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 (ΔG°) 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 reported2 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 fluorine9 to the 18.1 kcal mol−1 for the Me3N+ group10 (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 Eσ steric parameters,11 as reported by Dubois et al.12 (0.02 for chlorine and 0.50 for iodine).

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 –SiR3, –SnR3, –PR2, –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 diastereotropic
groups when, below a certain temperature, the interconversion for the two conformational enantiomers (atropisomers) by aryl–aryl rotation becomes slow enough. 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 para-position of 2-substituted biphenyls were tested for this purpose: Me$_2$CH, $i$-Pr$_2$Si, $i$-PrMe$_2$Si, $t$-Bu$_2$Si, $t$-Butylmagnesium chloride and phenyllithium, respectively, to the silicon bonded methyl signal is displayed in the case of the $^{13}$C(CF$_3$)$_2$OH 16.5 16.9 OCH$_2$OCH$_3$ 5.7 6.1

Table 1

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<th>ortho substituent</th>
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The computer line shape simulations reported on the right (Table 2) to aryl–aryl rotation of compounds 1–17.

Table 2

| Compd | R         | $\Delta G^{\text{rot}}_{\text{exper.}}$ | $\Delta E^{\text{rot}}_{\text{exper.}}$ | $|\theta|^\circ$ |
|-------|-----------|---------------------------------------|---------------------------------------|-----------------|
| 1     | CH$_3$    | 8.6                                   | 8.4                                   | 125             |
| 2     | SPh       | 8.3                                   | 8.8                                   | 125             |
| 3     | SOPh      | 8.6                                   | 8.1                                   | 55              |
| 4     | SO$_2$Ph  | 12.8                                  | 10.3                                  | 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                                  | 13.8                                  | 97              |
| 9     | PPh$_3$   | 9.4                                   | 9.2                                   | 66              |
| 10    | POP$_3$   | 10.2                                  | 11.3                                  | 56              |
| 11    | P(C$_6$H$_5$)$_2$ | 11.8                                 | 9.5                                   | 61              |
| 12    | PO(C$_6$H$_5$)$_2$ | 12.7                                | 12.9                                  | 59              |
| 13    | Si(CH$_3$)$_3$ | 10.4                                  | 10.0                                  | 115             |
| 14    | Si        | 12.1                                  | 11.2                                  | 115             |
| 15    | Sn(CH$_3$)$_3$ | 9.1                                   | 8.8                                   | 120             |
| 16    | Si(CH$_3$)$_2$C$_2$H$_5$ | 9.9                                | 10.2                                  | 116             |
| 17    | Si(CH$_3$)$_2$Ph | 9.8                                  | 10.9                                  | 63              |

$\theta$ is the computed twist angle (absolute value) of the substituted biphenyl. A number of diasterotopic probes in the para-position of 2-substituted biphenyls were tested for this purpose: Me$_2$CH, $i$-Pr$_2$Si, $i$-PrMe$_2$Si, $t$-Bu$_2$Si, $t$-Butylmagnesium chloride and phenyllithium, respectively, to the silicon bonded methyl signal is displayed in the case of the $^{13}$C(CF$_3$)$_2$OH 16.5 16.9 OCH$_2$OCH$_3$ 5.7 6.1

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 1. See experimental section for details. Aryl–aryl computed twist angle (absolute value) of 13.2 kcal mol$^{-1}$ at the CISD/6-31+G(d) level.
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$_2$Pr group. However calculations indicate that the anti rotamer, having the aryl and the CSO planes 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. 1 Left: temperature dependence of the silicon bonded $^1$H NMR methyl signal of ortho phenyl sulfide derivative 2 in CHF$_2$Cl/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$_2$Cl/CHFCl$_2$ at 600 MHz. Right: line shape simulation obtained with the indicated rate constants.
1.50, 1.54, 1.89, 2.15 Å when X is N+, C, Si and Sn, respectively. Longer the carbon methylstannyl (tert-butyl) C–X bond length of the substituent.

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 considerably 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. Remarkably this trend is quite reliable. As already observed, 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. Remarkably this trend is quite reliable. As already observed, 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.

Experimental

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. 1H, 13C and 31P 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–Miyaura19 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.1H NMR: δ 7.8 (s, 1 H), 7.3 (m, 6 H), 7.22 (ddd, J = 7.5 Hz, 1 H), 7.3 (m, 1 H), 7.2 (m, 2 H), 7.1 (m, 1 H), 6.64. δ 7.8 (s, 1 H), 7.3 (m, 6 H), 7.2 (m, 2 H), 7.1 (m, 1 H), 6.64; found C 69.89, H 6.66.

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

3-(Dimethylsilyloxy)phenyltellurobiphenyl (6). The reaction of 2-bromo-3-(dimethylsilyl)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.1H NMR: δ 7.55 (s, 1 H), 7.51 (d, J = 6.2 Hz, 1 H), 7.5 (m, 2 H), 7.3 (m, 5 H), 7.2 (m, 2 H), 0.97 (s, 6 H), 13C NMR: δ 143.6, 140.6, 138.3, 134.8, 134.8, 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 (%) 367 (M+), 347 (2), 319 (100), 303 (11), 287 (9), 195 (21), 165 (13), 135 (23), 77 (11), 43 (9). Analysis: calculated for C_{23}H_{24}OSeSi (409.50) C 67.46, H 6.40; found C 67.17, H 6.64.

3-(Dimethylsilyloxy)phenyltellurobiphenyl (6). The reaction of 2-bromo-3-(dimethylsilyl)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.1H 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). 13C 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, 117.7 (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 C25H26TeSi (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 methylithium (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%). 1H 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). 13C 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). 31P 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 C29H31PSi (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. 1H 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). 13C 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). 31P 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 C29H33OPSi (454.62) C 76.62, H 6.87; found C 76.64, H 6.84.

Dicyclohexyl[3-(dimethylisopropylsilyl)biphenyl-2’-yl]diphenylphosphine (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%). 1H 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). 13C NMR: δ 142.8, 140.1, 138.2, 137.2 (d, J = 8.3 Hz, 3 C), 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). 31P NMR: δ 20.40. MS: m/z (%) 450 (M+5, 54), 449 (100), 407 (8), 367 (30), 325 (11), 183 (32), 73 (22), 59 (21), 55 (15). Analysis: calcd for C39H53PSi (540.71) C 77.28, H 7.92; 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
(elucent, 1:4 (v/v) diethyl ether–petroleum ether mixture) gave 0.22 g (65%) of a colorless viscous compound. 1H 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). 13C 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). 31P NMR: δ 49.6. MS: m/z (%) 466 (M+1, 11), 423 (100), 383 (81), 341 (26), 301 (4), 283 (8), 183 (62), 75 (26), 55 (23). HRMS calculated for C20H30PSi (466.71) mass 466.2821. Found 466.2825.


3-Chloro-2′-(dimethylisopropylsilyl)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 ethynylmagnesium 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 washed with Na2SO4 and the solvent was evaporated at reduced pressure. Chromatography of the residue on silica gel (elucent, petroleum ether) allowed to recover 0.34 g (367 (M+1, 11), 423 (100), 383 (81), 341 (26), 301 (4), 223 (13), 195 (26), 126 (25), 101 (100), 73 (76), 59 (30). HRMS calculated for C20H30SiSn (418.1139) mass 418.1143; calculated for C19H27SiSn (M+1, 15) 403.0965; found 403.0962. 

Analysis: m/z (%) 326 (M+1, 10), 311 (8), 283 (18), 245 (100), 229 (52), 209 (30), 165 (27). Analysis: calculated for C19H27SiSn (M+1, 15) 403.0965; found 403.0962.

3-Chloro-2′(dimethylisopropylsilyl)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 ethynylmagnesium 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 washed with Na2SO4 and the solvent was evaporated at reduced pressure. Chromatography of the residue on silica gel (elucent, petroleum ether) allowed to recover 0.34 g (367 (M+1, 11), 423 (100), 383 (81), 341 (26), 301 (4), 223 (13), 195 (26), 126 (25), 101 (100), 73 (76), 59 (30). HRMS calculated for C20H30SiSn (418.1139) mass 418.1143; found 418.1143. Analysis: calculated for C19H27SiSn (M+1, 15) 403.0965; found 403.0962.

Analysis: calculated for C20H30SiSn (418.1139) mass 418.1143; found 418.1143. Analysis: calculated for C19H27SiSn (M+1, 15) 403.0965; found 403.0962.

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 1H). Spectra of compound 4 were recorded in CDCl3, spectra of 8 and 12 in CD2Cl2. 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-d₆ 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 CDFCl₂ 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 ¹H 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 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 ¹³C 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 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 ΔS°, as observed in the majority of conformational NMR dynamic processes.²³,²⁴

Computational work

A complete configurational 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 programs²⁷ using standard parameters (“Berny algorithm”²⁸). All the calculations employed the B3LYP hybrid HF-DFT method²⁹ 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 modes 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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Notes and References


13. In principle there are two different barriers for the forward and reverse process. The rate constants reported in Fig. 2 refer to the pathway from the more stable to the less stable diastereoisomer.


16. In the DFT calculations for the isolated molecule, the total energy difference is 0.8 kcal mol⁻¹ favouring the syn form.
26 Package TITAN 1.0.5, Wavefunction Inc., Irvine, CA.
30 Package GaussView 5.0.9, Gaussian Inc., Wallingford CT, 2009.