside addition of $SiCl_3^-$ (**TS3**) provides phosphorane **3**, which readily loses $OSiCl_3^-$ from the opposite face (**TS4**) to provide the phosphonium salt **4**. The remaining steps leading to liberation of the phosphine (Si−O bond formation and P−Si cleavage) are facile (see the Supporting Information).[15]

Conceivably, a loss of stereochemical integrity could arise if the intermediate phosphorane (**3**) were able to undergo pseudorotation prior to departure of $OSiCl_3^-$. Transition states for the pseudorotation of **3** were calculated but found to lie at or above 19.9 kcal/mol (cf. 1.2 kcal/mol for loss of $OSiCl_3^-$). Theory therefore predicts clean inversion of configuration, consistent with experiment.

An analogous backside-attack mechanism was explored for $Me_3P{=}S$. The calculated free energy surface is shown alongside that of $Me_3P{=}O$ in Figure 1. The sulfide reaction dispenses with some of the intermediates from the oxide pathway. For example, the reactants combine to give the phosphonium salt **6** directly (solid line) rather than forming an initial adduct (dashed line). The nucleophilic attack of $SiCl_3^-$ on phosphorus in **6** leads directly to the phosphonium salt **7** rather than to an intermediate phosphorane.

Most striking, however, is the enormous energetic difference between the $Me_3P{=}O$ and $Me_3P{=}S$ surfaces. Reduction of the sulfide has $\Delta G^{\ddagger}$ = 56 kcal/mol, which is decidedly incompatible with the reaction conditions (refluxing benzene). The overall reactivities of $Me_3P{=}O$ and $Me_3P{=}S$ toward Si_2Cl_6 differ by 35 kcal/mol ($\Delta\Delta G$), and the same difference is found in the transition states for the rate-limiting Si−Si cleavage (**TS6** vs **TS2**, $\Delta\Delta G^{\ddagger}$ = 34 kcal/mol). Compared to $Me_3P{=}O$, each species on the $Me_3P{=}S$ reaction pathway is destabilized by the much weaker bonding of P and Si to sulfur (cf. the P−O and Si−O bonding in the reaction of $Me_3P{=}O$).

The prohibitively high barrier for the $Me_3P{=}S$ reaction in Figure 1b accounts for the departure from a traditional backside-attack (stereoinversion) mechanism. It also, however, rules out the three stereoretentive pathways previously suggested (Scheme 2b), which all require passage through **TS6** en route to the phosphonium salt **6** (i.e., **B**).[16]

Calculations indicate instead that the reductions of phosphine sulfides follow the two nonionic pathways shown in Figure 2. An initial $Me_3P{=}S{\cdots}Si_2Cl_6$ adduct (**5**) is formed, which then undergoes one of two rearrangement processes: a 1,2-Cl shift (**TS9**) or an intramolecular nucleophilic substitution by sulfur (**TS12**). The 1,2-Cl shift (**TS9**) is followed by loss of $SiCl_4$ (**TS10**) to generate the Lewis base-stabilized dichlorosilylene[7] **10**, which then loses $Cl_2Si{=}S$ (**TS11**) to generate the phosphine. The reaction is endergonic up to this point but is driven thermodynamically by subsequent highly exothermic reactions of $Cl_2Si{=}S$, such as cyclooligomerization or reactions with nucleophiles.

Reduction of $Me_3P{=}S$ by the sulfur nucleophilic attack pathway (**TS12**) is favored by 2 kcal/mol over the 1,2-Cl shift sequence (**TS9**/**10**/**11**). In **TS12**, a new S−Si bond is formed, simultaneous with cleavage of both the Si−Si and P−S bonds. The phosphine is liberated directly.

Both of these mechanisms result in retention of configuration at phosphorus. Their relative importance is likely a function of the combination of *P*-substituents. Model calculations on $Me_2PhP{=}S$, for example, show that the **TS9**/**TS12** difference drops to 0.7 kcal/mol, and the activation energy for loss of $Cl_2Si{=}S$ from the $SiCl_2$ adduct (**TS11**) drops by 13.3 kcal/mol, compared with $Me_3P{=}S$.[17]

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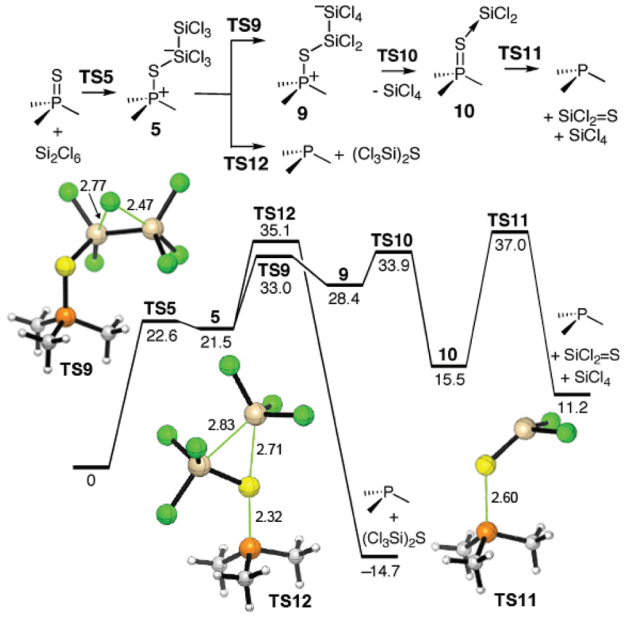

Figure 2. Proposed mechanisms for reduction of $Me_3P{=}S$ by Si_2Cl_6.

A theoretical test of the availability of these novel pathways to phosphine oxides was last made. The activation energies for passage of $Me_3P{=}O$ through transition states analogous to **TS11** and **TS12** were calculated. Barriers of ≥39 kcal/mol were obtained, indicating a kinetic preference of 17 kcal/mol for oxides to react instead by the phosphorane pathway.

Theory thus provides a clear explanation for the opposite stereoselectivities observed in reductions of phosphine oxides and sulfides by Si_2Cl_6. The most significant revelation is the role of phosphine sulfide-stabilized dichlorosilylenes (**10**). Only in 2009 was the first example of a donor-stabilized dichlorosilylene reported,[7] triggering a rapid growth in interest in the solution-phase chemistry of $SiCl_2$.[6,8,18] The *N*-heterocyclic carbene–$SiCl_2$ adducts discovered by Roesky et al.[7] function as labile $SiCl_2$ equivalents in solution and therefore should be capable of reducing phosphine sulfides (but not phosphine oxides) to phosphines. Holthausen, Lerner, et al. also recently reported the formation of amine–$SiCl_2$ adducts during the amine-induced disproportionation of Si_2Cl_6.[6] The revelation of a role for donor-stabilized dichlorosilylene in one of organophosphorus chemistry's classic transformations opens new opportunities for the design of selective reducing agents.

Computational Methods. Density functional theory and ab initio calculations were performed with the Gaussian 03[9] and Gaussian 09[10] programs. Geometries were optimized in the gas phase at the B3LYP/6-31G(d) level.[11] Conformational searching was performed at this level in order to identify each species' lowest energy conformer. Frequency calculations at the same level were used to identify the nature of each stationary point, and transition states were further verified by IRC calculations.[19] Thermochemical corrections were obtained from the unscaled B3LYP frequencies. Single-point energies were subsequently calculated at the SCS-MP2/6-311+G(d,p) level[12] on the B3LYP geometries. Free energies reported at this level incorporate the B3LYP thermochemical corrections. The influence of solvent was modeled by calculating free energies of solvation in benzene with the CPCM method[13] (B3LYP/6-31G(d), UAKS radii, Gaussian 03). Dispersion-corrected DFT energies were also computed with the B3LYP-D method.[14] Free energies are reported at 298.15 K with a standard state of 1 mol/L.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Calculated geometries and energies, B3LYP and B3LYP-D free-energy surfaces, and complete citations for refs 9 and 10. This material is available free of charge via the Internet at http://pubs.acs.org.

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(16) Transition states for these pathways were nevertheless calculated; S_N2 attack at sulfur was the lowest-energy pathway and had $\Delta G^{\ddagger}$ = 46.1 kcal/mol.
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