Tris(bicyclo[1.1.1]pentyl)phosphine – An exceptionally small tri-tert-alkyl phosphine and its bis-ligated Pd(0) complex

Griffin L. Perry and Nathan D. Schley*

Department of Chemistry, Vanderbilt University, Nashville, Tennessee 37235 United States

Supporting Information Placeholder

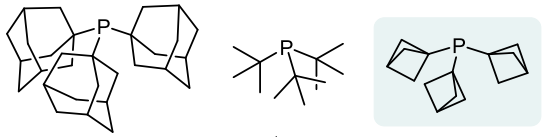
ABSTRACT: Tris(bicyclo[1.1.1]pentyl)phosphine can be prepared by radical addition of PH_3 to [1.1.1]propellane, giving the smallest tri-tert-alkyl phosphine known. $PBcp_3$ is substantially smaller than PCy_3 and is comparable in electron donating power to PEt_3. It gives a bis-ligated Pd(0) complex $Pd(PBcp_3)_2$ that is exceptionally reactive towards alkyl halide oxidative addition and functions as a general ligand for palladium-catalyzed cross-coupling of sp^3 electrophiles. Radical addition of [1.1.1]propellane to phenylphosphine gives the bis(bicyclo[1.1.1]pentyl)phosphine derivative $PBcp_2Ph$, illustrating the generality of this approach to bicyclopentyl phosphine synthesis.

INTRODUCTION

The use of organophosphines as ligands in organometallic chemistry has been an enabling technology in catalysis with applications spanning from hydroformylation to cross-coupling chemistry. As phosphines' primary role is to modify the reactivity of metal ions to which they are bound, there have been many attempts to develop new phosphine ligands with distinct properties and to describe them in terms of quantifiable dimensions that might confer predictive power to their applications.[1-3] Two of the most enduring phosphine descriptors relay information about electron donor power and size: the Tolman electronic parameter (TEP) and cone angle.[4] These parameters are both defined by properties of the corresponding nickel tricarbonyl complex and are controlled by the identity of the organic substituents, which complicates efforts to modulate electronic or steric features of a phosphine ligand independently. In particular, trialkylphosphines represent the most electron-donor subclass of organophosphines, but their electron donating power tends to strongly correlate with the degree of branching of the alkyl phosphine. Thus, trialkylphosphine electron donating power follows PMe_3 < PEt_3 < P^iPr_3 < P^tBu_3, spanning the range of Tolman electronic parameters (TEPs) from 2064 cm^{-1} to 2056 cm^{-1}, but also a range of cone angles from 118° to 182° following the same order.[4]

Within a family of trialkyl phosphines, steric and electronic parameters can be modulated over a narrow range by modifying the substituent (e.g. PCy_3 vs P^iPr_3 vs $PCyp_3$ [Cyp = cyclopentyl] for tri-sec-alkyl phosphines). Large libraries of related phosphines are necessary owing to the sensitivity of many catalytic transformations to small modifications in the supporting ligands. For instance, the Fu group has shown that alkyl electrophiles can undergo palladium-catalyzed cross-coupling without deleterious β-hydride elimination in several cases, but these transformations are exquisitely sensitive to the ligand employed, requiring subtly different ligands for otherwise closely-related transformations.[5-10]

Unlike for the tri-sec alkyl phosphines, comparatively few homoleptic tri-tert-alkyl phosphines have been reported despite the importance of the archetype P^tBu_3. In one recent report, the Carrow group described the synthesis and properties of PAd_3, which was shown to be one of the most donor trialkyl phosphines yet described while closely matching the size of P^tBu_3.[11] This appears to be a rare achievement, highlighting the importance of exploring new substituents in organophosphorus chemistry.

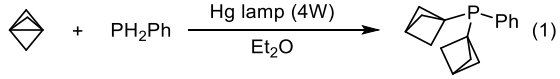


	PAd_3	P^tBu_3	$PBcp_3$
TEP (cm^{-1})	2052.1	2056.1	2061.0
Cone Angle	179°	182°	167°
$\%V_{bur\ [2.28Å]}$	40.5	40.0	30.6

Figure 1. Descriptive parameters of tri-tert-alkylphosphines.[4, 11]

RESULTS AND DISCUSSION

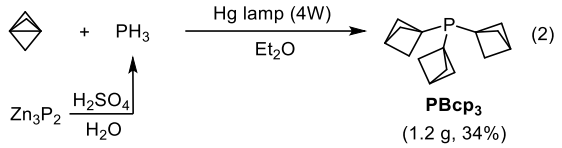
Inspired in part by the work of Carrow, we set out to expand the very small family of homoleptic tri-tert-alkylphosphines with the aim of synthesizing tris(bicyclo[1.1.1]pentyl)phosphine ($PBcp_3$, Bcp = bicyclo[1.1.1]pentyl) (Figure 1). Our preliminary computations identified this phosphine as a potential P^iPr_3 isostere, and the broad commercial availability of the precursor for [1.1.1]propellane convinced us that this aim was synthetically tractable. After briefly exploring the chemistry of bicyclopentyl tributyl stannane, we focused our synthetic efforts on direct radical alkylation of PH_3 by [1.1.1]propellane. This approach was inspired by Wiberg's synthesis of $PBcpPh_2$ from $HPPh_2$ and [1.1.1]propellane.[12] We found that this transformation could be easily extended to the dialkylation of H_2PPh to give $PBcp_2Ph$ by irradiation of a [1.1.1]propellane and phenylphosphine solution with a 4W low pressure Hg lamp (eqn. 1).



(1)

Direct synthesis of tris(bicyclopentyl)phosphine by the same approach would require use of PH_3, a toxic and highly flammable gas.[13] A recent report by Ball and coworkers showed that PH_3 can be safely generated by the acid hydrolysis of zinc phosphide in one chamber of a two-chamber vessel and consumed in the second.[14-15] For our initial attempts, we emulated this approach using a custom two-chamber

quartz vessel. Acid hydrolysis of zinc phosphide with aqueous sulfuric acid pressurized the headspace with phosphine. In the second chamber, a solution of [1.1.1]propellane was irradiated with a 4W Hg lamp (eqn. 2). Evaporation of the crude solution followed by sublimation gave colorless crystals with a faint odor reminiscent of PMe_3 and a melting point of 102 °C. To safely scale the synthesis, we developed modified conditions employing a Kipp generator as a self-regulating source of low-pressure PH_3. Irradiation of PH_3 and a [1.1.1]propellane solution in a quartz round-bottom flask allows the synthesis of *ca.* 1.2 g batches of $PBcp_3$ (34% yield) after purification by evaporation, sublimation and a final filtration. $^{31}P\{^1H\}$ NMR spectra of crude reactions suggest $PBcp_3$ is the major phosphorus-containing product in all cases. The convenient purification steps are required to remove small and variable amounts of the corresponding phosphine oxide, and an incompletely characterized byproduct which we suspect to be the homologated phosphine $(Bcp_2)P(C[CH_2]_3C\text{-}C[CH_2]_3CH)$ likely resulting from radical oligomerization.[12, 16]



The proton-decoupled ^{31}P NMR spectrum of $PBcp_3$ appears as a singlet at -32.3 ppm. The ^1H NMR spectrum is similarly simple with the methylene positions of the bicyclopentyl groups being completely equivalent and the methine positions appearing as a doublet with very large $^4J_{PH}$ coupling of 28 Hz. Wiberg has noted a comparably large coupling in his synthesis of (bicyclopentyl)diphenylphosphine.[12] Large transannular coupling in bicyclopentyl derivatives is believed to stem from spatial overlap of the bridgehead carbon orbitals. For instance, the HOMO of the parent hydrocarbon bicyclo[1.1.1]pentane is the antisymmetric combination of the two bridgehead C-H bonds.[17] Accordingly, the proton-coupled ^{31}P NMR of $PBcp_3$ appears as a quartet showing splitting by the three equivalent methines. We find that this transannular $^4J_{PH}$ coupling increases significantly on metal ion binding (See the supporting information).

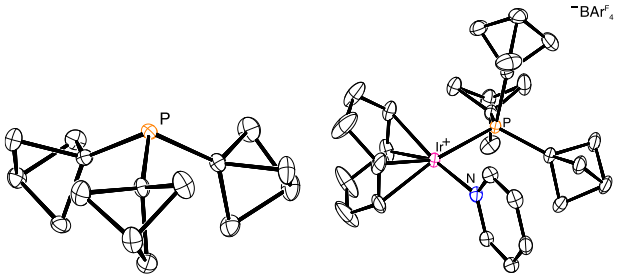


Figure 2. ORTEPs of $PBcp_3$ (left) and complex **3** (right) shown at 50% probability.

In crystalline form, $PBcp_3$ is stable in air for days. The high crystallinity and very high melting point of 102 °C versus -67 °C for P^iPr_3[18] and 19 °C for P^tBu_3[19] is an unusual feature which substantially simplifies its isolation and purification. X-ray crystallographic analysis of a single crystal confirms the expected structure and provides an opportunity to examine its structural features in detail (Figure 2, left). The structural metrical parameters revealed by single-crystal x-ray analysis describe a trialkyl phosphine with a sum of CPC angles of 305.2(1)°. The phosphorus atom is displaced from the CCC centroid by 0.814(1) Å, which is consistent with substantially increased pyramidalization relative to P^tBu_3 (0.699(1) Å).[19] The P-C bond lengths in $PBcp_3$ average 1.829(1) Å, which is substantially shorter than P^tBu_3 (1.911(2) Å)[19] or P^iPr_3 (1.862(7) Å)[18] and comparable to PPh_3 (1.832(3) Å),[20] potentially resulting from increased carbon s-character[17, 21] in the P-C bonds. The small bicyclopentyl substituents have a transannular distance of 1.886(3) Å, reflecting the bond strain in the bicyclic ring system which likely contributes to the short P-C bond. Intramolecular H···H contacts of 2.30(2) Å between adjacent methylenes on the same bicylopentyl group are much shorter than the sum of their VdW radii;[22-23] their intermolecular contacts being closer to 2.45(2) Å.

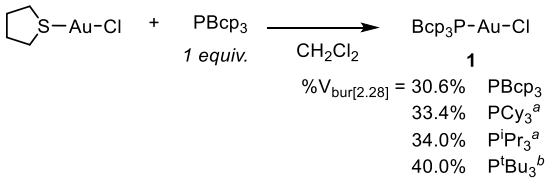
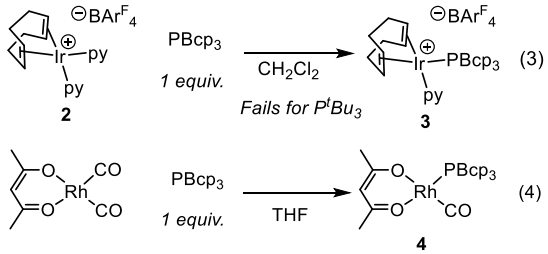


Figure 3. Synthesis of **1** and computation of its % buried volume ($\%V_{bur}$). [a]Reference 24, [b]Reference 11, but also reported as 38.1%.[24]

Steric Properties. Using reported methodology,[25] we calculated the cone angle of $PBcp_3$ to be 167°, substantially smaller than P^tBu_3's angle of 182° and even smaller than PCy_3 (170°).[4] Binding of $PBcp_3$ to (tht)AuCl (tht = tetrahydrothiophene) afforded the gold(I) complex $(Bcp_3P)AuCl$ (**1**) which provided structural information needed to determine its % buried volume ($\%V_{bur}$),[24, 26] (30.6% *d* = 2.28, 36.1% *d* = 2.00). These metrics define $PBcp_3$ as the smallest tri-tert-alkylphosphine yet prepared, aligning it closely in size to PCy_3 and P^iPr_3 in cone angle and much smaller than both in $\%V_{bur}$ (Figure 3). Its small size relative to P^tBu_3 can be demonstrated by the synthetic sequence shown in equation 3. Addition of $PBcp_3$ to $[(cod)Ir(pyridine)_2]BAr^F_4$ (**2**) (BAr^F_4 = tetrakis[3,5-bis(trifluoromethyl)phenyl]borate) gave the Crabtree's catalyst analogue **3** (eqn. 3). The corresponding P^iPr_3 and PCy_3 complexes are known,[27] but not the P^tBu_3 analogue. There has been extensive work[28-30] on such analogues since their discovery in the late 70s, yet **3** is the first tri-tert-alkylphosphine derivative yet reported. Attempts by our own group to prepare the P^tBu_3 derivative of **3** failed by multiple routes, and while we could find no corroborating reports of similar failure in the literature, their absence alongside our attempts would argue that the large size of P^tBu_3 prevents its binding.[29] As further evidence, one can examine the pair of analogous rhodium complexes (η^4-norbornadiene)$Rh(PR_3)Cl$ where R = Cy and tBu.[31] Their Rh-P bond lengths differ by more than 0.11 Å (2.3160(1) Å vs 2.4334(1) Å) with the latter falling in the top 2% of rhodium-trialkyl phosphine bond lengths in the CCDC. Thus, it seems that $PBcp_3$'s small size allows for the preparation of tri-tert-alkylphosphine complexes in cases where P^tBu_3 is unsuitably large.



Electronic Properties. The electronic properties of $PBcp_3$ were also investigated. Preliminary calculations of the TEP using reported DFT methods[32-33] known to be reliable for many ligand derivatives suggested that $PBcp_3$ should have a TEP of 2059 cm^{-1}, a value less donating than P^tBu_3 and in line with P^iPr_3. We also undertook the synthesis of the model rhodium complex (acac)Rh(CO)($PBcp_3$) (**4**) (eqn. 4) in order to obtain an experimental value which could be correlated to the TEP.[34] The CO stretch in **4** is observed at 1969 cm^{-1} in dichloromethane solution, which correlates with a TEP of 2064 cm^{-1}.[11, 34-35] While this value deviates from the computational prediction by only 5 cm^{-1}, nearly all trialkyl phosphines fall in this 5 cm^{-1}-wide range. Analysis of the experimental $^{31}P\text{-}^{77}Se$ coupling constant of the phosphine

selenide Se=PBcp$_3$ gave a value of 692 Hz, which correlates with a TEP of 2063 cm^{-1}.[36-38] The disagreement between predicted TEP values obtained by computational and experimental proxies encouraged us to prepare the benchmark (Bcp$_3$P)Ni(CO)$_3$ compound from Ni(CO)$_4$ *in-situ*[39-41] and measure its A$_1$ stretching frequency directly. The authentic nickel carbonyl stretch is observed in solution at 2061.0 cm^{-1} confirming that PBcp$_3$ is a surprisingly poor electron donor for a tri-tert-alkylphosphine. Its TEP is consistent with a phosphine less electron donating than P^{i}Pr$_3$ (2059.2 cm^{-1}) and very near to PEt$_3$ (2061.7 cm^{-1}).[4] The lack of accuracy in TEP prediction by typical methods[32-33, 36-38] also suggests that direct measurement of the LNi(CO)$_3$ infrared spectrum remains the only reliable means of rank ordering phosphine donor powers that fall in the narrow range occupied by trialkyl phosphines. That said, the (acac)Rh(CO)L system does successfully predict the TEP of PAd$_3$,[11] whose nickel tricarbonyl complex Ad$_3$PNi(CO)$_3$ absorbs at 2052.1 cm^{-1} (See supporting information).

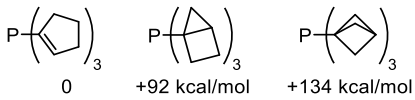
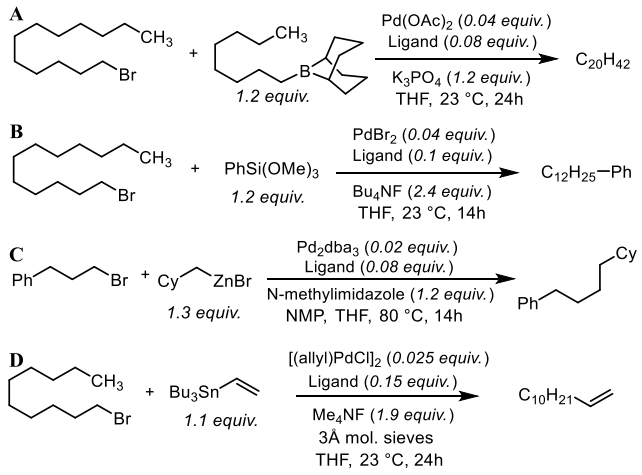


Figure 4. Computed relative strain energies in monocyclic and bicyclic P(C$_5$H$_7$)$_3$ isomers. Only PBcp$_3$ has been reported.

The unusual structure of the bicyclopentyl group imputes significant strain energy. Wiberg has calculated the parent hydrocarbon bicyclo[1.1.1]pentane to have a strain energy of 68 kcal·mol^{-1}.[42] Our calculations describe PBcp$_3$ as being uphill from the isomeric and as yet unreported tris(1-pentenyl)phosphine by 134 kcal/mol. PBcp$_3$ is also predicted to be uphill from tris(1-bicyclo[2.1.0]pentyl)phosphine (an isomeric and unreported derivative of housane) by 42 kcal/mol (Figure 4). The most significant manifestation of this strain is the small size of PBcp$_3$ relative to P^{t}Bu$_3$. Despite its strained structure, PBcp$_3$ appears to be thermally stable at least up to its melting point and apparently resistant to C-C scission in the case of the Au(I), Rh(I), Ir(I) and Pd(0) complexes described here.

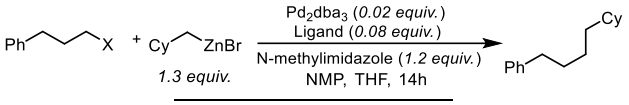


Ligand	A	B	C	D	Cone Angle	TEP (cm^{-1})
P^{t}Bu$_3$	0	0	4	0	182°	2056 [a]
PCy$_3$	84	9	89	64	170°	2056 [a]
PCyp$_3$	81	17	91	62	169°	2055
PBcp$_3$	81	69	84	55	167°	2061
PCy$_2$Ph	72	33	85	3	166°	2061 [b]
P^{t}Bu$_2$Me	80	80	26	64	164°	2059 [b]
P^{i}Pr$_3$	60	16	73	24	160°	2059 [a]
PPh$_3$	0	4	25	0	145°	2069 [a]

Figure 5. Comparison of phosphine ligands in a survey of sp^3 electrophile cross-coupling reactions. The reported optimized ligand for each reaction is outlined. [a]experimental.[4] [b]computed metrics.[43]

Catalytic Applications. Having explored the steric and electronic features of PBcp$_3$, we sought to investigate its properties as a supporting ligand in catalysis. After careful consideration we selected for study a family of palladium-catalyzed cross-coupling reactions of sp^3 electrophiles developed by the Fu group. In a series of reports over several years, Fu and coworkers showed that sp^3-hybridized electrophilic coupling partners bearing β-hydrogens can undergo productive palladium catalyzed cross-coupling with sp^2 and sp^3-hybridized nucleophilic coupling partners.[5-10] These transformations are remarkably sensitive to the phosphine, such that the relatively similar phosphines P^{t}Bu$_2$Me, P^{i}Pr$_3$, PCy$_3$, and PCyp$_3$ (Cyp = cyclopentyl) are most likely to perform well while P^{t}Bu$_3$ gives poor yields across the series of transformations. Under reported conditions, PBcp$_3$ performs remarkably well across the family of reactions shown in Figure 5, in all cases rivaling the ligand for which the transformation had been previously optimized. Although PBcp$_3$ is not superior to each reaction's optimized ligand under reported conditions, it is more general across the array of challenging reactions tested than any of the other ligands examined. This is most clear for the Hiyama[9] and Stille[10] reactions, which are the most sensitive to the ligand employed. Among the ligands tested, P^{t}Bu$_2$Me, P^{i}Pr$_3$, and PCyp$_3$ are all air-sensitive oils which incur hazardous shipping fees from major suppliers, illustrating a strength of PBcp$_3$ which it shares with PCy$_3$. The aryldialkyl phosphine PCy$_2$Ph provides an uneven showing despite possessing very similar electronic[43] and steric[44] parameters to PBcp$_3$, highlighting the importance of considering factors beyond those captured in Tolman's descriptive parameters.[1]

As a final catalytic test, we examined the Negishi reaction presented in Figure 5(C) in more detail. This transformation is the only one of the four tested to have been reported at elevated temperatures. When conducted at 23 °C instead of 80 °C the majority of phosphines give substantially diminished yields with PBcp$_3$ being least affected (Figure 6). The corresponding alkyl chloride gives <6% yield in all cases at 23 °C but undergoes cross-coupling by the Pd/PBcp$_3$ system in moderate yields at temperatures as low as 40 °C.



Ligand	X=Br 80 °C	X=Br 23 °C	X=Cl 40 °C
P^{t}Bu$_3$	4	0	0
PCy$_3$	89	36	26
PCyp$_3$	91	48	32
PBcp$_3$	84	65	45
PCy$_2$Ph	85	0	6
P^{t}Bu$_2$Me	26	35	21
P^{i}Pr$_3$	73	20	12
PPh$_3$	25	0	3

Figure 6. Effect of reaction temperature and alkyl halide in a sp^3-sp^3 Negishi reaction.

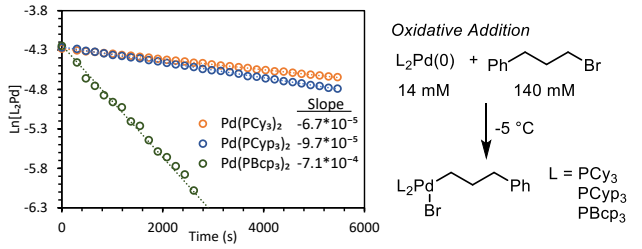


Figure 7. Rates of oxidative addition of $L_2Pd(0)$ complexes under pseudo first-order conditions.

$$Pd(OAc)_2 + \underset{2.1\ equiv.}{PBcp_3} \xrightarrow[toluene]{B_2pin_2\ (5\ equiv.)} \underset{\mathbf{5}}{Bcp_3P\text{–}Pd\text{–}PBcp_3} \quad (5)$$

The difference in catalytic performance of PCy_3 and P^tBu_3 in the cross-coupling of sp^3 electrophiles has been previously attributed to very different rates of oxidative addition of 1° alkyl halides to the corresponding bis-ligated palladium(0) complexes.[45] Fu and coworkers showed that $Pd(PCy_3)_2$ and $Pd(P^tBu_2Me)_2$ readily react with 1° alkyl halides at 0 °C, but $Pd(P^tBu_3)_2$ does not. In our hands, $PBcp_3$ forms the isolable Pd(0) complex $Pd(PBcp_3)_2$ (**5**) (eqn. 5) that is fiercely reactive with 1° alkyl halides. For instance, $Pd(PBcp_3)_2$ undergoes oxidative addition with 1-bromo-3-phenylpropane at -5 °C an order of magnitude faster than does $Pd(PCy_3)_2$ or $Pd(PCyp_3)_2$ (Figure 7). As this reaction likely takes place via an S_N2 process,[45-46] the high nucleophilicity of $Pd(PBcp_3)_2$ most probably stems from its small size relative to other isolable bis(phosphine)palladium complexes. $Pd(PBcp_3)_2$ readily crystalizes in a distorted linear geometry with a P-Pd-P angle of 168.62(3)°. This angle is intermediate between $Pd(PCyp_3)_2$ (173.28(2)°) and $Pd(PCy_3)_2$ (158.4(3)°) (Figure 8).[47] Bending in PdL_2 compounds has been attributed to dispersive interactions between the ligand groups.[23, 48] Additionally, $Pd(PBcp_3)_2$ (**5**) does not form $Pd(PBcp_3)_3$ on treatment with a third equivalent of ligand in solution at room temperature, which may contribute to $PBcp_3$'s impressive generality under the array of Pd/L ratios tested.

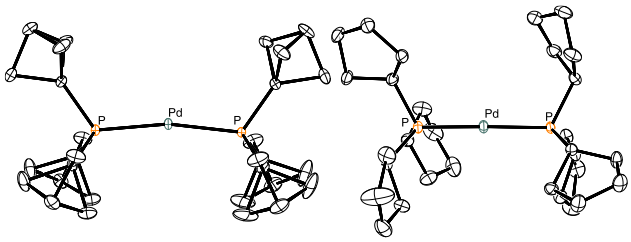


Figure 8. ORTEPs of $Pd(PBcp_3)_2$ (**5**) (left) and of $Pd(PCyp_3)_2$ (right) shown at 50% probability.

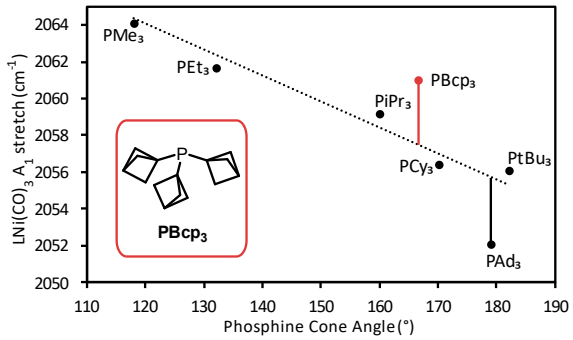


Figure 9. Plot of TEP versus Cone Angle for some trialkylphosphines.

CONCLUSION

These findings describe $PBcp_3$ as a highly unusual tri-tert-alkyl phosphine which is smaller than PCy_3 and less donating than all common tri-tert and sec-alkyl phosphines. Together, the three homoleptic tri-tert-alkylphosphines $PBcp_3$, P^tBu_3 and PAd_3 span a range of TEP from 2061[-1] to 2052 cm^{-1}, encompassing nearly the entire electronic range available to trialkyl phosphines (Figure 9). The reduced size of $PBcp_3$ relative to P^tBu_3 is exemplified in the synthesis of a Crabtree's catalyst derivative. Palladium complexes derived of $PBcp_3$ are excellent catalysts across a range of cross-coupling reactions of sp^3 electrophiles, which may stem from the reactivity of the isolable bis-ligated palladium(0) complex $Pd(PBcp_3)_2$ (**5**) towards 1° alkyl halides and its apparent stability with respect to formation of $Pd(PBcp_3)_3$. $PBcp_3$ can be prepared in a straightforward manner by radical alkylation of PH_3 with [1.1.1]propellane. A similar approach has been used to prepare $PBcp_2Ph$ from the corresponding primary phosphine. We anticipate the ease with which the bicyclo[1.1.1]pentyl group can be incorporated in organophosphorus chemistry will lead to myriad applications in coordination chemistry and homogeneous catalysis. Our ongoing and future studies aim to further develop the chemistry and applications of $PBcp_3$ and bis(bicyclopentyl)phosphine derivatives including in palladium-catalyzed cross-coupling reactions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at the ACS publications website at "http://pubs.acs.org."

Experimental procedures, summaries of computational and experimental results, and compound characterization data. (PDF)

Coordinates of computed species. (XYZ)

X-ray crystallographic data. (CIF)

CCDC 2204158– 2204162 and 2237661-2237662 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif.

AUTHOR INFORMATION

Corresponding Author

*nathan.schley@vanderbilt.edu.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

Funding from Vanderbilt University is gratefully acknowledged. The authors thank Don Stec for assistance with NMR experiments and Daryl Smith (Yale University) for custom quartz glassware used in the initial studies. This material is based upon work supported by the National Science Foundation under grant no. CHE-1847813.

REFERENCES

(1) Niemeyer, Z. L.; Milo, A.; Hickey, D. P.; Sigman, M. S., Parameterization of phosphine ligands reveals mechanistic pathways and predicts reaction outcomes. *Nature Chemistry* **2016**, *8*, 610-617.

(2) Jover, J.; Fey, N.; Harvey, J. N.; Lloyd-Jones, G. C.; Orpen, A. G.; Owen-Smith, G. J. J.; Murray, P.; Hose, D. R. J.; Osborne, R.; Purdie, M., Expansion of the Ligand Knowledge Base for Monodentate P-Donor Ligands (LKB-P). *Organometallics* **2010**, *29*, 6245-6258.

(3) Fey, N.; Tsipis, A. C.; Harris, S. E.; Harvey, J. N.; Orpen, A. G.; Mansson, R. A., Development of a Ligand Knowledge Base, Part 1: Computational Descriptors for Phosphorus Donor Ligands. *Chem. Eur. J.* **2006**, *12*, 291-302.

(4) Tolman, C. A., Steric effects of phosphorus ligands in organometallic chemistry and homogeneous catalysis. *Chem. Rev.* **1977**, *77*, 313-348.

(5) Netherton, M. R.; Dai, C.; Neuschütz, K.; Fu, G. C., Room-Temperature Alkyl–Alkyl Suzuki Cross-Coupling of Alkyl Bromides that Possess β Hydrogens. *J. Am. Chem. Soc.* **2001**, *123*, 10099-10100.

(6) Kirchhoff, J. H.; Netherton, M. R.; Hills, I. D.; Fu, G. C., Boronic Acids: New Coupling Partners in Room-Temperature Suzuki Reactions of Alkyl Bromides. Crystallographic Characterization of an Oxidative-Addition Adduct Generated under Remarkably Mild Conditions. *J. Am. Chem. Soc.* **2002**, *124*, 13662-13663.

(7) Kirchhoff, J. H.; Dai, C.; Fu, G. C., A Method for Palladium-Catalyzed Cross-Couplings of Simple Alkyl Chlorides: Suzuki Reactions Catalyzed by [Pd2(dba)3]/PCy3. *Angew. Chem. Int. Ed.* **2002**, *41*, 1945-1947.

(8) Zhou, J.; Fu, G. C., Palladium-Catalyzed Negishi Cross-Coupling Reactions of Unactivated Alkyl Iodides, Bromides, Chlorides, and Tosylates. *J. Am. Chem. Soc.* **2003**, *125*, 12527-12530.

(9) Lee, J.-Y.; Fu, G. C., Room-Temperature Hiyama Cross-Couplings of Arylsilanes with Alkyl Bromides and Iodides. *J. Am. Chem. Soc.* **2003**, *125*, 5616-5617.

(10) Menzel, K.; Fu, G. C., Room-Temperature Stille Cross-Couplings of Alkenyltin Reagents and Functionalized Alkyl Bromides that Possess β Hydrogens. *J. Am. Chem. Soc.* **2003**, *125*, 3718-3719.

(11) Chen, L.; Ren, P.; Carrow, B. P., Tri(1-adamantyl)phosphine: Expanding the Boundary of Electron-Releasing Character Available to Organophosphorus Compounds. *J. Am. Chem. Soc.* **2016**, *138*, 6392-6395.

(12) Wiberg, K. B.; Waddell, S. T., Reactions of [1.1.1]propellane. *J. Am. Chem. Soc.* **1990**, *112*, 2194-2216.

(13) Dillard, C. R., A phosphine fire flask. *J. Chem. Educ.* **1956**, *33*, 137.

(14) Barber, T.; Argent, S. P.; Ball, L. T., Expanding Ligand Space: Preparation, Characterization, and Synthetic Applications of Air-Stable, Odorless Di-tert-alkylphosphine Surrogates. *ACS Catalysis* **2020**, *10*, 5454-5461.

(15) Rothfelder, R.; Streitferdt, V.; Lennert, U.; Cammarata, J.; Scott, D. J.; Zeitler, K.; Gschwind, R. M.; Wolf, R., Photocatalytic Arylation of P_4 and PH_3: Reaction Development Through Mechanistic Insight. *Angew. Chem. Int. Ed.* **2021**, *60*, 24650-24658.

(16) Kaszynski, P.; Michl, J., [n]Staffanes: a molecular-size "Tinkertoy" construction set for nanotechnology. Preparation of end-functionalized telomers and a polymer of [1.1.1]propellane. *J. Am. Chem. Soc.* **1988**, *110*, 5225-5226.

(17) Lehn, J. M.; Wipff, G., The electronic structure of bicyclo [1.1.1] pentane systems. *Chem. Phys. Lett.* **1972**, *15*, 450-454.

(18) Bruckmann, J.; Kruger, C., Tris(n-propyl)phosphine and Tris(isopropyl)phosphine. *Acta Crystallogr. Sect. C* **1996**, *52*, 1733-1736.

(19) Bruckmann, J.; Kruger, C., Tris(n-butyl)phosphine, Tris(tert-butyl)phosphine and Tris(trimethylsilyl)phosphine. *Acta Crystallogr. Sect. C* **1995**, *51*, 1152-1155.

(20) Dunne, B. J.; Orpen, A. G., Triphenylphosphine: a redetermination. *Acta Crystallogr. Sect. C* **1991**, *47*, 345-347.

(21) Newton, M. D.; Schulman, J. M., Theoretical studies of tricyclo[1.1.1.01,3]pentane and bicyclo[1.1.1]pentane. *J. Am. Chem. Soc.* **1972**, *94*, 773-778.

(22) Bondi, A., van der Waals Volumes and Radii. *The Journal of Physical Chemistry* **1964**, *68*, 441-451.

(23) Liptrot, D. J.; Power, P. P., London dispersion forces in sterically crowded inorganic and organometallic molecules. *Nature Reviews Chemistry* **2017**, *1*, 0004.

(24) Clavier, H.; Nolan, S. P., Percent buried volume for phosphine and N-heterocyclic carbene ligands: steric properties in organometallic chemistry. *Chem. Commun.* **2010**, *46*, 841-861.

(25) Bilbrey, J. A.; Kazez, A. H.; Locklin, J.; Allen, W. D., Exact ligand cone angles. *J. Comput. Chem.* **2013**, *34*, 1189-1197.

(26) Hillier, A. C.; Sommer, W. J.; Yong, B. S.; Petersen, J. L.; Cavallo, L.; Nolan, S. P., A Combined Experimental and Theoretical Study Examining the Binding of N-Heterocyclic Carbenes (NHC) to the Cp*RuCl (Cp* = η^5-C_5Me_5) Moiety: Insight into Stereoelectronic Differences between Unsaturated and Saturated NHC Ligands. *Organometallics* **2003**, *22*, 4322-4326.

(27) Crabtree, R. H.; Felkin, H.; Morris, G. E., Cationic iridium diolefin complexes as alkene hydrogenation catalysts and the isolation of some related hydrido complexes. *J. Organomet. Chem.* **1977**, *141*, 205-215.

(28) Wüstenberg, B.; Pfaltz, A., Homogeneous Hydrogenation of Tri- and Tetrasubstituted Olefins: Comparison of Iridium-Phospinooxazoline [Ir-PHOX] Complexes and Crabtree Catalysts with Hexafluorophosphate (PF_6) and Tetrakis[3,5-bis(trifluoromethyl)phenyl]borate (BArF) as Counterions. *Adv. Synth. Catal.* **2008**, *350*, 174-178.

(29) Crabtree, R. H.; Morris, G. E., Some diolefin complexes of iridium(I) and a trans-influence series for the complexes [IrCl(cod)L]. *J. Organomet. Chem.* **1977**, *135*, 395-403.

(30) Vazquez-Serrano, L. D.; Buriak, J. M., The Quest for Longevity and Stability of Iridium-based Hydrogenation Catalysts: N-Heterocyclic Carbenes and Crabtree's Catalyst. *N-Heterocyclic Carbenes in Synthesis* **2006**, 241-255.

(31) Sparkes, H. A.; Chaplin, A. B.; Weller, A. S.; Howard, J. A. K., Bond catastrophes in rhodium complexes: experimental charge-density studies of $[Rh(C_7H_8)(P^tBu_3)Cl]$ and $[Rh(C_7H_8)(PCy_3)Cl]$. *Acta Crystallogr. Sect. B* **2010**, *66*, 503-514.

(32) Gusev, D. G., Donor Properties of a Series of Two-Electron Ligands. *Organometallics* **2009**, *28*, 763-770.

(33) Gusev, D. G., Electronic and Steric Parameters of 76 N-Heterocyclic Carbenes in $Ni(CO)_3(NHC)$. *Organometallics* **2009**, *28*, 6458-6461.

(34) Serron, S.; Huang, J.; Nolan, S. P., Solution Thermochemical Study of Tertiary Phosphine Ligand Substitution Reactions in the $Rh(acac)(CO)(PR_3)$ System. *Organometallics* **1998**, *17*, 534-539.

(35) Kühl, O., Predicting the net donating ability of phosphines—do we need sophisticated theoretical methods? *Coord. Chem. Rev.* **2005**, *249*, 693-704.

(36) Allen, D. W.; Taylor, B. F., The chemistry of heteroarylphosphorus compounds. Part 15. Phosphorus-31 nuclear magnetic resonance studies of the donor properties of heteroarylphosphines towards selenium and platinum(II). *J. Chem. Soc., Dalton Trans.* **1982**, 51-54.

(37) Socol, S. M.; Verkade, J. G., Ligation of phosphorus ligands to silver(I). 2. Electronic and steric effects in the coordination of one to four $P(OR)_3$ and PR_3 ligands. *Inorg. Chem.* **1984**, *23*, 3487-3493.

(38) Kelty, M. L.; McNeece, A. J.; Kurutz, J. W.; Filatov, A. S.; Anderson, J. S., Electrostatic vs. inductive effects in phosphine ligand donor properties and reactivity. *Chem. Sci.* **2022**, *13*, 4377-4387.

(39) Marín, M.; Moreno, J. J.; Navarro-Gilabert, C.; Álvarez, E.; Maya, C.; Peloso, R.; Nicasio, M. C.; Carmona, E., Synthesis, Structure and Nickel Carbonyl Complexes of Dialkylterphenyl Phosphines. *Chem. Eur. J.* **2019**, *25*, 260-272.

(40) Buchgraber, P.; Mercier, A.; Yeo, W. C.; Besnard, C.; Kündig, E. P., Functionalization of Planar Chiral Fused Arene Ruthenium Complexes: Synthesis, X-ray Structures, and Spectroscopic Characterization of Monodentate Triarylphosphines. *Organometallics* **2011**, *30*, 6303-6315.

(41) Hu, H.; Ichiryu, H.; Nakajima, K.; Ogasawara, M., Estimating Effective Steric and Electronic Impacts of a Ferrocenyl Group in Organophosphines. *ACS Omega* **2021**, *6*, 5981-5989.

(42) Wiberg, K. B., The Concept of Strain in Organic Chemistry. *Angew. Chem. Int. Ed.* **1986**, *25*, 312-322.

(43) Mansson, R. A.; Welsh, A. H.; Fey, N.; Orpen, A. G., Statistical Modeling of a Ligand Knowledge Base. *Journal of Chemical Information and Modeling* **2006**, *46*, 2591-2600.

(44) Wei, J.; Li, M.; Ding, J.; Dai, W.; Yang, Q.; Feng, Y.; Yang, C.; Yang, W.; Zheng, Y.; Wang, M.-Y.; Ma, X., Parameterization of Phosphine Ligands Modified Rh Complexes to Unravel Quantitative Structure-Activity Relationship and Mechanistic Pathways in Hydroformylation. *ChemCatChem* **2022**, *14*, e202200423.

(45) Hills, I. D.; Netherton, M. R.; Fu, G. C., Toward an Improved Understanding of the Unusual Reactivity of Pd0/Trialkylphosphane Catalysts in Cross-Couplings of Alkyl Electrophiles: Quantifying the Factors That Determine the Rate of Oxidative Addition. *Angew. Chem. Int. Ed.* **2003**, *42*, 5749-5752.

(46) Netherton, M. R.; Fu, G. C., Suzuki Cross-Couplings of Alkyl Tosylates that Possess β Hydrogen Atoms: Synthetic and Mechanistic Studies. *Angew. Chem. Int. Ed.* **2002**, *41*, 3910-3912.

(47) Immirzi, A.; Musco, A., Two-co-ordinate phosphine–palladium(0) complexes: X-ray structure of the tricyclohexyl- and the di(t-butyl)phenylphosphine derivatives. *J. Chem. Soc., Chem. Commun.* **1974**, 400-401.

(48) Wolters, L. P.; Koekkoek, R.; Bickelhaupt, F. M., Role of Steric Attraction and Bite-Angle Flexibility in Metal-Mediated C–H Bond Activation. *ACS Catalysis* **2015**, *5*, 5766-5775.

For Table of Contents Only