Chiral Modular *n*-Butyllithium Aggregates: *n*BuLi Complexes with Anisyl Fencholates

Bernd Goldfuss,* Melanie Steigelmann, Frank Rominger, and Heiko Urtel[a]

Dedicated to Professor Dieter Hoppe on the occasion of his 60th birthday

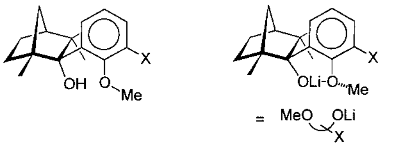
Abstract: Chiral, enantiopure aggregates are formed spontaneously by mixing solutions of *n*-butyllithium with anisyl fenchols. X-ray crystal analyses reveal the structures of these aggregates with different *ortho* substituents in the anisyl moieties (X), X = H (**1-H**), $SiMe_3$ (**2-H**), *t*Bu (**3-H**) $SiMe_2$(*t*Bu) (**4-H**) and Me (**5-H**). While the complex of **1-BuLi** shows a 3:1 composition, **2-BuLi**, **3-BuLi** and **4-BuLi** yield 2:2 stoichiometries. The aggregate **5-BuLi** crystallizes with a 2:4 composition and hence is a derivative of hexameric *n*-butyllithium, in which two *trans*-situated *n*BuLi molecules are substituted by lithium fencholate moieties. The variety in the synthesized chiral *n*BuLi aggregates demonstrates the high propensity of anisyl fencholates to chirally modify *n*BuLi. Variations in the modular ligand structures by alterations of the *ortho*-substituents (X) enable tunings of compositions and also of enantioselectivities in *n*BuLi additions to benzaldehyde.

Keywords: carbanions · chirality · enantioselectivity · lithium · structure elucidation

Introduction

n-Butyllithium (*n*BuLi) is among the most frequently employed organometallic reagents, and chiral modifications of *n*BuLi offer enormous potential in enantioselective syntheses.[1, 2] Suitable mediators are necessary for efficiently tuning reactivity and (enantio)selectivity of organolithium compounds.[3, 4] Structural investigations in solution[5] and in the solide state[1a, g, h, 6] yield precious information about the nature of chiral organolithium compounds[7] and hence provide the basis for a rational design of new reagents.[8] Although quite a few X-ray crystal analyses of achiral *n*BuLi complexes are known,[9] there is relatively little structural information on chirally modified *n*BuLi species. Williard et al. reported X-ray crystal structures of *n*-, *sec*- and *tert*-butyllithium complexes with lithium *N*-isopropyl-*O*-methylvalinolate.[6b] Additionally, the group of van Koten characterized a chiral, but racemic $(nBuLi)_2$ aggregate with lithiated 1-(dimethylamino)ethyl benzene.[6c] Organozinc fencholates[10] are efficient catalysts in diethylzinc additions to benzaldehyde and their modular structures help to explore origins of reactivities and enantioselectivities.[11] Lithium anisyl fencholates (e.g. **1-Li**, **2-Li**) exhibit a high propensity to form chiral aggregates with *n*-butyllithium.[12, 13]

Especially remarkable is the possibility to tune the binding modes, the stoichiometries and the enantioselectivities of these *n*BuLi aggregates through variation of *ortho* substituents (e.g. X = H (**1-H**), $SiMe_3$ (**2-H**)) in the anisyl moieties.[12] The unsubstituted anisyl fenchol system **1-H** (Scheme 1) reacts with *n*-butyllithium to form the aggregate **1-BuLi** (Figure 1), which exhibits a *n*BuLi:fencholate ratio of 1:3. In contrast to **1-H**, the $SiMe_3$-substituted anisyl fenchol **2-H** (Scheme 1) generates complex **2-BuLi** (Figure 2) with a 2:2 stoichiometry, agostic Li-CH_2(β) interactions and increased enantioselectivity in butylation reactions with benzaldehyde (80% *ee* for **2-BuLi**, 46% *ee* for **1-BuLi**; Scheme 2).[12]



X = H	**1-H**	**1-Li**
X = $SiMe_3$	**2-H**	**2-Li**
X = *t*Bu	**3-H**	**3-Li**
X = Si(*t*Bu)Me_2	**4-H**	**4-Li**
X = Me	**5-H**	**5-Li**

Scheme 1. Anisyl fenchols and lithium fencholates.

We demonstrate here that, in addition to **1-H** (X = H) and **2-H** (X = $SiMe_3$), lithium derivatives of the anisyl fenchols **3-H** (X = *t*Bu), **4-H** (X = Si*t*BuMe_2), and **5-H** (X = Me) are able to aggregate and chirally modify *n*-butyllithium over a broad

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[+] X-ray analyses.

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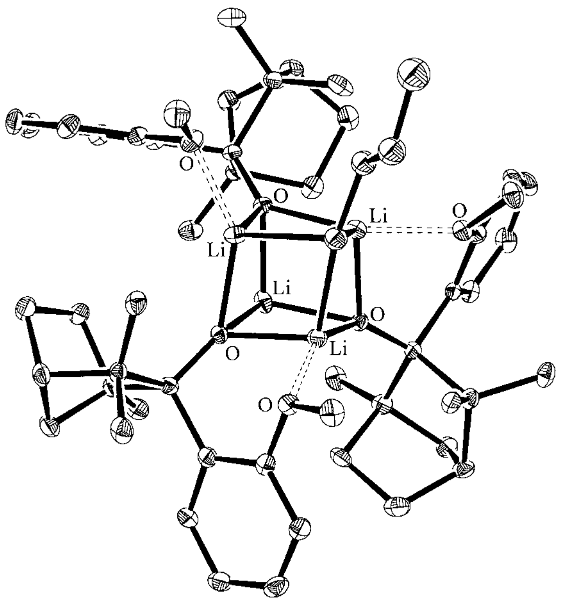


Figure 1. X-ray crystal structure of **1-BuLi** (X = H). Hydrogen atoms are omitted for clarity, the probability of the thermal elipsoids is 50%.

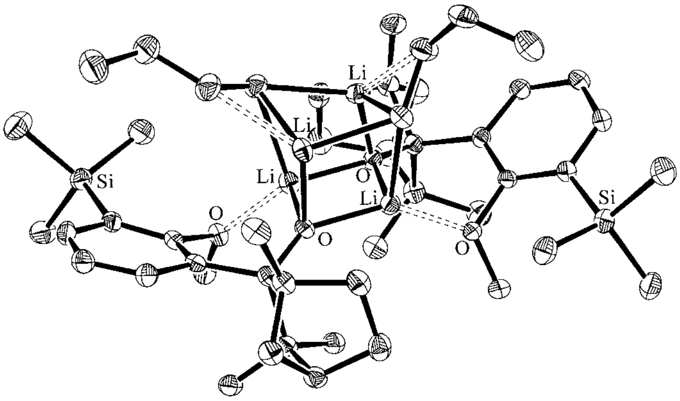


Figure 2. X-ray crystal structure of **2-BuLi** (X = $SiMe_3$). Hydrogen atoms are omitted for clarity, the probability of the thermal elipsoids is 50%.

range of *ortho* substituents (X). X-ray crystal analyses of the *n*BuLi anisyl fencholate aggregates show 2:2 ratios for **3-BuLi** and **4-BuLi** and, for **4-BuLi**, a hitherto unprecedented 2:4 composition (Scheme 2).

Results and Discussion

Reactions of the fenchols **1-H** or **2-H** with *n*-butyllithium in hexanes yield the *n*-butyllithium complex **1-BuLi**[12a] (Figure 1) or **2-BuLi** (Figure 2).[12b] Analogously, the fenchols **3-H**, **4-H**, and **5-H** form colorless precipitates in mixtures of *n*-butyllithium solutions in hexanes. Again, the pure lithium fencholates (**3-Li**, **4-Li**, **5-Li**) are not formed, but the lithium alcoholates generated in situ aggregate with *n*BuLi and form crystalline solids. Single crystal analyses yield the X-ray structures of the *n*-butyllithium lithium anisyl fencholate complexes **3-BuLi** (Figure 3), **4-BuLi** (Figure 4), and **5-BuLi** (Figure 5).

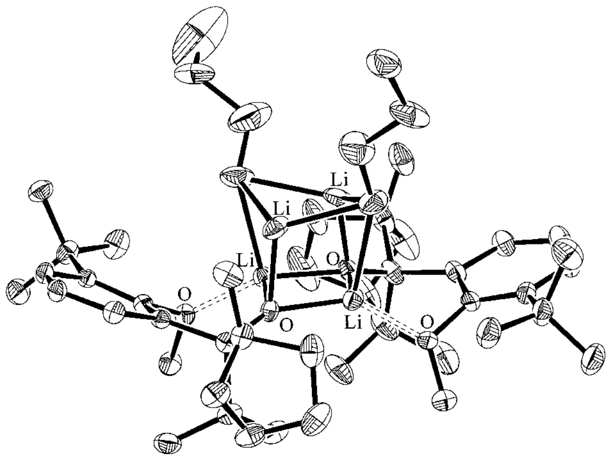


Figure 3. X-ray crystal structure of **3-BuLi** (X = *t*Bu). Hydrogen atoms are omitted for clarity, the probability of the thermal elipsoids is 50%.

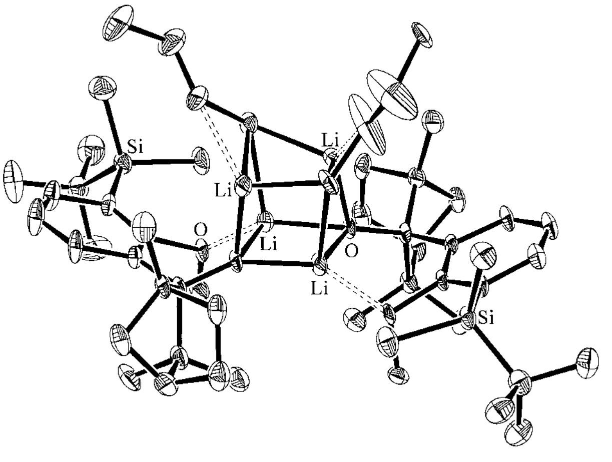
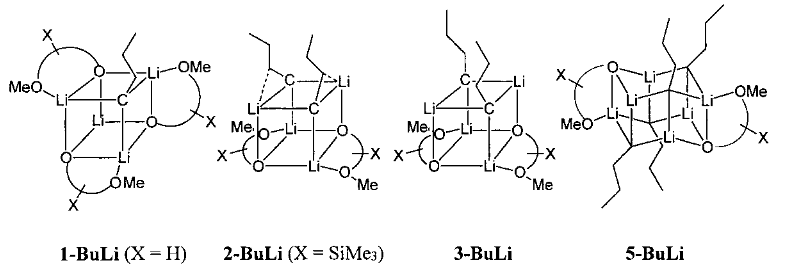


Figure 4. X-ray crystal structure of **4-BuLi** (X = Si*t*BuMe$_2$). Hydrogen atoms are omitted for clarity, the probability of the thermal elipsoids is 50%.

In **3-BuLi**, two *n*BuLi molecules and two lithium fencholate units (**3-Li**) form a distorted $Li_4C_2O_2$ cube (Figure 3). The structure of **3-BuLi** with a *t*Bu substituent (X) is similar to that of **2-BuLi** (Figure 2) with a $SiMe_3$ *ortho* substituent.[12b] However, the orientations of the *n*-butylide groups differ in **2-BuLi** and **3-BuLi**: In **2-BuLi**, *n*Bu-bridged C–Li edges are situated directly over lithium and oxygen atoms, which originate from the *same* lithium



1-BuLi (X = H) **2-BuLi** (X = $SiMe_3$) **4-BuLi** (X = Si*t*BuMe$_2$) **3-BuLi** (X = *t*Bu) **5-BuLi** (X = Me)

Scheme 2. *n*-Butyllithium anisyl fencholate aggregates.

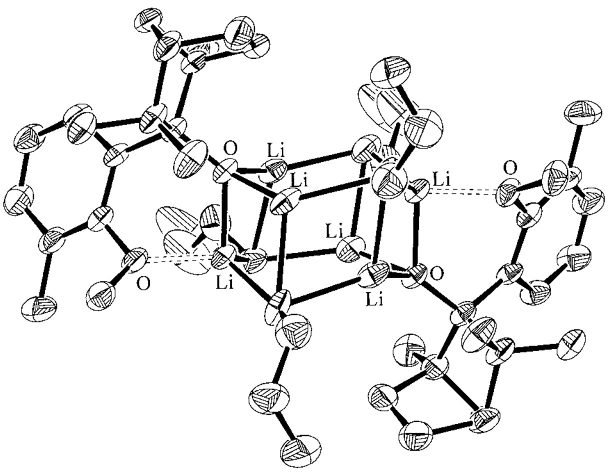


Figure 5. X-ray crystal structure of **5-BuLi** (X = Me). Hydrogen atoms are omitted for clarity, the probability of the thermal elipsoids is 50%.

fencholate fragment (**2-Li**). In contrast, analogous *n*Bu-bridged Li–C edges in **3-BuLi** are aligned over Li and O atoms, which belong to *different* lithium fencholate units (**3-Li**; Scheme 2).

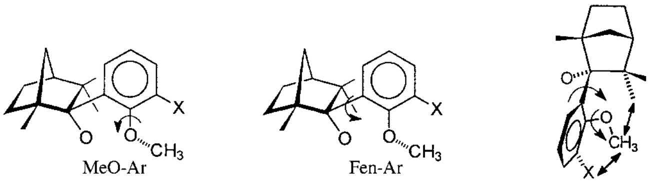
Aggregate **4-BuLi** (Figure 4) also composes of two *n*BuLi molecules and two lithium fencholates **4-Li**. The orientations of the *n*-butylide groups in **4-BuLi** are very similar to those in **2-BuLi**. The *t*Bu moieties at the silicon atoms in **4-Bu** point away from the (*n*BuLi)$_2$ unit, while the SiMe$_2$ groups generate a similar environment at the $C_2O_2Li_4$ core as the SiMe$_3$ groups in **2-BuLi** (Figure 2).

In the X-ray crystal structure of **5-BuLi**, four *n*BuLi molecules and two lithium fencholate units (**5-Li**) form a $Li_6C_4O_2$ core, which assembles from two stacked Li_3C_2O rings (Figure 5).[14] Hence, **5-BuLi** can be regarded as a "hetero-analogous" derivative of hexameric *n*-butyllithium, (*n*BuLi)$_6$:[15] in the (*n*BuLi)$_6$ aggregate two *trans*-situated *n*BuLi units are replaced by lithium fencholate moieties (**5-Li**) to form **5-BuLi** (Figure 5).

The appearance of (*n*BuLi)$_2$ subunits in the 2:2 aggregates of **2-BuLi**, **3-BuLi**, and **4-BuLi** corresponds to the relatively frequent formation of (*n*BuLi)$_2$ moieties in *n*BuLi complexes.[6c, 9a–c] The Li–C(α) distances in these (*n*BuLi)$_2$ lithium fencholates show a clear geometrical differentiation of (*n*BuLi)$_2$ subunits relative to the rest of the cubic $Li_4O_2C_2$ cores: the Li–C(α) distances are significantly shorter within the (*n*BuLi)$_2$ moieties (mean values: **2-BuLi**: 2.17 Å; **3-BuLi**: 2.20 Å; **4-BuLi**: 2.18 Å) than in contacts between (*n*BuLi)$_2$ and the lithium alkoxide units (mean values: **2-BuLi**: 2.45 Å; **3-BuLi**: 2.45 Å; **4-BuLi** 2.38 Å, Table 1). Much more uniform Li–C(α) distances are apparent in the cubic Li_4O_3C core of **1-BuLi** (Table 1). Slightly longer Li–C(α) distances are found in **5-BuLi** for contacts connecting the two stacked six-membered Li_3OC_2 rings (mean value: 2.26 Å) than for Li–C(α) contacts within the Li_3OC_2 rings (mean values: 2.19 Å and 2.21 Å).[16]

No agostic[17] Li-β-CH$_2$ interactions are possible in **1-BuLi**, because lithium ions neighbored to the butylide group are fourfold coordinated by contacts to the anisyl methoxy groups (Figure 1). In **2-BuLi**, threefold coordinated lithium ions are able to form agostic interactions with the butylide moieties (Figure 2). This is apparent from short distances between the lithium centers and β-CH$_2$ units (Li–C(β): 2.36 and 2.38 Å, Table 1).[12b] Despite the similar structure of **3-BuLi**, analogous Li–C(β) interactions are less pronounced (Li–C(β): 2.71 and 2.65 Å, Figure 3).[18] In **4-BuLi**, however, agostic interactions are again clearly apparent from short Li–C distances (Li–C(β): 2.36 Å and 2.37 Å). The hetero-hexameric structure of **5-BuLi** exhibits no such short Li–C(β) contacts (2.59 Å, 2.82 Å, Table 1, Figure 5).

The intrinsic steric influence of the *ortho* substituents (X) on the geometries of the ligand systems is apparent from two geometrical distortions: the bending of the methoxy groups out of the plane of the benzene rings (MeO–Ar dihedral angle, Scheme 3) and the torsion angles of the aryl moieties relative to the fenchane fragment (Fen–Ar dihedral angle, Scheme 3).



Scheme 3. Methoxy–aryl (MeO-Ar) and fenchyl–aryl (Fen-Ar) dihedral angles; steric repulsions (↔) between X, OMe, and *endo*-Me are shown.

These intrinsic steric effects of X are clearly apparent in X-ray crystal structures of fenchols **1** to **5**. With increasing steric demand of the substituents X, the bending of the methoxy groups out of the aryl planes (MeO–Ar dihedral angle) increases in the order X = H (–3.0°) < Me (–60.8°) < SiMe$_3$ (–72.4°) < *t*Bu (–82.6°)[19] < Si*t*BuMe$_2$ (–93.5°) (Table 1). The out-of-benzene-ring-plane bending of the

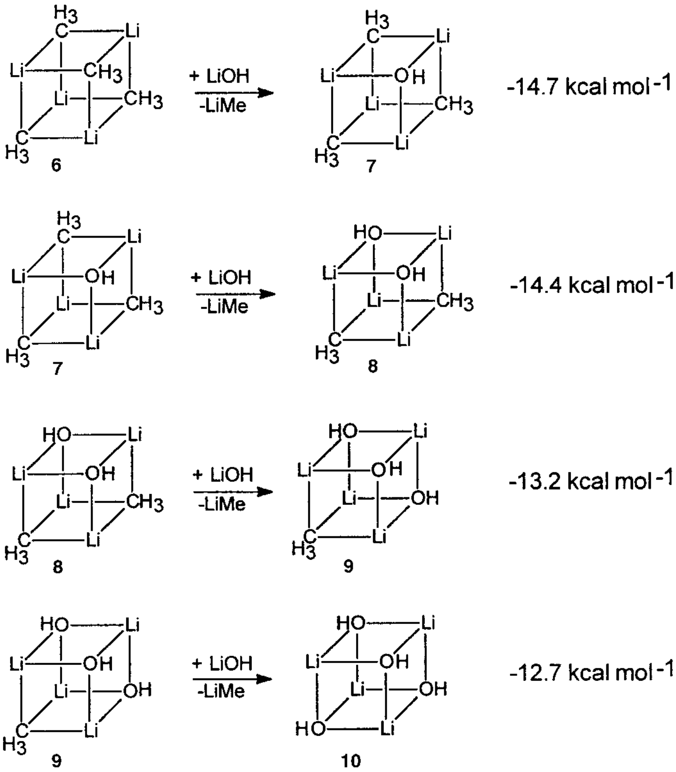
Table 1. Distances [Å] and angles [°] in the X-ray crystal structures of *n*BuLi lithium fencholate complexes and (in parentheses) of the parent fenchols.

	1-BuLi (1-H)	**2-BuLi (2-H)**	**3-BuLi (3-H)**	**4-BuLi (4-H)**	**5-BuLi [a] (5-H)**
Li–C(α)	2.195, 2.221, 2.225	2.173, 2.192, 2.450 2.157, 2.172, 2.446	2.181, 2.207, 2.478, 2.129, 2.280, 2.430	2.175, 2.180, 2.365, 2.157, 2.193, 2.396	2.200, 2.210, 2.291, 2.189, 2.211, 2.227
Li–C(β)	–	2.359, 2.381	2.653, 2.705	2.356, 2.371	2.593, 2.820
Li–O(Me)	1.982, 1.987, 2.025	1.974, 1.947	1.929, 1.955	1.950, 1.945	1.933
MeO–Ar angle[b]	–19.4, –19.7, –32.6 (–3.0)[c]	–63.4, –63.7 (–72.4)	–76.1, –75.1 (–82.6)	–70.2, –67.2 (–93.5)[d]	–62.8 (–60.8)
Fen–Ar angle[b]	51.2, 49.5, 46.6 (47.2)[c]	40.3, 43.6 (33.4)	36.2, 40.5 (30.3)	38.7, 39.2 (12.1)[d]	42.9 (42.4)

[a] Crystallographic C_2 symmetry. [b] Methoxy–aryl (MeO-Ar) and fenchyl–aryl (Fen-Ar) dihedral angles (Scheme 3). [c] Mean value of four independent molecules. [d] Disordered.

anisyl methoxy groups leads to repulsive interactions between methoxy and *endo*-methyl groups of the fenchane moieties (Scheme 3). Minimization of this repulsion gives rise to rotation around the fenchyl-aryl bond (*Fen-Ar*). Indeed, the Fen–Ar dihedral angle decreases as the MeO–Ar dihedral angle increases: X = H (47.2°) > Me (42.4°) > $SiMe_3$ (33.4°) > *t*Bu (30.3°)[19] > Si*t*BuMe_2 (12.1°) (Table 1). Hence, the steric demand of X indirectly determines the geometry of the chelating O⌒O unit of the anisyl fenchols and, for bulky substituents X, forces an increasingly coplanar arrangement of the O⌒O moiety (Scheme 3). In the *n*BuLi complexes, a similar increase in the mean value of the MeO–Aryl dihedral angles and a decrease in the mean Fen–Ar angles, respectively, is apparent from the order **1-BuLi** (23.9°, 50.4°), **5-BuLi** (62.8°, 42.9°), **2-BuLi** (63.6°, 43.5°), **4-BuLi** (68.7°, 39.0°), **3-BuLi** (75.6°, 38.4°) (Table 1).

The intrinsic driving force for the incorporation of LiOR moieties in Li_4C_4 clusters and the formation of mixed-anionic aggregates, like the lithium butylide fencholates, is evaluated computationally from the equations in Scheme 4 (Table 2).



Scheme 4. LiMe/LiOH replacement energies for cubic $Li_4O_nC_m$ ($n = 0, 1, 2, 3, 4$; $m = 4 - n$) aggregates (Table 2).

Table 2. Total (a. u. + ZPE)[a] and relative [kcal mol^{-1}][b] B3LYP/6–31 + G* energies of $Li_4O_nC_m$ aggregates ($n = 0, 1, 2, 3, 4$, $m = 4 - n$) (Scheme 4).

	6	7	8	9	10
total	– 189.67513	– 225.69679	– 261.71801	– 297.73723	– 333.75580
relative	0.0	– 14.7	– 29.1	– 42.3	– 55.0

[a] All equilibrium structures were optimized in C_1 symmetry, unscaled zero point energies are included. [b] The relative energies consider LiOH (a. u. + ZPE: – 83.36976) and LiMe (a. u. + ZPE: – 47.37150), according to Scheme 4.

The replacement of organolithium groups (i.e. LiMe) by LiOH units (as a model for lithium alkoxides) is favored for all cubic $Li_4O_nC_m$ aggregates ($n = 0, 1, 2, 3, 4$; $m = 4 - n$). The high degree of oxido moieties in the aggregates is supported electrostatically,[20] and cubic Li_4O_4 clusters are therefore intrinsically the most favorable (Scheme 4).

Inter-ligand repulsions between $SiMe_3$ groups and *endo*-methyl groups of the fenchane moieties were found to be responsible for the instability of a hypothetical 3:1 aggregate for X = $SiMe_3$, which preferentially forms the 2:2 complex (**2-BuLi**, Figure 2).[12b] The 3:1 composition, however, is more suitable for X = H in **1-BuLi** (Figure 1).[12a] This suggests that the steric demand of the bulky anisyl fenchane moiety prevents the formation of pure lithium fencholates, which should be favorable according to the equations in Scheme 4,[21] and stimulates instead the incorporation of the smaller *n*BuLi fragments to form the mixed *n*BuLi lithium fencholate aggregates.

The relative stabilities of mixed lithium fencholate *n*BuLi aggregates with 3:1 and 2:2 compositions are evaluated computationally by the aggregate formation energies for different *ortho* substituents X in Schemes 5 and 6 (Table 3).

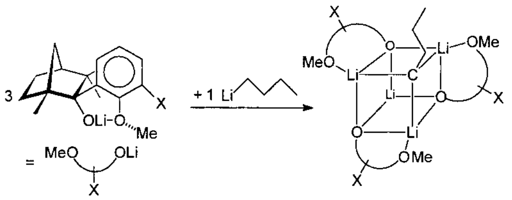
According to the higher intrinsic stability of the cubic Li_4O_3C core (Scheme 4) and due to the small steric demand of X = H, lithium fencholate **1-Li** and *n*BuLi preferentially form the 3:1 aggregate **1-BuLi-cmp**, cmp = denotes computed to differentiate from X-ray structures with 173 kcal mol^{-1} (Scheme 5), as the complex stabilization energy for the 2:2 species **1-(2:2)** is smaller (169 kcal mol^{-1}, Scheme 6).[22] This explains the experimental composition of the X-ray crystal structure **1-BuLi** (Figure 1), which corresponds to the computed **1-BuLi-cmp** structure.

In contrast to X = H, the bulky *ortho* substituents (X) *t*Bu, $SiMe_3$, or Si*t*BuMe_2 favor the formation of 2:2 aggregates (Scheme 6) over the 3:1 compositions (Scheme 5). Steric effects of the ligands obviously overcompensate the higher stability of the cubic Li_4O_3C cores versus the $Li_4O_2C_2$ arrangements (Scheme 4). While only two ligands surround the $Li_4O_2C_2$ core in 2:2 aggregates, three bulky fencholates

Table 3. Total (a. u. + ZPE)[a] and relative [kcal mol^{-1}][b] B3LYP/6–31G*//ONIOM(B3LYP(6–31 + G*): UFF energies for aggregate formation (Scheme 3 and 4).

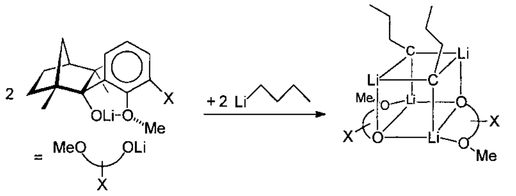
Li fencholate	a. u.	*n*BuLi aggregates 3:1	a. u./stability [kcal mol^{-1}]	*n*BuLi aggregates 2:2	a. u./stability [kcal mol^{-1}]
1-Li	– 819.60607	**1-BuLi-cmp**	– 2624.42572/ – 172.7	**1-(2:2)**	– 197.14538/ – 168.6
2-Li	– 1228.27372	**2-(3:1)**	– 3850.37232/ – 137.4	**2-BuLi-cmp**	– 2787.45500/ – 152.5
3-Li	– 976.83801	**3-(3:1)**	– 3096.06385/ – 136.5	**3-BuLi-cmp**	– 2284.57385/ – 146.4
4-Li	– 1346.19695	**4-(3:1)**	– 4204.16198/ – 149.9	**4-BuLi-cmp**	– 3023.30591/ – 155.3
5-Li	– 858.91680	**5-(3:1)**	– 2742.33259/ – 156.8	**5-(2:2)**	– 2048.74765/ – 156.4

[a] All equilibrium structures were optimized in C_1 symmetry and characterized as minima by frequency computations (ONIOM), zero point energies are not considered for the B3LYP/6–31G* single-point energies. [b] Evaluated with *n*-butyllithium, a. u.: – 165.33228.



			Stability (kcal mol^{-1})
X = H	**1-Li**	**1-BuLi-cmp**	-173 ←
X = SiMe$_3$	**2-Li**	**2-(3:1)**	-137
X = *t*Bu	**3-Li**	**3-(3:1)**	-137
X = Si*t*BuMe$_2$	**4-Li**	**4-(3:1)**	-150
X = Me	**5-Li**	**5-(3:1)**	-157

Scheme 5. Formation and stabilities of mixed lithium fencholate *n*BuLi aggregates with 3:1 compositions (B3LYP/6-31G*//ONIOM(B3LYP/6-31+G*:UFF, Table 3). The favored structure, relative to 2:2 aggregates (see Scheme 6), is highlighted (←).



			Stability (kcal mol^{-1})
X = H	**1-Li**	**1-(2:2)**	-169
X = SiMe$_3$	**2-Li**	**2-BuLi-cmp**	-152 ←
X = *t*Bu	**3-Li**	**3-BuLi-cmp**	-146 ←
X = Si*t*BuMe$_2$	**4-Li**	**4-BuLi-cmp**	-155 ←
X = Me	**5-Li**	**5-(2:2)**	-156

Scheme 6. Formation of mixed *n*BuLi lithium fencholate aggregates with 2:2 compositions (B3LYP/6-31G*//ONIOM(B3LYP/6-31+G*:UFF, Table 3). The favored structures, relative to 3:1 aggregates (see Scheme 5), are highlighted (←).

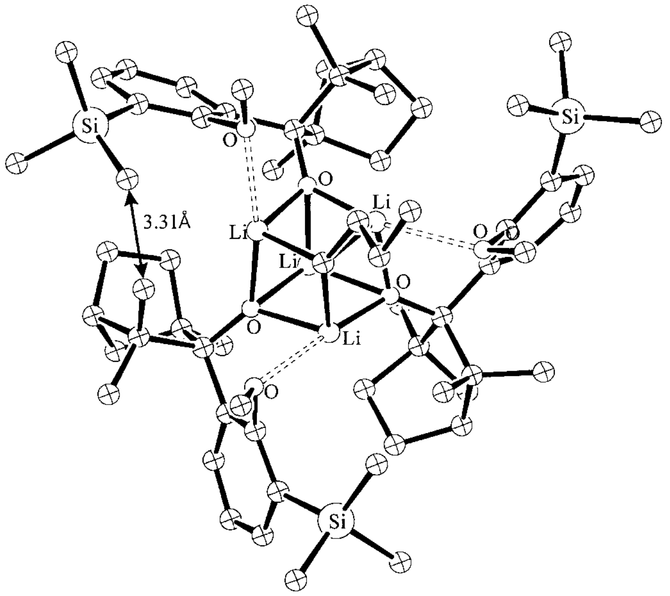


Figure 6. ONIOM (B3LYP/6-31+G*:UFF)-optimized structure of **2-(3:1)** (X = SiMe$_3$). Hydrogen atoms are omitted for clarity. The shortest inter-ligand C–C distances are shown.

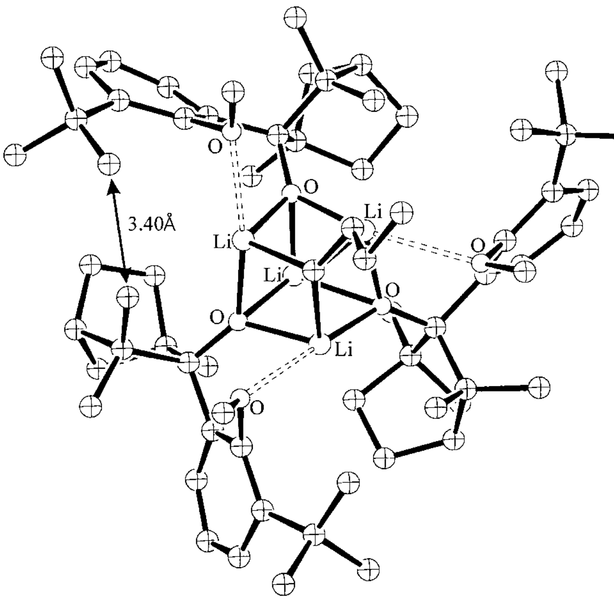


Figure 7. ONIOM (B3LYP/6-31+G*:UFF)-optimized structure of **3-(3:1)** (X = *t*Bu). Hydrogen atoms are omitted for clarity. The shortest inter-ligand C–C distances are shown.

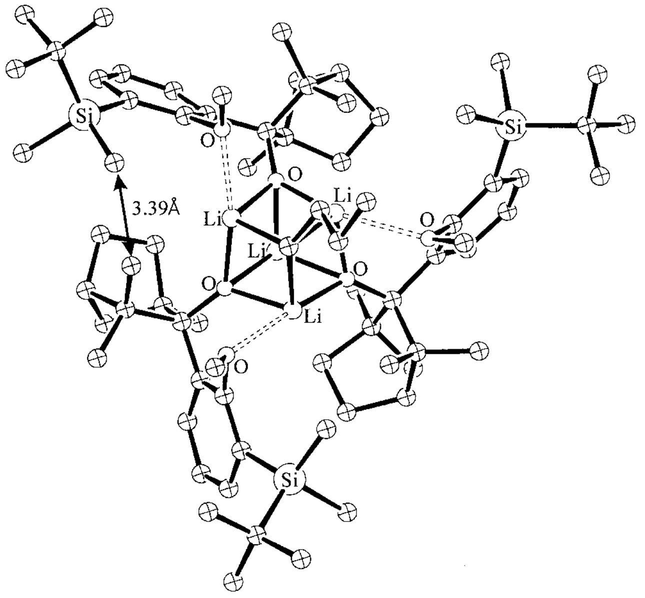


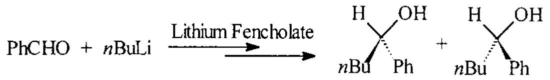
Figure 8. ONIOM (B3LYP/6-31+G*:UFF)-optimized structure of **4-(3:1)** (X = Si*t*BuMe$_2$). Hydrogen atoms are omitted for clarity. The shortest inter-ligand C–C distances are shown.

have to be arranged at the Li_4O_3C cubes in 3:1 complexes. The computed structures **2-(3:1)** (Figure 6), **3-(3:1)** (Figure 7), and **4-(3:1)** (Figure 8) exhibit analogous geometries to **1-BuLi** (Figure 1), but close inter-ligand distances appear between X substituents and *endo*-methyl groups of the fenchane moieties. This may account for the decreased stabilities of 3:1 arrangements relative to the 2:2 aggregates (Scheme 5) and agrees with the experimental formation of the structures **2-BuLi**, **3-BuLi**, and **4-BuLi**.[23]

For X = Me, very similar complex formation energies of 3:1 and 2:2 aggregates (Scheme 5 and Scheme 6) show that both developments are possible. Surprisingly, neither of them is formed experimentally but the 2:4 composition is observed instead in the X-ray crystal structure of aggregate **5-BuLi**.[14]

0947-6539/01/0720-4460 $ 17.50+.50/0

Enantioselective additions of *n*-butyllithium to benzaldehyde can be achieved with mixtures of *n*BuLi and the lithium fencholates **1-Li** to **5-Li** (Scheme 7), which form in situ after mixing an excess of *n*BuLi with the fenchols **1-H** to **5-H**.[24]



Scheme 7. Enantioselective *n*BuLi additions to benzaldehyde, mediated by lithium fencholates, yielding (*R*)-1-phenyl-1-pentanol as the major enantiomer (Table 4).

Increased ratios of lithium fencholates (i.e. 3:1 vs. 1:1) in mixtures with *n*BuLi give rise to increased enantioselectivities in reactions with benzaldehyde for the fencholates **1-Li** to **4-Li**. (Table 4). This suggests that higher enantioselectivities can be achieved with suppressed amounts of "free" *n*BuLi.[24] For both 3:1 and 1:1 ratios of lithium fencholates : *n*BuLi, enantioselectivities increase with the bulkiness of the substituent X in the order H < Me < *t*Bu < $SiMe_3$, but are lower again for Si*t*$BuMe_2$, indicating the best auxiliary structure for **2-Li** amongst the studied fencholates (Table 4).

Table 4. *n*-Butyllithium additions to benzaldehyde with lithium fencholate:*n*BuLi ratios of 1:1 and 3:1 (Scheme 7).[a]

1:1 ratio	X	% *ee*[b]	Yield[c]	3:1 ratio	X	% *ee*[b]	Yield[c]
1-Li	H	8	73	**1-Li**	H	14	30
2-Li	$SiMe_3$	66	86	**2-Li**	$SiMe_3$	76	99
3-Li	*t*Bu	55	81	**3-Li**	*t*Bu	62	99
4-Li	Si*t*$BuMe_2$	51	84	**4-Li**	Si*t*$BuMe_2$	56	99
5-Li	Me	24	76	**5-Li**	Me	28	92

[a] All reactions were performed by mixing fenchols and *n*BuLi in hexane solution, yielding the given lithium fencholate:*n*BuLi ratios. Benzaldehyde was added at −78 °C, see Experimental Section. [b] Enantioselectivities were determined by HPLC analyses, DAICEL OB-H, isopropanol:hexane = 0.8:99.2. [c] Yields were obtained by GC with hexadecane as internal standard.

^7Li NMR studies in [D_8]toluene show two different lithium ion environments for each of the lithium fencholate *n*-butyllithium aggregates **1-BuLi**, **2-BuLi**, **3-BuLi**, **4-BuLi** and **5-BuLi**. $^1H-^7Li$ COSY experiments reveal that one of the chemically different lithium ions is coordinated by methoxy groups, whilst the other lithium center exhibits no OMe coordination. This suggests that in nonpolar hydrocarbon solvents (e.g. toluene) similar structures to those in the solid state exist (Figures 1–5) and might also be involved in the enantioselective *n*BuLi transfer reactions.[25]

Conclusion

Anisyl fencholates with different substituents (X) in *ortho*-positions of aryl groups all form mixed aggregates with *n*-butyllithium in nonpolar solvents (i.e. hexanes, toluene). X-ray crystal structures of the lithium fencholate *n*BuLi complexes reveal 3:1 (X = H), 2:2 (X = *t*Bu, $SiMe_3$, Si*t*$BuMe_2$) and 4:2 (X = Me) compositions. Computational studies show that the formations of mixed aggregates with cubic cores originate from two competing effects: a) the tendency to form aggregates with high degrees of alkoxido units in the cubic cores, and b) inter-ligand repulsions, which prevent the incorporation of too many bulky alkoxido moieties. To complete the cubic core structures, smaller *n*-butyllithium units are incorporated, yielding the mixed aggregates. Effects like methoxy group coordination or solvation phenomena might also be crucial for the origin of the aggregates: a fenchol with CH_2NMe_2 instead of the OMe donor group yields no *n*BuLi complex[26] and the anisyl fenchol with X = Me yields a 4:2 aggregate. Enantioselectivities in *n*BuLi additions to benzaldehyde show that the chiral modular lithium fencholates are suitable mediators for enantioselective C–C bond formations. This points to further applications of these enantiopure mixed-anionic organolithium aggregates in organic syntheses.

Experimental Section

General: The reactions were carried out under an argon atmosphere (Schlenk and needle-septum techniques) with dried and degassed solvents. X-ray crystal analyses were performed on a Bruker Smart CCD diffractometer with $Mo_{K\alpha}$ radiation. NMR spectra were recorded on a Bruker AC300 and DRX500 (^1H, ^{13}C chemical shifts referenced to [D_8]toluene, ^7Li to LiBr), IR spectra on a Bruker Equinox 55 FT-IR spectrometer, and optical rotations on a Perkin Elmer P241 machine. GC analyses were carried out on a Chrompack (CP9001).

Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication nos. CCDC-148412 (**3-H**), CCDC-159905 (**4-H**), CCDC-148411 (**5-H**), CCDC-148414 (**3-BuLi**), CCDC-159906 (**4-BuLi**), and CCDC-148413 (**5-BuLi**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

Enantioselective reactions - general procedure: A solution of *n*-butyllithium (4 or 2 mmol for 3:1 or 1:1 ratios, respectively) in hexane (1.60 M) was added at room temperature to fenchol (3 (3:1 ratio) or 1 (1:1 ratio) mmol). After stirring the mixture for 20 min at −78 °C, benzaldehyde (1 mmol) was added. The reaction mixture was kept for 30 min at −78 °C and then warmed to room temperature (over 2 h). Hydrolytic workup, separation of the layers, drying over Na_2SO_4, and column chromatographic purification (silica gel, petroleum ether:ethylacetate (9:1)) yielded (*R*)-1-phenyl-1-pentanol as the major product (Table 4). Enantioselectivities were determined by HPLC analyses, DAICEL OB-H, isopropanol:hexane 0.8:99.2. Yields were obtained from GC with hexadecane as the internal standard.

Synthesis and characterization of 3-H: 2-*tert*-Butylanisol[27] (12.4 g, 0.076 mol) was added at 0 °C to a mixture of *n*-butyllithium (50.3 mL, 0.08 mol, 1.60 M solution in hexane) and TMEDA (12.1 mL, 0.08 mol). A colorless precipitate formed after 12 h stirring at room temperature. (−)-Fenchone (12.2 mL, 0.076 mol) was slowly added at 0 °C to this suspension, and the mixture was stirred for two days at room temperature. Hydrolytic workup, drying and concentration of the organic layer and recrystallization from pentane yielded colorless **3-H** (10.78 g, 0.034 mol, 45 %): m.p. 76 °C; elemental analysis (%): calcd: C 79.70, H 10.19, O 10.11; found C 79.64, H 10.22, O 10.14. ^1H NMR (300 MHz, $CDCl_3$, RT); $\delta = 0.54$ (s, 3 H), 1.06 (s, 3 H), 1.10 (m, 1 H), 1.13 (s, 3 H), 1.28 (m, 1 H), 1.39 (s, 9 H), 1.47 (m, 1 H), 1.74 (m, 2 H), 2.28 (m, 1 H), 2.40 (m, 1 H), 3.75 (s, 3 H), 6.01 (s, 1 H), 6.95 ("t", $J = 7.9$ Hz, 1 H) 7.22 (d, $J = 7.8$ Hz, 1 H), 7.39 (d, $J = 8.0$ Hz, 1 H); ^{13}C NMR (75.5 MHz, $CDCl_3$, RT) $\delta = 17.9$, 21.8, 23.6, 29.4, 31.9, 33.5, 35.6, 41.8, 46.5, 49.4, 54.3, 65.3, 86.7, 121.7, 126.6, 128.7, 136.3, 142.9, 158.9; MS(EI): m/z: 316.0 [M^+], 233.0 [$M^+ - C_6H_{11}$], 191.0 [$M^+ - C_9H_{17}$]; IR (KBr): $\tilde{\nu} = 3457$ (OH, s), 3074–3002 (aryl, w), 2967–2925 (alkyl, m), 1383, 1362 cm^{-1} (*t*Bu, m); $[\alpha]^{21}_{Na}$ (hexane) = −99.6; X-ray analysis of **3-H**:

SHELXTL V5.10, $C_{21}H_{32}O_2$, $M_r = 316.47$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, monoclinic crystal system, space group: $P2_1$, $Z = 2$, $a = 7.6760(2)$, $b = 10.9920(3)$, $c = 10.8986(3)$ Å, $\beta = 97.778(1)$, $V = 911.10(4)$ Å^3, $\rho_{calcd} = 1.154$ g cm^{-3}, collected reflections: 9426, independent reflections: 4147, observed reflections: 2650 ($I > 2\sigma(I)$), absorption coefficient μ: 0.072 mm^{-1}, Flack parameter: 0.5(16), R values ($I > 2\sigma(I)$): $R1 = 0.054$, $wR2 = 0.101$, largest difference peak and hole: 0.14, -0.19 e Å^{-3}; goodness-of-fit: 1.03.

Synthesis and characterization of 4-H: Anisol (10.8 g, 0.10 mol) was added at 0 °C to a mixture of *n*-butyllithium (68.8 mL, 0.11 mol, 1.60 M solution in hexane) and TMEDA (16.6 mL, 0.11 mol). A colorless precipitate of 2-lithioanisol formed after stirring for a few minutes. After 3 h, *tert*-butyldimethylsilyl chloride (15.1 g, 0.10 mol) in hexane (10 mL) was added at 0 °C. After the mixture had been stirred for 12 h followed by aqueous workup, the layers were separated and the organic layer was dried and concentrated. Distillation yielded *o*-(*tert*-butyldimethylsilyl)anisol (9.4 g, 0.042 mol; 42 % yield; b.p. 89 °C at 8.2×10^{-2} mbar).

o-(*tert*-Butyldimethylsilyl)anisol (9.4 g, 0.042 mol) was added at 0 °C to a mixture of *n*-butyllithium (28.8 mL, 0.046 mol of a 1.60 M solution in hexane) and TMEDA (6.9 mL, 0.046 mol). After the reaction mixture had been stirred for 6 h, (−)-fenchone (6.8 mL, 0.042 mol) was added at 0 °C and the mixture was stirred for 12 h. Hydrolytic workup and recrystallization from pentane yielded **4-H** (7.7 g, 0.021 mol, 50 %): m.p. 93 °C; elemental analysis (%) calcd: C 73.74, H 10.22; found: C 73.97, H 10.22. ^{1}H NMR (300 MHz, $CDCl_3$, RT): $\delta = 0.36$ (s, 3H), 0.39 (s, 3H), 0.51 (s, 3H), 0.81 (s, 9H), 1.11 (m, 1H), 1.12 (s, 3H), 1.14 (s, 3H), 1.31 (m, 1H), 1.43 (m, 1H), 1.76 (m, 2H), 2.29 (m, 1H), 2.43 (m, 1H) 3.74 (s, 3H), 5.89 (s, 1H), 7.07 ("t", $J = 7.5$ Hz, 1H), 7.32 (d, $J = 7.2$ Hz, 1H), 7.59 (d, $J = 8.1$ Hz, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$, RT): $\delta =$ -3.5, 18.0, 21.8, 23.8, 27.1, 29.6, 33.7, 37.4, 42.0, 46.7, 49.4, 54.0, 66.0, 86.4, 122.1, 130.7, 132.1, 135.1, 135.4, 164.8; MS(EI): *m*/*z* 374.3 [M^+], 317.2, [$M^+ - C_4H_9$], 249.1 [$M^+ - C_9H_{17}$]; IR (KBr): $\tilde{\nu} = 3467$, 3406 (OH, s), 3059–3000 (aryl, w), 2996–2876 (alkyl, s), 1362 cm^{-1} (*t*Bu, m); $[\alpha]^{21}_{Na}$ (*n*-hexane) $= -53.5$; X-ray analysis of **4-H**: SHELXTL V5.10, $C_{23}H_{38}O_2Si$, $M_r = 374.62$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, triclinic crystal system, space group: $P1$, $Z = 2$, $a = 7.7546(2)$, $b = 11.897$, $c = 13.1300(3)$ Å, $V = 1123.28(4)$ Å^3, $\rho_{calcd} = 1.11$ g cm^{-3}, reflections collected: 11605, independent reflections: 9538, observed reflections: 5945 ($I > 2\sigma(I)$), absorption coefficient μ: 0.12 mm^{-1}, Flack parameter: 0.1(12), R values ($I > 2\sigma(I)$): $R1 = 0.056$, $wR2 = 0.097$, largest difference peak and hole: 0.18, -0.25 e Å^{-3}; goodness-of-fit: 0.98.

Synthesis and characterization of 5-H: 2-Methylanisol (12.2 g, 0.10 mol) was added at 0 °C to a mixture of *n*-butyllithium (68.8 mL, 0.11 mol, 1.60 M solution in hexane) and TMEDA (16.6 mL, 0.11 mol). A colorless precipitate formed after stirring for 12 h. (−)-Fenchone (16.1 mL, 0.10 mol) was slowly added at 0 °C to this suspension, and stirred for two days at room temperature. Hydrolytic workup, drying, concentration of the organic layer, and removal of residual fenchone in vacuo yielded a yellowish substance. After recrystallization with pentane, colorless crystals of **5-H** were obtained (15.48 g, 0.056 mol, 56 %): m.p. 81 °C; elemental analysis (%) calcd: C 78.79, H 9.55, O 11.66; found: C 78.76, H 9.53, O 11.71; ^{1}H NMR (300 MHz, $CDCl_3$, RT): $\delta = 0.48$ (s, 3H), 1.10 (m, 1H), 1.11 (s, 3H), 1.19 (s, 3H), 1.28 (m, 1H), 1.39 (m, 1H), 1.74 (m, 2H), 2.27 (m, 1H), 2.30 (s, 3H), 2.42 (m, 1H), 3.85 (s, 3H), 5.55 (s, 1H), 6.91 ("t", $J = 7.6$ Hz, 1H), 7.00 (d, $J = 7.3$ Hz, 1H), 7.36 (d, $J = 8.0$ Hz, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$, RT): $\delta = 17.6$, 18.1, 21.7, 24.2, 29.7, 33.5, 41.4, 45.5, 49.6, 53.4, 61.4, 85.9, 122.0, 122.6, 129.8, 130.3, 135.9, 157.8; MS(EI): *m*/*z*: 274.1 [M^+], 191.0 [$M^+ - C_6H_{11}$], 149.0 [$M^+ - C_9H_{17}$]; IR (KBr): $\tilde{\nu} = 3479$ (OH, s), 3113–3060 (aryl, w), 2996–2876 cm^{-1} (alkyl, s); $[\alpha]^{21}_{Na}$ (*n*-hexane) $= -92.7$; X-ray analysis of **5-H**: SHELXTL V5.10, $C_{18}H_{26}O_2$, $M_r = 274.39$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, orthorhombic crystal system, space group: $P2_12_12_1$, $Z = 4$, $a = 7.6043(1)$, $b = 10.1176(1)$, $c = 19.9781(1)$ Å, $V = 1537.060(17)$ Å^3, $\rho_{calcd} = 1.186$ g cm^{-3}, reflections collected: 15694, independent reflections: 3528, observed reflections: 3087 ($I > 2\sigma(I)$), absorption coefficient μ: 0.075 mm^{-1}, Flack parameter: 0.1(12), R values ($I > 2\sigma(I)$): $R1 = 0.040$, $wR2 = 0.095$, largest difference peak and hole: 0.20, -0.19 e Å^{-3}; goodness-of-fit: 1.07.

Characterization of 1-BuLi: For the synthesis, see reference [12a]. Compound **1-BuLi** for NMR experiments was obtained after washing an amorphous precipitate with cold hexane (6×0.2 mL) in 31 % yield. Decomposition was observed at 204 °C. ^{1}H NMR (500 MHz, [D_8]toluene, −10 °C): $\delta = -0.63$ (t, $J = 12.4$ Hz, 1H; C_α H*H*, BuLi), −0.39 (t, $J = 13.3$ Hz, 1H; C_αH*H*, BuLi), 0.49 (s, 9H; 3CH_3), 0.97 (s, 9H; 3CH_3), 1.27 (s, 9H; 3CH_3), 0.26–2.40 (m, 18H; CH_2, ligand; m, 7H; CH_2, CH_3, BuLi), 3.68 (s, 9H; 3OCH_3), 6.70 (d, $J = 8.1$ Hz, 3H; 3H-*ortho*), 6.80 ("t", $J = 7.6$ Hz, 3H; 3H-*diortho*), 6.95 ("t", $J = 7.7$ Hz, 3H; 3H-*diortho*), 7.53 (d, $J = 8.1$ Hz, 3H; 3H-*ortho*); ^{13}C NMR (125 MHz, [D_8]toluene, −10 °C): $\delta = 10.0$ (C_α-BuLi), 14.3 (CH_3-BuLi), 23.1 (CH_3), 23.8 (CH_3), 25.4 (CH_2), 30.8 (CH_3), 32.0 (CH_2-BuLi), 34.8 (CH_2-BuLi), 35.4 (CH_2), 41.3 (CH_2), 44.5 (C_q), 50.9 (CH), 53.0 (C_q), 56.6 (OCH_3), 89.1 (C_q), 114.2 (C_{Ar}), 120.8 (C_{Ar}), 126.0 (C_{Ar}), 129.8 (C_{Ar}), 140.2 (C_{Ar}), 158.5 (C_{Ar}); ^{7}Li NMR (194 MHz, [D_8]toluene, −10 °C): $\delta = 1.06$ (coordinated by OCH_3), 1.39.

Characterization of 2-BuLi: For the synthesis, see reference [12b]. Compound **2-BuLi** for NMR experiments was obtained after washing an amorphous precipitate with cold hexane (6×0.2 mL) in 29 % yield. Evolution of gas and decomposition was observed at 100–160 °C. ^{1}H NMR (500 MHz, [D_8]toluene, −10 °C): $\delta = -0.97$ (m, 2H; $C_\alpha H_2$, BuLi), 0.33 (m, 1H; C_βH*H*, BuLi), 0.49 (s, 9H; $Si(CH_3)_3$), 0.76 (s, 3H; 10-CH_3), 0.80 (t, $J = 7.3$ Hz, 3H; CH_3, BuLi), 0.99 (m, 1H; C_βH*H*, BuLi), 1.18 (m, 1H; C_γH*H*, BuLi), 1.23 (m, 2H; H6-*exo*, H7-*anti*), 1.25 (s, 3H; 9-CH_3), 1.28 (s, 3H; 8-CH_3), 1.36 (m, 1H; C_γH*H*, BuLi), 1.53 (m, 1H; H5-*exo*), 1.76 (m, 1H; H5-*endo*), 1.82 (s, 1H; 4-CH), 2.25 (m, 1H; H6-*endo*), 2.39 (d, $J = 10.0$ Hz, 1H; H7-*syn*), 3.86 (s, 3H; OCH_3), 6.89 ("t", $J = 7.4$ Hz, 1H; H-*diortho*) 7.30 (d, $J = 7.2$ Hz, 1H; H-*ortho*), 7.53 (d, $J = 7.6$ Hz, 1H; H-*ortho*); ^{13}C NMR (125 MHz, [D_8]toluene, −10 °C): $\delta = 1.30$ ($Si(CH_3)_3$), 10.7 (C_α-BuLi), 14.4 (CH_3-BuLi), 19.2 (CH_3), 23.5 (CH_3), 24.4 (CH_2), 31.3 (CH_3), 32.9 (CH_2-BuLi), 33.0 (CH_2-BuLi), 35.8 (CH_2), 41.5 (CH_2), 44.0 (C_q), 51.0 (CH), 54.8 (C_q), 64.4 (OCH_3), 88.1 (C_q), 121.9 (C_{Ar}), 131.1 (C_{Ar}), 132.1 (C_{Ar}), 134.5 (C_{Ar}), 142.0 (C_{Ar}), 164.7 (C_{Ar}); ^{7}Li NMR (194 MHz, [D_8]toluene, −10 °C): $\delta = 1.08$ (coordinated by OCH_3), 2.06.

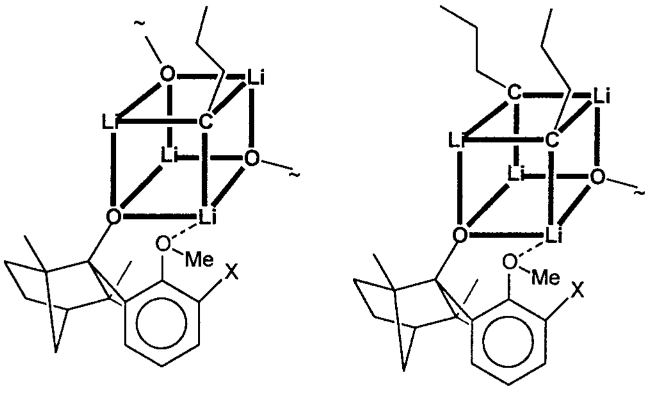
Synthesis and characterization of 3-BuLi: Compound **3-H** (0.158 g, 0.5 mmol) was added at RT to *n*BuLi (0.63 mL, 1.0 mmol of a 1.60 M solution in hexane). Slow evaporation of the hexane under reduced pressure yielded **3-BuLi** as colorless crystals. Compound **3-BuLi** for NMR experiments was obtained after washing an amorphous precipitate with cold hexane (6×0.2 mL) in 12 % yield: m.p. 122 °C; ^{1}H NMR (500 MHz, [D_8]toluene, −10 °C): $\delta = -0.85$ (t, $J = 12.6$ Hz, 1H; C_αH*H*, BuLi), −0.74 (t, 12.9, 1H; C_αH*H*, BuLi), 0.71 (m, 1H; C_βH*H*, BuLi), 0.85 (s, 3H; 10-CH_3), 0.89 (t, $J = 7.2$ Hz, 3H; CH_3, BuLi), 1.06 (m, 1H; C_βH*H*, BuLi), 1.19 (m, 2H; H6-*exo*, H7-*anti*), 1.24 (s, 3H; 9-CH_3), 1.25 (s, 3H; 8-CH_3), 1.41 (m, 2H; $C_\gamma H_2$, BuLi), 1.51 (m, 1H; H5-*exo*), 1.56 (s, 9H; $C(CH_3)_3$), 1.73 (m, 1H; H5-*endo*), 1.83 (s, 1H; 4-CH), 2.36 (m, 1H; H6-*endo*), 2.46 (d, $J = 10.1$ Hz, 1H; H7-*syn*), 3.71 (s, 3H; OCH_3), 6.85 ("t", $J = 7.8$ Hz, 1H; H-*diortho*), 7.17 (d, $J = 7.6$ Hz, 1H; H-*ortho*), 7.38 (d, $J = 7.7$ Hz, 1H; H-*ortho*); ^{13}C NMR (125 MHz, [D_8]toluene, −10 °C): $\delta = 11.2$ (C_α-BuLi), 14.4 (CH_3-BuLi), 19.4 (CH_3), 23.0 (CH_3), 24.1 (CH_2), 31.1 (CH_3), 32.7 (CH_2-BuLi), 33.0 ($C(\mathit{CH}_3)_3$), 33.3 (CH_2-BuLi), 35.7 ($\mathit{C}(CH_3)_3$), 36.4 (CH_2), 42.1 (CH_2), 44.4 (C_q), 51.1 (CH), 55.8 (C_q), 65.9 (OCH_3), 89.3 (C_q), 122.2 (C_{Ar}), 126.6 (C_{Ar}), 128.3 (C_{Ar}), 142.5 (C_{Ar}), 144.0 (C_{Ar}), 158.3 (C_{Ar}); ^{7}Li NMR (194 MHz, [D_8]toluene, −10 °C): $\delta = 1.05$ (coordinated by OCH_3), 2.17; X-ray crystal analysis of **3-BuLi**: SHELXTL V5.10, $C_{50}H_{80}Li_4O_4$, $M_r = 772.90$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, orthorhombic crystal system, space group: $P2_12_12_1$, $Z = 4$, $a = 13.0685(2)$, $b = 13.8204(3)$, $c = 26.1159(6)$ Å, $V = 4716.84(17)$ Å^3, $\rho_{calcd} = 1.314$ g cm^{-3}, reflections collected: 48849, independent reflections: 10772, observed reflections: 4613 ($I > 2\sigma(I)$), absorption coefficient μ: 0.092 mm^{-1}, Flack parameter: 1(2), R values ($I > 2\sigma(I)$): $R1 = 0.082$, $wR2 = 0.196$, largest difference peak and hole: 0.65, -0.29 e Å^{-3}; goodness-of-fit: 1.00.

Synthesis and characterization of 4-BuLi: Compound **4** (0.158 g, 0.5 mmol) was added at RT to *n*BuLi (0.63 mL, 1.0 mmol of a 1.60 M solution in hexane), and the mixture was stirred at 25 °C for 5 min. After freezing the solution to −80 °C, the precipitate formed was dissolved in hot hexane. Slowly cooling to room temperature yielded **4-BuLi** as colorless crystals. Compound **4-BuLi** for NMR experiments was obtained after washing an amorphous precipitate with cold hexane (6×0.2 mL) in 57 % yield. Evolution of gas and decomposition was observed at 171 °C. ^{1}H NMR (500 MHz, [D_8]toluene, −10 °C): $\delta = -0.93$ (m, 2H; $C_\alpha H_2$, BuLi), 0.40 (s, 3H; $SiCH_3$), 0.63 (m, 1H; C_βH*H*, BuLi), 0.71 (s, 3H; $SiCH_3$), 0.80 (s, 3H; 10-CH_3), 0.87 (t, $J = 7.3$ Hz, 3H; CH_3, BuLi), 0.92 (m, 1H; C_βH*H*, BuLi), 1.05 (s, 9H; $SiC(CH_3)_3$), 1.26 (m, 2H; H6-*exo*, H7-*anti*), 1.29 (s, 6H; 9-CH_3, 8-CH_3), 1.35 (m, 2H; $C_\gamma H_2$, BuLi), 1.57 (m, 1H; H5-*exo*), 1.83 (m, 2H; H5-*endo*, 4-CH), 2.32 (m, 1H; H6-*endo*), 2.41 (d, $J = 10.1$ Hz, 1H; H7-*syn*), 3.96 (s, 3H; OCH_3), 6.88 ("t", $J = 7.6$ Hz, 1H; H-*diortho*) 7.36 (d, $J = 7.3$ Hz, 1H; H-*ortho*), 7.54 (d, $J = 6.9$ Hz, 1H; H-*ortho*); ^{13}C NMR (125 MHz, [D_8]toluene, −10 °C): $\delta = -3.0$ ($SiCH_3$), −0.7 ($SiCH_3$), 10.7 (C_α-BuLi), 14.4

(CH_3-BuLi), 18.8 (CH_3), 24.4 (CH_3), 24.6 (CH_2), 28.4 ($SiC(CH_3)_3$), 31.2 (CH_3), 32.3 (CH_2-BuLi), 33.2 (CH_2-BuLi), 36.2 (CH_2), 37.2 ($SiC(CH_3)_3$), 42.0 (CH_2), 44.4 (C_q), 51.2 (CH), 55.3 (C_q), 65.1 (OCH_3), 88.9 (C_q), 121.6 (C_{Ar}), 131.4 (C_{Ar}), 134.0 (C_{Ar}), 134.5 (C_{Ar}), 136.4 (C_{Ar}), 164.9 (C_{Ar}); ^{7}Li NMR (194 MHz, [D_8]toluene, −10 °C): $\delta = 1.11$ (coordinated by OCH_3), 2.08; X-ray crystal analysis of **4-BuLi**: SHELXTL V5.10, $C_{54}H_{92}Li_4O_4Si_2$, $M_r = 889.22$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, monoclinic crystal system, space group: *C*2/c, $Z = 8$, $a = 36.9230(6)$, $b = 13.5888(1)$, $c = 22.4589(3)$ Å, $\beta = 101.24°$, $V = 11052.2(2)$ Å^3, $\rho_{calcd} = 1.07$ g cm^{-3}, reflections collected: 32985, independent reflections: 4403, observed reflections: 3460 ($I > 2\sigma(I)$), absorption coefficient μ: 0.10 mm^{-1}, Flack parameter: 1(2), *R* values ($I > 2\sigma(I)$): $R1 = 0.082$, $wR2 = 0.195$, largest difference peak and hole: 0.61, −0.39 e Å^{-3}; goodness-of-fit: 1.13.

Synthesis and characterization of 5-BuLi: Compound **5-H** (0.137 g, 0.5 mmol) was added at RT to *n*BuLi (0.94 mL, 1.5 mmol 1.60 M solution in hexane). Isothermal diffusion yielded **5-BuLi** as colorless crystals. Compound **5-BuLi** for NMR experiments was obtained after washing an amorphous precipitate with cold hexane (6 × 0.2 mL) in 73 % yield. Decomposition was observed at 160 °C. ^{1}H NMR (500 MHz, [D_8]toluene, −10 °C): $\delta = -0.84$ (m, 4 H; 2$C_\alpha H_2$, BuLi), 0.15 (m, 1 H; $C_\beta HH$, BuLi), 0.58 (m, 1 H; $C_\beta HH$, BuLi), 0.66 (s, 3 H; 10-CH_3), 0.85 (m, 1 H; $C_\beta HH$, BuLi), 0.93 (t, $J = 7.2$ Hz, 3 H; CH_3, BuLi), 1.00 (m, 3 H; CH_3, BuLi), 1.09 (m, 1 H; $C_\beta HH$, BuLi), 1.15 (s, 3 H; 9-CH_3), 1.17 (m, 2 H; H6-*exo*, H7-*anti*), 1.19 (s, 3 H; 8-CH_3), 1.42 (m, 5 H; 2 $C_\gamma H_2$, BuLi, H5-*exo*), 1.64 (m, 1 H; H5-*endo*), 1.71 (s, 1 H; 4-CH), 2.03 (m, 1 H; H6-*endo*), 2.18 (s, 3 H; CH_3) 2.35 (d, $J = 9.2$ Hz, 1 H; H7-*syn*), 3.70 (s, 3 H; OCH_3), 6.77 ("t", $J = 7.6$ Hz, 1 H; H-*diortho*) 6.81 (d, $J = 7.2$ Hz, 1 H; H-*ortho*), 7.34 (d, $J = 8.0$ Hz, 1 H; H-*ortho*); ^{13}C NMR (125 MHz, [D_8]toluene, −10 °C): $\delta = 10.0$ (C_α-BuLi), 13.8 (CH_3), 14.1 (CH_3-BuLi), 19.1 (CH_3), 23.5 (CH_3), 25.1 (CH_2), 31.2 (CH_{3Ar}), 32.8 (CH_2-BuLi), 32.9 (CH_2-BuLi), 35.1 (CH_2), 41.2 (CH_2), 44.1 (C_q), 50.9 (CH), 54.7 (C_q), 62.1 (OCH_3), 88.8 (C_q), 122.1 (C_{Ar}), 127.5 (C_{Ar}), 129.8 (C_{Ar}), 130.3 (C_{Ar}), 142.6 (C_{Ar}), 158.2 (C_{Ar}); ^{7}Li NMR (194 MHz, [D_8]toluene, −10 °C): $\delta = 1.02$ (coordinated by OCH_3), 2.23; X-ray analysis of **5-BuLi**: SHELXTL V5.10, $C_{52}H_{86}Li_6O_4$, $M_r = 816.85$, $T = 200(2)$ K, $\lambda = 0.71073$ Å, tetragonal crystal system, space group: $P4_32_12$, $Z = 4$, $a = 13.5798(1)$, $b = 13.5798(1)$, $c = 27.2532(4)$ Å, $V = 5025.79(9)$ Å^3, ρ_{calcd}: 1.080 g cm^{-3}, reflections collected: 35175, independent reflections: 3499, observed reflections: 2383 ($I > 2\sigma(I)$), absorption coefficient: μ: 0.063 mm^{-1}, Flack parameter: −2(3), *R* values ($I > 2\sigma(I)$): $R1 = 0.077$, $wR2 = 0.209$, largest difference peak and hole: 0.29 and −0.17 e Å^{-3}; goodness-of-fit: 1.03.

Computational section: All computed structures were fully optimized by using the program package GAUSSIAN 98.[28] For the ONIOM[29] computations, hydrogen atoms were used as linkers between the two layers. The "Universal Force Field" (UFF)[30] was employed for alkyl and aryl moieties and the hybrid density functional method B3LYP/6–31 + G*[31] was used for the polar $Li_4O_3(CH_2)$ and $Li_4O_2(CH_2)_2$ cubic cores (Scheme 8). All structures were analyzed by frequency computations and showed no imaginary frequencies. Single point energies of the structures were computed using the B3LYP/6–31G* method.



Scheme 8. Layers of ONIOM (B3LYP/6–31 + G* (bold):UFF) geometry optimizations.

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[20] The more suitable arrangement of Li–O contacts relative to Li–C bonds is due to shorter contacts and hence stronger electrostatic interactions for the oxido ligands. Also, three lone pairs at O are more suitable for $\mathrm{Li^+}$ coordination than one lone pair at the carbanionic unit, cf. ref. [7].

[21] Mixed anionic aggregates should also be favored entropically.

[22] The computed complex formation energies provide only crude assessments of aggregate stabilities because other, unconsidered species might also be involved in the complex development.

[23] The Si(*t*Bu)Me$_2$ group exhibits through the $\mathrm{SiMe_2}$ moiety a similar steric demand to $\mathrm{SiMe_3}$.

[24] To ensure identical conditions, mixtures of fencholates and *nBu*Li were used for the comparative alkylations. Higher enantioselectivities can be obtained with *isolated* complexes, for example, 46% *ee* for **1-BuLi** or 80% *ee* for **2-BuLi**.[12b]

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