Polyfluorinated Cyclopentadienones as Lewis Acids

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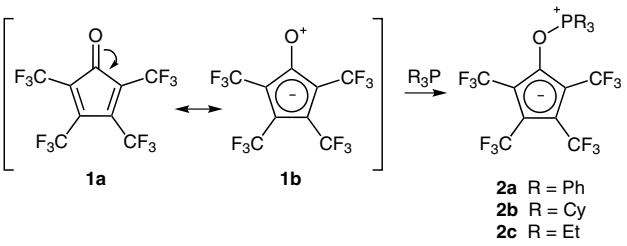
Abstract: The ability of 2,3,4,5-tetrakis(trifluoromethyl)cyclopenta-2,4-dien-1-one and 2,3,4,5-tetrakis(pentafluorophenyl)cyclopenta-2,4-dien-1-one to act as organic Lewis acids in the field of frustrated Lewis pair (FLP) chemistry was evaluated. Whereas the former ketone formed zwitterionic adducts with all phosphines studied, the latter did not react with bulky phosphines and, instead, gave completely organic FLPs. Unfortunately, these did not activate dihydrogen, even under high pressures.

Key words: Lewis acids, frustrated Lewis pairs, steric hindrance, ketones, fluorine, phosphines



Scheme 1 Resonance structures of ketone **1** and its reactivity towards phosphines

The activation of small molecules such as dihydrogen,[1] carbon dioxide,[2] nitric oxide,[3] disulfides,[4] or silanes[5] by the cooperative action of an unquenched combination of a Lewis acid and a Lewis base, known as a frustrated Lewis pair (FLP), has been intensively explored during the last decade. During this time, the nature of the Lewis base partner has evolved from the original phosphines to include N-heterocyclic carbenes,[6] amines,[7] or pyridines,[8] thereby permitting some control of the reactivity of the resulting FLP.[9] In sharp contrast, no such flexibility has been achieved for the Lewis acid partner, and polyfluorinated boranes are generally used, with only a few exceptions.[4b,10]

Intrigued by this limitation, we recently started a program devoted to evaluating the potential of alternative Lewis acids in this chemistry,[4d,11] and we primarily focused our attention on 2,3,4,5-tetrakis(trifluoromethyl)cyclopenta-2,4-dien-1-one (**1**).[12] In this compound, the betaine-type resonance form **1b**, with reverse polarization of the carbonyl group and a partial positive charge on the oxygen atom, is strongly favored due to the simultaneous occurrence of two factors: the natural tendency of the cyclopentadienyl ring to aromatize, accepting electron density from the C=O bond, and the additional stabilization of the negative charge provided by the four electron-withdrawing trifluoromethyl substituents. This umpolung of the carbonyl group explains why ketone **1** undergoes attack by phosphines at the electrophilic oxygen atom to give the corresponding zwitterionic adducts **2a**–**c** (Scheme 1).[13]

This unconventional reactivity prompted us to investigate whether combinations of ketone **1** with bulkier phosphines, such as tri(*tert*-butyl)phosphine (**3**), di-*tert*-butyl(2′,4′,6′-triisopropylbiphenyl-2-yl)phosphine (**4**; *t*-BuXPhos) or di-*tert*-butyl(2′,4′,6′-triisopropyl-3,4,5,6-tetramethylbiphenyl-2-yl)phosphine (**5**; tetramethyl *t*-BuXPhos), might form boron-free FLPs. However, mixtures of ketone **1** with phosphines **3**–**5** in toluene at –78 °C invariably generated orange solutions that slowly decolorized, and from which the adducts **6**–**8** could be isolated in moderate to good yields (Scheme 2).

The ORTEP diagram of **8**, shown in Scheme 2, is quite informative (for the solid-state structures of **6** and **7** see the Supporting Information).[14] The cyclopentadienyl moiety is completely planar and the C–C distances in the five membered ring are nearly equal (1.399–1.424 Å), as expected for a homoaromatic system. To accommodate the new substituent on phosphorus and to form the corresponding Lewis adduct, the sterically demanding phosphine moiety adopts a quite disfavored conformation in which the bulky 2,4,6-triisopropylphenyl group and one of the *tert*-butyl substituents are nearly eclipsed. In addition, the tetramethylated phenyl ring in **8** shows a severe distortion from planarity (P1–C18–C19–C24 torsion angle: 40.9°). The formation of adduct **8**, despite these energetically destabilizing factors, demonstrates the strong affinity between the two Lewis partners and suggested that bulkier analogues of ketone **1** might be suitable as Lewis acids for FLP chemistry.

With the aim of putting this idea into practice, we reasoned that formal exchange of the four trifluoromethyl substituents in ketone **1** for bulkier, but still inductively electron-withdrawing, pentafluorophenyl groups should increase the steric demand on the resulting ketone and might permit the formation of FLPs in the presence of common phosphines. We therefore identified 2,3,4,5-tetrakis(pentafluorophenyl)cyclopenta-2,4-dien-1-one (**9**) as our next target, and we prepared this ketone by following the known procedures.[15]

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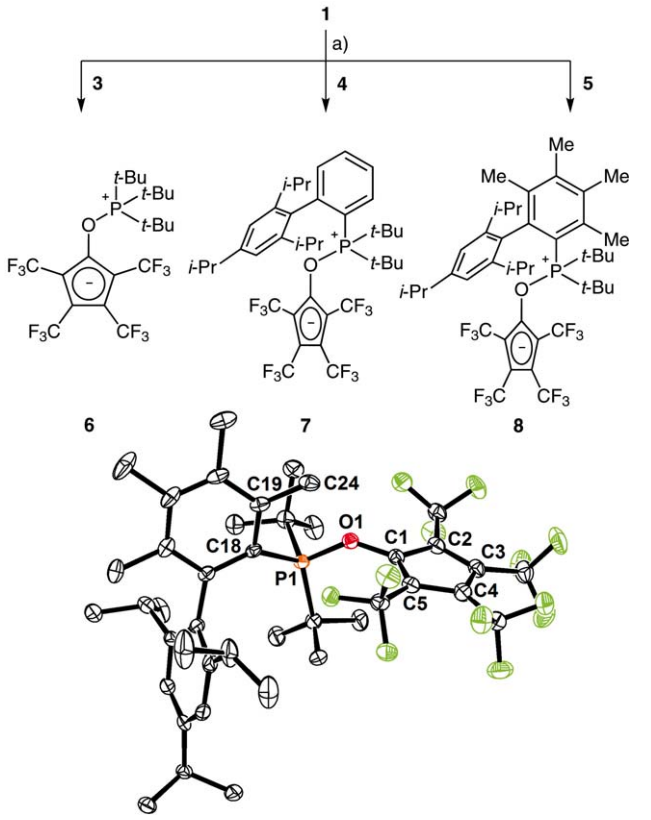
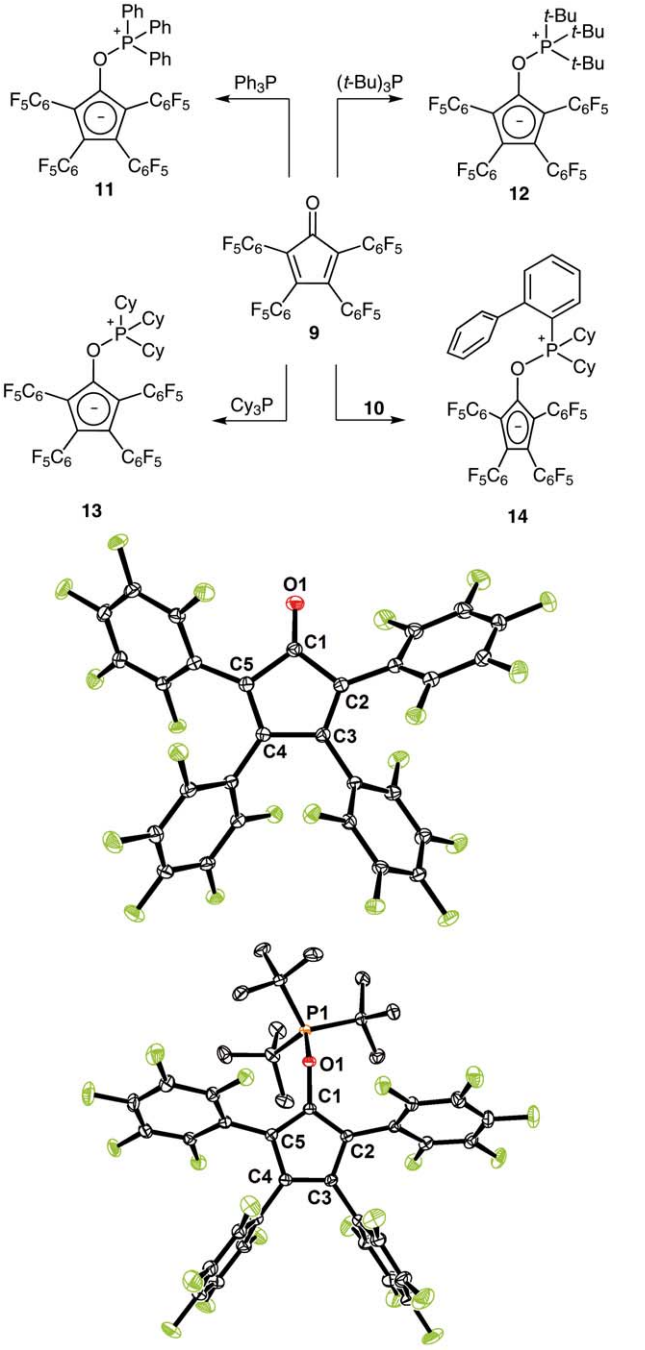


Scheme 2 Synthesis of adducts **6**–**8** and the molecular structure of **8** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms are removed for clarity.[14] (a) *Reaction conditions*: toluene, –78 °C to r.t. Yields: **6**, 43%; **7**, 76%; **8**, 81%.

When ketone **9** was mixed with triphenylphosphine, tri(*tert*-butyl)phosphine, tricyclohexylphosphine, or biphenyl-2-yl(dicyclohexyl)phosphine (**10**) in toluene at room temperature, the corresponding classical Lewis adducts **11**–**14** were isolated, demonstrating that ketone **9** retains Lewis-acid properties.[16] Crystals of ketone **9** and the newly prepared adducts **11**–**14** suitable for X-ray diffraction analysis[14] were obtained from dichloromethane–diethyl ether mixtures [see Scheme 3 (**9** and **12**) and Supporting Information (**11** and **14**)]. A comparison of the structures of ketone **9** and adduct **12** clearly shows the aromatic nature of the ketone fragment after coordination to phosphorus. Whereas in ketone **9**, an alternating single–double C–C bond pattern is observed in the cyclopentadienyl ring (C1–C2, 1.512 Å; C2–C3, 1.347 Å), in adduct **12**, all the C–C bonds are virtually identical and their lengths (1.394; 1.425 Å) are intermediate between the typical values for single and double bonds. In addition, the C=O double bond in ketone **9** (C1–O1, 1.208 Å) is elongated in adduct **12** (C1–O1, 1.425 Å), approaching the expected length for a single C–O bond. Finally, the formation of adducts **11**–**14** seemed to be irreversible, and no dissociation into their constituents was detected, even after heating to 120 °C for several hours. The strength of the newly formed P–O bond is probably responsible for this remarkable stability.



Scheme 3 Synthesis of adducts **11**–**14** and molecular structures of **9** and **12** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and solvents molecules removed for clarity.[14] (a) *Reaction conditions*: toluene, r.t: **11**, 98%; **12**, 86%; **13**, 89%; **14**, 93%.

Interestingly, when ketone **9** was mixed with trimesylphosphine (**15**) or with *t*-BuXPhos (**4**), NMR spectroscopy indicated no interaction between the partners and, therefore, the formation of an FLP. However, the desired activation of dihydrogen could not be realized with these FLPs, even under high pressures. We also obtained negative results when we attempted to activate terminal alkynes, ethers, or fluoroalkanes. It is likely that the limited Lewis acidity of ketone **9**, compared with that of poly-

fluorinated boranes or even with ketone **1**, is responsible for this lack of reactivity.

In conclusion, these preliminary results demonstrate that polyfluorinated ketone **9** can form FLPs in the presence of bulky phosphines. However, the 'frustration level' achieved by ketone **9** in combination with phosphines is insufficient to promote the activation of small molecules such as dihydrogen. The synthesis and design of new organic Lewis acids with potential applications in FLP chemistry are currently under investigation in our laboratory. These species are interesting since they might create bridges between two synthetically very powerful areas of chemistry, namely FLPs and organocatalysis.

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(14) Crystallographic data for compounds **6**, **7**, **8**, **11**, **12**, and **14** have been deposited with the accession numbers CCDC 999847, 999844, 999846, 999848, 999843 , and 999845, respectively, and can be obtained free of charge from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44(1223)336033; E-mail: deposit@ccdc.cam.ac.uk; Web site: www.ccdc.cam.ac.uk/conts/retrieving.html.

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(16) In a typical reaction, the appropriate phosphine was added in one portion to a solution of ketone **9** in toluene at r.t., and the resulting slurry was stirred at r.t. overnight. The solvent was then removed under vacuum and the crude product washed with pentane.
12: yellow solid; yield: 66 mg (86%); mp 235 °C (decomp.); IR (neat): 742, 856, 926, 991, 1053, 1093, 1104, 1347, 1402, 1494, 1504, 1523, 1978 cm^{-1}; ^1H NMR (400 MHz, CD_2Cl_2): δ = 1.40 (d, *J* = 14.7 Hz, 27 H); ^{13}C NMR (151 MHz, CD_2Cl_2): δ = 29.2, 42.1 (d, *J* = 33.9 Hz), 77.9, 96.1, 104.2, 113.6 (m), 114.0 (m), 137.2 (dm, *J* = 250.4 Hz), 137.9 (dm, *J* = 251.8 Hz), 139.6 (dm, *J* = 249.0 Hz), 139.9 (dm, *J* = 249.0 Hz), 144.7 (dm, *J* = 246.2 Hz), 145.5 (dm, *J* = 243.4 Hz); ^{31}P NMR (162 MHz, CD_2Cl_2): δ = 106.7; ^{19}F NMR (282 MHz, $CDCl_3$): δ = –(165.21–165.02) (m, 4 F), –(164.00–163.80) (m, 4 F), –(158.86–158.52) (m, 4 F), –(140.25–140.14) (m, 4 F), –(139.00–138.85) (m, 4 F); HRMS: *m/z* $[M + Na]^+$ calcd for $C_{41}H_{27}OF_{20}PNa$: 969.137244; found: 969.137923.
14: yellow solid; yield: 50 mg (93%); mp 229 °C (decomp.); IR (neat): 790, 852, 864, 894, 924, 969, 991, 1060, 1094, 1106, 1287, 1358, 1403, 1475, 1490, 1501, 1522, 1535, 2862, 2933; ^1H NMR (400 MHz, CD_2Cl_2): δ = 0.83–1.00 (m, 4 H), 1.07–1.27 (m, 6 H), 1.38–1.72 (m, 10 H), 2.01–2.12 (m, 2 H), 7.26–7.29 (m, 1 H), 7.32–7.38 (m, 3 H), 7.44–7.48 (m, 1 H), 7.55–7.57 (m, 3 H), 7.70–7.74 (m, 1 H); ^{13}C NMR (101 MHz, CD_2Cl_2) (partial): δ = 25.7 (d, *J* = 1.4 Hz), 26.3 (d, *J* = 3.8 Hz), 26.9 (d, *J* = 13.3 Hz), 37.2 (d, *J* = 51.9 Hz), 83.2, 95.5, 103.5, 113.0, 114.0, 127.7 (d, *J* = 11.4 Hz), 129.2, 129.7, 130.3, 131.9 (d, *J* = 10.0 Hz), 134.6 (d, *J* = 14.3 Hz), 134.7, 137.5 (dm, *J* = 242.7 Hz), 137.9 (dm, *J* = 247.0 Hz), 139.5 (d, *J* = 2.4 Hz), 144.7 (dm, *J* = 242.7 Hz), 145.5 (dm, *J* = 240.3 Hz), 148.5 (d, *J* = 8.6 Hz); ^{31}P NMR (162 MHz, CD_2Cl_2): δ = 80.5; ^{19}F NMR (282 MHz, $CDCl_3$): δ = –(165.21–165.09) (m, 4 F), –(163.99–163.84) (m, 4 F), –159.68 (t, *J* = 21.1 Hz, 2 F), –159.36 (t, *J* = 21.0 Hz, 2 F), –(140.52–140.34) (m, 4 F), –139.77 (dt, *J* = 25.0, 8.7 Hz, 4 F); HRMS: *m/z* $[M + Na]^+$ calcd for $C_{53}H_{31}OF_{20}PNa$: 1117.168543; found: 1117.169092.