

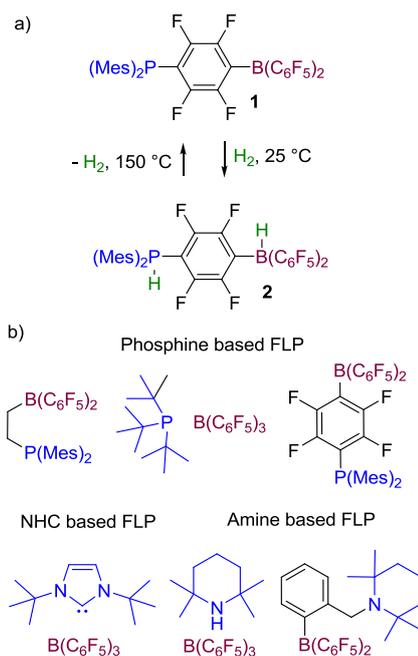
2.4.6 Research Area “Design, Synthesis and Applications of Organic Frustrated Lewis Pairs” (M. Alcarazo)

Involved: H. Bruns, S. Holle, B. Inés, D. Palomas

Objective: With the aim of overcoming the current limitations of frustrated Lewis pairs (FLP) as catalysts for the reduction of C=C and C=X functionalities, we started a program oriented to broaden the range of bases and acids that can be used in FLP chemistry. The activities in this field during the report period mainly concerned the use of carbodiphosphanes as carbon-based Lewis bases and electron poor allenes as surrogates of perfluorinated boranes.

Results: In 1923 G. N. Lewis classified molecules into those that behave as electron pair donors (bases), and inversely, those that are able to accept an electron pair (acids). Since then, this notion of Lewis acids and bases has proven to be extremely useful and it is a very powerful tool to explain and rationalize, from a molecular-orbital-based point of view, the reactivity of many main-group and transition metal complexes. When a Lewis acid is combined with a Lewis base a neutralization reaction takes place. However occasionally, some systems that deviate from this general principle have been found. For example, as early as in 1942, Brown discovered that 2,6-dimethylpyridine does not react with trimethylborane to form the pyridine-borane adduct. Based on molecular models, he assumed that the steric interactions between the methyl groups from the borane and those on the *ortho* position of the pyridine were responsible for this lack of reactivity.

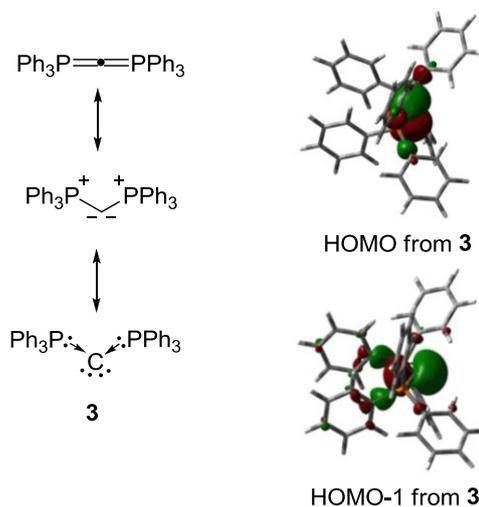
More than sixty years later the group of Stephan synthesized compound **1** in an attempt to study the reactivity of systems in which Lewis acid and base functions were incorporated into the same molecule but sterically protected in order to preclude self quenching, (Scheme 1a). Addition to H₂ to a solution of **1** generated the zwitterionic species **2** that upon heating at 150°C regenerated **1** and H₂. This reactivity represents the first example of a non-transition-metal system that is able to activate



Scheme 1. a) Reversible activation of H₂ by **1**. b) Other combinations of Lewis acids and based that form FLPs.

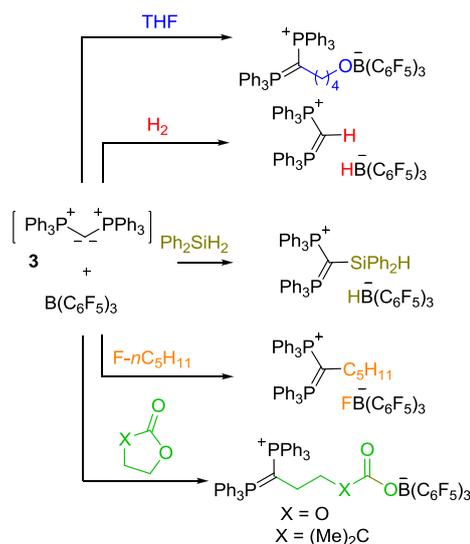
dihydrogen in a reversible manner. As compound **1** is a monomer in which steric demand precludes classical adduct formation, the term “frustrated Lewis pairs” (FLPs) was coined.

Since then many other combinations of Lewis bases and acids have also proven to form FLPs and share similar reactivity towards dihydrogen (Scheme 1b). Even more remarkable, Stephan and Erker were able to apply some of them on the metal free hydrogenation of imines using directly H_2 instead of any surrogate such as Hantzsch esters. Despite of the tremendous synthetic interest of this transformation the substrate scope is still extremely narrow. Only very sterically demanding imines can be reduced as they are the only ones that do not directly react with the borane used as Lewis acid partner for the FLP system.



Scheme 2. a) Electronic structure of **3**.

With the aim of overcoming these important limitations, we have started a program oriented to broaden the range of bases that can be used in FLP chemistry. In this regard we were inspired by the computational investigations of Tonner and Frenking on the nature of carbodiphosphoranes. They propose that these compounds should be considered as comprising two phosphine ligands coordinated to a central zerovalent carbon atom that retains its four valence electrons. This view has been subsequently confirmed experimentally by the work of Bertrand, Fürstner, and others (Scheme 2). The available information suggests that C(0) compounds must be exceptionally good nucleophiles. In fact, the calculated proton affinity for carbodiphosphoranes surpasses the values reported for amines, phosphines and even N-heterocyclic carbenes. It was envisaged therefore that, if sufficiently sterically hindered, C(0) compounds should qualify as bases in the framework of frustrated Lewis pair chemistry. In an

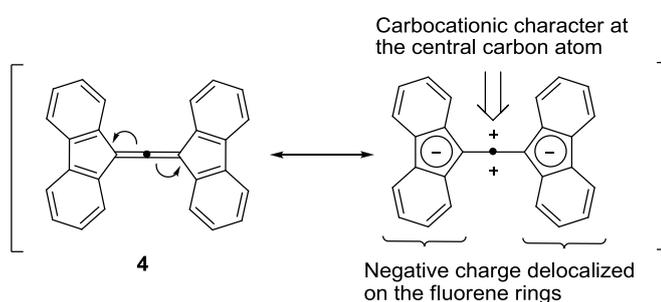


Scheme 3. Reactivity of the pair $C(PPh_3)_2 / B(C_6F_5)_3$.

attempt to address this issue, we studied the reactivity of the pair hexaphenylcarbodiphosphorane **3**/ $B(C_6F_5)_3$ towards several small molecules. The reactivity observed is summarized in Scheme 3. The system is not only able to achieve the already classical H-H, C-O and C-H bond cleavages, but also the activation of Si-H bonds and even alkyl fluorides. Moreover the peculiar electronic situation of the C(0) base makes the system unique: after the first protonation or alkylation, some degree of frustration persists, allowing for a second consecutive activation.

Additionally and with the same objective, we have also very recently studied the possibility of employing carbon-based Lewis acids instead of polyfluorinated boranes.

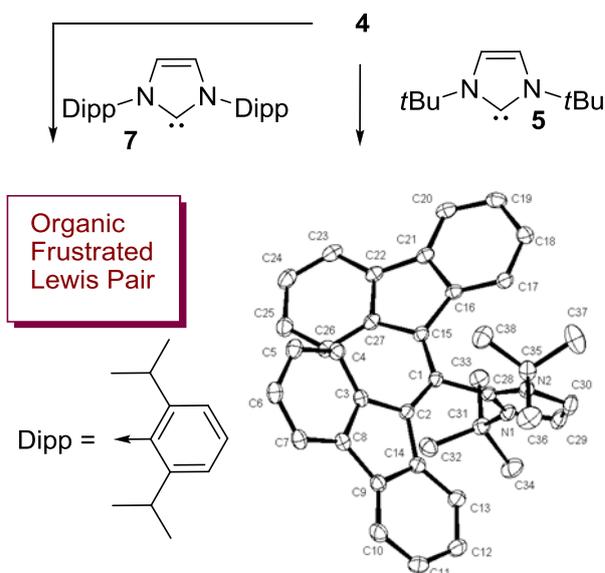
Especially, we realized that allene **4** can be envisaged as neutral trityl cation surrogate, and thus as a promising alternative to $B(C_6F_5)_3$. The intrinsic polarization/charge separation in this molecule, which is the result of the



Scheme 4. Electronic situation on allene **4**.

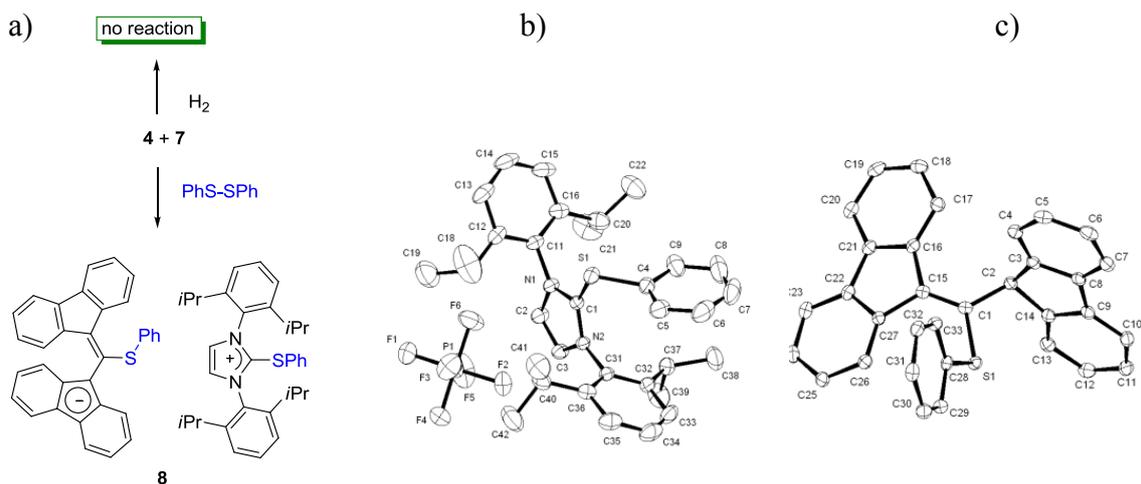
tendency of fluorene to accept a pair of electrons on the π system in order to gain aromatization, generates a partial carbocationic character on the allene central carbon. Likewise, the delocalized negative charge at both molecular extremes should prevent any undesired nucleophilic attack from the basic partner onto the periphery (Scheme 4).

In early attempts, the combination of 1,3-di-*tert*-butylimidazol-2-ylidene (*ItBu*) **5** with allene **4** was investigated as a possible FLP. However, that mixture generated deep blue solutions from which the classical Lewis adduct **6** was isolated (Scheme 5). In contrast, when **1** was mixed with 1,3-bis(2',6'-diisopropylphenyl)-imidazol-2-ylidene (IDipp) **7**, NMR spectroscopy indicated no interaction between the partners, denoting the formation of a frustrated Lewis pair (Scheme 5). At that point the Lewis acidity of allene **6** was quantified by the Childs



Scheme 5. Formation of adduct **6** between allene **4** and 1,3-di(*t*butyl)imidazol-2-ylidene and generation of an organic FLP with 1,3-bis(2',6'-diisopropylphenyl)imidazol-2-ylidene.

method using crotonaldehyde as the reference base. The obtained $\Delta\delta$ values rank the acidity of **4** as clearly weaker than polyfluorinated boranes but still of the order of $B(OPh)_3$. Due to this limited Lewis acidity of **4**, dihydrogen cleavage was neither expected nor has it been experimentally realized. However, a weaker non-polar covalent bond such as that of S-S in disulfides could be heterolytically cleaved, thus demonstrating the potential of these systems (Scheme 6).



Scheme 6. a) Activation of disulfides by the organic pair **4/7**. b) Crystal structure of the cationic part of **8**. c) Crystal structure of the anionic part **8**.

Publications resulting from this area: 285, 326

External funding: Regional Government of the Basque Country, Spain (fellowship to B. Inés); Fonds der Chemischen Industrie

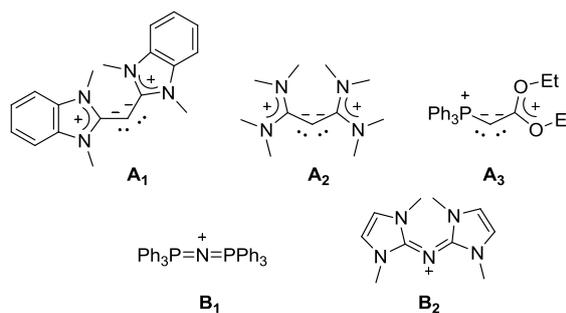
Cooperations: W. Thiel (Mülheim/Ruhr, DE)

2.4.7 Research Area “Design and Synthesis of Unconventional Ligands” (M. Alcarazo)

Involved: H. Bruns, J. Carreras, S. Holle, J. Petušková, A. Vázquez

Objective: Synthesis and study of the coordination properties of ligands based on N(I)

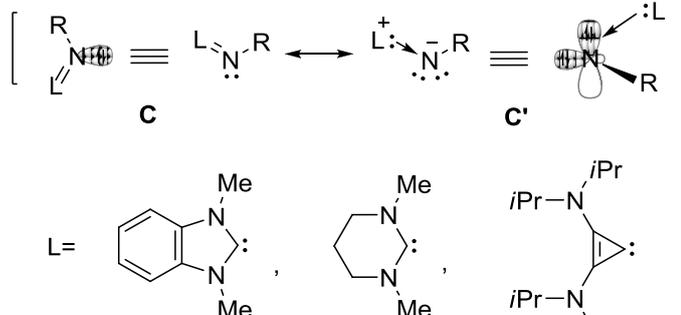
Results: In most organic compounds nitrogen uses three of its five valence electrons to form bonds with surrounding atoms while keeping the other two as a lone pair, having therefore a formal oxidation state of +3. Analogously with the exception of CO, carbenes and isonitriles, carbon is normally tetravalent in organic molecules. However, following



Scheme 1. Representative structures of carbodocarbenes **A**₁ and **A**₂, carbophosphinocarbenes **A**₃, bis(phosphine)iminium cations **B**₁ and bis(carbene)iminium cations **B**₂.

seminal work from Ramírez and inspiring theoretical studies from Tonner and Frenking, Bertrand and Fürstner have synthesized and evaluated the coordination behavior of carbodocarbenes **A**₁-**A**₂ and carbophosphinocarbenes **A**₃ (Scheme 1). These compounds may be considered as consisting of two carbene ligands, or a carbene and a phosphine, coordinated to a central zerovalent carbon atom. This bonding situation can, in principle, be extrapolated to **B**₁ and **B**₂, compounds where the central carbon in carbodiphosphanes or carbodocarbenes has been formally replaced by an isoelectronic N⁺ fragment. However, the positive charge introduced in the systems by such a formal substitution precludes interaction with metal centers. In fact bis(phosphine)iminium ions have been extensively used as non-interfering cations for the isolation and structural characterization of -ate species. A further structural change, directed to keep charge neutrality, is therefore essential.

Replacement of one of the carbene moieties in **B**₂ by anionic R⁻ or Ar⁻ groups eliminates the global positive charge, yet keeps the system isoelectronic with carbodocarbenes. To favor the particular electronic configuration



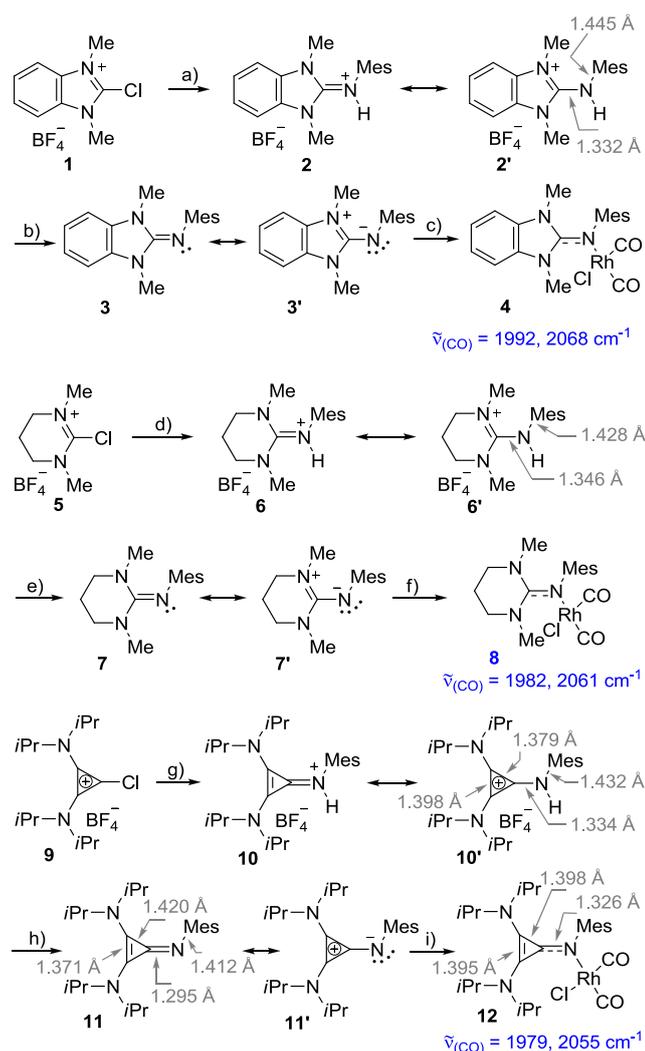
Scheme 2. Conceivable resonance extremes of C-type imines.

in which the nitrogen atom is able to donate four electrons, over the one typical of imines, an adequate selection of the ligand L is crucial. It must be a strong σ donor and at the same time a very poor π acceptor to minimize back donation from the central nitrogen to the carbene moiety.

This extreme situation, represented by resonance structure **C'**, is better characterized as a coordination complex in which a carbene donates two electrons into the empty orbital of a nitrene (Scheme 2). The preparation of these compounds starts with the condensation of readily available chloroiminium or chlorocyclopropenium salts and mesitylamine, followed by deprotonation with KH or KHMDS.

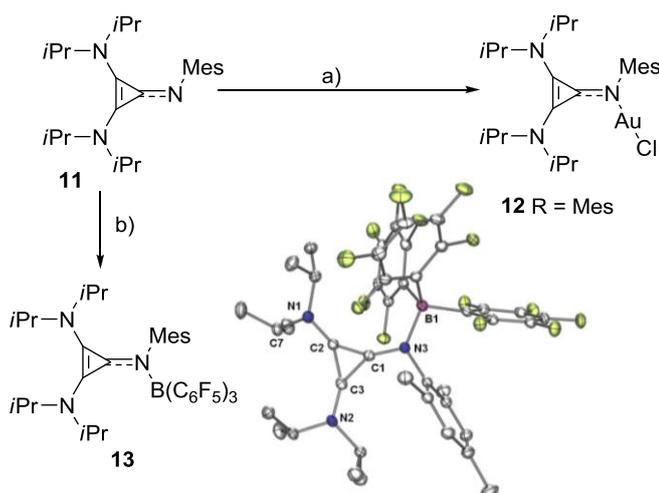
The donor ability of these ligands was evaluated by analysis of the CO stretching frequencies in complexes of type $[\text{RhCl}(\text{CO})_2\text{C}]$.

The corresponding data suggest that **3** has a donor capability similar to iminophosphoranes. Compound **7** surpasses the strongest electron releasing N-heterocyclic carbenes while **11** clearly rivals (amino)(ylide) carbenes and carbodicarbenes. These exceptional donor properties are highlighted by comparison with other nitrogen based ligands such as pyridines or imines. As an indicative example, the unsymmetrical stretching mode of the CO ligands in complex **12** appears at a frequency 36 cm^{-1} lower than in the analogous pyridine complex.



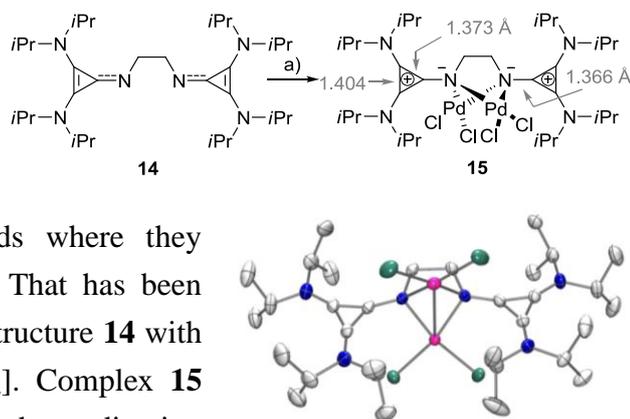
Scheme 3. Reagents and conditions: a) MesNH₂, MeCN, 160°C (microwaves), 1 h, 48%. b) KH, THF, 45°C, overnight, 56%. c) $[\text{RhCl}(\text{CO})_2]_2$, THF, 20 min, 88%. d) MesNH₂, *n*BuLi, THF, reflux, 12 h, 78%. e) KHMDS, toluene, -20°C, RT, 96%. f) $[\text{RhCl}(\text{CO})_2]_2$, THF, 20 min, 61%. g) MesNH₂, THF, reflux, 24 h, 93%. h) KH, THF, 60°C, overnight, 91%. i) $[\text{RhCl}(\text{CO})_2]_2$, THF, 20 min, 72%.

Once the bis(diisopropylamino) cyclopropenyl-ylidene was identified as the most appropriate carbene to produce extremely electron rich C'-type structures, the reactivity and coordination properties of these new compounds were studied. Compound **11** smoothly reacts with soft Lewis acids like [AuCl(Me₂S)] affording the desired metal complex **12** in good yield (Scheme 3). A hard Lewis acid like B(C₆F₅)₃ also reacts cleanly with **11** to form the corresponding adduct **13** as colorless crystals. A conclusive



Scheme 3. Reagents and conditions. a) AuCl(Me₂S), THF, RT, 76%. b) B(C₆F₅)₃, toluene, RT, 72%.

evidence of whether the central nitrogen atom in these species is a N(I) is the isolation of compounds where they formally donate two electron pairs. That has been achieved by reaction of the dimeric structure **14** with two equivalents of [PdCl₂(CH₃CN)₂]. Complex **15** thus obtained shows an unprecedented coordination mode for neutral imine-type ligands where the central nitrogen atoms donate four electrons each, one pair to each palladium centre (Scheme 4).



Scheme 4. Reagents and conditions: a) PdCl₂(MeCN)₂ (2 eq), THF, 21%.

Publications resulting from this area: 298

External funding: Spanish Ministerio de Educación y Ciencia, Spain (short stay fellowship to J. Carreras and A. Vázquez); Fonds der Chemischen Industrie

Cooperations: W. Thiel (Mülheim/Ruhr, DE)