

Synthesis and characterization of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin [☆]

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Abstract

The synthesis of 2,2'-difluoro-6,6'-dichlorobiphenyl, a precursor to dibenzometallopins, has been accomplished from bromination of 2-chloro-6-toluene followed by coupling of the benzyl bromide produced with PhLi. A variety of conditions were studied for conversion to a diGrignard reagent the most successful of which involved activated magnesium (Mg^{*}) produced from reduction of MgBr₂ and K. Reaction of the diGrignard with PhMeSiCl₂ produced 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin (**3a**). The silepin was characterized by an X-ray crystal structure in the solid state and in solution by ¹H, ¹³C, ²⁹Si and ¹⁹F NMR spectroscopy. The solid structure reveals a folded boat conformation for the central seven-membered ring and a butterfly angle for the tricyclic framework of 124°. The ¹H NMR data in solution exhibits a complex, unsymmetrical multiplet associated with the ethano-bridge protons. The conformations of **3a** were generated by MM2 calculations and the results demonstrated that there were four enantiomeric pairs of similar energy. The configuration with an axially oriented phenyl group corresponded closely to the configuration observed in the solid state.

Keywords: Silicon; Magnesium; Heterocyclics; Silepins; Group 14; Molecular mechanics

1. Introduction

For a number of years we have been interested in the synthesis of tricyclic compounds that contain a silicon heteroatom in the central ring. The basic framework is illustrated in Fig. 1 (1) where Z may be a one-, two- or three-atom bridge that may contain only carbon atoms and/or heteroatoms. Access to such heterocycles usually involves the condensation of an active organometallic Z(C₆H₄M-*o*)₂ (M = Li, MgBr, MgCl) with RR'SiCl₂. Solutions of these simple tricycles normally indicate rapid ring inversion at ambient temperatures. Appropriate substitution of the benzo-rings as illustrated in Fig. 1 (2 and 3) could increase the barrier to inversion. However, such systems are a synthetic challenge.

In a previous study [1] we demonstrated that substitution in the position ortho to the silicon center could result in the formation of a conformationally rigid hete-

rocycle if the substituents at the silicon center were appropriate. In the silepin system which contains a central seven-membered ring (Z in Fig. 1 is an ethano bridge) both 5,5'-bis(trimethylsilyl)-10,11-dihydro-5*H*-dibenzo[b,f]silepin (**1a**) (Z = CH₂CH₂; R = R' = SiMe₃) and 4,5,5',6-tetramethyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin (**2a**) (Z = CH₂CH₂; X = R = R' = Me), are fully fluxional between room temperature and –90 °C (183 K) as evidenced by a single ¹H NMR resonance for the ethano bridge over this temperature range. However, in **2b** (Z = CH₂CH₂; X = Me; R = R' = SiMe₃), where the methyl-substituents at silicon in compound **2a** have been replaced with trimethylsilyl groups, the ethano-bridge region exhibits an AA'BB' pattern at room temperature that coalesces to A₄ at 80 °C (353 K). The dynamic process, which has a free energy of activation of 16 kcal mol^{–1}, has been assigned to inversion of the central seven-membered ring. In a related study of 2,2':2'',2'''-bis(ethano)tetraaryltins (a spiro derivative of **2**, Sn replacing Si, X = Me) also exhibits an AA'BB' pattern for the ethano bridge which collapses to a singlet at 70 °C with (Δ*H*^{*} = 16.7 ± 0.5 kcal mol^{–1} [2].

[☆] Dedicated to Professor Hideki Sakurai on the occasion of his retirement from Tohoku University.

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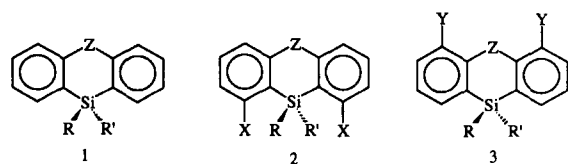
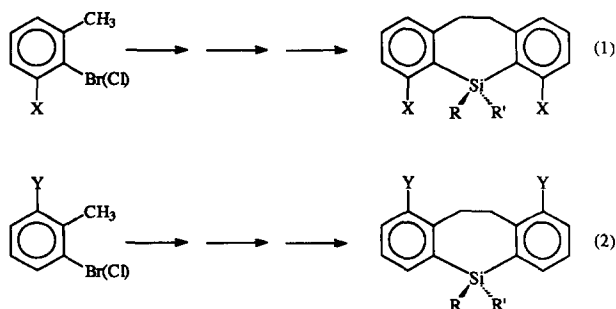


Fig. 1. Generalized structures for tricycles containing a silicon heteroatom.

Previous syntheses of the unsubstituted silepins have involved a three-step sequence from commercially available *o*-bromotoluene. Bromination of *o*-BrC₆H₄CH₃ with *N*-bromosuccinimide (NBS) provides *o*-BrC₆H₄CH₂Br which is then coupled using 1/2 equiv of PhLi to give *o,o'*-dibromobibenzyl [3]. In the last step the bibenzyl is converted to either the *o,o'*-dilithiobibenzyl [4] with *n*-BuLi or the diGrignard [5] reagent with Mg and then reacted with RR'SiCl₂ to provide **1** (Z = CH₂CH₂). To obtain the appropriate bibenzyl precursors to tricycles of the type **2** and **3** requires either a 2,3-substituted toluene or a 2,6-substituted toluene as outlined in Eqs. (1) and (2). Unfortunately, there are few, commercially available materials which would be suitable for this strategy. One of the simplest, 2-bromo-*m*-xylene (X = Me in Eq. (1)), was utilized to prepare **2** (Z = CH₂CH₂; X = Me (Fig. 1)). However, the related derivative required to prepare **3** would be 3-bromo-*o*-xylene (Y = Me; Eq. (2)). In this later case, reaction with NBS would require a rather fortuitous bromination of only the Me group adjacent to the bromo substituent. Therefore, another Y substituent was selected in order to utilize the same synthetic procedures. One of the few suitable, commercially available reagents that meets this requirement is 2-chloro-6-fluoro-toluene even though it can be anticipated that the chloro-substituent is less desirable for conversion to an active organometallic.



In this report we describe the preparation of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[*b,f*]silepin (**3**) (Z = CH₂CH₂; Y = F; R = CH₃; R' = C₆H₅), in which substitution occurs ortho to the ethano bridge, and characterization of this system by ¹H, ¹³C,

²⁹Si and ¹⁹F NMR spectroscopy as well as by X-ray crystallography.

2. Results and discussion

2.1. Synthesis of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[*b,f*]silepin

Bromination of 2-chloro-6-fluorotoluene by NBS occurred smoothly in CCl₄ and furnished 60% of distilled 2-chloro-6-fluorobenzyl bromide in 97% purity. Reaction of this benzyl bromide with PhLi provided 2,2'-difluoro-6,6'-dichlorobibenzyl (**4**) as a white solid in approximately 60% yield. Although the preparation of the bibenzyl went smoothly, several problems were encountered in converting the aryl chloride to the Grignard reagent. We have previously observed that considerably more rigorous conditions are required to prepare the diGrignard reagent than the monoGrignard from *o*-bromo-*o'*-chlorobiphenyl [6]. Since it has been shown that *p*-FC₆H₄CH₃ was converted within 5 min to the Grignard reagent in 58% yield with Mg* (activated magnesium) in refluxing THF in the presence of KI [7] other magnesium sources were surveyed. The reaction of **4** with various forms of Mg were run on a small scale for periods of up to 48 h and reactions were quenched with water as outlined in Eq. (3). If the diGrignard reagent is formed, the product from this sequence would be 2,2'-difluorobibenzyl (**5**). The reactions were monitored by gas chromatography (GC) and structural assignments of the products were made on the basis of GC mass spectrometry (GCMS) data. Attempts to prepare the diGrignard reagent of **4** from commercial Mg mesh were not successful. The reaction of **4** and Mg mesh promoted by ultrasound followed by aqueous quench demonstrated that only a minor conversion to **5** (< 10%) had been achieved. When Me₃SiCl was added as the quenching agent either after the reaction period or during the reaction period, the product contained < 10% of **5** and none of the expected 2,2'-difluoro-6,6'-bis(trimethylsilyl)bibenzyl. Deprotonation of the solvent by the Grignard reagent has been demonstrated in the studies of the reaction of *o*-bromo-*o'*-chlorobiphenyl with various magnesium sources [6]. Activated magnesium (Mg*) was prepared from MgCl₂/Li/Naph in THF according to published procedures [8] and reacted with **4**. When an aliquot was quenched with Me₂SiCl₂, a new, minor product was observed with a molecular weight of 274 (GCMS) which supports ring closure to silepin **3b** (Fig. 1: Z = CH₂CH₂; Y = R = R' = Me). No reaction between Mg* and **4** appeared to take place in Et₂O. In previous studies of the conversion of aryl chlorides we had determined that the best results were

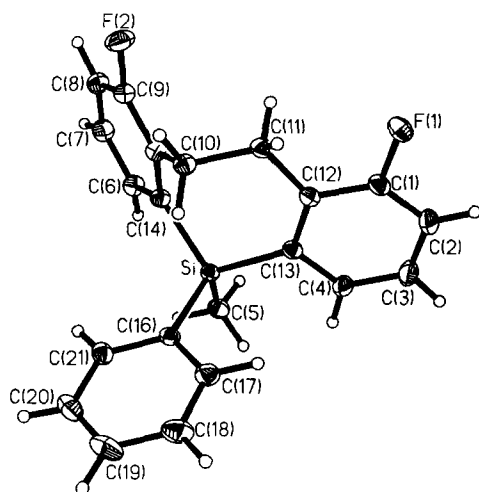
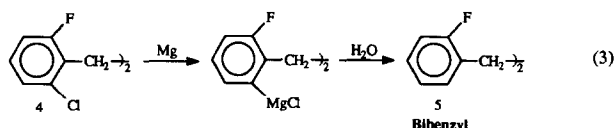


Fig. 2. ORTEP drawing of the molecular geometry of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5H-dibenzo[b,f]silepin (**3a**) (without hydrogen atoms) and atom numbering as used in Tables 3 and 4. Displacement ellipsoids are at the 50% probability level.

obtained when MgBr_2 (generated by reaction of ethylene dibromide with magnesium) was reduced with potassium [9]. Utilizing this approach a higher conversion to **5** was achieved and these conditions were then utilized for reactions that involved MePhSiCl_2 and Me_2SiCl_2 to give **3a** ($Z = \text{CH}_2\text{CH}_2$; $Y = \text{F}$; $R = \text{Me}$; $R' = \text{Ph}$) and **3b** ($Z = \text{CH}_2\text{CH}_2$; $Y = \text{F}$; $R = R' = \text{Me}$) respectively which were obtained from distillation. The silepin **3a** was isolated as a crystalline solid which could be obtained in analytical purity but **3b** co-crystallized with unreacted **4** and other byproducts from which it could not be separated.



2.2. Solid-state structure of **3a**

The solid-state structure of **3a** reveals the usual butterfly structure associated with the tricyclic skeleton and contains a central ring which exhibits a folded boat conformation. A view of the molecule is shown in Fig. 2. Crystal data are collected in Table 1, selected atomic coordinates for non-hydrogen atoms in Table 2 and selected bond distances and angles are presented in Table 3.

The pharmacological activity of tricyclic ring systems has been attributed, in part, to the conformation of the tricyclic framework. Efforts to relate structure to activity were first developed based on analysis of Dreiding models [10a]. Later, X-ray structural results pro-

Table 1

Crystallographic data for **3a**

Crystal Parameters	
Empirical formula	$\text{C}_{21}\text{H}_{18}\text{F}_2\text{Si}$
Formula weight	336.4
Crystal size (mm)	$0.3 \times 0.3 \times 0.2$
Crystal system	Triclinic
Space group	$\bar{P}1$
<i>a</i>	7.945(2) Å
<i>b</i>	8.129(2) Å
<i>c</i>	13.274(2) Å
α	98.92(2)°
β	101.44(2)°
γ	91.70(2)°
$V(\text{\AA}^3)$	828.5(2) Å ³
<i>Z</i>	2
Density (calc.)	1.349 g cm ⁻³
<i>F</i> (000)	352 e ⁻
Data Collection	
Temperature (K)	123
2 θ range	3.0 to 65.0°
Scan type	2 θ - θ
Scan speed	Variable; 3.97 to 14.65 min ⁻¹ in ω
Scan range (ω)	1.20° plus K α separation
Index ranges	$-12 \leq h \leq 10$, $-12 \leq k \leq 12$, $-20 \leq l \leq 20$
Reflections collected	7150
Independent reflections	6027 ($R_{\text{int}} = 2.47\%$)
Observed reflections	4786 ($F > 3.0\sigma(F)$)
Parameters	289
<i>R</i> , <i>R</i> _w	0.0416, 0.0563
GOF	0.97

vided the basis for another set of parameters. One of these parameters involves the bend angle between the planes of the benzo rings, called the butterfly angle, and

Table 2

Selected atomic coordinates ($\times 10^4$) and equivalent isotropic displacement coefficients (Å²) for non-Hydrogen atoms in **3a**^{a,b}

	<i>x</i>	<i>y</i>	<i>z</i>	<i>U</i> (eq)
Si	3287(1)	1883(1)	7012(1)	15(1)
F(1)	9545(1)	465(1)	8849(1)	27(1)
F(2)	8130(1)	4220(1)	5436(1)	30(1)
C(1)	7796(2)	172(2)	8665(1)	19(1)
C(2)	7178(2)	-1126(2)	9068(1)	24(1)
C(3)	5408(2)	-1446(2)	8876(1)	25(1)
C(4)	4348(2)	-463(2)	8293(1)	20(1)
C(5)	1351(2)	409(2)	6484(1)	21(1)
C(6)	3301(2)	1901(2)	4852(1)	20(1)
C(7)	4048(2)	2209(2)	4028(1)	23(1)
C(8)	5682(2)	2991(2)	4228(1)	24(1)
C(9)	6518(2)	3472(2)	5252(1)	21(1)
C(10)	6737(2)	3874(2)	7200(1)	18(1)
C(11)	7768(2)	2561(2)	7718(1)	19(1)
C(12)	6791(2)	1204(1)	8074(1)	16(1)
C(13)	4984(2)	855(1)	7871(1)	16(1)
C(14)	4162(2)	2415(2)	5888(1)	17(1)
C(15)	5800(2)	3249(2)	6098(1)	17(1)

^a Equivalent isotropic *U* defined as one third of the trace of the orthogonalized U_{ij} tensor.

^b Only the *ipso*-carbon of the phenyl substituent has been included.

Table 3
Selected bond distances (Å) and angles (°) for **3a**

Distances		Angles	
Si–C(5)	1.870(1)	C(13)–Si–C(14)	109.1(1)
Si–C(13)	1.889(1)	C(5)–Si–C(16)	107.4(1)
Si–C(14)	1.868(1)	C(2)–C(1)–C(12)	125.5(1)
Si–C(16)	1.879(1)	C(1)–C(2)–C(3)	117.6(1)
F(1)–C(1)	1.369(1)	C(2)–C(3)–C(4)	119.4(1)
F(2)–C(9)	1.362(2)	C(3)–C(4)–C(13)	122.9(1)
C(1)–C(2)	1.375(2)	C(7)–C(6)–C(14)	120.9(1)
C(1)–C(12)	1.397(2)	C(6)–C(7)–C(8)	120.0(1)
C(2)–C(3)	1.388(2)	C(7)–C(8)–C(9)	118.4(1)
C(3)–C(4)	1.386(2)	C(8)–C(9)–C(15)	123.7(1)
C(4)–C(13)	1.408(2)	C(11)–C(10)–C(15)	113.9(1)
C(6)–C(7)	1.395(2)	C(10)–C(11)–C(12)	118.1(1)
C(6)–C(14)	1.402(2)	C(1)–C(12)–C(11)	115.9(1)
C(7)–C(8)	1.386(2)	C(1)–C(12)–C(13)	116.5(1)
C(8)–C(9)	1.379(2)	C(11)–C(12)–C(13)	127.7(1)
C(9)–C(15)	1.389(2)	Si–C(13)–C(12)	127.1(1)
C(10)–C(11)	1.529(2)	C(4)–C(13)–C(12)	118.1(1)
C(10)–C(15)	1.506(2)	Si–C(14)–C(15)	118.1(1)
C(11)–C(12)	1.516(2)	C(6)–C(14)–C(15)	119.5(1)
C(12)–C(13)	1.419(2)	C(9)–C(15)–C(14)	117.5(1)
C(14)–C(15)	1.405(2)	C(10)–C(15)–C(14)	121.0(1)

another, the distance between the centers of the benzo rings [10b].

The values for the butterfly angle, the ring distance as well as the torsion angle that involves the carbons of the ethano bridge, $C_{\text{arom}}-\text{CH}_2\text{CH}_2C_{\text{arom}}$, are summarized in Table 4 for **3a** and 5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin (**1b**) ($Z = \text{CH}_2\text{CH}_2$; $R = \text{Me}$, $R' = \text{Ph}$.) [11]. Also included in Table 4 are the corresponding parameters for **2b** and its unsubstituted analog **1a**.

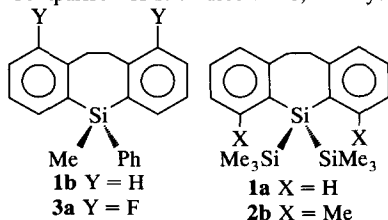
The butterfly angle (or bend angle) is usually a function of the heteroatom in the 5 position. When silicon heteroatoms are present the molecules tend to be flatter (larger bend angle) than is observed in the corre-

sponding carbocyclic or azepine systems. In derivatives of **1** this angle tends to be about 140°C [11], approximately the value observed in **1b** which has the same exocyclic substituents at silicon as does **3a**. When F atoms are substituted in positions adjacent to the ethano bridge, as in silepin **3a**, the bend angle decreases and the molecule becomes more folded. In fact, the bend angle in **3a** is the smallest observed for any of the crystallographically characterized tricyclic silepins observed thus far (**1**, $Z = \text{CH}_2\text{CH}_2$; $R = \text{Ph}$, $R' = \text{Me}$ [11], OMe [12a]; $R = p\text{-C}_6\text{H}_4\text{NMe}_2$, $R' = \text{H}$ [12b]; $R = (\text{CH}_2)_3\text{NMe}_2 \cdot \text{HCl}$, $R' = \text{Me}$ [12c]; $R = R' = \text{SiMe}_3$ [1]; **2**, $Z = \text{CH}_2\text{CH}_2$, $X = \text{CH}_3$, $R = R' = \text{SiMe}_3$ [1]). In contrast, substitution of the ring carbons adjacent to the silicon heteroatom, as in **2b**, causes the bend angle to increase (the framework becomes more flattened) relative to the ring-unsubstituted system with the same substituents (**1a**). When the bend angle decreases the distance between the benzo-ring centers decreases (compare **1a** and **1b** with **3a**) and when the bend angle increases this distance also increases (compare **2b** with **1a** and **1b**). The torsion angle that involves the ethano bridge is smallest for **3a** and comparable with those observed in carbon derivatives. As the bend angle increases in the series **3a**, **1b** and **2b** the torsion angle also increases.

2.3. Spectroscopic characterization of **3a**

The 300 MHz ^1H NMR spectrum of **3a** exhibits a complex, but apparently symmetrical multiplet for the ethano-bridge protons near 3 ppm in CDCl_3 and toluene- d_8 . A similar, but not identical multiplet is observed for the ethano-bridge region in the parent system, **1b** (the original ^1H NMR data obtained was on a 60 MHz instrument which showed a broad singlet for the ethano-bridge protons in **1b**) [13]. However, the 500

Table 4
Comparison of structures of 10,11-dihydrodibenzo[b,f]silepins



Parameter	1b	3a	2b ^a		1a
			A	B	
Bend angle (dihedral angle) (deg)	137.2	123.6	160	165	149
Distance between centers of benzo rings (Å)	5.53	5.33	5.78	5.79	5.73
$C_{\text{AR}}-\text{CH}_2-\text{CH}_2-C_{\text{AR}}$ Torsion angle (deg)	90	75	103	111	107

^a Two crystallographically distinct molecules in the asymmetric unit, half of each is unique.

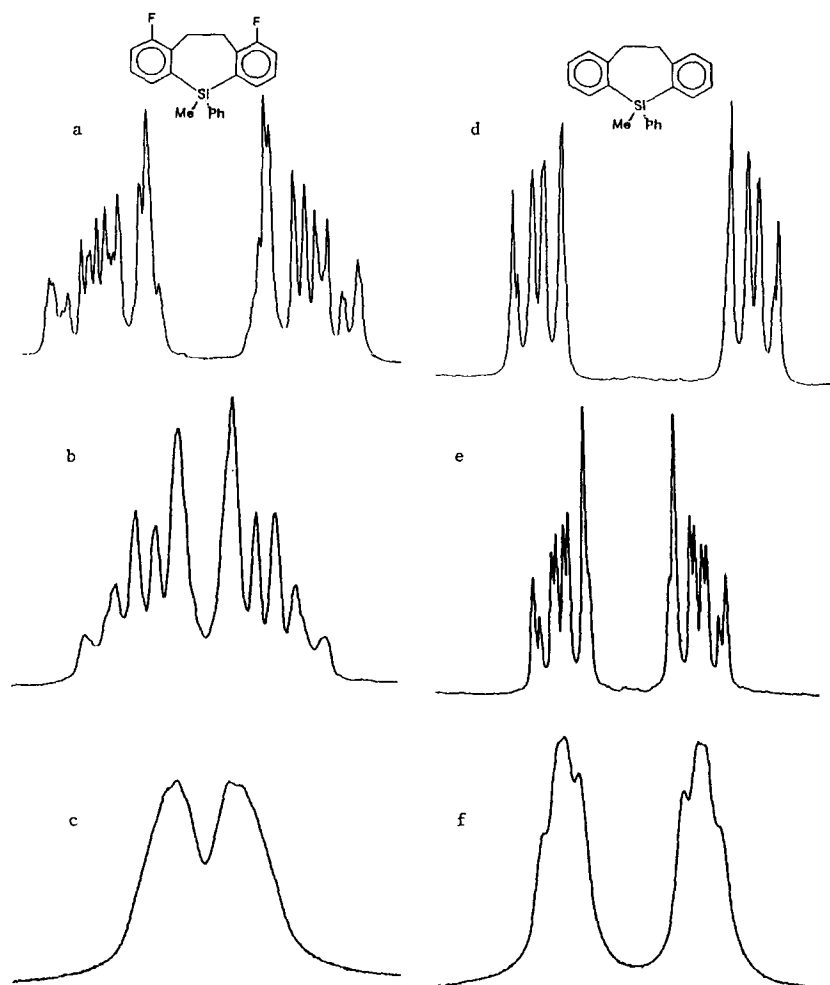
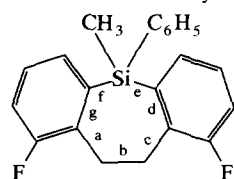


Fig. 3. ^1H NMR spectrum in toluene- d_8 of the ethano-bridge region of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo [b,f]silepin (**3a**) and 5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin (**1b**). (a) 500 MHz spectrum of **3a** at 26 °C; (b) 300 MHz spectrum of **3a** at 26 °C; (c) 300 MHz spectrum of **3a** at -90 °C; (d) 500 MHz spectrum of **1b** at 26 °C; (e) 300 MHz spectrum of **1b** at 26 °C; (f) 300 MHz spectrum of **1b** at -90 °C.

MHz ^1H spectrum reveals that the multiplet is more complex than is implied in the 300 MHz spectrum. The 500 and 300 MHz ^1H NMR spectra obtained at 26 °C

for the ethano-bridge region are shown in Fig. 3 for both **3a** (traces a and b, respectively) and **1b** (traces d and e, respectively). Data collected at temperatures up

Table 5
Conformational analysis of 1,9-difluoro-5-methyl-5-phenyl-10,11-dihydro-5*H*-dibenzo[b,f]silepin



Conformation	E^a	Internal ring dihedral angles						
		a	b	c	d	e	f	g
I	77.0	12.5	-76.9	78.5	-0.2	-54.5	34.7	3.6
X-ray		9.1	-75.3	85.5	-7.1	-48.4	34.1	5.0
II	77.5	75.6	-87.6	24.5	5.7	21.0	-46.2	2.0
III	78.0	74.2	-89.0	25.5	6.9	19.2	-46.7	4.0
IV	78.0	13.5	-78.1	78.3	0.5	-54.2	33.3	4.3

^a Steric Strain Energy (kJ mole⁻¹) based on MM2 calculations (MacroModel, V3.0).

to 80 °C exhibit no significant changes. Lowering the temperature from 26 °C in increments (0, –25, –50 and –90 °C) results in the gradual collapse of the complex multiplets. The spectra obtained at the lower limit of –90 °C are illustrated in traces c and f in Fig. 3 for **3a** and **1b** respectively. It is likely that several conformations similar in energy coexist in solution (see next section) making rigorous analysis of the system prohibitively difficult; it is possible, however, that slowing of the ring inversion ($\Delta G^\ddagger < 8 \text{ kcal mol}^{-1}$) accounts for the changes that occur in the spectral data upon lowering the temperature.

As a fluxional system, **3a** contains 12 unique carbon atoms. The $\{^1\text{H}\}^{13}\text{C}$ NMR spectrum shows the presence of all 12 and includes six doublets due to coupling to the fluorine substituent. The $^1J_{\text{CF}}$ for the ipso-carbon has the highest value (247 Hz) and four of the remaining five aryl carbon atoms exhibit coupling to fluorine with values ranging from 23 Hz to 4.7 Hz. Insufficient examples are available to assign the various doublets but it is likely that the value of 23 Hz corresponds to one of the carbon atoms ortho to the fluorine-substituted ipso-carbon. The coupling of the ethano-bridge carbon to the fluorine substituent, $^3J_{\text{CF}}$, is 5.3 Hz. The ^{29}Si NMR resonance exhibits a singlet at –11.8 (relative to TMS) and the ^{19}F resonance is an apparent doublet of doublets centered at –116.9 (relative to internal C_6F_6) with similar coupling of about 9 Hz, most likely to the benzo-ring hydrogens.

2.4. Conformational analysis of **3a**

The conformations of **3a** were generated by MM2 calculations using the Multiconformer subroutine of MACROMODEL (V 3.0); ring conformation and Si–phenyl rotation were included. Full minimization gave eight “low energy” conformations as four enantiomeric pairs. Table 5 gives the steric strain energy (in kJ mole^{-1}) and lists internal dihedral angles for a set of four

conformations having the same ring configuration. It is evident from these data (dihedral angles) that conformations I and IV possess very similar ring shapes, as do II and III, in fact Si–phenyl rotation appears to be the predominant difference between I and IV on the one hand, and II and III on the other. Examination of three-dimensional models revealed that the configuration at silicon distinguishes conformations I and IV from II and III, the former having an axially-oriented phenyl group, the latter an axial methyl.

The solid-state structure of **3b** appears to most closely resemble conformation I and is clearly different from II and III (see Table 5). A comparison of crystal structure and conformation I is presented in Fig. 4.

2.5. Conclusion

The preparation of 2,2'-difluoro-6,6'-dichlorobibenzyl (**4**) has been developed from bromination of 2-chloro-6-fluorotoluene followed by coupling of the benzyl bromide produced with PhLi . Rigorous conditions are required to convert the aryl chloride to the diGrignard reagent and the best conversion occurs with Mg^+ prepared by the reduction of MgBr_2 with K. The diGrignard reagent reacts with dichlorosilanes to produce 1,9-difluoro-10,11-dihydro-5*H*-dibenzo[b,f]silepins. The reaction with PhMeSiCl_2 produced **3a**, the first silepin isolated with substituents adjacent to the ethano bridge. Formation of 2,2'-difluorobibenzyl competes with coupling of the diGrignard and the silicon–chlorine bond, thus, the yield of **3a** is only about 50%. The silepin was characterized in the solid state and the effect of substituents adjacent to the ethano bridge is to produce a tricycle with a smaller butterfly angle (bend angle) than any other previously characterized silepin. Solutions of **3a** appear to be fluxional and the ethano bridge exhibits a complex multiplet at room temperature. Lowering the temperature results in the collapse of the multiplet which may result from a shift in the equilibrium popula-

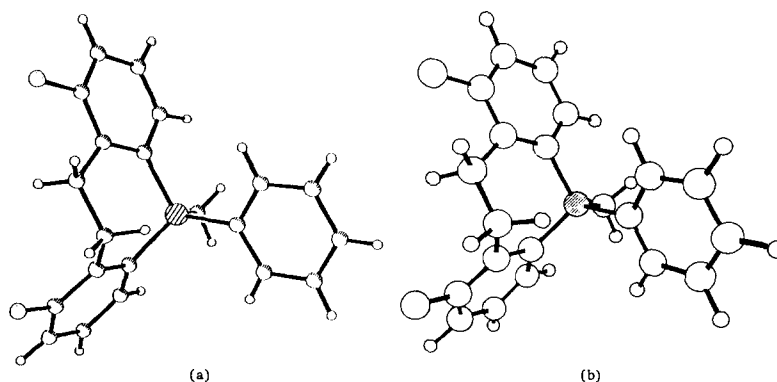


Fig. 4. Comparison of the solid-state structure of **3b** (a) and the calculated lowest energy conformation, I (b).

tions of conformers or to a slowing of the ring inversion. The conformations of **3a** were modeled using MM2 calculations and the results demonstrated that there were four enantiomeric pairs of similar energy. The configuration with an axially-oriented phenyl group corresponds closely to the configuration observed in the solid state.

3. Experimental

All reactions, unless otherwise noted, were carried out under an atmosphere of dry nitrogen or argon with standard Schlenk techniques. Ether solvents were distilled from sodium/benzophenone before use. All glassware was dried in an oven at 110–120 °C prior to use. The *N*-bromosuccinimide was purified by recrystallization from water and air dried. The Mg (50 mesh (Aldrich); 100 mesh (Alfa) and turnings (Aldrich)) was used as supplied and 2-chloro-6-fluorotoluene was a gift from the Mallinckrodt Chemical Company. Phenyl lithium [14] and **1b** [13] were prepared by literature methods.

¹H and ¹³C NMR data were recorded on either a Varian EM-360, a Varian XL-300 spectrometer equipped with a four-nucleus probe or a Bruker ARX500 equipped with either an inverse probe or a broad-band probe. ²⁹Si and ¹⁹F NMR data were recorded on the Bruker ARX500 spectrometer for ²⁹Si (99.36 Hz) and for ¹⁹F (470.59 Hz). NMR data are collected at ambient temperatures unless specified otherwise. Mass-spectral data were collected at 70 eV on a Hewlett–Packard Model 5988A GC/MS instrument equipped with an RTE-A data system, and gas chromatographic separations were performed in a split injection mode using a 12.5-m (HP-1) capillary column. The *m/z* values for peaks ≥ 10% of the base peak are included and data are uncorrected. The GC data were collected on a Varian 1400 gas chromatograph using a 15 m × 0.53 mm i.d., 1.5 μm film DB-17 column. Melting point determinations were obtained on a Mel-Temp apparatus and are uncorrected.

Combustion analyses were performed by Galbraith Laboratories.

3.1. 2-Chloro-6-fluorobenzyl bromide

In a three neck flask were placed 2-chloro-6-fluorotoluene (41 g, 0.29 mole), *N*-bromosuccinimide (48 g, 0.27 mole), benzoyl peroxide (0.5 g) and CCl₄ (300 ml). The mixture was heated to reflux and a sunlamp was used to initiate the reaction. Reflux was continued until all the solid present was less dense than CCl₄ and a GC analysis of an aliquot indicated > 90% consumption of the starting material. The solution was cooled

and filtered to remove the succinimide (26 g, 100%). After removal of the solvent from the filtrate, distillation provided a light yellow liquid, b.p. 65–70 °C/3.0 mmHg (38 g, 58% yield, 97% by GC) of 2-chloro-6-fluorobenzyl bromide. ¹H NMR (CCl₄, 60 MHz, TMS) δ 4.6 (s, 2H, CH₂Br), 6.8–7.3 (m, 3H, arom). Mass spectrum (*m/z* based on ⁷⁹Br and ³⁵Cl (relative intensities)): 222 (P⁺, 7.6%), 143 ((P–Br)⁺, 100), 108 (C₇H₄F, 17). The benzyl bromide, a potent lachrymator, was used without further purification.

3.2. 2,2'-difluoro-6,6'-dichlorobibenzyl (**4**)

Phenyllithium (0.180 mole in ether) was added dropwise to a solution of 2-chloro-6-fluorobenzyl bromide (60 g, 0.27 mol) in ether (60 ml) and the solution was stirred overnight. If a GC analysis of a hydrolyzed aliquot showed that benzyl bromide still remained, additional increments of PhLi solution were added until the benzyl bromide was consumed. After aqueous workup the ether layer was dried over magnesium sulfate and the volatile material removed. Kugelrohr distillation provided an oil, b.p. 160–170 °C/0.1 mmHg, which solidified. The solid was dissolved in a mixture of methylene chloride and ethanol and heated until the solution became turbid. After cooling, white needles, m.p. 102–103 °C were obtained (22 g, 57% yield; 97% by GC). An analytical sample was obtained by recrystallization from hexanes to give needles, m.p. 102.5–103.5 °C. Anal.: Calcd. C₁₄H₁₀F₂Cl₂; C, 58.56%; H, 3.48%. Found: C, 58.73%; H, 3.53%. ¹H NMR (C₇D₈, 300 MHz, TMS) δ 3.0 (s, 4H, CH₂), 6.8–7.1 (m, 6H, arom). Mass spectrum (*m/z* based on ³⁵Cl (relative intensities)): 286 (P⁺, 12), 143 (100), 107 (C₇H₄F⁺, 19).

3.3. Reaction of 2,2'-difluoro-6,6'-dichlorobibenzyl with magnesium sources

Mg mesh. To each of two small reaction flasks one of which contained Mg (50 mesh; 0.13 g, 5.3 mmol) and the second Mg (100 mesh, 0.13 g, 5.2 mmol) were added THF (5 ml), **4** (0.50 g, 1.7 mmol) and 1,2-dibromoethane (EDB) (0.1 ml). The mixture was stirred at room temperature for 28 h, after which a hydrolyzed aliquot showed by gas chromatography that only **4** was present.

Mg mesh with ultrasound. To a reaction flask were added **4** (0.50 g, 1.7 mmol), Mg (50, mesh; 0.13 g, 5.3 mmol), EDB (0.1 ml) and THF (3 ml). The flask was placed in an ultrasonic bath and after 48 h, hydrolysis of the reaction mixture showed that < 10% (by GC) of

2,2'-difluorobibenzyl (**5**) had formed. The remainder was starting material.

Mg mesh with Me₃SiCl. To a reaction flask were added **4** (0.50 g, 1.7 mmol), Mg (50 mesh, 0.13 g, 5.3 mmol), Me₃SiCl (0.75 g, 6.9 mmol), EDB (0.1 ml) and THF (5 ml). The flask was placed in an ultrasonic bath and after 28 h hydrolysis of the reaction mixture showed the presence of < 10% of **5** (by GC).

MgCl₂, Li and naphthalene in THF [7]. Into an Ar-filled flask was added MgCl₂ (1.5 g, 16 mmol), freshly cut lithium (0.22g, 32 mmol), naphthalene (0.39 g, 3.0 mmol) and THF (20 ml). The reaction was stirred vigorously overnight. After 24 h, **4** (2.25 g, 7.8 mmol) in THF (5 ml) was added and the mixture heated at reflux. After an additional 6 h, Me₂SiCl₂ (0.96 g, 7.4 mmol) was added and the reaction stirred for 24 h. A hydrolyzed aliquot indicated the presence of cyclized product, **3b** (*m/z* = 274) in 7% yield (GC and GCMS). Additional products included **4**, **5** (*m/z* = 218) and 2,2'-difluoro-6-chlorobibenzyl (*m/z* (based on ³⁵Cl) = 254).

MgCl₂, Li and naphthalene in Et₂O [7]. The reaction was conducted as described except that after the reaction of MgCl₂ with Li, THF was removed and replaced with ether (25 ml), **4** was added and the mixture was heated for 24 h. A GC analysis of a hydrolyzed aliquot indicated only the presence of **4**.

MgBr₂, K and KI. The MgBr₂ was freshly prepared by addition of EDB (5.2 g, 9.3 mmol) in THF (15 ml) to a slurry of magnesium shavings (0.25 g, 10 mmol) and THF (10 ml) followed by heating at reflux for 1 h. After cooling to room temperature the solvent was removed under vacuum and the apparatus brought to atmospheric pressure under argon. To the resultant white powder were added K (0.60 g, 15 mmol), KI (0.70 g, 4.2 mmol) and THF (30 ml) and the slurry heated to reflux for 1 h after which **4** (1.1 g, 11 mmol) in THF (5 ml) was added and heating continued for an additional 1 h. At this point a hydrolyzed aliquot showed the presence of **5** (40% by GC).

3.4. 1,9-Difluoro-5-methyl-5-phenyl-10,11-dihydro-5H-dibenzo[b,f]silepin (**3a**)

To magnesium shavings (0.75 g, 31 mmol) in THF (10 ml) was added EDB (5.2 g, 28 mmol) in THF (15 ml) and the slurry refluxed for 1 h and cooled to room temperature. After removal of the solvent under vacuum, K (1.7 g, 43 mmol), KI (2.1 g, 13 mmol) and THF (75 ml) were added. The mixture was heated at reflux for 1 h before addition of **4** (3.3 g, 11 mmol) in THF (5

ml). After 1 h at reflux, hydrolysis of an aliquot showed the presence of **5** (56%), C₁₄H₁₁F₂Cl (23%) and unreacted **4** (9%). PhMeSiCl₂ (2.6 g, 14 mmol) was added, the reaction mixture heated overnight and then hydrolyzed with NH₄Cl (20 ml, sat. soln.). The organic layer was dried over MgSO₄, and the volatiles removed. A GC analysis of the residual oil showed the presence of **5**, C₁₄H₁₁F₂Cl and **3a** (51% by GC). The resultant oil was distilled (Kugelrohr) to give a fraction, b.p. 175–200 °C/0.1 mmHg, 2.6 g, which solidified on cooling. Recrystallization from absolute ethanol provided a white powder, m.p. 105–107 °C, 1.2 g. A second recrystallization from absolute ethanol provided purified **3a** as large, flat, clear crystals, m.p. 106.5–107.5 °C which were used for the X-ray diffraction study. Anal. Calcd. for C₂₁H₁₉F₂Si: C, 74.98%; H, 5.39%. Found: C, 75.27%; H, 4.79%. Mass spectrum (*m/z* (relative intensities)): 336 (P⁺, not observed), 321 ((P–Me)⁺, 31), 258 ((P–C₆H₅)⁺, 100), 243 ((P–Me–C₆H₅)⁺, 39), 223 (12), 196 (C₁₄H₉F⁺, 70), 178 (C₁₄H₁₀, 12), 177 (15), 176 (22), 165 (10). ¹H NMR (CDCl₃, 300 MHz, TMS) δ 0.83 (s, SiCH₃, 3), 3.18 (m, CH₂CH₂, 4), 7–7.4 (m, arom, 6). ¹H NMR (C₇D₈, 300 MHz, TMS) δ 0.64 (s, SiCH₃, 3), 3.03 (m, CH₂CH₂, 4), 7–7.4 (m, arom, 6). ¹³C NMR (CDCl₃, 75 MHz, *J* in Hz) –1.54 (SiCH₃), 26.03 (d, ³*J*_{CF} = 5.3, CH₂CH₂), 116.70 (d, ²*J*_{CF} = 23), 127.06 (d, ³*J*_{CF} = 8.3), 127.97, 129.37, 130.80 (d, *J*_{CF} = 4.7), 134.43, 135.30 (d, *J*_{CF} = 13), 137.31, 137.58, 160.36 (d, ¹*J*_{CF} = 247). ²⁹Si NMR (CDCl₃, 59.6 MHz, TMS) δ –11.8. ¹⁹F (CDCl₃, 470.6 MHz, C₆F₆) δ –116.4 (apparent doublet of doublets with almost equal coupling of 9 Hz).

3.5. 1,9-Difluoro-5,5-dimethyl-10,11-dihydro-5H-dibenzo[b,f]silepin (**3**)

To the slurry of Mg* prepared as described for the preparation of **3a** from Mg (0.25 g, 10.4 mmol) and EDB (0.80 ml, 9.2 mmol) followed by reduction with K (0.50 g, 15 mmol) and KI (0.70 g) was added Me₂SiCl₂ (0.43 g, 3.3 mmol) and the solution was stirred at room temperature. After 4 days a hydrolyzed aliquot showed the presence of the following components identified by GC and GCMS: **5** (19%), C₁₄H₁₁F₂Cl (14%), **3b** (27%), **4** (7%) and several minor components. After aqueous workup, distillation provided a fraction, b.p. 80–90 °C/0.3 mmHg which solidified. The solid mixture contained **3b** and several byproducts. Recrystallization did not provide purified **3b** and thin layer chromatography showed that **3b** and the byproducts coeluted with a variety of solvents. Mass spectrum (*m/e* (relative intensities)): 274 (P⁺, 19), 259 ((P–Me)⁺, 100), 257 ((P–Me–H₂)⁺, 58), 209 (11), 197 (20), 196 (C₁₄H₉F⁺, 38), 195 (16), 190 (15), 189 (19), 178 (C₁₄H₁₀, 34), 177 (35), 176 (25), 165 (12), 151 (11).

3.6. Crystallographic studies

A crystal of **3a** was mounted on a glass fiber in random orientation. Preliminary examination and data collection were performed using a Siemens R3 automated single-crystal X-ray diffractometer using a graphite-monochromated MoK α radiation ($\lambda = 0.71073$ Å) at 127(5) K. Auto indexing of 10 centered reflections from the rotation photograph indicated a triclinic lattice. The final cell constants and orientation matrix for data collection were calculated by least-squares refinement of the setting angles for 25 reflections ($15^\circ < 2\theta < 30^\circ$). Intensity data were collected using $\theta/2\theta$ scans with variable scan speed. Three representative reflections measured every 50 reflections showed $< 5\%$ variation during data collection. Crystal data and intensity data collection parameters are listed in Table 1.

Data reduction and structure solution and refinement were carried out using the SHELXTL-PLUS (VMS) software package [15]. No absorption correction was applied to the data. The structure was solved by the Patterson Method and refined successfully in the space group $P\bar{1}$. Full matrix least-squares refinement was carried out by minimizing $\sum w(F_o - F_c)^2$ for **3a**. The non-hydrogen atoms were refined anisotropically to convergence. All hydrogen atoms were refined isotropically. The final residual values for **3a** were: $R(F) = 4.16$ for reflections $F > 3\sigma(F)$, $wR(F) = 5.63\%$, $S = 0.97$. Structure refinement parameters are listed in Table 1. The atomic coordinates for the non-hydrogen atoms and selected bond distances and angles are listed in Tables 2 and 3 respectively. A projection view of the molecule with non-hydrogen atoms represented by 50% probability ellipsoids for **3a** is presented in Fig. 2.

A complete list of bond distances and bond angles, positional and isotropic displacement coefficients for hydrogen atoms and a list of anisotropic displacement coefficients for the non-hydrogen atoms, and calculated and observed structure factors are available from the authors (NPR) and will be deposited in The Cambridge Crystallographic Data Center.

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