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Rationale Behind the Resistance of Dialkylbiaryl Phosphines toward Oxidation by Molecular Oxygen

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Abstract: Electron-rich dialkylbiaryl phosphines, which comprise a common class of supporting ligands for Pd-catalyzed cross-coupling reactions, are highly resistant toward oxidation by molecular oxygen. Presented herein are possible reasons why this class of phosphine ligands manifests this property. Experimental and theoretical data suggest that the two alkyl substituents on the phosphorus center and the 2′ and 6′ positions of the biaryl backbone play an important role in inhibiting oxidation of this class of ligands.

Introduction

The use of dialkylbiaryl phosphines as supporting ligands for Pd-catalyzed cross-coupling reactions has seen enormous growth since their introduction in 1998.[1] Dialkylbiaryl ligands can be prepared in a simple one-pot procedure,[2] and over 10 are now commercially available.[3] Although these phosphine ligands are electron-rich, due to the two alkyl substituents on phosphorus (most often cyclohexyl or *tert*-butyl), oxidation to the phosphine oxide does not readily occur. It has been determined that 2-(di-*tert*-butylphosphino)biphenyl can be stored on the benchtop for up to 4 years without any detection of phosphine oxide as evidenced by ^{31}P NMR. The inertness of these phosphines toward oxidation is often taken for granted, and as such, the reason(s) behind this property still remains largely unclear. Herein, we describe what we believe as plausible hypotheses as to this robustness, followed by experimental and theoretical experiments on various phosphines and their oxidation by O_2.

Postulations on the Resistance of Dialkylbiaryl Phosphines toward Oxidation. Our initial two hypotheses on the lack of reactivity of dialkylbiaryl phosphines toward oxidation by O_2 were the following: (1) there exists an electronic interaction between the lone pair of electrons on phosphorus and the non-phosphine-containing ring of the ligands which prevents the phosphorus from being oxidized (Figure 1a) and/or (2) a prereaction complex between O_2 and the phosphine ligand is highly unfavored as the O_2 molecule needs to navigate between the two in close contact with the phosphorus center (Figure 1b). In either case, we suggest that, for oxidation to occur by O_2, the phosphine center needs to invert or rotate such that the lone pair of electrons is facing *away* from the non-phosphine containing ring of the ligand prior to oxidation (**A-away**, Figure 2). However, little is known about the possibility of rotation/inversion of the phosphorus center in these ligands since only one species is observed via ^{31}P NMR for any given biaryl phosphine. Solid state analyses on various biaryl phosphines (via X-ray crystallography) and theoretical studies reveal that the lone pair of electrons on the phosphorus center is positioned above the non-phosphine-containing ring of the ligand in all examples examined to date (i.e., in a geometry such as **A**).[4] We therefore sought to conduct studies using NMR and DFT calculations on various biaryl-based as well as triaryl and trialkyl

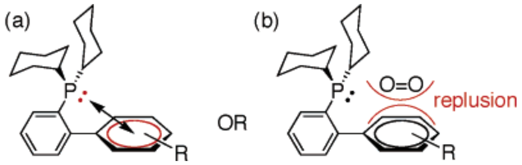

Figure 1. Two hypotheses as to the robustness of biaryl phosphines toward oxidation by molecular oxygen.

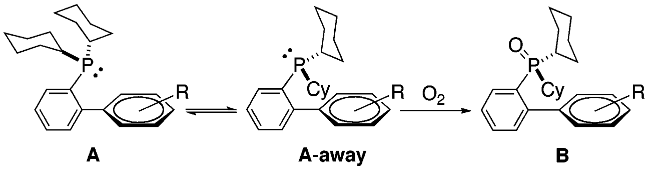

Figure 2. Possible consequence of either of the two hypotheses on the oxidation of biaryl phosphines.

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(1) Selected recent papers using biaryl phosphines in cross-coupling reactions: (a) Huang, X.; Anderson, K. W.; Zim, D.; Jiang, L.; Klapars, A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2003**, *125*, 6653−6655. (b) Walker, S. D.; Barder, T. E.; Martinelli, J. R.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2004**, *43*, 1871−1876. (c) Milne, J. E.; Buchwald, S. L. *J. Am. Chem. Soc.* **2004**, *126*, 13028−13032. (d) Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685−4696. (e) Billingsley, K. L.; Anderson, K. W.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 3483−3488. (f) Burgos, C. H.; Barder, T. E.; Huang, X.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 4321−4326. (g) Anderson, K. W.; Tundel, R. E.; Altman, R. A.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2006**, *45*, 6523−6527.

(2) Tomori, H.; Fox, J. M.; Buchwald, S. L. *J. Org. Chem.* **2000**, *65*, 5334−5341.

(3) A number of biaryl phosphines are available from Strem Chemicals, Inc. and Sigma-Aldrich Co.

(4) Biaryl phosphines analyzed via X-crystallography include the following: 2-(2′,4′,6′-triisopropylbiphenyl)diphenylphosphine, 2-(2′,4′,6′-triisopropylbiphenyl)-3,4,5,6-tetramethyl-di-*tert*-butylphosphine, and 2-(2′,4′,6′-triisopropylbiphenyl)-*tert*-butyl-*N*-(1-phenethyl)phosphine. ORTEP diagrams of these structures are included in the Supporting Information.

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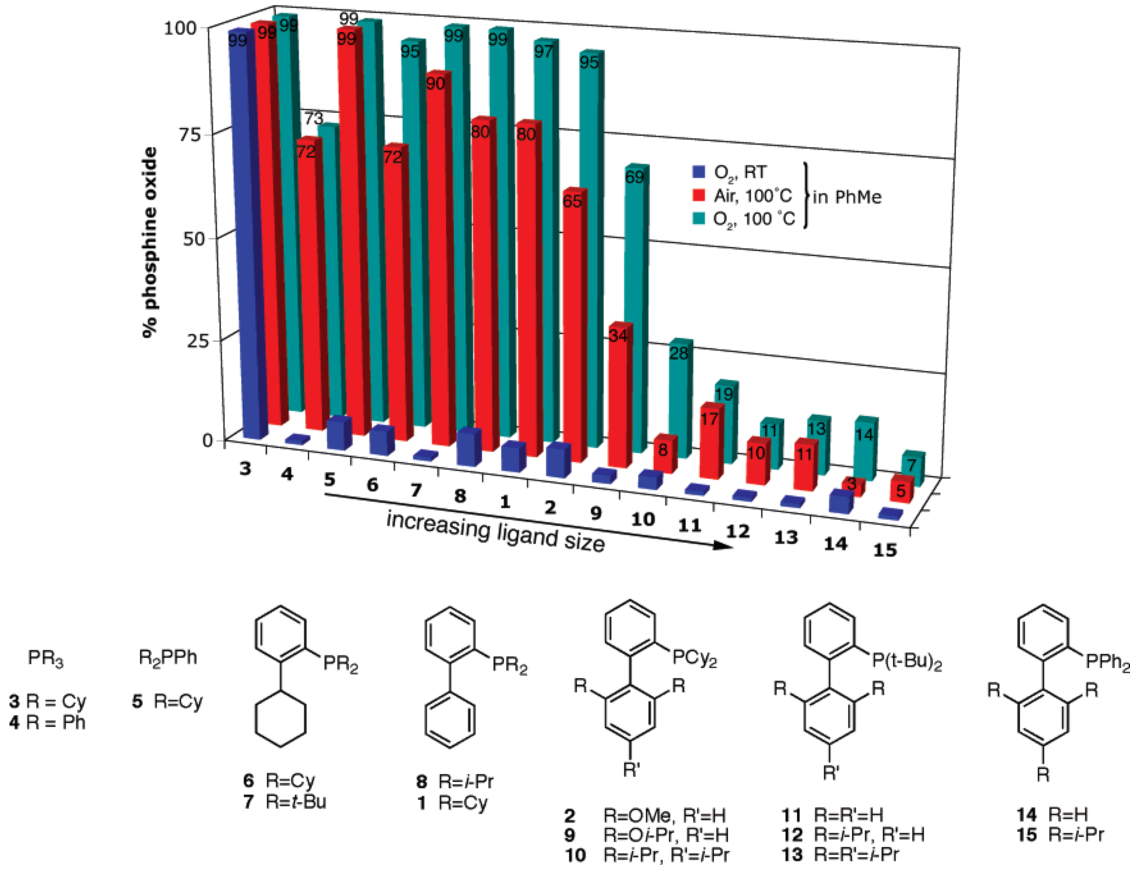

Figure 3. Bar graph illustrating the percentage of oxidized phosphine present (determined by ^{31}P NMR) after 65 h in PhMe under the given reaction conditions depicted for each ligand.[7]

phosphines, and transition state structures involving the oxidation of these ligands.

We first used DFT to analyze if a phosphine−arene interaction exists in biaryl phosphine ligands. The simplest dicyclohexylbiaryl phosphine, which possesses two cyclohexyl groups on phosphorus, **1**, was optimized using an all-atom DFT approach (B3LYP/6-31G(d))[5] using Gaussian 03[6] *without* any approximations (e.g., P(biphenyl)H_2 instead of the entire ligand structure). Although the optimization without any approximations requires more computational time, it is necessary to accurately analyze both the steric and electronic nature of the phosphorus center. Two distinct local minima were located: the first with the lone pair of electrons on phosphorus pointing toward the non-phosphine-containing ring (**1**, *cf.* **A** in Figure 2) and the second with the lone pair of electrons on phosphorus pointing away from the non-phosphine-containing ring of the ligand (**1-away**, *cf.* **A-away** in Figure 2). The energies of the MO containing the lone pair of electrons on phosphorus (HOMO) of each structure were compared and found to be identical (−0.207 eV). This suggests that the lone pair of electrons on phosphorus is not perturbed by the non-phosphine-containing ring of the ligand. Identical calculations were conducted on 2-(2′,6′-dimethoxybiphenyl)-dicyclohexylphosphine, **2**, and the HOMO energy levels for each isomer were found to be nearly identical as well (−0.196 eV vs −0.197 eV). We believe that if a P−arene interaction was present, noticeable differences would exist in the energy level of the HOMO in these calculations; however, as no such deviations are present, we rule out the possibility of a P−arene interaction in biaryl phosphine complexes.

In order to test the second hypothesis above, molecular oxygen was positioned above the non-phosphine-containing phenyl ring of the ligand in **1** and **2**. Although ground state optimizations determined that there was an interaction between the non-phosphine-containing ring of the ligands and $^1O_2$, no such interactions (favorable or unfavorable) were found while using $^3O_2$. Hence, we conclude that the unfavorable interaction between $^3O_2$ and the non-phosphine-containing ring of the ligand is present in a ligand−O_2 prereaction complex and the second hypothesis is ruled out. We next turned to experimental studies with various ligands and oxidizing conditions in attempts to observe a trend for oxidation of the various phosphine ligands employed.

Oxidation of Various Phosphines under Air and O_2. Several phosphines, ranging from triphenylphosphine to exceedingly bulky dialkylbiaryl phosphines, were subjected to various oxidizing conditions. In these experiments, 0.05 mmol of phosphine in 1 mL of toluene was vigorously stirred under either an air or O_2 atmosphere at 25 or 100 °C for 65 h (Figure 3). It is important to note that the mole fraction of 1.08 atm of O_2 in

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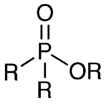
(5) (a) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648−5652. (b) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785.

(6) Frisch, M. J., et. al. *Gaussian 03*, revision B.05; Gaussian, Inc.: Wallingford, CT, 2004.

(7) For compounds **1**−**10**, a small amount of phosphinate ester was observed via ^{31}P NMR. Phosphinate esters are expected side products from phosphine oxidation: see ref 11.



toluene is known to be 0.001 01 at 298.41 K.[8] This value decreases slightly to 0.000 90 at 348.29 K (under 1.12 atm of O_2)[8] and likely decreases further as the temperature of toluene approaches 373 K (100 °C). Hence, a slightly greater amount of oxygen is present in the solution of reactions run under O_2 at 25 °C than 100 °C. Regardless of this fact, only a minimal amount of oxidation occurred here for any of the ligands examined (except PCy_3) when stirred under an atmosphere of O_2 at 25 °C for 65 h.

It was not surprising to find that, in the reaction of tricyclohexylphosphine (**3**), no free phosphine remained under any of the reaction conditions after 65 h. However, triphenylphosphine (**4**) did not completely oxidize even under an atmosphere of O_2 at 100 °C for 65 h. The comparison of triphenylphosphine and tricyclohexylphosphine confirms the well-known fact that electron density residing on the phosphorus center is a major factor that influences the rate of oxidation of phosphine ligands. Oxidation of dicyclohexylphenylphosphine (**5**), a less electron-rich phosphine relative to PCy_3, was quite slow at 25 °C in an atmosphere of O_2 for 65 h (only 7% phosphine oxide was detected by ^{31}P NMR). It is important to note here that the minimum value (V_{min}) of the molecular electrostatic potential (MESP), which corresponds to the electron-donating (more negative value) or -withdrawing ability (more positive value)[9] of the phosphorus center, differs only slightly between dicyclohexylphenylphosphine (**5**) and the dialkylbiaryl phosphines used in this study ($V_{min} = -41.2$ kcal/mol for **5** and $V_{min} = -43.9$ kcal/mol for **8** to -49.0 kcal/mol for **9**).[9b] This suggests that any differences between the oxidations of dicyclohexylphenylphosphine and dialkylbiaryl phosphines are due to steric, not electronic, factors as dialkylbiaryl phosphines are more electron-rich than dicyclohexylphenylphosphine according to the MESP minimum values. Oxidation of **6**, a phosphine similar to **1** with a cyclohexyl group instead of phenyl as the non-phosphine containing ring of the ligand, still readily occurred at 100 °C in air or under O_2 after 65 h. It was found that 72% of the oxidized phosphine was present after 65 h in an air atmosphere at 100 °C and 95% of the oxidized phosphine when the oxidation was conducted under O_2.

We next examined the oxidation of dialkylbiaryl phosphines under the three conditions listed in Figure 3. Ligands **1** and **2** demonstrate similar behaviors under these conditions (e.g., >95% phosphine oxide formed under O_2 at 100 °C). However, the inclusion of larger substituents at the 2′ and 6′ positions of the non-phosphine-containing ring of the biaryl backbone (e.g., −O*i*-Pr) significantly slowed the rate of oxidation, as demonstrated with **9** (69% phosphine oxide was observed under O_2 at 100 °C). Furthermore, as the bulk of the substituents at the 2′ and 6′ positions is increased (to isopropyl), as in **10**, oxidation becomes even more difficult. Under an atmosphere of O_2 at 100 °C only 28% of phosphine oxide was present after 65 h.

Replacing the two dicyclohexyl groups on phosphorus with *tert*-butyl groups had a pronounced effect on the rate of oxidation for the biaryl class of phosphines. The simplest biaryl ligand with two *tert*-butyl groups on phosphorus, **11**, was extremely resistant to oxidation and only 19% of the phosphine oxide was found to be present after subjecting this phosphine to an atmosphere of O_2 at 100 °C for 65 h. This is an interesting observation since oxidation of the analogous ligand with isopropyl groups (**8**) instead of *tert*-butyl groups at 100 °C in an atmosphere of O_2 was facile (99% phosphine oxide, respectively, after 65 h). This illustrates that the addition of only one methyl group on each of the alkyl substituents on the phosphorus center in **8** is responsible for such a dramatic decrease in oxidation of the phosphine! Furthermore, increasing the size of the non-phosphine-containing ring of the ligand also decreased the amount of oxidation observed. The addition of three isopropyl groups on the 2′, 4′, and 6′ positions of the non-phosphine-containing ring of the ligand (**13**) reduced the amount of phosphine oxide observed under an atmosphere of O_2 at 100 °C to only 13%. It was also determined that removal of the 4′ isopropyl group in **13**, to yield **12**, did not affect the amount of phosphine oxide formed under the three conditions employed.

Finally, two diarylbiaryl phosphines (**14** and **15**) with two phenyl groups on the phosphorus center were subjected to the three oxidizing conditions. As expected, very little phosphine oxide was observed in both cases as the electron density on the phosphorus center is substantially decreased relative to dialkylbiaryl phosphines.

Clearly, increasing the size of the two alkyl substituents on the phosphorus center has a dramatic influence on the rate of oxidation of *biaryl phosphine ligands,* as best illustrated by the oxidation of **8** and **11**. Additionally, it appears that inclusion of bulky substituents on the 2′ and 6′ positions of the non-phosphine-containing ring of the ligand (when alkyl substituents are present on the phosphorus center) also has a dramatic effect on the rate of ligand oxidation.

Theoretical Data on the Rotation/Inversion of the Phosphorus Center. It would be unusual if Pd (and Pd bound to other ligands beside the phosphine, e.g., Pd(Ph)Br) can efficiently bind to all of the phosphines in Figure 3 (all of the biaryl ligands depicted are efficient for cross-coupling reactions), but it is difficult for O_2 to bind and therefore oxidize the phosphorus center. Although our original two hypotheses were flawed, we postulated that certain aspects of these hypotheses may hold true (e.g., that the phosphorus center needs to rotate such that the lone pair of electrons is distal to the non-phosphine-containing ring of the ligand rather than above it) and help shed light on the fact that Pd-binding and subsequent reactions at the Pd center are rapid while oxidation is difficult. In order for the phosphine to arrive at a geometry that is depicted in **A-away**, either inversion of the phosphorus center or rotation of the phosphorus center must occur. However, the calculated activation energy for inversion of the phosphorus center in **2** is 31.9 kcal/mol. This value agrees well with a report from Baechler and Mislow[10] documenting experimental activation energies of inversion of various phosphines. Reaction temperatures of at least 130 °C were required to observe phosphine inversion in this report, and similar, if not more severe conditions, are likely required for inversion of the phosphorus center in the phosphines analyzed here. Hence we rule out inversion of the phosphorus center to arrive at a geometry such as **A-away**. We next returned to DFT to determine the thermodynamic and kinetic param-

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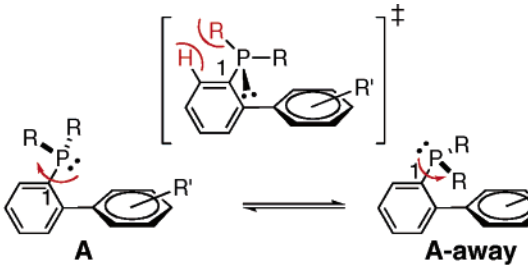
(8) Fischer, K.; Wilken, M. *J. Chem. Thermodyn.* **2001**, *33*, 1285−1308.

(9) (a) Politzer, P., Truhlar, D. G., Eds. *Chemical Applications of Atomic and Molecular Electrostatic Potentials*; Plenum Press: New York, 1981. (b) V_{min} from an MESP plot was recently proposed as a quantitative measure of the electron effect of phosphine ligands: Suresh, C. H.; Koga, N. *Inorg. Chem.* **2002**, *41*, 1573−1578.

(10) Baechler, R. D.; Mislow, K. *J. Am. Chem. Soc.* **1970**, *92*, 3090−3093.

Table 1. Thermodynamic and Kinetic Parameters for Rotation around the C1-P Bond in Various Ligands



	Ligand	$\Delta G^{\ddagger}$ (kcal/mol)	ΔG (kcal/mol)	% oxide 100 °C (O_2)
R = *i*-Pr	**8**	12.1	2.7	99
R = Cy	**1**	13.6	3.0	97
	2	14.1	5.4	95
	9	13.0	5.4	69
	10	12.5	6.3	28
R = *t*-Bu	**11**	26.3	8.7	20
	12	24.8	13.1	11
	13	24.6	12.6	13

eters involved in the rotation of the phosphorus center to point away from the non-phosphine-containing ring of the ligand.

Transition state structures for the rotation of the phosphorus center were determined for **1**, **2**, and **8**−**13**. Table 1 lists these ligands in order of increasing ligand size. Based upon the activation energies, it appears that rotation of the phosphorus center is relatively facile for ligands bearing two isopropyl or two cyclohexyl groups on the phosphorus center (**1**, **2**, and **8**−**10**). However, for ligands possessing two *tert*-butyl groups (**11**−**13**), rotation is much more difficult. As discussed above, the difference between the rate of oxidation of **8** and **11** may stem, in part, from this as $\Delta G^{\ddagger} = 12.1$ kcal/mol for the rotation of the phosphorus center in **8** and $\Delta G^{\ddagger} = 26.3$ kcal/mol for rotation of the phosphorus center in **11**. Additionally, as the size of the ligand is increased, ΔG for the rotation is also increased (2.7 kcal/mol for **8** to 13.1 kcal/mol for **12**). Hence, not only is phosphorus rotation more difficult as the size of the alkyl substituents on the phosphorus center are increased (from isopropyl → cyclohexyl → *tert*-butyl), but the ratio of products due to this rotation favors the **A** conformation over the **A-away** conformation. Somewhat surprisingly, it does not appear that the interaction between the alkyl groups on the phosphorus center and the substituents on the 2′ and 6′ positions of the non-phosphine-containing ring of the ligand influences the activation energy for rotation. Instead, the difficulty in rotation arises from the alkyl groups on phosphorus passing over the top ring of the ligand (highlighted in red in the transition state structure in Table 1). However, as the size of the alkyl groups on phosphorus as well as the groups on the 2′ and 6′ positions are increased, oxidation is clearly retarded. We do not believe this is due to a difficulty in molecular oxygen coming in close proximity to phosphorus but a difficulty in the following: (1) the ligand accessing a geometry with the lone pair of electrons on phosphorus being distal to the non-phosphine-containing ring of the ligand for ligands possessing two *tert*-butyl groups on the phosphorus center and (2) a second phosphine abstracting the second oxygen from compound **C** in Figure 5 for ligands possessing two cyclohexyl or isopropyl groups on the phosphorus center.

Discussion

Possible Reasons Behind the Lack of Oxidation of Dialkylbiaryl Phosphines. The basis for the mechanisms shown in Figure 4 has been previously proposed for the oxidation of phosphines by O_2;[11] however, these mechanism have not taken into consideration phosphines as large as dialkylbiaryl phosphines. The intermediate formed in the reaction between the phosphine and O_2 is not likely to undergo a reaction with a second phosphine in conformation **C** due to the difficulty in a bimolecular reaction with extremely large dialkylbiaryl phosphines. However, if the phosphorus center rotates prior to reaction with O_2, the subsequent reaction with a second phosphine is likely much more facile due to the temporary lack of bulk from the non-phosphine ring of the ligand. Additionally, it is possible that the product from the reaction of phosphine with O_2, **C**, may rotate to **C-away**; however, this rotation likely follows the same kinetic trend as illustrated in Table 1. Regardless of which pathway is active (phosphorus rotation first, phosphorus reacting with O_2 first, or a combination of both), the size of the alkyl substituents on the phosphine center and the size of the substituents on the 2′ and 6′ positions of the non-phosphine-containing ring of the ligand influence the rate of oxidation.

The fact that a nearly identical amount of phosphine oxide is observed for ligands **11**−**13** under an atmosphere of either air (∼20% O_2) or O_2 at 100 °C for 65 h suggests that the concentration of O_2 in toluene minimally influences the rate at which the phosphine oxide is formed. It is possible that, with these ligands, rotation of the phosphorus center such that the lone pair of electrons is distal to the non-phosphine-containing ring of the ligand is rate limiting, as no dependence on O_2 concentration is observed. This is consistent with the finding that the activation energy for phosphorus rotation in ligands **11**−**13** is high ($\Delta G^{\ddagger} > 25$ kcal/mol) and the fact that the equilibrium for phosphorus rotation lies heavily on the side of the conformation in which the lone pair of electrons on phosphorus is above the non-phosphine-containing ring (conformation **A**) of the ligand. For ligands **2**, **9**, and **10**, substantially more phosphine oxide is observed when these ligands are subjected to an atmosphere of O_2 at 100 °C for 65 h rather than an atmosphere of air at 100 °C for 65 h. In these cases, rotation of the phosphorus center is facile ($\Delta G^{\ddagger} < 15$ kcal/mol in all cases), which allows for a greater amount of the $R_3P{-}O{-}O$ species to be formed. This intermediate can then react with a second phosphine to form 2 equiv of the phosphine oxide. It seems plausible that the rate-limiting step for the oxidation of these ligands is the bimolecular process involving an $R_3P{-}O{-}O$ species with R_3P.

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[11] General mechanism: Kosolapoff, G. M.; Maier, L. *Organic Phosphorus Compounds*; Wiley-Interscience: New York, 1972; Vol. 3, p 346. For $^3O_2$: (a) Rauhut, M. M.; Currier, H. A. *J. Org. Chem.* **1961**, *26*, 4626−4628. (b) Burkett, H. D.; Hill, W. E.; Worley, S. D. *Phosphorus and Sulfur* **1984**, *20*, 169−172. For $^1O_2$: (a) Nahm, K.; Li, Y.; Evanseck, J. D.; Houk, K. N.; Foote, C. S. *J. Am. Chem. Soc.* **1993**, *115*, 4879−4884. (b) Tsuji, S.; Kondo, M.; Ishiguro, K.; Sawaki, Y. *J. Org. Chem.* **1993**, *58*, 5055−5059. (c) Ho, D. G.; Gao, R.; Celaje, J.; Chung, H.-Y.; Selke, M. *Science* **2003**, *302*, 259−262.

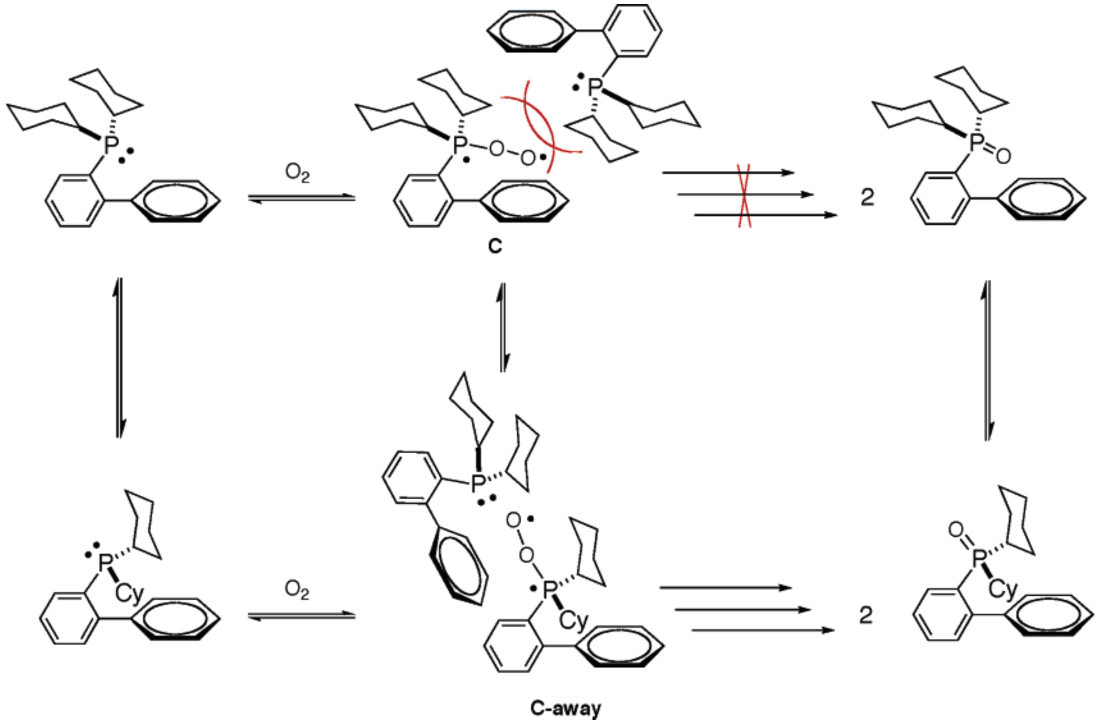

Figure 4. Possible mechanism to explain the resistance of biaryl phosphines toward oxidation by O_2.

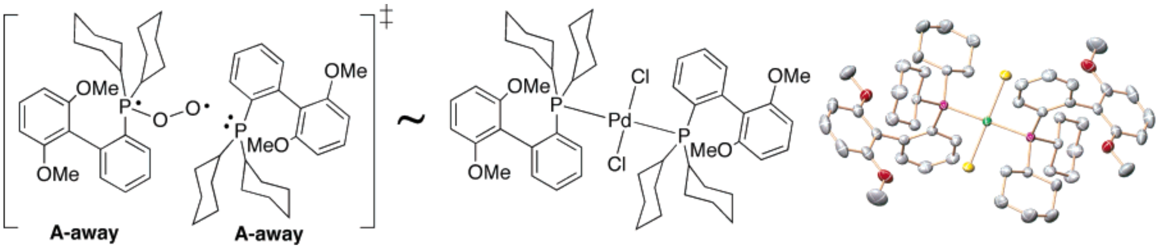

Figure 5. Comparison of a possible transition state structure of a second phosphine abstracting an oxygen from an R_3P-O-O species with the X-ray crystal structure of $[\mathbf{2}]_2PdCl_2$.[1d]

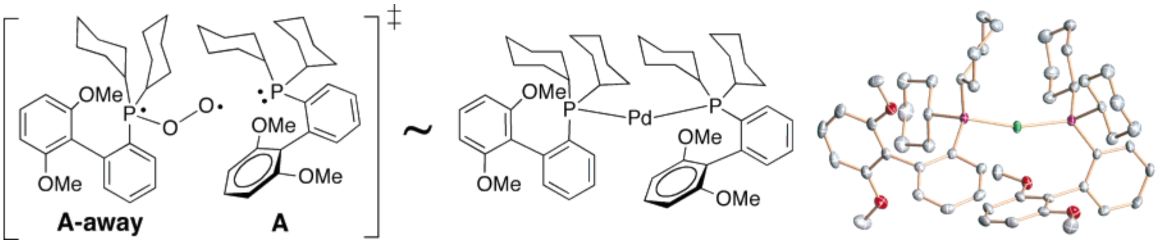

Figure 6. Comparison of a possible transition state structure of a second phosphine abstracting an oxygen from an R_3P-O-O species with the X-ray crystal structure of $[\mathbf{2}]_2Pd$.[1d]

It is worth noting that the amount of phosphine oxide observed with ligand **10** is more similar to the amount observed with ligands composed of (biaryl)P(*t*-Bu)$_2$ than with ligands composed of (biaryl)PCy$_2$. This is not due to the difficulty in rotation of the phosphorus center to an orientation such as that depicted in **A-away**, as the activation energy for this rotation with **10** is only 12.5 kcal/mol, but instead due to a difficulty in the R_3P-O-O species reacting with another molecule of **10**. Since the non-phosphine-containing ring of **10** is much larger than **8** or **9**, the biomolecular process is much more difficult; hence, the smaller amount of phosphine oxide is observed.

Further support for the mechanism depicted in Figure 4 is provided by examining various complexes composed of two biaryl phosphine ligands bound to a metal center. Several L$_2$-PdCl$_2$ complexes (where L = **2**, **9**, **10**, and 2-(2′-isopropylbiphenyl)dicyclohexylphosphine) have been prepared and structurally characterized.[1d,12] All of these complexes contain two biaryl phosphines that are in close proximity to one another (related to a bimolecular process depicted in Figure 4), and both phosphine ligands are in the **A-away** orientation. These data suggest that it is difficult for the phosphorus centers of two biaryl phosphines to come into close proximity when they exist in a geometry such as **A**. Rotation of the phosphorus to a geometry such as **A-away** allows for the phosphorus center in

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(12) See the Supporting Information for X-ray crystal structures of L$_2$PdCl$_2$ complexes.

biaryl phosphines to more readily exist in close contact (Figure 5). Additionally, a bis-phosphine complex ([**2**]$_2$Pd),[1d] which possesses a smaller metal center (Pd vs $PdCl_2$ above), positions one of the biaryl phosphines with the non-phosphine-containing ring of the ligand distal to the Pd (*cf.* **A-away**) while the other ligand has the non-phosphine-containing ring of the ligand directly below the Pd center (*cf.* **A**) (Figure 6). This structure suggests that two dialkylbiaryl phosphines can exist in close proximity with one of the non-phosphine-containing rings of the ligand in the **A** conformation; however, the other non-phosphine-containing ring of the ligand is required to exist in a geometry such as **A-away**. Finally, the fact that we have been unable to isolate larger L_2Pd(0) complexes (e.g., [**9**]$_2$Pd, [**10**]$_2$Pd) or even successfully synthesize larger L_2Pd(0) complexes (e.g., [**11**]$_2$Pd, [**12**]$_2$Pd) lends credence to the difficulty in two of these phosphine ligands existing in close proximity to one another (resembling the bimolecular process in Figure 4).

Conclusion

In conclusion, we have presented experimental and theoretical data that help elucidate possible reasons why dialkylbiaryl phosphine ligands are resistant toward oxidation by molecular oxygen. It is likely that abstraction of the second oxygen from an R_3P-O-O species by a second phosphine is difficult when the lone pair of electrons on the phosphorus center is above the non-phosphine-containing ring of the ligand. Rotation of the phosphorus center to a less hindered environment likely has to occur prior to abstraction of the second oxygen from an R_3P-O-O species. This rotation may even be rate limiting for ligands possessing two *tert*-butyl groups on the phosphorus center.

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Supporting Information Available: Experimental procedures for the oxidation of ligands, coordinates of all optimized structures, and the full citation for ref 6 (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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