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Theoretical Investigation of the Mechanisms and Stereoselectivities of Reductions of Acyclic Phosphine Oxides and Sulfides by Chlorosilanes

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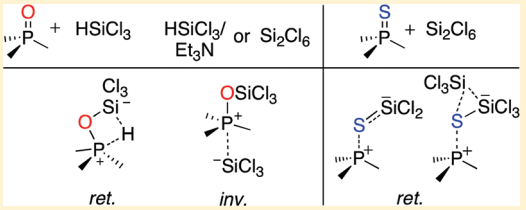
Supporting Information

ABSTRACT: Computational studies were performed to explain the highly varied stereoselectivities obtained in the reductions of acyclic phosphine oxides and sulfides by different chlorosilanes. The reductions of phosphine oxides by $HSiCl_3$, $HSiCl_3/Et_3N$, and Si_2Cl_6 and the reductions of phosphine sulfides by Si_2Cl_6 (all in benzene) were explored by means of B3LYP, B3LYP-D, and SCS-MP2 calculations. For the reductions of phosphine oxides by $HSiCl_3$, the calculations support the mechanism proposed by Horner in which a hydride is transferred from silicon to phosphorus through a four-centered, frontside transition state. This mechanism leads to retention of stereochemistry at phosphorus. For the other three reductions, two classes of mechanisms were explored. Phosphorane-based mechanisms that were previously proposed by Mislow and involve $SiCl_3^-$ were compared with novel alternative mechanisms that involve nonionic rearrangement processes. In one of these, donor-stabilized $SiCl_2$ is formed as an intermediate. The calculations support a phosphorane-based mechanism for the reductions of phosphine oxides by $HSiCl_3/Et_3N$ and Si_2Cl_6 (which proceed with inversion) but favor the rearrangement pathways for the reductions of phosphine sulfides by Si_2Cl_6 (which proceed with retention).



INTRODUCTION

Chlorosilanes rank among the most important reagents for reducing phosphine oxides and sulfides to the corresponding phosphines.[1−6] They are especially valuable for the synthesis of *P*-chiral phosphines, as their reactions with optically active *P*-chiral phosphine oxides or sulfides often provide the corresponding phosphines in high optical yield. However, the stereochemical outcomes of these reductions are strikingly varied. Either retention or inversion at phosphorus may occur,[7] depending on which chlorosilane is used and on whether the phosphorus precursor is an oxide or sulfide. Four different outcomes have been obtained from reductions of acyclic[8] phosphine oxides and sulfides in benzene, as illustrated in Scheme 1.[9]

(1) Reduction of a phosphine oxide by $HSiCl_3$, either alone or in combination with a weak base, takes place with predominant retention of configuration at phosphorus (Scheme 1a).
(2) Reduction of a phosphine oxide by $HSiCl_3$ in conjunction with a stronger base (Et_3N) leads to inversion (Scheme 1b).
(3) Reduction of a phosphine oxide by Si_2Cl_6 leads to inversion (Scheme 1c).
(4) Reduction of a phosphine sulfide by Si_2Cl_6 leads to retention (Scheme 1d).

Despite the longstanding importance of these reductions in organophosphorus chemistry, their mechanisms have escaped theoretical characterization, and the origins of their varied stereoselectivities remain unestablished. A theoretical investigation is reported here that explains the disparate stereoselectivities fully for the first time. Density functional theory and ab initio calculations are first used to examine mechanisms that have previously been proposed for the four types of reduction. The currently accepted mechanisms involve phosphorane intermediates and are described in detail in the following section. The energetics and stereoselectivities of these mechanisms are then compared with two novel alternative pathways that do not involve phosphorane intermediates. Theory is shown to support the phosphorane-based mechanisms for the reductions of phosphine oxides by $HSiCl_3$, $HSiCl_3/Et_3N$, and Si_2Cl_6 but not for the reductions of phosphine sulfides by Si_2Cl_6. The change in mechanism on going from oxide to sulfide provides an explanation for the unexpected reversal of stereoselectivity observed in experiments. A communication about the reductions involving Si_2Cl_6 has recently been published.[10]

BACKGROUND

Current mechanistic understanding about the reactions of phosphine oxides and sulfides with chlorosilanes originates from the work of Horner[11] and Mislow.[12−14] The generally

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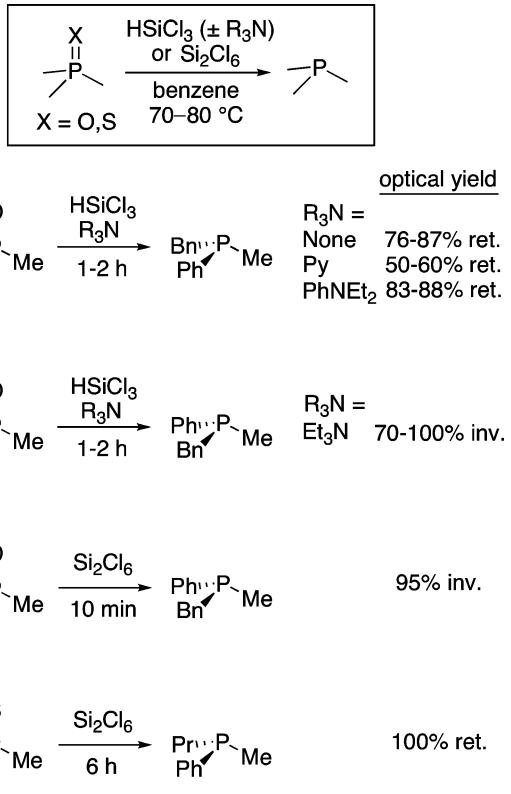
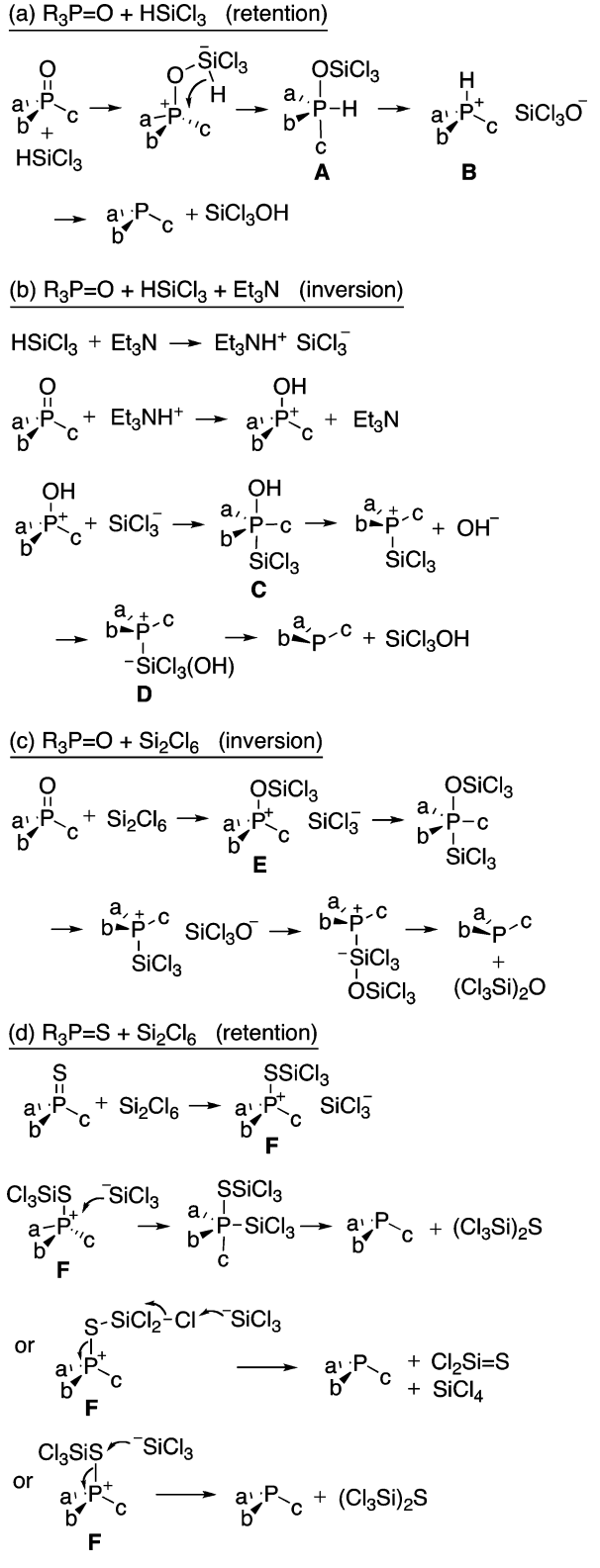
Scheme 1. Stereochemistry of Reductions of Phosphine Oxides and Sulfides by Chlorosilanes[11−13]



accepted mechanism for the reduction of an acyclic phosphine oxide by trichlorosilane (which proceeds with predominant retention of stereochemistry)[11,12] is shown in Scheme 2a. The key feature is a hydride transfer from silicon to phosphorus, which takes place through a four-centered transition state (TS) after coordination of the phosphine oxide to the silane. The resulting phosphorane (**A**) releases $SiCl_3O^-$, leaving an *H*-phosphonium cation (**B**); proton transfer then furnishes the phosphine. The frontside mode of hydride delivery means that the relative stereochemistry of the three phosphorus substituents does not change, provided that pseudorotation in the phosphorane **A** is slow. Marsi[15,16] proposed a similar four-centered hydride-transfer mechanism for the stereoretentive reductions of phosphine oxides by $PhSiH_3$.

Weak bases such as pyridine and diethylaniline have no major effect on the stereochemistry, but when the base strength is increased to below a pK_b of about 5 (e.g., triethylamine), a changeover from retention to inversion occurs.[11,12,17] Under these conditions the silane is deprotonated.[12,18] One mechanism suggested[12] for the reduction by $HSiCl_3/Et_3N$ is shown in Scheme 2b. The phosphine oxide (activated by protonation) undergoes backside attack by $SiCl_3^-$, giving phosphorane **C**. The apical P−OH bond of **C** breaks, and OH^- adds at silicon, to form the intermediate **D**, in which the phosphorus center has undergone inversion of configuration. Cleavage of the P−Si bond then liberates the phosphine.[19] Although this mechanism leads to the correct stereochemistry, Mislow noted[12] that the active reducing species in the $HSiCl_3/Et_3N$ system is actually more likely to be a compound (or mixture of compounds) containing an Si−Si bond. This was inferred from the fact that trichlorosilane reacted rapidly with Et_3N in benzene at room temperature to give a product that, upon treatment with aqueous base, produced H_2. This insight

Scheme 2. Mechanisms Previously Proposed[11−13] for the Reductions of Phosphine Oxides and Sulfides by Chlorosilanes



was the stimulus for the development of Si_2Cl_6 and Si_3Cl_8 as reducing agents, both of which reduce phosphine oxides with inversion of configuration.

The reduction of a phosphine oxide by the simplest perchloropolysilane (hexachlorodisilane) is thought to follow

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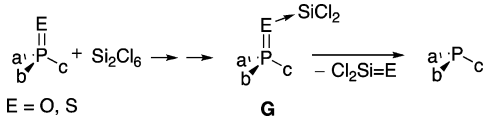
the mechanism shown in Scheme 2c.[12] The key steps are analogous to those in Scheme 2b. In this case, the $SiCl_3^-$ anion adds to the trichlorosiloxyphosphonium cation **E**. Inversion at phosphorus is the nett result.

In contrast, the reduction of a phosphine sulfide by Si_2Cl_6 gives retention. Evidently, backside attack by $SiCl_3^-$ on the sulfur-containing phosphonium ion, **F**, does not occur (Scheme 2d). Various alternative pathways were instead suggested,[13] including frontside attack at phosphorus, attack at chlorine, and attack at sulfur. Nevertheless, the absence of backside attack and the retention of stereochemistry remain difficult to reconcile with other related reactions: for example, the alkaline hydrolysis of [PhMePrP(SEt)]$SbCl_6$ proceeds with clean inversion.[13]

Chlorosilanes undergo complex decomposition reactions in the presence of nucleophiles.[20,21] During the original stereochemical studies, Mislow recognized that some dichlorosilylene may be present in the reaction mixture.[12] However, the existence of $SiCl_2$ in solution has proven difficult to demonstrate,[18] and until very recently, definitive evidence for the generation of $SiCl_2$ from silicon halides had only been obtained under conditions of gas-phase pyrolysis.[22] Several recent breakthroughs have occurred in this area. Karsch et al. reported the use of $HSiCl_3/R_3N$ as a dichlorosilylene synthon from which $SiCl_2$–diazabutadiene adducts could be prepared.[23] Jung et al. reported that adducts of $SiCl_2$ with a diene or alkyne could be trapped upon treatment of $HSiCl_3$ with catalytic [Bu_4P]Cl.[24] Very recently, Roesky, Stalke, et al. reported the first examples of isolable Lewis base-stabilized $SiCl_2$, prepared by treatment of $HSiCl_3$ with *N*-heterocyclic carbenes (NHCs).[25,26] The NHC adducts can also be prepared from Si_2Cl_6.[27] They are monomeric donor–acceptor complexes that function as sources of [$SiCl_2$] in solution.[28,29]

The possibility that $SiCl_2$ chemistry may be involved in the reductions of phosphine oxides or sulfides by $HSiCl_3/Et_3N$ and Si_2Cl_6 therefore warrants investigation. Herein, calculations are reported to explore the silylene-based reactions shown in Scheme 3 and to evaluate their mechanistic significance.

Scheme 3. Possible Silylene-Based Mechanisms for the Reduction of Phosphine Oxides or Sulfides



Reductions involving the $SiCl_2$ adduct **G** (E = O or S) would lead to a phosphine having the same relative stereochemistry as the starting oxide or sulfide; hence, this pathway ought only to be feasible for phosphine sulfides, and not for oxides. The potential energy surfaces for these transformations are explored below.

THEORETICAL CALCULATIONS

Density functional theory and ab initio calculations were performed with the Gaussian 03[30] and Gaussian 09[31] programs. Geometries were optimized in the gas phase at the B3LYP/6-31G(d) level.[32] Frequency calculations at this level were used to identify the nature of each stationary point, and transition states were further verified by intrinsic reaction coordinate (IRC) calculations.[33] Each species was subjected to conformational searching to identify the lowest energy conformer. Thermochemical corrections were obtained from the B3LYP frequencies and are unscaled. Single-point energy calculations were performed at the SCS-MP2/6-311+G(d,p)[34] level on the B3LYP geometries and used in conjunction with the B3LYP thermochemical corrections to obtain gas-phase free energies. Free energies of solvation in benzene were then computed with the CPCM method[35] (B3LYP/6-31G(d), UAKS radii, Gaussian 03). Free energies are quoted at 298.15 K with a standard state of 1 mol/L. Dispersion-corrected DFT calculations with B3LYP-D[36] were also performed, for comparison with the B3LYP and SCS-MP2 data. Molecular structures were drawn with the CYLview program.[37]

RESULTS AND DISCUSSION

Quantum mechanical calculations with the B3LYP, B3LYP-D, and SCS-MP2 methods were performed to explore the mechanisms of the four types of reduction illustrated in Scheme 1. Trimethylphosphine oxide and trimethylphosphine sulfide were used as model reactants, and the stereochemistry of the three *P*-Me groups was traced throughout each transformation. The SCS-MP2 data are discussed below, noting any variations obtained with B3LYP and B3LYP-D. The free energy surfaces obtained with these two density functional methods are provided in the Supporting Information.

Reductions of Phosphine Oxides by $HSiCl_3$ Alone. The free energy surface calculated for the reduction of $Me_3P{=}O$ by $HSiCl_3$ in benzene at the SCS-MP2/6-311+G(d,p)//B3LYP/6-31G(d) level is shown in Figure 1. The geometries of the transition states and the phosphorane intermediate are included. Solution-phase free energies were obtained by incorporating CPCM solvation energies computed at the B3LYP/6-31G(d) level. Similar free energy surfaces are obtained in the gas phase and from computations at the B3LYP and B3LYP-D levels.

The phosphine oxide first coordinates to $HSiCl_3$ to form the adduct **1**. Intramolecular hydride transfer then takes place through the four-centered transition state, **TS1**. This is the rate-determining step for the reduction and has a calculated activation energy ($\Delta G^{\ddagger}$) of 27.1 kcal/mol in solution. An intrinsic reaction coordinate (IRC) calculation on **TS1** showed that it leads to the phosphorane **2**, in which the hydride is equatorial and oxygen is apical. Once **2** is formed, there are several alternative pathways available. Dissociation of the P–O bond would lead to the ion pair, [Me_3PH][$OSiCl_3$], from which the products can be formed by proton transfer. The ion pair lies at 14.9 kcal/mol. Dissociation into the ion pair appears unnecessary, however, because a more facile alternative is the direct extrusion of the phosphine through transition state **TS2**. In **TS2**, the P–O and P–H bonds are cleaved at the same time as the O–H bond is formed.[38] This process has a barrier of only 3.3 kcal/mol.

One further pathway was explored. In this pathway, the intermediate **1** does not undergo 1,3-hydride transfer to phosphorus, but instead undergoes a 1,2-H shift to oxygen (**TS3b**).[39] The transition state for this process, which was found to occur with concomitant cleavage of the P–O bond, lies at very high energy (72 kcal/mol), however, and appears not to be mechanistically significant.

Hydride transfer to phosphorus and phosphine extrusion leave the relative stereochemistry of the three phosphorus substituents unchanged. Experimentally, however, some loss of stereochemical integrity is occasionally observed. In order to check whether this can be ascribed to stereochemical lability of the intermediate phosphorane (**2**), transition states for pseudorotation of **2** were calculated. The lowest energy pseudorotation transition state, **TS3**, lies at very high energy (35.4 kcal/mol). Thus, stereochemical scrambling appears not

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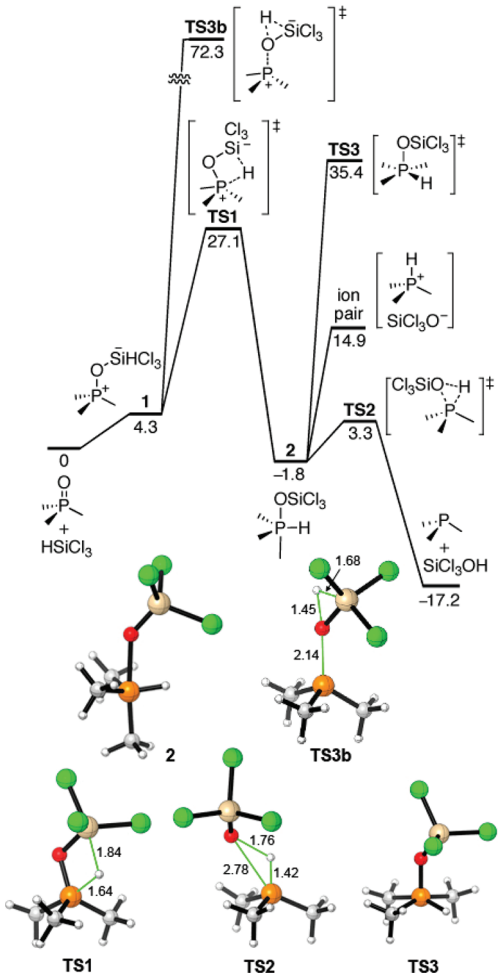

Figure 1. Free energy surface for the reduction of $Me_3P{=}O$ by $HSiCl_3$ in benzene, calculated at the SCS-MP2/6-311+G(d,p)//B3LYP/6-31G(d) level with CPCM (B3LYP) solvation corrections. The lowest-energy pathway involves hydride transfer to phosphorus followed by phosphine extrusion, and leads to retention of stereochemistry at phosphorus. Free energies in kcal/mol, bond lengths in Å.

to be an innate feature of the reduction pathway itself. The stereoselectivities of reductions by $HSiCl_3$ can be quite sensitive to the reaction conditions, requiring careful optimization.[4,5] While the enantioselectivities reported originally by Horner[11] were in the range 76−87%, more recent work by Yu and Spencer[40] demonstrated an optical yield of 99.7% for the reduction of (*R*)-(2-methoxyphenyl)methylphenylphosphine oxide by $HSiCl_3$.

Reductions of Phosphine Oxides by $HSiCl_3$/Et_3N. Although the active reductant in the $HSiCl_3$/Et_3N system is thought to be a perchloropolysilane such as Si_2Cl_6,[12] calculations were first performed to explore the mechanism shown in Scheme 2b, which involves protonation of the phosphine and nucleophilic attack by $SiCl_3^-$. The calculated free energy profile, transition structures, and intermediates for this mechanism are shown in Figure 2.

Two transition states were found for the initial reaction of $SiCl_3^-$ with protonated $Me_3P{=}O$. The favored transition state (**TS4**) corresponds to backside attack and leads to the phosphorane **3**. A frontside transition state was also located (**TS5**) but is disfavored by 3.2 kcal/mol compared to backside attack.[41]

Dissociation of phosphorane **3** into $Me_3P(SiCl_3)^+$ and OH^- is not a favorable process: the ion pair lies at 65 kcal/mol (Supporting Information). However, the loss of OH^- from **3** can be facilitated by proton transfer from a second equivalent of Et_3NH^+. The transition state for Et_3NH^+-assisted cleavage of the P−OH bond (**TS6**) lies only 0.4 kcal/mol above **3**. B3LYP predicts a higher energy for **TS6**, but when dispersion interactions are included (B3LYP-D) the energy surface parallels that predicted by SCS-MP2.

Once the P−O bond has been broken, the remaining steps leading to products (Si−O bond formation and P−Si bond cleavage) are facile. Transition states for pseudorotation of the intermediate phosphorane **3** were calculated, and the lowest such transition state (**TS9**) was found to lie some 3.9 kcal/mol above the transition state for the P−O cleavage.[42] Thus, theory predicts that stereochemical scrambling of **3** should not affect the stereochemical outcome.

Reductions of Phosphine Oxides by Si_2Cl_6. The calculated free energy surface, transition structures, and intermediates for the reduction of $Me_3P{=}O$ by Si_2Cl_6 in benzene are shown in Figure 3.

The reduction of $Me_3P{=}O$ by Si_2Cl_6 commences with formation of the adduct **6**. The subsequent cleavage of the Si−Si bond to form the phosphonium salt **7** is the rate-determining step of the reaction (**TS11**), and has a calculated barrier of 22.1 kcal/mol. Although the phosphonium cation of **7** may in principle undergo either backside or frontside attack by $SiCl_3^-$, only a backside transition state was located (**TS12**). Release of $SiCl_3O^-$ from the resulting phosphorane **8** is facile (**TS13**). A transition state for the addition of $SiCl_3O^-$ at silicon could not be located; however, by comparison with **TS7** (the transition state for Et_3NH^+-assisted addition of OH^-, Figure 2), this step is unlikely to be rate-determining. The ensuing cleavage of the P−Si bond also has a low barrier.

Stereochemical scrambling in the intermediate phosphorane is again not predicted to be a complicating factor. Transition states for pseudorotation of phosphorane **8** were found to lie at ≥19.9 kcal/mol (Supporting Information), which is 18.7 kcal/mol above the transition state for P−O cleavage.[42] The activation energies for pseudorotation of the phosphoranes **2**, **3**, and **8** are comparatively high.[43−47] This is probably partly due to the equatorial preference of Me groups attached to phosphorus;[48] however, the analysis is not clear-cut because the pseudorotation processes in **3** and **8** were found to be coupled to the transfer of the OX group (X = H, $SiCl_3$) from P to Si.

The energy profiles shown in Figures 2 and 3 lend support to the proposal that perchloropolysilanes are the actual reductants in reductions by $HSiCl_3$/Et_3N. The overall barrier for reduction of $Me_3P{=}O$ by Si_2Cl_6 (22.1 kcal/mol, Figure 3) is 3.2 kcal/mol lower than that for reduction by the protonation/nucleophilic attack pathway (25.3 kcal/mol, Figure 2). Thus, the perchloropolysilane pathway is favored by theory, even though the predictions regarding stereoselectivity are the same for both pathways.

Reductions of Phosphine Sulfides by Si_2Cl_6. For the reduction of $Me_3P{=}S$ by Si_2Cl_6, several types of mechanism were explored. The calculated free energy surfaces, transition structures, and intermediates are shown in Figure 4. Figure 4a depicts the previously proposed[13] pathways involving $SiCl_3^-$ (shown in Scheme 2d), while Figure 4b depicts alternative nonionic pathways including the silylene-based reaction proposed in Scheme 3.

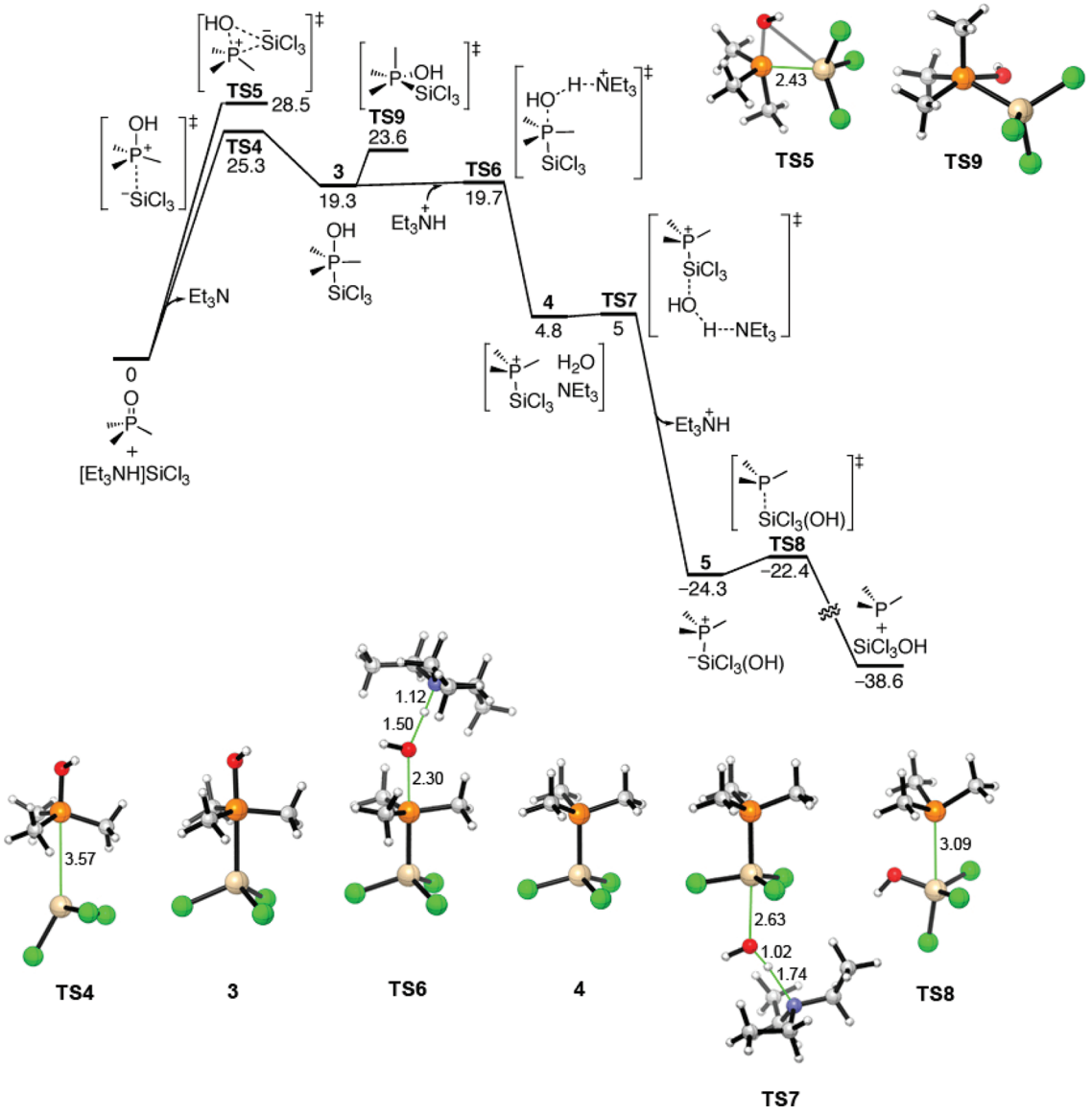

Figure 2. Free energy surface for the reduction of $Me_3P{=}O$ by $HSiCl_3/Et_3N$ in benzene via a hypothetical protonation/nucleophilic addition mechanism. The lowest energy pathway is assisted by Et_3NH^+ and involves backside displacement of OH^- from $Me_3P(OH)^+$ by $SiCl_3^-$, leading to inversion of configuration. Free energies in kcal/mol, bond lengths in Å.

In the ionic process (Figure 4a), the phosphonium salt **11** is generated by S_N2 attack of $Me_3P{=}S$ on Si_2Cl_6 (**TS16**). Consistent with the experimental stereoselectivities,[13] backside attack by $SiCl_3^-$ at phosphorus in **11** is disfavored. The backside TS (**TS18**) lies 10 kcal/mol above the transition state for attack at sulfur (**TS17**). The latter TS leads directly to the product phosphine with retention of stereochemistry. A transition state for attack at chlorine was also located (**TS19**) but is disfavored by 17 kcal/mol over sulfur attack. Both B3LYP and B3LYP-D differ from SCS-MP2 in that they predict **TS19** to be lower in energy than **TS18**; however, both functionals maintain the substantial preference for **TS17**. Although the relative energies of **TS17**−**TS19** do correctly predict the observed retention of stereochemistry, all three ionic pathways are rendered mechanistically insignificant by the enormous barrier associated with the formation of **11**. The activation energy of **TS16** (55.9 kcal/mol) is clearly incompatible with reaction in refluxing benzene.

Instead, the reduction of $Me_3P{=}S$ is predicted to follow the two nonionic mechanisms shown in Figure 4b. The reactants first combine to give adduct **12**. Rather than undergoing Si−Si cleavage, **12** undergoes one of two rearrangement processes. In the first, a 1,2-Cl shift (**TS22**) leads to the intermediate **13**, which loses $SiCl_4$ via **TS23** to generate the donor-stabilized dichlorosilylene **14**. Cleavage of the P−S bond of **14** (**TS24**) then provides the product phosphine plus $Cl_2Si{=}S$. An alternative pathway of similar energy was identified in which **12** generates the phosphine directly by a single step involving several bond-breaking and -forming processes (**TS21**). Transition state **TS21** comprises intramolecular nucleophilic attack by sulfur onto the terminal silicon atom, cleavage of the Si−Si bond, and cleavage of the P−S bond. The phosphine is formed with retention of configuration. Retention is also obtained in the pathway **TS22**/**TS23**/**TS24**. The latter pathway is uphill by 11.2 kcal/mol, but the reaction is driven by highly exergonic further reactions of $Cl_2Si{=}S$; for example, the

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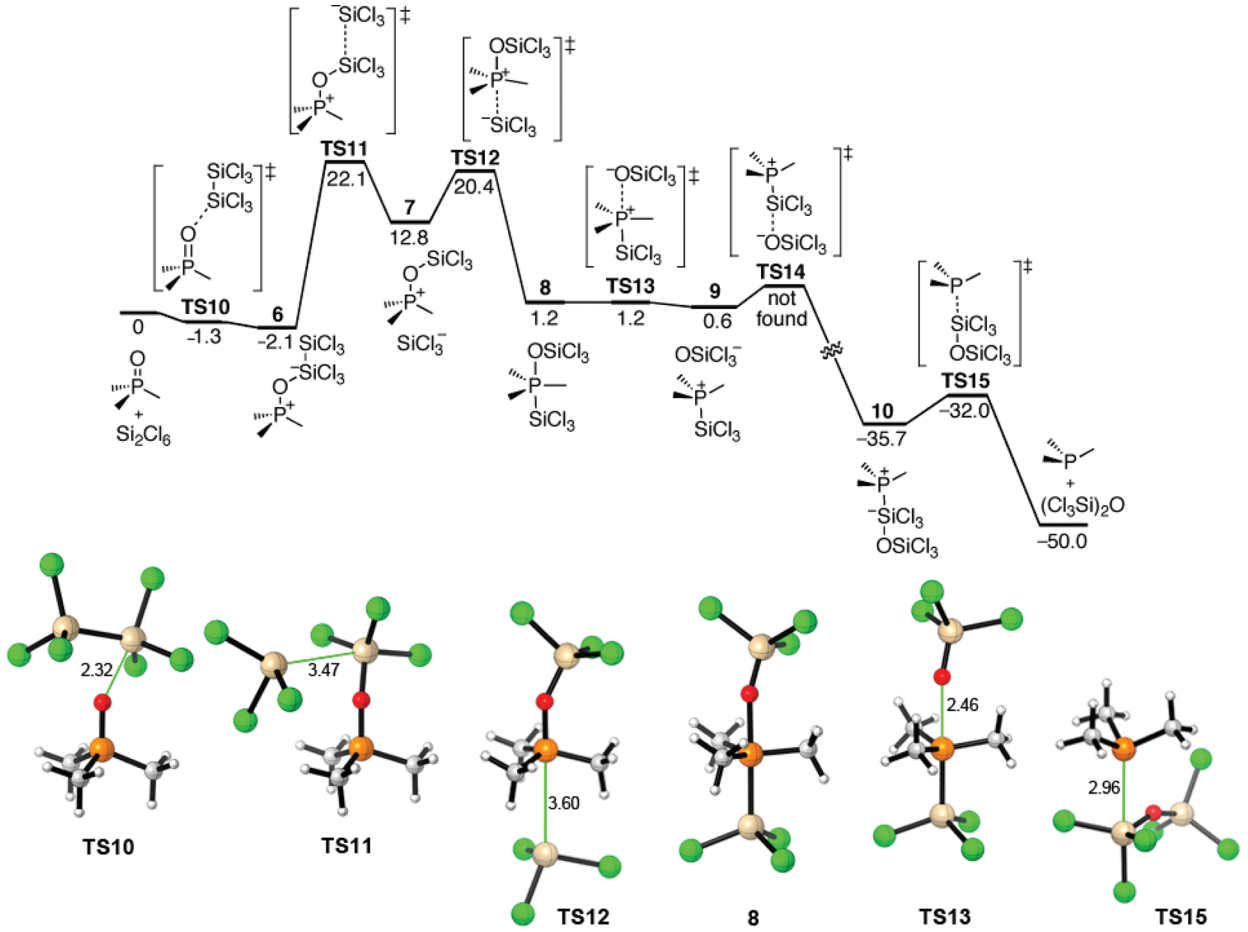

Figure 3. Free energy surface for the reduction of $Me_3P{=}O$ by Si_2Cl_6 in benzene. Backside attack by $SiCl_3^-$ on the phosphonium cation $Me_3P(OSiCl_3)^+$ leads to inversion of configuration at phosphorus. Free energies in kcal/mol, bond lengths in Å.

reaction $Cl_2Si{=}S + SiCl_3^- \rightarrow (Cl_3Si)SiCl_2S^-$ has $\Delta G = -44.7$ kcal/mol.

The two nonionic pathways (**TS21** and **TS22/23/24**) are favored by ≥18.9 kcal/mol over the ionic mechanisms depicted in Figure 4a. The preference for the nonionic processes is also predicted by B3LYP and B3LYP-D. The direct route to products (**TS21**) is favored by 1.9 kcal/mol over the 1,2-Cl shift sequence (**TS22/23/24**) for $Me_3P{=}S$, but the relative importance of these two pathways varies depending on the combination of *P*-substituents. For $Me_2PhP{=}S$, for example, **TS22** lies above **TS21**, while **TS24** lies much lower (Supporting Information).[49]

Calculations were performed to assess whether these nonionic pathways are also accessible to phosphine oxides. In Scheme 4 are shown the energies of $Me_3P{=}O$ analogues of **TS21** and **TS24**. The transition states have barriers of ≥39.2 kcal/mol, which are ≥17.1 kcal/mol higher than that of the rate-determining step in the conventional ionic pathway (Figure 3). The silylene-based transition state **TS24(*O*)** could also, in principle, be formed during the reduction of $Me_3P{=}O$ by $HSiCl_3/Et_3N$, but its energy is also prohibitively high in this reagent system ($\Delta G^{\ddagger}$ = 40.5 kcal/mol).[50]

The difference in mechanisms predicted for phosphine oxides and sulfides reflects the preference of phosphorus and silicon to bond to oxygen rather than to sulfur. A sulfide participates less easily in the conventional ionic mechanism because each intermediate or TS along the reaction pathway is destabilized by the presence of relatively weak P−S and Si−S bonds, compared to the strong P−O and Si−O bonds present for the oxide reaction. The same features also influence the first step of the nonionic mechanisms (**6** versus **12**), but after this point some reversals arise in the order of stabilities. The sulfur-containing transition state **TS21** has a lower energy than **TS21(*O*)**, even though the products from **TS21(*O*)** are much more stable. This result is likely due to atypical bond energies associated with ring strain in the cyclic TS. On the other hand, the energies of **TS24** and **TS24(*O*)** do mirror those of the products to which they lead, favoring the sulfide. Thermodynamically, the transfer of S from $Me_3P{=}S$ to $SiCl_2$ is 5.5 kcal/mol more favorable than the transfer of O from $Me_3P{=}O$ to $SiCl_2$.

In principle, an important route for loss of stereochemical integrity during reductions of phosphine oxides and sulfides consists of nucleophilic attack on the phosphonium salts **7** and **11** by nucleophiles other than $SiCl_3^-$ (e.g., the starting oxide/sulfide itself, or Cl^-).[12] It seems likely that the rates of these unwanted side reactions parallels the susceptibilities of **7** and **11** to backside attack by $SiCl_3^-$; hence, only for the oxide-derived phosphonium salt **7** would they be expected to play a significant role.

Consideration was also given to another possible mechanism for the reduction of phosphine sulfides by Si_2Cl_6. Because the sulfur atom of a P=S bond is more reactive toward radical addition than the oxygen atom of a P=O bond, calculations were performed to determine whether pathways involving $SiCl_3^{\bullet}$ radicals might be involved. Desulfurizations of phosphine

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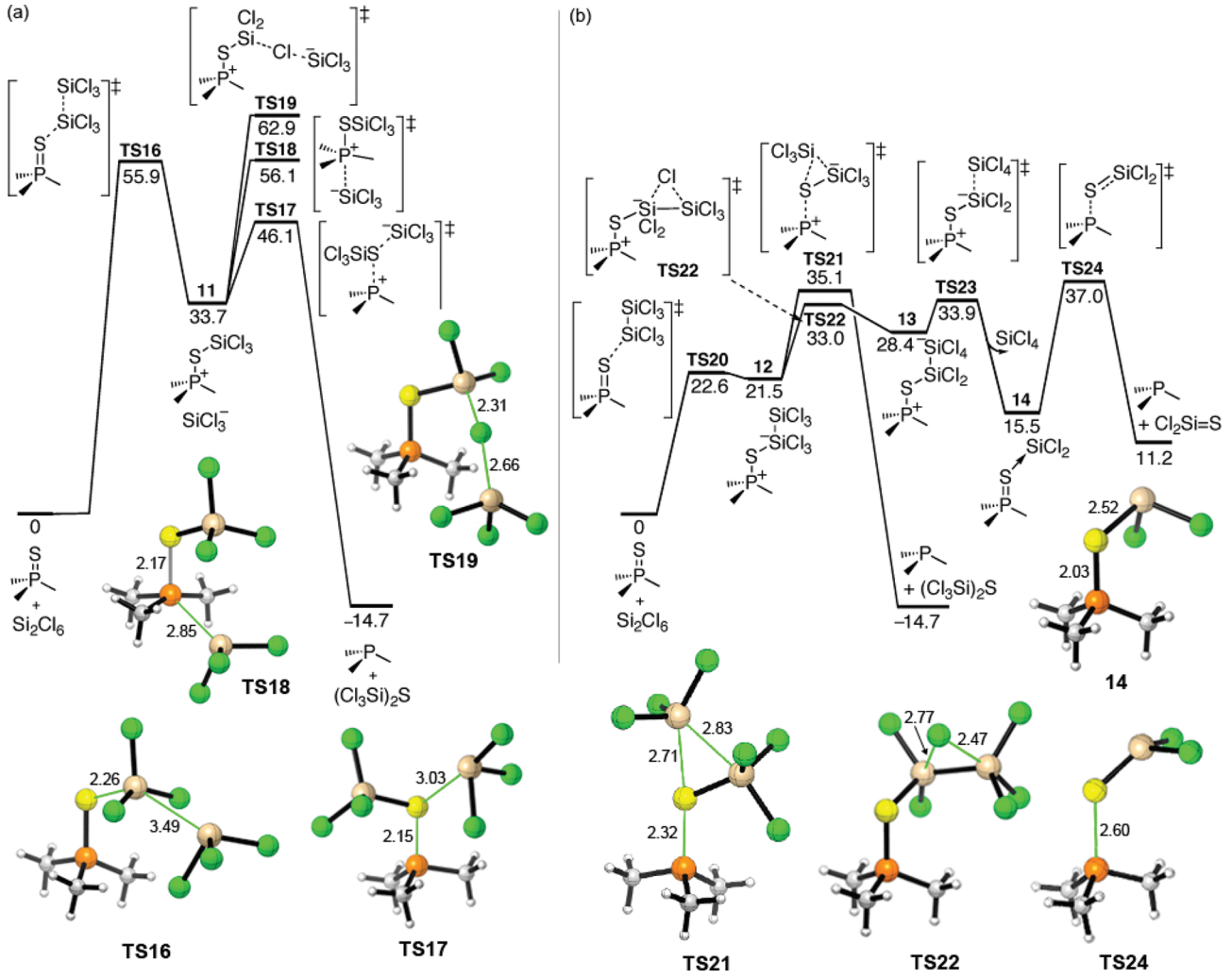
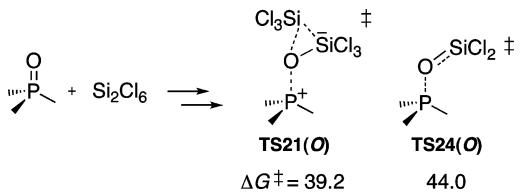
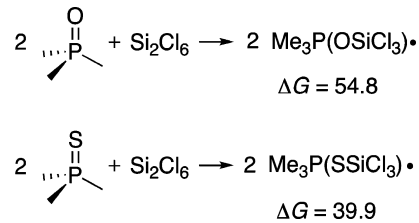


Figure 4. Free energy surfaces for the reduction of $Me_3P{=}S$ by Si_2Cl_6 in benzene, involving either (a) reactions of the phosphonium ion $Me_3P(SSiCl_3)^+$ with $SiCl_3^-$ or (b) nonionic rearrangement processes. The pathways in (b) are favored over those in (a) and lead to retention of configuration at phosphorus. Free energies in kcal/mol, bond lengths in Å.

Scheme 4. Activation Energies for Oxide Analogues of TS21 and TS24 (SCS-MP2, Benzene, kcal/mol)



Scheme 5. Free Energies of Possible Radical Intermediates Involved in the Reductions of $Me_3P{=}O$ and $Me_3P{=}S$ by Si_2Cl_6 (SCS-MP2, benzene, kcal/mol)



sulfides by organosilanes or $(TMS)_3SiH$ under free radical conditions have previously been reported,[51,52] and the latter reactions were shown to occur with retention of stereochemistry at phosphorus.[53] In Scheme 5 are shown the calculated energetics for the formation of $SiCl_3^•$ adducts of $Me_3P{=}O$ and $Me_3P{=}S$. These reactions would be a key step in radical-based mechanisms for reductions by Si_2Cl_6. Addition of $SiCl_3^•$ to $Me_3P{=}S$ is found to be favored by 14.9 kcal/mol over addition to $Me_3P{=}O$ but is still disfavored by at least 2.9 kcal/mol compared to the reduction mechanisms shown in Figure 4b, even ignoring the necessary Si−Si homolysis step. These reactions therefore do not appear to be mechanistically significant.

CONCLUSION

Density functional theory and ab initio calculations provide support for the mechanisms proposed by Horner[11] and Mislow[12] for the reductions of acyclic phosphine oxides by chlorosilanes. These reactions are predicted to involve phosphorane intermediates formed by addition of either a hydride (from $HSiCl_3$) or $SiCl_3^-$ anion (from $HSiCl_3/Et_3N$ or Si_2Cl_6) to phosphorus. The observed stereoselectivities result, respectively, from frontside hydride addition (retention) and backside $SiCl_3^-$ addition (inversion). These mechanisms may also apply to larger-ring cyclic phosphine oxides. Small- and

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medium-ring cyclic phosphine oxides represent a separate class of substrates because their reductions often have different stereoselectivities that are ascribed to ring strain in the phosphorane intermediates.[8,14,54] Phosphine sulfides are predicted not to form phosphorane intermediates during reduction by Si_2Cl_6. The formation of the requisite precursor ion pair $[Me_3P(SSiCl_3)][SiCl_3]$ is too difficult. Two lower energy nonionic pathways are available, both of which leave the stereochemistry at phosphorus unchanged. The involvement of donor-stabilized $SiCl_2$ in the reductions of sulfides is consistent with recent work in which this class of intermediates has been formed upon treatment of Si_2Cl_6 with other nucleophiles[21,27] and is a finding that may lead to the development of new, selective reducing agents.

■ ASSOCIATED CONTENT

Supporting Information

Calculated geometries and energies and B3LYP and B3LYP-D free energy surfaces. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(8) These findings pertain to acyclic phosphine oxides and sulfides. Cyclic phosphine oxides represent a different class of substrates, as the stereoselectivities of their reductions can differ markedly from those of their acyclic counterparts. For example, reductions of phosphetane oxides by Si_2Cl_6 with retention of configuration were reported in: DeBruin, K. E.; Zon, G.; Naumann, K.; Mislow, K. *J. Am. Chem. Soc.* **1969**, *91*, 7027−7030.

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