Chiral Dilithiomethane Derivatives: Structure Determination and Application in Stereoselective Reactions

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The synthesis and X-ray analysis of chiral dilithiomethane analogues derived from sulfoximines are presented. The structures of the sulfoximine-stabilised mono- and dilithio salts have been compared and allow a rationalization of the second lithiation. Organophosphorus-based dilithiomethane derivatives are also structurally described. The gas-phase structures of *N*,*S*,*S*-trimethylsulfoximine **19** and of its mono- and dilithiated isomers **20–21** were calculated by ab initio methods employing different levels of theory. For an application in asymmetric synthesis, the dilithiation of (*N*-methyl)-*S*-ethyl-*S*-phenylsulfoximine (**11**) afforded a chiral dinucleophile that undergoes highly regio- and stereoselective alkylation reactions with electrophiles. The transmetallation of a chiral dilithiomethane reagent such as **14** with $ClTi(OiPr)_3$ followed by addition of an aldehyde, constitutes a simple one-pot process for the formation of (*E*)-alkenylsulfoximines with excellent diastereoselectivity.

1. Introduction

Since its discovery, dilithiomethane (**2**) has challenged researchers in various fields of chemistry such as synthetic organic chemistry, organometallic chemistry, and computational chemistry. The first landmark was achieved by Ziegler et al. who developed the first synthetic route to dilithiomethane.[1]

$$\underset{\mathbf{1}}{2\,CH_3Li} \xrightarrow{\Delta} \underset{\mathbf{2}}{CH_2Li_2} + CH_4$$

The high reactivity of **2** towards oxygen and moisture, together with its notorious instability and poor solubility in organic solvents, complicated its structural characterisation. After early solid state NMR studies, Stucky et al. suggested an X-ray structure of CD_2Li_2 in 1990 derived from powder diffraction data.[2,3] Computational studies suggested various gas phase structures and even higher aggregates of **2**.[4] For synthetic purposes, however, heteroatom-substituted organolithiums are better qualified than simple alkyllithium compounds. The same is true for heteroatom-substituted geminal dilithiated organic compounds, which have been shown in recent years to possess great synthetic potential.[5] This led to the development of new synthetic strategies, with the aim of synthesising assemblies of complex molecular structures with a minimum of chemical steps more effici-

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MICROREVIEWS: This feature introduces the readers to the authors' research through a concise overview of the selected topic. Reference to important work from others in the field is included.

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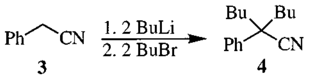
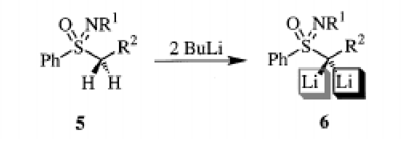
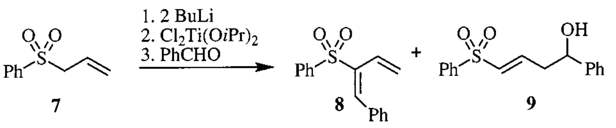
ently. For example, multiple C–C bond formations in a single reaction step have been reported from the reaction of dilithiated nitriles, sulfonamides, sulfones and phosphonates with various electrophiles.[6–9]



Unfortunately, a common drawback of all of these reagents is the lack of chirality, which prevents a successful application in asymmetric reactions. If such a dilithiomethane derivative bears a chiral auxiliary adjacent to its geminal dilithiated carbon atom, the two positions of the lithium atoms become nonequivalent because they are in a diastereotopic environment. We have chosen the sulfoximine group, the aza analogue of a sulfone, as a chiral auxiliary, which should allow the twofold abstraction of acidic hydrogen s bound to the adjacent carbon atom in **5**.[10] Phosphorus based chiral auxiliaries, which already have demonstrated a great versatility in asymmetric synthesis, have also to be taken in account.[11]



One would expect that the reactivity of each geminal bound lithium atom towards electrophiles differs, and might be used for synthetic purposes in asymmetric reactions. Transmetallation with one equivalent of a transition metal compound leads to mixed organodimetallics that are less reactive. This opens the possibility of directing the chemo-, regio-, and stereoselectivity by the appropriate choice of the second metal, which could induce better stereocontrol. Indeed, previous reports on an achiral sulfone **7** demonstrated that such doubly heterometallated lithium-titanium sulfones undergo highly diastereoselective addition to aldehydes forming predominantly (*E*)-alkenes **8** and **9**.[12]

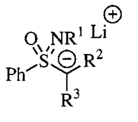


Early investigations into the reactivity of acceptor-substituted organodilithium compounds led finally to the conclusion that, derived from trapping reactions, the intermediates in general have to be geminal dilithio species. This assumption turned out to be erroneous as the first structural investigations of such intermediates have shown. In certain cases NMR and crystallographic studies led to the discovery of the so called "Quasi Dianion Complexes" (QUADAC's), which simulate a second lithiation, but in chemical reality these are complexes between a monolithium compound and a second equivalent of a lithium base as found, for instance, for a "doubly" lithiated nitrile.[13] True dilithiomethane derivatives derived from a sulfone or nitrile are formed only in the presence of a second stabilising group such as trimethylsilyl or vinyl.[14–16] As a consequence, the demand for a structural confirmation of a chiral dilithiomethane derivative has yet to be fulfilled before its synthetic properties can be explored. Recent developments in low temperature diffraction and crystallisation techniques make X-ray crystallography the most powerful instrument for the structure determination of organolithiums.[17] We took advantage of this and started our investigations on the elucidation of the solid-state structures of mono- and dilithiated sulfoximines in combination with quantum chemical calculations, which have been shown to be the method of choice for the determination of the gas phase structures of lithiumorganic compounds.[18]

2. Solid State Structures

2.1 Monolithiated Sulfoximines

Despite their significance in asymmetric synthesis, the structures of monolithiated sulfoximines had not been extensively examined at the time we initiated our studies.



10 a: $R^1 = Me, R^2 = R^3 = H$
10 b: $R^1 = R^2 = SiMe_3, R^3 = H$
10 c: $R^1 = SiMe_3, R^2 = H, R^3 = CH{=}C(Me)_2$
10 d: $R^1 = Me, R^2 = H, R^3 = CH{=}C(Ph)_2$
10 e: $R^1 = Me, R^2 = H, R^3 = Ph$
10 f: $R^1 = Me, R^2 = C(Ph)_2$

Only two crystal structures of lithiated alkyl sulfoximines **10a**, **b** were known and have already been reviewed by Boche in 1989.[19–21] A striking feature in both tetrameric (!) aggregates is the presence of Li–C bonds to the C(α) atom, which are in strong contrast to the typical structures of lithiosulfones, known not to contain any Li–C bonds. It later turned out that in the case of lithiated allylic sulfoximines close similarities to lithiated allylic sulfones are present. A structural study by Gais and co-workers provided evidence for a solvent-separated contact ion pair of **10c**, which is devoid of Li–C contacts.[22] The monomeric species **10c** consists of a [Li(12-crown-4)$_2$] cation and a sulfonimidoyl-substituted allylic anion. The conformation of the lone pair in **10c** suggests a stabilising n_C-$s^*_{S–Ph}$ interaction (negative hyperconjugation) reminiscent of lithiosulfones.[23] Deprotonation induced a planarization of the anionic carbon atom and a pronounced reduction of the S–C(α) bond from 1.794(4) to 1.62(1) Å (Figure 1).

The X-ray structure of a lithiated allylic sulfoximine determined by our group uncovered different structural features.[24] In **10d**, two lithioallylsulfoximine units with opposite chirality are linked by N–Li–O bridges to give an eight-membered ring with the atom sequence (Li–N–S–O)$_2$ (Figure 2). Such a coordination is in good agreement with analogous arrangements in lithiosulfones.[21,25] In dimer **10d** the lithium cations are in a distorted *tetrahedral* environment consisting of the O atoms of two THF molecules and the

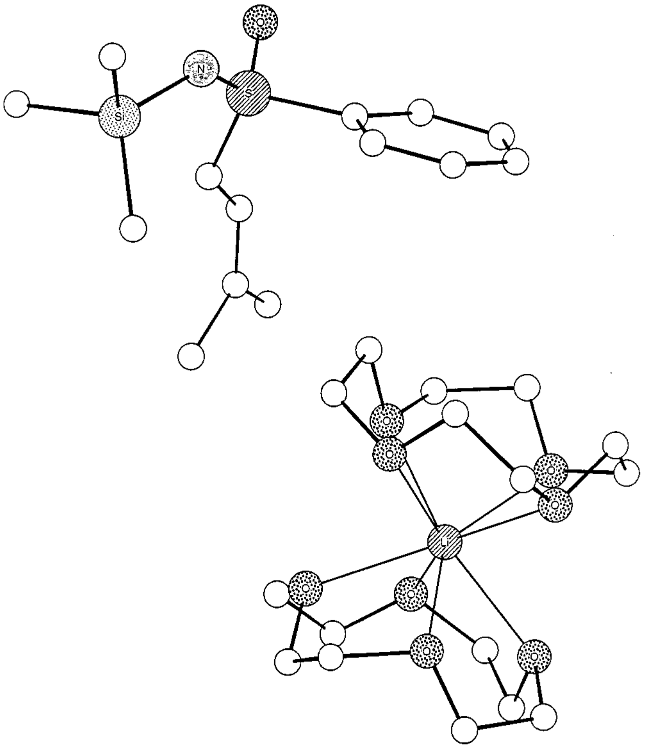


Figure 1. Molecular structure of **10c**; H atoms are omitted for clarity

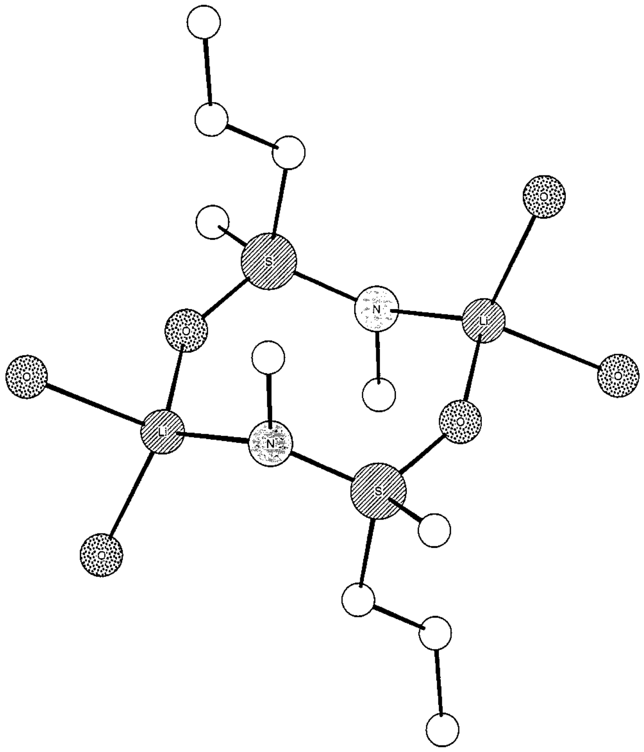


Figure 2. Molecular structure of **10d**; All H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) and of the THF ligands are omitted for clarity

sulfoximine O- and N-atoms. The Li–C bond found in lithioalkylsulfoximines is absent.[19,20] The stabilisation of the negative charge at the C(α) atom by conjugation with the allylic system is more favourable than forming a Li–C bond.

Interestingly, the C(α) atom is pyramidal in spite of the conjugation with the vinyl group and the lone pair at C(α) is orientated in a *gauche* conformation between the O- and N-atoms of the sulfonimidoyl moiety. This allows a stabilisation by negative hyperconjugation.[23] Deprotonation of **10d** is accompanied by a reduction in the S–C(α) bond length of about 0.11 Å, which corresponds to the situation in **10c**. After lithiation only one of the two possible diastereomeric enantiomer pairs has been found in the crystal.

For a benzylic sulfoximine, lithiation leads to dimer **10e** with N–Li–O bridges to give an eight-membered ring with the atom sequence $(Li–N–S–O)_2$ as in **10d**.[26] The lithium cations are in a distorted *tetrahedral* coordination geometry consisting of the N atoms of two TMEDA molecules and the sulfoximine O- and N-atoms. No Li–C bond is found.

The lone pair at C(α) is orientated in a *gauche* conformation between the O and N atoms of the sulfonimidoyl moiety as found for the allylic case. The question as to whether C(α) is pyramidal or not could not be answered with certainty because the benzylic proton has not been located. A significant reduction in the S–C(α) bond length from 1.783(2) Å in the starting material to 1.66(1) Å in **10e** is observed (Figure 3).

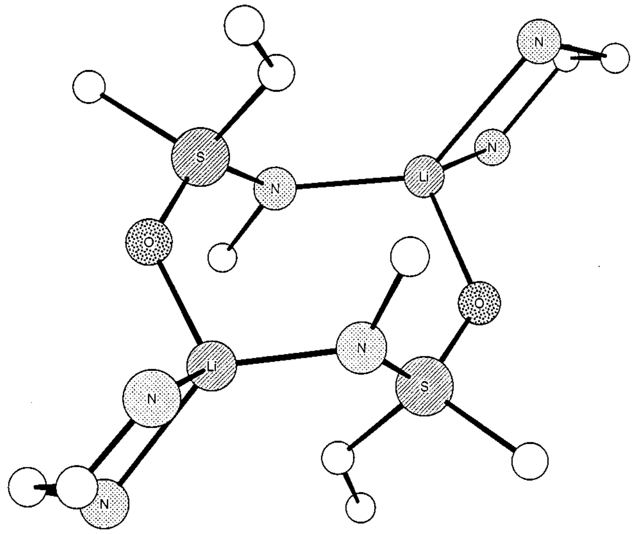


Figure 3. Molecular structure of **10e**; All H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) and of the methyl groups on TMEDA are omitted for clarity

The dinuclear lithium complex **10f** of a lithiated vinylic sulfoximine is bridged through Li-sulfoximine–O bonds, forming two eight-membered rings with the different atomic sequences $(Li–O–S–N)_2$ and $(Li–O–S–C)_2$, respectively.[27] The two halves of the molecule are related by a crystallographic centre of symmetry (Figure 4).

In this complex a Li–C contact with a distance of 2.209(6) Å leads, together with the lithium coordination to the sulfoximine-N-atom, to an Li–N–S–C four-membered ring chelate. In this respect, **10f** differs both from lithiovinylsulfones and lithioallyl(or benzyl)sulfoximines, which do not show Li–C bonds, and from higher associated lithioalkylsulfoximines.[19,20,22,24,28] The *tetrahedral* four-coordination of the lithium cation is completed by coordination

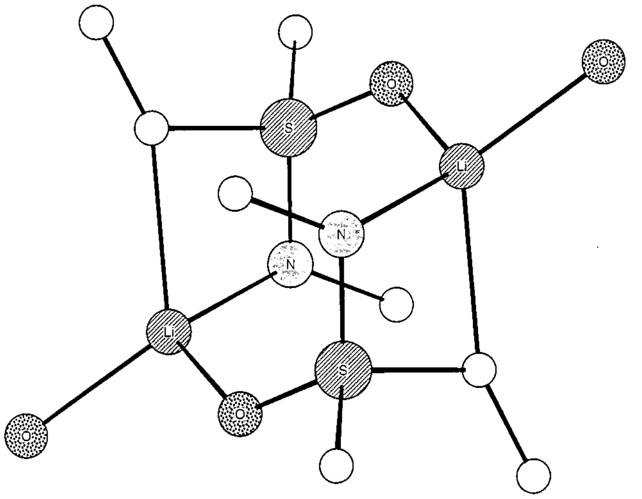


Figure 4. Molecular structure of **10f**; All H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) and of the THF ligands are omitted for clarity

to an O atom of a THF molecule. The S–C(α) bond length is slightly shortened from 1.753(2) Å in the C–H acid to 1.734(3) Å in **10f**. Compared to lithiovinylsulfones this reduction is small and reveals the minor stabilising abilities of the sulfonimidoyl group.[28]

2.2 Dilithiated Sulfoximines

Achiral sulfone- or nitrile-based dilithiomethane compounds have already been investigated in the solid state and have been reviewed previously.[14,15,21] However, an attempt to crystallise a chiral dilithiomethane derivative was first undertaken by our group.[29] Dilithiation of **11** leads to a mixed aggregate containing mono- and dilithiated (*N*-methyl)-*S*-ethyl-*S*-phenyl-sulfoximine units in a 2:2 ratio coordinated by 3 TMEDA ligands. Compound **12** crystallises in the space group *C*2/c and the unit cell contains 4 of the clusters together with 8 disordered TMEDA molecules (Figure 5). The unit cell contains two clusters each composed of two sulfoximine dianions in the (*R*) configuration and two sulfoximine monoanions in the (*S*) configuration. Since the lattice is centrosymmetric, there are two clusters in which these configurations are reversed. This means that an internal chiral resolution has taken place within the clusters. The centre of the aggregate is characterised by a distorted *octahedral* Li_6–O unit due to incorporated Li_2O. In certain cases, Li_2O has been observed in crystalline organolithium compounds where it served as a template for crystallisation.[30] The dianionic subunit in **12** is characterised by two Li–C contacts of the *ortho* C atom to form five-membered ring chelates with the heteroatoms on sulfur and not with a geminal dilithiated structural motif. For Li(2) a coordination to the sulfoximine-O atom, a single O atom derived from Li_2O and a C(α) atom of the neighbouring sulfoximine monoanion is found, whereas Li(4) is coordinated to a sulfoximine N atom, the oxygen of the Li_2O core and an N atom of one TMEDA ligand. For such an *ortho*-directing effect only little data exist for sulfoximines in contrast to sulfones, which are known to be powerful *ortho*-directing groups.[31,32] Despite being deprotonated, a Li–C bond to the C(α) atom is not observed. This is consistent with a substantial S–C multiple bond character, which lowers the basic character of this carbon atom and is supported by a short S–C(α) distance of 1.62 Å (vs. 1.73 Å in protonated sulfoximines).[22,24]

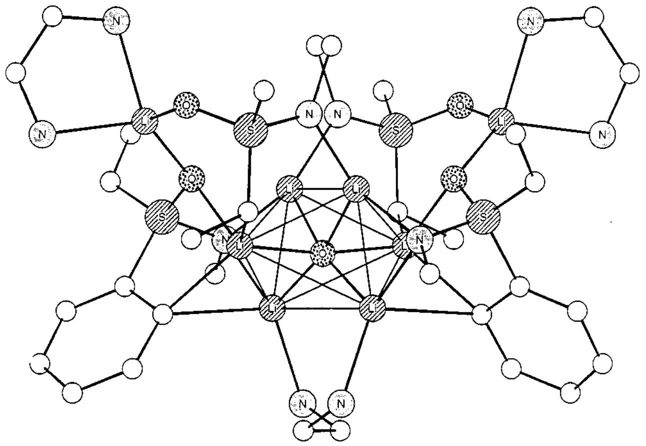
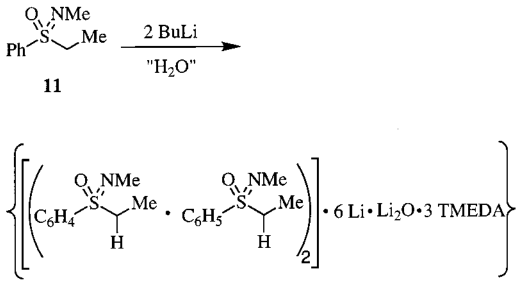


Figure 5. Molecular structure of **12**; all H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) of the monolithiated sulfoximine units and of the methyl groups on TMEDA are omitted for clarity; the thin lines serve to emphasise the geometrical relationship of the Li_6–O core and are not to be considered normal bonds



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The anionic C(α) atom has a nearly planar configuration. In the monoanionic sulfoximine moiety, a Li–C(α) contact is observed (2.25 Å) whereas the two heteroatoms are coordinated to two additional Li^+ cations, an arrangement unknown for monolithiated sulfoximines.[19,20,22,24,26,27] In this case, the C(α) atom has a distinct pyramidal configuration. The C(α)–Li bond is arranged in a *gauche* conformation between the N- and O-atoms of the sulfoximine moiety. The coordination sites of the Li atom bonded to the sulfoximine–O are occupied by two nitrogen atoms of the TMEDA ligands and the O atom of the dilithiated sulfoximine, which leads to a bridging of the mono- and dilithio sulfoximine units. A significant shortening of the S–C(α) bond is found (1.66 Å vs. 1.73 Å) in the monoanion, but this is not as pronounced as for the dianionic species where the S–C(α) bond length is 1.62 Å. This additional contraction for the dianion can be explained with the threefold and twofold lithium coordination of the sulfoximine O- and N-atoms, respectively.

The first true heterochiral dilithiomethane derivative was accessible from racemic **13** with 2.5 equivalents of *n*BuLi and traces of H_2O.[26] A tetrameric heterochiral aggregate **14**, consisting of four dilithiated sulfoximine units and one molecule of Li_2O, which acts as a template for crystallisation, was formed (Figure 6). The core of the aggregate is characterised by a distorted Li_6O-*octahedron*, a structural motif that has been found to be a characteristic feature in **12** and a dilithiated sulfone.[14]

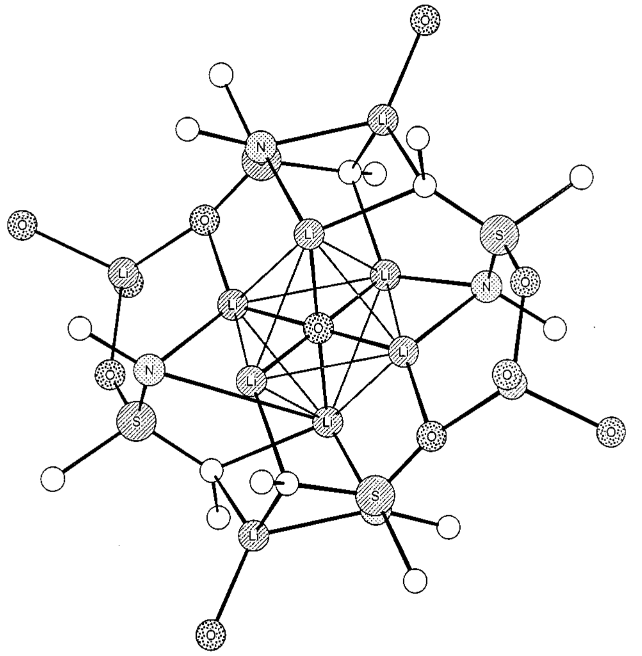
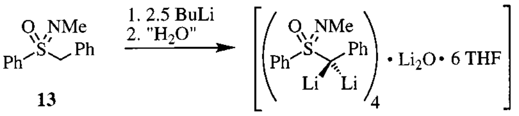


Figure 6. Molecular structure of **14**; all H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) and of the THF ligands are omitted for clarity; the thin lines serve to emphasise the geometrical relationship of the Li_6–O core and are not to be considered normal bonds



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Two different dilithiated C atoms are in the asymmetric unit, each connected to two Li^+ ions and therefore distinctly pyramidalized. At C(21) the two Li^+ ions coordinate to a neighbouring sulfoximine nitrogen, forming either Li–C–S–N four-membered ring motifs, as known from monolithiosulfoximines, or C–Li–N–Li–O–S six-membered rings. They also differ in their further coordination sphere: Li(2) shows heteroatom coordination (N,O), whereas Li(5) has one additional C–Li bond, while bridging two different dimetallated C atoms, and a Li–N contact. For C(1), Li(5) is also bound to C(21), leading to a Li–C–Li–C–S–N six-membered ring. The Li^+ in the bridging position complements its fourfold coordination by complexation to a THF oxygen. Li(2) coordinates to the central O atom of the Li_6O core, inducing a six-membered Li–O–Li–O–S–C ring, via the sulfoximine oxygen. The Li–C distances [range 2.19(2)–2.21(2) Å] are similar to that in the monolithiated sulfoximine **10f**. The Li–N distance within the Li–C–S–N chelate [2.23(2) Å] is comparable to that in **10f** and those found in previous investigations. The Li–O bond length to the sulfoximine-O atoms are significantly longer than those within the (Li_6–O) core. A characteristic property is the extremely short S–C(α) bonds [1.61(1), and 1.64(1) Å] compared to **13** [1.783(2) Å] and **10e** [ca. 1.66(1) Å], which is also typical for related sulfones,[14] phosphonates,[33] phosphinimines,[34] and nitriles.[15] The geminal-bound Li atoms adopt a *gauche* conformation between the N- and O-atoms of the sulfoximine moiety and between the sulfoximine-N atom and the *ipso*-C atom, thus confirming sp^3-hybridized C(α) atoms.

In summary, sulfoximines are clearly able to serve as chiral substrates for the creation of well defined chiral dilithio compounds. As a first rule, it seems that those monolithiosulfoximines that do contain C–Li bonds form α,*o*-dilithio salts after the second lithiation. There is no close proximity of the carbon-bound lithium ion to the *ortho* protons of the phenyl group, as one might expect to find for an *ortho* directing effect. We believe that *ortho* attack is favoured because there is less steric hindrance caused by the solvated and C(α)-bound Li^+. For sulfoximines bearing an additional stabilising substituent, such as a phenyl or vinyl group at the C(α) atom, no C–Li bonds but rather N- and O-sulfonimidoyl Li contacts are observed for its monolithiated salts. This induces a closer proximity to the *ortho* protons as in **10d**, **e**. The positioning of the Li ions in the dimeric scaffold in **10d**, **e** prevents the approach of the lithium base to the *ortho* position and directs the second lithiation to the adjacent and freely accessible C(α) atom.

2.3 Dilithiated Phosphonates

Chiral organophosphorus compounds are extraordinarily significant as reagents in asymmetric synthesis.[35] To date, however, phosphorus-stabilised dilithiomethane analogues have been rarely used in synthesis, and the lack of direct evidence led to doubt about the existence of such compounds.[36] The first experimental proof for a geminal dilithiated phosphorus compound is represented by the lithium cluster **16**.[33] The hexameric aggregate consists of six dilithiated phosphonate units and two molecules of dimethylamide. In addition, two Li^+ ions are coordinated by four TMEDA ligands in a distorted *tetrahedral* fashion, balancing the remaining two negative charges. The core of the aggregate is characterised by a Li–O–Li–O four-membered ring and contains the crystallographic inversion centre (Figure 7). Such a structural motif has been found to be an essential feature in these kinds of monolithiated phosphonate, which do not contain C–Li bonds.[37]

There are three different dilithiated C atoms in the asymmetric unit, each connected to two Li^+ ions and distinctly pyramidalized. These geminal bound Li^+ ions coordinate in a similar fashion to a neighbouring phosphonate oxygen, forming C–Li–O–Li four-membered ring motifs. The incorporation of lithium dimethylamide is due to the use of excess *n*BuLi in TMEDA, which leads to the decomposition products *N*,*N*-dimethylvinylamine and lithium dimethylamide at elevated temperatures.[38] However, the excess is essential for the formation of the aggregate because it be-

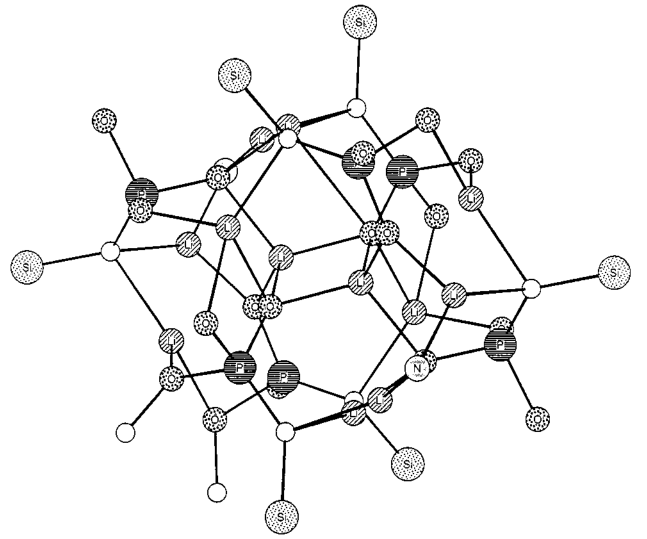
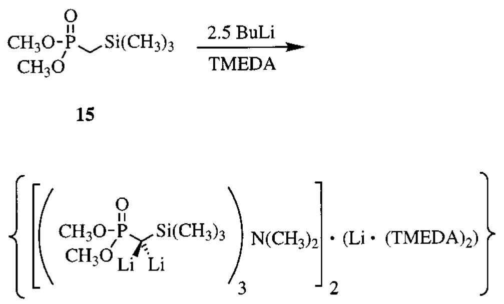


Figure 7. Molecular structure of **16**; all H atoms, the C atoms of the methyl groups on oxygen, nitrogen and silicon are omitted for clarity



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16

haves as a bridge between the Li atoms. The Li–C distances [range 2.13(1)–2.28(1) Å] can be compared with those in monolithiated phosphonates, which have Li–C distances of 2.21–2.26 Å.[37] The Li–O distances within each C–Li–O–Li chelate [range 1.95(1)–2.85(1) Å] are significantly longer than those within the $(Li–O)_2$ core [1.895(9) and 1.903(9) Å, respectively]. A striking feature is the extremely short P–C bond lengths [1.587(6), 1.604(5) and 1.619(6) Å] compared to neutral (1.80 Å) and monolithiated phosphonates (ca. 1.68 Å). The phosphonate oxygens adopt a *gauche* conformation between the geminal Li^+ cations, clearly indicating a significant degree of pyramidalization. The foundation of this aggregate seems to be the central $(Li–O)_2$ core, which is related to the fundamental structural unit derived from several monolithiophosphonates. We therefore conclude that, after the formation of the typical four-membered rhomboid motif, the incorporation of the second lithium affects only the aggregation sphere outside of the $(Li–O)_2$ core.

2.4 Dilithiated Phosphinimines

Recently, two reports on a remarkable geminal dilithiated phosphinimine were published independently.[34a,34b] The symmetrical bisphosphinime **17** could easily be deprotonated with two equivalents of a strong lithium base to give the dimer **18** (Figure 8).

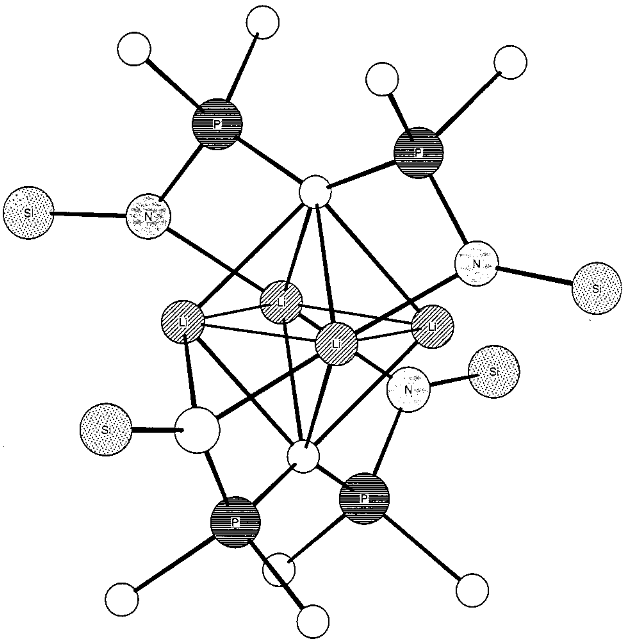
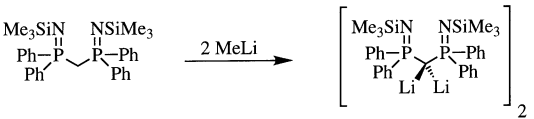


Figure 8. Molecular structure of **18**; all H atoms, the C atoms of the phenyl groups (except the *ipso*-C's) and of the methyl groups on silicon are omitted for clarity; the thin lines serve to emphasise the geometrical relationship of the Li atoms and are not to be considered normal bonds



17 **18**

In this aggregate, two dilithiated phosphinimine units are connected in a "head-to-head" manner, although repulsive interactions should be expected. This is presumably compensated by the chelating properties of the imino N atoms, which bridge two lithium atoms each. The four lithium atoms form a square plane which is capped above and below by the C(α) atoms of the P–C–P ligands, inducing a slightly dissymmetric C_2Li_4 pseudo-*octahedron*. Such a structural motif has already been predicted by computational investigations.[4] The coordination geometry around the dianionic carbon atoms is most remarkable: the N–P–C–P–N units are fairly close to planarity and adopt a perpendicular orientation to each other. In addition, they are also *orthogonal* to the central lithium square. The coordination sphere around each lithium atom is markedly distorted from the ideal *tetrahedral* geometry. The Li–C (ca. 2.38 Å) and the Li–N distances (2.09–2.15 Å) are within the range of related compounds.

3. Computational Investigations

3.1 Mono- and Dilithiated Sulfoximines

Ab initio calculations have been able to determine with considerable success the gas phase structures of achiral and chiral oxygen-, nitrogen-, phosphorus-, and sulfur-stabilized (mono)lithiocarbanions.[39–42] It was our objective to extend these studies from chiral monolithio- to dilithiosulfoximines and to elucidate the possible structures and stabilities of these dilithio intermediates by classical ab initio methods and Density Functional Theory (B3LYP).[24,43] The prochiral model system (*N*-methyl)dimethylsulfoximine **19** was chosen for our computational investigations. Ab initio calculations of the lithiated dimethylsulfoximine **20** yielded 3 different major structural minima **20a–c** (Figure 9).

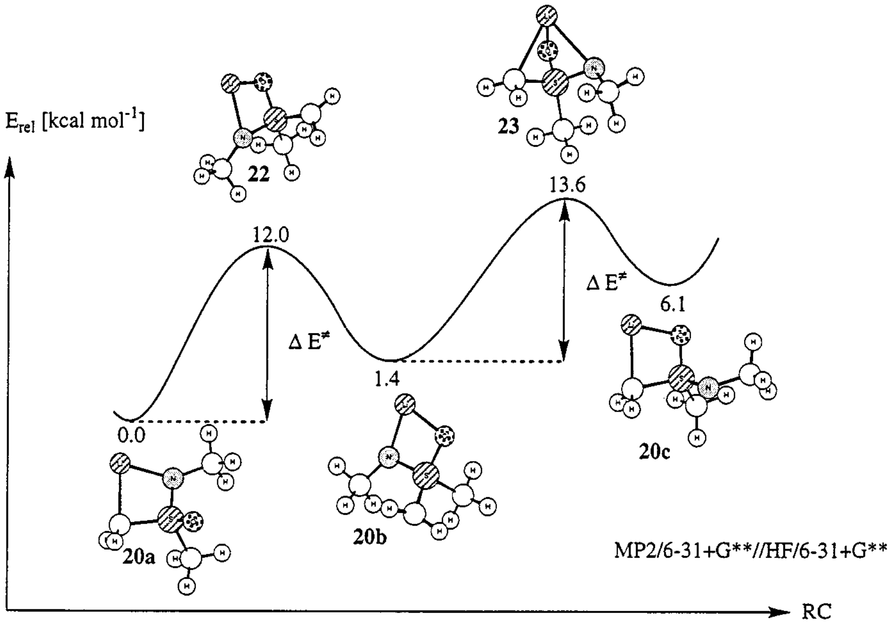
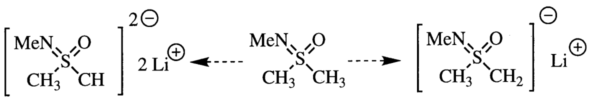


Figure 9. Local energy minima of **20a–c**



21 **19** **20**

Of these, **20a** exhibits a Li–C–S–N four-membered chelate ring; Li–O complexation and a Li–C contact are found in **20c** whereas in **20b** no Li–C contact occurs. In the latter case the sulfoximine O- and N-atoms coordinate to the lithium cation in an orientation reminiscent of typical lithiophenylsulfones and lithioallylsulfoximines.[21,24,25] The Li–N chelate **20a** represents the structure lowest in energy but, surprisingly, the sulfoximine *O*- and *N*-coordinated lithium salt **20b** is only 1.4 kcal/mol higher in energy, whereas the Li–O chelation in **20c** is clearly energetically disfavoured by 6.1 kcal/mol compared to **20a** and **20b**. Lithiation of the dimethylsulfoximine **19** causes a number of distinctive structural changes in **20a–c**: in **20a** a lengthening of the S–N (1.53 vs. 1.58 Å) bond is observed. Similarly the O,C chelation in **20c** lengthens the S–O bond from 1.45 to 1.51 Å while in **20b**, with Li–N, *O*-coordination, both the S–N and S–O bonds are lengthened. The C(α)–Li contact allows only a small shortening of the S–C(α) bond in **20a** (1.72 Å) and **20c** (1.73 Å) whereas in **20b** a significant shortening of the S–C(α) bond is observed (1.63 vs. 1.77 Å in **19**). Structure **22** shows a coordination of the lithium ion to the O and N atoms and can be interpreted as the transition state between the structure minima **20a** and **20b**. The isomers **20b** and **20c** are separated by the transition state **23** by 12.2 kcal/mol. In **23** an unsymmetrical tridentate bonding of the lithium to the O, N, and C(α) atoms is found in contrast to **22** where no Li–C bonding is observed. These characteristics suggest an interconversion mechanism of **20b** to **20c** with **23** as an intermediate. Dilithiation afforded three different local energy minima (Structures **21a–c,** Figure 10).

The isomer **21a** is lowest in energy and exhibits a dilithiospirostructure containing two Li–N–S–C and Li–O–S–C chelates with two different C(α) atoms. A small change in both S–C(α) bond lengths is observed compared to the protonated parent **19** (1.77 Å in **19** vs. 1.73 and 1.75 Å in **21a**). The Li–C distances are 2.09 Å in either case. The lone pairs at the anionic C atoms point away from one another in the direction of each lithium atom, thus minimising the repulsion caused by the two negative charges. Structure **21b** represents a local minimum that is only 2.7 kcal/mol higher in energy. It is characterised by an α,α-dilithiosulfoximine arrangement in which both lithiums are attached to the same C(α) atom. In addition, each lithium is coordinated to one of the two heteroatoms of the sulfonimidoyl moiety, thereby forming (Li–N–S–C) and (Li–O–S–C) four-membered ring chelates, respectively. The S–C(α) bond is signi-

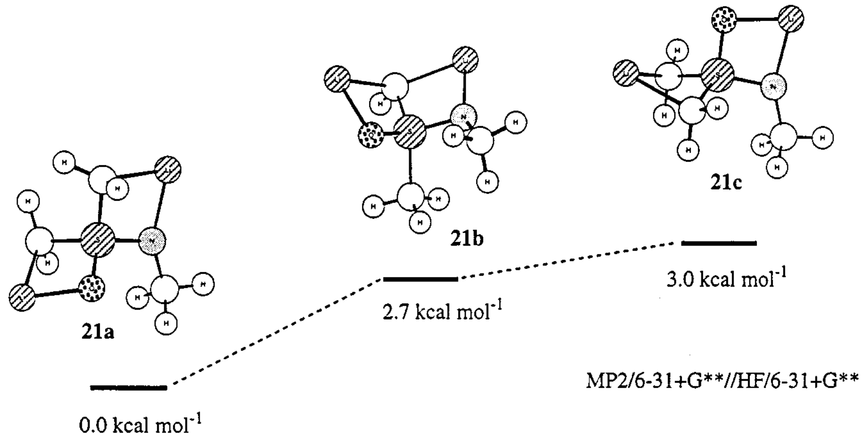


Figure 10. Local energy minima of **21a–c**

ficantly shortened after dimetallation from 1.77 Å to 1.66 Å. The lithium atom coordinating to the sulfoximine oxygen yields the longer Li–C bond with 2.11 Å. In contrast, in the N-chelate the Li–C bond is markedly shorter (2.04 Å). Both planes that are defined by the two four-membered ring chelates form a butterfly-type structure. The lithium atoms are in a diastereotopic environment, which are interesting for synthetic purposes. The local minimum structure **21c** lies 0.3 kcal/mol higher in energy than **21b**. Remarkably, in **21c** one lithium is exclusively coordinated to the heteroatoms of the sulfoximine group whereas the other shows a symmetrical bridging to the C(α) atoms. The twofold carbon coordination of the lithium is unusual, because all other chelation modes of the lithium atoms correspond to structural motifs that have already been calculated for monolithiosulfoximines. The Li–C distances are elongated to 2.23 Å in comparison to the structures **21a** (2.09Å) and **21b** (2.04 and 2.11Å).

A comparison of these major structural minima with the results of MP2(full)/6-31+G** calculations yielded only marginal changes in their geometries and energies. Greater accuracy in the determination of the relative energies may be achieved by applying CBS-Q.[44] These results show a reverse order in the relative stabilities: **21b** becomes slightly energetically favoured over **21c**, but the difference in their energies remains small (see Table 1).

Table 1. Relative energies [in kcal mol^{-1}]

	21a	21b	21c
MP2/6-31+G**//HF/6-31+G**	0.00	2.74	3.01
B3LYP/6-31+G**	0.00	4.87	2.79
CBS-Q (0 K)	0.00	2.23	1.07
CBS-4 (0 K)	0.00	0.72	2.23
MP2 (full)/6-31+G**	0.00	3.02	3.55

The same observation is made for B3LYP/6-31+G**, where **21b** is about 2.1 kcal/mol higher in energy than **21c**.[45] In conclusion, all applied methods show compound **21a** as the global minimum. The isomers **21b** and **21c** are in general 1–5 kcal/mol higher in energy and are fairly close to one another.

3.2 Gas Phase Structures of the Monolithio Sulfoximine Anions and Lithium-Free Dianions

The successive removal of a lithium cation in **21a** resulted in two different monolithiated anions **24a**$^-$ and **24b**$^-$, in which the Li–N–S–C chelate **24a**$^-$ is energetically favoured by ca. 7 kcal/mol over the Li–O–S–C complexation in **24b**$^-$ (see Figure 11 and Table 2).

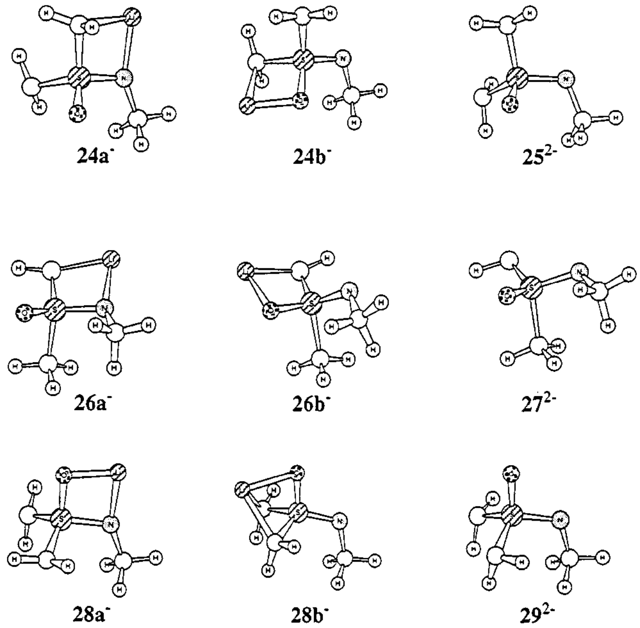


Figure 11. Structure of the monolithio anions **24a,b**$^-$, **26a,b**$^-$, **28a,b**$^-$ and the lithium-free dianions **25**$^{2-}$, **27**$^{2-}$, **29**$^{2-}$

The analogous procedure was also performed with the dilithio salt **21b**. After removal of one lithium the Li–N–S–C complexation is energetically favoured over the Li–O–S–C coordination. The resulting monolithio intermediates **26a**$^-$ and **26b**$^-$ differ distinctly from the structures derived from **21a** even though the complexation energies are similar. The unusual coordination mode of the lithium cations in **21c** leads, after decomplexation of one lithium, either to an exclusively heteroatom-*N*,*O*-coordinated monolithioanion

Table 2. Relative energies of the resulting anions after removal of the lithium cations [in kcal mol^{-1} based on MP2(full)/6-31+G**//HF/6-31+G** calculations]

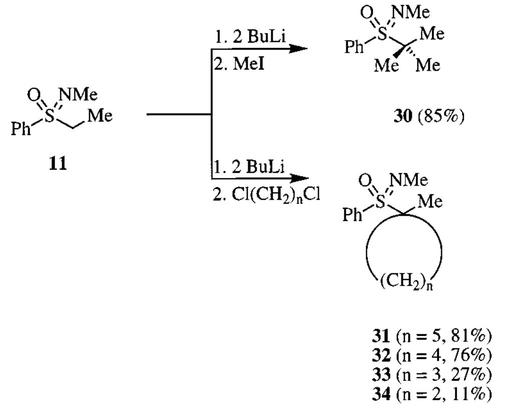
	Geometries		
	Optimised	Non-optimised	ΔE
24a$^-$	171.6	180.9	9.3
26a$^-$	172.0	181.4	9.4
28a$^-$	169.1	188.3	9.2
24b$^-$	178.4	187.0	8.6
26b$^-$	177.8	192.1	12.3
28b$^-$	170.2	177.1	6.9
25^{2-}	437.6	449.4	11.8
27^{2-}	451.7	465.8	14.1
29^{2-}	439.9	447.6	7.5

28a$^-$ or to a threefold lithium-coordinated monolithioanion **28b**$^-$. The removal of the second lithium produces a naked 1,3-dianionic species **25**$^{2-}$. The total delithiation requires 437 kcal/mol when starting from the dilithiosulfoximine **21a**. The energy required for the second delithiation amounts to 266 kcal/mol from **24a**$^-$ and 259 kcal/mol from **24b**$^-$. Removal of the second lithium cation affords the α,α-dianion **27**$^{2-}$. The energy required for the twofold delithiation of **21b** amounts to 451 kcal/mol. After removal of the second lithium ion the 1,3-dianion **29**$^{2-}$ is generated (439 kcal/mol), which is closely related to the dianionic species **25**$^{2-}$ with only small differences in their conformations and energies.

4. Applications in Asymmetric Synthesis

4.1 Regio- and Diastereoselective Cyclisations with Biselectrophiles

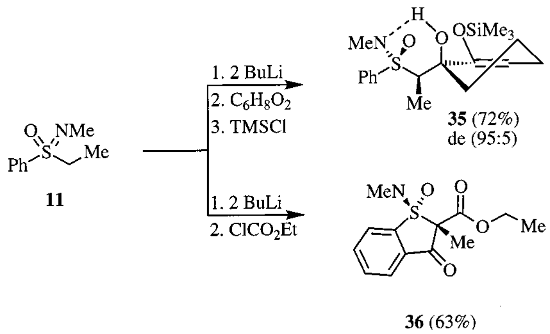
For the investigation into the use of a chiral dilithiated sulfoximine in asymmetric synthesis, the generated dilithio intermediate **12** has been trapped with various electrophiles.[29] Addition of MeI afforded nearly regioselectively the α,α-dimethylated *S-tert*-butyl-*S*-phenylsulfoximine **30** in high yield (85%). Such behaviour was unknown for sulfoximines but is not unusual for sulfones, where an α,*o*-dilithiated species has also been observed that showed a similar reactivity with alkylhalides.[46] NMR-spectroscopic studies by Gais et al. have demonstrated that a temperature dependent transmetallation of an α,*o*- to an α,α-dilithio species is possible.[16] Taking this into account, it becomes reasonable to suggest a transmetallation process as a possible explanation for the observed regioselectivity with dilithiated **11**. This means that, after the first alkylation step in the α-position, a translithiation takes place leading finally to the α,α-dialkylated product. Performing this procedure with a biselectrophile like 1,5-diiodopentane, we expected a similar regioselectivity to the reaction with MeI, which should lead to a ring closure in the α-position.



Indeed, a six-membered ring in **31** is formed without any regioisomers and in high yield (81%). With 1,4-diiodobutane a five-membered ring species **32** was obtained in good yield (76%). Cyclisation reactions with shorter bridged biselectrophiles showed dramatically lower yields, presumably due to undesired side reactions. The cyclobutane derivative **33** and the cyclopropyl-sulfoximine **34** are therefore only accessible in yields of 27% and 11%.

4.2 Addition to Prochiral Electrophiles

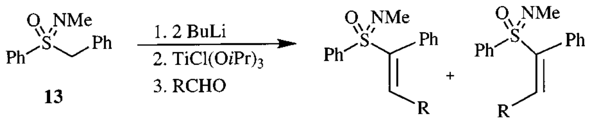
In contrast to the simple biselectrophiles discussed above, cyclohexane-1,2-dione, in the presence of TMSCl, did not undergo ring closure to a cyclopropane derivative. Instead the α,*o*-dilithio species **12** acted as a base and a nucleophile leading, in a synergistic manner in a single reaction-step, to the β-hydroxysulfoximine **35** in high yield (72%) and excellent diastereomeric ratio (95:5). The absolute stereochemistry of the major isomer of **35** has been determined by X-ray structure analysis.



Typical of β-hydroxysulfoximines is the ability to build intramolecular hydrogen bonds to the imino nitrogen to give a six-membered ring with a chair conformation.[47] The methyl group on C(α) and the larger, silyloxy-containing substituent on C(β) are oriented in a pseudo-equatorial fashion. The reaction of the dilithiosulfoximine **12** with ethyl chloroformate afforded, in good yield (63%), the heterocycle **36** as single diastereoisomer. This cyclisation must proceed by a third deprotonation step. NOE experiments confirm that the cis configuration of the C-methyl and *N*-methyl groups is present in the five-membered heterocycle.

4.3 Transmetallation and Alkene Formation

If there are two different metals bound to the same carbon atom of a chiral reagent a new stereocentre might be induced. This principle can be used for the transformation of chiral information, but has rarely been applied in stereoselective reactions.[12,48] Our approach took advantage of the transmetallation of a geminal dilithiated sulfoximine **14** with $ClTi(OiPr)_3$. Addition of several aldehydes to such a titanated dilithiosulfoximine did not lead to β-hydroxysulfoximines and, instead, only the alkenylsulfoximines **37**–**39** were formed. The reactions proceed in a highly diastereoselective fashion leading predominantly to the (*E*)-alkenes.



37 R = Ph, 74%, E:Z = 95:5
38 R = *t*Bu, 77%, E:Z = 99:1
39 R = Et, 68%, E:Z = 90:10

5. Conclusion

The first heterochiral dilithiomethane derivative **14** was structurally confirmed by X-ray analysis. A comparison with its monolithiated precursor **10e** revealed a dimer devoid of Li–C contacts. In our opinion, the free accessibility to the anionic C(α) atom in **10e** is responsible for the geminal dilithiation. This is not the case for lithiosulfoximines that form C–Li bonds, as can be seen in lithiated alkyl- or alkenyl-substituted sulfoximines **10a**,**b**,**f**. The second metallation leads to an α,*o*-dilithiosulfoximine. The structures of achiral phosphorus-stabilised geminal dilithio salts have only very recently been confirmed. Since chiral modifications of such compounds are easy to perform, one might expect to use the derived dilithio salts in asymmetric synthesis. The X-ray crystallographic studies on mono- and dilithiated sulfoximines were complemented by quantum chemical calculations on the lithiated (*N*-methyl)dimethylsulfoximine **19**. Three different major energy minima were obtained with the lithium-*N*,*C*-chelate **20a** and the sulfoximine-*N*,*O*-coordinated lithium salt **20b** representing the most stable isomers. In contrast, lithium-*O*,*C*-coordination in **20c** is energetically disfavoured, so that *N*,*C*- and *N*,*O*-coordination should be preferred to *O*,*C*-coordination. Three equilibrium structures for the dilithiated *N*,*S*,*S*-trimethylsulfoximine system were also found, with the dilithiospiro structure **21a** representing the most stable isomer. Only ca. 1–5 kcal/mol higher in energy were the α,α-dilithiosulfoximine **21b** and the isomer **21c**, which have heteroatom contacts to one lithium while the second lithium is associated with both anionic carbon atoms. In conclusion, these results have some important implications for asymmetric synthesis: because reactions with achiral dilithio salts are already meaningful in synthetic sequences one can imagine further synthetic approaches with chiral dilithio compounds derived from the discussed dilithiosulfoximine intermediates **21a** or **21b**. The first multiple stereoselective C–C bond formations with prochiral biselectrophiles have been applied in cyclisation reactions and have led to a new and powerful methodology for the synthesis of new carbo- and heterocycles. The reaction of the dilithiated sulfoximine **11** with cyclohexane-1,2-dione afforded a β-hydroxysulfoximine with high stereocontrol. Transmetallation of **14** with $ClTi(OiPr)_3$ followed by addition of an aldehyde allowed the highly diastereoselective synthesis of (*E*)-alkenylsulfoximines. This new methodology works for the single-step formation of multiple C–C bonds under high regio- and diastereocontrol. Our further studies will focus on this novel concept to create chiral mixed organodimetallics and to apply these compounds in asymmetric synthesis.

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[1] K. Ziegler, K. Nagel, M. Patheiger, *Z. Anorg. Allg. Chem.* **1955**, *282*, 345–352.

[2] J. A. Gurak, J. W. Chinn, R. J. Lagow, H. Steinfink, S. C. Yannoni, *Inorg. Chem.* **1984**, *23*, 3717–3720.

[3] G. D. Stucky, M. M. Eddy, W. H. Harrison, R. Lagow, H. Kawa, D. E. Cox, *J. Am. Chem. Soc.* **1990**, *112*, 2425–2427.

[4] [4a] J. B. Collins, J. D. Dill, E. D. Jemmis, Y. Apoloig, P. v. R. Schleyer, R. Seeger, J. A. Pople, *J. Am. Chem. Soc.* **1976**, *98*, 5419–5427. – [4b] E. D. Jemmis, P. v. R. Schleyer, J. A. Pople, *J. Organomet. Chem.* **1978**, *154*, 327–335.

[5] [5a] I. Marek, J.-F. Normant, *Chem. Rev.* **1996**, *96*, 3241–3267. – [5b] C. M. Thomson, in: *Dianion Chemistry in Organic Synthesis*, CRC Press, Boca Raton, Florida, **1994**, pp. 1–250. – [5c] A. Maerker, in: *Lithium Chemistry* (Eds.: A.-M. Sapse, P. v. R. Schleyer), Wiley, New York, **1995**, p. 477–577. – [5d] A. Maerker, M. Theis, *Top. Curr. Chem.* **1987**, *138*, 1–61.

[6] S. Brenner, M. Bovete, *Tetrahedron* **1975**, *31*, 153–158.

[7] [7a] E. M. Kaiser, L. E. Solter, R. A. Schwarz, R. D. Beard, C. R. Hauser, *J. Am. Chem. Soc.* **1971**, *93*, 4237–4242. – [7b] E. M. Kaiser, J. D. Petty, P. L. A. Knutson, *Synthesis* **1977**, 509–550.

[8] [8a] F. Caturia, C. Nájera, *Tetrahedron Lett.* **1996**, *37*, 2833–2836. – [8b] P. Bonete, C. Nájera, *Tetrahedron* **1996**, *52*, 4111–4122.

[9] B. Iorga, F. Eymery, P. Savignac, *Tetrahedron Lett.* **1998**, *39*, 3693–3696.

[10] [10a] C. R. Johnson, *Aldrichim. Acta* **1985**, *18*, 3–11. – [10b] C. Bolm, J. Müller, G. Schlingloff, M. Zehnder, M. Neuburger, *J. Chem. Soc., Chem. Commun.* **1993**, 182–183. – [10c] H.-J. Gais, H. Müller, J. Bund, M. Scommoda, J. Brandt, G. Raabe, *J. Am. Chem. Soc.* **1995**, *117*, 2453–2466. – [10d] M. Reggelin, H. Weinberger, *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 444–446.

[11] [11a] L. Horner, H. Hoffmann, H. G. Wippel, *Chem. Ber.* **1958**, *91*, 61–63. – [11b] W. S. J. Wadsworth, W. D. Emmons, *J. Am. Chem. Soc.* **1961**, *83*, 1733–1738.

[12] J. Vollhardt, H.-J. Gais, K. L. Lukas, *Angew. Chem. Int. Ed.* **1985**, 24, 608–609.

[13] W. Zarges, M. Marsch, K. Harms, G. Boche, *Angew. Chem. Int. Ed.* **1989**, *28*, 1392–1393.

[14] H.-J. Gais, J. Vollhardt, H. Günther, D. Moskau, H. J. Lindner, S. Braun, *J. Am. Chem. Soc.* **1988**, *110*, 978–980.

[15] W. Zarges, M. Marsch, K. Harms, G. Boche, *Chem. Ber.* **1989**, *122*, 1307–1311.

[16] H.-J. Gais, J. Vollhardt, *Tetrahedron Lett.* **1988**, *29*, 1529–1532.

[17] [17a] T. Kottke, R. J. Lagow, D. Stalke, *J. Appl. Crystallogr.* **1996**, *29*, 465–468.[17b] T. Kottke, D. Stalke, *J. Appl. Crystallogr.* **1993**, *26*, 615–619.

[18] A. Streitwieser, S. M. Bachrach, A. Dorigo, P. v. R. Schleyer, in: *Lithium Chemistry* (Eds.: A.-M. Sapse, P. v. R. Schleyer), Wiley, New York, **1995**, p. 1–43.

[19] H.-J. Gais, I. Erdelmeier, H. J. Lindner, J. Vollhardt, *Angew. Chem. Int. Ed.* **1986**, *25*, 938–939.

[20] H.-J. Gais, U. Dingerdissen, C. Krüger, K. Angermund, *J. Am. Chem. Soc.* **1987**, *109*, 3775–3776.

[21] G. Boche, *Angew. Chem. Int. Ed.* **1989**, *28*, 277–297.

[22] H.-J. Gais, D. Lenz, G. Raabe, *Tetrahedron Lett.* **1995**, *36*, 7437–7440.

[23] [23a] U. Salzner, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1993**, *115*,

10231–10236.[23b] G. Raabe, H.-J. Gais, J. Fleischhauer, *J. Am. Chem. Soc*. **1996**, *118*, 4622–4630.

[24] J. F. K. Müller, R. Batra, B. Spingler, M. Zehnder, *Helv. Chim. Acta* **1996**, *79*, 820–826.

[25] [25a] H.-J. Gais, J. Mueller, J. Vollhardt, *J. Am. Chem. Soc.* **1991**, *113*, 4002–4003. – [25b] H.-J. Gais, G. Hellmann, H. J. Lindner, *Angew. Chem. Int. Ed.* **1990**, *29*, 100–102. – [25c] H.-J. Gais, G. Hellmann, H. Guenther, F. Lopez, H. J. Braun, *Angew. Chem. Int. Ed.* **1989**, *28*, 1025–1027. – [25d] W. Hollstein, M. Marsch, K. Harms, G. Boche, *Angew. Chem. Int. Ed.* **1988**, *27*, 846–847. – [25e] H.-J. Gais, J. Vollhardt, G. Hellmann, H. Paulus, H. J. Lindner, *Tetrahedron Lett.* **1988**, *22*, 1259–1262. – [25f] H.-J. Gais, J. Vollhardt, H. J. Lindner, *Angew. Chem. Int. Ed.* **1986**, *25*, 939–940. – [25g] H.-J. Gais, H. J. Lindner, J. Vollhardt, *Angew. Chem. Int. Ed.* **1985**, *24*, 859–860. – [25h] G. Boche, M. Marsch, K. Harms, G. M. Sheldrick, *Angew. Chem. Int. Ed.* **1985**, *24*, 573–574.

[26] J. F. K. Müller, M. Neuburger, B. Spingler, *Angew. Chem. Int. Ed.* **1999**, *38*, 3549–3552.

[27] J. F. K. Müller, M. Neuburger, M. Zehnder, *Acta Crystallogr., Sect. C* **1997**, *53*, 419–422.

[28] J. F. K. Müller, M. Neuburger, M. Zehnder, *Helv. Chim. Acta* **1995**, *78*, 615–618.

[29] J. F. K. Müller, M. Neuburger, M. Zehnder, *Helv. Chim. Acta* **1997**, *80*, 2182–2190.

[30] [30a] W. Clegg, L. Horsburgh, P. R. Dennison, F. M. Mackenzie, R. E. Mulvey, *Chem. Commun.* **1996**, 1065–1066.[30b] S. C. Ball, I. Cragg-Hine, M. G. Davidson, R. P. Davies, M. I. Lopez-Solera, P. R. Raithby, D. Reed, R. Snaith, E. M. Vogel, *J. Chem. Soc., Chem. Commun.* **1995**, 2147–2148.[30c] C. Lambert, F. Hampel, P. v. R. Schleyer, M. G. Davidson, R. Snaith, *J. Organomet. Chem.* **1995**, *487*, 139–141. – [30d] H. Dietrich, D. Rewicki, *J. Organomet. Chem.* **1981**, *205*, 281–289.

[31] R. F. W. Jackson, A. D. Briggs, P. A. Brown, W. Clegg, M. R. J. Elsegood, C. Frampton, *J. Chem. Soc., Perkin Trans. 1* **1996**, 1673–1682.

[32] For a comprehensive review on *ortho*-metallation reactions see: V. Snieckus, *Chem. Rev.* **1990**, *90*, 879–933.

[33] J. F. K. Müller, M. Neuburger, B. Spingler, *Angew. Chem. Int. Ed.* **1999**, *38*, 92–94.

[34] [34a] C. M. Ong, D. W. Stephan, *J. Am. Chem. Soc*. **1999**, *121*, 2939–2940. – [34b] A. Kasani, R. P. Kamalesh Babu, R. McDonald, R. G. Cavell, *Angew. Chem. Int. Ed.* **1999**, *38*, 1483–1484. – [34c] A. Müller, B. Neumüller, K. Dehnicke, *Chem. Ber.* **1996**, *129*, 253–257.

[35] [35a] J. Clayden, S. Warren, *Angew. Chem. Int. Ed.* **1996**, *35*, 241–270. – [35b] B. E. Maryanoff, A. B. Reitz, *Chem. Rev.* **1989**, *89*, 863–927.

[36] B. Iorga, F. Eymery, P. Savignac, *Tetrahedron Lett.* **1998**, *39*, 4477–4480.

[37] [37a] W. Zarges, M. Marsch, K. Harms, F. Haller, G. Frenking, G. Boche, *Chem. Ber.* **1991**, *124*, 861–866. – [37b] S. E. Denmark, K. A. Swiss, P. C. Miller, S. R. Wilson, *Heteroatom Chem.* **1998**, *9*, 209–218.

[38] G. G. Eberhardt, W. A. Butte, *J. Org. Chem.* **1964**, *29*, 2928–2932.

[39] [39a] G. W. Spitznagel, T. Clark, J. Chandrasekhar, P. v. R. Schleyer, *J. Comput. Chem. 3* **1982**, 363–371. – [39b] F. Bernardi, A. Bottoni, A. Venturini, A. Mangini, *J. Am. Chem. Soc*. **1986**, *108*, 8171–8175.

[40] [40a] T. Clark, P. v. R. Schleyer, K. N. Houk, N. G. Rondan, *J. Chem. Soc., Chem. Commun.* **1981**, 579–581. – [40b] P. v. R. Schleyer, T. Clark, A. J. Kos, G. W. Spitznagel, G. Rohde, D. Arad, K. N. Houk, N. G. Rondan, *J. Am. Chem. Soc*. **1984**, *106*, 6467–6475. – [40c] G. Boche, J. C. W. Lohrenz, A. Opel, in: *Lithium Chemistry* (Eds.: A.-M. Sapse, P. v. R. Schleyer), Wiley, New York, **1995**, 195–226. – [40d] A. M. El-Nahas, P. v. R. Schleyer, *J. Comput. Chem*. **1994**, *15*, 596–625.

[41] [41a] A. Streitwieser Jr., A. Rajca, R. S. McDowell, R. Glaser, *J. Am. Chem. Soc*. **1987**, *109*, 4184–4188. – [41b] S. E. Denmark, C. J. Cramer, *J. Org. Chem*. **1990**, *55*, 1806–1813. – [41c] C. J. Cramer, S. E. Denmark, P. C. Miller, R. L. Dorow, K. A. Swiss, S. R. Wilson, *J. Am. Chem. Soc*. **1994**, *116*, 2437–2447. – [41d] R. Koch, E. Anders, *J. Org. Chem*. **1995**, *60*, 5861–5866. – [41f] M. Kranz, S. E. Denmark, *J. Org. Chem*. **1995**, *60*, 5867–5877. – [41e] M. Kranz, S. E. Denmark, K. A. Swiss, S. R. Wilson, *J. Org. Chem*. **1996**, *61*, 8551–8563.

[42] [42a] S. Wolfe, A. Rauk, I. G. Csizmadia, *J. Am. Chem. Soc.* **1969**, *91*, 1567–1569. – [42b] S. Wolfe, A. Rauk, L. M. Tel, I. G. Csizmadia, *J. Chem. Soc., Chem. Commun*. **1970**, 96–97. – [42c] A. Streitwieser Jr., J. E. Williams, Jr., *J. Am. Chem. Soc*. **1975**, *97*, 191–192. – [42d] S. Wolfe, A. Stolow, L. A. La John, *Tetrahedron Lett.* **1983**, *24*, 4071–4074. – [42e] S. Wolfe, L. A. La John, D. F. Weaver, *Tetrahedron Lett.* **1984**, *25*, 2863–2866. – [42f] T. Clark, in: *Sulfur Centered Reactive Intermediates In Chemistry and Biology* (Eds.: C. Chatgiliaoglu, K.-D. Asmus), NATO ASI Series A, Life Sciences 197, Plenum Press, New York, **1990**, p 13. – [42g] R. Koch, E. Anders, *J. Org. Chem.* **1994**, *59*, 4529–4534.

[43] J. F. K. Müller, R. Batra, *J. Organomet. Chem*. **1999**, *584*, 27–32.

[44] [44a] J. W. Ochterski, G. A. Petersson, K. B. Wiberg, *J. Am. Chem. Soc*. **1995**, *117*, 11299–11308. – [44b] J. W. Ochterski, G. A. Petersson, J. Montgomery, Jr., *J. Chem. Phys*. **1996**, *104*, 2598–2619.

[45] [45a] P. Hohenberg, W. Kohn, *Phys. Rev.* **1964**, *136*, B 864. – [45b] W. Kohn, L. Sham, *J. Phys. Rev.* **1965**, *140*, A 1133. – [45c] J. C. Slater, *International Series in Pure and Applied Physics*, vol. 4 ("The Self-Consistent Field of Molecules and Solids. Quantum Theory") McGraw-Hill, New York, **1974**. – [45d] A. D. Becke, *Phys. Rev. A* **1988**, *38*, 3098. – [45e] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 1372–1377. – [45f] J. P. Perdew, Y. Wang, *Phys. Rev. B* **1992**, *45*, 13244. – [45g] R. G. Parr, Y. Wang, *Density-Functional Theory of Atoms and Molecules*, Oxford University Press, Oxford, **1989**.

[46] J. Vollhardt, H.-J. Gais, L. Lukas, *Angew. Chem. Int. Ed.* **1985**, *24*, 608–610.

[47] K.-J. Hwang, E. W. Logusch, L. H. Brannigan, M. R. Thompson, *J. Org. Chem.* **1987**, *52*, 3435–3441.

[48] [48a] J. Vollhardt, H.-J. Gais, K. L. Lukas, *Angew. Chem. Int. Ed.* **1985**, *24*, 696–697. – [48b] H.-J. Gais, J. Vollhardt, H. J. Lindner, H. Paulus, *Angew. Chem. Int. Ed.* **1988**, 27, 1540–1542.

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