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PAPER

Rotational barriers of biphenyls having heavy heteroatoms as *ortho*-substituents: experimental and theoretical determination of steric effects†

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The free energies of activation for the aryl–aryl rotation of 17 biphenyl derivatives, bearing a heavy heteroatom (S, Se, Te, P, Si, Sn) as *ortho* substituent, have been measured by variable temperature NMR. These numbers, so called *B* values, represent a meaningful measure of the steric hindrance exerted by the selected substituents. DFT computations match quite satisfactorily the experimental barriers and the ground state geometries as well (determined, in two cases, by X-ray diffraction). The present values extend the available list of *B* values and thus provide an enlarged basis for the compilation of the space requirements of standard substituents, based solely on experimental determinations.

Introduction

An indicator often used for estimating the steric hindrance of various groups is based upon the free energy difference ($\Delta G°$ in kcal mol^{-1}) between equatorially- and axially-substituted conformers of cyclohexane.[1,2] These quantities are known as *A* values and cover a range of between 0.28 (fluorine) and 4.9 kcal mol^{-1} (*tert*-butyl).[1c,2] A very large *A* value indicates that the proportion of the axial conformer is so small that it is impossible to measure directly the conformer ratio and to obtain a reliable determination solely on an experimental basis. The investigators thus resorted to an indirect determination by means of the so called counterpoised method using disubstituted cyclohexanes and assuming additivity of the *A* values.[2–4] There are also negative *A* values, that occur when the axial is more stable than the equatorial conformer, as in the case of organomercuric derivatives of cyclohexane.[5] In addition, it has to be pointed out that other effects, besides the size of the substituent, play a role in determining the ratio of these conformers. For instance chlorine is reported[2] to have an *A* value of 0.51–0.53 whereas iodine (which is obviously bulkier than chlorine) has, nonetheless, a smaller *A* value (0.47–0.49).[2]

In a different approach, Sternhell *et al.*[6] assessed the torsional barriers of *ortho*-substituted biphenyls by variable temperature NMR. However, in order to detect decoalescence of diastereotopic groups in a temperature range accessible to their instrumentation, they introduced two *ortho*-substituents and thus had to postulate additivity of the repulsion caused by the two substituents in order to extract the individual steric parameters. But this assumption was unwarranted: indeed when the rotation barrier of mono-substituted *ortho*-biphenyl derivatives could be subsequently measured,[7] the experimental barriers were found to be significantly lower than those deduced on the basis of the additivity assumption. For this reason we undertook the task of measuring a number of these barriers (called *B* values): we have been able, so far, to measure 29 such values,[7–10] ranging from the 4.4 kcal mol^{-1} for fluorine[9] to the 18.1 kcal mol^{-1} for the Me_3N^+ group[8] (Table 1). As an example, this scale correctly indicates that the *B* value of chlorine (7.7) is actually smaller than that of the bulkier iodine (9.9)[7a] in agreement with the trend of the Taft-type E'_s steric parameters,[11] as reported by Dubois *et al.*[12] (0.02 for chlorine and 0.50 for iodine).

In order to get information about the steric requirements of groups containing a heavy heteroatom bonded to the *ortho* position of biphenyls, we determined in the present work the *B* values of substituents like $–SiR_3$, $–SnR_3$, $–PR_2$, –SR, –SeR, –TeR (R = alkyl or phenyl).

Results and discussion

To measure by NMR spectroscopy the rotational barrier of *ortho*-substituted biphenyls it is necessary to place in the *meta*'-position two enantiotopic groups that turn into diastereotopic

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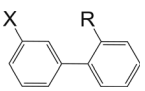
Table 1 Experimental *B* values ($\Delta G^{\neq}_{rot}$ in kcal mol^{-1}) and computed rotational barriers ($\Delta E^{\neq}_{rot}$ in kcal mol^{-1}) to aryl–aryl rotation of biphenyl derivatives bearing a single *ortho* substituent[7–10]

ortho substituent	$\Delta G^{\neq}_{rot}$ exper.	$\Delta E^{\neq}_{rot}$ calc.	*ortho* substituent	$\Delta G^{\neq}_{rot}$ exper	$\Delta E^{\neq}_{rot}$ calc.
Me	7.4	7.1	Br	8.7	8.5
Et	8.7	8.6	I	10.0	9.9
i-Pr	11.1	11.1	OH	5.4	5.3
t-Bu	15.4	15.3	OMe	5.6	4.5
CF_3	10.5	9.2	OCF_3	5.5	4.8
$C(CF_3)_2OH$	16.5	16.9	OCH_2OCH_3	5.7	6.1
CH_2OH	7.9	7.8	$CH{=}CH_2$	8.2	8.5
C_6H_5	7.5	7.4	C≡CH	6.0	5.3
C_6F_5	7.7	8.1	C≡N	5.9	5.2
NH_2	8.1	8.4	CHO	10.2	11.0
NO_2	7.6	7.8	COOH	7.7	8.5
NMe_2	6.9	6.8	COOMe	7.7	8.3
$^{+}NMe_3$	18.1	18.2	MeCO	8.0	8.3
F	4.4	4.3	*t*-BuCO	6.7	7.2
Cl	7.7	7.3			

groups when, below a certain temperature, the interconversion for the two conformational enantiomers (atropisomers) by aryl–aryl rotation becomes slow enough.[7] The interconversion barrier between these two enantiomers corresponds to the rotational barrier (*i.e.* the *B* value) of the substituted biphenyl. A number of diasterotopic probes in the 3′-position of 2-substituted biphenyls were tested for this purpose: Me_2CH,[7] $(i\text{-Pr})_3Si$,[8] $i\text{-PrMe}_2Si$,[8,10] $(CF_3)_2COH$[9] and it was demonstrated that the rotational barrier was found to remain the same, within the experimental uncertainty of ±0.15 kcal mol^{-1}, regardless of the choice of probe. For instance the barriers determined using the isopropyl group as a probe were found[7] to be 15.4, 8.75 and 9.9 kcal mol^{-1} for biphenyls bearing, as an *ortho* substituent, *t*-Bu, Br and I, respectively. When the $i\text{-PrMe}_2Si$ probe was employed, these values were found to be 15.5, 8.7 and 10.0 kcal mol^{-1}, respectively.[8]

The present study relied exclusively on the isopropyldimethylsilyl group as the diastereotopicity probe for compounds **1–15** (listed in Table 2). The isopropyldimethylsilyl substituent, in fact, can be incorporated in the biphenyl moiety by Suzuki–Miyaura coupling of dimethyl(3-iodophenyl)isopropylsilane with 2-bromophenylboronic acid. The resulting 2-bromo-3′-(dimethylisopropylsilyl)biphenyl is the common precursor to products **1–15** that were obtained by lithium/bromine permutation with *tert*-butyllithium followed by the reaction with the suitable electrophile. Both 2-benzenesulfinyl and 2-benzenesolfonyl derivatives were prepared from the corresponding 2-phenylthio derivative by selective oxidation procedures. If the substituent in the 2-position bears two enantiotopic groups, as in compounds **16** and **17**, then we need a second substituent in the 3′-position (chlorine in our case) to generate conformational enantiomers. The silylation at the 2-position of a biphenyl moiety using bulky trialkylchlorosilane is anything but straightforward. Thus, the 2-silyl derivatives, **16** and **17**, were satisfactorily prepared from 2-bromo-3′-chlorobiphenyl in a one-pot procedure consisting in the lithium/bromine permutation with *tert*-butyllithium, followed by reaction of the resulting 2-lithiobiphenyl with dichlorodimethylsilane and, finally, addition of 2-ethylmagnesium chloride and phenyllithium, respectively, to the (biphenyl-2-yl)chlorodimethylsilane intermediate.

Table 2 Experimental *B* values ($\Delta G^{\neq}_{rot}$ in kcal mol^{-1}) and DFT computed rotational barriers ($\Delta E^{\neq}_{rot}$ in kcal mol^{-1}) for the aryl–aryl rotation of compounds **1–17**[a]



Compd	R	$\Delta G^{\neq}_{rot}$ exper.	$\Delta E^{\neq}_{rot}$ calc.[b]	$\lvert\theta\rvert$[c]
1	SCH_3	8.6	8.4	125
2	SPh	8.3	8.8	125
3	SOPh	8.6	8.1	55
4	SO_2Ph	12.8	10.3[d]	59
5	SePh	9.1	9.2	116
6	TePh	9.9	10.2	117
7	$P(CH_3)_2$	9.1	10.0	125
8	$PO(CH_3)_2$	11.8	13.3	97
9	PPh_2	9.4	9.2	66
10	$POPh_2$	10.2	11.3	56
11	$P(C_6H_{11})_2$	11.8	9.5	61
12	$PO(C_6H_{11})_2$	12.7	12.9	59
13	$Si(CH_3)_3$	10.4	10.0	115
14	$Si[CH(CH_3)_2]_3$	12.1	11.2	115
15	$Sn(CH_3)_3$	9.1	8.8	120
16	$Si(CH_3)_2C_2H_5$	9.9	10.2	116
17	$Si(CH_3)_2Ph$	9.8	10.9	63

[a] X = $Si(CH_3)_2[CH(CH_3)_2]$ for compounds **1–15** and X = Cl for compounds **16**, **17**. [b] See experimental section for details. [c] Aryl–aryl computed twist angle (absolute value). [d] 13.2 kcal mol^{-1} at the CISD/6-31+G(d) level.

A typical example of the variable temperature NMR experiment is shown in Fig. 1, where the temperature dependence of the silicon bonded methyl signal is displayed in the case of the *ortho* substituted PhS derivative **2**. The single methyl line broadens on cooling, decoalesces at about −113 °C and splits into two sharp signals separated by 8.5 Hz (at 600 MHz) at −128 °C.

The computer line shape simulations reported on the right provide the rate constants for the aryl–aryl rotation process, corresponding to a free energy of activation ($\Delta G^{\neq}$) of 8.3 kcal mol^{-1} (*i.e.*, *B* value). Table 2 lists the values obtained for the compounds **1–17** investigated.

In the case of the sulfoxide **3**, the situation is different from that of the other compounds since the sulfur atom is itself a chiral center. For this reason the silicon bonded methyls are

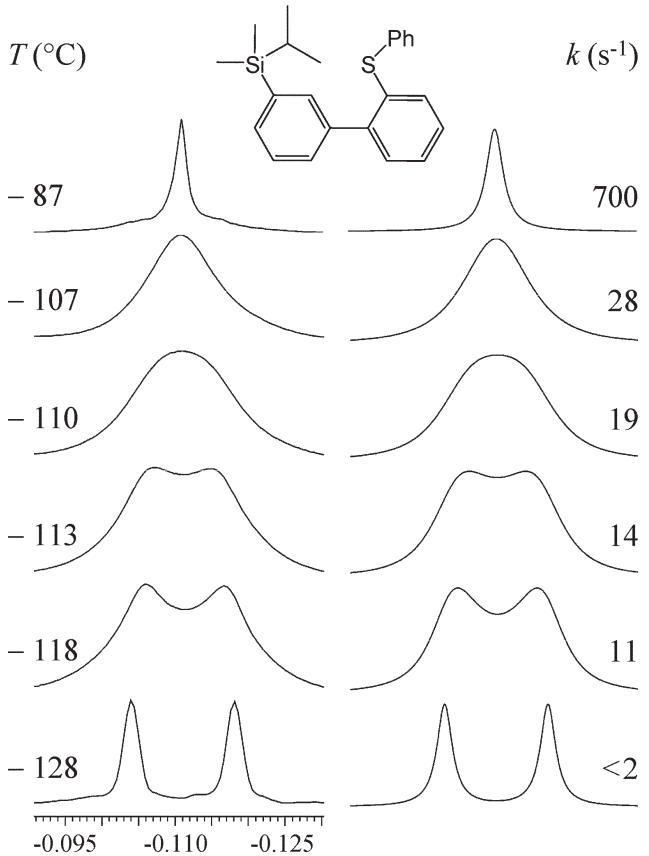


Fig. 1 Left: temperature dependence of the silicon bonded ^{1}H NMR methyl signal of *ortho* phenyl sulfide derivative **2** in $CHF_2Cl/CHFCl_2$ at 600 MHz. Right: line shape simulation obtained with the indicated rate constants.

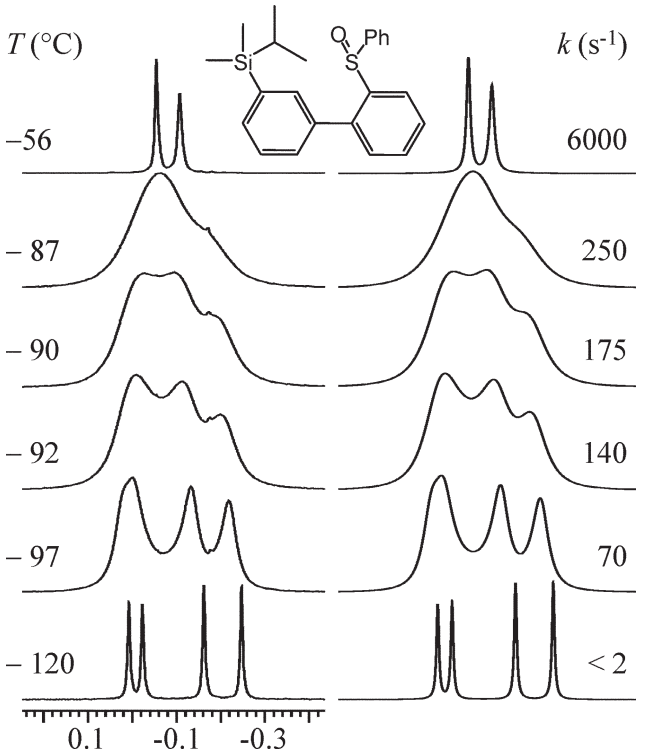


Fig. 2 Left: temperature dependence of the silicon bonded ^{1}H NMR methyl signals of *ortho* phenyl sulfoxide derivative **3** in $CHF_2Cl/CHFCl_2$ at 600 MHz. Right: line shape simulation obtained with the indicated rate constants.

diastereotopic even at ambient temperature and thus display two equally intense signals. At low temperature the aryl–aryl axis behaves as a stereogenic axis and therefore two conformational diastereoisomers, with different populations, are generated. In fact, as shown in Fig. 2, at −120 °C two pairs of lines emerge with a 55 : 45 intensity ratio. At intermediate temperatures (between −50 and −110 °C) these lines are broadened by the exchange process and the line shape simulation provides the corresponding rate constants.[13]

In principle the two mentioned diastereoisomers could be alternatively generated by the restricted rotation around the aryl–SO bond rather than around the aryl–aryl bond. In fact, the effects due to the restricted aryl–SO bond rotation have been detected in the low temperature NMR spectra of a number of sulfoxides.[14,15]

In the present case, such a rotation would generate two differently populated rotamers having the sulfoxide oxygen either *syn* or *anti* to the phenyl bearing the –$SiMe_2{}^i$Pr group. However calculations indicate that the *anti* rotamer, having the aryl and the CSO planes coplanar, is 1.8 kcal mol^{-1} more stable than the *syn* rotamer, where aryl and the CSO plane are not coplanar, the latter accounting for a population of only 0.3% at −120 °C. This ratio is at variance with the observation of the 55 : 45 ratio, so that the observed process cannot be attributed to the aryl–SO rotation as only one of these rotamers would be expected to be significantly populated. On the other hand, calculations [B3LYP/6-31G(d) level] indicate that the two conformational diastereoisomers generated by the restricted aryl–aryl rotation have an energy difference of only 0.1 kcal mol^{-1}, corresponding to a 58 : 42 population ratio at −120 °C, the diastereoisomer (*R**), (*P**) being more stable. This ratio is in good agreement with the experimental value, thus confirming that the measured barrier is due to the aryl–aryl rotation. Calculations also explain why the barrier for the aryl–aryl rotation in the sulfoxide **3** (8.6 kcal mol^{-1}) is essentially equal, within the experimental uncertainty, to that of the sulfide **2** (8.3 kcal mol^{-1}). In the transition state for the aryl–aryl rotation the oxygen of sulfoxide points away from the biphenyl moiety (see Fig. S1 of ESI†) so that its steric hindrance is analogous to that of the sulfide. In the case of sulfone **4**, the reverse is true in that there is always at least one oxygen pointing toward the biphenyl moiety and this explains the substantially higher barrier observed (12.8 kcal mol^{-1}). This interpretation is confirmed by the trend of the computed barriers showing that the theoretical value for **4** (10.3 or 13.2 kcal mol^{-1}, depending on calculations) is indeed significantly higher than those of **2** and **3** (see Table 2).

In order to corroborate the reliability of our computational approach it would be instructive to compare the calculated parameters with their experimental counterpart. This was accomplished in the case of phosphine oxide **10** which is a solid compound and yielded appropriate single crystals. In Fig. 3 its X-ray structure is displayed, together with the two structures having the lowest energies, as computed by the DFT approach. The latter differ by the relative position of the silicon atom with respect to the oxygen of the phosphine oxide (*syn* or *anti*), but

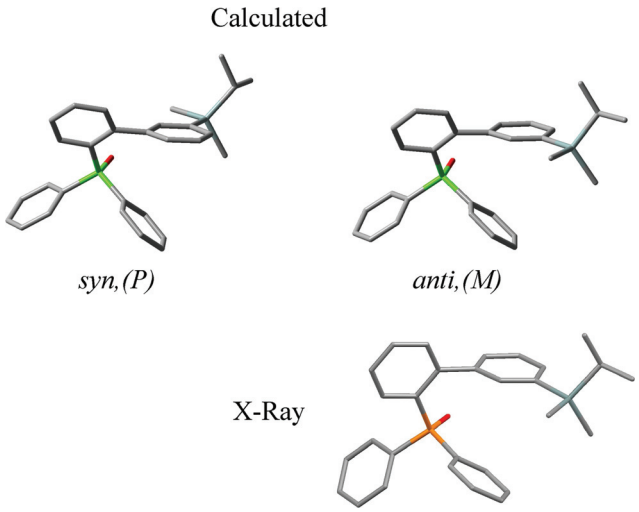


Fig. 3 Top: Structures, according to DFT computation, [B3LYP/6-31G(d) level] of the two most stable conformers of compound **10**. *Syn* and *anti* descriptions refer to the relative position of the oxygen with respect to the *i*-PrMe$_2$Si group and (*M*),(*P*) descriptions refer to the aryl–aryl chirality axis. Bottom: experimental structure according to X-ray diffraction.

they have exactly the same free energy when the zero point correction[16] is applied to the total energy. The presence in the solid state of only one of these two structures, corresponding to the *anti* form, is probably due to the crystal field effect.[15] As it appears in Fig. 3 (right), computations reproduce very well the experimental structure. A good agreement was also observed when the structure of the most stable computed conformer of phosphine **9** was compared with its X-ray structure (Fig. S2 of ESI†). This indicates that these computations are quite reliable. As already observed,[7–10] B3LYP calculations are also able to reproduce, rather satisfactorily, the experimental barriers (*B* values) of compounds **1–17**. In fact, the average deviation between the computed and experimental barriers is only 0.6 kcal mol^{-1}, a value which is in line with the deviation previously observed for the derivatives reported in Table 1.

Conclusions

The data collected in Table 1 and 2 reveal the trimethylammonio group to be the bulkiest (*B* = 18.1) whereas *tert*-butyl is somewhat smaller (*B* = 15.4) and trimethylsilyl (*B* = 10.4) and trimethylstannyl (*B* = 9.1) are considerable smaller. Obviously the longer the carbon–heteroatom bond, the farther away are the sterically interfering methyl groups. The X–C bond lengths are 1.50, 1.54, 1.89, 2.15 Å when X is N$^+$, C, Si and Sn, respectively.[17] Remarkably this trend is at variance with Taft's type parameters that rank *tert*-butyl (E'_s = 1.43) below trimethylsilyl (E'_s = 1.79).[12]

In the case of the model compounds, **2**, **5**, **6**, bearing a phenyl group, the steric effect is essentially determined by the size of the atom X and thus increases with the van der Waals radius, as shown by the 8.3, 9.1, 9.9 *B* values for X = S, Se, Te, respectively (Table 2), the radii being 1.80, 1.90, and 2.06 Å, respectively.[18] Although the *B* value for OPh is not yet available, the corresponding steric effect is certainly even lower, as shown by the *B* values measured for various OR groups (R = H, Me, CF_3, CH_2OMe) that all lie in the very restricted range of 5.4–5.7 (Table 1). Indeed our present calculations indicate that the DFT computed barrier (*B* value) for the OPh substituent (4.1 kcal mol^{-1}) is, as conceived, definitely lower than that computed for SPh (8.8 kcal mol^{-1}, as in Table 2). As a further evidence, the *B* value determined for OMe (5.6, as in Table 1) is much smaller than that measured for SCH_3 (8.6, as in Table 2), due to the smaller van der Waals radius of oxygen (1.52 Å) with respect to sulfur (1.80 Å).[18] According to computations, the phenyl of the X-Ph groups (and likewise the R substituents of the various X-R groups) point away from the *ortho*-hydrogens of the 3′ substituted ring and thus should not contribute significantly to the steric effect. This would explain why such an effect, in this series, is essentially determined by the X atom size rather than by the C–X bond length of the substituent.

With the addition of the present measurements, as many as 46 steric parameters of this type (*B* values) become available (collected in Table 1 and 2): this represents a quite large body of values useful for estimating the steric effect of substituents based solely on experimental determinations.

Experimental

General

All commercial reagents were used without further purification. Starting materials were purchased from Aldrich-Fluka (CH-9479 Buchs). Air- and moisture-sensitive compounds were stored in Schlenk tubes or Schlenk burettes. They were protected and handled under an atmosphere of 99.995% pure nitrogen, using appropriate glassware. Tetrahydrofuran and diethyl ether were stored over potassium hydroxide pellets in the presence of cuprous chloride, from which they were distilled, before being redistilled from sodium wire in the presence of benzophenone. The constant temperature of −75 °C was maintained by using liquid nitrogen/butyl acetate baths. Ice baths were used for reactions carried out at 0 °C. Melting points were corrected after the thermometer calibration by authentic standards. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded at 400, 100.6 and 161.9 MHz, respectively, in deuterochloroform solutions. Chemical shifts (δ) are given in ppm by using tetramethylsilane and phosphoric acid as internal standards. Mass spectra were obtained by electron impact fragmentation at 70 eV ionization potential. The purity of all final products was testified by elemental analyses (performed by Dr. E. Solari of the Analytical Services of EPFL-ISIC and the REDOX Company in Monza) and by gas chromatography using two capillary columns of different polarity (30 m × 0.35 mm × 0.25 μm DB 5MS [5% phenylmethylpolysiloxane] and 30 m × 0.35 mm × 0.25 μm DB23 [50% cyanopropylmethylpolysiloxane]).

Product preparation

2-Bromo-3′-(dimethylisopropylsilyl)biphenyl, precursor of products **1–15**, was available from previous work.[8]

2-Bromo-3′-chlorobiphenyl. The precursor to products **16** and **17**, was prepared according to the Suzuki–Miyaura[19] protocol.

Ethanol (20 mL), benzene (40 mL), 1-chloro-3-iodobenzene (2.0 g, 8.4 mmol), 2.0 M aqueous potassium carbonate (6.5 mL), tetrakis[triphenylphosphine] palladium(0) (0.16 g, 0.14 mmol) were added consecutively to 2-bromophenylboronic acid (1.9 g, 9.5 mmol). The mixture was kept at reflux for 3 h. After cooling and addition of water, the mixture was extracted with diethyl ether (80 mL) and the organic phase was dried with sodium sulfate. After the solvent was evaporated, chromatography of the residue on silica gel (0.2 L, eluent, petroleum ether) provided the pure product (2.041 g, 91%) as a colorless oil; ^{1}H NMR: δ 7.4 (m, 1 H), 7.3 (m, 6 H), 7.22 (ddd, J = 8.0, 7.3 and 1.9 Hz, 1 H). ^{13}C NMR: δ 142.6, 141.1, 133.7, 133.2, 131.1, 129.4, 129.2, 129.1, 127.7, 127.6, 127.4, 122.3. MS: m/z (%) 270 (M^+ + 3, 23), 269 (M^+ + 2, 12), 268 (M^+ + 1, 91), 266 (M^+ − 1, 72), 186 (6), 152 (100), 126 (9), 75 (15). Analysis: calcd for $C_{12}H_8BrCl$ (267.55) : C 53.87, H 3.01; found C 53.59, H 3.18.

3-(Dimethyisopropylsilyl)-2′-(methylthio)biphenyl (1). At −75 °C, *tert*-butyllithium (1.5 mmol) in hexanes (0.8 mL) and, 30 min later, dimethyl disulfide (0.14 g, 1.5 mmol) were added to 2-bromo-3′-(isopropyldimethylsilyl)biphenyl (0.50 g, 1.5 mmol) in diethyl ether (5.0 mL) while stirring. The temperature was allowed to rise to +25 °C and, after solvent evaporation at reduced pressure, followed by chromatography of the residue on silica gel (30 mL, eluent, petroleum ether), 0.364 g (81%) of a colorless viscous oil was collected. ^{1}H NMR: δ 7.55 (s, 1 H), 7.5 (m, 1 H), 7.4 (m, 2 H), 7.3 (m, 2 H), 7.2 (m, 2 H), 2.34 (s, 3 H), 0.98 (bs, 7 H), 0.26 (s, 6 H). ^{13}C NMR: δ 141.3, 139.6, 138.3, 137.2, 134.9, 133.0, 130.0, 129.5, 127.8, 127.3, 125.4, 124.7, 17.6 (2 C), 16.0, 13.8, −5.3 (2 C). MS: m/z (%) 300 (M^+, 42), 285 (1), 257 (100), 241 (23), 227 (10), 197 (26), 128 (15), 59 (21). Analysis: calcd for $C_{18}H_{24}SSi$ (300.53) C 71.94, H 8.05; found C 72.13, H 7.98.

3-(Dimethylisopropylsilyl)-2′-(phenylsulfenyl)biphenyl (2) was prepared from the 2-bromo-3′-(dimethylisopropylsilyl) biphenyl (1.0 g, 3.0 mmol) and phenyl disulfide (0.66 g, 3.0 mmol) analogously as described in the preceding paragraph. Chromatography of the crude product on silica gel (60 g, eluent, petroleum ether) afforded the pure product (0.946 g, 87%) as a viscous opalescent oil. ^{1}H NMR: δ 7.52 (bs, 1 H), 7.5 (m, 1 H), 7.42–7.14 (m, 11 H), 0.94 (s, 7 H), 0.21 (s, 6 H). ^{13}C NMR: δ 143.6, 139.6, 138.0, 136.0, 134.8, 134.5, 132.9, 131.8, 131.2 (2 C), 130.6, 129.5, 129.0 (2 C), 127.9, 127.1, 126.9, 126.8, 17.5 (2 C), 13.7, −5.4 (2 C). MS: m/z (%) 362 (M^+, 6), 347 (2), 319 (100), 303 (11), 287 (9), 195 (21), 165 (13), 135 (23), 77 (11), 43 (9). Analysis: calcd for $C_{23}H_{26}SSi$ (362.60) C 76.18, H 7.23; found C 76.20, H 7.39.

3-(Dimethylisopropylsilyl)-2′-(phenylsulfinyl)biphenyl (3). *N*-Chlorosuccinimide (0.12 g, 0.90 mmol) was added to 3-(isopropyldimethylsilyl)-2′-(phenylsulfenyl)biphenyl (0.30 g, 0.83 mmol) in methanol (5.0 mL) and the mixture was stirred for 1 h at 0 °C and then 30 min at +25 °C. The solvent was evaporated under reduced pressure, diethyl ether was added (3.0 mL) and the mixture was filtered to remove the insoluble succinimide. After the solvent evaporation and chromatography of the residue on silica gel (25 mL, diethyl ether–petroleum ether 1 : 1 v/v) 0.290 g (89%) of product as a colorless viscous oil was collected. ^{1}H NMR: δ 8.19 (dd, J = 7.9 and 0.9 Hz, 1 H), 7.60 (td, J = 7.8 and 1.2 Hz, 1 H), 7.5 (m, 2 H), 7.36 (t, J = 7.5 Hz, 1 H), 7.34 (s, 1 H), 7.3 (m, 2 H), 7.2 (m, 3 H), 7.02 (d, J = 7.3 Hz, 2 H), 0.97 (s, 7 H), 0.25 (s, 3 H), 0.21 (s, 3 H). ^{13}C NMR: δ 144.8, 143.4, 140.9, 139.2, 137.1, 134.9, 133.6, 130.7, 130.6, 130.3, 129.8, 128.7 (2 C), 128.4, 127.6, 125.5 (2 C), 123.8, 17.5 (2 C), 13.6, –5.4 (2 C). MS: m/z (%) 378 (M^+, 1), 363 (3), 335 (100), 319 (20), 319 (20), 261 (37), 184 (15), 75 (12), 43 (3). Analysis: calcd for $C_{23}H_{26}OSSi$ (378.60) C 72.96, H 6.92; found C 72.63, H 7.07.

3-(Dimethylisopropylsilyl)-2′-(phenylsulfonyl)biphenyl (4). Carbon tetrachloride (2.0 mL), acetonitrile (2.0 mL), water (4.0 mL) sodium periodate (0.53 g, 2.5 mmol) and ruthenium trichloride hydrate (about 0.1 mg, 0.05 mol%) were added consecutively to sulfide **2** (0.30 g, 0.83 mmol) and the suspension was stirred at +25 °C for 1 h while a red precipitate formed. Water (30 mL) and ether (30 mL) were added, the organic layer was separated, washed with saturated sodium bicarbonate (30 mL), then with brine (30 mL), and dried with sodium sulfate. The solvent was evaporated at reduced pressure, and the crude product was passed on silica gel (30 mL, 1 : 1 (v/v) diethyl ether–petroleum ether mixture as the eluent). After solvent evaporation, the residue was kept for 3 h at +40 °C per 0.05 mmHg leaving a colorless very viscous oil (0.314 g, 96%). ^{1}H NMR: δ 8.46 (dd, J = 7.0 and 2.0 Hz, 1 H), 7.6 (m, 2 H), 7.43 (dt, J = 7.4 and 1.2 Hz, 1 H), 7.35 (tt, J = 7.2 and 1.5 Hz, 1 H), 7.2 (m, 6 H), 7.1 (m, 1 H), 7.02 (ddd, J = 7.6, 1.9 and 1.3 Hz, 1 H), 0.96 (s, 7 H), 0.18 (s, 6 H). ^{13}C NMR: δ 142.6, 140.8, 139.6, 137.6, 137.2, 135.3, 133.1, 132.8, 132.7, 132.3, 130.5, 128.5, 128.1 (2 C), 127.6 (2 C), 127.5, 126.4, 17.5 (2 C), 13.5, –5.4 (2 C). MS: m/z (%) 394 (M^+, 1), 379 (8), 351 (100), 337 (5), 226 (23), 211 (36), 195 (27), 167 (70), 152 (22) 109 (10), 77 (34), 43 (15). Analysis: calcd for $C_{23}H_{26}IO_2SSi$ (394.61) C 70.01, H 6.64; found C 69.89, H 6.66.

The same procedure described above for the synthesis of thioethers **1** and **2** was employed to prepare compounds **5**, **6**, **7**, **9**, **11**, **13** and **14** from the 2-bromo-3′-(dimethylisopropylsilyl) biphenyl and an equimolar amount of the appropriate electrophilic reagent.

3-(Dimethylisopropylsilyl)-2′-(phenylseleno)biphenyl (5). From 2-bromo-3′-(dimethylisopropylsilyl)biphenyl (0.50 g, 1.5 mmol) and diphenyl diselenide (0.47 g, 1.5 mmol) a slightly yellow oil (0.430 g, 70%) was obtained after chromatography of the crude product on silica gel. ^{1}H NMR: δ 7.55 (s, 1 H), 7.51 (d, J = 6.2 Hz, 1 H), 7.5 (m, 2 H), 7.4 (m, 2 H), 7.3 (m, 5 H), 7.2 (m, 2 H), 0.97 (s, 7 H), 0.25 (s, 6 H). ^{13}C NMR: δ 143.6, 140.6, 138.3, 134.8 (2 C), 134.5, 133.1, 132.4, 131.6, 130.4, 130.1, 129.3 (2 C), 129.2, 127.9, 127.8, 127.3, 126.6, 16.7 (2 C), 13.7, −5.4 (2 C). MS: m/z (%) 410 (M^+, 30), 367 (25), 289 (6), 195 (16), 165 (13), 135 (100), 77 (5), 43 (4). Analysis: calcd for $C_{23}H_{26}SeSi$ (409.50) C 67.46, H 6.40; found C 67.17, H 6.64.

3-(Dimethylisopropylsilyl)-2′-(phenyltelluro)biphenyl (6). The reaction of 2-bromo-3′-(dimethylisopropylsilyl)biphenyl (0.50 g, 1.5 mmol) with diphenyl ditelluride (0.61 g, 1.5 mmol) gave a pale orange oil (0.420 g, 61%), after chromatography of the crude reaction product on silica gel. ^{1}H NMR: δ 7.82 (dd, J = 7.8 and 0.9 Hz, 2 H), 7.5 (m, 2 H), 7.43 (t, J = 7.5 Hz, 1 H), 7.4

(m, 2 H), 7.3 (m, 5 H), 7.05 (bt, J = 6.7 Hz, 1 H), 0.99 (bs, 7 H), 0.29 (s, 6 H). ^{13}C NMR: δ 146.4, 142.9, 140.6 (2 C), 138.9, 134.2, 133.6, 133.5, 129.6 (2 C), 129.3, 128.7, 128.5, 128.1, 127.7, 126.8, 119.6, 114.9, 17.7 (2 C), 13.8, −5.3 (2 C). MS: m/z (%) 460 (M^++2, 21), 458 (M^+, 19), 339 (7), 337 (6), 195 (12), 165 (10), 77 (5), 53 (3). Analysis: calcd for $C_{23}H_{26}TeSi$ (458.14) C 60.30, H 5.72; found C 60.51, H 5.85.

2-Dimethylphosphino-3′-(dimethylisopropylsilyl)biphenyl (7). *tert*-Butyllithium (0.5 mL, 1 mmol) was added to 2-bromo-3′-(dimethylisopropylsilyl)biphenyl (0.33 g, 1.0 mmol) in diethyl ether at −75 °C under argon atmosphere. After 30 min, phosphorus trichloride (0.090 mL, 0.14 g, 1.02 mmol) was added and the temperature was allowed to rise to −40 °C. A dense white precipitate formed. The mixture was allowed to react at that temperature for 1 h while stirring before it was cooled at −75 °C and methyllithium (2.1 mmol) in dimethoxymethane (0.7 mL) was added. The cold bath was removed, the temperature was allowed to rise to 0 °C. After the white precipitate had settled the supernatant ethereal solution was transferred under argon in a second Schlenk tube and the solvent was evaporated by argon bubbling through. GC-MS analysis of the resulting orange viscous oil (0.16 g) diluted in argon saturated diethyl ether showed the presence of the expected biphenyldimethylphosphine together with 3-(dimethylisopropylsilyl)biphenyl (about 30%) and traces of the starting material. An aliquot (0.020 g) of this mixture was used as such in dynamic NMR experiments. The remaining amount was rapidly passed through 1.0 g of argon purged silica gel allowing the eluted solution to percolate under argon atmosphere into a 30 mL Schlenk tube. The solvent was evaporated under vacuum (0.1 mmHg) leaving a slightly yellow oil behind (0.052 g, 32%). ^{1}H NMR: δ 7.59 (ddd, J = 9.7, 8.4 and 1.3 Hz, 1 H), 7.53 (bs, 1 H), 7.50 (bd, J = 7.4 Hz, 1 H), 7.4 (m, 3 H), 7.3 (m, 2 H), 1.10 (d, J = 3.9 Hz, 6 H), 0.90 (bs, 7 H), 0.26 (s, 6 H). ^{13}C NMR: δ 141.1 (d, J = 5.6 Hz), 138.3 (d, J = 13 Hz), 137.9 (d, J = 15 Hz), 133.0, 132.7, 130.1 (2 C), 129.2, 128.1 (d, J = 20 Hz), 127.5, 127.3, 127.0, 17.8 (2 C), 14.3 (d, J = 14 Hz, 2 C), 14.0, −5.1 (2 C). ^{31}P NMR: δ −50.0. MS: m/z (%) 314 (M+, 37), 313 (100), 299 (2), 271 (33), 213 (8), 183 (11), 135 (14), 73 (13). Analysis: calcd for $C_{19}H_{27}PSi$ (314.48) C 72.57, H 8.65; found C 72.74, H 8.83.

2-Dimethylphosphinoyl-3′-(dimethyisopropylsilyl)biphenyl (8) was prepared by adding a slight excess of hydrogen peroxide to an ethereal solution of the above biphenyldimethylphosphine **7** (0.050 g, 0.16 mmol). After the solvent evaporation at reduced pressure, chromatography of the crude product on silica gel (eluent diethyl ether) afforded a colorless viscous oil (0.033 g, 63%). ^{1}H NMR: δ 8.19 (ddd, J = 13, 6.7 and 2.3 Hz, 1 H), 7.5 (m, 3 H), 7.44 (bs, 1 H), 7.41 (t, J = 7.3 Hz, 1 H), 7.3 (m, 2 H), 1.36 (d, J = 13 Hz, 6 H), 0.95 (bs, 7 H), 0.26 (s, 6 H). ^{13}C NMR: δ 144.6, 144.5 (d, J = 31 Hz), 140.4 (d, J = 3.3 Hz), 138.8, 134.8, 133.6, 132.2 (d, J = 8.0 Hz), 131.1, 131.0 (d, J = 9.9 Hz), 129.9, 127.3 (d, J = 11), 127.2, 18.9 (d, J = 71 Hz, 2 C), 17.5 (2 C), 13.6, −5.4 (2 C). ^{31}P NMR: δ 35.81. MS: m/z (%) 330 (M^+, 0.5), 329 (1), 315 (3), 287 (100), 271 (2), 213 (33), 183 (16), 165 (7), 73 (3). Analysis: calcd for $C_{19}H_{27}OPSi$ (330.48) C 69.05, H 8.23; found C 69.35, H 8.50.

[3-(Dimethylisopropylsilyl)biphenyl-2′-yl]diphenylphosphine (9) was prepared from 2-bromo-3′-(dimethylisopropylsilyl) biphenyl (0.5 g, 1.5 mmol) and chlorodiphenylphosphine (0.33 g, 1.5 mmol). Half volume (5.0 mL) of the ethereal solution of the crude reaction product was concentrated at reduced pressure and passed through argon purged silica gel (30 mL) by eluting with degassed petroleum ether. The product (0.296 g, 90%) was collected as white rhombic crystals, m.p. 95–96 °C. CCDC ref. number: 849731. ^{1}H NMR: δ 7.57 (bt, J = 7.7, 1 H), 7.3 (m, 15 H), 7.0 (m, 2 H), 0.85 (bs, 7 H), 0.05 (s, 6 H). ^{13}C NMR: δ 148.6 (d, J = 29 Hz), 140.8 (d, J = 6.0 Hz), 137.8 (d, J = 12 Hz, 2 C), 137.7, 135.6 (d, J = 14 Hz), 135.2 (d, J = 4.4 Hz, 2 C), 134.3, 133.8 (d, J = 20 Hz, 4 C), 132.8, 130.2 (d, J = 5.7 Hz), 129.8, 128.5 (d, J = 30 Hz, 2 C), 128.3 (d, J = 7.4 Hz, 4 C), 127.2, 126.9, 17.6 (2 C), 13.5, −5.6 (2 C). ^{31}P NMR: δ −12.2. MS: m/z (%) 438 (M^+, 60), 437 (100), 395 (35), 337 (32), 183 (55), 135 (39), 73 (39), 43 (29). Analysis: calcd for $C_{29}H_{31}PSi$ (438.19) C 79.41, H 7.12; found C 79.09, H 7.03.

[3-(Dimethylisopropylsilyl)biphenyl-2′-yl]diphenylphosphine oxide (10). The crude **9** (5.0 mL) was treated with 30% aqueous hydrogen peroxide (0.2 mL, 1.6 mmol) at +25 °C and after 5 min, the solvent was evaporated at reduced pressure. Chromatography of the residue on silica gel (30 mL) by eluting with 1 : 4 diethyl ether–petroleum ether mixture allowed to collect the product (0.297 g, 87%) as white rhombic crystals, m. p. 112–113 °C. CCDC ref. number: 849732. ^{1}H NMR: δ 7.6 (m, 5 H), 7.46 (ddd, J = 13, 7.8 and 1.1 Hz, 1 H), 7.3 (m, 10 H), 7.20 (dt, J = 7.3 and 1.2 Hz, 1 H), 7.04 (t, J = 7.3 Hz, 1 H), 0.90 (s, 7 H), 0.14 (s, 6 H). ^{13}C NMR: δ 148.0 (d, J = 4 Hz), 139.6 (d, J = 4.5 Hz, 2 C), 137.4, 135.1, 134.2 (d, J = 12 Hz), 133.3, 132.8, 132.3, 132.2 (d, J = 9.9 Hz), 131.8 (d, J = 3.5 Hz), 131.5 (d, J = 9.4 Hz, 4 C), 131.1 (d, J = 3.5 Hz, 2 C), 130.7, 128.0 (d, J = 12 Hz, 4 C), 126.4 (d, J = 12 Hz), 126.4, 17.6 (2 C), 13.4, −5.4 (2 C). ^{31}P NMR: δ 29.4. MS: m/z (%) 454 (M^+, 2), 439 (3), 411 (100), 337 (32), 195 (39), 77 (26), 43 (52). Analysis: calcd for $C_{29}H_{31}OPSi$ (454.62) C 76.62, H 6.87; found C 76.64, H 6.84.

Dicyclohexyl[3-(dimethylisopropylsilyl)biphenyl-2′-yl]phosphine (11) was analogously prepared from the 2-bromo-3′-(dimethylisopropylsilyl)biphenyl (0.50 g, 1.5 mmol) and chlorodicyclohexylphosphine (0.35 g, 1.5 mmol). Half of the ethereal solution of the crude product (5.0 mL) was concentrated at reduced pressure and passed through argon purged silica gel (30 mL) by eluting with degassed petroleum ether to obtain a colorless viscous oil (0.189 g, 60%). ^{1}H NMR: δ 8.1 (m, 1 H) 7.5 (m, 4 H), 7.3 (m, 3 H), 1.7 (m, 10 H), 1.5 (m, 4 H), 1.2 (m, 8 H), 0.96 (bs, 7 H), 0.25 (s, 6 H).). ^{13}C NMR: δ 142.8, 140.1, 138.2, 137.2 (d, J = 8.3 Hz), 134.9, 133.0 (2 C), 131.2, 129.5, 128.5, 127.2 (d, J = 18 Hz), 126.3, 38.0 (d, J = 31 Hz, 2 C), 28.1 (d, J = 17 Hz, 2 C), 26.8, 26.0 (4 C), 25.9 (2 C), 25.6, 17.5 (2 C), 13.6, −5.3 (2 C). ^{31}P NMR: δ 20.40. MS: m/z (%) 450 (M^+, 54), 449 (100), 407 (8), 367 (30), 325 (11), 183 (32), 73 (22), 59 (21), 55 (15). Analysis: calcd for $C_{29}H_{43}PSi$ (450.71) C 77.28, H 9.62; found C 77.08, H 9.92.

Dicyclohexyl[3-(dimethylisopropylsilyl)biphenyl-2′-yl]phosphine oxide (12). Aqueous (30%) hydrogen peroxide (0.10 mL, 0.88 mmol) was added to the second portion of the above ethereal solution of **11** (5.0 mL) and 5 min later the solvent was evaporated. Chromatography of the crude product on silica gel

(eluent, 1 : 4 (v/v) diethyl ether–petroleum ether mixture) gave 0.22 g (65%) of a colorless viscous compound. ^{1}H NMR: δ 8.1 (m, 1 H), 7.49 (bd, J = 7.3 Hz, 1 H), 7.4 (m, 2 H), 7.3 (m, 1 H), 7.25 (bs, 1 H), 7.1 (m, 2 H), 1.6 (m, 10 H), 1.3 (m, 6 H), 1.0 (m, 6 H), 0.92 (bs, 7 H), 0.20 (s, 6 H). ^{13}C NMR: δ 147.9 (d, J = 7.0 Hz), 143.9 (d, J = 5.9 Hz), 141.5, 138.5, 134.3 (d, J = 5.5 Hz), 133.4 (d, J = 4.0 Hz, 2 C), 131.1 (d, J = 9.6 Hz), 130.4, 129.5 127.2 (d, J = 3.0 Hz), 127.0 (d, J = 15 Hz), 37.9 (d, J = 65 Hz, 2 C), 26.3 (2 C), 26.2 (6 C), 25.5 (2 C), 17.5 (2 C), 13.8, −5.3 (2 C). ^{31}P NMR: δ 49.6. MS: m/z (%) 466 (M^+, 11), 423 (100), 383 (81), 341 (26), 301 (4), 283 (8), 183 (62), 75 (26), 55 (23). HRMS calcd for $C_{29}H_{43}OPSi$ 466.2821; found 466.2825. Analysis: calcd for $C_{29}H_{43}OPSi$ (466.71) C 74.63, H 9.29; found C 74.06, H 9.51.

3-(Dimethylisopropylsilyl)-2′-(trimethylsilyl)biphenyl (13). At −75 °C, *tert*-butyllithium (0.4 mL, 0.64 mmol) was added to 2-bromo-3′-(isopropyldimethylsilyl)biphenyl (0.21 g, 0.63 mmol) in THF (5 mL). After 5 min, chlorotrimethylsilane (0.12 mL, 0.96 mmol) was added with a glass syringe and the mixture was kept 1 h before the cold bath was removed and the temperature was allowed to rise to +25 °C. Water (20 mL) was added, the mixture was extracted with diethyl ether (3 × 10 mL) and the collected organic extracts were dried with Na_2SO_4. After solvent evaporation at reduced pressure, chromatography of the residue on silica gel (eluent, petroleum ether) allowed to collect 0.150 g (73%) of the product as a colorless oil. ^{1}H NMR: δ 7.63 (dd, J = 7.1 and 1.4 Hz, 1 H), 7.49 (dt, J = 7.3 and 1.2 Hz, 1 H), 7.41 (broad s, 1 H), 7.4 (m, 3 H), 7.3 (m, 2 H), 0.9 (m, 7 H), 0.24 (s, 6 H), −0.02 (s, 9 H); ^{13}C NMR: δ 149.5, 143.6, 138.5, 138.0, 134.7, 134.5, 132.6, 129.7, 129.5, 128.4, 126.9, 126.2, 17.6 (2), 13.8, 0.51(3), −0.52 (2). MS: m/z (%) 326 (M^+, 10), 311 (8), 283 (11), 195 (100), 126 (18), 73 (60). Analysis: calcd for $C_{20}H_{30}Si_2$ (326.62) C 73.54, H 9.26; found C 73.49, H 9.35.

3-(Dimethylisopropylsilyl)-2′-(triisopropylsilyl)biphenyl (14). At −75 °C *tert*-butyllithium (0.4 mL, 0.64 mmol) was added to a solution of 2-bromo-3′-(isopropyldimethylsilyl)biphenyl (0.21 g, 0.63 mmol) in diethyl ether saturated with lithium perchlorate (5 mL). After 5 min, chlorotriisopropylsilane (0.27 mL, 1.3 mmol) was added with a glass syringe and the mixture was allowed to react 1 h before the cold bath was removed and the temperature was allowed to rise to +25 °C. After 12 h, water was added, the organic layer was separated and the aqueous layer was extracted with diethyl ether (3 × 20 mL). The collected organic phases were dried with sodium sulfate and the solvent was evaporated at reduced pressure. Chromatography on silica gel allowed to recover the main product 3-(dimethylisopropylsilyl)biphenyl (0.122 g, 75%) and 0.042 g (11%) of the expected product as a colorless oil. ^{1}H NMR: δ 7.6 (m, 1 H), 7.4 (m, 6 H), 7.2 (m, 1 H), 0.96 (m, 28 H), 0.22 (s, 6 H). ^{13}C NMR: (CD_3CN): δ 150.3, 144.4, 137.7, 136.8, 134.7, 133.9, 132.9, 131.0, 130.3, 128.3, 126.9, 126.0, 18.9 (6 C), 17.1 (3 C), 13.7, 12.6 (2 C), −6.0 (2 C). MS: m/z (%) 367 ($M^+ - C_3H_7$, 38), 281 (4), 223 (13), 195 (26), 126 (25), 101 (100), 73 (76), 59 (30). HRMS: calcd for $C_{26}H_{42}Si_2$ 410.2825; found 410.2821.

3-(Dimethylisopropylsilyl)-2′-(trimethylstannyl)biphenyl (15) was prepared analogously as the disilylated biphenyl **14** from 2-bromo-3′-(isopropyldimethylsilyl)biphenyl (0.50 g, 1.5 mmol) and trimethyltin chloride (0.30 g, 1.5 mmol). A portion of the crude product was purified by HPLC on a Kromasil C18 column (250 × 10, 5 µm) using acetonitrile as mobile phase. ^{1}H NMR: δ 7.5 (m, 1 H), 7.42 (dt, J = 7.3 and 2.9 Hz, 1 H), 7.36 (bs, 1 H), 7.3 (m, 4 H), 7.26 (dt, J = 7.7 and 1.6 Hz, 1 H), 0.9 (m, 7 H), 0.19 (s, 6 H), −0.10 (s, 9 H). ^{13}C NMR: δ 150.7, 144.5, 142.2, 138.7, 136.2, 134.1, 132.7, 129.3, 128.7, 128.2, 127.3, 126.3, 17.5 (2 C), 13.7, −5.3 (2 C), −8.1 (3 C). MS: m/z (%) 418 (M^+, 1), 403 (68), 287 (24), 195 (24), 180 (17), 165 (29), 73 (100), 59 (30), 43 (3). HRMS: calcd for $C_{20}H_{30}SiSn$ 418.1139; found 418.1143; calcd for $C_{19}H_{27}SiSn$ (M − Me) 403.0904; found 403.0905.

3-Chloro-2′-(dimethylethylsilyl)biphenyl (16). At −75 °C, *tert*-butyllithium (1.9 mmol) in hexanes (1.1 mL) was added to 2-bromo-3′-chlorobiphenyl (0.50 g, 1.9 mmol) in diethyl ether (5.0 mL). After 30 min, dichlorodimethylsilane (0.17 mL, 1.9 mmol) and ethylmagnesium chloride (0.94 mL, 1.9 mmol) were added by a glass syringe and the mixture was allowed to react 1 h before the cold bath was removed allowing the temperature to rise to +25 °C. Water (50 mL) was added and the mixture was extracted with diethyl ether (3 × 20 mL). The collected organic phases were dried with Na_2SO_4 and the solvent was evaporated at reduced pressure. Chromatography of the residue on silica gel (eluent, petroleum ether) allowed to recover 0.34 g (66%) of the expected product as a colourless oil. ^{1}H NMR: δ 7.63 (dd, J = 6.4 and 1.3 Hz, 1 H), 7.3 (m, 5 H), 7.2 (m, 2 H), 0.86 (t, J = 7.9 Hz, 3 H), 0.52 (q, J = 7.9 Hz, 2 H), 0.01 (s, 6 H). ^{13}C NMR: δ 147.7, 146.2, 137.3, 135.1, 133.4, 129.5, 129.2, 128.9, 128.5, 127.4, 127.1, 126.6, 8.4 (2), 7.4, −1.8. MS: m/z (%) 259 (M^+ − 15, 8), 245 (100), 229 (52), 209 (30), 165 (27). Analysis: calcd for $C_{16}H_{19}ClSi$ (274.86) C 69.92, H 6.97; found C 69.90, H 6.86.

3-Chloro-2′-(dimethylphenylsilyl)biphenyl (17). At −75 °C, *tert*-butyllithium (1.9 mmol) in hexanes (1.1 mL) was added to 2-bromo-3′-chlorobiphenyl (0.50 g, 1.9 mmol) in diethyl ether (5 mL). After 30 min, dichlorodimethylsilane (0.17 mL, 1.9 mmol) and phenyllithium (1.0 mL, 1.9 mmol) were added with a glass syringe and the mixture was allowed to react 1 h before the cold bath was removed allowing the temperature to rise to +25 °C. After the usual work up, chromatography of the residue on silica gel (eluent, petroleum ether) gave the expected product as colorless needle shaped crystals, 0.477 g (79%), m. p. 77–78 °C (after crystallization from petroleum ether). ^{1}H NMR: δ 7.66 (dd, J = 6.9 and 1.4 Hz, 1 H), 7.3 (m, 8 H), 7.18 (dd, J = 6.9 and 1.2 Hz, 1 H), 7.13 (t, J = 7.7 Hz, 1 H), 7.02 (s, 1 H), 6.95 (d, J = 7.6 Hz, 1 H), 0.24 (s, 6 H). ^{13}C NMR: δ 148.0, 145.6, 139.4, 136.5, 135.7, 133.7 (2 C), 133.4, 129.5, 129.4, 129.0, 128.8, 128.7, 127.7 (2 C), 127.5, 127.0, 126.7, −1.2 (2 C). MS: m/z (%) 322 (M^+, 3), 307 (58), 229 (100), 165 (2), 155 (9). Analysis: calcd for $C_{20}H_{19}ClSi$ (322.90) C 74.39, H 5.93; found C 74.42, H 6.00.

Variable temperature NMR measurements

Variable temperature NMR spectra were recorded with a Varian INOVA spectrometer operating at a field of 14.4 Tesla (600 MHz for ^{1}H). Spectra of compound **4** were recorded in $CDCl_3$, spectra of **8** and **12** in CD_2Cl_2. When the temperature had to be

decreased below −100 °C, the NMR tubes containing the compound were manipulated at a vacuum line. First a small amount (approx. 0.05 mL) of hexadeuterobenzene (or acetone-d_6 in the case of **7**) was introduced by means of a microsyringe for locking purposes. The NMR tube was immersed in liquid nitrogen and evacuated in order to condense about 0.45 mL of chlorodifluoromethane (Freon 22) and about 0.15 mL of dichlorofluoromethane (Freon 21) transferred as gases from lecture bottles (samples of compounds **9**, **10**, **11** and **17** were prepared using $CDFCl_2$ as a single solvent). The tubes were subsequently sealed under reduced pressure (0.01 mbar) using a methane/oxygen torch. After a few hours at ambient temperature, the samples could be safely introduced into the probe head of the spectrometer, pre-cooled to −30 °C. Low temperature 600 MHz ^{1}H spectra (compounds **1–13**, **15–17**) were acquired without spinning, using a 5 mm dual direct probe with a 9000 Hz spectral width, 2.0 μs (20° tip angle) pulse width, 3 s acquisition time and 1 s delay time. A shifted sine bell weighting function[20] equal to the acquisition time (*i.e.*, 3 s) was applied before the Fourier transformation. Usually 32 to 64 scans were collected. Low temperature 150.8 MHz ^{13}C spectra (compounds **2**, **3**, **6**, **11**, **14**, **16**, **17**) were acquired without spinning and under proton decoupling conditions with a 38 000 Hz spectral width, 4.2 μs (60° tip angle) pulse width, 1 s acquisition time and 1 s delay time. A line broadening function of 1–2 Hz was applied before the Fourier transformation. Usually 128 to 512 scans were collected.

Temperature calibrations were performed before the experiments, using a digital thermometer and a Cu/Ni thermocouple (models C9001 and KX2384, respectively, Comark Ltd., Hertfordshire, UK) placed in an NMR tube filled with isopentane. The conditions were kept as equal as possible with all subsequent work. The uncertainty in temperature measurements was estimated as ±2 °C. Line shape simulations were performed using a PC version of the QCPE DNMR6 program.[21] Electronic superimposition of the original spectrum and of the simulated one enabled the determination of the most reliable rate constant. The rate constants obtained at various temperatures afforded the free energy of activation $\Delta G^{\ddagger}$ for bond rotation by applying the Eyring equation.[22] Although the transition states of the present compounds are intrinsically more ordered than the ground states, the experimental free activation energies do not display appreciable variations with temperature within the experimental uncertainty. This implies a rather small activation entropy $\Delta S^{\ddagger}$, as observed in the majority of conformational NMR dynamic processes.[23,24]

Computational work

A complete conformational search was preliminarily carried out by means of the Molecular Mechanics Force Field (MMFF),[25] using the Monte-Carlo method implemented in the package TITAN 1.0.5.[26] The most stable conformers thus identified were subsequently energy-minimized by DFT computations. Those were performed by the Gaussian 09 rev A.02 series of programs[27] using standard parameters ("Berny algorithm"[28]). All the calculations employed the B3LYP hybrid HF-DFT method[29] and the 6-31G(d) (compounds **1–4**, **7–14**, **16**, **17**), 6–311++G(2d,p) (compound **5**), DGDZVP (compounds **6**, **15**) basis sets. Harmonic vibrational frequencies were calculated for all stationary points. As revealed by the frequency analysis, imaginary frequencies were absent in all ground states whereas just one imaginary frequency was associated with each transition state. Visual inspection of the corresponding normal mode[30] validated the identification of the transition states.

The energy values listed in Table 2 represent total electronic energies. In general, these give the best fit with experimental DNMR data.[31] Therefore, the computed value have not been corrected for zero-point energy contributions or other thermodynamic parameters. This avoids artifacts that might result from the ambiguous choice of an adequate reference temperature, from empirical scaling factors,[32] and from the idealization of low-frequency vibrators as harmonic oscillators.[33]

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