Lewis Acid Catalysis

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Taming the Silylium Ion for Low-Temperature Diels–Alder Reactions**

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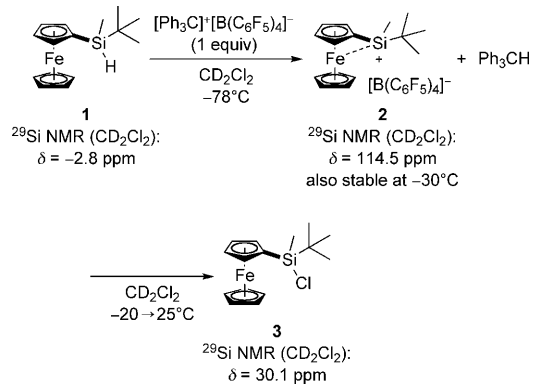
The silylium ion, a trivalent silicon cation, has a varied history regarding its isolation and characterization in its free form in the condensed phase.[1,2] An electron sextet at the silicon atom renders these electron-deficient compounds extremely potent Lewis acids, so strong that even weak Lewis bases (solvent molecules), which are normally considered inert, will coordinate.[3] Both steric shielding of the empty orbital at the silicon atom,[4,5] and the clever design of weakly coordinating anions[6,7] allowed the structural determination of a silylium ion.[8] Aside from these elementary insights, an equally fundamental question is posed: Are such reactive intermediates useful to synthetic chemistry? Yes, Ozerov and co-workers[9] and likewise Müller and co-workers[10] had identified silylium ions to be catalytically active in $C(sp^3)$–F bond activation.[11] Conversely, the self-evident use of silylium ions in Lewis acid catalysis is elusive,[12–16] presumably because of the irreversible formation of Lewis pairs.

Inspired by a seminal attempt by Corey et al.[17] and a recent contribution by Manners and co-workers,[18] we set out to employ an electron-rich late transition metal for intramolecular stabilization of a trivalent silicon cation; our goal was realized by the ferrocene-based **2** (see the Supporting Information for straightforward preparation of its precursor **1**), which is decorated with both a small and a large group (Scheme 1). Whereas the iron–silicon interaction attenuates Lewis acidity, the deliberate choice of the substituents at the silicon atom also seems to be vital.[19] These parameters bring about the perfect balance of inherent Lewis acidity and steric accessibility to the silicon atom, thereby securing reversible coordination of Lewis basic functional groups essential for catalytic turnover.

Lewis acid **2** is formed quantitatively at −78 °C within seconds by conventional Bartlett–Condon–Schneider silicon-to-carbon hydride transfer[20] (**1**→**2**, Scheme 1 and Figure 1), displaying remarkable chemical stability in CD_2Cl_2[6a,21] at a synthetically practical temperature window ranging from −78 °C to −30 °C. Its formation by rapid hydride abstraction



Scheme 1. Fast generation of the silylium ion (**1**→**2**) and its slow decomposition through chloride-abstraction from CD_2Cl_2 (**2**→**3**).

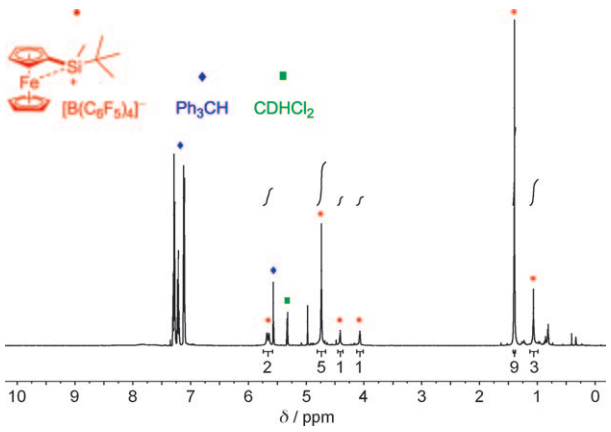


Figure 1. ^{1}H NMR spectrum (500 MHz) of **2** recorded in CD_2Cl_2 at −40 °C.

(**1**→**2**), and decomposition by chloride abstraction from CD_2Cl_2 (**2**→**3**) both proceed exceptionally cleanly, as monitored by ^{1}H NMR spectroscopy (see the Supporting Information for variable temperature ^{1}H NMR spectroscopy). The structure of **3** was detected by GC/MS measurements and unambiguously assigned by comparison with an authentic sample. We were pleased to see that the ^{29}Si NMR spectrum of **2** showed a diagnostic signal at $\delta = 114.5$ ppm, a significant downfield shift (Figure 2). In comparison with the reported ^{29}Si NMR chemical shifts (Figure 3),[3–6,10,18] the observed value indicates to us that the iron-stabilized silylium ion is not "quenched" by a solvent molecule and is therefore still a reasonably strong Lewis acid.

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[+] NMR spectroscopic measurements

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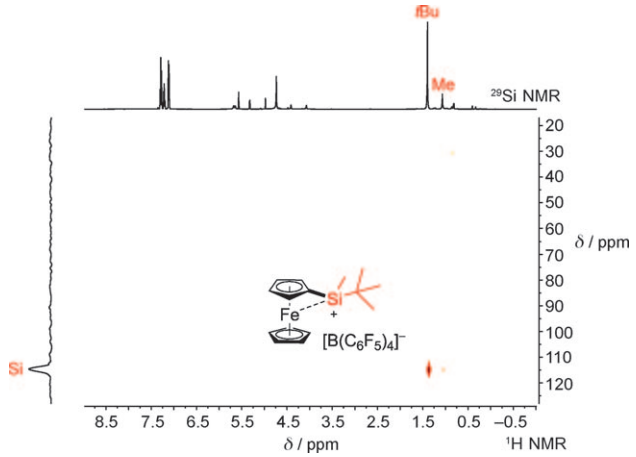


Figure 2. $^{1}H,^{29}Si$ HMQC spectrum of **2** recorded in CD_2Cl_2 at −40 °C.

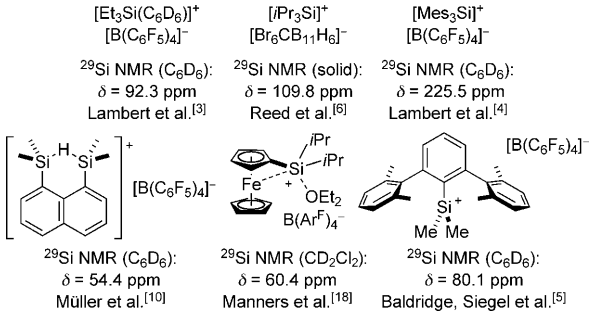
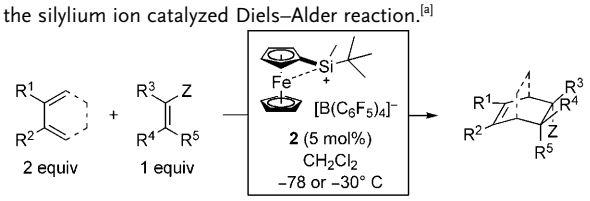


Figure 3. Reported ^{29}Si NMR chemical shifts of selected silylium ions (Mes = 2,4,6-trimethylphenyl, Ar^F = 3,5-bis(trifluoromethyl)phenyl).

For testing the potential of the novel complex **2**, we chose to investigate challenging Diels–Alder reactions.[22,23] Our survey commenced with 1,3-cyclohexadiene (ca. 500 times less reactive than cyclopentadiene) and three dienophiles of gradually decreasing reactivity. We were delighted to find that **2** (5 mol%) invariably catalyzed these cycloadditions with superb *endo* selectivity within hours at −78 °C with the expected reaction rates k: $k_{aldehyde} > k_{ketone} \approx k_{ester}$ (Table 1, entries 1–3). Moreover, additional substitution on the dienophile was tolerated (Table 1, entries 4 and 5), and representative cyclic α,β-unsaturated ketones also participated while requiring a slightly elevated reaction temperature (Table 1, entries 6 and 7). As an example, we successfully tested a simple acyclic diene of moderate reactivity (Table 1, entry 8). Even the Diels–Alder reaction of a markedly deactivated butadiene proceeded with high regioselectivity (Table 1, entry 9).[24]

In summary, a tamed silylium ion catalyzes demanding Diels–Alder reactions in an unprecedented temperature range. A comparison with the reported data on silicon Lewis acids demonstrates the outstanding level of reactivity (Scheme 2).[12,15a,c] We believe that the novel Lewis acid **2** opens a whole new facet of (asymmetric) Lewis acid catalysis, realizing that stereochemical information is already present at the silicon atom (central chirality), and might also be introduced into the ferrocene platform (planar chirality).

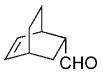
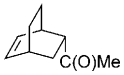
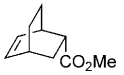
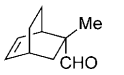
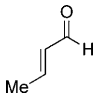
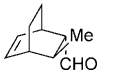
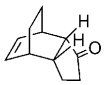
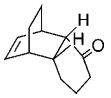
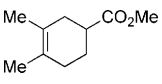
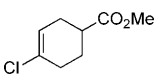
Table 1: Scope of the silylium ion catalyzed Diels–Alder reaction.[a]



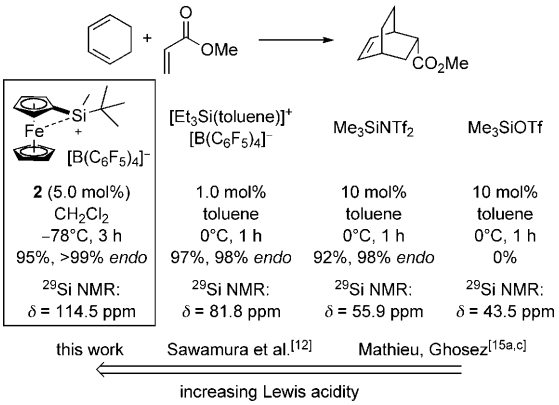
diene: $R^1 = R^2 = H$ (cyclic); $R^1 = R^2 = Me$ or $R^1 = H$ and $R^2 = Cl$ (acyclic)

dienophile (cyclic): Z and R^5 = -C(O)$(CH_2)_n$- n = 2 and 3

dienophile (acyclic): Z = CHO, C(O)Me, CO_2Me R^3 and R^4 = H or Me

Entry	Diene	Dienophile	t [h]	T [°C]	Product	*endo*/*exo*[b]	Yield [%][c]
1			1	−78		97:3	94
2			3	−78		99:1	93
3			3	−78		>99:1	95
4			4	−78		92:8	91
5			4	−78		>99:1	96
6			12	−40		96:4	85
7			24	−40		96:4	80
8			1	−78		–	97
9			24	−30		–[d]	68

[a] All reactions were conducted according to the general procedure (see the Supporting Information for details). [b] Diastereoselectivities were determined by GC analysis. [c] Yield refers to isolated material after purification by flash chromatography on silica gel. [d] *para*/*meta* ratio >99:1.



Scheme 2. Comparison with reported "silylium ion" catalysts.

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[1] a) J. B. Lambert, Y. Zhao, S. M. Zhang, *J. Phys. Org. Chem.* **2001**, *14*, 370 – 379; b) C. A. Reed, *Acc. Chem. Res.* **1998**, *31*, 325 – 332; c) J. B. Lambert, L. Kania, S. Zhang, *Chem. Rev.* **1995**, *95*, 1191 – 1201.

[2] For a Highlight, see: J. Belzner, *Angew. Chem.* **1997**, *109*, 1331 – 1334; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1277 – 1280.

[3] a) J. B. Lambert, S. Zhang, C. L. Stern, J. C. Huffman, *Science* **1993**, *260*, 1917 – 1918; b) J. B. Lambert, S. Zhang, S. M. Ciro, *Organometallics* **1994**, *13*, 2430 – 2443; c) an insightful series of comments on those papers: G. A. Olah, G. Rasul, X.-y. Li, H. A. Buchholz, G. Sandford, G. K. S. Prakash, *Science* **1994**, *263*, 983 – 984; J. B. Lambert, S. Zhang, *Science* **1994**, *263*, 984 – 985; C. A. Reed, Z. Xie, *Science* **1994**, *263*, 985 – 986.

[4] a) J. B. Lambert, Y. Zhao, *Angew. Chem.* **1997**, *109*, 389 – 391; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 400 – 401; b) J. B. Lambert, Y. Zhao, H. Wu, W. C. Tse, B. Kuhlmann, *J. Am. Chem. Soc.* **1999**, *121*, 5001 – 5008.

[5] S. Duttwyler, Q.-Q. Do, A. Linden, K. K. Baldridge, J. S. Siegel, *Angew. Chem.* **2008**, *120*, 1743 – 1746; *Angew. Chem. Int. Ed.* **2008**, *47*, 1719 – 1722.

[6] a) C. A. Reed, Z. Xie, R. Bau, A. Benesi, *Science* **1993**, *262*, 402 – 404; b) Z. Xie, J. Manning, R. W. Reed, R. Mathur, P. D. W. Boyd, A. Benesi, C. A. Reed, *J. Am. Chem. Soc.* **1996**, *118*, 2922 – 2928.

[7] a) I. Krossing, I. Raabe, *Angew. Chem.* **2004**, *116*, 2116 – 2142; *Angew. Chem. Int. Ed.* **2004**, *43*, 2066 – 2090; b) S. H. Strauss, *Chem. Rev.* **1993**, *93*, 927 – 942.

[8] K.-C. Kim, C. A. Reed, D. W. Elliott, L. J. Mueller, F. Tham, L. Lin, J. B. Lambert, *Science* **2002**, *297*, 825 – 827.

[9] a) V. J. Scott, R. Çelenligil-Çetin, O. V. Ozerov, *J. Am. Chem. Soc.* **2005**, *127*, 2852 – 2853; b) C. Douvris, O. V. Ozerov, *Science* **2008**, *321*, 1188 – 1190.

[10] R. Panisch, M. Bolte, T. Müller, *J. Am. Chem. Soc.* **2006**, *128*, 9676 – 9682.

[11] Highlight: G. Meier, T. Braun, *Angew. Chem.* **2009**, *121*, 1575 – 1577; *Angew. Chem. Int. Ed.* **2009**, *48*, 1546 – 1548.

[12] K. Hara, R. Akiyama, M. Sawamura, *Org. Lett.* **2005**, *7*, 5621 – 5623.

[13] A. D. Dilman, S. L. Ioffe, *Chem. Rev.* **2003**, *103*, 733 – 772.

[14] a) M. Johannsen, K. A. Jørgensen, G. Helmchen, *J. Am. Chem. Soc.* **1998**, *120*, 7637 – 7638; b) clarification of that work: G. A. Olah, G. Rasul, G. K. S. Prakash, *J. Am. Chem. Soc.* **1999**, *121*, 9615 – 9617.

[15] For neutral (chiral) silicon-based Lewis acids in Diels–Alder chemistry, see: a) B. Mathieu, L. Ghosez, *Tetrahedron Lett.* **1997**, *38*, 5497 – 5500; b) B. Mathieu, L. de Fays, L. Ghosez, *Tetrahedron Lett.* **2000**, *41*, 9561 – 9564; c) B. Mathieu, L. Ghosez, *Tetrahedron* **2002**, *58*, 8219 – 8226.

[16] For a chiral, strained silicon Lewis acid in Diels–Alder reactions, see: K. Kubota, C. L. Hamblett, X. Wang, J. L. Leighton, *Tetrahedron* **2006**, *62*, 11397 – 11401.

[17] a) J. Y. Corey, D. Gust, K. Mislow, *J. Organomet. Chem.* **1975**, *101*, C7 – C8; b) reconsideration of that work: J. B. Lambert, H.-n. Sun, *J. Am. Chem. Soc.* **1976**, *98*, 5611 – 5615; T. J. Barton, A. K. Hovland, C. R. Tully, *J. Am. Chem. Soc.* **1976**, *98*, 5695 – 5696.

[18] S. C. Bourke, M. J. MacLachlan, A. J. Lough, I. Manners, *Chem. Eur. J.* **2005**, *11*, 1989 – 2000.

[19] This statement is based on the observed chemical stability of **2** in CD_2Cl_2 and our difficulties to spectroscopically characterize less hindered systems.

[20] J. Y. Corey, *J. Am. Chem. Soc.* **1975**, *97*, 3237 – 3238.

[21] M. Kira, T. Hino, H. Sakurai, *J. Am. Chem. Soc.* **1992**, *114*, 6697 – 6700.

[22] F. Frinquelli, A. Taticchi, *The Diels–Alder Reaction: Selected Practical Methods*, Wiley, Chichester, **2002**.

[23] For remarkable approaches to facilitate demanding Diels–Alder reactions, see: a) K. Furuta, S. Shimizu, Y. Miwa, H. Yamamoto, *J. Org. Chem.* **1989**, *54*, 1481 – 1483; b) K. A. Ahrendt, C. J. Borths, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2000**, *122*, 4243 – 4244; c) E. J. Corey, T. Shibata, T. W. Lee, *J. Am. Chem. Soc.* **2002**, *124*, 3808 – 3809; d) W. Liu, F. You, C. J. Mocella, W. D. Harman, *J. Am. Chem. Soc.* **2006**, *128*, 1426 – 1427.

[24] For an example of a Diels–Alder reaction of 2-chloro-1,3-butadiene at −78 °C using equimolar amounts of BCl_3, see: G. Sarakinos, E. J. Corey, *Org. Lett.* **1999**, *1*, 1741 – 1744.

