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Synthesis and Dienophilic Reactivity of 1,2-Difluorovinylphenylsulfone

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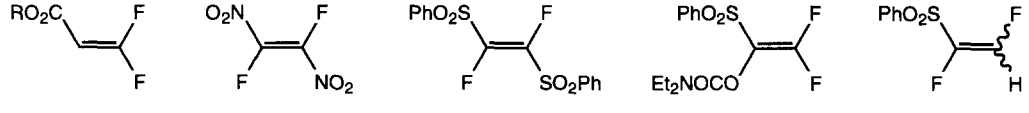
Abstract: 1,2-Difluorovinylphenylsulfone **5** was conveniently prepared in three steps from chlorotrifluoroethylene. Both *E* and *Z* isomers of **5** gave excellent yields of [4+2] cycloadducts with cyclopentadiene. The *E* isomer reacted with high kinetic *exo* selectivity. 1,2-Difluorovinylphenylsulfone **5** did not give cycloadducts with highly polar and reactive dienes. Only complex mixtures were obtained. This was assigned to competitive pathways resulting from addition-elimination sequences. Products resulting from such an addition-elimination sequence were obtained from representative nucleophilic reagents. © 1997 Elsevier Science Ltd.

INTRODUCTION

The current level of interest in the preparation of selectively fluorinated molecules results from the profound and often unexpected effects of fluorine substitution on the chemical and biological properties of a molecule.[1,2] Despite considerable progresses in the synthesis of fluorinated building blocks, examples of useful [4+2] cycloaddition reactions to polyfluorinated olefins are scarce. Methyl and ethyl 3,3-difluoroacrylates **1** were shown to react with furan[3] while the strongly activated *trans*-1,2-difluorodinitroethylene **2** reacted with cyclopentadiene and anthracene under mild conditions to give Diels-Alder adducts in moderate yields[4] (Figure 1). The corresponding disulfone **3** was reacted successfully (94% yield) with butadiene at 115°C.[5] However, 2,2-difluorovinylphenylsulfone **4** gave a monofluoro-cycloadduct (67% yield) in the presence of cyclopentadiene. This was explained by an hydride reduction of **4** prior to cycloaddition.[6]



1 (R=Me, Et) **2** **3** **4** **5**

Figure 1

The preparation of a dienophilic equivalent of difluoroacetylene, a highly endothermic and hazardous compound,[7-9] would offer a potential access to six-membered rings bearing vicinal fluorine atoms for which there is no general route.

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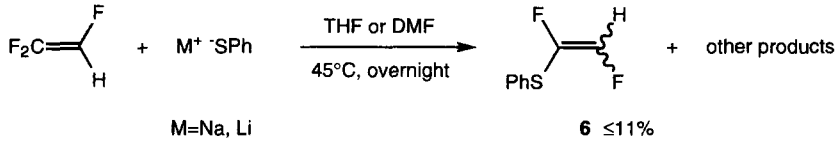
This paper describes the synthesis of the hitherto unknown 1,2-difluorovinylphenylsulfone **5** and a study of its dienophilic properties.

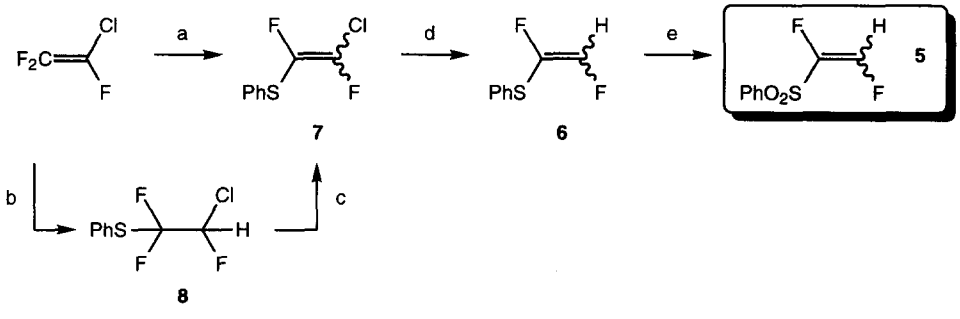
SYNTHESIS OF 1,2-DIFLUOROVINYLPHENYLSULFONE

Our first attempts to prepare phenylvinylsulfide **6** by direct substitution on trifluoroethylene using sodium or lithium thiophenoxide in aprotic solvents (THF or DMF) were unsuccessful. These reactions led to complex mixtures of products containing no more than 11% of **6** (Scheme 1).



Scheme 1

However, compound **6** was conveniently prepared in three steps from commercially available chlorotrifluoroethylene by the sequences outlined in Scheme 2. 2-Chloro-1,2-difluoro-1-(phenylthio)ethylene **7** was prepared according to the procedure of Sauvêtre and Normant.[10] When the reaction was run in a protic solvent, the addition product **8**[11] was isolated. Elimination of hydrogen fluoride under solid-liquid phase transfer catalytic conditions yielded **7**. In both cases, olefin **7** was obtained as a mixture of stereoisomers.



Reagents and conditions: a. PhSNa, THF, -30°C then RT, 1h. (60%, *E:Z*~1:1) ; b. PhSNa, EtOH, RT, 15h. (76%) ; c. KOH, Aliquat 336®, 90-100°C, 8h. (75%, *E:Z* 1.2:1) ; d. *t*-BuLi, THF, -105°C, 1h. then MeOH (81%, *E:Z* 1:1.2) ; e. *m*-CPBA, CH_2Cl_2, Δ, 29h. (92%, *E:Z* 1:1.2)

Scheme 2

1,2-Difluoro-1-(phenylthio)ethylene **6** was prepared *via* metal-halogen exchange by reaction of **7** with *tert*-butyllithium at -105°C in tetrahydrofuran followed by addition of methanol. The use of *n*-butyllithium led to the formation of unknown side products probably arising from competitive substitution reactions. Oxidation of **6** with 2.2 equivalents of *m*-CPBA in refluxing dichloromethane yielded the corresponding sulfone **5**. Isomers *E* and *Z* of **5** could easily be separated by chromatography on silica gel.

The assignment of the stereochemistry of olefins **5** and **6** was based upon the values of vicinal coupling constants $J_{F\text{-}F}$ and $J_{H\text{-}F}$ as illustrated in Figure 2.[12,13]

6 *(E)* $J_{F\text{-}F}$=13 Hz ; $^3J_{H\text{-}F}$=13 Hz

6 *(Z)* $J_{F\text{-}F}$=145 Hz ; $^3J_{H\text{-}F}$=0 Hz

5 *(E)* $J_{F\text{-}F}$=4 Hz ; $^3J_{H\text{-}F}$=14 Hz

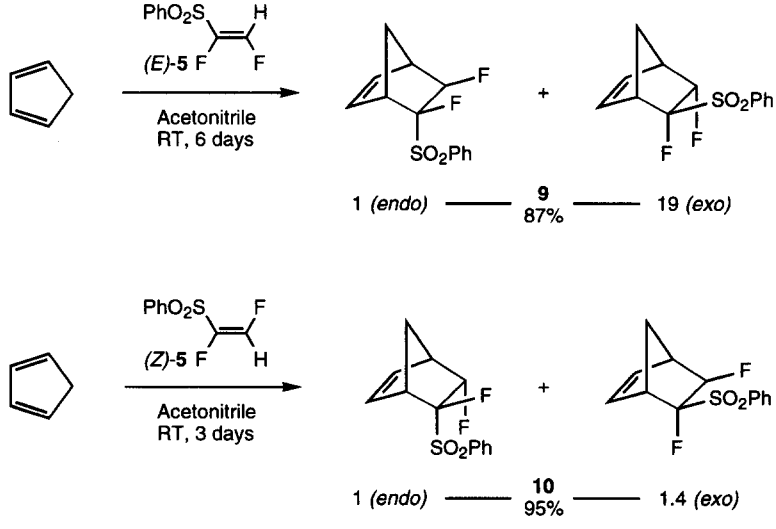
5 *(Z)* $J_{F\text{-}F}$=139 Hz ; $^3J_{H\text{-}F}$=4 Hz

Figure 2

[4+2] CYCLOADDITIONS OF 1,2-DIFLUOROVINYLPHENYLSULFONE

Cycloadditions with cyclopentadiene

Both *E* and *Z* isomers of 1,2-difluorovinylphenylsulfone **5** reacted with an excess of cyclopentadiene to give cycloadducts **9** and **10** in high yields (Scheme 3).



Scheme 3

Cycloaddition of *(E)*-**5** showed high *exo* diastereoselectivity in contrast with that of isomer *(Z)*-**5**. We ensured that the stereochemical outcome of these reactions was not the result of a reversible reaction by following the *endo:exo* ratio throughout the reactions. Comparatively phenylvinylsulfone[14] and 1-fluorovinylphenylsulfone[15] reacted with cyclopentadiene to give respectively 2.4:1 and 1:1 mixtures of *endo:exo* adducts.

The stereochemical assignments were based upon the values of vicinal and long-range coupling constants J_{F-F} and J_{H-F} (Figure 3).[16-18]

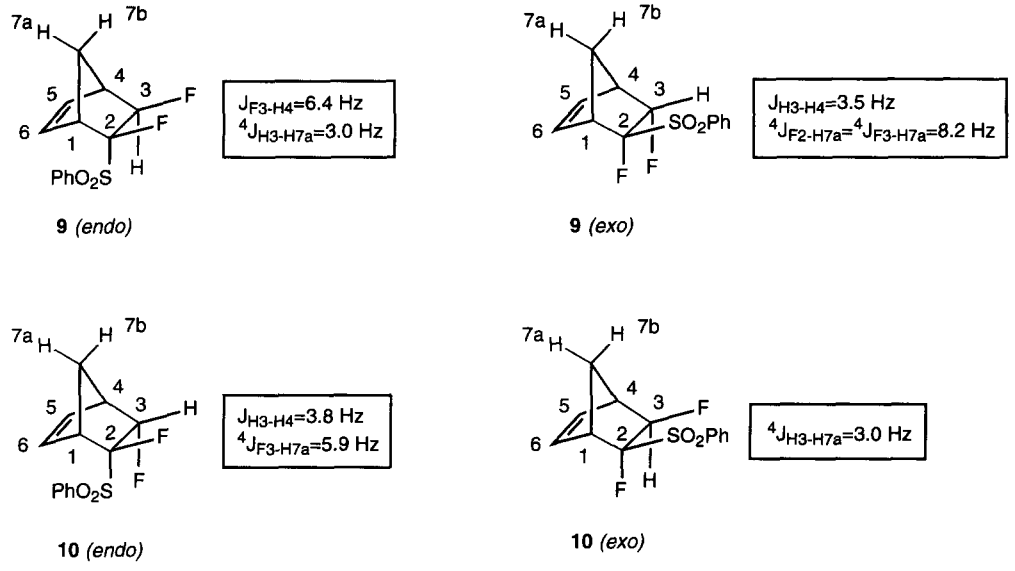


Figure 3

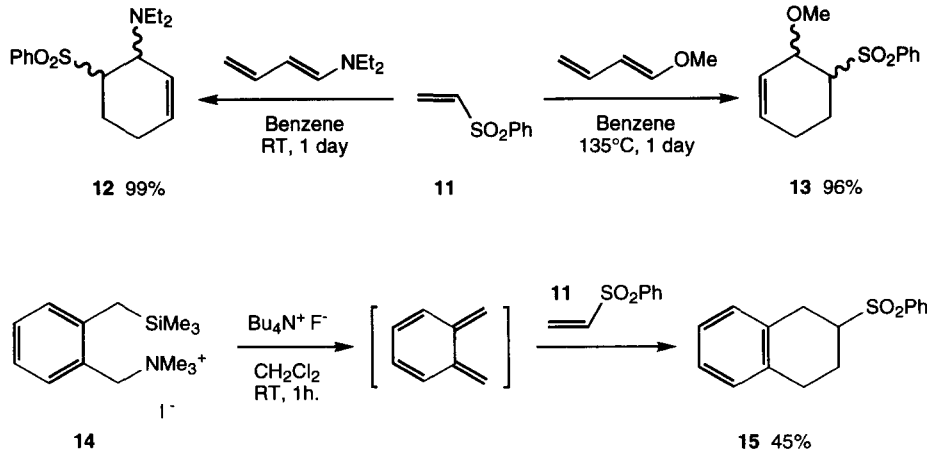
The ^1H NMR spectra of *exo*-SO_2Ph **9** and *endo*-SO_2Ph **10** showed $^3J_{H3-H4}\approx3.5$ Hz consistent with the *exo* stereochemistry of H^3. For adducts *endo*-SO_2Ph **9** and *exo*-SO_2Ph **10**, this coupling constant was not observed.

$^3J_{F3-H4}=6.4$ Hz detected in both ^1H and ^{19}F NMR spectra of bicyclic *endo*-SO_2Ph **9** reflected an equatorial-equatorial relationship between those two atoms.

Finally, long-range coupling constants ($^4J_{F2-H7a}=^4J_{F3-H7a}=8.2$ Hz and $^4J_{H3-H7a}=3.0$ Hz) confirmed respectively the *exo* and the *endo* stereochemistry of both diastereoisomers of **9**. The stereochemistry of *exo* and *endo*-SO_2Ph **10** was proven by ^4J coupling constants between H^3 and H^{7a} (3.0 Hz) and F^3 and H^{7a} (5.9 Hz) respectively.

Cycloadditions with functionalised dienes

Phenylvinylsulfone **11** had been shown to react with activated dienes such as Danishefsky's diene[19] or alkoxy-2-azadienes.[20] In this study, we also found that **11** reacted smoothly with 1-diethylamino-,[21] 1-methoxybutadienes and *o*-xylylene[22,23] (Scheme 4).



Scheme 4

Surprisingly, both isomers of 1,2-difluorovinylphenylsulfone **5** did not give cycloadducts with dienes shown in Figure 4 but rather led to complex mixtures of products.

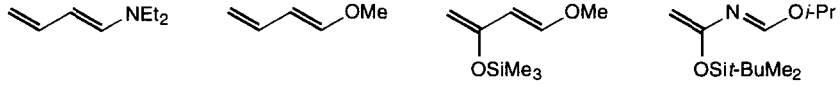
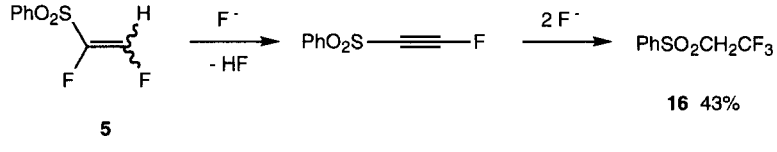


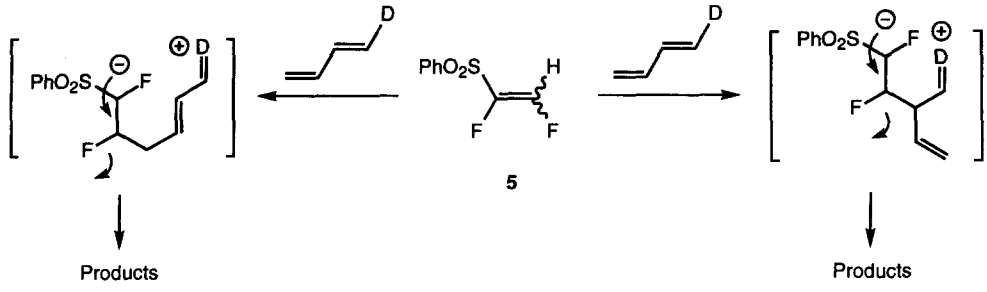
Figure 4

The reaction of **5** with *o*-xylylene also yielded no cycloadduct but gave a 43% yield of 2,2,2-trifluoroethylphenylsulfone **16**.[24] The formation of **16** probably resulted from the presence of fluoride ions used for the *in situ* generation of the diene: dehydrofluorination of **5** followed by double addition of HF to the resulting acetylene would generate **16** (Scheme 5).



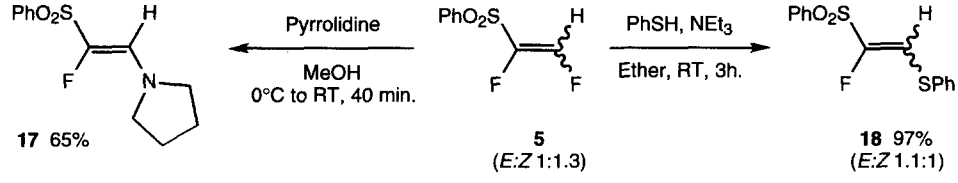
Scheme 5

It appears thus that the highly electrophilic double bond of **5** is not a suitable partner for the Diels-Alder reaction with nucleophilic dienes. Reaction of these polar dienes with **5** could lead to the formation of 1,4 or 1,6 dipoles which could then lose a fluoride ion as illustrated in Scheme 6.



Scheme 6

On the other hand, we found that protic nucleophiles reacted smoothly with **5** to yield the corresponding substitution products (Scheme 7).



Scheme 7

Compound **17** was obtained as a single isomer. The assignment of its configuration was supported by the value (28 Hz) of the vicinal coupling between fluorine and vinylic hydrogen. Examination of the ^{13}C NMR spectrum of **17** showed no evidence for a coupling between carbon 2 and fluorine suggesting a *cis* relationship between fluorine and the pyrrolidino group (Figure 5).[25]

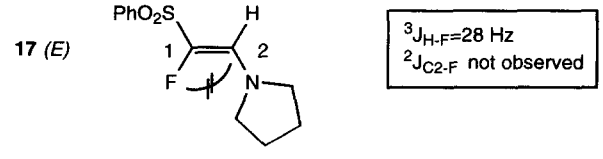


Figure 5

The assignment of the stereochemistry of **18** was based upon the values of $^3J_{H\text{-}F}$ as shown in Figure 6.

Figure 6

CONCLUSION

We have thus developed a practical synthesis of both isomers of 1,2-difluorovinylphenylsulfone **5**. However the goal of the study has not been fulfilled. Compounds *(E)*-**5** and *(Z)*-**5** only yielded cycloadducts with cyclopentadiene. With more polar dienes which probably reacted with **5** to give dipolar intermediates, no cycloadducts were obtained. We can therefore conclude that compound **5** is **not** a suitable dienophilic equivalent of difluoroacetylene.

EXPERIMENTAL SECTION

Melting points were measured on a LEITZ-WETZLAR HM-LUX apparatus and are uncorrected. IR spectra were recorded on a Perkin-Elmer 681 spectrophotometer. ^{1}H, ^{19}F and ^{13}C NMR spectra were recorded on a GEMINI 200 or a GEMINI 300 spectrometer. All NMR spectra were recorded in $CDCl_3$. All chemical shifts are reported in parts per million downfield (positive) of the standard on the δ scale and coupling constants J are given in Hz. ^{19}F NMR spectra are referenced against internal $CFCl_3$, ^{1}H and ^{13}C against internal tetramethylsilane. Mass spectra (MS) were measured on a FINNIGAN-MAT TSQ-70 spectrometer at 70 eV in the electronic impact mode (EI). GC/MS were obtained at 70 eV in the EI mode. Microanalyses were performed by the laboratory of Dr Stones, University College of London (England). High resolution mass spectra were performed by the laboratory of Prof. Flammang, Université de Mons-Hainaut (Belgium). All dry solvents were distilled under argon. Benzene, ether and tetrahydrofuran were distilled from sodium-benzophenone ketyl. Acetonitrile, dichloromethane, pyrrolidine and triethylamine were distilled on calcium hydride. All reactions requiring anhydrous or inert conditions were run under a positive pressure of argon. Chlorotrifluoroethylene (bp -36.5°C) was purchased from Air Products (Belgium).

SYNTHESIS OF 1,2-DIFLUOROVINYLPHENYLSULFONE 5

Preparation of 2-Chloro-1,2-difluoro-1-(phenylthio)ethylene 7

Method A: Substitution of chlorotrifluoroethylene with sodium thiophenoxide

2-Chloro-1,2-difluoro-1-(phenylthio)ethylene **7** was prepared as described in the literature by Sauvêtre and Normant[10] from 0.80 ml (10.00 mmol) of chlorotrifluoroethylene and 1.32 g (10.00 mmol) of sodium thiophenoxide ; yield: 1.24 g (60%, *E:Z* 1:1.1) ; colorless liquid ; bp 58°C/1 mm Hg. ^{1}H NMR (for *E:Z* 1:1.1): 7.20-7.50 (m, 5H). ^{19}F NMR (for *E:Z* 1:1.1): -123.67 *(E)* (d, $^{3}J_{FF}$=140.20, 0.48F), -112.73 *(Z)* (d, $^{3}J_{FF}$= 17.30, 0.52F), -104.17 *(E)* (d, $^{3}J_{FF}$=140.20, 0.48F), -86.94 *(Z)* (d, $^{3}J_{FF}$=17.30, 0.52F). ^{13}C NMR (for *E:Z* 1:1.1): 128.40, 128.44, 129.58, 130.16, 130.53, 130.83, 130.86, 139.93 (dd, $^{1}J_{CF}$=295.60, $^{2}J_{CF}$=22.90), 141.09 (dd, $^{1}J_{CF}$=289.00, $^{2}J_{CF}$=49.60), 142.52 (dd, $^{1}J_{CF}$=291.80, $^{2}J_{CF}$=61.10), 143.36 (dd, $^{1}J_{CF}$=314.00, $^{2}J_{CF}$=44.90).

Method B: Dehydrofluorination of 2-chloro-1,1,2-trifluoro-1-(phenylthio)ethane 8

Preparation of 2-chloro-1,1,2-trifluoro-1-(phenylthio)ethane **8**[11]

12.62 ml (158.67 mmol) of chlorotrifluoroethylene were rapidly added to a solution of 6.99 g (52.89 mmol) of sodium thiophenoxide in ethanol 97% (28 ml) in a 100 ml autoclave cooled to -78°C *via* dry ice/isopropanol bath. The autoclave was sealed and warmed up to room temperature for 15 hours. The autoclave was then cooled to -78°C and opened. The residue was concentrated under *vacuum*, poured into 90 ml of water and extracted with 2 x 90 ml of dichloromethane. The combined organic layers were dried ($MgSO_4$), filtered and concentrated under *vacuum*. The residue was distilled to give 9.10 g (76%) of 2-chloro-1,1,2-trifluoro-1-(phenylthio)ethane **8** ; colorless liquid ; bp 89-92°C/14 mm Hg. IR (CH_2Cl_2): 1580, 1480, 1470. ^{1}H NMR: 6.09 (ddd, $^{1}J_{HF}$=48.29, $^{3}J_{HF}$=7.74, $^{3}J_{HF}$=4.09, 1H), 7.37-7.67 (m, 5H). ^{19}F NMR: -148.00 (dt, $^{2}J_{FH}$=48.30, $^{3}J_{FF}$=18.77, 1F), -90.17 (ddd, $^{2}J_{FF}$=221.45, $^{3}J_{FF}$=17.70, $^{3}J_{FH}$=7.80, 1F), -85.47 (ddd, $^{2}J_{FF}$=221.40, $^{3}J_{FF}$=19.35, $^{3}J_{FH}$=4.03, 1F). ^{13}C NMR: 96.96 (Ddd, $^{1}J_{CF}$=252.80, $^{2}J_{CF}$=33.77 and 38.02),

123.99 (Td, $^1J_{CF}$=285.50, $^2J_{CF}$=27.3), 124.04 (t, $^3J_{CF}$=2.70), 129.44, 130.73, 136.94. MS: m/z=228 ($(M+2)^{+\cdot}$, 5%), 226 ($M^{+\cdot}$, 13%), 159 (41%), 109 (71%), 77 (100%).

Preparation of 2-Chloro-1,2-difluoro-1-(phenylthio)ethylene **7**

4.56 g (20.12 mmol) of 2-chloro-1,1,2-trifluoro-1-(phenylthio)ethane **8** were added to 1.35 g (24.13 mmol) of potassium hydroxide finely ground and 903 mg (1.99 mmol) of Aliquat 336®. After being vigorously stirred for 5 minutes, the mixture was heated for 8 hours at 90-100°C. After cooling, organic products were removed by filtration on Florisil® after addition of ethyl acetate (25 ml). The crude mixture was purified by column chromatography on silica gel (petroleum ether) to give 3.12 g (75%, *E:Z* 1.2:1) of 2-Chloro-1,2-difluoro-1-(phenylthio)ethylene **7** (R_f=0.25, UV).

Preparation of 1,2-difluoro-1-(phenylthio)ethylene 6

8.05 ml (12.08 mmol) of *t*-BuLi (1.5M/pentane) were added dropwise to a solution of 1.92 g (9.29 mmol) of 2-chloro-1,2-difluoro-1-(phenylthio)ethylene **7** (*E:Z* 1.3:1) in tetrahydrofuran (22 ml) cooled to -105°C *via* liquid N_2/tetrahydrofuran bath. After being vigorously stirred at this temperature for 1 hour, the mixture was cautiously treated with 7.50 ml (185.80 mmol) of methanol and stirred again for 10 minutes. 8 ml of 3M H_2SO_4 were added and the solution was allowed to slowly warm up to room temperature. 20 ml of water were added and organic materials extracted with 2 x 25 ml of dichloromethane. The combined organic layers were dried ($MgSO_4$), filtered and concentrated under *vacuum*. The residue was purified by column chromatography on silica gel (petroleum ether) to give 1.29 g (81%, *E:Z* 1:1.2) of 1,2-difluoro-1-(phenylthio)ethylene **6** (R_f=0.33, UV) ; colorless liquid. IR (CH_2Cl_2): 3050, 2960-2870, 1675, 1580. ^1H NMR (for *E:Z* 1:1.2): 6.78 *(E)* (dd, $^2J_{HF}$=74.53, $^3J_{HF}$=13.80, 0.45H), 7.20-7.65 (m, 5.55H) ; ^{19}F NMR (for *E:Z* 1:1.2): -157.44 *(Z)* (dd, $^3J_{FF}$=145.70, $^2J_{FH}$=77.10, 0.55F), -138.51 *(Z)* (d, $^3J_{FF}$=145.50, 0.55F), -133.70 *(E)* (dd, $^2J_{FH}$=74.70, $^3J_{FF}$=13.80, 0.45F), -114.83 *(E)* (t, $^3J_{FF}$=$^3J_{FH}$=13.05, 0.45F). ^{13}C NMR (for *E:Z* 1:1.2): 127.84, 127.95, 129.10, 129.36, 130.21, 130.96, 131.63, 139.62 (dd, $^1J_{CF}$=279.05, $^2J_{CF}$=20.00), 145.33 (dd, $^1J_{CF}$=252.95, $^2J_{CF}$=71.30), 143.61 (dd, $^1J_{CF}$=300.30, $^2J_{CF}$=14.10), 148.57 (dd, $^1J_{CF}$=284.50, $^2J_{CF}$=39.70). GC/MS (for *E:Z* 1:1.2): (1) m/z=172 ($M^{+\cdot}$, 100%), 152 (23%), 109 (63%), 77 (23%), 51 (20%) ; (2) m/z=172 ($M^{+\cdot}$, 100%), 152 (20%), 109 (55%), 77 (22%), 51 (19%). HRMS (for *E:Z* 1:1.2): calculated for $C_8H_6F_2S$: 172.015829, found: 172.015900.

Preparation of 1,2-difluorovinylphenylsulfone 5

1.78 g (7.20 mmol) of 3-chloroperoxybenzoic acid (70% in benzoic acid) were slowly added to a solution of 564 mg (3.27 mmol) of 1,2-difluoro-1-(phenylthio)ethylene **6** in dichloromethane (87 ml). The mixture was refluxed for 29 hours. After cooling, it was washed with 2 x 80 ml of 5% $NaHCO_3$. The organic layer was dried ($MgSO_4$), filtered and concentrated under *vacuum*. The residue was purified by column chromatography on silica gel (petroleum ether/dichloromethane 1/1) to give 211 mg (31.5%) of *(E)* (R_f=0.39), 136 mg (20%) of a mixture of *(E)* and *(Z)* and 272 mg (41%) of *(Z)*-1,2-difluorovinylphenylsulfone **5** (R_f=0.27) ; colorless liquids:

(E)-1,2-difluorovinylphenylsulfone **5**: IR (CH_2Cl_2): 3120-3060, 1695, 1590, 1460, 1350, 1160. ^1H NMR: 7.51 (dd, $^2J_{HF}$=69.00, $^3J_{HF}$=14.00, 1H), 7.57-7.99 (m, 5H). ^{19}F NMR: -145.63 (dd, $^2J_{FH}$=69.10, $^3J_{FF}$=4.60, 1F), -145.28 (dd, $^3J_{FH}$=13.60, $^3J_{FF}$=4.00, 1F). ^{13}C NMR: 128.57, 129.62, 134.95, 136.86 (d, $^3J_{CF}$=1.90), 142.15 (dd, $^1J_{CF}$=284.55, $^2J_{CF}$=6.75), 147.42 (dd, $^1J_{CF}$=296.80, $^2J_{CF}$=9.50). MS: m/z=204 ($M^{+\cdot}$, 9%), 141 (2%), 125 (51%), 77 (100%), 51 (57%). Anal.: calculated: C 47.06, H 2.96, S 15.70 ; found: C 47.06, H 2.89, S 15.72.

(Z)-1,2-difluorovinylphenylsulfone **5**: IR (CH_2Cl_2) : 3080-3060, 1670, 1590, 1450, 1350, 1160. ^1H NMR: 7.32 (dd, $^2J_{HF}$=71.05, $^3J_{HF}$=3.96, 1H), 7.56-8.04 (m, 5H). ^{19}F NMR: -163.14 (dd, $^3J_{FF}$=138.80, $^3J_{FH}$=4.20, 1F), -153.80 (dd, $^3J_{FF}$=138.85, $^2J_{FH}$=70.40, 1F). ^{13}C NMR: 128.40, 129.57, 134.98, 137.85, 144.55 (dd, $^1J_{CF}$=272.70, $^2J_{CF}$=55.10), 149.93 (dd, $^1J_{CF}$=281.35, $^2J_{CF}$=32.25). MS: m/z=204 ($M^{+\cdot}$, 2%), 141 (3%), 125 (53%), 77 (100%), 51 (63%). Anal.: calculated: C 47.06, H 2.96, S 15.70 ; found: C 47.11, H 2.96, S 15.45.

[4+2] CYCLOADDITIONS WITH CYCLOPENTADIENE

General procedure

An excess of freshly cracked cyclopentadiene was added to a solution of olefin in acetonitrile. The solution was stirred at room temperature for several days. Evaporation of the solvent and chromatography of the residue on silica gel gave the corresponding adduct.

Cycloaddition of *(E)*-1,2-difluorovinylphenylsulfone 5

160 µl (1.96 mmol) of cyclopentadiene, 100 mg (0.49 mmol) of *(E)*-1,2-difluorovinylphenylsulfone **5** in acetonitrile (1 ml), RT, 6 days ; *endo:exo* 1:19 measured by GC on the crude mixture ; purification: SiO_2, petroleum ether/dichloromethane 1/1 ; yield: 85 mg of *exo* (R_f=0.40) and 30 mg of a mixture of *exo* and *endo*-cycloadducts (R_f=0.40 and 0.38) (87% overall yield).
Cis-5,6-difluoro-*exo*-5-(phenylsulfonyl)bicyclo[2.2.1]hept-2-ene **9**: white solid ; mp 90.4-91.5°C. IR (CH_2Cl_2): 1330, 1160. ^1H NMR: 1.78 (dtm, $^2J_{HH}$=10.28, $^4J_{HF}$=8.18, $^3J_{HH}$=1.92 (irradiation), $^3J_{HH}$=2.17 (irradiation), 1H), 2.10 (dm, $^2J_{HH}$=10.60, $^3J_{HH}$=1.58 (irradiation), $^3J_{HH}$=1.62 (irradiation), 1H), 3.28 (m, 1H), 3.46 (m, 1H), 5.45 (dt, $^2J_{HF}$=52.89, $^3J_{HH}$=$^3J_{HF}$= 3.50, 1H), 6.21 (dd, $^3J_{HH}$=5.68 and 3.22, 1H), 6.42 (dd, $^3J_{HH}$=5.68 and 2.95, 1H). ^{19}F NMR: -194.77 (dt, $^2J_{FH}$=52.60, $^4J_{FH}$=$^3J_{FF}$=8.50, 1F), -161.59 (t, $^4J_{FH}$=$^3J_{FF}$=8.50, 1F). ^{13}C NMR: 41.40, 45.79 (d, $^2J_{CF}$=18.20), 47.68 (d, $^2J_{CF}$=19.10), 90.33 (Dd, $^1J_{CF}$=209.40, $^2J_{CF}$=13.10), 108.56 (Dd, $^1J_{CF}$=240.20, $^2J_{CF}$=15.60), 129.27, 129.93, 134.12, 134.71, 134.90, 137.37. MS: m/z=125 (15%), 109 (100%), 77 (45%), 66 (58%). Anal.: calculated: C 57.77, H 4.47, S 11.86 ; found: C 57.65, H 4.72, S 11.82.
Cis-5,6-difluoro-*endo*-5-(phenylsulfonyl)bicyclo[2.2.1]hept-2-ene **9**: NMR caracteristics determined from a mixture of *endo* and *exo*-adduct ; ^1H NMR: 1.99 (dm, $^2J_{HH}$=9.80, 1H), 2.27 (dm, $^2J_{HH}$=9.76, 1H), 3.02 (m, 1H), 3.10 (m, 1H), 5.00 (dt, $^2J_{HF}$=53.35, $^4J_{HH}$=$^3J_{HF}$=2.96, 1H), 6.2 (masked by a proton of the *exo*-adduct) (1H), 6.32 (dd, $^3J_{HH}$=5.81 and 2.98, 1H), 7.59-7.95 (m, 5H). ^{19}F NMR: -191.55 (ddd, $^2J_{FH}$=52.30, $^3J_{FF}$=20.40, $^3J_{FH}$=6.43, 1F), -156.11 (dm, $^3J_{FF}$=20.40, 1F). MS: m/z=270 ($M^{+\cdot}$, 2%), 125 (7%), 109 (88%), 77 (64%), 66 (100%).

Cycloaddition of *(Z)*-1,2-difluorovinylphenylsulfone 5

74 µl (0.90 mmol) of cyclopentadiene, 46 mg (0.23 mmol) of *(Z)*-1,2-difluorovinylphenylsulfone **5** in acetonitrile (1 ml), RT, 3 days ; *endo:exo* 1:1.4 measured by ^{19}F NMR on the crude mixture ; purification: SiO_2, petroleum ether/dichloromethane 1/1.5 ; yield: 34 mg of *exo* (R_f=0.33) and 24 mg of *endo*-cycloadduct **10** (R_f=0.25) (95% overall yield).
Trans-5,6-difluoro-*exo*-5-(phenylsulfonyl)bicyclo[2.2.1]hept-2-ene **10**: white solid ; mp 97.8-98.3°C. IR (CH_2Cl_2): 1330, 1160. ^1H NMR: 2.02 (m, 1H), 2.80 (dm, $^2J_{HH}$=10.17, 1H), 3.14 (m, 1H), 3.40 (m, 1H), 4.52 (ddd, $^2J_{HF}$=52.15, $^3J_{HF}$=14.92, $^4J_{HH}$=2.96 (irradiation), 1H), 6.19 (dd, $^3J_{HH}$=5.52 and 3.05, 1H), 6.28 (dm, $^3J_{HH}$=5.23, 1H), 7.51-8.10 (m, 5H). ^{19}F NMR: -186.25 (d, $^2J_{FH}$=54.60, 1F), -141.30 (d, $^3J_{FH}$=15.30, 1F). ^{13}C NMR: 46.52, 46.72 (d, $^2J_{CF}$=19.50), 47.66 (dd, $^2J_{CF}$=22.55, $^3J_{CF}$=2.75), 96.64 (Dd, $^1J_{CF}$=203.65, $^2J_{CF}$=24.15), 112.17 (Dd, $^1J_{CF}$=227.95, $^2J_{CF}$=20.20), 128.78, 130.33, 134.33, 135.65 (d, $^3J_{CF}$=8.90), 136.13 (d, $^3J_{CF}$=5.60), 136.40. MS: m/z=270 ($M^{+\cdot}$, 1%), 125 (28%), 109 (100%), 66 (16%). Anal.: calculated: C 57.77, H 4.47, S 11.86 ; found: C 57.57, H 4.48, S 11.83.
Trans-5,6-difluoro-*endo*-5-(phenylsulfonyl)bicyclo[2.2.1]hept-2-ene **10**: white solid ; mp 142.6-144°C. IR (CH_2Cl_2): 1130, 1150. ^1H NMR: 1.78 (m, 1H), 1.86 (m, 1H), 3.18 (m, 1H), 3.22 (m, 1H), 5.17 (ddd, $^2J_{HF}$=52.73, $^3J_{HF}$=22.45, $^3J_{HH}$=3.85 (irradiation), 1H), 6.41 (m, 1H), 6.52 (m, 1H), 7.56-8.20 (m, 5H). ^{19}F NMR: -186.17 (dd, $^2J_{FH}$=52.75, $^4J_{FH}$=5.95, 1F), -137.38 (dm, $^3J_{FH}$=21.40, 1F). ^{13}C NMR: 43.25, 45.22 (dd, $^2J_{CF}$=20.70, $^3J_{CF}$=2.00), 49.76 (d, $^2J_{CF}$=21.10), 98.08 (Dd, $^1J_{CF}$=199.30, $^2J_{CF}$=30.70), 111.84 (Dd, $^1J_{CF}$=223.40, $^2J_{CF}$=21.30), 128.89, 130.19, 132.60 (d, $^3J_{CF}$=6.80), 134.36, 134.97 (m), 136.59. MS: m/z=270 ($M^{+\cdot}$, 9%), 109 (100%), 77 (22%), 66 (55%). HRMS: calculated for $C_{13}H_{12}F_2O_2S$: 270.052608, found: 270.053000.

[4+2] CYCLOADDITIONS WITH FUNCTIONALISED DIENES

Cycloaddition of phenylvinylsulfone 11 with 1-diethylaminobutadiene[21]

A solution of 103 mg (0.61 mmol) of phenylvinylsulfone **11** and 153 mg (1.22 mmol) of 1-diethylamino-butadiene in benzene (2 ml) was stirred at room temperature for 1 day. The solvent was evaporated and the residue purified by column chromatography on silica gel (dichloromethane/ethyl acetate 10/1) to give 16 mg of *trans*- (R_f=0.44), 120 mg of *cis*- (R_f=0.19) and 41 mg of a mixture of *cis*- and *trans*-3-diethylamino-4-(phenylsulfonyl)cyclohexene **12** (99% overall yield). *Endo:exo* ratio not determined.
Trans-3-diethylamino-4-(phenylsulfonyl)cyclohexene **12**: colorless oil. IR (CH_2Cl_2): 2980, 2900, 1310, 1150. ^1H NMR: 0.74 (t, ^3J=7.14, 6H), 1.80-2.32 (m, 4H), 2.50-2.65 (m, 4H), 3.26 (ddd, ^3J=13.38, 3.04 and 4.95, 1H), 3.88 (m, 1H), 5.68 (m, 1H), 5.86 (m, 1H), 7.48-7.80 (m, 5H). ^{13}C NMR: 11.48 (Q, ^1J= 125.50), 19.07 (Tm, ^1J=132.30), 25.10 (Tm, ^1J=129.00), 44.60 (Tm, ^1J=134.40), 54.25 (Dm, ^1J=139.40),

67.50 (Dm, ^1J=130.60), 126.55 (Dm, ^1J=160.60), 128.36 (Dm, ^1J=162.60), 128.98 (masked under other aromatic carbons), 129.12 (Dm, ^1J=165.20), 132.80 (Dt, ^1J=161.20, ^3J=6.94), 141.11 (m). MS: m/z=293 ($M^{+\cdot}$, 6%), 151 (15%), 125 (100%), 77 (42%).

Cis-3-diethylamino-4-(phenylsulfonyl)cyclohexene **12**: white solid ; mp 52.6-53.8°C. IR (CH_2Cl_2): 2980, 2850, 1310, 1145. ^1H NMR: 0.67 (t, ^3J=7.14, 6H), 1.90-2.38 (m, 8H), 3.33 (ddd, ^3J=9.86, 7.41 and 3.60, 1H), 3.92 (dm, ^3J=9.89, 1H), 5.62 (dm, ^3J=10.12, 1H), 5.87 (m, 1H), 7.45-7.82 (m, 5H). ^{13}C NMR: 12.90 (Qt, ^1J=125.50, ^2J=3.00), 20.70 (Tm, ^1J=131.90), 23.65 (Tm, ^1J=128.70), 43.03 (Tpent, ^1J=131.50, ^2J=^3J=4.60), 56.31 (Dm, ^1J=135.00), 61.84 (Dm, ^1J=136.60), 126.37 (masked under other aromatic carbons), 128.24 (Dt, ^1J=162.80, ^3J=6.70), 128.52 (Dd, ^1J=161.70, ^3J=7.60), 128.90 (Dm, ^1J=160.20), 132.79 (Dt, ^1J=160.90, ^3J=6.90), 141.07 (t, ^3J=8.40). MS: m/z=293 ($M^{+\cdot}$, 12%), 151 (17%), 125 (100%). Anal.: calculated: C 65.49, H 7.90, N 4.77, S 10.93 ; found: 65.47, H 8.02, N 4.67, S 11.03.

Cycloaddition of phenylvinylsulfone 11 with 1-methoxybutadiene

159 mg (0.94 mmol) of phenylvinylsulfone **11**, 192 µl (1.89 mmol) of 1-methoxybutadiene and a few cristals of benzoquinone were dissolved in benzene (1 ml) and heated in a Carius tube for 1 day at 135°C. The solvent was evaporated and the residue purified by column chromatography on silica gel (dichloromethane) to give 229 mg (96%) of a 5.2:1 mixture of *cis*- and *trans*-3-methoxy-4-(phenylsulfonyl)cyclohexene **13** (R_f=0.15, UV); yellow solid. IR (CH_2Cl_2): 3050, 2950, 2900, 1310, 1150, 1190, 1090. ^1H NMR (for *cis:trans* 5.2:1): 1.80-2.40 (m, 4H), 3.05 (s, 2.52H), 3.34 (s, 0.48H), 3.19 (m, 0.16H), 3.29 (m, 0.84H), 4.10 (m, 0.16H), 4.20 (0.84H), 5.55-6.05 (m, 2H), 7.50-8.00 (m, 5H). ^{13}C NMR (for *cis:trans* 5.2:1): 18.09 (Tm, ^1J=133.10), 20.06 (Tm, ^1J=131.55), 23.90 (Tm, ^1J=129.05), 25.63 (Tm, ^1J=130.10), 55.17 (Qd, ^1J=141.60, ^3J=4.58), 56.26 (Qd, ^1J=141.63, ^3J=3.40), 64.02 (Dm, ^1J=138.50), 67.68 (Dm, ^1J=130.90), 69.65 (Dm, ^1J=146.30), 73.86 (Dm, ^1J=144.30), 123.99 (Dm, ^1J=159.40), 124.84 (Dm, ^1J=161.70), 128.28 (Dm, ^1J=164.90), 128.45 (Dm, ^1J=157.50), 128.73 (Dd, ^1J=163.25, ^3J=7.25), 129.25 (Dm, ^1J=165.40), 129.65 (Dm, ^1J=161.40), 131.88 (masked under other aromatic carbons), 133.31 (Dt, ^1J=161.80, ^3J=6.93), 138.83 (m), 139.76 (t, ^3J=7.55). MS: m/z=142 (33%), 110 ($(M-C_6H_5SO_2H)^{+\cdot}$, 100%). MS (CI, CH_4-NO_2): m/z=253 ($(M+1)^+$, 20%), 221 (22%), 143 (100%), 125 (35%). HRMS: calculated for $C_7H_{10}O$ (M-$PhSO_2H$): 110.073165, found: 110.072800.

Cycloadditions with *o*-xylylene

General procedure

A solution of tetrabutylammonium fluoride (1M/THF) in dichloromethane was added dropwise to a solution of [o-(trimethylsilylmethyl)benzyl]trimethylammonium iodide **14**[23] and dienophile in dichloromethane. The mixture was stirred at room temperature for 1 hour. After removal of the solvent, the residue was purified by column chromatography on silica gel.

Reaction with phenylvinylsulfone **11**

330 µl (0.33 mmol) of tetrabutylammonium fluoride (1M/THF) in dichloromethane (3.5 ml), 92 mg (0.25 mmol) of [o-(trimethylsilylmethyl)benzyl]trimethylammonium iodide **14** and 128 mg (0.76 mmol) of phenylvinylsulfone **11** in dichloromethane (1.5 ml). Purification: SiO_2 (cyclohexane/ethyl acetate 3/1) ; yield: 31 mg (45%) of 2-(phenylsulfonyl)-1,2,3,4-tetrahydronaphthalene **15** (R_f=0.37, UV) ; white solid ; mp 105.5-106.6°C. IR (CH_2Cl_2): 3050, 2950, 2800, 1580, 1310, 1140. ^1H NMR: 1.83 (dq, ^2J=12.61, ^3J=5.88, 1H), 2.39 (dm, ^2J=12.00, 1H), 2.76-3.08 (m, 4H), 3.36 (m, 1H), 7.20 (m, 5H), 7.65-8.10 (m, 5H). ^{13}C NMR: 22.59, 28.25, 28.68, 60.51, 126.23, 126.47, 128.73, 129.04, 129.20, 133.82, 132.83, 134.77, 137.01. MS: m/z=272 ($M^{+\cdot}$, <1%), 130 (100%). Anal.: calculated: C 70.56, H 5.92, S 11.77 ; found: C 70.28, H 6.04, S 11.78.

Reaction with a mixture of (E) and (Z)-1,2-difluorovinylphenylsulfone **5**

385 µl (0.38 mmol) of tetrabutylammonium fluoride (1M/THF) in dichloromethane (4 ml), 107 mg (0.30 mmol) of [o-(trimethylsilylmethyl)benzyl]trimethylammonium iodide **14** and 181 mg (0.89 mmol) of 1,2-difluorovinylphenylsulfone **5** in dichloromethane (1.8 ml). Purification: SiO_2 (cyclohexane/ethyl acetate 3/1) ; yield: 85 mg (43%) of 2,2,2-trifluoroethylphenylsulfone **16**[24] (R_f=0.30, UV) ; white solid ; mp 109.7-110.5°C. ^1H NMR: 3.91 (q, $^3J_{HF}$=8.94, 2H), 7.59-8.01 (m, 5H). ^{19}F NMR: -61.82 (t, $^3J_{FH}$=8.80).

REACTIONS WITH NUCLEOPHILES

Reaction with pyrrolidine

17 µl (0.20 mmol) of pyrrolidine were added to a solution of 41 mg (0.20 mmol) of 1,2-difluorovinylphenylsulfone **5** (*E:Z* 1:1.3) in methanol (1 ml) cooled to 0°C *via* an ice bath. The solution was stirred at room temperature for 40 minutes. The solvent was evaporated and the residue poured into isopropanol (3 ml). Finally the *(E)*-1-fluoro-1-(phenylsulfonyl)-2-pyrrolidinoethylene **17** was isolated by filtration ; yield: 33 mg (65%) ; pale yellow solid ; mp 104.6-105.3°C. IR (CH_2Cl_2): 3050, 2950-2800, 1660, 1330, 1150. ^1H NMR: 1.84-1.92 (m, 4H), 3.40-3.45 (m, 4H), 6.94 (d, $^3J_{HF}$=27.47, 1H), 7.51-7.94 (m, 5H). ^{19}F NMR: -177.10 (dpent, $^3J_{FH}$=27.82, $^5J_{FH}$=3.76). ^{13}C NMR: 25.42, 50.42, 126.64, 127.31, 129.00, 133.84 (D, $^1J_{CF}$=259.30), 141.06. MS: m/z=255 ($M^{+\cdot}$, 100%), 113 (76%). HRMS: calculated for $C_{12}H_{14}FNO_2S$: 255.072929, found: 255.072300.

Reaction with thiophenol

32 µl (0.23 mmol) of triethylamine were added to a solution of 43 mg (0.21 mmol) of 1,2-difluorovinylphenylsulfone **5** (*E:Z* 1:1.3) and 23 µl (0.22 mmol) of thiophenol in ether (1 ml). The mixture was stirred at room temperature for 3 hours. The solvent was removed under *vacuum*. The residue was poured into 10 ml of water and extracted with 2 x 10 ml of dichloromethane. The combined organic layers were dried ($MgSO_4$), filtered and concentrated under *vacuum*. The residue was purified by column chromatography on silica gel (petroleum ether/dichloromethane 1/2) to give 60 mg (97%, *E:Z* 1.1:1) of 1-fluoro-1-(phenylsulfonyl)-2-(phenylthio)ethylene **18** (R_f=0.60, UV) ; colorless oil. IR (CH_2Cl_2): 3050, 1620, 1590, 1350, 1160. ^1H NMR (for *E:Z* 1.1:1): 6.83 *(Z)* (d, $^3J_{HF}$=18.48, 0.48H), 7.19 *(E)* (d, $^3J_{HF}$=30.94, 0.52H), 7.30-8.10 *(E:Z)* (m, 10H). ^{19}F NMR (for *E:Z* 1.1:1): -123.18 *(E)* (d, $^3J_{FH}$=30.90, 0.52F) ; -120.23 *(Z)* (d, $^3J_{FH}$=18.30, 0.48F). ^{13}C NMR (for *E:Z* 1.1:1): 119.93 (d, $^2J_{CF}$=8.80), 122.76 (d, $^2J_{CF}$=22.10), 128.11, 128.45, 128.54, 128.91, 129.24, 129.57, 129.66, 131.02, 131.36, 134.37, 134.61, 133.95, 137.43, 138.20, 147.13 (D, $^1J_{CF}$=289.50), 149.65 (D, $^1J_{CF}$=292.80). MS (for *E:Z* 1.1:1): m/z=294 ($M^{+\cdot}$, 68%), 152 (100%), 141 (12%), 125 (22%), 109 (54%), 77 (51%). HRMS (for *E:Z* 1.1:1): calculated for $C_{14}H_{11}FO_2S_2$: 294.018452, found : 294.018400.

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