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Electrophilic trifluoromethylthiolation of thiols with trifluoromethanesulfenamide†

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The highly selective and effective, metal-free, acid promoted trifluoromethylthiolation of thiols to the corresponding trifluoromethyl disulfides is described. The aryl-, benzyl-, aliphatic-, and heteroaromatic thiols reacted selectively, thus proving excellent reaction generality. The method offers practical and easy access to the previously mostly unknown or rarely reported trifluoromethyl disulfides. Comparison of the relative reactivity of thiophenols suggests formation of an electron-deficient intermediate in the transition state, which was supported by quantum chemical calculations. The supposed reaction course is discussed.

Introduction

Fluorinated organic molecules have been gaining significance in different fields *i.e.* medicinal and agrochemistry, high-performance advanced materials and new reaction media such as fluorinated ionic liquids and perfluorinated solvents.[1] The fluorine atom in an organic molecule brings about several stereoelectronic changes, and the C–F bond is an important conformational and bioisosteric tool in bioorganic chemistry.[2] The fluorine atom is important in inter- and intramolecular interactions; moreover, it is of particular significance in molecular recognition[3] and crystal engineering.[4] The trifluoromethyl group is one of the strategic fluorine-containing substituents and there has been immense interest in its introduction into organic molecules.[5,6] The discovery of the first electrophilic CF_3-transfer agent, by Yagupolskii in 1984,[7] induced new developments in this field.[8,9] The introduction of the trifluoromethyl group into organic molecules using nucleophilic,[10] radical[11] and metal-based[12] CF_3 sources has also progressed very rapidly.

A very attractive modulation of the CF_3– group is CF_3S– trifluoromethylthiol group, although its introduction have been studied much less than that of the CF_3– group. The trifluoromethylthiol group CF_3S– exhibits a remarkably high lipophilicity parameter, and is one of the key fragments in certain biologically relevant compounds.[13] The 2′-SCF_3 substituted uridine derivative was found to be a potent label for probing structure and function of RNA by ^{19}F NMR spectroscopy.[14] There are different ways of introduction of CF_3S– functionality. The introduction of the CF_3S– group could be performed directly,[15] by interconversion of functional groups[16] or by trifluoromethylation of suitable sulfur-containing moieties.[17] Direct methods usually rely on heavy-metal-based reagents[18] and/or catalysts or on the use of extremely toxic and hazardous trifluoromethyldisulfide[19] or trifluoromethylsulfenyl chloride.[20] Recently, considerable steps forward have been made in the direct introduction of the CF_3S– functionality.[21] Several new SCF_3 transfer agents have been developed, particular of an electrophilic nature. The recent progress was initiated by the work of Billard, Langlois and coworkers when they published a synthesis of $PhNHSCF_3$ **1** and its derivatives.[22] These compounds are easy-to-handle electrophilic SCF_3 reagents that can react with alkenes and alkynes,[23] indoles,[24] organometallic species,[25] tryptamines,[26] amines,[27] allyl silanes[28] and phenols.[29] An interesting cyclization was observed with different internal alkynes and $PhNHSCF_3$ furnishing the corresponding trifluoromethylthio substituted indoles,[30] benzofurans and benzothiophenes,[31] 1*H*-isochromen-1-ones,[32] 2*H*-benzo[*e*][1,2]thiazine 1,1-dioxides[33] and benzofulvenes.[34] A recently developed trifluoromethanesulfonyl hypervalent iodonium ylide was shown to be an effective trifluoromethylthiolating agent after an *in situ* reduction of trifluoromethanesulfonyl group.[35] *N*-(Trifluoromethylthio)succinimide was utilized in a selective trifluoromethylthiolation of arenes,[36] while an *in situ*-generated reagent from $AgSCF_3$ and NCS was applied for the trifluoromethylthiolation of terminal alkynes.[37] *N*-Trifluoromethylthiophthalimide was employed in trifluoromethylthiolation of boronic acids,[38] alkynes,[39] amines and thiols,[40] and a combination with cinchona alkaloids was utilized in a catalytic asymmetric trifluoromethylthiolation of oxindoles[41] and β-ketoesters.[42] One interesting trifluoromethylthiolating agent is a thioperoxide-based reagent containing a reactive O–S bond.[43,44] It was found to be effective in trifluoromethylthiolation of boronic acids,[45] Grignard reagents, alkynes, indoles, β-ketoesters, oxindoles, indoles,[46] sodium

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sulfinates[47] and carboxylic acids.[48] It was also utilized in the activation of thioglycoside donors[49] and in catalytic asymmetric trifluoromethylthiolations.[50] *N*-Trifluoromethylthiosaccharin[51] was applied in the trifluoromethylthiolation of alcohols, amines, thiols, arenes,[52] aldehydes, ketones, acyclic β-ketoesters, and alkynes. Functionalization of allylic alcohols furnished the corresponding trifluoromethyl sulfoxides *via* a [2,3]-sigmatropic rearrangement.[53] A combination of $AgSCF_3$ and trichloroisocyanuric acid was utilized as an *in situ* electrophilic SCF_3 source in enantioselective catalytic functionalization of oxindoles[54] and in the synthesis of 3-((trifluoromethyl)thio)-4*H*-chromen-4-ones.[55] Carbonyl compounds[56] and arenes[57] were trifluoromethylthiolated with a new *N*-((trifluoromethyl)thio) benzenesulfonamide type of reagent.

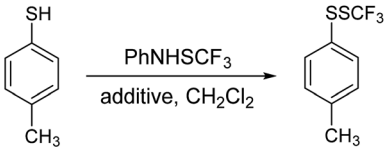
Trifluoromethyl disulfides are important as precursors of biologically active trifluoromethyl thiosulfonates[58,59] and can be prepared from thiols[60] and CF_3SCl or uncommon pyrole-SCF_3 derivatives,[61] upon reaction of bis(trifluoromethyl) trisulfide and organolithium reagents,[62] and *via* the photochemical reaction of trifluoromethylated thioesters with disulfides.[63] The first of these[20] is not very convenient or safe, while the latter two methods[62,63] were neither selective nor synthetically useful. The recently developed reagents *N*-trifluoromethylthiosaccharin[51] and *N*-trifluoromethylthiophthalimide[40] were demonstrated to be suitable for the synthesis of trifluoromethyl disulfides. We were interested in the reactivity of **1** with thiols because several different transformations are possible. Aromatic ring functionalization could take place; oxidation of thiols into the corresponding disulfides and synthesis of the trifluoromethyl disulfides are the other options. Here, we report on a straightforward, selective and efficient synthesis of trifluoromethyl disulfides.

Results and discussion

Initially, 4-methylthiophenol **2a** was reacted with **1** in dichloromethane (DCM), and only traces of 4-methylphenyl trifluoromethyl disulfide **3a** were noted (Table 1, entry 1). Yields were determined by ^{19}F NMR spectroscopy using octafluoronaphthalene as internal standard. Structures of the products were further verified independently. It is known that the electrophilic power of **1** is not high enough to react without promoters/additives.[23] Several potential additives in the transformation of **2a** were examined; the results are summarized in Table 1.

Reaction of **2a** with **1** in the presence of 2 equivalents of trifluoroacetic anhydride (TFAA) gave **3a** in 51% yield (entry 2). Transformations of **2a** in the presence of some other Lewis acids were not very selective and efficient (entries 3–6). Consequently, we turned our attention to Brønsted acids such as trifluoromethanesulfonic acid (TfOH). Conversion of **2a** in the presence of 0.5 equivalents of TfOH was only 20% (entry 7). The reaction progressed well in the presence of 1 equivalent of TfOH, however 10% of **2a** remained unreacted (entry 8). Full conversion of **2a** was achieved with 1.2 equivalents of TfOH, and **3a** was isolated in good yield (entry 8); while a little amount of **2a** remained unreacted with 1.1 equivalents of TfOH. Methanesulfonic acid (MSA) was tested similarly. Conversion of **2a** in the presence of 0.5 equivalents of MSA was as low as 9% (entry 10), while it rose up to 38% when using 1 equivalent of MSA (entry 11). Transformation of **2a** in the presence of 1.2 equivalents of MSA was almost complete, while full conversion was achieved in the presence of 1.3 equivalents of MSA (entry 12). The product **3a** was isolated in a good yield as a sole product. The best reaction selectivity was obtained in entries 9 and 12 yielding **3a** only. We decided to use MSA as an additive; however, in some cases better results were obtained with TfOH.

Table 1 Optimization of the reaction conditions[a]



2a **3a**

Entry	Additive/(equiv.)	Yield[b] (%)
1	—	Traces[c]
2	$(CF_3CO)_2O$/2	51
3	CF_3COOH/2	35[d]
4	$BF_3 \cdot Et_2O$/5	46[e]
5	TMSOTf/2	57
6	Tf_2O/2	51
7	CF_3SO_3H/0.5	20
8	CF_3SO_3H/1.0	62
9	CF_3SO_3H/1.2	81 [72][f]
10	CH_3SO_3H/0.5	9
11	CH_3SO_3H/1.0	38
12	CH_3SO_3H/1.3	82 [72][f]

[a] Reaction conditions: **2a** (0.2 mmol), **1** (0.24 mmol), additive, CH_2Cl_2 (2 mL), Ar atmosphere, rt, 12 h. [b] Yields were determined by ^{19}F NMR spectroscopy using octafluoronaphthalene as internal standard. [c] Di(4-methylphenyl) disulfide was the main product. [d] Ratio **3a**/the disulfide by-product (1.9/1) was determined by ^1H NMR spectroscopy. [e] Ratio **3a**/the disulfide by-product (3.5/1) was determined by ^1H NMR spectroscopy. [f] Isolated yield.

The role of solvent polarity on the reaction course of **2a** with **1** was also examined (Table 2). Functionalization in hexane was completely selective; however, the conversion was not complete (entry 1). Selectivity in toluene was somewhat lower as well as the yield of **3a** (entry 2). Diethyl ether would not be a suitable solvent because of low conversion of **2a** into **3a** (entry 3). Conversion in acetone was good, but some **2a** remained unreacted (entry 4). Methanol was a poor solvent for this transformation, since the conversion of **2a** remained low (entry 5). In acetonitrile, reaction took place well; however, a part of **2a** remained unreacted (entry 6). Functionalization was completely suppressed in water where only traces of **3a** were detected, and **2a** and **1** were recovered (entry 7). Interestingly, good yields were obtained in hexane and in acetonitrile in spite of a remarkably different polarity. The protic solvents and water are obviously not suitable for this transformation. Dichloromethane was found to be the best solvent for this reaction (entry 8).

Table 2 The role of solvent polarity on the reaction course[a]

2a 3a

Entry	Solvent	Yield[b] (%)
1	Hexane	71
2	Toluene	70
3	Diethyl ether	36
4	Acetone	63
5	Methanol	32
6	Acetonitrile	62
7	Water	Traces
8	Dichloromethane	82 [72][c]

[a] Reaction conditions: **2a** (0.2 mmol), **1** (0.24 mmol), MSA (0.26 mmol), solvent (2 mL), Ar atmosphere, rt, 12 h. [b] Yields were determined by ^{19}F NMR spectroscopy using octafluoronaphthalene as internal standard. [c] Isolated yield.

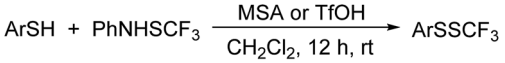
The reactivity of different thiols with **1** in dichloromethane under argon atmosphere was tested, and the optimal amount of acid (1.2 and 1.3 equivalents) was used. The results are summarized in Table 3. The model thiol **2a** was efficiently converted into **3a**, which was isolated on 0.5 mmol scale in higher yield than on a 0.2 mmol scale (entry 1, Table 3).

The highly activated 4-methoxythiophenol **2b** selectively yielded **3b** in the presence of MSA, whereas TfOH produced poorer results. A small amount of by-product was formed, which was not isolated, but, as could be judged from the NMR spectra, trifluoromethylthiolation of the aromatic ring took place. The functionalization of 4-hydroxythiophenol **2c**, 2-methoxythiophenol **2d** and 2,4-dimethylthiophenol **2e** smoothly yielded the corresponding trifluoromethyl disulfides **3c**, **3d** and **3e** in the presence of MSA (entries 3–5, Table 3). The less electron-rich 2,5-dimethylthiophenol **2f**, 3,5-dimethylthiophenol **2g**, 4-*i*-propylthiophenol **2h**, 2-naphthalenethiol **2i** and 4-chlorothiophenol **2j** were selectively converted into their trifluoromethylthio derivatives **3f–3j** in the presence of MSA (entries 6–10, Table 3). It was established that thiols bearing electron-withdrawing groups as a rule required stronger activation in comparison with the thiols bearing electron-donating groups. Thiophenol **2k**, 3-methoxythiophenol **2l**, fluoro-substituted thiophenols **2m–2o** and dichloro-substituted thiophenols **2p** and **2q** were transformed into the desired trifluoromethyl disulfides **3k–3q** in the presence of TfOH (entries 11–17, Table 3).

The reactions were selective without substantial formation of other side-products. Functionalization of electron-deficient 3-(trifluoromethyl)thiophenol **2r** and 4-nitrothiophenol **2s** with **1** took place efficiently in the presence of TfOH yielding the desired products **3r** and **3s** (entries 18 and 19, Table 2). For illustration, **2p** and **2s** did not react completely in the presence of 1.5 equiv. of MSA, while the full conversion was observed in the presence of 1.2 equiv. of TfOH.

Reactivity of benzyl thiols with **1** was also examined (Table 4). 4-Methoxybenzyl thiol **4a** was selectively transformed into its trifluoromethyl disulfide **5a** in the presence of MSA (entry 1, Table 4). It was established that benzyl thiols were of higher

Table 3 Functionalization of aryl thiols with $PhNHSCF_3$[a]

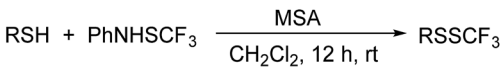


2 1 3

Entry	Ar	Acid/equiv.	3	Yield[b] (%)
1	4-Me–C_6H_4– **2a**	MSA/1.3	**3a**	82
2	4-OMe–C_6H_4– **2b**	MSA/1.2	**3b**	76
3	4-OH–C_6H_4– **2c**	MSA/1.3	**3c**	88
4	2-OMe–C_6H_4– **2d**	MSA/1.2	**3d**	91
5	2,4-DiMe–C_6H_3– **2e**	MSA/1.2	**3e**	90
6	2,5-DiMe–C_6H_3– **2f**	MSA/1.3	**3f**	92
7	3,5-DiMe–C_6H_3– **2g**	MSA/1.3	**3g**	89
8	4-*i*Pr–C_6H_4– **2h**	MSA/1.4	**3h**	90
9	2-Naphthyl– **2i**	MSA/1.3	**3i**	91
10	4-Cl–C_6H_4– **2j**	MSA/1.3	**3j**	84
11	4-H–C_6H_4– **2k**	TfOH/1.2	**3k**	75
12	3-OMe–C_6H_4– **2l**	TfOH/1.2	**3l**	88
13	4-F–C_6H_4– **2m**	TfOH/1.2	**3m**	83
14	2-F–C_6H_4– **2n**	TfOH/1.2	**3n**	83
15	2,4-DiF–C_6H_3– **2o**	TfOH/1.2	**3o**	80
16	3,4-DiCl–C_6H_3– **2p**	TfOH/1.2	**3p**	88
17	2,5-DiCl–C_6H_3– **2q**	TfOH/1.2	**3q**	89
18	3-CF_3–C_6H_4– **2r**	TfOH/1.2	**3r**	82
19	4-NO_2–C_6H_4– **2s**	TfOH/1.2	**3s**	87

[a] Reaction conditions: (a) Thiols **2a–2j** (0.5 mmol), **1** (0.6 mmol) and MSA (0.6–0.7 mmol) in DCM (5 mL) at rt for 12 h under Ar. Thiols (**2k–2s**) were functionalized under the same reaction conditions in the presence of TfOH (0.6 mmol). [b] Isolated yields.

Table 4 Transformation of benzylic and aliphatic thiols with **1**[a]

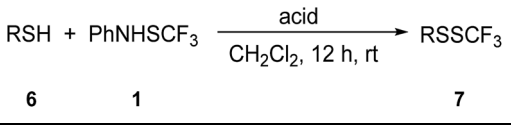


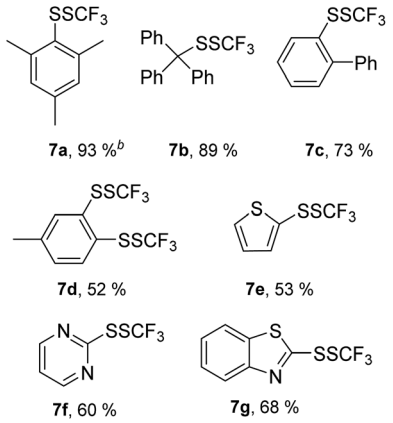
4 1 5

Entry	R	4	5	Yield[b] (%)
1	4-MeO–C_6H_4–CH_2–	**4a**	**5a**	94
2	4-H–C_6H_4–CH_2–	**4b**	**5b**	80
3	4-F–C_6H_4–CH_2–	**4c**	**5c**	78
4	4-Cl–C_6H_4–CH_2–	**4d**	**5d**	87
5	3-CF_3–C_6H_4–CH_2–	**4e**	**5e**	93
6	Ph(Me)CH–	**4f**	**5f**	58
7	*n*-C_8H_{17}–	**4g**	**5g**	83
8	*n*-$C_{12}H_{25}$–	**4h**	**5h**	86
9	*c*-C_6H_{11}–	**4i**	**5i**	57
10	–$(CH_2)_6$–	**4j**	**5j**	88

[a] Reaction conditions: Thiol **4** (0.5 mmol), **1** (0.6 mmol), MSA (0.6–0.65 mmol) in DCM (5 mL) at rt for 12 h under Ar. Entry 10: **4j** (0.5 mmol), **1** (1.2 mmol), MSA (1.3 mmol) in DCM (5 mL) at rt for 12 h under Ar. [b] Isolated yields.

Table 5 Functionalization of sterically hindered and heteroaromatic thiols with **1**[a]





7a, 93 %[b] **7b**, 89 % **7c**, 73 %

7d, 52 % **7e**, 53 %

7f, 60 % **7g**, 68 %

[a] Reaction conditions: Thiol **6** (1.0 equiv.), **1** (1.2 equiv.), acid in DCM at rt for 12 h under Ar. Acids: **6a** and **6b** (1.2 equiv. of TfOH). **6d** (1.3 equiv. of TfOH per SH group). **6c**, **6f** and **6g** (5 equiv. of *p*TSA·H_2O). **6e** (2 equiv. of MSA). [b] Isolated yields.

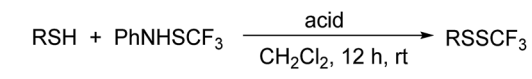
reactivity than thiophenols and MSA was found to be a suitable additive regardless on the substituents. Reactions of benzyl thiols in the presence of TfOH were much more complex with more unidentified by-products. Benzyl thiol **4b**, 4-fluorobenzyl thiol **4c**, 4-chlorobenzyl thiol **4d**, and 3-(trifluoromethyl)benzyl thiol **4e** were efficiently converted into the corresponding trifluoromethyl disulfides **5b–5e** (entries 2–5, Table 4). It is once again obvious, that a relationship for the higher yield exists between the nucleophilicity of the thiols and strength of the promoter, *i.e.* strongly nucleophilic thiols require milder activation. 1-Phenylethanethiol **4f** was detected in a peel oil extract of Pontianak oranges as a mixture of enantiomers ((*R*) : (*S*)) = 76 : 24, and it contributes to the characteristic odor of this citrus fruit. The compound has a very low odour threshold of 0.005 ng L^{-1} in the air.[64] Functionalization of racemic **4f** with **1** in the presence of MSA led to the desired product **5f** (entry 6, Table 4).

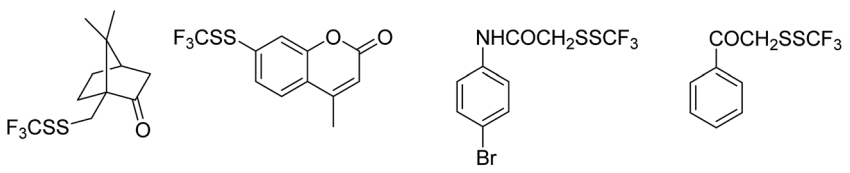
Some aliphatic thiols were also examined in reaction with **1**. As could have been anticipated, the suitable additive was MSA. 1-Octanethiol **4g** and 1-dodecanethiol **4h** selectively furnished the related trifluoromethyl disulfides **5g** and **5h** (entries 7 and 8, Table 4). The reaction of cyclohexanethiol **4i** yielded the corresponding product **5i** in a reasonable yield (entry 9, Table 4). 1,6-Hexanedithiol **4j** was tested, and double functionalization took place, thus yielding **5j** in a high yield (entry 10, Table 4).

Furthermore, we focused on the reactivity of sterically hindered- and heteroaromatic thiols (Table 5). 2,4,6-Trimethylthiophenol **6a** was successfully converted into trimethyl disulfide **7a** in the presence of TfOH, while MSA was not an effective promoter. A remarkably sterically hindered thiol group in triphenylmethanethiol **6b** was efficiently functionalized in the presence of TfOH, and product **7b** was isolated in a high yield. 2-Phenylthiophenol **6c** gave the expected trifluoromethyl disulfide **7c** in the presence of 5 equiv. of *p*-toluenesulfonic acid hydrate. 4-Methyl-1,2-benzenedithiol **6d** possesses two adjacent thiol groups, and both were functionalized with **1** in the presence of TfOH giving **7d**.

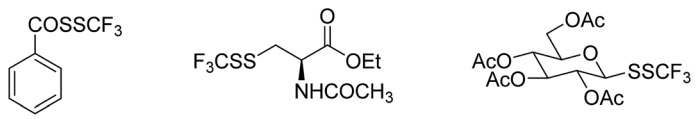
The transformation of 2-thiophenethiol **6e** into **7e** occurred in the presence of MSA, while selectivity dropped remarkably in the presence of TfOH. 2-Mercaptopyrimidine **6f** and

Table 6 Functionalization of the acid sensitive and biologically important thiols[a]





9a, 69 %[b] **9b**, 77 % **9c**, 30 % **9d**, 39 %



9e, 37 % **9f**, 58 % **9g**, 69 %

[a] Reaction conditions: Thiol **8** (1 equiv.), **1** (1.2 equiv.), acid in DCM at rt for 12 h under Ar. Acids: **8a**, **8c** and **8e** (1.3 equiv. of TfOH). **8b** and **8g** (1.2 equiv. of TfOH). **8d** (5 equiv. of BF_3·Et_2O). **8f** (1.2 equiv. of MSA). [b] Isolated yields.

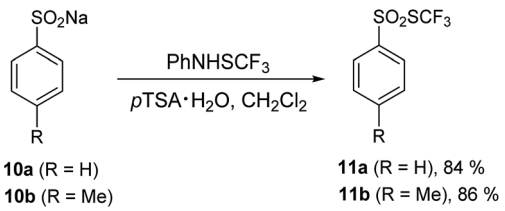
2-mercaptobenzothiazole **6g** were converted into the related trifluoromethyl disulfides **7f** and **7g** in the presence of 5 equiv. of *p*-toluenesulfonic acid hydrate. It could be concluded that sterically hindered- and heteroaromatic thiols could be effectively functionalized with **1**.

Next, we turned our attention to the structurally diverse, acid-sensitive and biologically important thiols (Table 6). It is known that the camphor skeleton could undergo an acid-catalyzed rearrangement, and it is frequently used in organocatalysis as well as a chiral auxiliary. (±)-7,7-Dimethylbicyclo-1-(mercaptomethyl)bicyclo[2.2.1]heptan-2-one **8a** yielded the expected trifluoromethyl disulfide **9a** in the presence of TfOH, and no rearrangement was noted.

This is a significant indication that the applied acidic reaction conditions turned to be compatible with acid-labile substrates. 7-Mercapto-4-methylcoumarin **8b** was selectively converted into **3j** in the presence of TfOH in spite of the presence of the acid-labile lactone group. Amide **8c** was converted into **9c** in the presence of TfOH in a moderate yield. The functionalization of 2-mercapto-1-phenylethanone **8d** with **1** in the presence of $BF_3 \cdot Et_2O$ led to the related α-trifluoromethyldisulfido ketone **9d**. The reaction of thiobenzoic acid **8e** in the presence of TfOH produced **9e**, although it was isolated in a moderate yield.

In addition, we examined the reactivity of two biologically relevant thiols, *i.e.* the protected cysteine derivative **8f** and 1-thioglucose derivative **8g**. The both substrates are particularly challenging because of the acidic reaction conditions. The functionalization of **8f** proceeded completely in the presence of 1.2 equiv. of MSA, and **9f** was obtained in a 58% yield. The reaction of **8g** in the presence of 1.2 equiv. of MSA took place smoothly; however, two sets of signals were observed in ^{1}H NMR spectrum. Interestingly, the transformation of **8g** in the presence of 1.2 equivalents of TfOH furnished a single stereoisomer **9g**, and no epimerization took place. We were pleased that protecting groups were compatible with the acidic reaction conditions and that epimerization in the case of **8g** could be avoided.

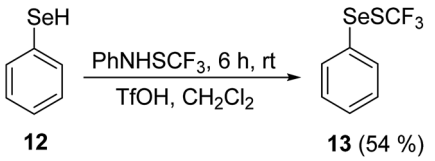
There is hardly any mention of trifluoromethyl thiosulfonates in the literature.[65] Recently, an efficient synthetic method starting from sodium sulfonates was published.[47] Thiosulfonates possess different biological activities[58,59] and could be utilized as sulfenylating agents.[66] Upon reaction with **1** in the presence of 5 equiv. of *p*TSA·H_2O, sodium sulfinates **10a** and **10b** produced the corresponding trifluoromethyl thiosulfonates **11a** and **11b** in high yields (Scheme 1).



10a (R = H)
10b (R = Me)

11a (R = H), 84 %
11b (R = Me), 86 %

Scheme 1 Transformation of sodium sulfinates with $PhNHSCF_3$.



12 **13** (54 %)

Scheme 2 Reaction of benzeneselenol **12** with $PhNHSCF_3$.

Additionally, the reactivity of the selenium analog **12** was examined (Scheme 2). Benzeneselenol **12** reacted fully with **1** in the presence of 1.5 equivalents of MSA, giving product **13** and a substantial amount of diphenyl diselenide.

The reaction of **12** in the presence of 1.2 equiv. of TfOH was considerably more selective, and phenylselenyl(trifluoromethyl) sulfide **13** was obtained as the sole product. The starting material **12** already contained a small amount of diphenyl diselenide; however, no appreciable additional oxidation of **12** took place.

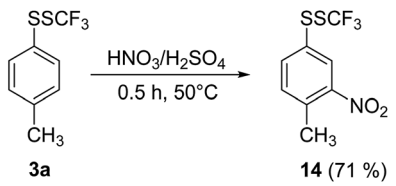
The $SSCF_3$ group is a relatively strong electron-withdrawing group, and the reactivity of trifluoromethyl disulfides is substantially unexplored. We were interested in how the $SSCF_3$ group affects the reactivity of the aromatic ring. A model disulfide **3a** was reacted with a mixture of concentrated HNO_3/H_2SO_4 at 50 °C (Scheme 3).

Trace amounts of the 3-nitro regioisomer were also detected in the crude reaction mixture. No oxidation of the sulfur atoms or of the methyl group was noted, while nitration took place, furnishing 2-nitro derivative **14** as the main product.

Mechanism

A detailed reaction mechanism is not known, although several conclusions could be drawn. The relative reactivity of the aryl-substituted thiols with **1** was determined, and a slope of the Hammett linear free energy relationship was obtained to be $\rho = -1.65$ with a good correlation ($r^2 > 0.95$) (Fig. 1).

The more electron-deficient thiols are of lower reactivity than the electron-rich ones, thus indicating that the electron density on the sulfur atom is more important than the acidity of the starting thiol. The Hammett correlation indicated that an important amount of the positive charge was developed in the transition state. The formation of the thiolate anion under the acidic reaction conditions was likely not to be a significant process, but thiols remained in the molecular form that is presumably able to react with the activated form of the reagent **1**. An unactivated reagent **1** is essentially an amine of relatively low electrophilic power. The acid seemingly protonates **1** on the



3a **14** (71 %)

Scheme 3 Functionalization of **3a** with HNO_3/H_2SO_4.

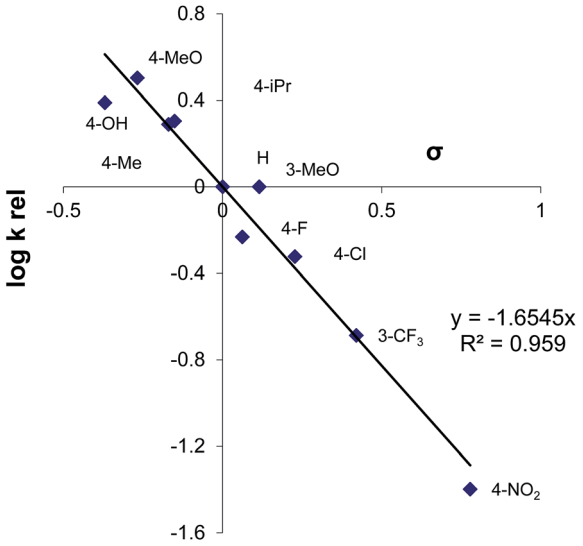


Fig. 1 Hammett correlation for functionalization of the aryl-substituted thiols with **1**.

nitrogen atom, thus generating a species of higher electrophilicity, able to react with thiols as nucleophiles. The reaction of **2a** with **1**/TfOH was examined in the presence of TEMPO, and the full conversion of **2a** into **3a** was noted. The yield of the product was practically the same as without TEMPO, and radicals are not likely to be important reaction intermediates.[9e]

Some additional experiments were performed in order to get a deeper insight into a reaction mechanism. The acid has a double role in this transformation; it acts as a promoter and as a reagent, since one of the final products is a salt of an aromatic amine. Reagent **1** was dissolved in $CDCl_3$ and separately treated with MSA and TfOH in two NMR tubes. **1** reacted fully with TfOH immediately, and an instantaneous downfield shift of one major and two minor singlets appeared in the ^{19}F NMR spectrum. This is an indication that protonation of **1** occurred, moreover it appears that there was an equilibrium between several species. On the contrary, reaction of **1** and MSA was far from completion after five minutes at room temperature; however there appeared three downfield shifted singlets in the ^{19}F NMR spectrum, indicating a partial protonation of **1**. MSA is likely too weak to protonate **1** in a weakly polar medium to an appreciable extent. The subsequent addition of **2a** to both NMR tubes resulted in an immediate formation of **3a** in both cases. In the case of TfOH, the activated form of **1** was already present, while addition of **2a** in the case of MSA was a driving force to shift equilibrium with the activated form of **1** completely in the direction of formation of **3a**. Based on the Hammett ρ value, we proposed a reaction of the protonated **1** with thiol as a nucleophilic substitution on the sulfur atom in a bimolecular reaction.

To elucidate further the reaction course, the quantum chemical calculations were performed. **1**, methanethiol and methanesulfonic acid were chosen as a model system. Since the formation of ionic intermediates and/or transition states was proposed, calculations in vacuum would give erroneous results, therefore all calculations were carried out for species in dichloromethane solution, using the Poisson–Boltzmann model. Still, when energies of the participating species were computed individually, some computed energies were unrealistically high. In poorly polar medium, such as dichloromethane, extensive ion pairing exists, and when this was taken into account, a more realistic picture was obtained, presented in Fig. 2.

The reaction is, according to calculations, a two-step (A + D) nucleophilic substitution, starting with attack of thiol to a protonated amine. In the first step of the reaction, an intermediate is formed in a shallow depression. In this step, no appreciable activation barrier was found. The central S atom in the intermediate bears formally ten valence electrons, which causes the N–S–S bonding to be essentially a 3c-4e (hypervalent) bond. This is reflected in elongated bonds, nearly linear arrangement of N–S–S atoms and typical charge distribution (see ESI†). In the intermediate and the transition state a charge of +0.561 and +0.775 a.u. (NBO), respectively, appears on methanethiol moiety, which is in accordance with value of the measured Hammett ρ constant. The process in and around the transition state is essentially a movement of sulfonate anion,

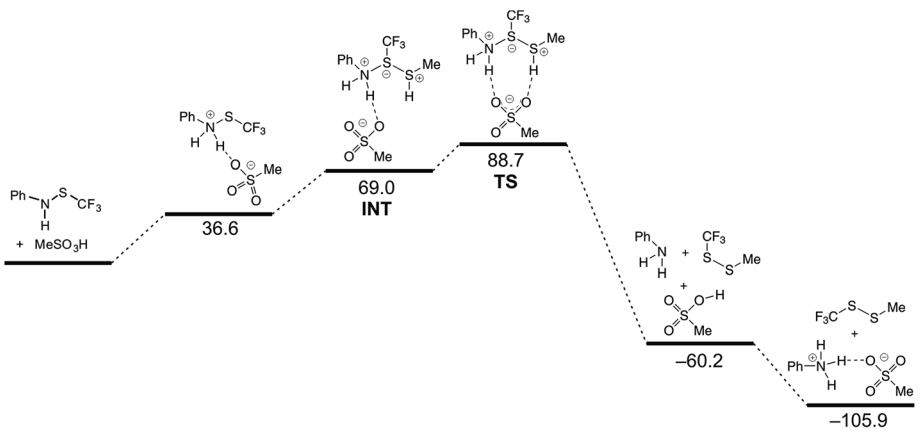


Fig. 2 Energy diagram of the reaction of *N*-[(trifluoromethyl)thio]aniline with methanethiol and methanesulfonic acid in dichloromethane, computed at MPW1K/6-311+G** level. Enthalpies in kJ mol^{-1}, in first two structures methanethiol is omitted.

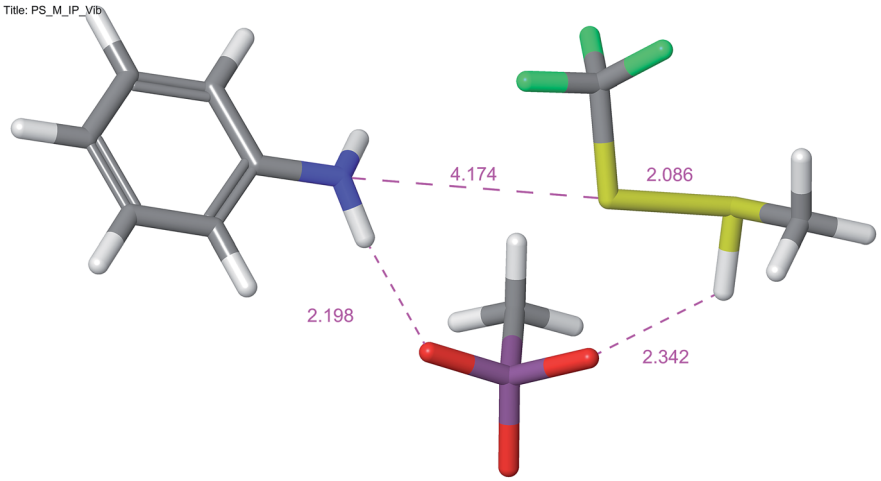


Fig. 3 Transition state for the nucleophilic substitution on the sulfur atom of **1** with methanethiol, MPW1K/6-311+G**.

attached initially to an N–H proton, towards the S–H proton. Removal of the latter proton causes simultaneous cleavage of the NH–O and N–S bonds and disintegration of the aggregate into products (Fig. 3).

Conclusions

The reactivity of the electrophilic trifluoromethylthiolating reagent $PhNHSCF_3$ was tested on aryl-, benzyl-, alkyl-, heteroaryl-, sterically hindered-, biologically relevant- and acid sensitive thiols in the presence of acidic additives. The aryl-substituted thiols reacted well, regardless of the nature of the substituents. Trifluoromethyl disulfides were obtained as the sole products, no aromatic ring functionalization or parent disulfides formation were noted. Some acid-sensitive substrates were efficiently functionalized, thus proving compatibility with the acidic reaction conditions. The more electron-rich thiophenols required milder activation (methanesulfonic acid), and the more electron-deficient thiols required triflic acid. The nucleophilicity of the starting thiols appears to be of higher importance than their acidity. Sodium sulfonates were demonstrated to be suitable substrates for the synthesis of trifluoromethyl thiosulfonates using **1** and *p*-toluenesulfonic acid hydrate as an additive. Benzeneselenol was conveniently transformed into $PhSeSCF_3$, a novel type of selenium compounds. The reactivity of trifluoromethyl disulfide product **3a** with HNO_3/H_2SO_4 was examined. Nitration of the aromatic ring took place, and no oxidation of sulfur atoms or methyl group was observed. The Hammett correlation analysis on the functionalization of the substituted thiophenols revealed the formation of the electron-deficient intermediate $\rho = -1.65$. MSA or TfOH most likely protonated **1** and enhanced its reactivity due to the stronger polarization between sulfur and nitrogen atoms. The generated sulfur electrophile is then able to react with thiols. Reactions in the presence of free radical TEMPO revealed that radicals are not very likely to be important reaction intermediates. The quantum chemical calculations indicated protonation of **1** in the initial stage, followed by a nucleophilic attack of thiol to the protonated **1**, forming an intermediate, which decomposes through a transition state in which the sulfonate anion, attached initially by hydrogen bonding to an N–H proton, approaches the S–H proton. Removal of the S–H proton brings about an instantaneous collapse of the transition aggregate into products. In the intermediate and transition state a considerably positive charge is formed on the thiol moiety, which is in a good agreement with the Hammett correlation study.

Experimental section

General information

All reactions were carried under an argon atmosphere with stirring at room or elevated temperature. Dichloromethane (>99.9%) was used as received. Most of thiols, benzeneselenol, other catalysts and acids were obtained from commercial sources and used as received.

Crude trifluoromethylthiolated products were purified by column chromatography on silica gel (63–200 μm, 70–230 mesh ASTM; Fluka) using hexane or hexane/diethyl ether. TLC was performed on Merck-60-F_{254} plates using mixtures of hexane and diethyl ether. The melting points were determined in open-capillaries on Büchi 535 apparatus and are uncorrected. All products were characterized by their ^{1}H NMR, ^{19}F NMR, ^{13}C NMR spectra, IR, HRMS and/or elemental analysis. HRMS data were obtained on Agilent 6224 Accurate Mass TOF LC/MS instrument (ESI-TOF) at Infrastructure Centre at UL FCCT in Ljubljana and on Thermo Scientific Q-Exactive spectrometer with Ion Max ion source equipped with a Syagen Technology PhotoMate Krypton lamp (APCI and APPI with orbitrap mass analyzer) in the Central Laboratory for Environmental, Plant & Microbial Metabolomics at the Karl-Franzens-University in Graz. The ^{1}H and ^{13}C NMR spectra were recorded on Bruker Avance 300 DPX, Bruker Avance III 500, and on Varian System 600 MHz instruments. The ^{19}F NMR spectra were only recorded on Bruker Avance III 500 instrument. Chemical shifts are reported in δ (ppm) values relative to the TMS ($\delta = 0.00$ ppm) and to the residual $CHCl_3$ ($\delta = 7.26$ ppm) for ^{1}H NMR, to the

central line of $CDCl_3$ ($\delta = 77.0$ ppm) and to the central line of acetone-d_6 ($\delta = 30.83$ ppm) for ^{13}C NMR. ^{19}F NMR spectra are referred to $CFCl_3$ ($\delta = 0.00$ ppm).

Computational details. For DFT calculations, all structures are fully optimized on MPW1K/6-311+G** level of theory. B3LYP functional gives similar results, however MPW1K was chosen because it is better suited for structures with elongated bonds and transition states.[67] All geometries were optimized for species in dichloromethane solution, using Poisson–Boltzmann model. Vibrational frequencies were calculated in vacuum on solution-optimized structures. Atomic charges were calculated using NBO analysis.[68] All calculations were run on Jaguar, Schrödinger Release 2014-4: Jaguar, version 8.6, Schrödinger, LLC, New York, NY, 2014.

Preparation of 1 and starting thiols. *N*-[(Trifluoromethyl)-thio]aniline **1** was prepared according to the published procedure.[22] **8f** was prepared from L-cysteine ethyl ester hydrochloride,[69] and **8g** was prepared according to the known method.[70] KSAc was prepared according to the published procedure.[71] 2-Mercapto-1-phenylethanone **8d** was prepared from 2-bromoacetophenone in two steps.[72] The first step was modified, while the literature procedure was followed in the second step. The first step: to a solution of 2-bromoacetophenone (15 mmol, 3.0 g) in DMF (20 mL) KSAc (20.9 mmol, 2.39 g) was added and the mixture was stirred for 2 h at room temperature (TLC indicated consumption of the starting ketone). The reaction mixture was diluted with water (30 mL) and the product extracted with diethyl ether (3 × 30 mL). The ethereal phase was washed with water, dried over anhydrous Na_2SO_4, and the solvent evaporated. The thus-obtained crude 2-acetylthioacetophenone was transformed into 2-mercapto-1-phenylethanone **8d**, according to the published procedure.[72] (±)-1-Phenylethanethiol **4f** and (±)-10-thiocamphor **8a** were prepared according to the published procedure.[73] *N*-(4-Bromophenyl)-2-mercaptoacetamide **8c** was prepared in three steps, starting from 4-bromoaniline (20 mmol, 3.44 g), and bromoacetyl bromide thus producing *N*-(4-bromophenyl)-2-bromoacetamide (13.9 mmol, 4.08 g) according to the published procedure.[74] In the second step, *N*-(4-bromophenyl)-2-bromoacetamide was reacted with KSAc in DMF as described above, and *N*-(4-bromophenyl)-2-thioacetylacetamide (10.2 mmol, 2.9 g) was isolated in the same way as described above in the case of **8d**. In the last step, the crude *N*-(4-bromophenyl)-2-thioacetylacetamide was dissolved in a mixture of diethyl ether (10 mL) and THF (15 mL) and 20 mL of aqueous solution of NaOH (50 mmol, 2 g) was added. The mixture was stirred vigorously for 2 h at room temperature (TLC indicated consumption of the starting material). The reaction mixture was acidified with a 37% aqueous solution of HCl (3 mL) to acidic pH. The product was extracted with dichloromethane (3 × 20 mL), washed twice with water and dried over anhydrous Na_2SO_4, and the solvent evaporated. Yellowish crystals of *N*-(4-bromophenyl)-2-mercaptoacetamide[75] **8c** were purified by crystallization from dichloromethane/hexane. 2-Phenylbenzenethiol[76] **6c** was prepared according to the published procedure.[77] **10a** and **10b** were prepared according to the known procedure.[78]

Representative procedure for the trifluoromethylthiolation of thiols with $PhNHSCF_3$

To a solution of 4-methybenzenethiol **2a** (0.5 mmol, 62 mg) in dichloromethane (5 mL), *N*-[(trifluoromethyl)thio]aniline **1** (0.6 mmol, 116 mg) and trifluoromethanesulfonic acid (0.65 mmol, 63 mg) were added and the mixture was stirred under argon for 12 h. The mixture was diluted with 15 mL of CH_2Cl_2, washed with aqueous solution of $NaHCO_3$, water and dried over anhydrous Na_2SO_4. After filtration, the solvent was evaporated and the crude reaction mixture was analyzed by ^1H and ^{19}F NMR spectroscopy. Pure product **3a** as yellow oil (92 mg, 82%) was obtained after column chromatography on silica gel using hexane as eluent.

The same procedure was used also in the case of benzeneselenol **12**.

Experimental procedure for nitration of 3a

65% nitric acid (3.1 mmol, 300 mg) and 98% sulfuric acid (1.5 mmol, 150 mg) were added to **3a** (0.6 mmol, 135 mg), and the mixture was stirred at 50 °C for 30 minutes. Full consumption of **3a** was noted by TLC. The reaction mixture was cooled to rt, diluted with 15 mL of dichloromethane washed with aqueous solution of $NaHCO_3$, water and dried over anhydrous Na_2SO_4. After filtration, the solvent was evaporated and the crude reaction mixture was analyzed by ^1H and ^{19}F NMR spectroscopy. Pure product **14** as yellow solid (114 mg, 71%) was obtained after column chromatography on silica gel using hexane/diethyl ether (1/10) as eluent.

Determination of the relative reactivity of the substituted thiophenols in the Hammett correlation analysis

The relative rates of substituted thiophenols (Fig. 1) were determined by competitive reactions as follows: to a mixture of two substrates (reference PhSH (0.2 mmol) and the examined substituted thiophenol (0.2 mmol)), $PhNHSCF_3$ (0.2 mmol) and MSA or TfOH (0.24–0.26 mmol) were added, and the mixture was stirred for 12 h at rt. The reaction was quenched with water, and products were extracted with DCM (2 × 10 mL) and washed with water. The phases were separated and the organic layer was dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure, and the reaction mixture was analyzed by ^{19}F NMR. Octafluoronaphthalene was used as internal standard. The difference in reactivity of PhSH and 4-nitrothiophenol was too high to obtain reliable k_{rel} in this manner. For this reason, 4-chlorothiophenol was taken as a second reference molecule for 4-nitrothiophenol. The relative reactivity of 4-nitrothiophenol *vs.* PhSH was therefore determined indirectly: k(4-NO_2)/k(4-H) was obtained from: k(4-Cl)/k(4-H) and k(4-Cl)/k(4-NO_2). Relative reactivities expressed by the relative rate factors k_R were calculated from the equation[79] $k_R = k_A/k_B = \log((A - X)/A)/\log((B - Y)/B)$, derived from the Ingold–Shaw relation,[80] where A and B are the amounts of starting material and X and Y the amounts of products derived from them. The relative rate factors thus obtained, presented in Fig. 1, are the averages of at least three measurements.

1-Methyl-4-((trifluoromethyl)sulfinothioyl)benzene (3a).[51] (0.5 mmol of **2a**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (92 mg, 82%). ^{1}H NMR ($CDCl_3$): δ 2.37 (s, 3H), 7.15–7.20 (m, 2H), 7.47–7.52 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 21.2, 129.3 (q, J = 313.9 Hz, SCF_3), 130.2, 131.2, 131.5, 139.8. IR (neat) cm^{-1}: 1140, 1096, 804, 751. HRMS: (APCI + PI) calcd for $C_8H_7F_3S_2$ 223.9936, found 223.9927.

1-Methoxy-4-((trifluoromethyl)sulfinothioyl)benzene (3b). (0.5 mmol of **2b**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (91 mg, 76%). ^{1}H NMR ($CDCl_3$): δ 3.83 (s, 3H), 6.87–6.91 (m, 2H), 7.54–7.59 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.2 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 55.4, 115.0, 125.3, 129.5 (q, J = 313.6 Hz, SCF_3), 134.8, 161.2. IR (neat) cm^{-1}: 1590, 1492, 1291, 1250, 1137, 1095, 1031, 826, 751. HRMS: (APCI + PI) calcd for $C_8H_7F_3OS_2$ 239.9885, found 239.9876.

1-Hydroxy-4-((trifluoromethyl)sulfinothioyl)benzene (3c). (0.5 mmol of **2c**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (99 mg, 88%). ^{1}H NMR ($CDCl_3$): δ 5.27 (br s, 1H), 6.79–6.86 (m, 2H), 7.48–7.55 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.2 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 116.4, 125.6, 129.4 (q, J = 313.6 Hz, SCF_3), 135.0, 157.2. IR (neat) cm^{-1}: 3330, 1583, 1493, 1431, 1244, 1137, 1088, 825, 751. HRMS: (ESI-TOF) calcd for $C_7H_4F_3OS_2$ 224.9664, found 224.9664 $(M - H)^+$.

1-Methoxy-2-((trifluoromethyl)sulfinothioyl)benzene (3d). (0.5 mmol of **2d**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (109 mg, 91%). ^{1}H NMR ($CDCl_3$): δ 3.91 (s, 3H), 6.88–6.93 (m, 1H), 6.98 (dt, J = 7.6, 1.0 Hz, 1H), 7.31–7.37 (m, 1H), 7.64 (dd, J = 7.7, 1.3 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.1 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 56.0, 111.2, 121.2, 122.2, 129.3 (q, J = 313.9 Hz, SCF_3), 130.6, 131.6, 158.0; IR (neat) cm^{-1}: 2940, 2839, 1582, 1475, 1463, 1434, 1295, 1275, 1244, 1132, 1097, 1060, 1038, 1023, 798, 748, 678. HRMS: (CI + PI) calcd for $C_8H_7F_3OS_2$ 239.9885, found 239.9884.

2,4-Dimethyl-1-((trifluoromethyl)sulfinothioyl)benzene (3e). (0.5 mmol of **2e**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (107 mg, 90%). ^{1}H NMR ($CDCl_3$): δ 2.33 (s, 3H), 2.46 (s, 3H), 7.00–7.04 (m, 1H), 7.05–7.08 (m, 1H), 7.55 (d, J = 7.9 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 20.4, 21.1, 127.8, 129.4 (q, J = 313.9 Hz, SCF_3), 130.0, 131.6, 133.4, 140.3, 140.3. IR (neat) cm^{-1}: 2923, 1602, 1475, 1446, 1378, 1140, 1096, 1044, 875, 810, 751. HRMS: (CI) calcd for $C_9H_9F_3S_2$ 238.0092, found 238.0092.

1,4-Dimethyl-2-((trifluoromethyl)sulfinothioyl)benzene (3f). (0.5 mmol of **2f**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (109 mg, 92%). ^{1}H NMR ($CDCl_3$): δ 2.33 (s, 3H), 2.44 (s, 3H), 7.05–7.09 (m, 1H), 7.09–7.13 (m, 1H), 7.46–7.49 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 19.8, 20.8, 129.3 (q, J = 314.0 Hz, SCF_3), 130.4, 130.6, 132.7, 132.9, 136.5, 136.8. IR (neat) cm^{-1}: 2923, 1488, 1447, 1380, 1097, 874, 811, 751, 704. HRMS: (CI + PI) calcd for $C_9H_9F_3S_2$ 238.0092, found 238.0094.

1,3-Dimethyl-5-((trifluoromethyl)sulfinothioyl)benzene (3g). (0.5 mmol of **2g**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (106 mg, 89%). ^{1}H NMR ($CDCl_3$): δ 2.32 (s, 6H), 6.96–6.99 (m, 1H), 7.18–7.21 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 21.2, 128.0, 129.2 (q, J = 314.0 Hz, SCF_3), 130.9, 134.1, 139.2. IR (neat) cm^{-1}: 2921, 1602, 1579, 1142, 1097, 839, 751, 681. HRMS: (CI + PI) calcd for $C_9H_9F_3S_2$ 238.0092, found 238.0095.

1-Isopropyl-4-((trifluoromethyl)sulfinothioyl)benzene (3h). (0.5 mmol of **2h**, 0.6 mmol of **1**, 0.70 mmol of MSA). Yellow oil (113 mg, 90%). ^{1}H NMR ($CDCl_3$): δ 1.26 (d, J = 6.9 Hz, 6H), 2.93 (sept, J = 6.9 Hz, 1H), 7.20–7.26 (m, 2H), 7.49–7.56 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 23.8, 33.9, 127.6, 129.3 (q, J = 313.9 Hz, SCF_3), 131.4, 131.4, 150.6. IR (neat) cm^{-1}: 2963, 1142, 1098, 1052, 824, 752. HRMS: (CI + PI) calcd for $C_{10}H_{11}F_3S_2$ 252.0249, found 252.0251.

2-((Trifluoromethyl)sulfinothioyl)naphthalene (3i).[40] (0.5 mmol of **2i**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (118 mg, 91%). ^{1}H NMR ($CDCl_3$): δ 7.50–7.56 (m, 2H), 7.64 (dd, J = 8.6, 1.9 Hz, 1H), 7.80–7.88 (m, 3H), 8.08 (d, J = 1.9 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.2 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 127.0, 127.2, 127.2, 127.8, 129.2 (q, J = 314.2 Hz, SCF_3), 129.4, 130.1, 131.6, 133.1, 133.3. IR (neat) cm^{-1}: 1140, 1094, 853, 808, 742. HRMS: (APCI) calcd for $C_{11}H_7F_3S_2$ 259.9936, found 259.9935.

1-Chloro-4-((trifluoromethyl)sulfinothioyl)benzene (3j).[51] (0.5 mmol of **2j**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (103 mg, 84%). ^{1}H NMR ($CDCl_3$): δ 7.33–7.37 (m, 2H), 7.51–7.55 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 129.0 (q, J = 314.2 Hz, SCF_3), 129.6, 131.9, 133.1, 135.5. IR (neat) cm^{-1}: 1475, 1389, 1143, 1092, 1012, 815, 752. HRMS: (APCI) calcd for $C_7H_4ClF_3S_2$ 243.9389, found 243.9380.

((Trifluoromethyl)sulfinothioyl)benzene (3k).[63] (0.5 mmol of **2k**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (79 mg, 75%). ^{1}H NMR ($CDCl_3$): δ 7.34–7.40 (m, 3H), 7.57–7.62 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 129.0, 129.1 (q, J = 314.1 Hz, SCF_3), 129.4, 130.4, 134.6. IR (neat) cm^{-1}: 2923, 2853, 1590, 1493, 1291, 1251, 1143, 1100, 1032, 751, 687. HRMS: (APCI) calcd for $C_7H_5F_3S_2$ 209.9779, found 209.9779.

1-Methoxy-3-((trifluoromethyl)sulfinothioyl)benzene (3l). (0.5 mmol of **2l**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (106 mg, 88%). ^{1}H NMR ($CDCl_3$): δ 3.82 (s, 3H), 6.86–6.91 (m, 1H), 7.11–7.14 (m, 1H), 7.14–7.18 (m, 1H), 7.25–7.30 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 55.4, 114.9, 115.0, 122.1, 129.0 (q, J = 314.2 Hz, SCF_3), 130.2, 135.7, 160.1; IR (neat) cm^{-1}: 2837, 1590, 1576, 1478, 1425, 1284, 1249, 1232, 1140, 1096, 1039, 992, 858, 770, 752, 683. HRMS: (PI) calcd for $C_8H_7F_3OS_2$ 239.9885, found 239.9883.

1-Fluoro-4-((trifluoromethyl)sulfinothioyl)benzene (3m).[51] (0.5 mmol of **2m**, 0.55 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (95 mg, 83%). ^{1}H NMR ($CDCl_3$): δ 7.04–7.11 (m, 2H), 7.57–7.63 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3), −111.1 (m, 1F); ^{13}C NMR ($CDCl_3$): δ 116.7 (d, J = 22.3 Hz), 129.2 (q, J = 313.9 Hz, SCF_3), 130.0 (d, J = 3.3 Hz), 133.9 (d, J = 8.6 Hz), 163.5 (d, J = 250.8 Hz). IR (neat) cm^{-1}: 1589, 1489, 1234, 1142, 1096, 1013, 828, 752, 627. HRMS: (CI) calcd for $C_7H_4F_4S_2$ 227.9685, found 227.9684.

1-Fluoro-2-((trifluoromethyl)sulfinothioyl)benzene (3n). (0.5 mmol of **2n**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (95 mg, 83%). ^{1}H NMR ($CDCl_3$): δ 7.10–7.15 (m, 1H), 7.16–7.21 (m, 1H), 7.35–7.43 (m, 1H), 7.63–7.69 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.3 (d, J = 2.4 Hz, SCF_3), −108.3 (m, 1F); ^{13}C NMR ($CDCl_3$): δ 116.3 (d, J = 21.9 Hz), 121.7 (d, J = 17.3 Hz), 124.9 (d, J = 3.9 Hz),

129.1 (q, J = 314.0 Hz, SCF_3), 131.8 (d, J = 8.0 Hz), 133.7, 161.5 (d, J = 249.6 Hz). IR (neat) cm^{-1}: 1472, 1448, 1263, 1229, 1143, 1096, 826, 752. HRMS: (CI + PI) calcd for $C_7H_4F_4S_2$ 227.9685, found 227.9685.

2,4-Difluoro-1-((trifluoromethyl)sulfinothioyl)benzene (3o). (0.5 mmol of **2o**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (99 mg, 80%). ^1H NMR ($CDCl_3$): δ 6.87–6.97 (m, 2H), 7.62–7.69 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.3 (d, J = 3.0 Hz, SCF_3), −102.0 (m, 1F), −105.1 (m, 1F); ^{13}C NMR ($CDCl_3$): δ 105.1 (t, J = 26.0 Hz), 112.5 (dd, J = 21.9, 3.9 Hz), 117.5 (dd, J = 18.1, 4.1 Hz), 129.1 (q, J = 313.8 Hz, SCF_3), 136.2 (d, J = 10.0 Hz), 162.5 (dd, J = 252.9, 12.7 Hz), 164.5 (dd, J = 254.3, 11.3 Hz); IR (neat) cm^{-1}: 2926, 2854, 1596, 1484, 1466, 1421, 1268, 1143, 1099, 966, 852, 810, 752. HRMS: (PI) calcd for $C_7H_3F_5S_2$ 245.9591, found 245.9589.

1,2-Dichloro-4-((trifluoromethyl)sulfinothioyl)benzene (3p). (0.5 mmol of **2p**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (123 mg, 88%). ^1H NMR ($CDCl_3$): δ 7.41 (dd, J = 8.4, 2.1 Hz, 1H), 7.45 (d, J = 8.4 Hz, 1H), 7.67 (d, J = 2.1 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.2 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 128.8 (q, J = 314.5 Hz, SCF_3), 129.1, 131.1, 131.5, 133.5, 133.6, 134.5. IR (neat) cm^{-1}: 1458, 1367, 1143, 1095, 1031, 808, 752. HRMS: (APCI + PI) calcd for $C_7H_3Cl_2F_3S_2$ 277.9000, found 277.8999.

1,4-Dichloro-2-((trifluoromethyl)sulfinothioyl)benzene (3q). (0.5 mmol of **2q**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (125 mg, 89%). ^1H NMR ($CDCl_3$): δ 7.24 (dd, J = 8.5, 2.4 Hz, 1H), 7.33 (d, J = 8.5 Hz, 1H), 7.71 (d, J = 2.4 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 128.6 (q, J = 314.8 Hz, SCF_3), 129.0, 129.5, 131.0, 131.5, 133.7, 134.9. IR (neat) cm^{-1}: 1447, 1149, 1091, 1030, 868, 810, 752. HRMS: (CI) calcd for $C_7H_3Cl_2F_3S_2$ 277.9000, found 277.9003.

1-(Trifluoromethyl)-3-((trifluoromethyl)sulfinothioyl)benzene (3r). (0.5 mmol of **2r**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (114 mg, 82%). ^1H NMR ($CDCl_3$): δ 7.49–7.55 (m, 1H), 7.58–7.63 (m, 1H), 7.75–7.80 (m, 1H), 7.82–7.86 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3), −63.4 (s, CF_3); ^{13}C NMR ($CDCl_3$): δ 123.4 (q, J = 272.7 Hz, CF_3), 125.6 (q, J = 3.6 Hz), 126.3 (q, J = 3.6 Hz), 128.8 (q, J = 314.4 Hz, SCF_3), 129.9, 131.9 (q, J = 32.9 Hz, SCF_3), 132.7, 136.1. IR (neat) cm^{-1}: 1321, 1284, 1129, 1096, 1071, 794, 752, 694, 683, 651. HRMS: (CI + PI) calcd for $C_8H_4F_6S_2$ 277.9653, found 277.9655.

1-Nitro-4-((trifluoromethyl)sulfinothioyl)benzene (3s).[51] (0.5 mmol of **2s**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (111 mg, 87%). ^1H NMR ($CDCl_3$): δ 7.69–7.75 (m, 2H), 8.22–8.27 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.1 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 124.4, 127.8, 128.5 (q, J = 315.0 Hz, SCF_3), 142.9, 147.4. IR (neat) cm^{-1}: 1578, 1518, 1339, 1145, 1092, 843, 740, 680. HRMS: (ESI-TOF) calcd for $C_7H_5F_3NO_2S_2$ 255.9708, found 255.9715 $(M + H)^+$.

1-Methoxy-4-(((trifluoromethyl)sulfinothioyl)methyl)benzene (5a). (0.5 mmol of **4a**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (120 mg, 94%). ^1H NMR ($CDCl_3$): δ 3.81 (s, 3H), 4.05 (s, 2H), 6.84–6.91 (m, 2H), 7.20–7.27 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 43.9, 55.3, 114.2, 127.1, 129.7 (q, J = 313.6 Hz, SCF_3), 130.7, 159.5; IR (neat) cm^{-1}: 1609, 1510, 1302, 1250, 1235, 1135, 1096, 1033, 830, 749. HRMS: (CI + PI) calcd for $C_9H_8F_3OS_2$ 252.9963, found 252.9963 $(M - H)^+$.

(((Trifluoromethyl)sulfinothioyl)methyl)benzene (5b).[40] (0.5 mmol of **4b**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (90 mg, 80%). ^1H NMR ($CDCl_3$): δ 4.09 (s, 2H), 7.28–7.39 (m, 5H); ^{19}F NMR ($CDCl_3$): δ −46.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 44.4, 128.1, 128.8, 129.5, 129.6 (q, J = 313.7 Hz, SCF_3), 135.3. IR (neat) cm^{-1}: 1135, 1097, 751, 696. HRMS: (APCI + PI) calcd for $C_8H_6F_3S_2$ 222.9857, found 222.9858 $(M - H)^+$.

1-Fluoro-4-(((trifluoromethyl)sulfinothioyl)methyl)benzene (5c). (0.5 mmol of **4c**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (95 mg, 78%). ^1H NMR ($CDCl_3$): δ 4.05 (s, 2H), 7.01–7.07 (m, 2H), 7.24–7.30 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3), −114.1 (m, 1F); ^{13}C NMR ($CDCl_3$): δ 43.4, 115.7 (d, J = 21.7 Hz), 129.5 (q, J = 313.7 Hz, SCF_3), 131.1 (d, J = 3.2 Hz), 131.2 (d, J = 8.3 Hz), 162.5 (d, J = 247.3 Hz). IR (neat) cm^{-1}: 1509, 1227, 1137, 1098, 834. HRMS: (CI + PI) calcd for $C_8H_6F_4S_2$ 241.9841, found 241.9843.

1-Chloro-4-(((trifluoromethyl)sulfinothioyl)methyl)benzene (5d). (0.5 mmol of **4d**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (113 mg, 87%). ^1H NMR ($CDCl_3$): δ 4.03 (s, 2H), 7.22–7.27 (m, 2H), 7.31–7.35 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 43.5, 129.0, 129.5 (q, J = 313.8 Hz, SCF_3), 130.8, 133.8, 134.1. IR (neat) cm^{-1}: 1490, 1136, 1093, 1015, 831. HRMS: (APCI + PI) calcd for $C_8H_5ClF_3S_2$ 256.9468, found 256.9468 $(M - H)^+$.

1-(Trifluoromethyl)-3-(((trifluoromethyl)sulfinothioyl)methyl)-benzene (5e). (0.5 mmol of **4e**, 0.6 mmol of **1**, 0.6 mmol of MSA). Yellow oil (136 mg, 93%). ^1H NMR ($CDCl_3$): δ 4.10 (s, 2H), 7.47–7.52 (m, 2H), 7.55–7.60 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.2 (s, SCF_3), −63.3 (s, CF_3); ^{13}C NMR ($CDCl_3$): δ 43.5, 123.8 (q, J = 272.3 Hz), 124.9 (q, J = 3.5 Hz), 126.2 (q, J = 3.7 Hz), 129.3, 129.4 (q, J = 313.9 Hz, SCF_3), 131.2 (q, J = 32.5 Hz), 132.8, 136.4. IR (neat) cm^{-1}: 1329, 1124, 1099, 1075, 906, 888, 803, 750, 700, 659. HRMS: (PI) calcd for $C_9H_5F_6S_2$ 290.9731, found 290.9724 $(M - H)^+$.

1-(((Trifluoromethyl)sulfinothioyl)ethyl)benzene (5f). (1 mmol of **4f**, 1.2 mmol of **1**, 1.3 mmol of MSA). Slightly yellow oil (138 mg, 58%). ^1H NMR ($CDCl_3$): δ 1.73 (d, J = 7.0 Hz, 3H), 4.25 (q, J = 7.0 Hz, 1H), 7.28–7.38 (m, 5H); ^{19}F NMR($CDCl_3$): δ −46.2 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 20.4, 50.9, 127.8, 128.2, 128.7, 129.4 (q, J = 313.7 Hz, SCF_3) 140.1. IR (neat) cm^{-1}: 3032, 2973, 2929, 1493, 1454, 1376, 1135, 1099, 764, 751, 696. HRMS: (PI) calcd for $C_9H_8F_3S_2$ 237.0014, found: 237.0005 $(M - H)^+$.

1-((Trifluoromethyl)sulfinothioyl)octane (5g). (0.5 mmol of **4g**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (102 mg, 83%). ^1H NMR ($CDCl_3$): δ 0.89 (t, J = 7.1 Hz, 3H), 1.21–1.35 (m, 8H), 1.35–1.44 (m, 2H), 1.66–1.74 (m, 2H), 2.83–2.89 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.7 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 14.1, 22.6, 28.2, 28.6, 29.0, 29.1, 31.8, 39.9, 129.6 (q, J = 313.4 Hz, SCF_3); IR (neat) cm^{-1}: 2958, 2926, 2856, 1140, 1101, 751. HRMS: (PI) calcd for $C_9H_{17}F_3S_2$ 246.0718, found 246.0714.

1-((Trifluoromethyl)sulfinothioyl)dodecane (5h). (0.5 mmol of **4h**, 0.6 mmol of **1**, 0.65 mmol of MSA). Yellow oil (130 mg, 86%). ^1H NMR ($CDCl_3$): δ 0.87 (t, J = 6.9 Hz, 3H), 1.20–1.44 (m, 18H), 1.63–1.76 (m, 2H), 2.86 (t, J = 7.4 Hz, 2H); ^{19}F NMR ($CDCl_3$): δ −46.7 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 14.1, 22.7, 28.3, 28.6, 29.1, 29.3, 29.4, 29.5, 29.6, 31.9, 40.0, 129.6 (q, J = 313.5

Hz, SCF_3). IR (neat) cm^{-1}: 2924, 2854, 1140, 1102, 751. HRMS: (APCI + PI) calcd for $C_{13}H_{25}F_3S_2$ 302.1344, found 302.1341.

((Trifluoromethyl)sulfinothioyl)cyclohexane (5i). (1 mmol of **4i**, 1.2 mmol of **1**, 2 mmol of MSA). Slightly yellow oil (123 mg, 57%). ^1H NMR ($CDCl_3$): δ 1.18–1.43 (m, 5H), 1.60–1.68 (m, 1H), 1.75–1.87 (m, 2H), 2.02–2.13 (m, 2H), 2.86–2.98 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −46.6 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 25.4, 25.8, 32.3, 50.1, 129.3 (q, J = 313.4 Hz, SCF_3); IR (neat) cm^{-1}: 2933, 2856, 1449, 1137, 1099, 996, 751. HRMS: (PI) calcd for $C_7H_{11}F_3S_2$ 216.0249, found 216.0248.

1,6-Bis((trifluoromethyl)sulfinothioyl)hexane (5j). (0.5 mmol of **4j**, 1.2 mmol of **1**, 1.3 mmol of MSA). Yellow oil (154 mg, 88%). ^1H NMR ($CDCl_3$): δ 1.40–1.47 (m, 4H), 1.68–1.77 (m, 4H), 2.87 (t, J = 7.3 Hz, 4H); ^{19}F NMR ($CDCl_3$): δ −46.6 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 27.7, 28.4, 39.7, 129.5 (q, J = 313.5 Hz, SCF_3). IR (neat) cm^{-1}: 2932, 1135, 1097, 750. HRMS: (APCI + PI) calcd for $C_8H_{12}F_6S_4$ 349.9720, found 349.9719.

1,3,5-Trimethyl-2-((trifluoromethyl)sulfinothioyl)benzene (7a). (0.5 mmol of **6a**, 0.6 mmol of **1**, 0.6 mmol of TfOH). Yellow oil (118 mg, 93%). ^1H NMR ($CDCl_3$): δ 2.29 (s, 3H), 2.52 (s, 6H), 6.96 (s, 2H); ^{19}F NMR ($CDCl_3$): δ −45.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 21.1, 21.4, 129.2, 129.6, 129.6 (q, J = 313.6 Hz, SCF_3), 140.6, 142.8. IR (neat) cm^{-1}: 2925, 1601, 1459, 1377, 1138, 1096, 850, 752. HRMS: (PI) calcd for $C_{10}H_{11}F_3S_2$ 252.0249, found 252.0248.

(((Trifluoromethyl)sulfinothioyl)methanetriyl)tribenzene (7b). (0.5 mmol of **6b**, 0.6 mmol of **1**, 0.6 mmol of TfOH). White crystals (168 mg, 89%), mp 72.5–73.4 °C. ^1H NMR ($CDCl_3$): δ 7.25–7.39 (m, 15H); ^{19}F NMR ($CDCl_3$): δ −43.6 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 73.3, 127.5, 128.0, 128.3 (q, J = 315.9 Hz, SCF_3), 130.1, 142.6. IR (neat) cm^{-1}: 1488, 1439, 1137, 1093, 1032, 1000, 757, 726, 698, 664, 625, 616. Anal. calcd for $C_{20}H_{15}F_3S_2$: C, 63.81; H, 4.02. Found: C, 63.64; H, 3.73.

2-((Trifluoromethyl)sulfinothioyl)-1,1′-biphenyl (7c). (0.8 mmol of **6c**, 0.96.0 mmol of **1**, 4.0 mmol of *p*-toluenesulfonic acid hydrate). Yellow oil (167 mg, 73%). ^1H NMR ($CDCl_3$): δ 7.29 (dd, J = 7.5, 1.6 Hz, 1H), 7.34–7.47 (m, 7H), 7.83 (dd, J = 7.8, 1.1 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 128.0, 128.2, 128.3, 128.4, 129.0 (q, J = 314.5 Hz, SCF_3), 129.2 (q, J = 1.0 Hz), 129.5, 130.6, 132.9, 139.3, 142.7. IR (neat) cm^{-1}: 1586, 1142, 1100, 748, 700. Anal. calcd for $C_{13}H_9F_3S_2$: C 54.53; H 3.17. Found: C 54.38; H 2.89.

4-Methyl-1,2-bis((trifluoromethyl)sulfinothioyl)benzene (7d). (1 mmol of **6d**, 2.4 mmol of **1**, 2.6 mmol of TfOH). Slightly yellow oil (185 mg, 52%). ^1H NMR ($CDCl_3$): δ 2.41 (s, 3H), 7.18 (dd, J = 8.0, 1.1 Hz, 1H), 7.57 (d, J = 1.1 Hz, 1H), 7.62 (d, J = 8.0 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.6 (s, SCF_3), −45.7 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 21.2, 128.9 (q, J = 314.5 Hz, SCF_3), 129.2 (q, J = 314.2 Hz, SCF_3), 130.6, 131.2, 131.7, 132.9, 136.6, 141.3. IR (neat) cm^{-1}: 2049, 1587, 1457, 1140, 1087, 1030, 813, 751. HRMS (CI + PI): calcd for $C_9H_6F_6S_4$: 355.9251, found: 355.9248.

2-((Trifluoromethyl)sulfinothioyl)thiophene (7e). (1 mmol of **6e**. 1.2 mmol of **1**, 2 mmol of MSA). Yellow oil (115 mg, 53%). ^1H NMR ($CDCl_3$): δ 7.03 (dd, J = 5.3, 3.7 Hz, 1H), 7.42 (dd, J = 3.7, 1.1 Hz, 1H), 7.53 (dd, J = 5.3, 1.1 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 127.9, 129.3 (q, J = 313.2 Hz, SCF_3), 132.6, 133.3, 137.4. IR (neat) cm^{-1}: 1140, 1096, 991, 851, 837, 752, 705. HRMS: (CI + PI) calcd for $C_5H_3F_3S_3$ 215.9343, found 215.9343.

2-((Trifluoromethyl)sulfinothioyl)pyrimidine (7f). (1.0 mmol of **6f**, 1.2 mmol of **1**, 5.0 mmol of *p*-toluenesulfonic acid hydrate). Bright brown solid (127 mg, 60%), mp = 42–45 °C. ^1H NMR ($CDCl_3$): δ 7.20 (t, J = 4.8 Hz, 1H), 8.68 (d, J = 4.8 Hz, 2H); ^{19}F NMR ($CDCl_3$): δ −46.4 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 118.9, 128.6 (q, J = 314.2 Hz, SCF_3), 158.2, 168.0. IR (neat) cm^{-1}: 3482, 2930, 2854, 1445, 984, 955, 755, 700. HRMS: (ESI-TOF): calcd for $C_5H_4F_3N_2S_2$ 212.9768, found: 212.9762 $(M + H)^+$.

2-((Trifluoromethyl)sulfinothioyl)benzo[*d*]thiazole (7g).[50] (0.8 mmol of **6g**, 0.96 mmol of **1**, 4.0 mmol of *p*-toluenesulfonic acid hydrate). Bright brown oil (146 mg, 68%). ^1H NMR ($CDCl_3$): δ 7.38–7.43 (m, 1H), 7.47–7.52 (m, 1H), 7.82–7.86 (m, 1H), 7.93–7.97 (m, 1H); ^{19}F NMR ($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 121.3, 122.8, 125.6, 126.7, 128.2 (q, J = 315.5 Hz, SCF_3), 136.2, 154.1, 166.5. IR (neat) cm^{-1}: 3062, 1465, 1427, 1151, 1101, 1006, 751, 724. HRMS: (ESI-TOF): calcd for $C_8H_5F_3NS_3$ 267.9536, found: 267.9532 $(M + H)^+$.

(±)-7,7-Dimethyl-1-(((trifluoromethyl)sulfinothioyl)methyl)-bicyclo[2.2.1]heptan-2-one (9a). (1 mmol of **8a**, 1.2 mmol of **1**, 1.3 mmol of TfOH). Slightly yellow oil (196 mg, 69%). ^1H NMR ($CDCl_3$): δ 0.92 (s, 3H), 1.05 (s, 3H), 1.38–1.46 (m, 1H), 1.65–1.74 (m, 1H), 1.90 (d, J = 18.5 Hz, 1H), 1.96–2.07 (m, 2H), 2.12 (t, J = 4.5 Hz, 1H), 2.35 (ddd, J = 18.5, 4.7, 2.4 Hz, 1H), 2.87 (d, J = 13.1 Hz, 1H), 3.40 (d, J = 13.1 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −47.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 19.8, 20.1, 26.5, 26.7, 40.6, 42.9, 43.6, 48.0, 61.6, 129.7 (q, J = 313.5 Hz, SCF_3), 216.6. IR (neat) cm^{-1}: 2961, 1740, 1416, 1392, 1374, 1134, 1101, 751. HRMS: (ESI-TOF): calcd for $C_{11}H_{16}F_3OS_2$ 285.0595, found: 285.0600 $(M + H)^+$.

4-Methyl-7-((trifluoromethyl)sulfinothioyl)-2*H*-chromen-2-one (9b). (0.5 mmol of **8b**, 0.6 mmol of **1**, 0.6 mmol of TfOH). White solid (113 mg, 77%), mp 95.2–96.7 °C. ^1H NMR ($CDCl_3$): δ 2.44 (d, J = 1.1 Hz, 3H), 6.32 (m, 1H), 7.46 (dd, J = 8.5, 2.0 Hz, 1H), 7.56 (d, J = 2.0 Hz, 1H), 7.60 (d, J = 8.5 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.1 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 18.7, 115.6, 116.4, 119.9, 123.6, 125.4, 128.7 (q, J = 314.8 Hz, SCF_3), 139.2, 151.6, 153.7, 160.0. IR (neat) cm^{-1}: 1737, 1548, 1365, 1108, 948, 877, 862, 768, 707. Anal. calcd for $C_{11}H_7F_3O_2S_2$: C, 45.20; H, 2.41. Found: C, 45.12; H, 2.35.

***N*-(4-Bromophenyl)-2-((trifluoromethyl)sulfinothioyl)acetamide (9c).** (2 mmol of **8c**, 2.4 mmol of **1**, 2.6 mmol of TfOH). Slightly yellow solid (208 mg, 30%), mp 87–90 °C. ^1H NMR ($CDCl_3$): δ 3.75 (s, 2H), 7.41–7.50 (m, 4H), 7.67 (br s, 1H); ^{19}F NMR($CDCl_3$): δ −46.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 44.3, 117.9, 121.7, 129.1 (q, J = 314.0 Hz, SCF_3), 132.1, 136.0, 164.6. IR (neat) cm^{-1}: 3272, 1645, 1587, 1532, 1487, 1435, 1349, 1315, 1243, 1126, 1104, 1070, 1011, 971, 936, 822, 684. HRMS: (ESI-TOF) calcd for $C_9H_8BrF_3NOS_2$ 345.9183, found: 345.9184 $(M + H)^+$.

1-Phenyl-2-((trifluoromethyl)sulfinothioyl)ethan-1-one (9d). (2 mmol of **8d**, 2.3 mmol of **1**, 10 mmol of $BF_3 \cdot Et_2O$). Yellow oil (197 mg, 39%). ^1H NMR ($CDCl_3$): δ 4.42 (s, 2H), 7.49–7.54 (m, 2H), 7.61–7.66 (m, 1H), 7.93–7.97 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −46.5 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 46.9, 128.5, 128.9, 129.4 (q, J = 313.8 Hz, SCF_3), 134.1, 135.0, 192.9. IR (neat) cm^{-1}: 1677, 1597, 1581, 1449, 1394, 1321, 1276, 1196, 1135, 1097, 997, 750,

686, 636. HRMS: (ESI-TOF) calcd for $C_9H_8F_3OS_2$ 252.9969, found: 252.9970 $(M + H)^+$.

Phenyl((trifluoromethyl)sulfinothioyl)methanone (9e). (2 mmol of **8e**, 2.6 mmol of **1**, 2.6 mmol of TfOH). Slightly yellow oil (176 mg, 37%). ^{1}H NMR ($CDCl_3$): δ 7.50–7.58 (m, 2H), 7.65–7.72 (m, 1H), 7.79–8.05 (m, 2H); ^{19}F NMR($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 128.2, 128.3 (q, J = 313.6 Hz, SCF_3), 129.2, 134.6, 134.9, 184.5. IR (neat) cm^{-1}: 1760, 1708, 1597, 1581, 1449, 1201, 1145, 1096, 876, 770, 754, 684, 674, 643, 615. HRMS: (ESI-TOF) calcd for $C_8H_6F_3OS_2$ 238.9812, found: 238.9818 $(M + H)^+$.

Ethyl acetyl((trifluoromethyl)sulfinothioyl)-D-alaninate (9f). (1 mmol of **8f**, 1.2 mmol of **1**, 1.2 mmol of MSA). White solid (169 mg, 58%), mp 41.8–44.7 °C. ^{1}H NMR($CDCl_3$): δ 1.30 (t, J = 4.2 Hz, 3H), 2.05 (s, 3H), 3.32 (dd, J = 14.1, 5.0 Hz, 1H), 3.46 (dd, J = 14.1, 5.0 Hz, 1H), 4.24 (q, J = 7.2 Hz, 2H), 4.85–4.90 (m, 1H), 6.38 (d, J = 6.5 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −46.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 14.0, 23.0, 41.8, 51.6, 62.3, 129.2 (q, J = 313.5 Hz, SCF_3), 169.9, 169.9. IR (neat) cm^{-1}: 3337, 1735, 1647, 1521, 1376, 1316, 1189, 1152, 1126, 1103, 1034, 862, 752. $[\alpha]_D^{20}$ = +37.7 (c = 0.26 in CH_2Cl_2). HRMS: (ESI-TOF) calcd for $C_8H_{13}F_3NO_3S_2$ 292.0283, found 292.0279 $(M + H)^+$.

(2*R*,3*R*,4*S*,5*R*,6*S*)-2-(acetoxymethyl)-6-((trifluoromethyl)sulfinothioyl)tetrahydro-2*H*-pyran-3,4,5-triyl triacetate (9g). (0.5 mmol of **8g**, 0.6 mmol of **1**, 0.6 mmol of TfOH). White solid (160 mg, 69%), mp 113.9–116.2 °C. ^{1}H NMR ($CDCl_3$): δ 2.02 (s, 3H), 2.04 (s, 3H), 2.07 (s, 3H), 2.09 (s, 3H), 3.75–3.79 (m, 1H), 4.16 (dd, J = 12.5, 2.2 Hz, 1H), 4.25 (dd, J = 12.5, 4.7 Hz, 1H), 4.62 (d, J = 10.0 Hz, 1H), 5.11 (dt, J = 9.8, 2.3 Hz, 2H), 5.26 (t, J = 9.4 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.9 (s, SCF_3); ^{13}C NMR (CD_3COCD_3): δ 21.5, 21.5, 21.5, 63.7, 69.8, 71.3, 74.8, 77.6, 87.9, 130.5 (q, J = 313.0 Hz, SCF_3), 170.9, 171.0, 171.2, 171.6. IR (neat) cm^{-1}: 1742, 1366, 1221, 1142, 1102, 1060, 1031, 913. $[\alpha]_D^{20}$ = −100.8 (c = 0.25 in CH_2Cl_2). Anal. calcd for $C_{15}H_{19}F_3O_9S_2$: C, 38.79; H, 4.12. Found: C, 39.18; H, 3.80.

***S*-(Trifluoromethyl) benzenesulfonothioate (11a).**[47] (1 mmol of **10a**, 1.2 mmol of **1**, 5 mmol of *p*-toluenesulfonic acid monohydrate). Yellow oil (204 mg, 84%). ^{1}H NMR ($CDCl_3$): δ 7.59–7.66 (m, 2H), 7.71–7.77 (m, 1H), 7.99–8.04 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −38.9 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 127.2 (q, J = 313.1 Hz, SCF_3), 127.6, 129.6, 135.1, 144.6; IR (neat) cm^{-1}: 1449, 1359, 1153, 1095, 1069, 760, 752, 714, 680. Anal. calcd for $C_7H_5F_3O_2S_2$: C, 34.71; H, 2.08. Found: C, 34.64; H, 2.09.

***S*-(Trifluoromethyl) 4-methylbenzenesulfonothioate (11b).**[59] (1 mmol of **10b**, 1.2 mmol of **1**, 5 mmol of *p*-toluenesulfonic acid monohydrate). Yellow oil (221 mg, 86%). ^{1}H NMR ($CDCl_3$): δ 2.49 (s, 3H), 7.37–7.44 (m, 2H), 7.85–7.92 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −39.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 21.8, 127.3 (q, J = 312.9 Hz, SCF_3), 127.7, 130.2, 141.8, 146.7. IR (neat) cm^{-1}: 1593, 1357, 1152, 1097, 1071, 812, 760, 700, 650. Anal. calcd for $C_8H_7F_3O_2S_2$: C, 37.49; H, 2.75. Found: C, 37.31; H, 2.65.

(Phenyl(trifluoromethyl)-λ^4-selanylidene)sulfane (13). (1 mmol of **12**, 1.2 mmol of **1**, 1.2 mmol of TfOH). Yellow oil (70 mg, 54%). ^{1}H NMR ($CDCl_3$): δ 7.34–7.40 (m, 3H), 7.67–7.72 (m, 2H); ^{19}F NMR ($CDCl_3$): δ −43.3 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 128.7 (q, J = 311.4 Hz, SCF_3), 129.4, 129.5, 130.5, 132.7. IR (neat) cm^{-1}: 1135, 1090, 733, 685. HRMS: (APCI + PI) calcd for $C_7H_5F_3SSe$ 257.9229, found 257.9224.

1-Methyl-2-nitro-4-((trifluoromethyl)sulfinothioyl)benzene (14). Yellow solid (114 mg, 71%), mp 51.0–52.0 °C. ^{1}H NMR ($CDCl_3$): δ 2.47 (s, 3H), 7.55 (dd, J = 8.4, 1.1 Hz, 1H), 8.03 (d, J = 8.4 Hz, 1H), 8.11 (d, J = 1.1 Hz, 1H); ^{19}F NMR ($CDCl_3$): δ −45.0 (s, SCF_3); ^{13}C NMR ($CDCl_3$): δ 20.5, 126.3, 127.3, 128.7 (q, J = 314.6 Hz, SCF_3), 130.9, 135.6, 138.4, 145.4. IR (neat) cm^{-1}: 2923, 1514, 1463, 1329, 1294, 1143, 1091, 829, 802, 750. HRMS: (APCI + PI) calcd for $C_8H_6F_3NO_2S_2$ 268.9786, found 268.9785.

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