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Liquid Crystals Based on Hypervalent Sulfur Fluorides: The *trans*-(Trifluoromethyl)tetrafluorosulfuranyl Group[‡]

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Selective direct fluorination provides a convenient access to new classes of liquid crystals and dyes carrying a *trans*-(trifluoromethyl)tetrafluorosulfuranyl group, a building block in organic chemistry with highly unusual and interesting properties.

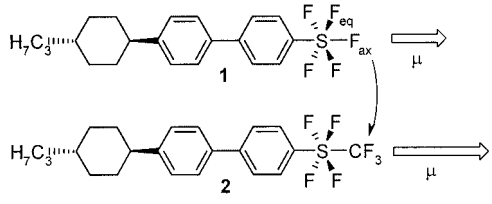
Introduction

In the recent few years mobile electronic devices such as cellular phones, personal digital assistants (PDA) or notebook PCs have permeated every aspect of our daily lives.[2] Most of them have full color, high-resolution liquid-crystal displays (LCD) based on active matrix (AM) technology. The requirements for the materials used in AM-LCDs are very stringent: in addition to extremely high purity the liquid crystals must not contain any hetero atoms or other molecular substructures with significant ion coordination capability. So far this target can only be achieved with so-called super fluorinated materials (SFM) which derive their molecular dipole moment and – on the supramolecular level – their dielectric anisotropy ($\Delta\varepsilon$) from the polarity of the carbon–fluorine bond.

One of the major development targets in order to improve the energy efficiency and thus the battery lifetime of mobile devices is a reduction of the operating voltage of the LCD. The most effective way to achieve this is to increase the dielectric anisotropy of the liquid crystal by increasing its dipole moment into the direction of the long molecular axis.[3] Nevertheless, the polarity which can be achieved with "conventional" fluorinated polar terminal groups, such as fluorine or the trifluoromethoxy group, is quite limited. Also the often successfully applied concept of additional lateral fluorination[4] of the mesogenic core structure has already met its limitations.

In order to gain access to a new class of highly polar liquid crystals that fulfill the requirements of active matrix technology we focused our attention on hypervalent sulfur fluorides. The highly stable pentafluorosulfuranyl (SF_5) group is so far the most polar functional group compatible with AM-LCD technology,[1,5] but in contrast to other polar groups its polarity cannot be significantly increased by lateral fluorination, due to unusual steric effects.[1a]

A closer look on the geometry of the SF_5 group indicates that the four equatorial sulfur–fluorine bonds are cancelling their local dipole moments and therefore do not contribute significantly to the overall group dipole moment (Scheme 1). On the other hand, the main contribution to the dipole moment of the liquid crystal **1**[1b] comes from the one axial fluorine substituent which is oriented towards the direction of the long molecular axis. If this axial substituent is replaced by the more polar trifluoromethyl group, the resulting *trans*-SF_4CF_3 function is expected to have a strongly increased group dipole moment. Consequently, the liquid crystal **2** based the new terminal group should show the desired improvement of the dielectric anisotropy.



Scheme 1. The main contributor to the molecular dipole moment of pentafluorosulfuranyl-substituted liquid crystals (**1**)[1b] is the axial fluorine atom, which can be replaced by a more polar trifluoromethyl group (**2**).

[‡] Liquid Crystals Based on Hypervalent Sulfur Fluorides, 3. Parts 1 and 2: Ref.[1]

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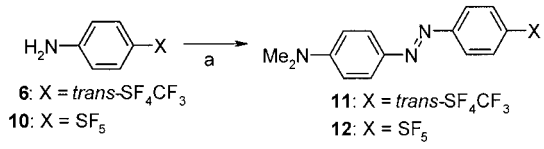
Results and Discussion

Synthesis and Characterization of Liquid Crystals

Most organic SF_4CF_3 derivatives so far reported in the literature are small and often perfluorinated aliphatic molecules.[6] We expected the group to have similar properties and chemical stability[7] as the SF_5 group. The general strategy leading to the *trans*-SF_4CF_3 substituent was therefore analogous to the synthesis of *trans*-diaryltetrafluorosulfuranes we reported previously.[8] The conversion of the resulting key intermediate *trans*-(4-nitrophenyl)(trifluoromethyl)tetrafluorosulfurane (**3**) on the route to our target compound **2** was planned in analogy to the synthesis of **1**.

Starting from commercially available 4-iodonitrobenzene (**4**) the reaction with $CuSCF_3$[9] gave 60% of **5**.[10] The trifluoromethyl aryl thioether **5** was then treated in acetonitrile with a 10% F_2/N_2 mixture at 0 °C, furnishing 50% of a 85:15 mixture of *cis* and *trans*-**3** as a yellow oil, from which the *trans* isomer started to crystallize after a few hours at room temperature. A first attempt to isomerize the mixture to the desired *trans*-**3** with a catalytic quantity of boron trifluoride–diethyl ether failed.[8] Using nearly equimolar quantities of the stronger Lewis acid aluminum trichloride we succeeded in obtaining 48% of pure *trans*-**3**. The nitro compound *trans*-**3** was hydrogenated to the aniline **6** (87%) and subsequently converted into the bromide **7** (52%) by a Sandmeyer reaction. Whilst moderately reductive as well as strongly acidic reaction conditions were tolerated by the SF_4CF_3 group, an attempt to achieve a halogen metal exchange using *tert*-butyllithium in diethyl ether at –78 °C resulted in immediate, exothermic decomposition of most the starting material. Anyhow, a small quantity of the lithio intermediate **8** must have been retained, because quenching of the reaction mixture with water afforded 11% of the corresponding benzene derivative **9**, although in moderate purity (92.5% by GC). The palladium-catalyzed coupling of **7** with 4-(*trans*-4-propylcyclohexyl)-benzene boronic acid furnished 14% of the liquid crystal **2** (Scheme 2).

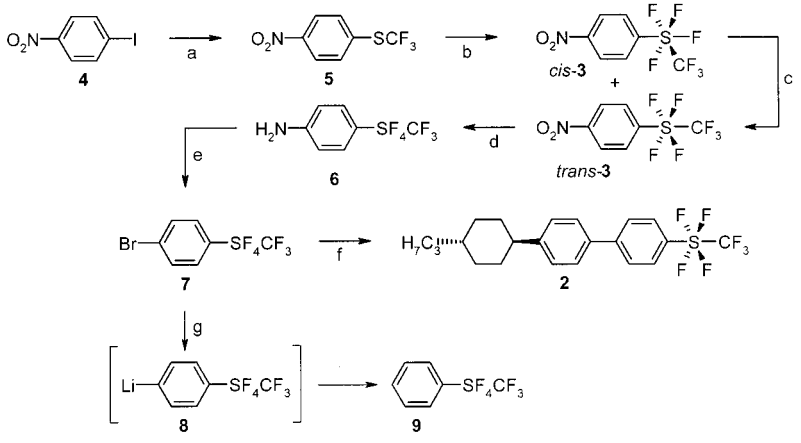
In order to gain further insight into the physicochemical characteristics (in particular the lipophilicity increment π_p and the Hammett constant σ_p) of the functional groups based on hypervalent sulfur fluorides, the azo dyes **11** and **12** were prepared[11] and characterized by UV/Vis spectroscopy and by HPLC (Scheme 3).



Scheme 3. Synthesis of the azo dyes **11** and **12**: a) 1. 37% HCl, H_2O, acetone, $NaNO_2$; 0–5 °C, 30 min; 2. *N*,*N*-dimethylaniline; 0 °C to room temp. (**11**: 23%, **12**: 36%).

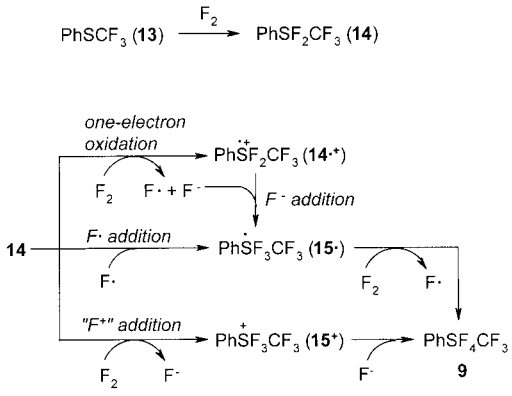
The predominant formation of *cis*-**3** as the primary fluorination product (*cis*-*trans* ratio of 85:15) is somewhat counter-intuitive, since DFT calculations [B3LYP/6-311+G(2d,p)//B3LYP/6-31(d)+ZPE level of theory][12] show for the model system **9** that *trans*-**9** is more stable than *cis*-**9** by 7.2 kcal·mol^{-1}. A similar apparent discrepancy between experimental results and thermodynamic stability had already been reported earlier for the formation of bis(4-nitrophenyl)tetrafluorosulfurane.[8]

Nevertheless, a closer look on the different, hypothetically possible pathways (Scheme 4) for the fluorination leading from the common intermediate **14** to the product *cis*/*trans*-**9**, and analysis of the intermediates by DFT calculations (Scheme 5)[12] reveals the probable reason for this unexpected behaviour: neither intermediate **14** nor any of the other potential intermediates from oxidative, radical or electrophilic reaction pathways show a low energy, stationary structure with a linear phenyl–S–CF_3 arrangement as a possible direct precursor of *trans*-**9**. This means that the predominant formation of *cis*-**9** (and *cis*-**3** for the experi-



Scheme 2. Synthesis of the liquid crystal **2** and [*trans*-(trifluoromethyl)tetrafluorosulfuranyl]benzene (**9**): a) $CuSCF_3$, DMF; 130 °C (60%). b) 10% F_2/N_2, CH_3CN; –3–2 °C (50% of a *cis*/*trans*, 85:15 mixture). c) $AlCl_3$ (0.8 equiv.), CH_2Cl_2; –10 °C, 30 min (48% pure *trans*). d) Cat. Raney-Ni, H_2, THF; room temp., 1 bar (87%). e) 1. $NaNO_2$, 47% HBr; 0–5 °C; 2. CuBr; 85 °C (52%). f) 4-(*trans*-4-propylcyclohexyl)-benzeneboronic acid, $NaBO_2{\cdot}8H_2O$, H_2O, THF, cat. $Pd(PPh_3)_4$; 60 °C, 5 h (14%). g) 1. *tert*-BuLi, Et_2O; –70 °C, 1.5 h; 2. H_2O; –70 °C → room temp. (11%).

mental system as well) as the main fluorination product is a kinetic effect, controlled by the bent structures of the reaction intermediates.

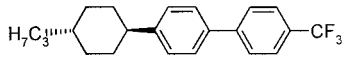


Scheme 4. Hypothetical reaction pathways (oxidative, radical and electrophilic mechanisms) for the fluorination of **13** to *cis*/*trans*-**9** via the common intermediate **14**.

When *trans*-**3** and *cis*-**3** are brought into an equilibrium via the sulfuranonium cation **16**$^+$ by the action of a Lewis acid ($AlCl_3$), conversion to the thermodynamically preferred *trans*-**3** occurs (Scheme 6). A minor byproduct of the isomerization reaction is the trifluoromethylthio-substituted starting material **5**, which is presumably generated by reduction of **16**$^+$ either by chloride ions or by the solvent. No traces of any chlorine containing byproducts are found, which might be expected to result from fluorine–chlorine exchange via the cation **16**$^+$.

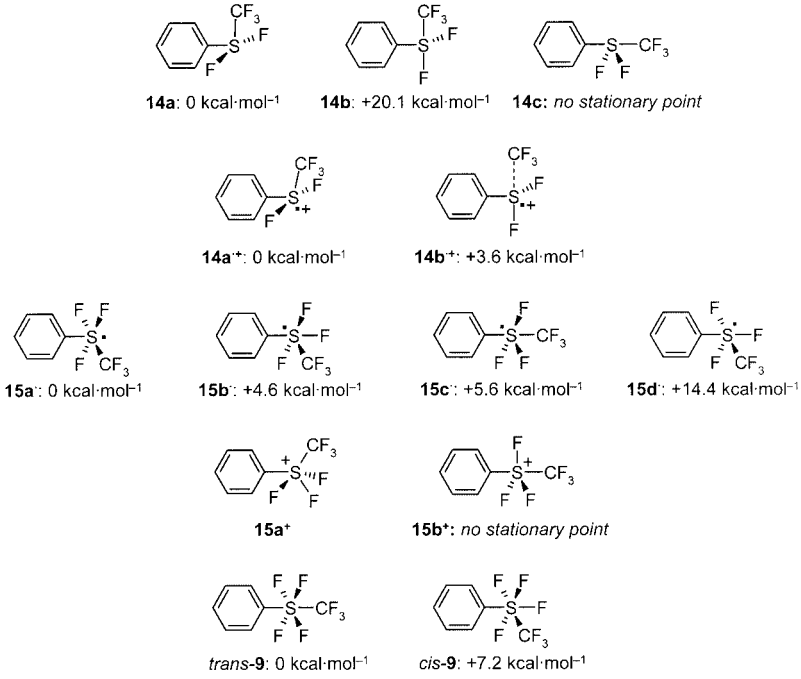
The physical characterization of the *trans*-SF_4CF_3-substituted liquid crystal **2** gave quite unexpected results (Table 1): The dielectric anisotropy ($\Delta\varepsilon_{virt}$ = 10.6) was not only far lower than the value for the SF_5 analogue **1** ($\Delta\varepsilon_{virt}$ = 14.3) but even lower than for the CF_3 analogue **17** ($\Delta\varepsilon_{virt}$

Table 1. The physical properties of the liquid crystals **1**, **2** and **17** in comparison. The virtual electrooptical parameters ($\Delta\varepsilon_{virt}$, Δn_{virt}) and clearing points ($T_{NI,virt}$) were extrapolated from the Merck mixture ZLI-4792.[13] (C = crystalline, N = nematic, I = isotropic. The phase transition temperatures are given in °C, the number in parentheses denotes a monotropic phase transition).

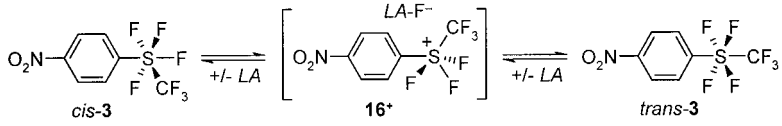


17

Compound	Phase sequence	$\Delta\varepsilon_{virt}$	Δn_{virt}	$T_{NI,virt}$
1	C 109 N (87.8) I	14.3	0.154	94.6
2	C 197 N 209.7 I	10.6	0.150	182.6
17	C 134 I	13.0	0.165	108.6



Scheme 5. Structures and relative energies of the different configurations of **14** and other potential intermediates for the fluorination of **13** to **9** [B3LYP/6-311+G(2d,p)//B3LYP/6-31G(d)+ZPE level of theory].[12] The species **14b**$^{\bullet+}$ is a minimum on this level of theory but its S–CF_3 bond is with 2.75 Å very long for a covalent bond. For the other intermediates this bond measures typically around 2 Å.



Scheme 6. Lewis acid (LA) catalyzed isomerization of **3** restores the thermodynamic equilibrium between *cis*- and *trans*-**3** via the cation **16**$^+$, leading to the energetically preferred (by ca. 7.2 kcal·mol^{-1} for the analogous system **9**) *trans* isomer.

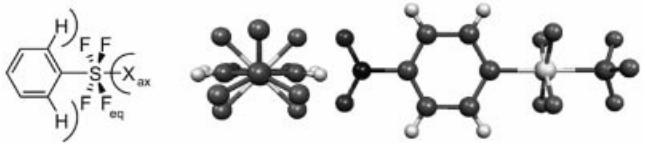
= 13.0). On the other hand, the clearing temperature of **2** (T_{NI} = 209.7 °C) is about 100 K higher than for **1** (T_{NI} = 109 °C). This is the usual effect of the increased length-breadth ratio of **2** compared to **1** by the more elongated shape of the *trans*-SF_4CF_3 group compared to SF_5. Of the compounds in Table 1, the SF_4CF_3 derivative **2** is the only one showing a thermodynamically stable, although narrow nematic phase range. In spite of its high melting point (m.p. 197 °C), the solubility of **2** in organic solvents and in the standard fluorinated nematic screening host ZLI-4792 is excellent.

Quantum Chemical Calculations

Comparative DFT calculations [structure optimization on the B3LYP/6-31(d) level of theory][12] on *trans*-phenyl-(trifluoromethyl)tetrafluorosulfurane (**9**) and (pentafluorosulfuranyl)benzene (**18**) offer an explanation for the unexpectedly low dielectric anisotropy of **2**. Generally, the contribution of the four equatorial fluorine substituents to the molecular dipole moment is negligible since the local S–F dipole moments are cancelling each other for symmetry reasons. This situation changes, if the central sulfur atom is located outside the plane formed by the four equatorial fluorine atoms. Such a deformation can be achieved easily, requiring only about 1 kcal·mol^{-1} of strain energy per degree of distortion of the C_{ar}–S–F_{eq} angle, and leading to a corresponding change of about 0.3 D in the group dipole moment.[1b] In the case of **9** there are two competing steric influences on the equatorial fluorine "belt": the aromatic *ortho*-hydrogen substituents are pushing them "forward", potentially increasing the group dipole moment, whereas the axial trifluoromethyl group is pushing them "backwards", partially cancelling the local dipole moment of the CF_3 group. Comparison of the DFT structures of **9** and **18** shows, that in the case of **9** the steric repulsion of the axial CF_3 group dominates over the effect of the aromatic *ortho*-hydrogen atoms, pushing the equatorial fluorine ring back by about 0.6°. This leads to a significant local dipole moment opposed to the direction by the CF_3 group, reducing on the intramolecular level the group dipole moment and – on the supramolecular level in the nematic phase – the dielectric anisotropy ($\Delta\varepsilon$) of the liquid crystal **2**.

The geometry of the *trans*-SF_4CF_3 group in **9**, calculated using DFT (Table 2), is also in reasonable agreement with an X-ray structure analysis of *trans*-**3**.[14]

Table 2. DFT calculations [geometry optimization on the B3LYP/6-31G(d) level of theory][12] indicate how the four equatorial fluorine atoms F_{eq} respond to the competing steric influences of the phenyl moiety and the axial substituent X_{ax} (*top left*). The values for *trans*-**3** were obtained by X-ray crystallography. Two different views of the crystal structure of *trans*-**3** are represented on top: frontal along the CF_3–S–Car axis (*middle*), and perpendicular to the aromatic ring plain (*right*).



	18: X = F	**9**: X = CF_3	*trans*-**3**
C_{ar}–S [Å]	1.825	1.829	1.813(8)
S–X_{ax} [Å]	1.623	1.931	1.924(9)
S–F_{eq} [Å]	1.631	1.654, 1.662	1.623(3), 1.589(4)
C_{ar}–S–F_{eq} [°]	92.40	91.77	91.52(19), 91.85(18)
μ [D]	4.03	2.93	–

Substituent Effects of the *trans*-SF_4CF_3 Group

Whilst DFT calculations are known to give reasonably good geometries,[1b] they fail completely to provide accurate dipole moments of hypervalent sulfur compounds: The calculated dipole moment for pentafluorosulfuranyl benzene is 4.03 D, whereas the experimentally determined value is 3.44 D.[5a]

So far there is not much data on the physicochemical characteristics of the *trans*-SF_4CF_3 group, which define its potential usefulness as a building block for medicinal chemistry and materials science. Therefore, we used the azo dye **11** in order to determine its lipophilicity increment (π_p)[15] and Hammett substituent parameter (σ_p).[16]

The lipophilicity parameters log*P* (*P* being the distribution coefficient in an *n*-octanol/water system) for the analogous compounds **11** and **12** were measured by an HPLC based method:[17] for **11**, log*P* is 7.4, and for **12**, log*P* is 6.5. Since the SF_5 group (in **12**) is known to have a lipophilicity increment π_p of +1.23,[4,15] the π_p increment for the *trans*-SF_4CF_3 group (in **11**) was deduced to be +2.13.

The Hammett substituent parameter σ_p of the *trans*-SF_4CF_3 group was determined by a method established by L. M. Yagupolskii and co-workers.[18] In order to obtain a calibration function, for a series of methyl orange analogues carrying different substituents the differences in UV absorption maxima ($\Delta\lambda_{max}$) in a neutral (EtOH) and a strongly acidic medium (EtOH/37% HCl 1:2 v/v) were plotted against the known σ_p values of their substituents (Table 3 and Figure 1). For substituents with a predominantly inductive effect the relationship is approximately linear. The *trans*-SF_4CF_3 substituted azo dye **11** was found to have the same shift $\Delta\lambda_{max}$ as its SF_5 analogue **12**, therefore having the same σ_p value of +0.68 as the SF_5 group and fitting well into the linear portion of the curve depicted in Figure 1.

The *trans*-SF_4CF_3 group (π_p = +2.13) is one of the most hydrophobic functional groups in existence.[4,15] Its lipophilicity increment is significantly higher than that of the CF_3 (+0.88) and SF_5 group (+1.23), and it even exceeds the lipophilicity of SCF_3 (+1.44) – the current hydrophobicity record holder for small groups – by far. The Hammett substituent parameter σ_p of the *trans*-SF_4CF_3 function (+0.68) is also amongst the highest for electron-withdrawing functional groups with a predominantly inductive (–*I*) effect. The value is the same as for the SF_5 group (+0.68), significantly higher than for CF_3 (+0.53), even slightly higher

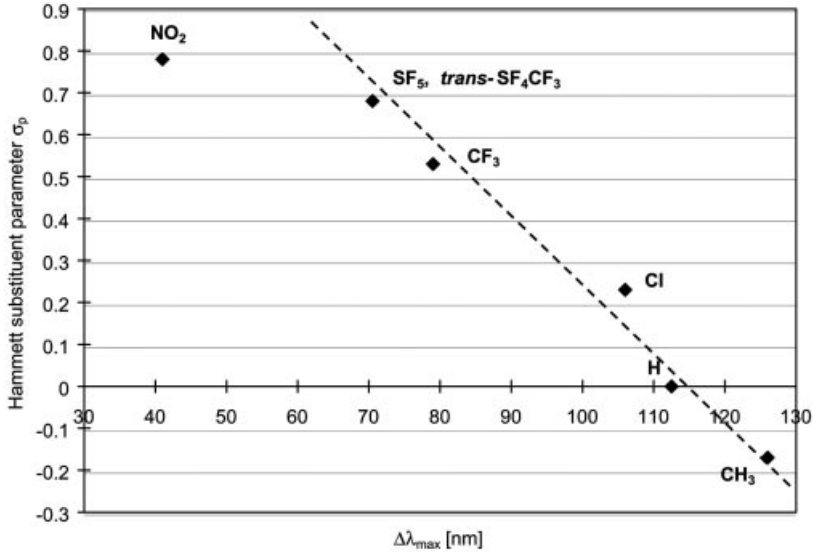
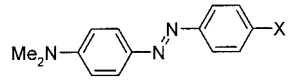


Figure 1. UV/Vis spectrometric analysis of the differently substituted (X) azo dyes **11**, **12**, **19**–**23**: $\Delta\lambda_{max} = \lambda_{max}$(EtOH/35% HCl, 1:2 v/v) – λ_{max}(EtOH) correlates with the Hammett parameters σ_p obtained by different methods.[4,18]

Table 3. UV absorptions for methyl orange analogues with various substituents X (**11**, **12**, **19**–**23**). The absorption wavelengths λ_{max} and the corresponding shifts $\Delta\lambda_{max}$ are denoted in nm, the concentration was ca. 1 mg of analyte per 100 mL of solvent.



11: X = *trans*-SF_4CF_3 **21**: X = Cl
12: X = SF_5 **22**: X = H
19: X = NO_2 **23**: X = CH_3
20: X = CF_3

X	λ_{max} (EtOH/HCl) [a]	λ_{max} (EtOH)	$\Delta\lambda_{max}$	σ_p
CH_3	531.0	405.0	126.0	–0.17
H	519.0	406.5	112.5	0
Cl	521.5	415.5	106.0	+0.23
CF_3	504.0	425.0	79.0	+0.53
SF_5	502.0	431.5	70.5	+0.68
trans-SF_4CF_3	503.0	432.5	70.5	+0.68
NO_2	511.5	470.5	34.0	+0.78

[a] EtOH/37% HCl 1:2 (v/v).

than for CN (+0.66). It is surpassed only by groups with a strong –*M* effect, such as NO_2 (+0.78). With this particular combination of high π_p and high σ_p, the *trans*-SF_4CF_3 group fits into the concept of "polar hydrophobicity",[19] a unique characteristic of many highly fluorinated compounds. This physicochemical profile together with its excellent chemical stability renders this functional group an interesting new building block for medicinal chemistry.

Conclusions

For the first time, aromatic compounds having a *trans*-SF_4CF_3 group have been synthesized and fully characterized. The preferred formation of the thermodynamically less stable *cis*-SF_4CF_3 group by direct fluorination of SCF_3 arenes is mechanistically rationalized by DFT calculations. The SF_4CF_3 derivatives were found to be chemically very stable, allowing the conversion into various other compounds. Due to steric effects, the dielectric anisotropy ($\Delta\varepsilon$) of liquid crystals with a *trans*-SF_4CF_3 terminal group is much lower than expected. On the other hand, the group shows a unique combination of a strong inductive substituent effect and extremely high lipophilicity. These unusual characteristics render the *trans*-SF_4CF_3 group an attractive new addition to the toolbox of organic chemistry.

Experimental Section

General: The fluorinations were done under a well-ventilated hood in a 1-L PFA bottle with PTFE and PFA tubings. Even traces of non-fluorine resistant organic compounds, such as lubricants, can combust spontaneously. Before and after operation the apparatus was purged with dry nitrogen. Excess fluorine and hydrofluoric acid was scrubbed by a column filled with a mixture of granulated charcoal and aluminum oxide pearls. The acetonitrile used as the reaction solvent (Merck KGaA, DNA synthesis grade) contained less than 10 ppm of water.

Caution: Working with elemental fluorine is potentially hazardous![20]

Compound 3 (isomer mixture): A solution of **5**[9,10] (20.0 g, 86.9 mmol) in dry acetonitrile (600 mL) was cooled to –3 °C and purged with dry nitrogen. Into the vigorously stirred solution a stream of 10% F_2/N_2 was bubbled at a rate of 400 ml·min^{-1} and a maximum temperature of +2 °C for 7.5 h under GC-MS control (the samples were injected into the GC without prior aqueous work-up, in order to avoid extraction of water-soluble intermediates). After completion of the reaction, the apparatus was purged with nitrogen for 30 min, and the solution was evaporated to dryness. The residue was dissolved in CH_2Cl_2 (300 mL) and stirred for 20 min with ice-cold 10% (w/v) aqueous NaOH (500 mL). The organic layer was separated, and the aqueous phase was extracted once with CH_2Cl_2. The combined organic phases were washed twice with 10% aqueous NaOH and twice with water, dried with

Na_2SO_4 and the solvents evaporated to dryness. The residue was chromatographed over silica gel (1-chlorobutane/*n*-heptane, 3:2; R_f = 0.7) to yield crude **3** (isomer mixture with a *cis*/*trans* ratio of 85:15; 13.0 g, 50%) as a yellow oil (90% purity by GC).

***trans*-3:** A dispersion of anhydrous sublimed $AlCl_3$ (3.5 g, 26.2 mmol) in CH_2Cl_2 (130 mL) was cooled to –10 °C. Then, a solution of crude *cis*/*trans*-**3** (11.3 g, purity 90%, 34.0 mmol) in CH_2Cl_2 (20 mL) was added dropwise at a maximum temperature of –8 °C. After stirring for additional 30 min at –10 °C, the mixture was poured into ice water (300 mL) and diluted with CH_2Cl_2 (100 mL). The aqueous phase was separated and extracted with CH_2Cl_2. The combined organic phases were washed with water, dried with Na_2SO_4 and the solvents evaporated to dryness. The residue (9.1 g) was chromatographed over a short silica gel column (1-chlorobutane/*n*-heptane, 3:2) and crystallized from *n*-heptane at –20 °C to yield *trans*-**3** (4.9 g, 48%) as yellow crystals, m.p. 114 °C (98.8% purity by GC). Crystals suitable for an X-ray structure analysis were obtained from acetonitrile. ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 8.34 (br. d, J = 9.1 Hz, 2 H, ar-*H*), 8.00 (d, J = 9.1 Hz, 2 H, ar-*H*; split by a higher-order coupling) ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 42.6 (q, J = 24.7 Hz, 4F, SF_{eq}), –61.7 (quint, J = 24.7 Hz, 3F, CF_3) ppm. MS (EI, 70 eV): *m*/*z* (%) = 299 [M^+] (100), 253 (11), 230 (15), 192 (35), 141 (17), 139 (18), 111 (24), 95 (38), 89 (14), 83 (19), 75 (99).

***cis*-3:** Chromatography of the isomer mixture of *cis*/*trans*-**3** over silica gel (1-chlorobutane/*n*-heptane, 3:2) furnished a fraction of slightly enriched *cis*-**3** (ca. 90% purity by HPLC) as a yellow oil. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 84.7 (dtq, J = 183.6 Hz, J = 86.6 Hz, J = 10.1 Hz, 1F, S*F*), 65.6 (dtq, J = 183.6 Hz, J = 106.1 Hz, J = 23.3 Hz, 1F, S*F*), 22.5 (ddq, J = 106.1 Hz, J = 86.6 Hz, J = 16.5 Hz, 2F, S*F*), –65.7 (ddt, J = 23.3 Hz, J = 16.5 Hz, J = 10.1 Hz, 3F, CF_3) ppm.

6: A solution of *trans*-**3** (10.8 g, 35.7 mmol) in THF (220 mL) was hydrogenated in the presence of Raney nickel (8 g) at 30 °C and a hydrogen pressure of 4.6 bar for 56 h, until completion of the reduction. The catalyst was filtered off over celite, the solution evaporated to dryness, and the residue crystallized from *n*-heptane at –25 °C to yield colorless crystals of **6** (8.2 g, 87%), m.p. 57 °C (99.2% purity by GC). ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.55 (d, J = 7.0 Hz, 2 H, ar-*H*; split by a higher-order coupling), 6.61 (br. d, J = 7.0 Hz, 2 H, ar-*H*), 3.98 (br. S, 2 H, NH_2) ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 40.6 (q, J = 25.4 Hz, 4F, SF_{eq}), –65.0 (quint, J = 25.4 Hz, 3F, CF_3) ppm. ^{13}C NMR (63 MHz, $CDCl_3$, 300 K): δ = 149.3, 127.8, 113.8. MS (EI, 70 eV): *m*/*z* (%) = 269 [M^+] (90), 200 (12), 162 (12), 111 (100), 92 (24), 84 (10), 65 (22) ppm. HRMS ($C_7H_6NF_7S$): calcd. 269.0109, found 269.0111.

7: A solution of **6** (8.2 g, 30.5 mmol) in 24% (w/v) HBr (150 mL) was cooled to 0 °C. A solution of $NaNO_2$ (2.8 g, 40.6 mmol) in water (20 mL) was added dropwise, keeping the temperature below 5 °C. After stirring for 30 min, urea (1.0 g) was added in order to destroy residues of nitrous acid. Then, a solution of CuBr (9.0 g, 62.7 mmol) in 47% (w/v) HBr (40 mL) was added at 0–5 °C. The mixture was heated to 85 °C and kept for 2 h at this temperature until the evolution of nitrogen subseded. After cooling down, the mixture was poured into ice water (500 mL) and diluted with *n*-pentane (150 mL). The organic layer was separated, and the aqueous phase extracted again with *n*-pentane. The combined organic phases were washed with water and aqueous $NaHCO_3$ solution, dried with Na_2SO_4 and the solvents evaporated to dryness. The residue (13.1 g) was chromatographed (silica gel; *n*-pentane, R_f = 0.6) to yield **7** (5.5 g, 52%) as a colorless oil (96.6% purity by GC). ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.68–7.57 (m, 4 H, ar-*H*) ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 42.7 (q, J = 25.0 Hz, 4F, SF_{eq}), –61.6 (quint, J = 25.0 Hz, 3F, CF_3) ppm. ^{13}C NMR (63 MHz, $CDCl_3$, 300 K): δ = 132.3, 128.0, 126.4 ppm. MS (EI, 70 eV): *m*/*z* (%) = 332 [M^+] (100), 263 (8), 225 (18), 174 (50), 155 (17), 95 (61), 89 (16), 75 (43), 69 (25). HRMS ($C_7H_4BrF_7S$): calcd. 331.9105, found 331.9109.

9: A solution of **7** (2.4 g, 7.2 mmol) in diethyl ether (50 mL) was treated dropwise with *tert*-butyllithium (15% in *n*-pentane; 10 mL, 14.8 mmol) at –70 °C. The reaction was violently exothermic, and immediate dark coloration occurred. After stirring for 90 min at –70 °C, water (20 mL) was added carefully. The mixture was acidified by addition of 2 N HCl, the organic phase was separated and washed with brine. The combined aqueous phases were extracted with methyl *tert*-butyl ether (50 mL), and the combined organic phases were dried with Na_2SO_4, filtered and the solvent was removed in vacuo. The residue (1.9 g) was dissolved in *n*-pentane and filtered through a short silica gel column. The crude product (350 mg) was subsequently distilled in a kugelrohr apparatus. A first fraction was collected at 60 °C/60 mbar and discarded. The product fraction of **9** (210 mg, 11%) was obtained at 91 °C/60 mbar (92.5% purity by GC), n_D^{20} = 1.4175. ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.82–7.76 (m, 2 H, ar-*H*), 7.53–7.40 (m, 3 H, ar-*H*) ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 38.0 (q, J = 25.1 Hz, 4F, SF_{eq}), –66.0 (quint, J = 25.1 Hz, 3F, CF_3) ppm. MS (EI, 70 eV): *m*/*z* (%) = 254 [M^+] (83), 185 (11), 165 (6), 147 (38), 96 (100), 89 (16), 77 (75), 75 (10), 69 (24). HRMS ($C_7H_5F_7S$): calcd. 254.0000, found 254.0021.

2: To a solution of $NaBO_2 \cdot 8H_2O$ (550 mg, 2.4 mmol) in water (5 mL), a solution of **7** (1.0 g, 3.0 mmol) in THF (35 mL) was added, followed by $PdCl_2(PPh_3)_2$ (100 mg, 0.14 mmol) and $N_2H_4 \cdot H_2O$ (50 µL, 1.0 mmol). Then, a solution of 4-(*trans*-4-propylcyclohexyl)benzeneboronic acid (800 mg, 3.3 mmol) in THF (15 mL) was added. The mixture was stirred for 15 min at room temperature, then for 5 h at 60 °C. After cooling down, the solution was diluted with methyl *tert*-butyl ether (100 mL) and water (20 mL). The organic phase was separated, washed with brine, dried with Na_2SO_4 and the solvents evaporated to dryness. The crude product was purified by chromatography (silica gel; *n*-heptane) and crystallized twice from *n*-heptane at –25 °C to yield **2** (200 mg, 14%) as colourless crystals (98.9% purity by HPLC), m.p. 197 °C, nematic, 209.7 °C, isotropic. ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.82 (d, J = 8.9 Hz, 2 H, ar-*H*), 7.63 (d, J = 8.9 Hz, 2 H, ar-*H*), 7.51 (d, J = 8.3 Hz, 2 H, ar-*H*), 7.32 (d, J = 8.3 Hz, 2 H, ar-*H*), 1.97–1.87 (m, 4 H), 1.47–1.05 (m, 10 H), 0.91 (t, J = 7.1 Hz, CH_3) ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 40.8 (q, J = 25.0 Hz, 4F, SF_{eq}), –63.7 (quint, J = 25.0 Hz, 3F, CF_3) ppm. MS (EI, 70 eV): *m*/*z* (%) = 454 [M^+] (100), 369 (18), 356 (43), 198 (24), 192 (35), 185 (12), 178 (12), 165 (12), 69 (12).

11: To a mixture of water (10 mL) and acetone (10 mL), 37% hydrochloric acid (1.4 mL) was added, followed by **6** (1.0 g, 3.7 mmol). After stirring for 1 h at room temperature, the mixture was cooled to 0 °C. Then a solution of $NaNO_2$ (300 mg, 3.9 mmol) in water (10 mL) was added dropwise, keeping the temperature below 5 °C. After stirring for 30 min, a solution of *N*,*N*-dimethylaniline (450 mg, 3.7 mmol) was added dropwise. After removal of the cooling bath, the solution was stirred for 1 h, neutralized by addition of 1 M aqueous NaOH and diluted with water (20 mL). The precipitated crude product was collected by filtration and dried by azeotropic evaporation with toluene. After chromatography (silica gel; CH_2Cl_2), the residue was dissolved in hot *n*-heptane (10 mL) with addition of ca. 5 mL of toluene. After cooling orange crystals

of **11** (350 mg, 23%) were obtained, m.p. 196 °C (96.6% purity by HPLC). ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.91–7.87 (m, 6 H, ar-*H*), 6.76 (d, J = 9.2 Hz, 2 H, ar-*H*), 3.11 [s, 6 H, N(CH_3)$_2$] ppm. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 41.7 (q, J = 25.0 Hz, 4F, SF_{eq}), –62.8 (quint, J = 25.0 Hz, 3F, CF_3) ppm. MS (EI, 70 eV): m/z (%) = 401 [M^+] (58), 313 (4), 224 (5), 148 (13), 120 (100), 105 (13), 77 (11). $C_{15}H_{14}F_7N_3S$ (401.347): calcd. C 44.9, H 3.5, N 10.5; found C 44.7, H 3.3, N 10.1.

12: Preparation in analogy to **11**, starting from **10** (6.0 g, 27.4 mmol).[5b] Yield: Dark red crystals of **12** (3.5 g, 36%), m.p. 180 °C; (99.0% purity by HPLC). ^{1}H NMR (300 MHz, $CDCl_3$, 303 K): δ = 7.91–7.85 (m, 6 H, ar-*H*), 6.75 (d, J = 9.1 Hz, 2 H, ar-*H*), 3.10 [s, 6 H, N(CH_3)$_2$]. ^{19}F NMR (235 MHz, $CDCl_3$, 300 K; standard $CFCl_3$): δ = 84.8 (quint, J = 148 Hz, 1F, S$F_{ax.}$), 63.4 (d, J = 148 Hz, 4F, SF_{eq}). MS (EI, 70 eV): m/z (%) = 351 [M^+] (14), 224 (6), 148 (10), 120 (100), 105 (18), 95 (8), 91 (8), 77 (15). $C_{14}H_{14}F_5N_3S$ (351.339): calcd. C 47.9, H 4.0, N 12.0; found C 48.0, H 3.9, N 12.0.

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[14] Crystal structure data for *trans*-**3** ($C_7H_4F_7NO_2S$), by crystallization from acetonitrile: orthorhombic, *P*nma, a = 8.096(2) Å, b = 10.059(1) Å, c = 11.967(3) Å, $\alpha = \beta = \gamma$ = 90°, V = 974.6(4) Å^3, Z = 4, $\rho_{calcd.}$ = 2.039 g·cm^{-1}, $R(F)$ = 14.9% for 1041 observed independent reflections (4.24° ≤ ϑ ≤ 26.36°). The data were collected at 100 K, additional diffuse scattering was observed. CCDC-283724 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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