

Solvent-Dependent Lithium Bridging in
Allenyl–Propargyllithium Reagents

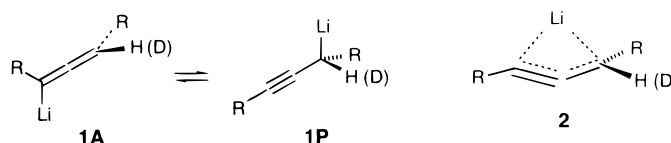
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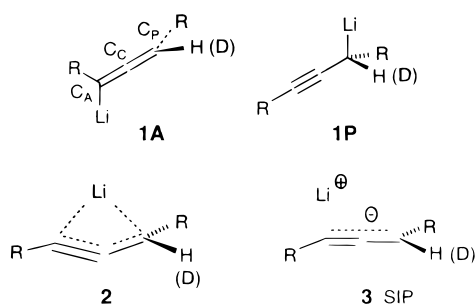
ABSTRACT



The solution structures of two allenyl–propargyllithium reagents (6-Li and 7-Li) which give ^{13}C NMR chemical shifts intermediate between those expected for the allenyl and propargyl isomers have been studied by the Saunders isotope perturbation technique. Variable equilibrium isotope shifts were detected, showing that these reagents adopt structures ranging from equilibrating localized allenyl- and propargyllithium reagents ($1\text{A} \rightleftharpoons 1\text{B}$) to equilibrating unsymmetrically bridged structures (11) and symmetrically bridged structures (2), depending mostly on the details of solvation.

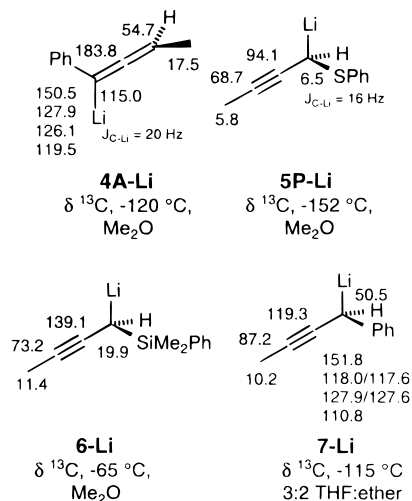
Important aspects of the chemistry of allenyl-propargyl (A–P) lithium reagents are likely to depend on the association between carbon and lithium, which can have the limiting forms 1–3. Reagents with innocuous substituents such as

structures of compounds such as 6-Li^{1b} and 7-Li which show ^{13}C shifts intermediate between the allenyl and propargyl compounds that we address here.



H and alkyl at either C_P or C_A , as well as most of those with anion stabilizing groups such as PhSe, PhS, RO, R_3Si , and Ph at C_A (e.g., 4A-Li), have the allenyl structure 1A, on the basis of the strongly deshielded central carbon atom C_C in the ^{13}C NMR spectra (170–190 ppm) and well-defined C–Li coupling at the lithium-bearing carbon.^{1a,b,2}

Reagents having anion stabilizing groups at C_P show more diverse structures. Those with alkoxy substituents at C_P are allenyllithiums; those with PhSe and PhS (e.g., 5P-Li) are localized propargyllithiums (C_C at 90–100 ppm).^{1a} It is the



Several explanations for the ^{13}C chemical shifts of 6-Li, 7-Li, and their analogues can be offered: (a) the compounds have the bridged structure 2 as suggested by computational studies^{3a} and single-crystal X-ray structures,⁴ (b) they are equilibrating mixtures of 1A and 1P isomers (with K_{eq} near

1) or equilibrating structures intermediate between **1** and **2**, (c) they are separated ion pairs (SIPs) **3**,^{1b,5a} or (d) they are equilibrating mixtures of contact ion pairs (CIPs⁶), either **1** or **2**, and SIPs. A careful study of the solvent and temperature dependence of the ¹³C NMR chemical shifts has provided circumstantial evidence that **6-Li** and its analogues are equilibrating A–P isomers with a barrier to isomerization of less than 4 kcal/mol.^{1b}

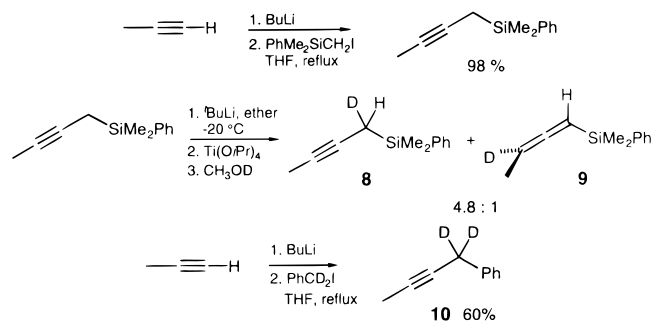
The Saunders isotope perturbation technique⁷ can unambiguously distinguish between static and rapidly equilibrating structures. Static structures will show only intrinsic H/D isotope effects on chemical shifts ($\Delta\delta_{D-H}$). The $\Delta\delta_{D-H}$ values have little or no temperature dependence, and they are rapidly attenuated as the distance from the site of isotopic substitution increases. Equilibrating structures will show temperature-dependent $\Delta\delta_{D-H}$ values, provided that two criteria are met: there must be a difference in the C–H(D) bond strength between the two isomers, and the nucleus observed must have a chemical shift difference ($\Delta\delta$) in the two isomers. In fact, unlike the intrinsic shifts, the equilibrium isotope shifts are independent of the number of bonds separating the site of isotopic substitution and the observed nucleus but are directly proportional to $\Delta\delta$.

Static structures such as **2** and **3** (explanations a and c) should show only intrinsic isotope effects. Rapidly equilibrating structures such as **1** or a mixture of CIPs⁶ and SIPs (explanations b and d) should show isotopic perturbation effects since the hybridization at C_P in **1A** or **3** is expected to be near sp², whereas in **1P** this carbon is pyramidalized.¹⁰ Deuterium substitution at C_P would move the equilibrium away from **1P** and toward **1A** and **3**, on the basis of the

observation that ¹J_{CH} is larger in SIPs of this type than in CIPs^{10a} and larger in C_P of allenyllithiums than in propargyllithiums.^{10b} We assume that ¹J_{CH} at least qualitatively correlates with bond strength and bond stiffness.

The required deuterated precursors **8** and **10** were prepared as shown in Scheme 1. The small amount of deuterated allene

Scheme 1. Preparation of the Deuterated Precursors for **6-Li** and **7-Li**



9 formed during deuteration of the allenyl–titanium reagent was removed by a partial metalation and carboxylation (**9** is kinetically more acidic than **8**). Solutions of the lithium reagents were prepared in the appropriate solvents by in situ metalations of 1-(phenyldimethylsilyl)-2-butyne and 1-phenyl-2-butyne (and deuterated analogues) with *t*-BuLi and *n*-BuLi, respectively. These solutions had to be kept cold to avoid prototropic isomerization and other decompositions.

We have examined the ¹³C NMR spectra of mixtures of the H and D isotopomers at C_P of **6-Li** and **7-Li** in THF, 2,5-dimethyltetrahydrofuran, diethyl ether, and/or dimethyl ether at several temperatures. Both compounds show substantial equilibrium isotope shifts ($\Delta\delta_{D-H}$, defined as $\delta_D - \delta_H$)¹¹ under almost all conditions for C_A, C_C, and the CH₃ group. The resonance for C_C is the most sensitive because of the large chemical shift difference (approximately 80 ppm) between the A and P isomers but is sometimes rather broad. The isotope shifts for C_P are hard to measure because of the low sensitivity of the deuterated carbons (splitting, no Overhauser enhancement) and because at low temperatures deuterium quadrupolar relaxation is sufficiently fast that a well-resolved peak is not seen for the CD carbon. Some partial ¹³C NMR spectra and representative isotope shift data

(1) (a) Reich, H. J.; Holladay, J. E. *J. Am. Chem. Soc.* **1995**, *117*, 8470–8471. Reich, H. J.; Holladay, J. E.; Mason, J. D.; Sikorski, W. H. *J. Am. Chem. Soc.* **1995**, *117*, 12137–12150. (b) Reich, H. J.; Holladay, J. E.; Walker, T. G.; Thompson, J. L. *J. Am. Chem. Soc.* **1999**, *121*, 9769–9780. Reich, H. J.; Holladay, J. E. *Angew. Chem., Int. Ed.* **1996**, *35*, 2365–2367. (c) Reich, H. J.; Borst, J. P.; Dykstra, R. R.; Green, D. P. *J. Am. Chem. Soc.* **1993**, *115*, 8728–8741.

(2) Van Dongen, J. P. C. M.; van Dijkman, H. W. D.; de Bie, M. J. A. *Recl. Trav. Chim. Pays-Bas* **1974**, *93*, 29–32.

(3) Lambert, C.; Schleyer, P. v. R.; Würthwein, E.-U. *J. Org. Chem.* **1993**, *58*, 6377–6389.

(4) Several X-ray crystal structures of allenyl–propargyllithium reagents have shown dimeric structures, with lithium coordination to both C_A and C_P: (a) Schleyer, P. v. R. *Pure Appl. Chem.* **1984**, *56*, 151–162. (b) Setzer, W. N.; Schleyer, P. v. R. *Adv. Organomet. Chem.* **1985**, *24*, 353–451. (c) Dem'yanov, P.; Boche, G.; Marsch, M.; Harms, K.; Fyodorova, G.; Petrosyan, V. *Liebigs Ann.* **1995**, 457–460.

(5) (a) Dem'yanov, P. I.; Styrkov, I. M.; Krut'ko, D. P.; Vener, M. V.; Petrosyan, V. S. *J. Organomet. Chem.* **1992**, *438*, 265–88. Dem'yanov, P. I.; Krut'ko, D. P.; Borzov, M. V.; Luk'yanov, E. V.; Petrosyan, V. S. *Russ. Chem. Bull. (Engl. Transl.)* **1997**, *46*, 1939–1947. (b) Maercker, A.; Fischenich, J. *Tetrahedron* **1995**, *51*, 10209–10218.

(6) We make no distinction between contact ion pairs (CIPs) and “covalent” organolithium reagents and use the term simply to identify lithium reagents with a C–Li contact and distinguish such species from separated ion pairs (SIPs), where there is no C–Li contact.

(7) Siehl, H.-U. *Adv. Phys. Org. Chem.* **1987**, *23*, 63–163. This technique has been occasionally applied to problems in carbanion chemistry,⁸ especially to the structures of allylmetals.^{8a–d}

(8) (a) Schlosser, M.; Stähle, M. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 487–489. (b) Faller, J. W.; Murray, H. H.; Saunders: M. *J. Am. Chem. Soc.* **1980**, *102*, 2306–2309. (c) Equilibrating bridged structures have been proposed for allyllithium dimer: Winchester, W. R.; Bauer, W.; Schleyer, P. v. R. *J. Chem. Soc., Chem. Commun.* **1987**, 177–179.⁹ (d) Fraenkel, G.; Chow, A.; Winchester, W. R. *J. Am. Chem. Soc.* **1990**, *112*, 1382–1386. (e) Ahlberg, P.; Davidsson, Ö.; Löwendahl, M.; Hilmersson, G.; Karlsson, A.; Håkansson, M. *J. Am. Chem. Soc.* **1997**, *119*, 1745–1750. (f) Jonsäll, G.; Ahlberg, P. *J. Chem. Soc., Perkin Trans. 2* **1987**, 461–467.

(9) Allyllithiums can become substantially localized in nonpolar solvents or when chelation effects favor such structures: Fraenkel, G.; Martin, K. V. *J. Am. Chem. Soc.* **1995**, *117*, 10336–10344. Fraenkel, G.; Qiu, F. *J. Am. Chem. Soc.* **1997**, *119*, 3571–3579 and references therein.

(10) (a) For **7-Li** ¹J_{C–H} is 155 Hz in 3:2 THF–ether and 161 Hz in THF–ether–HMPA, where the compound is fully ion separated. For **5P-Li** ¹J_{C–H} at C_P is 155 Hz in the CIP and 175 Hz in the SIP.^{1a} (b) Comparison of ¹J_{C–H} values in allenyl and propargyl structures is difficult, since substituents have to be different, but ¹J_{C–H} at C_P in allenyllithium itself is 162 Hz,² somewhat larger than the value for **5P-Li** (155 Hz). Sulfur substitution increases ¹J_{C–H} (CH₄, 125 Hz; CH₃–S–CH₃, 137.9 Hz).

(11) Isotope shifts were typically measured at six to eight temperatures between –135 and 0 °C. As required for an isotope perturbation shift, all showed a substantial temperature dependence (e.g., $\Delta\delta_{D-H}$ for C_C in **6-Li** varied between 1376 ppb at –107 °C and 716 ppb at –1 °C in 4.8:3.2:1 THF–ether–pentane).

for the lithium reagents and the precursor **6P-H** are reported in Figures 1 and 2. As expected from the observation that

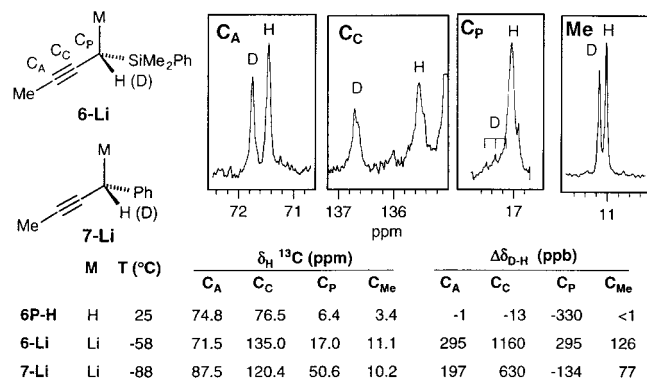


Figure 1. 90.56 MHz ^{13}C NMR spectra of a 1.2:1 mixture of **6-Li** and **6-Li-d** at -58°C in 3:2 THF–ether: chemical shifts (for the proton compound) and ^{13}C isotope shifts of H/D labeled **6-Li** and **7-Li** and the precursor **6P-H**.

the chemical shifts of each of the four carbons in the allenyl isomer are downfield of those in the propargyl isomer (see **4A-Li** and **5P-Li**), the deuterated compound gives the downfield signal for each carbon, in the opposite direction to the intrinsic isotope shifts.

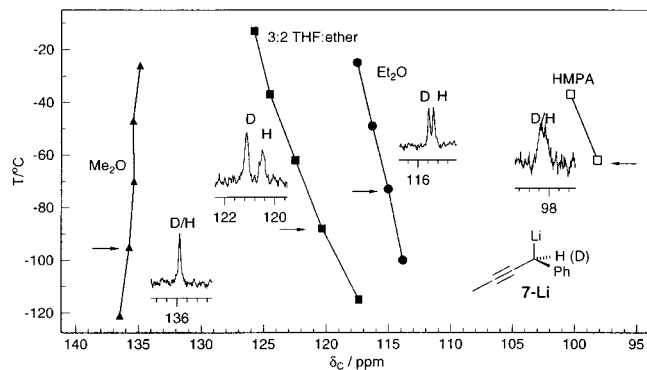


Figure 2. Temperature-dependent ^{13}C chemical shifts and 90.56 MHz ^{13}C NMR spectra illustrating the isotope perturbation shifts observed for C_C of **7-Li** in several solvents.

The detection of substantial isotope shifts rules out the static bridged structure **2** for **6-Li** under all conditions and for **7-Li** under all conditions except in dimethyl ether at low temperature. Before we can conclude that these are equilibrating mixtures of the **1A** and **1P** isomers, however, we have to consider the alternative of a CIP/SIP equilibrium. The most distinctive feature of a CIP⁶ is the observation of C–Li J coupling; unfortunately, no such coupling could be observed for either **6-Li** or **7-Li**¹² even at temperatures down to -155°C . However, **6-Li** can be firmly identified as a CIP in THF–ether mixtures (without a significant fraction

of SIP) by its NMR spectroscopic behavior during a low-temperature HMPA titration.^{1c,13}

An extensive spectroscopic study of a series of phenylated allenyl–propargyllithiums showed that many were at least partially SIPs in THF solution;^{4c,5} therefore, this is also a real possibility for **7-Li**. Although the HMPA titrations of **7-Li** in ether solvents were significantly different from those of fully separated ions, they lack some of the most distinct signatures of CIPs.¹⁴ Nevertheless, a CIP/SIP explanation for the observed isotope shifts can also be ruled out. It is implausible that **7-Li** would be partially ion separated over the range of solvent polarities (from pure ether to 60% THF/40% ether) and temperatures (from -151 to 14°C) over which isotope perturbations were observed. A more direct argument is that the direction of the isotope shift is wrong for an CIP/SIP explanation. The separated ion has the stronger C–H bond (as indicated by $J_{\text{C-H}}^{10}$); thus, deuterium substitution should favor the SIP over the CIP. *Since the ^{13}C chemical shift of C_C of the SIP (formed with excess HMPA) is upfield of that in the CIP (Figure 2), the signal for the deuterated isotopomer should be upfield of that for the protonated one, instead of downfield as is actually observed.*

This isotope perturbation experiment is more complicated than in most previous applications of the technique in organometallic chemistry⁸ because the equilibrium constant between the two species is infinitely variable. In another sense the interpretation is simpler since the most useful carbon is β to deuterium, where intrinsic isotope shifts are almost negligible. The magnitude of the isotope perturbation shift depends principally on three factors: (1) the chemical shift difference ($\Delta\delta$) between the two equilibrating species (ca 80 ppm for **1A/1P**), (2) the ratio of the two species at equilibrium ($\Delta\delta_{\text{D-H}}$ is maximum at a 1:1 ratio of isomers, corresponding to a δ value of ca. 140 ppm for C_C), and (3) the isotope effect on the free energy difference between the two species ($\Delta\Delta G_{\text{D-H}}^{14}$). Figure 3 shows in graphical form

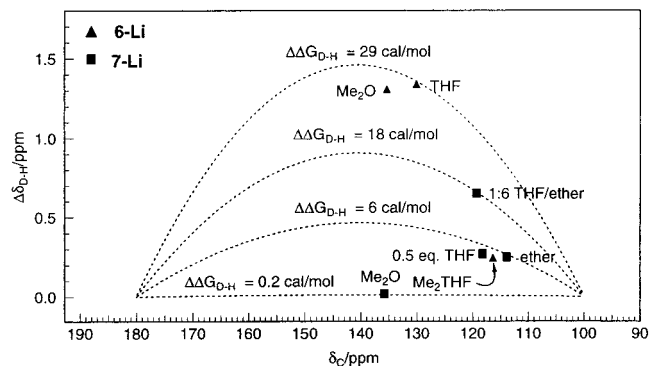


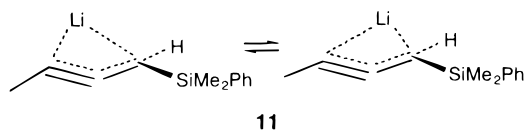
Figure 3. Isotope perturbation shifts for C_C in **6-Li** and **7-Li** in various solvents, $T = -90$ to -100°C . The dotted lines are calculated values for the $\Delta\Delta G_{\text{D-H}}$ values indicated, assuming a **1A/1P** equilibrium with $\delta_{1\text{P}}$ 100 ppm and $\delta_{1\text{A}}$ 180 ppm.

some of the observed shifts and the theoretical curves for $\Delta\Delta G_{D-H} = 0.2, 6, 18,$ and 29 cal/mol.

We can make an estimate for $\Delta\Delta G_{D-H}$ as follows. The observed $\Delta\delta_{D-H}$ value of 1.9 ppm for allylmagnesium bromide at 24 °C corresponds to a $\Delta\Delta G_{D-H} = 43$ cal/mol ($RT \ln(K)$), using an estimated difference of 70 ppm for the chemical shifts of C-1 and C-3.^{8a} Similarly, a $\Delta\Delta G_{D-H}$ value of 24 cal/mol can be calculated for the (trimethylstannyl)-cyclopentadiene system studied by Faller, Murray, and Saunders.^{8b} The bonding in both of these structures is likely to be localized.¹⁵ The highest $\Delta\delta_{D-H}$ value observed with the allenyl-propargyllithium reagents studied (1.4 ppm for **6-Li** in 3:2 THF/ether) corresponds to a $\Delta\Delta G_{D-H}$ value of 29 cal/mol, which is in the same range as the examples above and thus consistent with a largely localized pair of structures. A smaller value of $\Delta\Delta G_{D-H}$ is expected for a lithium than for a magnesium or stannyl reagent because of smaller degree of covalency in the C–Li bond. However, the wide variation in the $\Delta\delta_{D-H}$ values cannot be explained simply by the variability in the fraction of A and P isomers (ΔG_{A-P}) in the equilibrium mixture (see Figure 3). Thus, either the isotope effect $\Delta\Delta G_{D-H}$ and/or the chemical shifts of the two species in equilibrium must be changing as a function of solvent.

The isotope perturbation and other NMR data can be understood in terms of structures which range from essentially localized equilibrating A–P isomers (**6-Li** in dimethyl ether), to equilibrating mixtures of partially bridged

structures,^{8c} to fully bridged structures such as **2**.⁹ We propose a static bridged structure for **7-Li** in dimethyl ether, since under these conditions there is no detectable isotopic perturbation (<18 ppb), although δ is near the centroid of the chemical shift range where the largest $\Delta\delta_{D-H}$ values are expected. Other features of the NMR data are also supportive of a different structure for **7-Li** in dimethyl ether compared to either THF or diethyl ether. In dimethyl ether the chemical shifts of C_C have the opposite temperature dependence and are substantially more allenic in character than in either ether or THF, although dimethyl ether is between the two solvents in donor ability (Figure 2). Similarly, the isotope shifts for **6-Li** in 2,5-dimethyltetrahydrofuran are very small, suggesting equilibration between structures (**11**) with a substantial degree of bridging in this solvent. This reagent shows essentially temperature-independent shifts in 2,5-dimethyltetrahydrofuran but strongly temperature-dependent chemical shifts in dimethyl ether and THF, where the isotope shifts are also much larger (C_C changes by 30.7 ppm between -35 and -155 °C in dimethyl ether).^{1b}



(12) Although lithium–carbon coupling has only rarely been detected for benzyl (Fraenkel, G.; Duncan, J. H.; Martin, K.; Wang, J. H. *J. Am. Chem. Soc.* **1999**, *121*, 10538–10544) and allyllithiums,⁹ we had no difficulty in observing C–Li coupling in **4A-Li**. The coupling constant is comparable in size to that found for other allenyllithiums.^{1b}

(13) Some of the features that distinguish CIPs from SIPs during an HMPA titration are as follows. RLi species that are contact and do not undergo ion separation form at most $\text{RLi}(\text{HMPA})_2$ species even with excess HMPA. Species which are CIPs but undergo ion separation when HMPA is added will skip an HMPA coordination number on ion separation (e.g., they will go from $\text{RLi}(\text{HMPA})$ to mostly $\text{R}^-/\text{Li}^+(\text{HMPA})_3$). RLi species which are SIPs will show a characteristic progression from the mono- to the tetra-HMPA complex as HMPA is added.^{1c} There is an intermediate class of easily separated CIPs such as **7-Li**, where the differences are subtle and the distinction cannot be made easily.

(14) The value $\Delta\Delta G_{D-H}$ is defined by the amount that the A–P equilibrium constant is perturbed by replacing H with D at C_p. The curves in Figure 3 are drawn by assuming that this value is independent of the K_{eq} value between the A and P isomers. Thus: $K_{\text{eq-H}} = \exp(-\Delta G_{A-P}/RT)$, $K_{\text{eq-D}} = \exp(-(\Delta G_{A-P} + \Delta\Delta G_{D-H})/RT)$.

(15) Allylmagnesium chloride–TMEDA has a localized σ structure in the crystal: Marsch, M.; Harms, K.; Massa, W.; Boche, G. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 696–697.

It is not the specific solvent but the interplay between anion structure and lithium solvation that is important. For example, in dimethyl ether **7-Li** shows the smallest and **6-Li** one of the largest isotope shifts we found. It appears that minor differences in steric effects and solvation have a major influence on the extent to which the lithium is locally bonded to a single carbon (where maximum solvation is possible), bonded unsymmetrically to both carbons, or even bonded symmetrically.¹⁶ These results are consistent with the preference for bridged structures found in computational studies³ as well as the very low barrier to interconversion of the A and P isomers of **6-Li**.^{1b}

Acknowledgment. We thank the National Science Foundation for financial support of this work.

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(16) An interesting example where a lithium bonds in an η^3 fashion to indenyl anion when bis-coordinated to sparteine and in an η^1 fashion when tris-solvated by THF is provided by: Hoppe, I.; Marsch, M.; Harms, K.; Boche, G.; Hoppe, D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2158–2160.