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Generation of *ortho*-SF_5-Benzyne and Its Diels–Alder Reactions with Furans: Synthesis of 1-SF_5-Naphthalene, Its Derivatives, and 1,6(1,7)-Bis-SF_5-naphthalenes

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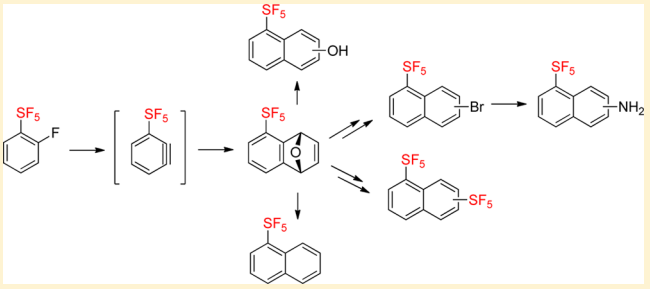
Supporting Information

ABSTRACT: Generation of *ortho*-SF_5-benzyne was achieved by a lithiation/elimination sequence starting from 2-fluoro-SF_5-benzene. The highly reactive *ortho*-SF_5-benzyne intermediate was trapped by furan or 2-methylfuran *in situ*, and the obtained stable Diels–Alder adducts were subjected to the series of further chemical transformation, which led to the formation of previously unknown 1-SF_5-naphthalene and its derivatives with bromo, amino, hydroxy, and methyl substituents, including bis-SF_5-substituted naphthalenes. NMR spectroscopy experiments revealed characteristic through-space coupling between the SF_5-group's equatorial fluorines and proton/carbon nuclei of −H, $-CH_3$, and −OH substituents in the *peri*-position to the SF_5-group of 1-SF_5-naphthalenes.

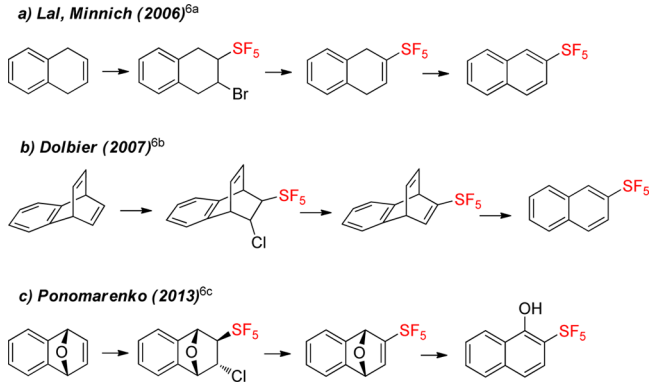


INTRODUCTION

Small fluorinated substituents and fluorine itself continue to play a vital role in life sciences research.[1] Among fluorinated substituents, the pentafluorosulfanyl (SF_5) group is a relatively new one, in which practical interest has emerged only recently.[2] When compared to the trifluoromethyl (CF_3) group, the SF_5-group is often described as its advanced analog, because of some unique and beneficial properties of the SF_5-group, which include tetragonal bipyramidal shape, large steric volume, high electronegativity and lipophilicity, and good chemical and thermal stability. These features of the SF_5 substituent significantly influence the physicochemical properties of the entire parent molecule. In relation to a biologically active compound, this has a particular impact on its pharmacological profile allowing fine-tuning of the important pharmacokinetic parameters such as log *D*, pK_a, solubility, membrane permeability, and metabolic stability.[3] Recent studies revealed that the SF_5-substituent should be considered as a bioisostere of the CF_3-group and possibly of the *tert*-butyl substituent in drug discovery programs.[4] Although the application of SF_5 building blocks in medicinal chemistry is growing in magnitude, it is still not a very common tool because of their limited commercial availability and their challenging syntheses. That is why development of synthetic methods for new SF_5-containing building blocks remains an important field of endeavor for fluorine chemists.

The recent breakthrough in the chemistry of SF_5-arenes achieved by Umemoto and co-workers[5] which allowed large-scale preparation of these compounds made a wide range of simple SF_5-arene building blocks readily available. Despite this fact, SF_5 substituted naphthalenes are still quite a rare class of compounds with only a few examples of 2-SF_5-naphthalenes appearing in the literature.[6] The known approaches to 2-SF_5-naphthalene are based on the initial radical addition[7] of SF_5Cl (SF_5Br) either to 1,4-dihydronaphthalene (Scheme 1a)[6a] or to benzobarralene (Scheme 1b).[6b] Both adducts were converted into 2-SF_5-naphthalene via the series of further chemical transformations.[6a,b] No examples of subsequent chemistry directed toward the preparation of substituted 2-SF_5-naphthalenes were provided, most likely because of the availability of multiple reactive centers in such substrates,

Scheme 1. Known Synthetic Routes toward 2-SF_5-Naphthalenes[6a−c]



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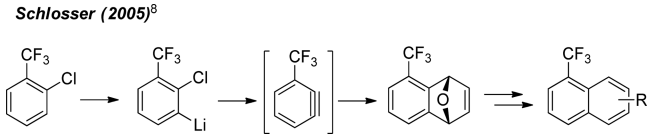
with the probable result of formation of a number of regioisomers in typical SNAr/SEAr reactions. One example of a substituted 2-SF_5-naphthalene, 2-SF_5-1-naphthol was recently described by Ponomarenko.[6c] Again, SF_5Cl was used as the source of the SF_5-group in the radical addition to oxabenzonorbornadiene. The resulting adduct was then subjected to dehydrochlorination and subsequent acid-catalyzed ring opening to furnish 2-SF_5-1-naphthol (Scheme 1c).

Recognizing that new SF_5-containing building blocks might attract research interest from chemists involved in the design and synthesis of biologically active compounds and new materials, we turned our attention to SF_5-naphthalenes as an underrepresented class of SF_5-substituted arenes.

RESULTS AND DISCUSSION

With the aim to develop a strategy for the synthesis of SF_5-naphthalenes and their derivatives without the need of using toxic and not readily available gases (i.e., SF_5Cl and SF_5Br) and with a particular interest in the preparation of the yet unknown 1-SF_5-substituted naphthalenes, we considered investigating the "benzyne route" toward SF_5-naphthalenes. A similar approach has previously been used by Schlosser and co-workers for the preparation of various naphthalenes with a CF_3-group.[8] For example, in their synthesis of 1-CF_3-naphthalenes, lithiated 2-chlorobenzotrifluoride eliminated LiCl and generated *ortho*-CF_3-benzyne, which then underwent reaction with furan to give the corresponding Diels–Alder adduct. Subsequent additional chemical transformations led to 1-CF_3-naphthalene and a number of derivatives (Scheme 2).[8]

Scheme 2. Schlosser's Synthesis of 1-CF_3-Naphthalenes[8]



Considering a possible precursor for the *ortho*-SF_5-benzene we took a close look at 2-fluoro-SF_5-benzene (**1**), the only *ortho*-substituted SF_5-benzene that can be directly prepared in two steps from 2-fluorothiophenol using Umemoto's method.[5a] Other thiophenols, with any *ortho*-substituent bulkier than fluorine, were observed to be substantially more sluggish toward further oxidative chlorination/fluorination of the respective aryl-SF_3 intermediates because of the high steric demand of a six-coordinate sulfur substituent. The requisite precursor **1** was prepared in 46% yield by the usual Umemoto procedure starting from 2-fluorothiophenol (Scheme 3).[5a]

In our initial experiments (Table 1), a solution of 2-fluoro-SF_5-benzene (**1**) in THF or Et_2O was treated with 1.1 equiv of *n*-BuLi at −78 °C, and after 15–20 min at −78 °C an excess of furan (10 equiv) was added in one portion. The cooling bath was then removed, and the reaction mixture was stirred for 16 h. After quenching with 10% aq. HCl (entries 2–9) or sat. aq.

Scheme 3. Synthesis of 2-Fluoro-SF_5-benzene (1)

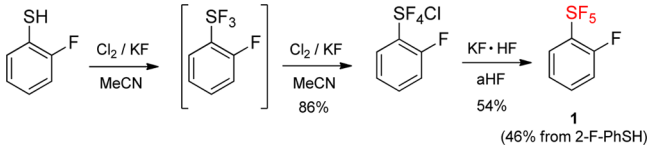
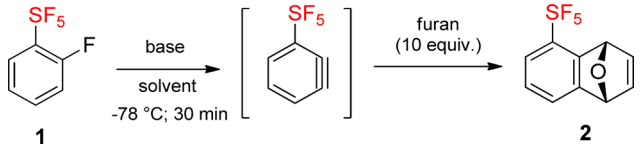


Table 1. Optimization of the Reaction Conditions for the Preparation of 2



entry	solvent	Base	equiv of base	ratio **1**/**2**[a]
1	THF	*n*BuLi	1.1	100/0
2	Et_2O	*n*BuLi	1.1	80/20
3	Et_2O	*sec*BuLi	1.1	50/50
4	Et_2O	*t*BuLi	1.1	50/50
5	Et_2O	LiHMDS	1.1	100/0
6	Et_2O	KHMDS	1.1	100/0
7	Et_2O	*t*BuLi	1.5	25/75
8	**Et_2O**	***t*BuLi**	**2.0**	**0/100**
9	Et_2O	*t*BuLi	2.2	0/100

[a]Ratio determined from ^{19}F NMR of organic phase after quenching reaction mixture with sat. aq. NH_4Cl (entry 1) or with 10% aq. HCl (entries 2–9).

NH_4Cl (entry 1), the separated organic phase was analyzed by ^{19}F NMR. The remaining starting material **1** was easy to differentiate from possible reaction products on the basis of the characteristic pattern of the four equatorial fluorine atoms of its SF_5-group, which appears as a doublet of doublets as a result of the additional through-space fluorine–fluorine coupling of these equatorial fluorines with the *ortho*-fluorine substituent ($^{TS}J_{F-F}$ = 25 Hz). Thus, it was observed that no product and mainly starting material **1** was detected when THF was used as a solvent (entry 1), but ∼20% of some new product was obtained when the reaction was carried out in Et_2O (entry 2). This reaction product was isolated, and its structure was confirmed to be **2** based on its ^1H, ^{19}F, ^{13}C NMR and HRMS data.[9] With the exact ^{19}F NMR shift of the desired product **2** known, it was then easy to further optimize the reaction conditions. Screening of other bases revealed that sterically hindered *sec*-BuLi and *t*-BuLi led to a higher conversion (∼50/50) (entries 3 and 4), whereas reactions with LiHMDS or KHMDS resulted in no product formation (entries 5 and 6). Further increases of the amount of *t*-BuLi to 1.5, 2, and 2.2 equiv showed consistent improved conversion, but little difference was noticed if 2 or 2.2 equiv of *t*-BuLi were used, and in both cases all the starting material **1** was totally consumed (entries 7–9). The reaction was scaled-up using 10 g of **1** under the optimized conditions, with the addition product **2** being isolated in 45% yield as a low melting solid (mp 48–49 °C) after SiO_2 chromatography.

The obtained Diels–Alder adduct **2** was then subjected to additional chemical transformations which led to preparation of a series of 1-SF_5-substituted naphthalenes. Thus, deoxygenation of epoxynaphthalene **2** using low-valent titanium species[8] resulted in the clean formation of the 1-SF_5-naphthalene **3** (81% yield). The ^{19}F NMR spectrum of **3** shows significant deshielding of the SF_5-group fluorine atoms (δ_F: +69.4 (d), +87.0 (m)) when compared with the chemical shifts reported for 2-SF_5-naphthalene[6b] (δ_F: +63.0 (d), +84.4 (m)) and SF_5-benzene[10] (δ_F: +62.2 (d), +84.2 (m)).

The acid-catalyzed opening of the epoxy bridge in **2** provided 8-SF_5-1-naphthol **4a** as a major reaction product, which can be readily separated from the minor more polar 5-SF_5-1-naphthol **4b** by SiO_2 chromatography (ratio of **4a**/**4b** is 85:15 according

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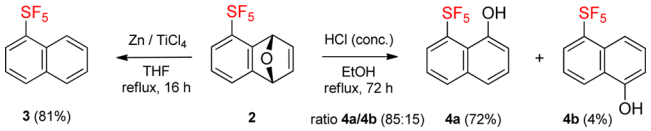
to ^{19}F NMR of the reaction mixture) (Scheme 4). Both naphthols were isolated as solids in 72% (**4a**) and 4% (**4b**) yields.

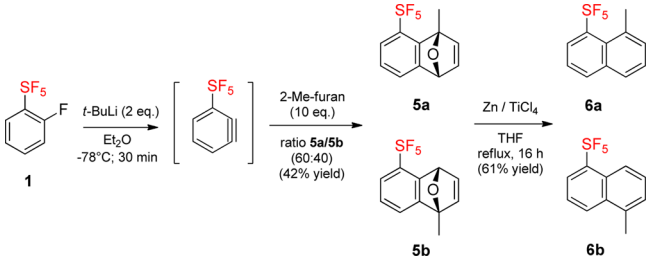
Scheme 4. Synthesis of 1-SF_5-Naphthalene (3) and 5(8)-SF_5-Naphthols (4a,b)



When 2-Me-furan was used to intercept the benzyne intermediate derived from **1**, two regioisomeric adducts **5a** and **5b** were formed in a 60/40 ratio (**5a**/**5b**). Both regioisomers **5a** and **5b** have identical R_f values and were isolated as a mixture after SiO_2 chromatography in 42% yield. However, their ratio can be easily determined from the ^{1}H NMR spectrum of the mixture, where the CH_3-group of **5a** appears as a pentuplet with $^{TS}J_{H-F}$ = 2.8 Hz (δ_H 2.05 in $CDCl_3$) and the CH_3-group of **5b** as a singlet (δ_H 1.96 in $CDCl_3$). In its ^{13}C NMR spectrum, through-space coupling between the CH_3-group and the equatorial fluorines of the SF_5-group of **5a** is also observed ($^{TS}J_{C-F}$ = 5.6 Hz; δ_C 17.8 in $CDCl_3$).

Deoxygenation of this regioisomeric mixture led to the corresponding 1-Me-8-SF_5-naphthalene **6a** and 1-Me-5-SF_5-naphthalene **6b**. Again very close R_f values did not allow one to isolate **6a** and **6b** as individual compounds, and after SiO_2 chromatography a mixture of regioisomers in 55/45 ratio (**6a**/**6b**) was obtained in 61% yield (Scheme 5). ^{1}H and ^{13}C NMR spectra of the mixture also show characteristic through-space coupling between the equatorial fluorine atoms of the SF_5-group and the protons ($^{TS}J_{H-F}$ = 3.3 Hz; δ_H 2.93 in $CDCl_3$) and carbon ($^{TS}J_{C-F}$ = 10.6 Hz; δ_C 26.3 in $CDCl_3$) of the CH_3-group of **6a**.

Scheme 5. Synthesis of 1-Methyl-5(8)-SF_5-naphthalenes (6a,b)

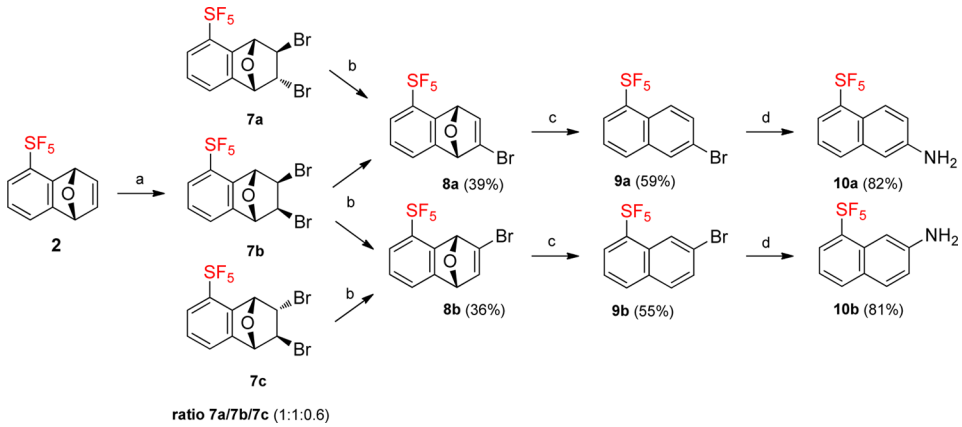


Addition of bromine to the double bond of **2** (Br_2/CCl_4/reflux) provided three stereoisomers **7a**–**c** as major reaction products in the 1:1:0.6 ratio (**7a**:**7b**:**7c**) as established on the basis of the ^{1}H and ^{19}F NMR spectra of the crude product. All three stereoisomers were isolated as individual compounds after SiO_2 chromatography. Structural assignment was based not only on the obtained NMR data compared to the corresponding CF_3-congeners described by Schlosser[8] but also on the structures of the dehydrobromination reaction products, which were specific for each of the stereoisomers. With the knowledge that *exo-syn*-elimination will be favored for each of the isomers under the same dehydrobromination conditions (*t*-BuOK/THF/rt),[11] stereoisomer **7a** formed product **8a** exclusively, stereoisomer **7c** gave only product **8b**, and stereoisomer **7b** reacted sluggishly affording the mixture of products **8a** and **8b** in 40/60 ratio (**8a**/**8b**) (Scheme 6). Alternatively, dehydrobromination (*t*-BuOK/THF; rt)[11] performed on the crude mixture of **7** provided regioisomers **8a** and **8b** (60/40 ratio) which were readily separable by SiO_2 chromatography (R_f = 0.5 (**8a**), R_f = 0.2 (**8b**); PE/EA 9:1) and were obtained in 39% (**8a**) and 36% (**8b**) yields, respectively.

Deoxygenation of regioisomers **8a** and **8b** gave the corresponding 2-bromo-8-SF_5-naphthalene **9b** (55%) and 2-bromo-5-SF_5-naphthalene **9a** (59%) as colorless solids (Scheme 6). Structural elucidation of each of the regioisomers was done on the basis of their NMR spectroscopy data. ^{1}H NMR spectra of **9a** and **9b** show a distinctive difference for the proton's signal in *peri*-position to the SF_5 group. Thus, for **9a** it appears as a well resolved doublet of pentuplets ($^{TS}J_{H-F}$ = 2.9 Hz and $^3J_{H-H}$ = 9.5 Hz), whereas, for **9b**, it appears as an unresolved multiplet due to the two similar coupling constants ($^{TS}J_{H-F} \approx {}^4J_{H-H} \approx$ 2.6 Hz) plus due to additional peak broadening imposed by quadrupolar relaxation of the neighboring bromine atom.

With the aim to further diversify 1-SF_5-substituted naphthalene building blocks, bromonaphthalenes **9a** and **9b**

Scheme 6. Addition of Bromine to 2: Synthesis of 2-Bromo-5(8)-SF_5-naphthalenes and 2-Amino-5(8)-SF_5-naphthalenes[a]



[a]Reaction conditions: (a) Br_2, CCl_4, reflux, 30 min; (b) *t*-BuOK, THF, rt, 3 days; (c) Zn, $TiCl_4$, THF, reflux, 16 h; (d) trans-4-hydroxy-L-proline (40 mol %), CuI (20 mol %), K_2CO_3 (3 equiv), 28% aq. NH_4OH, DMSO, 75 °C, 48 h.

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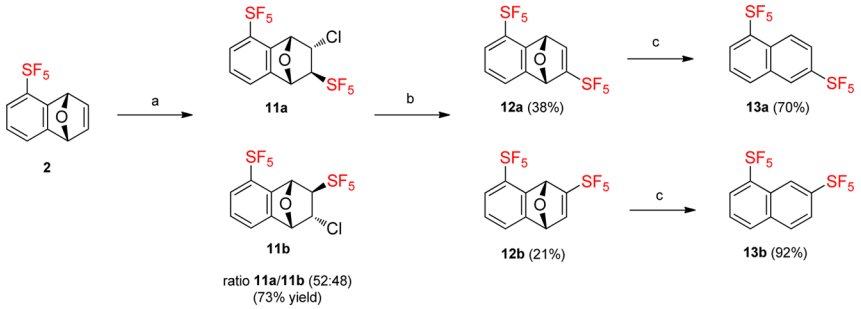
Scheme 7. Addition of SF_5Cl to 2: Synthesis of 1,6(1,7)-Bis-SF_5-naphthalenes 13a,b[a]



[a]Reaction conditions: (a) SF_5Cl (2 equiv), Et_3B (10 mol %), CH_2Cl_2, −30 °C, 18 h then 25 °C, 6 h; (b) LiOH (5 equiv), DMSO, rt, 24 h; (c) Zn, $TiCl_4$, THF, reflux, 16 h.

were converted into the corresponding naphthylamines **10a** (82% yield) and **10b** (81% yield). This transformation was performed under the coupling conditions developed by Ma and co-workers[12] using the CuI/4-hydroxy-L-proline/NH_4OH system in DMSO at 75 °C (Scheme 6).

Low temperature radical addition of SF_5Cl to the double bond of **2** was achieved using Et_3B in CH_2Cl_2[7] while maintaining the reaction mixture at −30 °C for 18 h. Similar conditions were applied recently by Ponomarenko for the addition of SF_5Cl to the unsubstituted analog of **2**, 1,4-dihydro-1,4-epoxynaphthalene.[6c] Predictably, two regioisomeric adducts **11a** and **11b** were formed in almost equal amounts (ratio **11a**/**11b** 52:48) and each regioisomer was formed as a single stereoisomer with *trans* disposition of *exo*-SF_5- and *endo*-Cl-substituents.[6c] Efficient separation of **11a**/**11b** was not possible using SiO_2 chromatography, and a mixture of both regioisomers was isolated in 73% yield (Scheme 7).

Dehydrochlorination (5 equiv of LiOH/DMSO; rt, 18 h)[13] performed on the mixture of **11a,b** provided corresponding compounds **12a** and **12b** in 59% total yield, which were readily separable by SiO_2 chromatography. 2,5-Bis-SF_5-substituted oxabenzonorbornadiene **12a** appeared as an oil (R_f = 0.55 (PE/EA 9:1); 38% yield), while 2,8-bis-SF_5-substituted **12b** was isolated as a colorless solid (R_f = 0.1 (PE/EA 9:1); 21% yield) (Scheme 7). Interestingly, through-space coupling ($^{TS}J_{F-F}$ = 6.7 Hz) between equatorial fluorine atoms of both SF_5-groups in **12b** can be observed in its ^{19}F NMR spectrum.

Finally, deoxygenation of **12a** and **12b** under the previously established conditions (Zn/$TiCl_4$/THF; reflux, 16 h) gave the corresponding 1,6-bis-SF_5-substituted naphthalene **13a** (70% yield) and the 1,7-bis-SF_5-substituted naphthalene **13b** (92% yield) as colorless solids (mp: 108−109 °C (**13a**); mp: 105−106 °C (**13b**)). These constitute the first reported examples of bis-SF_5-substituted naphthalenes (Scheme 7). Because of the greater distance between SF_5-groups in planar naphthalene **13b** compared to **12b**, through-space coupling was no longer observed in its ^{19}F NMR spectrum.

CONCLUSIONS

In summary, we have developed convenient access to previously unknown 1-SF_5-substituted naphthalenes starting from readily available 2-fluoro-SF_5-benzene. Our approach relies on the lithiation of 2-fluoro-SF_5-benzene, resulting in *ortho*-SF_5-benzyne formation and subsequent trapping of this highly reactive intermediate by furan *in situ*. Further simple chemical transformations of the obtained oxabenzonorbornadiene type of adduct led to 1-SF_5-naphthalene and a series of its substituted derivatives, including bis-SF_5-naphthalenes. One of the remarkable features of 1-SF_5-naphthalenes is the through-space coupling between proton (and carbon) nuclei of −H, $-CH_3$, and −OH substituents in the *peri*-position to the SF_5 group and its equatorial fluorines atoms, revealed by NMR spectroscopy.

EXPERIMENTAL SECTION

General Experimental Methods. NMR spectra were recorded in $CDCl_3$ at 25 °C at 300/500 MHz for ^1H NMR; 125 MHz for ^{13}C NMR, and 282 MHz for ^{19}F NMR. Chemical shifts (δ) are reported in ppm and are referenced to the solvent signal as an internal standard ($CHCl_3$ at 7.26 ppm for ^1H NMR, and $CDCl_3$ at 77.16 ppm for ^{13}C NMR). ^{19}F NMR spectra are referenced to $CFCl_3$ as an internal standard. Coupling constants (J) are reported in Hz. Multiplicities are abbreviated as follows: s (singlet), d (doublet), t (triplet), q (quartet), p (pentuplet), m (multiplet or unresolved), and br (broad signal). Reactions were monitored by TLC and/or ^{19}F NMR. TLC was performed on Sorbtech silica gel UV254 polyester backed 200 μm thickness TLC plates and visualized with UV light. Chromatographic purification was performed as flash chromatography using Sorbtech silica gel 60A 40−63 μm (230−400 mesh) at positive nitrogen pressure. HRMS spectra were obtained using a TOF mass analyzer in positive or negative ESI or DART ionization modes. Melting points were determined using a capillary melting point apparatus. Anhydrous and regular solvents were used as received from commercial suppliers. All other reagents were obtained from common vendors unless otherwise stated. SF_5Cl was supplied by Synquest Laboratories, Inc.

Note: The identities of compounds **2**, **10**, **12**, and **13** were established on the basis of ^1H, ^{13}C, ^{19}F NMR and HRMS data. For compounds **3**−**9** and **11**, relevant HRMS data were not able to be obtained, and accordingly they are characterized on the basis of ^1H, ^{13}C, ^{19}F NMR and GC/MS (LC/MS), as well as from the logic of the synthetic sequences.

Caution! Anhydrous hydrogen fluoride (bp 20 °C) is a very toxic and extremely hazardous material. All of the experiments using anhydrous hydrogen fluoride should be performed in an efficient fume hood by personnel wearing proper protective clothing who are well familiar with the precautions necessary for safe handling of anhydrous hydrogen fluoride![14]

2-Fluorophenylsulfur Pentafluoride (1).[5a] Prepared according to the general literature procedure[5a] for making arylsulfur pentafluorides from aromatic thiols. Thus, 2-fluorothiophenol (200 g; 1.56 mol) was converted into 2-fluorophenylsulfur chlorotetrafluoride[5a] using KF/Cl_2 in CH_3CN: 320 g (86% yield) of the crude material were obtained, which was then treated with a mixture of anhydrous HF (790 g; 39.5 mol; 29 equiv) and KHF_2 (115 g; 1.5 mol; 1.1 equiv) in a sealed 2 L PTFE reactor. The reaction mixture was stirred at ambient temperature for 65 h, and after the usual workup and distillation, **1** was isolated as a colorless liquid. Yield: 160 g (54%; 46% from 2-fluorothiophenol); bp 159−160 °C/760 mmHg. ^1H NMR (300 MHz, $CDCl_3$): δ 7.76 (m, 1H), 7.52 (m, 1H), 7.23 (m, 1H). ^{13}C NMR (125

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MHz, $CDCl_3$): δ 156.2 (dp, $^1J_{C-F}$ = 260 Hz, $^3J_{C-F}$ = 1.9 Hz), 140.2 (dp, $^2J_{C-F}$ = 18.5 Hz, $^2J_{C-F}$ = 11.3 Hz), 133.9 (d, $^3J_{C-F}$ = 9 Hz), 128.7 (p, $^3J_{C-F}$ = 4.9 Hz), 124.2 (d, $^4J_{C-F}$ = 3.7 Hz), 118.1 (d, $^2J_{C-F}$ = 23.7 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 81.3 (m, 1F, SF_5), 67.6 (ddm, $^2J_{F-F}$ = 149.0 Hz, $^{TS}J_{F-F}$ = 25 Hz, 4F, SF_5), −108.8 (pm, $^{TS}J_{F-F}$ = 25 Hz, 1F, C−F).

*5-(Pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**2**).*[9] *t*-BuLi (53 mL of 1.7 M solution in pentane; 5.75 g; 90 mmol; 2 equiv) was added dropwise at −78 °C to a solution of **1** (10 g; 45 mmol) in anhydrous Et_2O (80 mL) over 30 min. After addition, the reaction mixture was stirred at −78 °C for more 30 min. Then furan (30 g; 0.45 mol; 20 equiv) was added fast in one portion, and the cooling bath was removed. After 16 h of stirring, the reaction mixture was poured into 10% HCl (100 mL). More Et_2O (50 mL) was added, the organic layer was separated, and the aqueous layer was extracted with Et_2O (80 mL). The combined organic phase was washed with water (2 × 100 mL), dried with $MgSO_4$, and evaporated. The residue was purified by column chromatography (PE/DCM (1:1); R_f = 0.5) to give **2** as a yellowish solid. Yield: 5.5 g (45%); mp 48−49 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.34 (d, *J* = 7.9 Hz, 1H), 7.30 (d, *J* = 8.4 Hz, 1H), 7.02−7.10 (m, 3H), 6.10 (m, 1H), 5.80 (s, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.9, 147.4 (p, $^2J_{C-F}$ = 18 Hz), 146.8 (p, $^3J_{C-F}$ = 3 Hz), 144.3, 142.2, 126.3, 122.8, 122.3 (p, $^3J_{C-F}$ = 4.8 Hz), 84.0 (p, $^4J_{C-F}$ = 3.3 Hz), 82.6. ^{19}F NMR (282 MHz, $CDCl_3$): δ 83.8 (m, 1F, SF_5), 64.1 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). HRMS (ESI+/DART): calcd for $[C_{10}H_8F_5OS]^+$: 271.0211, found: 271.0218 $[M + H]^+$.

*1-Pentafluorosulfanylnaphthalene (**3**).* To a suspension of Zn powder (1.3 g; 20 mmol) in dry THF (10 mL), stirred and cooled in an ice/water bath, was slowly added $TiCl_4$ (1.9 g; 10 mmol). After addition, the cooling bath was removed and the green/yellow suspension was heated under reflux for 15 min. The resulted black suspension was cooled to ambient, and a solution of **2** (0.55 g; 2 mmol) in dry THF (5 mL) was added. The reaction mixture was maintained at reflux for 16 h, then cooled, and poured into a mixture of 10% HCl (50 mL) and Et_2O (30 mL), followed by stirring until the remaining Zn dissolved. The Et_2O layer was separated, and the aqueous layer was extracted with Et_2O (30 mL). The combined organic phase was washed with water (2 × 30 mL), dried with $MgSO_4$, and evaporated. The residue after evaporation was purified by column chromatography (pentane; R_f = 0.6) to give pure **3** as a colorless oil. Yield: 0.42 g (81%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.47 (dm, 1H, H-8), 8.09 (dd, *J* = 7.9 Hz, *J* = 0.9 Hz, 1H), 8.02 (d, *J* = 8.2 Hz, 1H), 7.91 (d, *J* = 8.2 Hz, 1H), 7.66 (ddd, *J* = 9.1 Hz, *J* = 6.9 Hz, *J* = 1.4 Hz, 1H), 7.57 (tm, *J* = 7.6 Hz, *J* = 0.7 Hz, 1H), 7.52 (t, *J* = 8.0 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.8 (p, $^2J_{C-F}$ = 14 Hz), 134.9, 133.7, 129.1, 128.5, 127.8, 127.7 (p, $^3J_{C-F}$ = 5.8 Hz), 126.4, 125.4 (p, $^4J_{C-F}$ = 5.3 Hz), 123.8. ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.0 (m, 1F, SF_5), 69.4 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 254 $[M^+]$.

*8-Pentafluorosulfanyl-1-naphthol (**4a**) and 5-Pentafluorosulfanyl-1-naphthol (**4b**).* To a solution of **2** (0.55 g; 2 mmol) in EtOH (15 mL) was added 38% HCl (3 mL), and the reaction mixture was stirred under reflux for 72 h. Solvent was evaporated, DCM (50 mL) was added to the residue, and the organic phase was washed with water (2 × 30 mL), dried with $MgSO_4$, and evaporated. The obtained residue was purified by column chromatography (PE/EA (9:1)) to give **4a** as a light brown solid (R_f = 0.2) and **4b** as a dark green solid (R_f = 0.12). **4a**: mp 70−72 °C. Yield: 0.42 g (72%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.16 (d, *J* = 8.0 Hz, 1H), 8.00 (d, *J* = 8.1 Hz, 1H), 7.54 (dd, *J* = 8.1 Hz, *J* = 1.0 Hz, 1H), 7.44 (m, 2H), 7.18 (dd, *J* = 7.6 Hz, *J* = 1.3 Hz, 1H), 6.23 (p, $^{TS}J_{H-F}$ = 4.0 Hz, 1H, OH). ^{13}C NMR (125 MHz, $CDCl_3$): δ 150.4 (p, $^2J_{C-F}$ = 17 Hz), 150.0, 137.3, 134.8, 128.9 (p, $^3J_{C-F}$ = 7.5 Hz), 127.1, 123.5, 123.2, 119.1, 117.0. ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.7 (m, 1F, SF_5), 72.7 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 271 $[M^+]$; RT 9.22 min. **4b**: yield: 22 mg (4%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.52 (d, *J* = 8.4 Hz, 1H), 8.10 (dd, *J* = 7.9 Hz, *J* = 1.2 Hz, 1H), 8.03 (dp, *J* = 9.2 Hz, *J* = 3.0 Hz, 1H), 7.50 (m, 1H), 7.45 (dd, *J* = 9.0 Hz, *J* = 7.6 Hz, 1H), 6.88 (d, *J* = 7.6 Hz, 1H), 5.59 (br s, 1H, OH). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.8 (p, $^2J_{C-F}$ = 14.6 Hz), 151.7, 129.0, 128.4 (p, $^3J_{C-F}$ = 5.8 Hz), 128.3, 127.4, 126.3, 123.1, 118.1 (p, $^4J_{C-F}$ = 5.3 Hz), 108.9. ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.1 (m, 1F, SF_5), 69.3 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). LC/MS (-ESI): *m*/*z* 269 $[M - H]^-$; RT 36.67 min.

*1-Methyl-8-(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**5a**) and 1-Methyl-5-(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**5b**).* Prepared analogously to **2** from **1** (1 g; 4.5 mmol) and 2-methylfuran (3.7 g; 45 mmol; 10 equiv). Inseparable mixture of **5a** and **5b** (60:40) was obtained in 42% yield (0.54 g) after column chromatography (PE/DCM 3:1; R_f = 0.2). **5a (major)**: ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.35 (d, *J* = 8.3 Hz, 1H), 7.29 (d, *J* = 6.6 Hz, 1H), 7.06 (m, 1H), 7.03 (m, 1H), 6.77 (d, *J* = 5.4 Hz, 1H), 5.66 (d, *J* = 1.8 Hz, 1H), 2.05 (p, $^{TS}J_{H-F}$ = 2.8 Hz, 3H, CH_3). ^{13}C NMR (125 MHz, $CDCl_3$): δ 154.2, 147.9 (p, $^3J_{C-F}$ = 2.5 Hz), 147.8 (p, $^2J_{C-F}$ = 18 Hz), 145.6, 145.1, 126.1, 123.3 (p, $^3J_{C-F}$ = 5.6 Hz), 122.4, 93.3, 81.0, 17.8 (p, $^{TS}J_{C-F}$ = 5.6 Hz, CH_3). ^{19}F NMR (282 MHz, $CDCl_3$): δ 83.8 (m, 1F, SF_5), 66.4 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 284 $[M^+]$; RT 12.72 min. **5b (minor)**: ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.28 (d, *J* = 8.9 Hz, 1H), 7.25 (d, *J* = 7.2 Hz, 1H), 7.08 (m, 1H), 7.04 (m, 1H), 6.81 (d, *J* = 5.4 Hz, 1H), 6.00 (m, 1H), 1.96 (s, 3H, CH_3). ^{13}C NMR (125 MHz, $CDCl_3$): δ 154.4, 148.1 (p, $^3J_{C-F}$ = 2.9 Hz), 147.0 (p, $^2J_{C-F}$ = 18 Hz), 146.7, 143.3, 126.2, 121.9 (p, $^3J_{C-F}$ = 4.8 Hz), 121.3, 89.8, 83.2 (p, $^4J_{C-F}$ = 3.1 Hz), 14.9. ^{19}F NMR (282 MHz, $CDCl_3$): δ 84.3 (m, 1F, SF_5), 64.2 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 284 $[M^+]$; RT 12.2 min.

*1-Methyl-8-(pentafluorosulfanyl)naphthalene (**6a**) and 1-Methyl-5-(pentafluorosulfanyl)naphthalene (**6b**).* Prepared analogously to **3** from the mixture of **5a** and **5b** (0.4 g; 1.4 mmol). An inseparable mixture of **6a** and **6b** (55:45) was obtained in 61% yield (0.23 g) after column chromatography (pentane; R_f = 0.6). **6a (major)**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.28 (d, *J* = 8.0 Hz, 1H), 8.00 (d, *J* = 8.0 Hz, 1H), 7.76 (d, *J* = 8.0 Hz, 1H), 7.58 (m, 1H), 7.42 (m, 2H), 2.93 (p, $^{TS}J_{H-F}$ = 3.3 Hz, 3H, CH_3). ^{13}C NMR (125 MHz, $CDCl_3$): δ 152.1 (p, $^2J_{C-F}$ = 15.4 Hz), 137.0, 134.8, 133.8, 129.5 (p, $^3J_{C-F}$ = 7.8 Hz), 129.1, 128.9, 127.4, 126.0, 123.6, 26.3 (p, $^{TS}J_{C-F}$ = 10.6 Hz, CH_3). ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.3 (m, 1F, SF_5), 72.7 (dp, $^2J_{F-F}$ = 149.0 Hz, $^{TS}J_{F-H}$ = 2.7 Hz, 4F, SF_5). GC-MS (*m*/*z*): 268 $[M^+]$; RT 8.84 min. **6b (minor)**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.37 (dp, *J* = 9.0 Hz, *J* = 3.0 Hz, 1H), 8.24 (d, *J* = 8.4 Hz, 1H), 8.11 (dd, *J* = 7.9 Hz, *J* = 1.0 Hz, 1H), 7.55 (d, *J* = 9.0 Hz, 1H), 7.53 (d, *J* = 9.1 Hz, 1H), 7.45 (m, 1H), 2.74 (s, 3H, CH_3). ^{13}C NMR (125 MHz, $CDCl_3$): δ 152.5 (p, $^2J_{C-F}$ = 14.2 Hz), 135.7, 135.0, 134.2, 129.3, 127.9, 128.0, 127.4 (p, $^3J_{C-F}$ = 5.8 Hz), 123.7 (p, $^4J_{C-F}$ = 5.3 Hz), 123.1, 20.4. ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.8(m, 1F, SF_5), 69.8 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 268 $[M^+]$; RT 8.84 min.

*2,3-Dibromo-1,4-epoxy-1,2,3,4-tetrahydro-5-(pentafluorosulfanyl)naphthalenes (**7a−c**).* A solution of **2** (5.15 g; 19 mmol) in CCl_4 (35 mL) was stirred at reflux while a solution of Br_2 (4.8 g; 30 mmol) in CCl_4 (15 mL) was added to it dropwise over 15 min. After addition, the reaction mixture was maintained at reflux for more 30 min, then it was cooled, and evaporated to dryness. A part of the obtained residue was purified by SiO_2 chromatography (PE/DCM 4:1), and analytically pure samples of each of the stereoisomers **7a−c** were obtained. Another part of the crude residue was directly subjected to the further dehydrobromination step. **Stereoisomer 7a**: R_f = 0.52 (PE/DCM 4:1); mp 82−85 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.64 (d, *J* = 8.3 Hz, 1H), 7.55 (d, *J* = 7.3 Hz, 1H), 7.44 (m, 1H), 5.81 (m, 1H), 5.49 (dd, *J* = 4.7 Hz, *J* = 0.9 Hz, 1H), 4.53 (dd, *J* = 4.7 Hz, *J* = 2.7 Hz, 1H), 3.78 (d, *J* = 2.7 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 146.9 (p, $^2J_{C-F}$ = 19.1 Hz), 143.7, 138.3 (p, $^3J_{C-F}$ = 2.5 Hz), 128.7, 126.7, 125.7 (p, $^3J_{C-F}$ = 4.9 Hz), 88.4 (p, $^4J_{C-F}$ = 3.2 Hz), 83.4, 51.4, 50.2. ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.7 (m, 1F, SF_5), 64.3 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 348 $[M - Br]^+$; RT 10.27 min. **Stereoisomer 7b**: R_f = 0.33 (PE/DCM 4:1); mp 128−130 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.61 (d, *J* = 8.2 Hz, 1H), 7.52 (d, *J* = 7.2 Hz, 1H), 7.40 (m, 1H), 5.84 (m, 1H), 5.59 (s, 1H), 4.23 (s, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 147.3 (p, $^2J_{C-F}$ = 19.2 Hz), 144.9, 139.4 (p, $^3J_{C-F}$ = 2.5 Hz), 129.6, 125.7 (p, $^3J_{C-F}$ = 4.8 Hz), 123.9, 89.1 (p, $^4J_{C-F}$ = 2.9 Hz), 87.9, 51.2, 50.4. ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.4 (m, 1F, SF_5), 64.3 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). GC-MS (*m*/*z*): 348 $[M - Br]^+$; RT 11.32 min. **Stereoisomer 7c**: R_f = 0.45 (PE/

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DCM 4:1); mp 137−139 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.69 (d, J = 8.4 Hz, 1H), 7.53 (d, J = 7.2 Hz, 1H), 7.43 (m, 1H), 5.87 (m, 1H), 5.51 (s, 1H), 4.54 (dd, J = 4.7 Hz, J = 2.5 Hz, 1H), 3.94 (d, J = 2.5 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.3 (p, $^2J_{C-F}$ = 18.2 Hz), 143.8, 139.1 (p, $^3J_{C-F}$ = 2.5 Hz), 129.4, 125.7 (p, $^3J_{C-F}$ = 5.1 Hz), 123.9, 86.8, 84.1 (p, $^4J_{C-F}$ = 2.2 Hz), 52.8, 49.2. ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.9 (m, 1F, SF_5), 66.1 (d, $^2J_{F-F}$ = 151.0 Hz, 4F, SF_5). GC-MS (m/z): 348 [M − Br] $^+$; RT 10.70 min.

*2-Bromo-5-(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**8a**) and 2-Bromo-8-(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**8b**).* To a solution of crude **7** (4.3 g; 10 mmol) in anhydrous THF (50 mL) was added *t*BuOK (1.15 g; 10 mmol), and the reaction mixture was stirred for 72 h. Solvent was evaporated, and the residue was partitioned between Et_2O (75 mL) and water (75 mL). After separation of the Et_2O layer, the water phase was extracted with more Et_2O (2 × 50 mL), and the combined organic phase was washed with water, dried with $MgSO_4$, and evaporated. The obtained residue was purified by column chromatography (PE/EA (9:1)) to give **8a** as a light brown oil (R_f = 0.5) and **8b** as a light brown solid (R_f = 0.2) in 75% total yield. *(Alternatively when a pure sample of each of the stereoisomers **7a−c** was subjected to the above-mentioned dehydrobromination conditions, stereoisomer **7a** formed product **8a** exclusively, stereoisomer **7c** gave product **8b** only, and stereoisomer **7b** afforded products **8a** and **8b** in a 40/60 ratio (**8a**/**8b**) as was determined by ^{19}F NMR of their* reaction *mixtures).* **8a**: Yield: 1.35 g (39%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.48 (d, J = 7.1 Hz, 1H), 7.38 (d, J = 8.4 Hz, 1H), 7.14 (m, 1H), 6.95 (d, J = 2.0 Hz, 1H), 6.11 (m, 1H), 5.54 (d, J = 1.0 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.8, 147.2 (p, $^2J_{C-F}$ = 18.6 Hz), 145.2 (p, $^3J_{C-F}$ = 3.1 Hz), 138.7, 137.9, 126.7, 123.4, 123.2 (p, $^3J_{C-F}$ = 4.8 Hz), 87.2, 85.9 (p, $^4J_{C-F}$ = 3.3 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 83.4 (m, 1F, SF_5), 64.2 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). GC-MS (m/z): 347 [M$^+$]; RT 8.87 min. **8b**: mp 67−69 °C. Yield: 1.25 g (36%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.37 (d, J = 6.8 Hz, 1H), 7.36 (d, J = 8.6 Hz, 1H), 7.17 (m, 1H), 7.06 (d, J = 2.1 Hz, 1H), 5.90 (m, 1H), 5.79 (dd, J = 2.1 Hz, J = 1.1 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 150.1, 147.6 (p, $^2J_{C-F}$ = 18.6 Hz), 144.9 (p, $^3J_{C-F}$ = 3.1 Hz), 141.1, 136.0, 127.3, 122.8, 122.7 (p, $^3J_{C-F}$ = 4.8 Hz), 87.9 (p, $^4J_{C-F}$ = 2.5 Hz), 84.4 (C-4). ^{19}F NMR (282 MHz, $CDCl_3$): δ 83.0 (m, 1F, SF_5), 65.2 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). GC-MS (m/z): 347 [M$^+$]; RT 10.94 min.

*2-Bromo-5-(pentafluorosulfanyl)naphthalene (**9a**).* Prepared analogously to **3** from **8a** (1.19 g; 3.4 mmol). R_f = 0.55 (PE); mp 76−78 °C (colorless solid). Yield: 0.67 g (59%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.32 (dp, J = 9.5 Hz, J = 2.9 Hz, 1H), 8.09 (d, J = 7.9 Hz, 1H), 8.07 (d, J = 2.2 Hz, 1H), 7.92 (d, J = 8.2 Hz, 1H), 7.72 (dd, J = 9.5 Hz, J = 2.2 Hz, 1H), 7.54 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.9 (p, $^2J_{C-F}$ = 15.4 Hz), 135.9, 132.6, 131.7, 130.9, 127.9 (p, $^3J_{C-F}$ = 5.7 Hz), 127.2 (p, $^4J_{C-F}$ = 5.2 Hz), 126.2, 125.0, 120.8. ^{19}F NMR (282 MHz, $CDCl_3$): δ 86.3 (m, 1F, SF_5), 69.3 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (m/z): 334 [M$^+$]; RT 9.58 min.

*2-Bromo-8-(pentafluorosulfanyl)naphthalene (**9b**).* Prepared analogously to **3** from **8b** (1.05 g; 3 mmol). R_f = 0.5 (PE); mp 74−76 °C. Yield: 0.55 g (55%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.63 (m, 1H), 8.10 (dd, J = 7.9 Hz, J = 1.0 Hz, 1H), 7.99 (d, J = 8.1 Hz, 1H), 7.78 (d, J = 8.8 Hz, 1H), 7.66 (dd, J = 8.8 Hz, J = 1.7 Hz, 1H), 7.54 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 150.8 (p, $^2J_{C-F}$ = 14.5 Hz), 133.5, 133.2, 130.5, 130.0, 128.6 (p, $^3J_{C-F}$ = 5.6 Hz), 128.5, 127.7 (p, $^4J_{C-F}$ = 5.3 Hz), 124.3, 123.3. ^{19}F NMR (282 MHz, $CDCl_3$): δ 86.2 (m, 1F, SF_5), 69.2 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). GC-MS (m/z): 334 [M$^+$]; RT 9.59 min.

*2-Amino-5-(pentafluorosulfanyl)naphthalene (**10a**).* Prepared analogously to **10b** from **9a** (0.24 g; 0.72 mmol). R_f = 0.3 (PE/CH_2Cl_2 1:1); light brown oil. Yield: 0.16 g (82%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.26 (dp, J = 9.4 Hz, J = 3.0 Hz, 1H), 7.79 (d, J = 7.8 Hz, 1H), 7.73 (d, J = 8.2 Hz, 1H), 7.36 (m, 1H), 7.09 (dd, J = 9.5 Hz, J = 2.5 Hz, 1H), 7.00 (d, J = 2.5 Hz, 1H), 3.96 (br s, 2H, NH_2). ^{13}C NMR (125 MHz, $CDCl_3$): δ 152.0 (p, $^2J_{C-F}$ = 13.7 Hz), 144.4, 136.8, 131.3, 126.7 (p, $^3J_{C-F}$ = 5.1 Hz), 124.2, 124.0 (p, $^4J_{C-F}$ = 5.8 Hz), 121.5, 120.4, 109.0. ^{19}F NMR (282 MHz, $CDCl_3$): δ 87.6 (m, 1F, SF_5), 69.3 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). HRMS (ESI+): calcd for $[C_{10}H_9F_5NS]^+$: 270.0370, found: 270.0369.

*2-Amino-8-(pentafluorosulfanyl)naphthalene (**10b**).* In a 5 mL glass pressure tube to a solution of **9b** (0.33 g; 1 mmol) in DMSO (2.5 mL) were added *trans*-4-hydroxy-L-proline (55 mg; 0.4 mmol), CuI (40 mg; 0.2 mmol), K_2CO_3 (0.42 g; 3 mmol), and 28% aq. NH_4OH (1.5 mL). The tube was sealed with a closure and vigorously stirred at 75 °C for 48 h. The cold reaction mixture was then partitioned between water (25 mL) and EtOAc (25 mL). After separation of the EtOAc layer, the water phase was extracted with more EtOAc (25 mL), and the organic phase was combined, washed with brine, dried with $MgSO_4$, and evaporated. The obtained residue was purified by SiO_2 chromatography (R_f = 0.3; PE/CH_2Cl_2 1:1) to give **10b**: mp 80−81 °C (beige solid). Yield: 0.22 g (81%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.97 (dd, J = 8.0 Hz, J = 1.1 Hz, 1H), 7.83 (d, J = 8.0 Hz, 1H), 7.69 (d, J = 8.8 Hz, 1H), 7.52 (m, 1H), 7.21 (m, 1H), 6.99 (dd, J = 8.8 Hz, J = 2.2 Hz, 1H), 4.08 (br s, 2H, NH_2). ^{13}C NMR (125 MHz, $CDCl_3$): δ 150.0 (p, $^2J_{C-F}$ = 14.0 Hz), 146.4, 133.3, 130.6, 129.6, 129.4, 128.3 (p, $^3J_{C-F}$ = 5.8 Hz), 119.9, 118.5, 105.7 (p, $^4J_{C-F}$ = 4.9 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 88.3 (m, 1F, SF_5), 68.5 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5). HRMS (ESI+): calcd for $[C_{10}H_9F_5NS]^+$: 270.0370, found: 270.0381.

*endo-2-Chloro-exo-3,8-bis(pentafluorosulfanyl)-1,2,3,4-tetrahydro-1,4-epoxynaphthalene (**11a**) and endo-2-Chloro-exo-3,5-bis(pentafluorosulfanyl)-1,2,3,4-tetrahydro-1,4-epoxynaphthalene (**11b**).* In 100 mL glass pressure tube containing a solution of **2** (2.03 g; 7.5 mmol) in anhydrous CH_2Cl_2 (20 mL) at −50 °C, SF_5Cl (2.45 g; 15 mmol) was condensed under the solvent surface. Then 1.5 mL of 1 M hexane solution of Et_3B (0.15 g; 1.5 mmol) was added. The tube was sealed with a PTFE closure, and the reaction mixture was stirred at −30 °C (cryostat) for 18 h and then at 25 °C for 6 h. It was diluted with CH_2Cl_2 (30 mL), washed with brine, and dried with $MgSO_4$ and evaporated. The obtained residue was purified by column chromatography (PE/EA (9:1)) to give 2.36 g (73%) of **11a** and **11b** (ratio **11a**/**11b** (60:40)) as a white solid (R_f = 0.25; PE/EA (95:5)). **11a**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.71 (d, J = 6.6 Hz, 1H), 7.58 (d, J = 7.0 Hz, 1H), 7.47 (m, 1H), 5.94 (s, 1H), 5.90 (m, 1H), 5.07 (tm, J = 4.2 Hz, 1H), 3.96 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.6 (p, $^2J_{C-F}$ = 19.2 Hz), 143.9, 138.6 (p, $^3J_{C-F}$ = 2.5 Hz), 129.8, 126.2 (p, $^3J_{C-F}$ = 5.1 Hz), 123.6, 93.0 (p, $^2J_{C-F}$ = 11.7 Hz), 83.4 (m), 83.1 (p, $^4J_{C-F}$ = 4.8 Hz), 55.1 (p, $^3J_{C-F}$ = 4.2 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.4 (m, 1F, SF_5), 82.3 (m, 1F, SF_5), 65.8 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5), 61.6 (dd, $^2J_{F-F}$ = 146.0 Hz, $^3J_{F-H}$ = 6.0 Hz, 4F, SF_5). GC-MS (m/z): 304 [M − SF_5] $^+$; RT 9.33 min. **11b**: ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.69 (d, J = 8.2 Hz, 1H), 7.60 (d, J = 7.2 Hz, 1H), 7.46 (m, 1H), 6.27 (s, 1H), 5.53 (d, J = 4.9 Hz, 1H), 5.04 (tm, J = 4.5 Hz, 1H), 3.84 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 146.7 (p, $^2J_{C-F}$ = 19.6 Hz), 143.6, 138.2 (m), 129.3, 126.8, 126.1 (p, $^3J_{C-F}$ = 4.8 Hz), 92.2 (p, $^2J_{C-F}$ = 12.0 Hz), 84.7 (m), 82.5, 55.4 (p, $^3J_{C-F}$ = 4.1 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.2 (m, 1F, SF_5), 82.0 (m, 1F, SF_5), 64.2 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5), 62.3 (dd, $^2J_{F-F}$ = 146.0 Hz, $^3J_{F-H}$ = 4.8 Hz, 4F, SF_5). GC-MS (m/z): 304 [M − SF_5] $^+$; RT 9.21 min.

*2,5-Bis(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**12a**) and 2,8-bis(pentafluorosulfanyl)-1,4-dihydro-1,4-epoxynaphthalene (**12b**).* A mixture of regioisomers **11a** and **11b** (*ca.* 60:40) (1.75 g; 4 mmol) was dissolved in anhydrous DMSO (25 mL), and LiOH (0.49 g; 20 mmol) was added. The reaction mixture was stirred for 24 h, then diluted with water (200 mL) and saturated aq. $NaHCO_3$ solution, and extracted with EA (4 × 50 mL). The combined organic phase was washed with brine (2 × 50 mL), dried with $MgSO_4$, and evaporated. The obtained residue was purified by column chromatography (PE/EA (9:1)) to give **12a** as an oil (R_f = 0.55) and **12b** as a white solid (R_f = 0.1) in 59% total yield. **12a**: yield: 0.61 g (38%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.51 (d, J = 7.1 Hz, 1H), 7.43 (d, J = 8.4 Hz, 1H), 7.34 (m, 1H), 7.22 (m, 1H), 6.24 (m, 1H), 5.96 (d, J = 1.0 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 170.4 (dp, $^2J_{C-F}$ = 20.8 Hz, $^6J_{C-F}$ = 1.5 Hz), 149.4, 148.1 (p, $^2J_{C-F}$ = 18.9 Hz), 143.8, 142.8 (p, $^3J_{C-F}$ = 6.1 Hz), 127.7, 124.1, 123.6 (p, $^3J_{C-F}$ = 4.8 Hz), 84.6 (p, $^4J_{C-F}$ = 3.3 Hz), 83.7 (p, $^3J_{C-F}$ = 3.8 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.9 (m, 1F, SF_5), 80.2 (m, 1F, SF_5), 65.5 (d, $^2J_{F-F}$ = 153.0 Hz, 4F,

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SF_5), 64.1 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). HRMS (nESI/DART): calcd for $[C_{10}H_5F_{10}OS_2]^-$: 394.9628, found: 394.9634 [M − H]$^-$. **12b**: mp 79−80 °C. Yield: 0.33 g (21%). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.53 (m, 1H), 7.47 (2 × d, *overlapped*, 2H), 7.24 (m, 1H), 6.30 (m, 1H), 5.88 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 169.3 (dp, $^2J_{C-F}$ = 21.3 Hz, $^5J_{C-F}$ = 1.7 Hz), 148.8, 148.1 (p, $^2J_{C-F}$ = 19.4 Hz), 145.3 (p, $^3J_{C-F}$ = 6.8 Hz), 143.6 (p, $^3J_{C-F}$ = 2.9 Hz), 127.8, 124.04, 123.99 (p, $^3J_{C-F}$ = 5.1 Hz), 84.8 (p, $^4J_{C-F}$ = 3.3 Hz), 83.0. ^{19}F NMR (282 MHz, $CDCl_3$): δ 82.0 (m, 1F, SF_5), 79.9 (m, 1F, SF_5), 66.1 (dm, $^2J_{F-F}$ = 152.0 Hz, 4F, SF_5), 64.6 (dp, $^2J_{F-F}$ = 149.0 Hz, $^{TS}J_{F-F}$ = 6.7 Hz, 4F, SF_5). HRMS (ESI-): calcd for $[C_{10}H_6ClF_{10}OS_2]^-$: 430.9394, found: 430.9398 [M + Cl]$^-$.

*1,6-Bis-pentafluorosulfanylnaphthalene (**13a**).* Prepared analogously to **3** from **12a** (0.61 g; 1.54 mmol). R_f = 0.4 (PE), mp 108−109 °C (colorless solid). Yield: 0.41 g (70%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.55 (dm, J = 9.6 Hz, 1H), 8.35 (d, J = 2.4 Hz, 1H), 8.24 (dd, J = 7.9 Hz, J = 1.1 Hz, 1H), 8.15 (d, J = 8.2 Hz, 1H), 7.97 (dd, J = 9.8 Hz, J = 2.5 Hz, 1H), 7.68 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.6 (p, $^2J_{C-F}$ = 15.3 Hz), 151.3 (p, $^2J_{C-F}$ = 18.4 Hz), 134.8, 133.7, 130.2 (p, $^3J_{C-F}$ = 5.6 Hz), 128.5, 127.3 (p, $^3J_{C-F}$ = 4.9 Hz), 126.7 (p, $^3J_{C-F}$ = 5.1 Hz), 125.8, 124.7 (p, $^3J_{C-F}$ = 4.2 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 85.5 (m, 1F, SF_5), 82.7 (m, 1F, SF_5), 69.2 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5), 62.6 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). HRMS (ESI-): calcd for $[C_{10}H_6ClF_{10}S_2]^-$: 414.9440, found: 414.9456 [M + Cl]$^-$.

*1,7-Bis-pentafluorosulfanylnaphthalene (**13b**).* Prepared analogously to **3** from **12b** (0.33 g; 0.85 mmol). R_f = 0.4 (PE), mp 105−106 °C (colorless solid). Yield: 0.29 g (92%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.95 (m, 1H), 8.20 (dd, J = 7.9 Hz, J = 1.0 Hz, 1H), 8.08 (d, J = 8.2 Hz, 1H), 7.99 (d, J = 9.0 Hz, 1H), 7.90 (dd, J = 9.0 Hz, J = 2.0 Hz, 1H), 7.68 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 153.3 (p, $^2J_{C-F}$ = 17.7 Hz), 152.6 (p, $^2J_{C-F}$ = 15.4 Hz), 135.1, 133.2, 129.8, 129.3 (p, $^3J_{C-F}$ = 5.6 Hz), 126.7, 126.5, 124.4 (m), 123.2 (p, $^3J_{C-F}$ = 4.2 Hz). ^{19}F NMR (282 MHz, $CDCl_3$): δ 85.4 (m, 1F, SF_5), 82.8 (m, 1F, SF_5), 69.5 (d, $^2J_{F-F}$ = 149.0 Hz, 4F, SF_5), 62.3 (d, $^2J_{F-F}$ = 150.0 Hz, 4F, SF_5). HRMS (ESI-): calcd for $[C_{10}H_6ClF_{10}S_2]^-$: 414.9440, found: 414.9461 [M + Cl]$^-$.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02276.

Copies of ^{1}H, ^{13}C, and ^{19}F NMR spectra for compounds **1**−**13** (PDF)

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Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) (a) Ojima, I. *Fluorine in medicinal chemistry and chemical biology*; Wiley-Blackwell: Chichester, U.K., 2009. (b) Gouverneur, V.; Muller, K., Eds. Fluorine in Pharmaceutical and Medicinal Chemistry: From Biophysical Aspects to Clinical Applications. *Molecular Medicine and Medicinal Chemistry, Vol. 6*; Imperial College Press: London, U.K., 2012. (c) Kirsch, P. Modern Fluoroorganic Chemistry. *Synthesis, Reactivity, Applications*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2013.

(2) General reviews on SF_5-substituent chemistry: (a) Savoie, P. R.; Welch, J. T. *Chem. Rev.* **2015**, *115*, 1130. (2015). (b) von Hahmann, C. N.; Savoie, P. R.; Welch, J. T. *Curr. Org. Chem.* **2015**, *19*, 1592. (c) Altomonte, S.; Zanda, M. J. *J. Fluorine Chem.* **2012**, *143*, 57.

(3) Reviews covering application of the SF_5-substituent in medicinal chemistry: (a) Barnes-Seeman, D.; Beck, J.; Springer, C. *Curr. Top. Med. Chem.* **2014**, *14*, 855. (b) Bassetto, M.; Ferla, S.; Pertusati, F. *Future Med. Chem.* **2015**, *7*, 527. (c) Gillis, E. P.; Eastman, K. J.; Hill, M. D.; Donnelly, D. J.; Meanwell, N. A. J. *J. Med. Chem.* **2015**, *58*, 8315. (d) Welch, J. T. *Application of SF_5 Substitution in Life Sciences Research* (Chapter 6 in ref 1b).

(4) (a) Joliton, A.; Plancher, J.-M.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2016**, *55*, 2113−2117. (b) Westphal, M. V.; Wolfstädter, B. T.; Plancher, J.-M.; Gatfield, J.; Carreira, E. M. *ChemMedChem* **2015**, *10*, 461−469. (c) Altomonte, S.; Baillie, G. L.; Ross, R. A.; Riley, J.; Zanda, M. *RSC Adv.* **2014**, *4*, 20164−20176.

(5) (a) Umemoto, T.; Garrick, L. M.; Saito, N. *Beilstein J. Org. Chem.* **2012**, *8*, 461−471. (b) Umemoto, T. Patent WO2008/118787. (c) Umemoto, T. Patent US 2009/7592491. (d) Umemoto, T. Patent US2010/7820864. (e) Umemoto, T. Patent US2010/7851646. (f) Umemoto, T. Patent US2010/0130790. (g) Umemoto, T. Patent WO2010/033930.

(6) (a) Lal, G. S.; Minnich, K. E. Patent US 2006/0069285 A1. (b) Dolbier, W. R., Jr.; Mitani, A.; Warren, R. D. *Tetrahedron Lett.* **2007**, *48*, 1325−1326. (c) Ponomarenko, M. V.; Lummer, K.; Fokin, A. A.; Serguchev, Y. A.; Bassil, B. S.; Röschenthaler, G.-V. *Org. Biomol. Chem.* **2013**, *11*, 8103−8112.

(7) Aït-Mohand, S.; Dolbier, W. R., Jr. *Org. Lett.* **2002**, *4*, 3013−3015.

(8) Bailly, F.; Cottet, F.; Schlosser, M. *Synthesis* **2005**, *2005*, 791−797.

(9) During the preparation of our manuscript, the work describing access to various substituted benzynes starting from aryl(mesityl)-iodonium tosylates has been published, which also included examples of SF_5-benzynes and their adducts with furan, i.e. compound **2** and its regioisomer. However, no further conversion into naphthalenes was reported: Sundalam, S. K.; Nilova, A.; Seidl, T. L.; Stuart, D. R. *Angew. Chem., Int. Ed.* **2016**, *55*, 8431−8434.

(10) Dolbier, W. R., Jr.; Sergeeva, T. A. *Org. Lett.* **2004**, *6*, 2417−2419.

(11) Altundas, A.; Dastan, A.; McKee, M. M.; Balci, M. *Tetrahedron* **2000**, *56*, 6115−6120.

(12) Jiang, L.; Lu, X.; Zhang, H.; Jiang, Y.; Ma, D. *J. Org. Chem.* **2009**, *74*, 4542−4546.

(13) Dolbier, W. R., Jr.; Aït-Mohand, S.; Schertz, T. D.; Sergeeva, T. A.; Cradlebaugh, J. A.; Mitani, A.; Gard, G. L.; Winter, R. W.; Thrasher, J. S. *J. Fluorine Chem.* **2006**, *127*, 1302−1310.

(14) For example, see: Miethchen, R.; Peters, D. *General Instructions for the Handling of Hydrogen Fluoride in Houben-Weyl Methods of Organic Chemistry*, Vol. E 10a; Organo-Fluorine Compounds; Georg Thieme Verlag: Stuttgart, Germany, 2000; pp 95−100.

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