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Chiral sulfoxides in the enantioselective allylation of aldehydes with allyltrichlorosilane: a kinetic study†

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The mechanism of the allylation of aldehydes in the presence of allyltrichlorosilane employing the commercially available (R)-methyl p-tolyl sulfoxide as a Lewis base has been investigated. The combination of kinetic measurements, conductivity analysis and quantum chemical calculations indicates that the reaction proceeds through a dissociative pathway in which an octahedral cationic complex with two sulfoxides is involved. The lack of turnover is ascribed to the formation of neutral sulfurane derivatives.

1. Introduction

The enantioselective allylation of aldehydes is one of the most important tools to obtain chiral homoallylic alcohols, useful building blocks for the synthesis of complex chiral molecules.[1]

Different strategies, including the use of chirally modified allylmetal reagents, chiral Lewis-acid catalysed addition of allylmetal reagents to aldehydes, and chiral Lewis-base activation of allyltrichlorosilane, have been applied to achieve this transformation. Thanks to the high control of the diastereoselectivity and to the development of several enantioselective versions, the Lewis base approach, discovered by Denmark[2a] and Kobayashi,[2b] has attracted the attention of several groups during the last few decades. The very good control of the diastereoselectivity, which reflects the E/Z ratio of substituted allyltrichlorosilane, was explained with a highly ordered cyclic chair-like transition state.[2] In particular a variety of chiral Lewis bases such as phosphoramides,[2] pyridine N-oxides,[3] sulfoxides,[4,5] formamides[6] and phosphine oxides[7] proved to be effective in this enantioselective allylation of aldehydes. Among the chiral Lewis bases, structurally complex chiral bisphosphoramides[2c–g] and N-oxides[5] proved to be the most efficient catalysts in terms of catalyst loading and asymmetric induction.

Conversely, despite the promising enantioselectivity and the high diastereoselectivities obtained in the allylation and crotylation of aldehydes[4,5] and hydrazones,[8] chiral sulfoxides present the main drawback of being required in large excess.

Considering the advance in the knowledge of the reaction mechanism for other classes of Lewis bases,[2c,h,3h] the basic information on the kinetic equation and the turnover limiting steps for the allylation reactions promoted by chiral sulfoxides is still lacking.[4c,5d] This is a serious limitation for the identification of more efficient chiral sulfoxides as Lewis bases in the allylation reaction. In fact a great number of chiral sulfoxides have been reported as important and widespread chiral controllers in several asymmetric transformations due to their ready availability in high enantiomeric purity and to their usual configurational stability at sulfur.[9]

Therefore, our article discloses the efforts to investigate the kinetic mechanism of enantioselective allylation of aldehydes with allyltrichlorosilane in the presence of a simple chiral monodentate sulfoxide, the commercially available (R)-methyl p-tolyl sulfoxide.

2. Results and discussion

In the course of the last few years, several groups have reported the use of diverse chiral sulfoxides in the allylation of aldehydes[4,5] and hydrazones with allyltrichlorosilane.[8] However in most of the cases the leitmotif of these studies is the necessity to use an excess to guarantee high yields. This situation is well represented by the model reaction of benzaldehyde (1) with allyltrichlorosilane (2), in the presence of variable amounts of (R)-methyl p-tolyl sulfoxide (4) as a promoter and dichloromethane (DCM) as a solvent (Scheme 1 and Table 1).

From the data reported in the table, it can be noted that 3 or 2 equiv. of 4 are necessary to obtain high yields in reasonable reaction time (entries 1 and 2), while lower amounts (1.5 or 1 equiv.) led to significant lower yields even after prolonged

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†Electronic supplementary information (ESI) available: Experimental procedures. Gas chromatographic analysis. Description of the geometries obtained from the quantum chemical calculations and molecular models of the lowest energy structures. Complete author list for ref. 23. See DOI: 10.1039/c2ob27022f
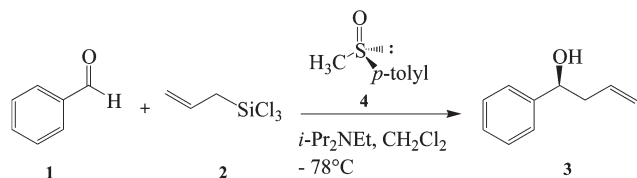
Scheme 1 Allylation of model benzaldehyde with (R)-methyl p-tolyl sulfoxide.

Table 1 Preliminary experiments employing different amounts of (R)-methyl p-tolyl sulfoxide **4**

Entries	Equiv. sulfoxide	Reaction time (h)	Yield (%)[a]	ee (%)[b]
1[c]	3.0	8	99	60
2[c]	2.0	8	84	62
3[c]	1.5	7	44	61
4[d]	1.5	65	63	60
5[c]	1	8	40	60
6[d]	1	67	38	60
7[e]	1	72	78	65

[a] Isolated yield. [b] Determined by chiral GC. [c] **4** recovered in >90% yield and >95% ee. [d] **4** recovered in 85% yield and 50% ee. [e] Reaction was performed with 6 equiv. of silane. **4** recovered in 85% yield and 40% ee.

time (entries 3–6). However, these prolonged reaction times did not affect the observed enantioselectivity, documenting a lack of turn-over or the occurrence of side reactions. Another important feature that must be taken into account in the discussion of the reaction mechanism is that, at the end of the reaction, **4** is usually recovered in quantitative yields but with an enantiomeric purity decreasing with the increase of the reaction time. Very interestingly, this racemization does not affect the enantioselectivity of the reaction and could be related at the same time to the lack of turn-over and to the occurrence of side reactions, as previously observed.

Moreover, in the presence of 1 equiv. of **4**, a notable increase of the yield with a concomitant slight increase of the ee was obtained when an excess of silane was used (6 equiv.), indicating the possibility that different mechanistic pathways can occur depending on the reaction conditions (entry 7).

In this complex picture other features must be taken into account during these kinetic studies. In particular we[4] and other groups[8a] have found that sulfoxides are effective in the allylation only at a temperature lower than −50 °C. Higher temperature, in agreement with Denmark's studies,[2a,b] led to the decomposition of the sulfoxide with the isolation of the corresponding sulphide. This can be explained by the occurrence of a deoxygenation process promoted by the silicon compound, as reported for related systems.[10] Moreover, the presence of iPr₂EtN (DIPEA) is also mandatory to avoid the decomposition of the Lewis base.[4a]

The evident complexity of this system calls for the adoption of several techniques to propose a kinetic mechanism consistent with the observed experimental outcomes. Therefore, we addressed the problem by a combination of kinetic
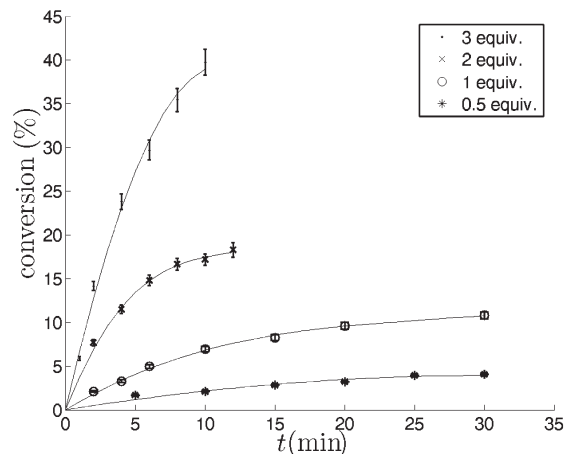

Fig. 1 Determination of the initial rates for runs with different amounts of **4**.

experiments, conductivity measurements and quantum chemical calculations.

2.1 Kinetic experiments

We have applied the method of the initial rates for the determination of the partial order in each component (sulfoxide, benzaldehyde and silane). In particular we adapted the method of ref. 3h to our system in which the gas chromatographic sampling technique, employing an internal standard, was used to monitor product formation.

2.1.1 KINETIC EXPERIMENTS: PARTIAL ORDER WITH RESPECT TO SULFOXIDE. We started our investigation determining the partial order with respect to sulfoxide **4**. In order to achieve this goal, we determined the production of the alcohol **3** as a function of time, using different amounts of **4** (0.5, 1, 2 and 3 equiv., Fig. 1).

From the analysis of the obtained data, it is noteworthy that in the time interval of conversions similar to those used in ref. 3h, we obtained curved plots, instead of linear plots. However attempt at lowering the time intervals to get linear plots leads to smaller amounts of products and thus increased uncertainties in their quantitative determination. We thus preferred to recover the initial velocity v_0 by polynomial fitting. This gave the opportunity to obtain the initial rates with good confidence for every experimental plot in Fig. 1. Then a log–log plot of the initial rate *versus* the concentration of **4** yielded a partial order of 1.87 ± 0.09 (Fig. 2). This 'almost two' partial order is consistent with the participation of two molecules of sulfoxide in the rate limiting step, even if a concomitant less important mono-coordinated pathway cannot be excluded, as reported with chiral phosphoramides[2h] and N-oxides[3h] and as the allylation in the presence of 6 equiv. of silane can suggest (entry 7 of Table 1).

Apparently a 'two-ligated' pathway could not explain the almost lack of non-linear effects for benzaldehyde as observed in our previous studies.[4c] However according to Kagan studies this lack is expected if both the homo- and hetero-chiral complexes show similar reactivity, because of the absence of the
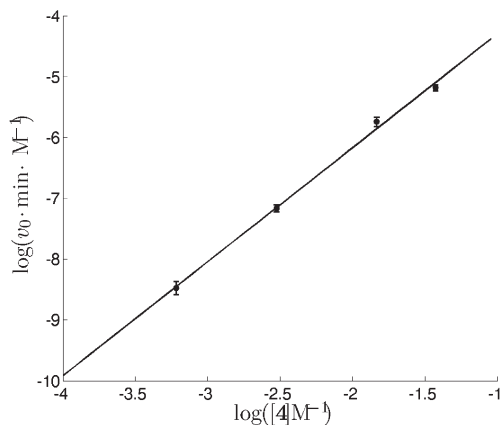
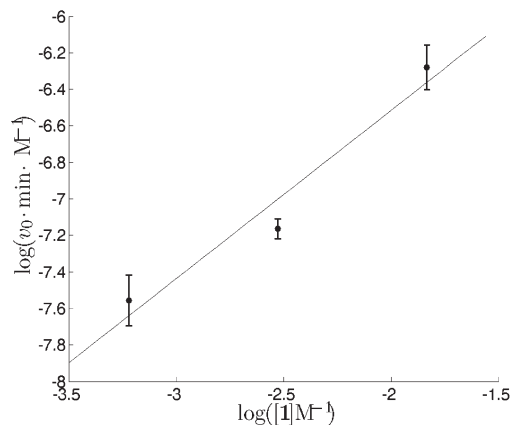**Fig. 2** Determination of the reaction order of sulfoxide.

Fig. 3 Determination of the reaction order of benzaldehyde.

Fig. 4 Log–log plot of initial velocity *vs.* silane concentration. The non-linearity indicates that the order of reaction changes upon changing the concentration of the silane.

reservoir effect.[11] Moreover it cannot be ignored that similar results, the lack of non-linear effects and a partial order in Lewis base >1, were also found by Denmark for chiral monodentate phosphoramides, a system that seems to be very similar to ours.[12]

From the data in Fig. 1, it should be noted that the increase of the reaction rate passing from 2 to 3 equiv. parallels the necessity to use the large excess of the sulfoxide to obtain quantitative yield of the homoallylic alcohol in reasonable reaction time as previously observed (Table 1). This feature is also very relevant for the depiction of a mechanism in which a pre-equilibrium is involved. In fact in this pre-equilibrium only a fraction of the sulfoxides should be bonded to the silicon and an increase of the sulfoxide amount should lead to an increase of the dicoordinated neutral and cationic silicon species.

Then we applied this kinetic method to determine the partial order in **4**, using an excess of silane, always intrigued by the experiment 7 of Table 1. Very interestingly, the order with respect to the sulfoxide estimated from two runs (1 and 2 equiv. of **4**, see ESI†) with a large excess of silane (6 equiv.) lowers to 1.00 ± 0.14, which indicates that an active species with a single sulfoxide coordinated to silicon, which shows similar enantioselectivity, becomes prevalent under different conditions. This aspect must be taken into account in the depiction of the reaction mechanism.

2.1.2 KINETIC EXPERIMENTS: PARTIAL ORDER WITH RESPECT TO BENZ-ALDEHYDE. Then we used the same method of the initial rates for the determination of the partial order with respect to benzaldehyde. We performed kinetic experiments in the presence of 0.5, 1 and 2 equiv. of **1** as detailed in the ESI.† Then from the initial rate of every curve we determined a partial order of 0.9 ± 0.2 (Fig. 3). This is consistent with the participation of a single molecule of benzaldehyde in the rate limiting step, as was also found using different Lewis bases.[2c,h,3h]

2.1.3 KINETIC EXPERIMENTS: PARTIAL ORDER WITH RESPECT TO SILANE. In the case of determination of the order with respect to silane, we performed kinetic experiments in the presence of 0.5, 1, 2, 3, 4, 5 and 6 equiv. of **2** (see ESI† for details).
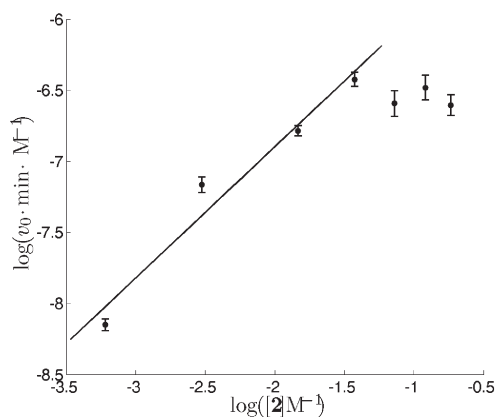
Interestingly the initial rates gave a linear fit only for the first 4 values in the range 0.5–3 equiv. of **2** (Fig. 4), leading to an order of 0.87 ± 0.12. This indicates that at lower concentrations a dominant species contributes with an almost partial first order. However at higher silane molar ratios (4–6 equiv.), the silane partial order becomes close to zero. This behavior indicates a complex mechanism; a somewhat similar trend has been already reported for QUINOX-catalyzed allylation, where the intervention of silicon dimers has been hypothesized.[3h] In our case, the change of the reaction order at higher silane molar ratios prompts us to consider that more than a single species for the silane can operate under these conditions, a consideration that has been anticipated by the already cited experiment 7 of Table 1.

2.2 Conductometric measurements

Taking into account the kinetic studies on the allylation of aldehydes with allyltrichlorosilane in the presence of other Lewis bases,[2c,h,3h,6] a partial order in sulfoxide close to 2 as well as a partial order of almost 1 for both aldehyde and silane can be explained by the formation of a hypervalent octahedral

complex for the transition structure, in which one aldehyde and two sulfoxides are bonded to the silicon centre. This implies the predominance of a dissociative mechanism with the loss of a chloride ligand from the silicon centre and with the concomitant formation of cationic species.

In order to detect the presence of such ionic species, conductivity measurements were performed on dichloromethane solutions of several combinations of the components of our system. Solutions containing other readily available Lewis bases were also considered for comparison. All the measurements were performed under the standard conditions at −78 °C, also because the sulfoxide is not stable above −50 °C.

As can be seen from Table 2 the conductivity was zero for a mixture of solvent, **2** and DIPEA, thus documenting that the system is kept anhydrous and no background hydrolysis of **2** is eventually occurring to increase ionic conductivity of the mixture (entries 2–4). No conductivity was observed in the presence of different mixtures of silane and benzaldehyde, confirming that benzaldehyde is not sufficiently basic to give ionization of the silane (entries 5–7). The experiment with Bu_4NCl documents a significant increase of conductivity, consistently with an appreciable dissociation of Bu_4NCl (entry 8). Interestingly the addition of sulfoxide **4** to the silane (entries 9 and 10) gave an increase of the conductivity with respect to other silane mixtures (entries 2–7), even if this was two orders of magnitude smaller than that of the Bu_4NCl (entry 8). However the molar conductivity in entry 9, *i.e.* $\Lambda_9 = 1.29$ μS $cm^{-1}/0.027$ M = 47.8 mS cm^2, is comparable with the value of 40 mS cm^2, reported for a 0.03 M solution of the hexacoordinated dichlorosilicon complex of ref. 13, which is described as almost completely undissociated. The use of higher amounts of **4** (3 equiv.) gives a similar conductivity (entry 10). The low absolute value of conductivity and its constancy with change of the amount of sulfoxide indicate that only a tiny amount of dissociated species is present in our system, while almost all of the complexes remain undissociated or in contact ion pairs.

In comparison to **4**, both pyridine *N*-oxide and DMF gave higher conductivity than sulfoxide under similar conditions (Table 3). According to the obtained data, we observed an

increase of conductivity (and of dissociation) in the order **4** < DMF < pyridine *N*-oxide. Interestingly, the same order is reported in the literature for the effectiveness of the Lewis bases in allylation of aldehydes using allyltrichlorosilane.

The low values observed for the conductivity in the presence of **4** have prompted us to study the effect of the addition of the aldehyde to the system. In practice we detected at different times the conductivity during the allylation process. We obtained the plots reported in Fig. 5. As can be seen, in all cases the conductivity first increases and then slowly decreases. Since at high dilution the conductivity results from the molar conductivities of ionic species weighted by their concentration, it is tempting to interpret the increase of conductivity in terms of formation of products. In other words, considering that the conductivity before the addition of the aldehyde is low, the reasonable hypothesis is that the reaction produces species dissociated to a greater extent than the reagents: in this way there should be a correlation between conductivity and product concentration. A consequence of this analysis is that the curves in Fig. 5 could mimic the kinetic measurements. In order to verify this hypothesis, exploiting the same methodology of the initial rates as described in the previous sections, we determined the initial slope of the $\Delta\kappa/t$ plots and, from the couples of slopes at lower concentration in sulfoxide and silane, we determined their partial orders of
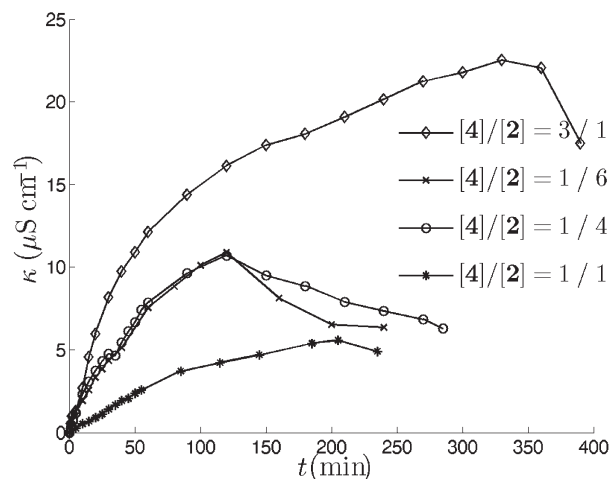
Table 2 Conductivity measurements at −78 °C

Entry[a]	Mixtures	κ (μS cm^{-1})
1	CH_2Cl_2	0.00
2	CH_2Cl_2 + iPr_2NEt	0.00
3	CH_2Cl_2 + **2**	0.00
4	CH_2Cl_2 + **2** + iPr_2NEt (1/1)	0.05
5	CH_2Cl_2 + **2** + **1** (1/1)	0.00
6	CH_2Cl_2 + **2** + **1** (1/9)	0.00
7	CH_2Cl_2 + **2** + **1** (6/1)	0.00
8	CH_2Cl_2 + Bu_4NCl	96.3
9	CH_2Cl_2 + **2** + iPr_2NEt + **4** (1/1/1)	1.29
10	CH_2Cl_2 + **2** + iPr_2NEt + **4** (1/1/3)	1.15

[a] The concentration of the limiting reagent was 0.027 M in dry CH_2Cl_2 (0.40 mmol in 15 mL CH_2Cl_2). The used amounts of all the components can be easily calculated from the equivalents reported in parentheses. The procedure follows the order reported in column 2. For more details see the ESI.†

Table 3 Conductivity of other Lewis bases

Entry[a]	Mixtures	κ (μS cm^{-1})
1	CH_2Cl_2 + iPr_2NEt + pyridine *N*-oxide	0.01
2	CH_2Cl_2 + iPr_2NEt + pyridine *N*-oxide + **2** (1/1/1)	12.43
3	CH_2Cl_2 + iPr_2NEt + DMF (1/1)	0.00
4	CH_2Cl_2 + iPr_2NEt + DMF + **2** (1/1/1)	2.78

[a] See the note of Table 2.

Fig. 5 Time dependence of the conductivity of reaction mixtures for different ratios of sulfoxide and silane. The concentration of the limiting reagent was 0.027 M in dry dichloromethane.

1.65 ± 0.11 and 0.86 ± 0.05, respectively. The fact that these values parallel quite well the orders determined from the concentration of products gives further experimental support to the assumption that the main product is more dissociated than reagents.

From these results it is very interesting to note that the possibility of following the kinetic events of the allylation reaction in terms of conductometric measurements should not be underestimated. This can give a further tool for kinetic investigations also for other new sulfoxides that eventually can be tested in this reaction.

Furthermore, it is worthy to note the particular two-sided shape of all the conductivity curves in Fig. 5. This could suggest that, besides the allylation reaction, a novel chemical event is happening in the reaction mixture at longer time.

This feature seems a characteristic of sulfoxides, as we observed a monotonous decreasing change of conductivity in an allylation catalysed by pyridine N-oxide by a starting value of 13.5 μS cm^{-1} to 4 μS cm^{-1} after the reaction time of 6 hours, at the end of the reaction.

2.3 Racemization at sulfur

The reduction of the conductivity at long time of Fig. 5 necessarily hints at a process involving the further reaction of the products in terms of the formation of species which are either neutral or intimate ion pairs. The formation of neutral or intimate ion pairs is reasonably due to the association of the cationic silicon reaction products with anionic species, which in our system can be constituted by the free chlorides. This broadly hints at a chloride attack on a sulfur atom, rendered electrophilic by the coordination to the Lewis acidic silicon. A similar process was reported by Denmark for the epimerization at stereogenic phosphorus centers of chiral monodentate phosphoramides (a chloride attack at the P=O).[2h] The attack at sulfur would generate a chlorosulfurane covalently bonded to the silicon centre, a known species which is expected to have a see-saw geometry and unusually long and weak apical bonds, as widely reported in the literature.[14] Moreover the formation of tetracoordinated neutral chlorosulfurane could allow explaining the racemization of the sulfoxide through inversion of configuration at sulfur.[15] Indeed, chlorosulfurane species are reported to hydrolyze and to give back the sulfoxide with partial racemization.[14]

In principle a process that involves the reaction and the subsequent deactivation of the sulfoxide through the formation of unstable sulfuranes can start already from the early stages of the allylation reaction as a slow but competing side process. To test for such a possibility, we looked for changes in the chirality of sulfoxides when a 2 : 1 mixture of enantiopure (R)-methyl p-tolyl sulfoxide and silane, in the presence of the iPr$_2$NEt and without the aldehyde, was let to react at −78 °C. Very interestingly, after 24 h we recovered the sulfoxide quantitatively but with 40% ee as detected by chiral HPLC analysis. Moreover, in a similar experiment with the addition of 1 equiv. of benzaldehyde after the delay time of 24 h, no product was detected and the sulfoxide was recovered again after work-up

in quantitative yield and with a 30% ee. These experiments indicate that we should take into account new chemical events in our system for the depiction of the sulfoxide racemization and the lack of turnover.

2.4 Quantum chemical calculations

Quantum chemical calculations on the allylation reaction have been reported, considering the reactivity of **2** coordinated with a single mono-hapto[3h,16] Lewis base and **2**$^+$ coordinated with a bi-hapto[17] Lewis base. No computations have been reported for a system like ours, where, according to kinetic and conductometric data, two sulfoxides are bound to silicon, forming a cationic complex **2(4)**$_2$$^+$. A recent investigation has clearly shown that, in addition to the common computational problems encountered in the description of any reactant and transition structure (level of theory for the description of the electronic structure, effect of nuclear motion and solvent), the reaction in question faces the problem that the selection of kinetically relevant structure(s) among the many stereoisomers determined by the arrangement of ligands around silicon is far from obvious.[17d] An exploration of all stereoisomers, only performed in ref. 17d, is computationally very demanding, especially if the further complication of the conformational freedom of the ligands is considered. This notwithstanding, taking advantage of the information available on the geometries of close compounds,[12,18] we built a small set of test geometries to get a first estimate of the energy variations in the principal steps of our mechanism.

2.4.1 THE SULFOXIDE COORDINATION NUMBER AT SILICON. The second order with respect to **4** indicates that di-coordinate species are the most relevant in kinetics, which could mean that the di-coordinated species are the most abundant and/or that they react considerably faster than monocoordinated ones. To check whether mono- or di-coordinated silane is energetically favored, we optimized the structures of **2**, **2(4)** and **2(4)**$_2$ (Table 4).
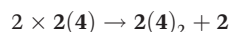
We considered a single trigonal bipyramidal geometry for **2(4)** with the three chlorine atoms in the equatorial plane. More geometries were analyzed for **2(4)**$_2$, all with a meridional disposition of chloride atoms. The two lowest energy conformations have a *cis* orientation of sulfoxides and present a π-stacking of the aromatic rings. Probably similar interactions are responsible for the appearance of strong NMR signals from

Table 4 Computed reaction energies in kcal mol^{-1} computed *in vacuo* and in DCM, at the B97D/def2-TZVP//B97D/6-31G(d,p) level. Reaction energies in DCM have been estimated by single point calculations on the structures optimized at the B97D/6-31G(d,p) level and using Bondi atomic radii

Reaction	ΔU_{vac}	ΔU_{DCM}
2 × Siall(**4**)Cl$_3$ → SiallCl$_3$ + Siall(**4**)$_2$Cl$_3$	−12.1	−17.0
SiallCl$_2$(**4**)$_2$$^+$ + Si(OR)Cl$_3$(**4**)$_2$ → SiallCl$_3$(**4**)$_2$ + Si(OR)Cl$_2$(**4**)$_2$$^+$	−2.9	−3.7
SiORCl$_3$(**4**)$_2$ → SiORCl$_2$(**4**)OSCl	−2.0	0.2
SiORCl$_3$(**4**)$_2$ → **4**···*cyc*-[(SiCl$_2$)OSRR′-CH$_2$CHClCH$_2$]	−17.8	−13.8
SiallCl$_2$(**4**)$_2$$^+$-**1** → [SiallCl$_2$(**4**)$_2$$^+$-**1**]$^{\neq}$	3.0	3.9

cis coordinated aromatic phosphoramides to SiCl$_4$, which contrasts with the net prevalence of *trans* coordination of the non-aromatic HMPA.[12]

Rather than computing the association energies, which are more computationally demanding, we addressed the reaction energy for the isodesmic and isomolecular process

$$2 \times 2(4) \rightarrow 2(4)_2 + 2$$

The reaction energy computed for this process is −12.0 kcal mol^{-1}, and even more negative in DCM, strongly suggesting that the formation of the di-coordinated species is well favored over that of the mono-coordinated one (Table 4). This result is fully consistent with the behavior of a similar SiCl$_4$ in the presence of monodentate phosphoramides.[12] It is thus conceivable that the di-coordinated species forms preferentially and only upon increasing the [2]/[4] ratio does the mono-coordinated species form appreciably (Table 4). In fact the partial order for the sulfoxides becomes almost 1 when 6 equiv. of silane are used.

2.4.2 IONIC DISSOCIATION. This aspect is very relevant for the depiction of the reaction mechanism, because the dissociation of a chloride is necessary for the following coordination of the aldehyde to give hexa-coordinate silicon complexes. However, according to the conductivity data, the simple system silane/sulfoxide dissociates to a small extent, while reaction products are significantly more dissociated (see Fig. 5 for allylation reaction followed by conductometry measurements). Thus we were prompted to compare the chloride dissociation from $2(4)_2$ and Si(OR)Cl$_3(4)_2$, where OR is the alkoxy part of the alcohol produced.

Taking advantage of the structures considered in ref. 12, we considered the *mer-cis* isomer of Si(OR)Cl$_3(4)_2$, and trigonal bipyramidal geometries with apical sulfoxides for the cationic species SiallCl$_2(4)_2^+$ and Si(OR)Cl$_2(4)_2^+$. Several conformers were tried, as detailed in the ESI.† For both molecules the orientation of sulfoxides appears to have a considerable freedom and the occurrence of many conformations is expected.

Once again, in order to soften the computational requirements, rather than comparing energy changes for the dissociation processes we can compare the dissociation of the allyl and alkoxy-bound species through the isodesmic and isomolecular reaction.

$$\text{Si(OR)Cl}_3(4)_2 + \text{SiallCl}_2(4)_2^+ \rightarrow \text{SiallCl}_3(4)_2 + \text{Si(OR)Cl}_2(4)_2^+$$
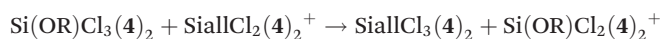
The computed reaction energy of the above process amounts to −2.9 (−3.7) kcal mol^{-1} *in vacuo* (in DCM) and is thus consistent with the increase of conductivity measured during the reaction (Fig. 5).

2.4.3 TETRACOORDINATE SULFUR SPECIES. In order to test the possibility of formation of sulfuranes, we built some structures considering the alkoxy product and the starting allylsilane. First, we optimized the structures of a few models of the neutral chlorosulfurane Si(OR)Cl$_2(4)$-OSMe(*p*Tol)Cl. The most stable conformer (Fig. 6) has an energy 2.0 kcal mol^{-1} lower
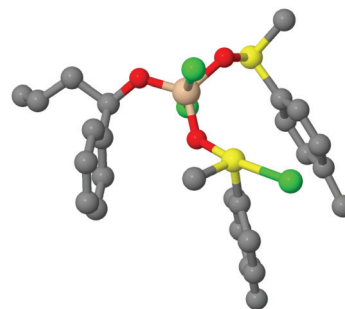

Fig. 6 Lowest energy conformer found for the neutral chlorosulfurane, the silicon has a trigonal bipyramidal geometry with three oxygen atoms in the equatorial plane and two axial chlorines; one of the sulfoxides is bound to a chlorine atom thus forming a see-saw chlorosulfurane. The length of the S–Cl apical bond is as long as 2.55 Å, which is in line with general trends for this class of compounds.

in vacuo than the lowest energy conformer found for the reaction product Si(OR)Cl$_3(4)_2$. Even if the energy of the reaction becomes slightly positive in DCM, the calculations can be considered as giving some support to the formation of tetracoordinated neutral chlorosulfuranes, also considering that more geometrical isomers are possible for trigonal-bipyramidal silicon species than for the octahedral ones.

Nevertheless, besides chlorosulfuranes, other tetracoordinated sulfur species can be hypothesised that in principle can lead to the racemization and lack of turn-over. For example, sulfuranes can also derive from a chloride attack at the C═C bond of the allyl group and with a subsequent carbon–sulfur bond formation. This can lead to the cyclic neutral adduct in Fig. 7, which shows an energy lower than that of the parent complex SiallCl$_3(4)_2$ by as much as 17.8 (13.8) kcal mol^{-1} *in vacuo* (in DCM). This high exoergicity gives a strong support to the hypothesis that sulfuranes are important by-products of the reaction. Notably, a reversible rearrangement of allylic sulfoxides has been reported in connection with the racemization of allyl aryl sulfoxides.[19]

2.4.4 TRANSITION STATE MODELLING. Despite the many possible isomers, given by the theoretical combination of the components of our system, a simplified analysis can be performed considering the obtained experimental data in comparison with the similar systems reported in the literature. A partial order of almost 2 for the sulfoxide at low silane amounts and of 1 for the aldehyde and silane is the evidence that an octahedral complex is involved in the transition structure, as reported for other Lewis bases, after the loss of a chloride ligand.[1a,2c,h] We also have to take into account the observed high diastereoselectivity using *E*-crotyl trichlorosilane,[4c] in which the *anti* isomer is obtained with high selectivity. This can be explained invoking a cyclic chair like transition state. To strengthen this hypothesis, we selected a single isomer with apical chlorines, which can be expected to be the lowest energy one. We obtained indeed a transition structure (with a single imaginary frequency) with a chair-like structure (Fig. 8). The activation energy is as low as 3.0 kcal mol^{-1}
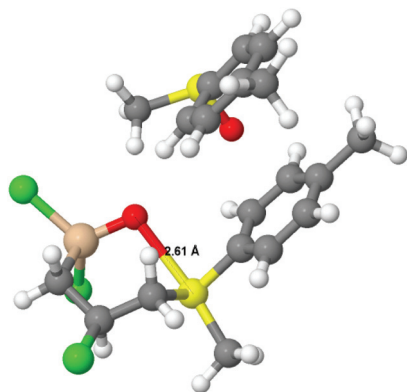
Fig. 7 Lowest energy conformer found for the neutral cyclic oxosulfurane. The silicon has a tetrahedral geometry and the oxosulfurane has the typical see-saw geometry with a very long apical S–O bond (2.61 Å).
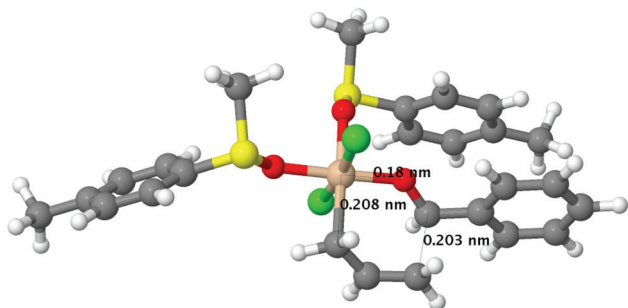

Fig. 8 A transition structure for the allylation of *Re* benzaldehyde. The similar lengths of breaking Si–C and forming C–C bond (2.08 and 2.03 Å) exceed the respective standard lengths for single bonds (1.86 and 1.54 Å, respectively) for a different amount, as expected for an early transition state. The single imaginary frequency of the structure at 290i cm^{-1} mainly stems from out-of-phase stretchings of forming C–C and breaking Si–C bonds.

(2.9 kcal mol^{-1} in DCM), which parallels the low enthalpies of activation (0.3–1.5 kcal mol^{-1}) determined for phosphoramide-activated silicon-based aldolizations,[20] which have a very similar reaction mechanism to that proposed here for the sulfoxide-activated silicon-based allylation.

These hints are very important to model the transition structure, and eventually to unravel the origin of the enantioselectivity. However, a quantitative interpretation of the enantioselectivity should still face the many octahedral isomers which are still possible, and is most demanding in the case of benzaldehyde for which the experimental enantiomeric excesses are only moderate and therefore we did not tackle this problem at the moment.

2.5 Reaction mechanism

A kinetic mechanism trying to explain all the observed results is discussed in this section (Scheme 2). As widely discussed before, a partial order of almost 2 for the sulfoxide, 1 for silane (at low silane amounts) and of 1 for the aldehyde, coupled with the detected conductivity, is consistent with the formation of an octahedral cationic complex in the transition structure, in which two sulfoxides and one aldehyde are coordinated. As also confirmed by quantum chemical calculations, this can be explained with the prevalence of the dissociative mechanistic pathway A, involving a di-coordinated active species **III** (Scheme 2).

Nevertheless a slower concomitant mono-coordinated pathway B cannot be excluded. The first order in sulfoxide, detected at a high silane/aldehyde molar ratio, can indicate that the allylation process (pathway B) becomes faster than the coordination of the second sulfoxide, when silane is used in excess.

The comparatively low conductivity of our system at −78 °C in DCM with respect to DMF and pyridine *N*-oxide can be explained if the ionization of the di-coordinated species **II** to give the catalytically active complex **III** is not particularly favoured. The low concentration of these species can be also related to the observed increase of the reaction rate passing from 2 to 3 equiv. of sulfoxide as previously detailed in the kinetic studies (see Fig. 1).

Because of its cationic nature, complex **III** shows increased Lewis acidity and, after aldehyde coordination, the highly ordered cyclic chair-like transition state (**TS**) leads to the formation of the cationic complex **IV**.

Besides the strong evidence regarding a dissociative mechanistic pathway, all the experimental data highlight a lack of turn-over for this allylation process. At high product conversions, we observed a slow decrease of the conductivity (Fig. 5), and in the case of the reaction with 3 equiv. of sulfoxide this value decreased from 22 to 7 μS cm^{-1} after 24 h. At the same time, as reported in Table 1, longer reaction times did not guarantee any increase of the yield, when lower amounts of **4** were used, but a decrease of the enantiomeric purity of the sulfoxide was observed without affecting the enantioselectivity of the allylation. Even if (*R*)-methyl *p*-tolyl sulfoxide is reported to be configurationally stable and it gives inversion only at high temperature[21] or in the presence of acids,[22] the possibility to form tetracoordinate sulfurane species can lead to the loss of enantiomeric purity and deactivation of sulfoxide.[14b,15]

Other studies are underway to investigate this fascinating behaviour that combines the chemistry of silicon and sulfur compounds in a unique fashion with important implications in a fundamental organic transformation like enantioselective allylation of aldehydes.

3. Conclusions

In spite of the lack of non-linear effects, the kinetic, conductometric and computational data indicate that the allylation of benzaldehyde with allyltrichlorosilane, promoted by commercially available (*R*)-methyl *p*-tolyl sulfoxide **4**, is likely to proceed *via* a dissociative mechanism through a cationic octahedral hypervalent silicon complex **III**. In agreement with the reaction promoted by chiral monodentate phosphoramides,

Pathway A: second order in sulfoxide
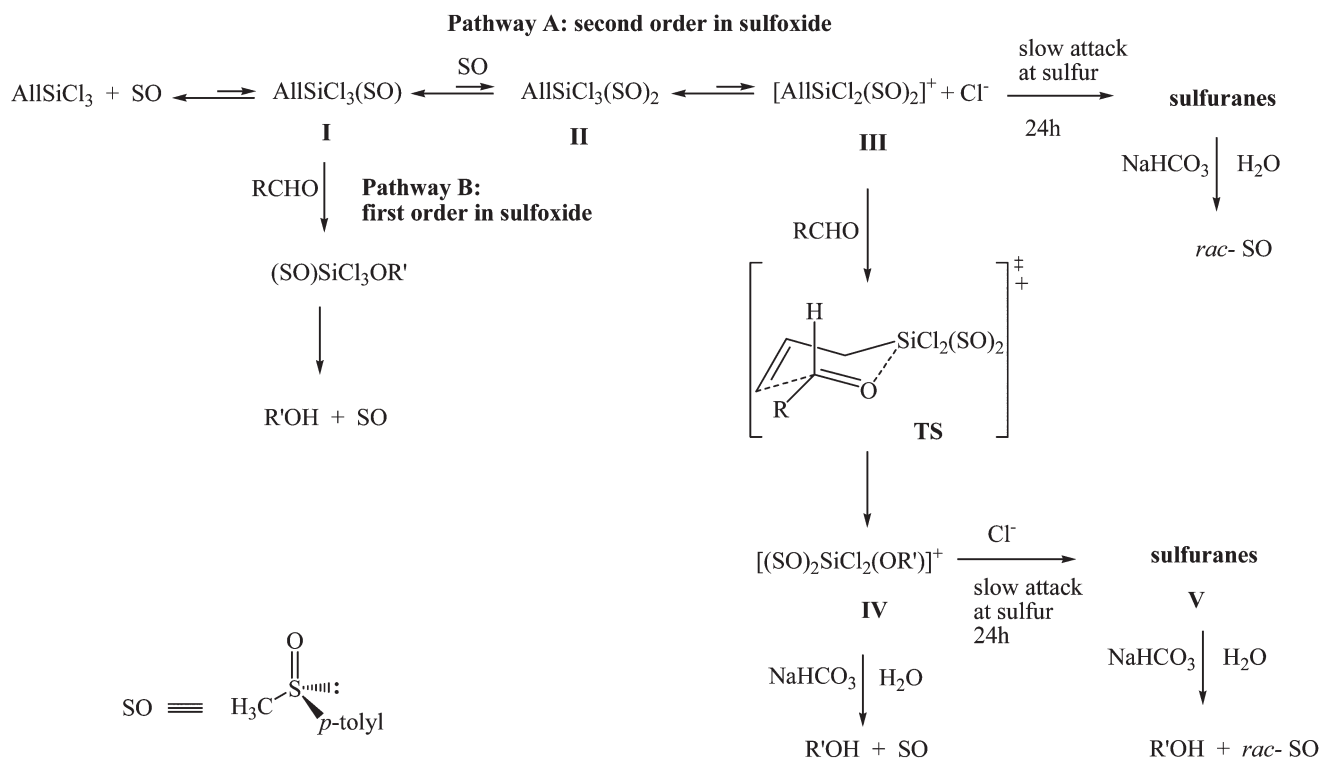
Scheme 2 Mechanistic pathway.

two molecules of **4** are involved in the rate- and selectivity-determining step. The reaction presumably proceeds *via* a cyclic chairlike transition state and is characterized by high diastereoselectivity and by an enantioselectivity depending on the used substrate. Particular attention was devoted to the lack of turnover and the partial racemization of the sulfoxide, which were found also in allylations promoted by other chiral sulfoxides.[4,5,8] These features were interpreted at once with the formation of sulfuranes covalently bonded to the silicon center. The identification of this undesired reaction adds a novel case of relevance of the hypervalent sulfur compound in organic chemistry and yields a key tool for the interpretation of the low effectiveness of sulfoxides in allylation reactions of aldehydes and hydrazones. This aspect can open the way to improve considerably the enantioselective allylation by sulfoxides.

4.   Experimental section

General remarks

All reactions were performed in oven-dried (140 °C) or flame-dried glassware under dry N_2. Dichloromethane was reagent grade and was dried and distilled immediately from CaH_2 before use. Column chromatographic purification of products was carried out using silica gel 60 (70–230 mesh, Merck). The reagents (Aldrich and Fluka) were used without further purification. The NMR spectra were recorded on Bruker DRX 400, 300, 250 spectrometers (400 MHz, 300 MHz, 250 MHz).

Spectra were referenced to residual $CHCl_3$ (7.26 ppm, ^{1}H, 77.23 ppm, ^{13}C). Coupling constants J are reported in Hz. Yields are given for isolated products showing one spot on a TLC plate and no impurities detectable in the NMR spectrum. Elemental analyses were performed with FLASHEA 1112 series-Thermo Scientific for CHNS-O apparatus.

The enantiomeric excesses of alcohol **3** were determined by GC analysis, with Agilent 6850 equipment, using a Supelco β-DEX 120; oven: 100 °C for 2 min, then 0.5 °C min^{-1} to 200 °C, 10 min at that temperature. The chiral GC methods were calibrated with the corresponding racemic mixtures. The absolute configuration of the products was determined by comparison of their optical rotations (measured in $CHCl_3$ and their GC retention times with the literature data).

The enantiomeric excesses of sulfoxide **4** were determined by HPLC analysis, with Waters 2487, using an OD-H column, 0.6 mL min^{-1}, in a 90 : 10 hexane–i-PrOH mixture, 254 nm. The chiral HPLC method was calibrated with the corresponding racemic mixtures. The absolute configuration of the products was determined by comparison with literature data.

The conductometric analysis was performed using a conductivity meter AMEL mod. 133 equipped with a standard electrode.

Procedure for allylation of aldehyde

In a flame dried two-necked round bottom flask, benzaldehyde **1** (0.40 mmol) was added to a solution of sulfoxide **2** (1, 2 or 3 equiv.), diisopropylethylamine (0.40 mmol) and allyltrichlorosilane (0.48 mmol), in dry CH_2Cl_2 (2.0 mL) at −78 °C under

argon. Then saturated aqueous $NaHCO_3$ (20 mL) and CH_2Cl_2 (30 mL) were added, the organic layer was separated and the aqueous phase was extracted with CH_2Cl_2 (2 × 40 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated at reduced pressure. The residue was purified by flash chromatography on silica gel with a petroleum ether–Et_2O mixture (from 95 : 5 to 90 : 10) to afford pure **3**, followed by AcOEt to recover the pure sulfoxide **4**.

Procedure for the kinetic runs

In a flame dried two-necked round bottom flask, benzaldehyde **1** (X mmol) was added to a solution of sulfoxide **2** (Y mmol), naphthalene (10.3 mg, 0.0804 mmol), diisopropylethylamine (0.40 mmol) and allyltrichlorosilane (Z mmol), in dry CH_2Cl_2 (5.0 mL) at −78 °C under argon. Then aliquots (50 μL) were taken after the time reported in the tables (see experiments 1–16). Each sample was quickly quenched with saturated aqueous $NaHCO_3$ (0.15 mL) and the resulting mixture was diluted with 1 mL of $CHCl_3$. Then, it was filtered through a short pad of silica gel on pipette Pasteur, and the plug was washed with $CHCl_3$ to adjust the total sample volume to 4 mL. The samples were injected into the GC three times.

Initial velocities were determined by polynomial fitting as detailed in the ESI.†

Procedure for conductometric measurements: data of Table 2

Under nitrogen, the standard conductometric cell, fitted with a suitable rubber septum, was fixed to a previously flamed three-necked round bottom flask and all the equipment was submitted to a series of high vacuum-nitrogen cycles. Then the reagents, according to the order of addition reported in column 2 of Table 2, were consecutively added to 15 mL of dry CH_2Cl_2 at −78 °C. The conductometric measurements were detected after 1 min of the addition of the last component. The quantities are those reported in brackets and refer to 0.40 mmol in 15 mL of dry CH_2Cl_2 for the limiting component. The used amounts of all the components can be easily calculated from the reported equivalents in brackets of column 2 of Table 2.

Procedure for dynamic conductometric measurements

The same equipment used for the experiments in Table 2 was employed in the determination of conductometric curves in Fig. 4. In a typical experimental procedure, benzaldehyde **1** (0.40 mmol) was added to a solution of sulfoxide **2** (1, 2 or 3 equiv.), diisopropylethylamine (0.40 mmol) and allyltrichlorosilane (0.48 mmol), in dry CH_2Cl_2 (15.0 mL) at −78 °C under argon.

Quantum chemical calculations

All calculations were performed using Gaussian 09,[23] using Grimme's dispersion corrected functional B97-D.[24] In consideration of the considerable amount of computational resources required for siliconate complexes, and considering that previous work has successfully adopted double-ζ basis sets,[3h,17a,b] geometry optimization has been performed with the rather small 6-31G(d,p) basis set. The energies of the optimized geometries have then been refined with the larger basis set def2-TZVP,[25] retrieved from the EMSL Basis Set Exchange database.[26] The energy change due to DCM has been estimated with the polarizable continuum model (PCM)[27] applied at the optimized geometry with cavities built using Bondi atomic radii,[28] along with the same basis def2-TZVP.

References

1 For a review: (*a*) S. E. Denmark and G. L. Beutner, *Angew. Chem., Int. Ed.*, 2008, **47**, 1560–1638; (*b*) P. Kočovsky and V. Malkov, in *Enantioselective Organocatalysis*, ed. H. I. Dalko, Wiley-VCH, Weinheim, 1st edn, 2007, vol. 7, pp. 255–264; (*c*) S. N. Tandura, M. G. Voronkov and N. V. Alekseev, *Top. Curr. Chem.*, 1986, **131**, 99–189.

2 (*a*) S. E. Denmark, D. M. Coe, N. E. Pratt and B. D. Griedel, *J. Org. Chem.*, 1994, **59**, 6161–6163; (*b*) S. Kobayashi and K. Nishio, *J. Org. Chem.*, 1994, **59**, 6620–6628; (*c*) S. E. Denmark, J. Fu and M. J. Lawler, *J. Org. Chem.*, 2006, **71**, 1523–1536; (*d*) S. E. Denmark and J. Fu, *J. Am. Chem. Soc.*, 2000, **122**, 12021–12022; (*e*) S. E. Denmark and J. Fu, *J. Am. Chem. Soc.*, 2001, **123**, 9488–9489; (*f*) S. E. Denmark and J. Fu, *J. Am. Chem. Soc.*, 2003, **125**, 2208–2216; (*g*) S. E. Denmark and J. Fu, *Org. Lett.*, 2002, **4**, 1951–1953; (*h*) S. E. Denmark, J. Fu, D. M. Coe, X. Su, N. E. Pratt and B. D. Griedel, *J. Org. Chem.*, 2006, **71**, 1513–1522; (*i*) K. Iseki, Y. Kuroki, M. Takahashi and Y. Kobayashi, *Tetrahedron Lett.*, 1996, **37**, 5149–5150; (*j*) K. Iseki, Y. Kuroki, M. Takahashi, S. Kishimoto and Y. Kobayashi, *Tetrahedron*, 1997, **53**, 3513–3526.

3 (*a*) M. Nakajima, M. Saito, M. Shiro and S. Hashimoto, *J. Am. Chem. Soc.*, 1998, **120**, 6419–6420; (*b*) A. V. Malkov, M. Orsini, D. Pernazza, K. W. Muir, V. Langer, P. Maghani and P. Kočovsky, *Org. Lett.*, 2002, **4**, 1047–1049; (*c*) T. Shimada, A. Kina, S. Ikeda and T. Hayashi, *Org. Lett.*, 2002, **4**, 2799–2801; (*d*) A. V. Malkov, M. Bell, M. Orsini, D. Pernazza, A. Massa, P. Herrmann, P. Meghani and P. Kočovsky, *J. Org. Chem.*, 2003, **68**, 9659–9668; (*e*) A. V. Malkov, L. Dufkova, L. Farrugia and P. Kočovsky, *Angew. Chem., Int. Ed.*, 2003, **42**, 3674–3677; (*f*) J. F. Traverse, Y. Zhao, A. H. Hoveyda and M. L. Snapper, *Org. Lett.*, 2005, **7**, 3151–3154; (*g*) L. Pignataro, M. Benaglia, R. Annunziata, M. Cinquini, F. Cozzi and G. Celentano, *J. Org. Chem.*, 2006, **71**, 1458–1463; (*h*) A. V. Malkov, P. Ramizer-Lopez, L. Biedermannova, L. Rulisek, L. Dufkova, M. Kotora, F. Zhu and P. Kočovsky, *J. Am. Chem. Soc.*, 2008, **130**, 5431–5348; (*i*) P. Kwiatkowski,

P. Mucha, G. Mloston and J. Jurczak, *Synlett*, 2009, **11**, 1757–1760; (*j*) M. Kotora, *Pure Appl. Chem.*, 2010, **82**, 1813–1826; (*k*) K. Vlasana, R. Hrdina, I. Valterova and M. Kotora, *Eur. J. Org. Chem.*, 2010, **36**, 7040–7044; (*l*) J. R. Fulton, J. E. Glover, L. Kamara and G. J. Rowlands, *Chem. Commun.*, 2011, **47**, 433–435; (*m*) E. Gnanamani, N. Someshwar and C. R. Ramanathan, *Adv. Synth. Catal.*, 2012, **354**, 2101–2106; (*n*) B. Bai, H.-J. Zhu and W. Pan, *Tetrahedron*, 2012, **68**, 6829–6836.

4 (*a*) A. Massa, A. V. Malkov, P. Kočovsky and A. Scettri, *Tetrahedron Lett.*, 2003, **44**, 7179–7181; (*b*) A. Massa, A. V. Malkov, P. Kočovsky and A. Scettri, *Tetrahedron Lett.*, 2003, **44**, 9067; (*c*) V. De Sio, A. Massa and A. Scettri, *Org. Biomol. Chem.*, 2010, **8**, 3055; (*d*) A. Massa, M. R. Acocella, V. De Sio, R. Villano and A. Scettri, *Tetrahedron: Asymmetry*, 2009, **20**, 202–204.

5 (*a*) G. J. Rowlands and W. K. Barnes, *Chem. Commun.*, 2003, 2712–2713; (*b*) J. R. Fulton, L. M. Kamara, S. C. Morton and G. J. Rowlands, *Tetrahedron*, 2009, **65**, 9134–9141; (*c*) H. Zhao, M. M. Kayser, Y. Wang, R. Palkovits and F. Schuth, *Microporous Mesoporous Mater.*, 2008, **116**, 196–203; (*d*) P. Wang, J. Chen, L. Cun, J. Deng, J. Zhua and J. Liao, *Org. Biomol. Chem.*, 2009, **7**, 3741–3747; (*e*) V. De Sio, M. R. Acocella, R. Villano and A. Scettri, *Tetrahedron: Asymmetry*, 2010, **21**, 1432–1435.

6 (*a*) K. Iseki, S. Mizuno, Y. Kuroki and Y. Kobayashi, *Tetrahedron Lett.*, 1998, **39**, 2767–2770; (*b*) K. Iseki, S. Mizuno, Y. Kuroki and Y. Kobayashi, *Tetrahedron*, 1999, **55**, 977–988.

7 (*a*) M. Nakajima, S. Kotani, T. Ishizuka and S. Hashimoto, *Tetrahedron Lett.*, 2005, **46**, 157–159; (*b*) S. Kotani, S. Hashimoto and M. Nakajima, *Tetrahedron*, 2007, **63**, 3122–3132; (*c*) V. Simonini, M. Tenaglia and T. Benincori, *Adv. Synth. Catal.*, 2008, **350**, 561–564.

8 (*a*) S. Kobayashi, C. Ogana, H. Konishi and M. Sugiura, *J. Am. Chem. Soc.*, 2003, **125**, 6610–6611; (*b*) I. Fernandez, V. Valdivia, B. Gori, F. Alcudia, E. Alvarez and N. Khiar, *Org. Lett.*, 2005, **7**, 1307–1310; (*c*) I. Fernandez, V. Valdivia, M. P. Leal and N. Khiar, *Org. Lett.*, 2007, **9**, 2215–2218; (*d*) F. Garcia-Flores, L. S. Flores-Michel and E. Juaristi, *Tetrahedron Lett.*, 2006, **47**, 8235–8238.

9 (*a*) For a recent review on enantioselective synthesis and applications of chiral sulfoxides see: E. Wojaczynska and J. Wojaczynski, *Chem. Rev.*, 2010, **110**, 4303–4356; (*b*) H. Pellissier, *Tetrahedron*, 2006, **62**, 5559–5601; (*c*) C. H. Senanayake, D. Krishnamurthy, Z. H. Lu, Z. Han and I. Gallou, *Aldrichimica Acta*, 2005, **38**, 93–104; (*d*) I. Fernandez and N. Khiar, *Chem. Rev.*, 2003, **103**, 3651–3706.

10 For an interesting study on sulfoxides deoxygenation promoted by trichlorosilane see: T. H. Chan and A. Melnyk, *J. Am. Chem. Soc.*, 1970, **92**, 3718.

11 (*a*) D. Guillaneux, S.-H. Zhao, O. Samuel, D. Rainford and H. B. Kagan, *J. Am. Chem. Soc.*, 1994, **116**, 9430–9439; (*b*) D. Fenwick and H. B. Kagan, *Top. Stereochem.*, 1999, **22**,

257–296; (*c*) G. L. Girard and H. B. Kagan, *Angew. Chem., Int. Ed.*, 1998, **37**, 2922–2959; (*d*) M. Avalos, R. Babiano, P. Cintas, J. L. Jimenez and J. C. Palacios, *Tetrahedron: Asymmetry*, 1997, **8**, 2997–3017; (*e*) N. Kitamura, S. Okada, S. Suga and R. Noyori, *J. Am. Chem. Soc.*, 1989, **111**, 4028–4036; (*f*) N. Kitamura, S. Suga, H. Oka and R. Noyori, *J. Am. Chem. Soc.*, 1998, **120**, 9800–9809.

12 S. E. Denmark, B. M. Exlov, P. J. Yao and M. D. Eastgate, *J. Am. Chem. Soc.*, 2009, **131**, 11770–11787.

13 V. Jouikov, B. Gostevskii, I. Kalikhmann and D. Kost, *Organometallics*, 2007, **26**, 5791.

14 (*a*) T. M. Balthazor and J. C. Martin, *J. Am. Chem. Soc.*, 1975, **97**, 5635; (*b*) J. C. Martin and E. F. Perozzi, *Science*, 1976, **191**, 154; (*c*) J. C. Martin and T. M. Balthazor, *J. Am. Chem. Soc.*, 1977, **99**, 152; (*d*) A. K. Datta and P. D. Livant, *J. Org. Chem.*, 1983, **48**, 2445; (*e*) P. D. Livant, *J. Org. Chem.*, 1986, **51**, 5384.

15 T. Satoh, H. Momochi and T. Noguchi, *Tetrahedron: Asymmetry*, 2010, **21**, 382.

16 K. Sakata and H. Fujimoto, *Organometallics*, 2010, **29**, 1004.

17 (*a*) R. Hrdina, F. Opekar, J. Roithová and M. Kotora, *Chem. Commun.*, 2009, 2314; (*b*) A. Kadlčíková, I. Valterová, L. Ducháčková, J. Roithová and M. Kotora, *Chem.–Eur. J.*, 2010, **16**, 9442; (*c*) L. Ducháčková, A. Kadlčíková, M. Kotora and J. Roithová, *J. Am. Chem. Soc.*, 2010, **132**, 12660–12667; (*d*) T. Lu, R. Zhu, Y. An and S. E. Wheeler, *J. Am. Chem. Soc.*, 2012, **134**, 3095.

18 M. Calligaris and O. Carugo, *Coord. Chem. Rev.*, 1996, **153**, 83–154.

19 (*a*) R. Tang and K. Mislow, *J. Am. Chem. Soc.*, 1970, **92**, 2100; (*b*) P. Bickart, F. W. Carson, J. Jacobus, E. G. Miller and K. Mislow, *J. Am. Chem. Soc.*, 1968, **90**, 4869; (*c*) D. K. Jones-Hertzog and W. L. Jorgensen, *J. Am. Chem. Soc.*, 1995, **117**, 9077.

20 S.E. Denmark, S. M. Pham, R. A. Stavenger, X. Su, K.-T. Wong and Y. Nishigaichi, *J. Org. Chem.*, 2006, **71**, 3904–3922.

21 D. R. Rayner, A. J. Gordon and K. Mislow, *J. Am. Chem. Soc.*, 1968, **90**, 4854.

22 G. Modena, U. Quintily and G. Scorrano, *J. Am. Chem. Soc.*, 1972, **94**, 202.

23 M. J. Frisch, *et al.*, *GAUSSIAN 09 (Revision A.02)*, Gaussian, Inc., Wallingford CT, 2009.

24 S. Grimme, *J. Comput. Chem.*, 2006, **27**, 1787–1799.

25 F. Weigend and R. Ahlrichs, *Phys. Chem. Chem. Phys.*, 2005, **7**, 3297–3305.

26 (*a*) D. Feller, *J. Comput. Chem.*, 1996, **17**, 1571–1586; (*b*) K. L. Schuchardt, B. T. Didier, T. Elsethagen, L. Sun, V. Gurumoorthi, J. Chase, J. Li and T. L. Windus, *J. Chem. Inf. Model.*, 2007, **47**, 1045–1052.

27 J. Tomasi, B. Mennucci and R. Cammi, *Chem. Rev.*, 2005, **105**, 2999–3093.

28 A. Bondi, *J. Phys. Chem.*, 1964, **68**, 441–451.