

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

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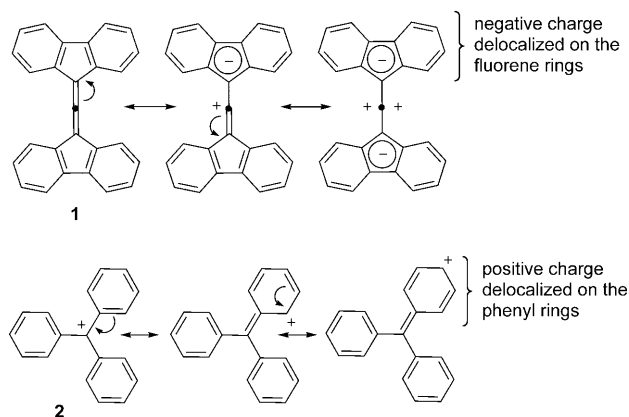
Dedicated to Professor Eloísa Martín Zamora

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]

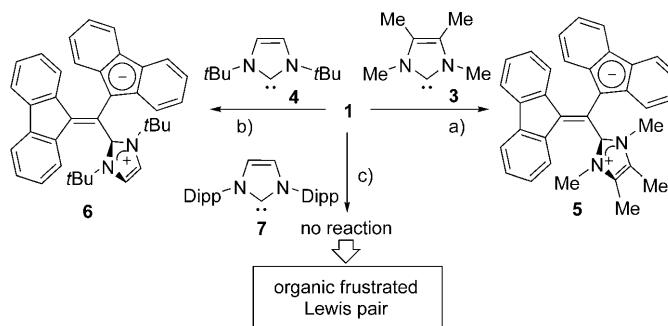
Herein we describe the reactivity of an electron-poor allene **1**^[12] towards different Lewis bases and demonstrate that the combination of **1** with a very bulky N-heterocyclic carbene, such as 1,3-bis(2',6'-diisopropylphenyl)imidazol-2-ylidene, generates an FLP able to heterolytically cleave the 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).

In early attempts, combinations of 1,3,4,5-tetramethylimidazol-2-ylidene (**3**) and 1,3-di-*tert*-butylimidazol-2-ylidene (tBu, **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



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.

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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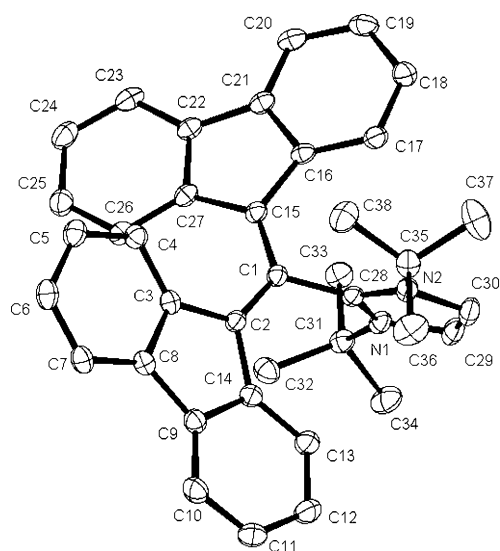
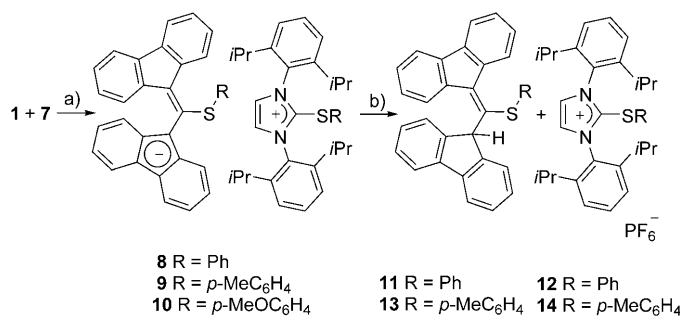


Figure 1. Molecular structure of adduct **6** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and solvent molecules have been removed for clarity.^[21]

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



Scheme 3. Activation of disulfides by an organic frustrated Lewis pair: a) disulfide (1 equiv), toluene, $-78^{\circ}\text{C} \rightarrow \text{RT}$, (**8**: 86%; **9**: 91%; **10**: 78%); b) HPF₆, CH₂Cl₂.

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 *t*BuSS*t*Bu was added to the combination of **1** and **7**, probably as a result of the bulkiness of the *t*Bu groups.^[20]

In an effort to obtain further structural evidence to confirm the composition of these salts, we treated solutions of compounds **8** and **9** with HPF₆ (1 equiv). The addition of HPF₆ 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**.

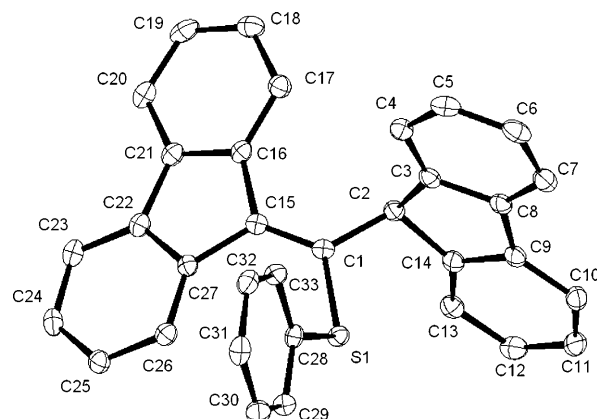


Figure 2. Molecular structure of **11** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms have been removed for clarity.^[21]

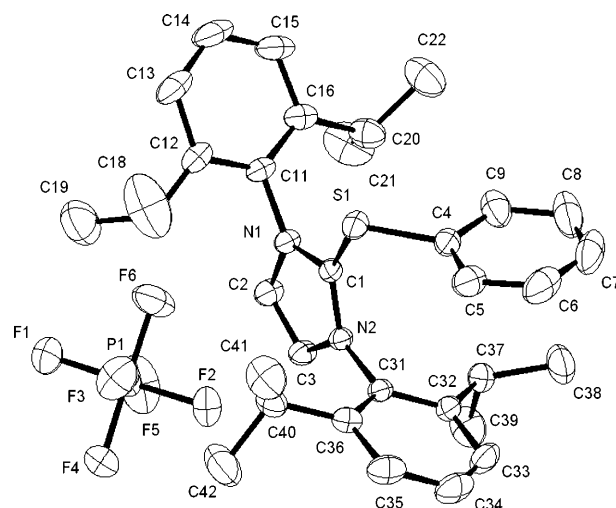


Figure 3. Molecular structure of **12** in the solid state. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and solvent molecules have been removed for clarity.^[21]

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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- [1] a) G. C. Welch, R. R. S. Juan, J. D. Masuda, D. W. Stephan, *Science* **2006**, *314*, 1124–1126; b) A. L. Kenward, W. E. Piers, *Angew. Chem.* **2008**, *120*, 38–42; *Angew. Chem. Int. Ed.* **2008**, *47*, 38–41; for a recent review on the chemistry of frustrated Lewis pairs, see: c) D. W. Stephan, G. Erker, *Angew. Chem.* **2010**, *122*, 50–81; *Angew. Chem. Int. Ed.* **2010**, *49*, 46–77; for metal-free catalyzed hydrogenation, see: d) P. Spies, S. Schwendemann, S. Lange, G. Kehr, R. Frölich, G. Erker, *Angew. Chem.* **2008**, *120*, 7654–7657; *Angew. Chem. Int. Ed.* **2008**, *47*, 7543–7546; e) P. A. Chase, G. C. Welch, T. Jurca, D. W. Stephan, *Angew. Chem.* **2007**, *119*, 8196–8199; *Angew. Chem. Int. Ed.* **2007**, *46*, 8050–8053.
- [2] For theoretical mechanistic studies, see: a) T. A. Rokob, A. Hamza, A. Stirling, T. Soós, I. Pápai, *Angew. Chem.* **2008**, *120*, 2469–2472; *Angew. Chem. Int. Ed.* **2008**, *47*, 2435–2438; b) T. A. Rokob, A. Hamza, I. Pápai, *J. Am. Chem. Soc.* **2009**, *131*, 10701–10710; c) S. Grimme, H. Kruse, L. Goerigk, G. Erker, *Angew. Chem.* **2010**, *122*, 1444–1447; *Angew. Chem. Int. Ed.* **2010**, *49*, 1402–1405; d) for the splitting of dihydrogen through the use of a single carbon center, see: G. D. Frey, V. Lavallo, B. Donnadieu, W. W. Schoeller, G. Bertrand, *Science* **2007**, *316*, 439–441.
- [3] a) S. J. Geier, D. W. Stephan, *J. Am. Chem. Soc.* **2009**, *131*, 3476–3477; b) G. C. Welch, J. D. Masuda, D. W. Stephan, *Inorg. Chem.* **2006**, *45*, 478–480.
- [4] M. A. Dureen, D. W. Stephan, *J. Am. Chem. Soc.* **2009**, *131*, 8396–8397.
- [5] M. A. Dureen, G. C. Welch, T. M. Gilbert, D. W. Stephan, *Inorg. Chem.* **2009**, *48*, 9910–9917.
- [6] M. A. Dureen, A. Lough, T. M. Gilbert, D. W. Stephan, *Chem. Commun.* **2008**, 4303–4305.
- [7] a) V. Sumerin, F. Schulz, M. Nieger, M. Leskelä, T. Repo, B. Rieger, *Angew. Chem.* **2008**, *120*, 6090–6092; *Angew. Chem. Int. Ed.* **2008**, *47*, 6001–6003; b) P. Chase, T. Jurca, D. W. Stephan, *Chem. Commun.* **2008**, 1701–1703.
- [8] a) S. J. Geier, A. L. Gille, T. M. Gilgert, D. W. Stephan, *Inorg. Chem.* **2009**, *48*, 10466–10474.
- [9] a) D. Holschumacher, T. Bannenberg, C. G. Hrib, P. G. Jones, M. Tamm, *Angew. Chem.* **2008**, *120*, 7538–7542; *Angew. Chem. Int. Ed.* **2008**, *47*, 7428–7432; for a recent review on the synthesis and coordination chemistry of N-heterocyclic carbenes, see: b) F. E. Hahn, M. C. Jahnke, *Angew. Chem.* **2008**, *120*, 3166–3216; *Angew. Chem. Int. Ed.* **2008**, *47*, 3122–3172; for recent studies on the use of NHCs to activate small molecules, see: c) T. W. Hudnall, J. P. Moerdyk, C. W. Bielawski, *Chem. Commun.* **2010**, *46*, 4288–4290; d) T. W. Hudnall, E. J. Moorhead, D. G. Gusev, C. W. Bielawski, *J. Org. Chem.* **2010**, *75*, 2763–2766; e) T. W. Hudnall, C. W. Bielawski, *J. Am. Chem. Soc.* **2009**, *131*, 16039–16041.
- [10] M. Alcarazo, C. Gomez, S. Holle, R. Goddard, *Angew. Chem.* **2010**, *122*, 5924–5927; *Angew. Chem. Int. Ed.* **2010**, *49*, 5788–5791.
- [11] L. Cabrera, G. C. Welch, J. D. Masuda, P. Wei, D. W. Stephan, *Inorg. Chim. Acta* **2006**, *359*, 3066–3071.
- [12] E. Weber, W. Seichter, I. Goldberg, *Chem. Ber.* **1990**, *123*, 811–820. For a previous elucidation of the X-ray crystal structure of **1**, see: E. Weber, W. Seichter, B. Hess, G. Will, H. J. Dasting, *J. Phys. Org. Chem.* **1995**, *8*, 94–96.
- [13] For the synthesis of electron-rich allenes and related species and the study of their properties as Lewis bases, see: a) H. G. Viehe, Z. Janousek, R. Gompper, D. Lach, *Angew. Chem.* **1973**, *85*, 581–582; *Angew. Chem. Int. Ed. Engl.* **1973**, *12*, 566–567; b) A. Fürstner, M. Alcarazo, H. Krause, *Org. Synth.* **2009**, *86*, 298–307; c) H. J. Bestmann, R. W. Saalfrank, J. P. Snyder, *Chem. Ber.* **1973**, *106*, 2601–2609; d) C. A. Dyker, V. Lavallo, B. Donnadieu, G. Bertrand, *Angew. Chem.* **2008**, *120*, 3250–3253; *Angew. Chem. Int. Ed.* **2008**, *47*, 3206–3209; e) M. Alcarazo, C. W. Lehmann, A. Anoop, W. Thiel, A. Fürstner, *Nat. Chem.* **2009**, *1*, 295–301; f) C. A. Dyker, G. Bertrand, *Nat. Chem.* **2009**, *1*, 265–266; g) A. Fürstner, M. Alcarazo, R. Goddard, C. W. Lehmann, *Angew. Chem.* **2008**, *120*, 3254–3258; *Angew. Chem. Int. Ed.* **2008**, *47*, 3210–3214; h) V. Lavallo, C. A. Dyker, B. Donnadieu, G. Bertrand, *Angew. Chem.* **2009**, *121*, 1568–1570; *Angew. Chem. Int. Ed.* **2009**, *48*, 1540–1542; i) M. Melaimi, P. Parameswaran, B. Donnadieu, G. Frenking, G. Bertrand, *Angew. Chem.* **2009**, *121*, 4886–4889; *Angew. Chem. Int. Ed.* **2009**, *48*, 4792–4795; and reference [10]; for theoretical analyses, see: j) R. Tonner, G. Frenking, *Chem. Eur. J.* **2008**, *14*, 3260–3272; k) R. Tonner, G. Frenking, *Chem. Eur. J.* **2008**, *14*, 3273–3289; l) R. Tonner, G. Frenking, *Angew. Chem.* **2007**, *119*, 8850–8853; *Angew. Chem. Int. Ed.* **2007**, *46*, 8695–8698; m) R. Tonner, F. Öxler, B. Neumüller, W. Petz, G. Frenking, *Angew. Chem.* **2006**, *118*, 8206–8211; *Angew. Chem. Int. Ed.* **2006**, *45*, 8038–8042; n) O. Kaufhold, F. E. Hahn, *Angew. Chem.* **2008**, *120*, 4122–4126; *Angew. Chem. Int. Ed.* **2008**, *47*, 4057–4061.
- [14] The direct treatment of Lewis bases with other electron-poor allenes to form classical Lewis adducts has been described previously; see: R. Gompper, U. Wolf, *Liebigs Ann. Chem.* **1979**, 1406–1425.
- [15] The distinct reactivity shown by IrBu and IDipp when combined with **1** or B(C₆F₅)₃ clearly speaks for substantially different steric requirements of these two Lewis acids; see: P. A. Chase, D. W. Stephan, *Angew. Chem.* **2008**, *120*, 7543–7547; *Angew. Chem. Int. Ed.* **2008**, *47*, 7433–7437.
- [16] R. F. Childs, D. L. Mulholland, A. Nixon, *Can. J. Chem.* **1982**, *60*, 801–808.
- [17] G. J. P. Britovsek, J. Ugoletti, A. J. P. White, *Organometallics* **2005**, *24*, 1685–1691.
- [18] a) C. Jutz, H. Amschler, *Angew. Chem.* **1961**, *73*, 806; b) D. Bladauski, D. Rewicki, *Chem. Ber.* **1977**, *110*, 3920–3929.
- [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.
- [22] G. Erös, H. Mehdi, I. Pápai, T. A. Rokob, P. Király, G. Tárkányi, T. Soós, *Angew. Chem.* **2010**, *122*, 6709–6713; *Angew. Chem. Int. Ed.* **2010**, *49*, 6559–6563.
- [23] C. T. Chen, S. D. Chao, K. C. Yen, C. H. Chen, I. C. Chou, S. W. Hon, *J. Am. Chem. Soc.* **1997**, *119*, 11341–11342.