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Organic Frustrated Lewis Pairs

Heterolytic S–S Bond Cleavage by a Purely Carbogenic Frustrated Lewis Pair**

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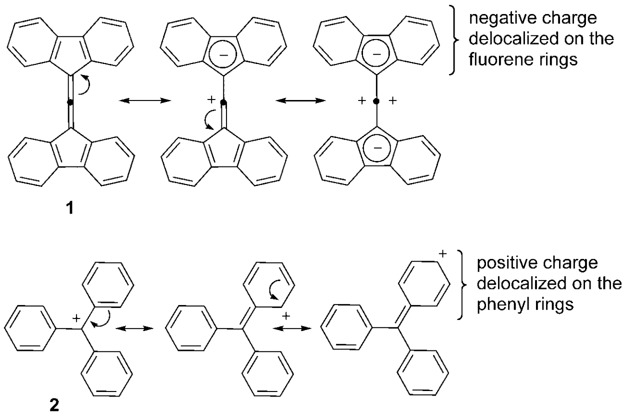
Dedicated to Professor Eloísa Martín Zamora

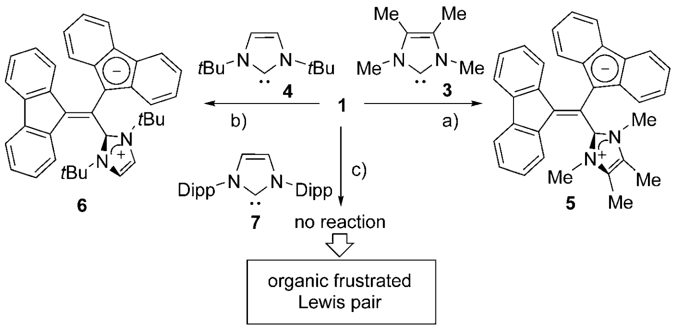
Since the discovery by Stephan and co-workers of the unique ability of frustrated Lewis pairs (FLPs) to activate small molecules,[1] FLPs have been used to cleave many different bonds, such as H–H,[2] C–O,[3] C–H,[4] S–S,[5] and B–H bonds.[6] Furthermore, the type of Lewis bases employed in FLP chemistry has expanded from the original phosphines to include amines,[7] pyridines,[3a,8] N-heterocyclic carbenes,[9] and carbodiphosphoranes.[10] In contrast, the acid partner has remained limited to polyfluorinated boranes or, in some exceptional cases, polyfluorinated alanes.[4] Attempts to overcome this limitation by the use of carbon-based Lewis acids, for example, trityl cations, were not successful owing to the strong tendency of this system to undergo nucleophilic aromatic substitution at a position *para* to the central carbon atom.[11]

Herein we describe the reactivity of an electron-poor allene **1**[12] towards different Lewis bases and demonstrate that the combination of **1** with a very bulky N-heterocyclic carbene, such as 1,3-bis(2′,6′-diisopropylphenyl)imidazol-2-ylidene, generates an FLP able to heterolytically cleave the S–S bond in some disulfides. In this remarkable FLP, not only the Lewis base but also the Lewis acid is carbon-based.

Allene **1** exhibits an intrinsic charge separation that comes from the natural tendency of the fluorene moieties to accept a pair of electrons to gain aromatization. In this way, the central allene carbon atom has partial carbocationic character, and negative charge is delocalized at both termini.[13] Since this electronic distribution does not result in the delocalization of positive charge on the aromatic substituents, undesired nucleophilic attack by the base, as observed in trityl cations (e.g. **2**), is prevented (Scheme 1).



Scheme 1. Resonance extremes of allene **1** and trityl cation **2** emphasizing the different charge distribution.



Scheme 2. Reactivity of allene **1** towards N-heterocyclic carbenes: a) **3**, toluene, −78 °C→RT (94 %); b) **4**, toluene, −78 °C→RT (98 %); c) **7**, toluene, −78 °C→RT.

In early attempts, combinations of 1,3,4,5-tetramethylimidazol-2-ylidene (**3**) and 1,3-di-*tert*-butylimidazol-2-ylidene (I*t*Bu, **4**) with allene **1** were investigated as possible FLPs (Scheme 2). However, in both cases, mixing of the carbene and the allene in toluene at −78 °C generated deep-blue solutions, from which classical Lewis adducts (**5** and **6**, respectively) were isolated (see Figure 1 and the Supporting Information).[14] 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 and thus the formation of a frustrated Lewis pair.[15]

The Lewis acidity of allene **1** was quantified by the Childs method with crotonaldehyde as the reference base.[16] The obtained $\Delta\delta$ values rank the acidity of **1** as clearly weaker than that of polyfluorinated boranes but still of the order of that of $B(OPh)_3$ (see the Supporting Information).[17] Owing to the limited Lewis acidity of **1**, dihydrogen cleavage was neither expected nor realized experimentally. However, we recognized that a weaker nonpolar covalent bond, such as the S–S bond in disulfides, could in principle be activated by this system.

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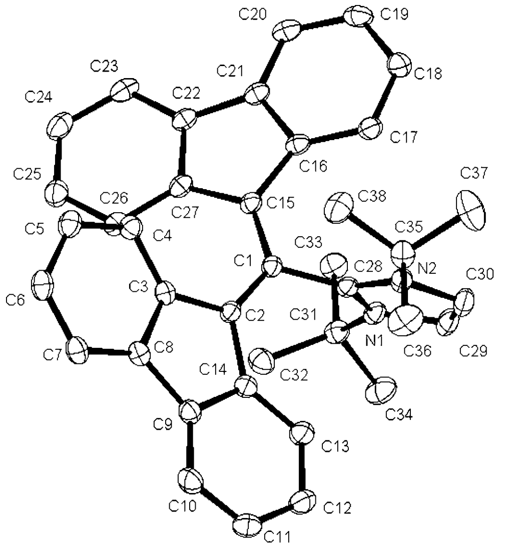
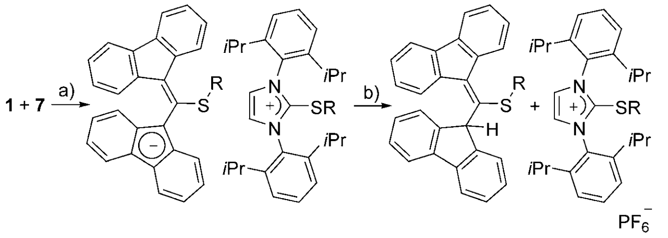


Figure 1. Molecular structure of adduct **6** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and solvent molecules have been removed for clarity.[21]

To check this hypothesis, we added several disulfides to mixtures of **1** and **7** in toluene at −78 °C (Scheme 3). The initially orange solutions gradually acquired an intense blue color upon warming to room temperature. This color is indicative of negative-charge delocalization on the fluorene rings.[18] Removal of the solvent in vacuo and washing with pentane afforded compounds **8**–**10**, which were isolated as foams with an intense blue-violet color. Unfortunately, these compounds did not crystallize despite many attempts.[19] No reaction was observed when tBuSStBu was added to the combination of **1** and **7**, probably as a result of the bulkiness of the *t*Bu groups.[20]



8 R = Ph
9 R = *p*-MeC$_6$H$_4$
10 R = *p*-MeOC$_6$H$_4$

11 R = Ph
13 R = *p*-MeC$_6$H$_4$

12 R = Ph
14 R = *p*-MeC$_6$H$_4$

Scheme 3. Activation of disulfides by an organic frustrated Lewis pair: a) disulfide (1 equiv), toluene, −78 °C→RT, (**8**: 86%; **9**: 91%; **10**: 78%); b) HPF$_6$, CH$_2$Cl$_2$.

In an effort to obtain further structural evidence to confirm the composition of these salts, we treated solutions of compounds **8** and **9** with HPF$_6$ (1 equiv). The addition of HPF$_6$ led to rapid decolorization of the solutions. In each case, two main products were isolated by chromatography (see the Supporting Information). Compounds **11** and **13**, formed by protonation of the bisfluorenyl anion, were obtained as light-yellow solids in 93 and 81% yield, respectively, and the imidazolium hexafluorophosphate salts **12** and **14** were isolated in 84 and 76% yield, respectively. The formation of these compounds (**11** and **12** were also characterized crystallographically; Figure 2 and Figure 3) proves the proposed heterolytic cleavage of disulfides by the FLP formed upon the mixing of **1** and **7**.

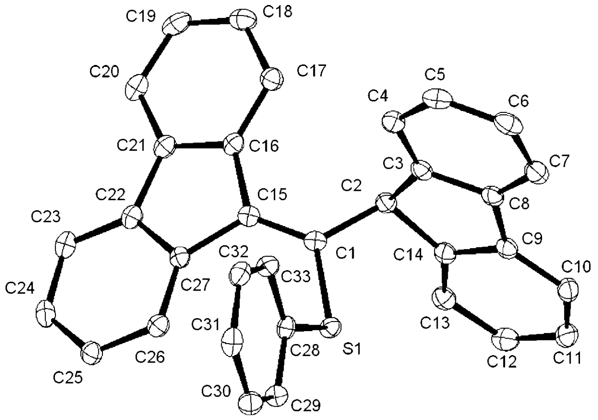


Figure 2. Molecular structure of **11** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms have been removed for clarity.[21]

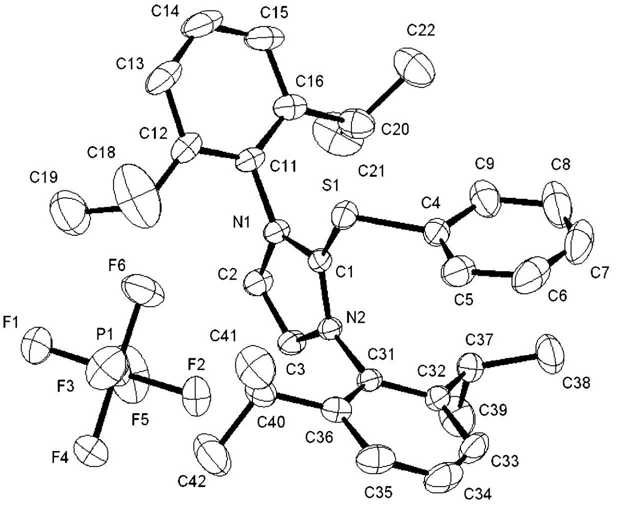


Figure 3. Molecular structure of **12** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and solvent molecules have been removed for clarity.[21]

In conclusion, these results demonstrate that a pure hydrocarbon, such as allene **1**, can be used as a Lewis acid in the framework of FLP chemistry. Even though the grade of "frustration" attained with combinations of **1** and a bulky NHC is lower than that observed for some well-established borane/phosphine pairs, it can be envisaged that modifications, such as the introduction of electron-withdrawing groups on the fluorene skeleton, might make it possible to increase the Lewis acidity of **1** to the level necessary for the activation of a wider range of molecules. Similarly, the decoration of allene **1** with bulky substituents may enable the use of other

Lewis bases that are less sterically demanding than 1,3-bis(2′,6′-diisopropylphenyl)imidazol-2-ylidene.[22] We are currently investigating the reactivity of these new organic FLPs with other substrates as well as the potential of **1** and derivatives as carbon-based Lewis acids in the field of organocatalysis.[23]

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[19] Owing to the failure of the foams to crystallize and the sensitivity of **8**–**10**, no analytically pure samples of these compounds were obtained.

[20] The same lack of reactivity of this substrate was observed by Stephan and co-workers.[5]

[21] CCDC 783365 (**1**), 783366 (**6**), 783367 (**11**), and 783368 (**12**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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