Highly Selective Fluorinating Agents: A Counteranion-Bound *N*-Fluoropyridinium Salt System

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A series of alkyl- or (trifluoromethyl)-substituted *N*-fluoropyridinium-2-sulfonates **2a–h**, differing in fluorinating power, were synthesized, and assessment was made of the effectiveness of each selective fluorinating agent. *N*-Fluoropyridinium-3- and -4-sulfonates **3** and **4** were also synthesized. Power-variables **2a-h** were found to be highly selective fluorinating agents for a wide range of nucleophilic substrates such as activated aromatics, enol trialkylsilyl and alkyl ethers, active methylene compounds, activated olefins, and sulfides. Thus, phenol, naphthol, phenylurethane, and the trimethylsilyl ether of phenol were exclusively or highly selectively fluorinated at the *o*-position with **2f–h**. Conjugated enol trialkylsilyl ethers of a steroid were regioselectively fluorinated at the 6-position with moderately powerful **2b–e**. This regioselectivity increased with the bulkiness of the silyl part, and with the most bulky triisopropylsilyl group exclusive 6-fluorination was achieved. Preferential β-stereoselective fluorination at the 6-position was observed. *N*-Fluoropyridinium-2-sulfonates were activated with an acid. This acid-catalyzed fluorination led to the preferential *p*-fluorination of anisole. The present results can be explained based on the capacity of the 2-sulfonate anion to interact with the hydroxy group of phenol or naphthol, NH group of phenylurethane, silicon atoms of silyl ethers, or protons of acids.

Introduction

Fluorinated organic compounds are becoming increasingly important for the production of medicines and agricultural chemicals and other useful materials owing to the characteristics of fluorine.[1] Since molecular fluorine is extremely reactive, much effort has been made to develop mild and selective electrophilic fluorinating agents.[2] According, many *N*-fluoro compounds such as *N*-fluoroperfluoropiperidine,[3] *N*-fluoropyridone,[4] *N*-fluorosulfonamide,[5] *N*-fluoropyridinium salts,[6] *N*-fluoroquinuclidinium salts,[7] *N*-fluorobis(perfluoroalkylsulfonyl)-imides,[8] *N*-fluoroamides,[9] *N*-fluorodisulfonimides,[10] and *N*-fluoro-*N'*-alkyl-1,4-diazoniabicyclo[2.2.2]octane salts[11] have been produced.

A series of *N*-fluoropyridinium salts developed by the present authors as power and structure-variable fluorinating agents[6a,d,f] have been successfully applied to the fluorination of a wide range of nucleophilic organic compounds.[6] *N*-Fluoropyridinium-2-sulfonate and its 6-chloro derivative have been shown to have excellent selectivity in fluorination,[6d] but due to low solubility in organic solvents, these reagents exhibited low reactivity or gave products in low yield. *N*-Fluoropyridinium-sulfonates possessing a lipophilic alkyl or trifluoromethyl substituent(s) should be useful for the enhancing fluori-

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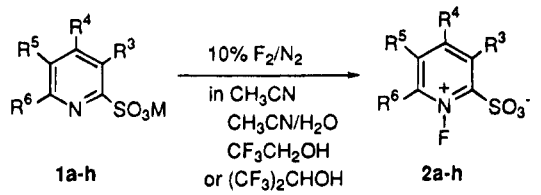
Scheme 1



a $R^{4,6}$=CH_3, $R^{3,5}$=H
b R^4=CH_3, $R^{3,5,6}$=H
c R^4=C_2H_5, $R^{3,5,6}$=H
d R^4=t-C_4H_9, $R^{3,5,6}$=H
e R^6=CH_3, $R^{3,5,6}$=H
f R^5=CF_3, $R^{3,4,6}$=H
g R^5=CF_3, R^3=Cl, $R^{4,6}$=H
h $R^{4,6}$=CF_3, $R^{3,5}$=H

nating reactivity and yield. According to the power variation rule established by the authors,[6d,g,12] an electron-donating alkyl group should decrease the fluorinating power of the *N*-fluoropyridiniumsulfonate, while an electron-withdrawing trifluoromethyl group should increase it. Thus, a new series of power-variable *N*-fluoropyridinium salts, i.e., a counteranion-bound *N*-fluoropyridinium salt system, was developed as a source of highly selective and practically useful fluorinating agents. This paper describes the synthesis of alkyl- and (trifluoromethyl)-substituted *N*-fluoropyridinium-2-sulfonates and their analogs and highly selective fluorination based on novel function of SO_3^- counteranion bound at the 2-position.

Results and Discussion

Synthesis of *N*-Fluoropyridinium-2-Sulfonates and Their Analogs. *N*-Fluoropyridinium-2-sulfonates **2a**–**h** were synthesized by fluorinating the corresponding pyridinesulfonic acids or sodium or amine salts with molecular fluorine (F_2) diluted with nitrogen in acetonitrile, aqueous acetonitrile, or a polyfluoro alcohol (Scheme 1 and Table 1).

The fluorination of 4,6-dimethylpyridine-2-sulfonic acid (**1a**, M = H), which actually exists in zwitterion form (Scheme 2),[13] with 10%F_2/N_2 proceeded very slowly. However, the sodium or amine salt was effectively fluorinated. Thus, *N*-fluoro-4,6-dimethylpyridinium-2-sulfonate (**2a**) was synthesized in high yield by fluorinating **1a** (M = Na) or **1a** (M = Et_3NH) with 10%F_2/N_2 in aqueous acetonitrile at low temperature (runs 1 and 2 in Table 1). Pyridinesulfonic acids, more acidic than **1a** (M = H), were easily fluorinated. The fluorination of 4-methyl-, -ethyl-, -*tert*-butyl-, and 6-methylpyridinesulfonic acids **1b**–**e** (M = H) in anhyd acetonitrile or aqueous acetonitrile gave *N*-fluoro-4-methyl-, -ethyl-, -*tert*-butyl-, and -6-methylpyridinium-2-sulfonates **2b**–**e** in good yields, respectively (runs 3, 7, 8, and 9). *N*-Fluoro-5-(trifluoromethyl)-, -3-chloro-5-(trifluoromethyl)-, and -4,6-bis(trifluoromethyl)pyridinium-2-sulfonates **2f**, **2g**, and **2h** were synthesized in high yields by fluorinating the corresponding sulfonic acids in anhyd acetonitrile (runs 10, 13, and 15). The above results indicate that the ease of fluorination depends on N^+–H bonding strength in zwitterion form. Thus, weak acids of strong N^+–H bonding such as **1a** (M = H) are inactive, while strong acids of weak N^+–H bonding such as **1b**–**h** (M = H) are reactive toward F_2. The most acidic **1h** (M = H) could easily undergo fluorination even at −40 °C (run 15). The nonzwitterionic form may be the species undergoing fluorination (Scheme 2).

The addition of a catalytic amount (5–10 mol %) of triethylamine was effective for the fluorination. Thus, the fluorination of pyridinesulfonic acids **1b** (M = H) and **1f** (M = H) in the presence of 5 mol % of triethylamine gave high yields of **2b** and **2f** (runs 4 and 11). Under the conditions without triethylamine, **2b** and **2f** were hardly obtained. Success in the use of catalytic triethylamine for the easy fluorination suggests the base-catalytic action of $Et_3NH^+F^-$ produced through fluorination. When triethylamine was not used but the solvent was used in excess to dissolve **1f**, a high yield of **2f** was obtained (run 10).

Fluorination capacity depends on the solubility of pyridinesulfonic acids or their salts in a given solvent. Acetonitrile poorly or scarcely dissolves most pyridinesulfonic acids. Water or alcohols dissolve these acids, but they decompose the products if they are an electron-withdrawing group(s)-substituted *N*-fluoropyridiniumsulfonates. Polyfluoro alcohols were found to be superior solvents for fluorination. Polyfluoro alcohols easily dissolve pyridinesulfonic acids or their salts without the product decomposition. Sulfonic acids **1f** (M = H) and **1g** (M = H) could thus be fluorinated in 1,1,1,3,3,3-hexafluoro-2-propanol to give sulfonates **2f** and **2g** in high yields, respectively (runs 12 and 14). Sodium salt **1b** (M = Na) was fluorinated in 2,2,2-trifluoroethanol and in hexafluoro-2-propanol to give sulfonate **2b** in high yields (runs 5 and 6).

N-Fluoropyridinium-2-sulfonate (**2**) was first synthesized by the fluorination of 2-pyridinesulfonic acid in aqueous acetonitrile (Figure 1).[6f] However, this method was not applicable to the syntheses of *N*-fluoropyridinium-3- and -4-sulfonates **3** and **4**, possibly since the starting 3- and 4-pyridinesulfonic acids were not soluble in the solvent. 3-Sulfonate **3** was synthesized in 87% yield by fluorination in 1,1,1,3,3,3-hexafluoro-2-propanol at 0 °C in the presence of an solid amine resin, Amberlite. 2-Sulfonate **2** was prepared in 80% yield in the same manner. After fluorination, the solid resin could be removed by filtration. But, with 4-pyridinesulfonic acid, this method hardly afforded 4-sulfonate **4**. This may have been due to the acidity of 4-pyridinesulfonic acid; the pK_a's of 2-, 3-, and 4-pyridinesulfonic acids were 1.75, 3.22, and 3.44, respectively.[14] Sulfonate **4** was synthesized in 74% yield by the fluorination of reactive sodium pyridine-4-sulfonate in hexafluoro-2-propanol at 0 °C.

All *N*-fluoropyridiniumsulfonates synthesized above were stable crystals that could be easily handled.

The starting materials, 5-(trifluoromethyl)-, 3-chloro-5-(trifluoromethyl)-, and 4,6-bis(trifluoromethyl)pyridine-2-sulfonic acids **1f** (M = H), **1g** (M = H), and **1h** (M = H) were prepared in high yields by treating the corresponding 2-chloropyridines **5**, **6**, and **7** with sodium sulfite (Scheme 3).

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Table 1. Synthesis of *N*-Fluoropyridinium-2-Sulfonates 2a–h

run[a]	starting material	solvent	additive	T^b (°C)	product	yield[c] (%)
1	**1a** (M = Na) 20 mmol	CH_3CN/H_2O (10/1) 44 mL		−20	**2a**	88
2	**1a** (M = Et_3NH) 2 mmol	CH_3CN/H_2O (100/1) 4.04 mL		−40	**2a**	78
3	**1b** (M = H) 20 mmol	CH_3CN/H_2O (10/1) 66 mL		−20	**2b**	80
4	**1b** (M = H) 10 mmol	CH_3CN 10 mL	Et_3N 0.5 mmol	−20	**2b**	91
5	**1b** (M = Na) 3 mmol	CF_3CH_2OH 6 mL		0	**2b**	92
6	**1b** (M = Na) 3 mmol	$(CF_3)_2CHOH$ 6 mL		0	**2b**	89
7	**1c** (M = H) 10 mmol	CH_3CN 20 mL		−20	**2c**	79
8	**1d** (M = H) 20 mmol	CH_3CN/H_2O (20/1) 42 mL		−20	**2d**	84
9	**1e** (M = H) 60 mmol	CH_3CN/H_2O (10/1) 120 mL		−20	**2e**	65
10	**1f** (M = H) 1 mmol	CH_3CN 65 mL		−10	**2f**	86
11	**1f** (M = H) 2 mmol	CH_3CN 4 mL	Et_3N 0.1 mmol	−20	**2f**	95
12	**1f** (M = H) 5 mmol	$(CF_3)_2CHOH$ 10 mL		0	**2f**	90
13	**1g** (M = H) 10 mmol	CH_3CN 20 mL		−10	**2g**	84
14	**1g** (M = H) 1.82 mmol	$(CF_3)_2CHOH$ 4 mL		0	**2g**	88
15	**1h** (M = H) 2.64 mmol	CH_3CN 6 mL		−40	**2h**	95

[a] See Experimental Section. [b] Bath temperature. [c] Isolated yields.

Scheme 2

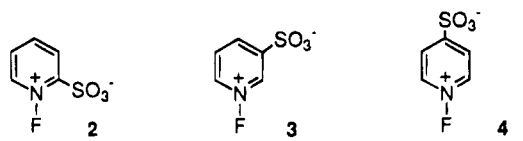
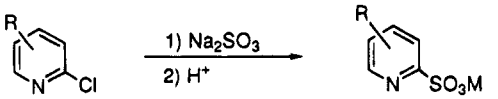


Figure 1.

Fluorination with *N*-Fluoropyridinium-2-sulfonates and Their Analogs. Since the fluorinating power of the *N*-fluoropyridinium salt system correlates with the pK_a of the pyridines,[6d,g,12] the fluorinating power of **2a–h** should increase in the order **2a** < **2b** ~ **2c** ~ **2d** ~ **2e** < **2f** < **2g** < **2h**. These substituted *N*-fluoropyridinium-2-sulfonates were successfully used as highly selective fluorinating agents according to our fluorination concept; the more powerful *N*-fluoropyridinium salts effectively fluorinate less reactive nucleophiles such as aromatics and olefins, while less powerful *N*-fluoro salts effectively fluorinate more reactive nucleophiles such as carbanions and heteroatom compounds and intermediately powerful *N*-fluoro salts effectively fluorinate intermediately reactive nucleophiles such as enol alkyl and trialkylsilyl ethers.[6d]

Table 2 shows the results of the fluorination of phenol with *N*-fluoropyridinium-2-, -3-, and -4-sulfonates **2**, **2b**, **2f-h**, **3**, and **4**. The most powerful **2h** smoothly fluorinated phenol in dichloromethane under mild conditions to give almost exclusively *o*-fluorinated phenol (*o*/*p* ≥ 40/1) in high yield (runs 5 and 6). *p*-Fluorophenol (≤ 2%) could be detected only in trace amounts by gas chromatography. Sulfonates **2g**, **2f**, and **2b** underwent similar exclusive *o*-fluorination (*o*/*p* ≥ 57/1), though a higher temperature or longer reaction time was needed in the order of **2g** < **2f** < **2b** (runs 3, 2, and 1). Methyl-substituted **2b** was faster than unsubstituted **2** (runs 1 and 10), although the actual fluorinating power of **2b** is less than **2** since the 4-methyl substituent increases the pK_a.[15] This demonstates the effectiveness of the lipophilic alkyl substituent. 3-Sulfonate **3** was much slower in fluorination than **2**, and its *o*-selectivity decreased greatly (run 11). 4-Sulfonate **4** underwent virtually no reaction even after 11 days (run 12). A non-counteranion-bound salt, *N*-fluoro-3,5-dichloropyridinium triflate, gave a reduced *o*/*p* ratio (3.3/1) of phenol.[6d] Thus, the almost exclusive *o*-fluorination by counteranion-bound *N*-fluoro salts may be explained by hydrogen bonding interactions between SO_3^- anions and phenol hydroxy groups in transition state **8** through π-complexation between the π-electron-deficient pyridinium ring and π-electron-rich phenol ring (Scheme 4), as previously proposed.[6d] This possibility is further supported by the new findings that polar acetonitrile and 1,1,1,3,3,3-hexafluoro-2-propanol solvent gave reduced *o*/*p* ratios (3.3/1 in run 7 and 4/1 in run 8) and that the addition of triflic acid led to a reduced

Scheme 3



5; R=5-CF_3 **1f** (M=H); 88%

6; R=3-Cl-5-CF_3 **1g** (M=H); 92%

7; R=4,6-di-CF_3 **1h** (M=H); 97%

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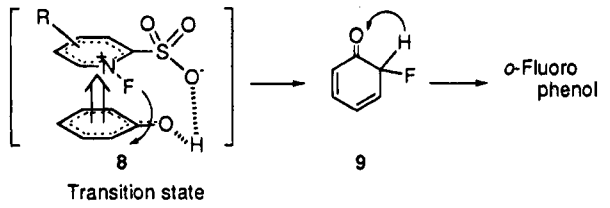
Table 2. Fluorination of Phenol with *N*-Fluoropyridiniumsulfonates

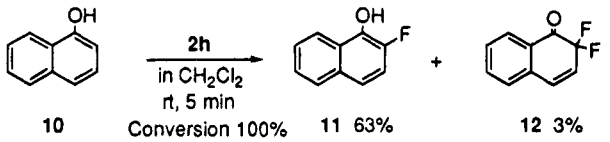
run	"F+"	solvent	*T* (°C)	time[a] (h)	additive	convn[b] (%)	product[c] (%)		
							o-fluorophenol	*p*-fluorophenol	2,4-difluorophenol
1	**2b**	Cl_2CHCH_2Cl	100	24		81	57	<1	0
2	**2f**	Cl_2CHCH_2Cl	100	18		71	59	<1	0
3	**2g**	Cl_2CHCH_2Cl	100	1.5		85	88	<1	0
4	**2h**	Cl_2CHCH_2Cl	100	0.05		81	72	3	0
5	**2h**	CH_2Cl_2	reflux	2		88	80	2	0
6	**2h**	CH_2Cl_2	rt	13		87	84	1	0
7	**2h**	CH_3CN	40	3		82	63	20	11
8	**2h**	$(CF_3)_2CHOH$	5	0.25		83	52	13	6
9	**2h**	CH_2Cl_2	rt	2.5	TfOH(1 equiv)	88	44	12	8
10	**2**	Cl_2CHCH_2Cl	100	84		85	87	<1	0
11	**3**	Cl_2CHCH_2Cl	100	11 days		57	23	12	<1
12[d]	**4**	Cl_2CHCH_2Cl	100	11 days		3			

[a] Each reaction time was the time when *N*-fluoropyridinium-sulfonate was consumed, except for run 12. [b] Determined by GC. [c] Determined by GC on the basis of the consumed phenol. [d] The reaction hardly occurred, and 97% of phenol remained intact.

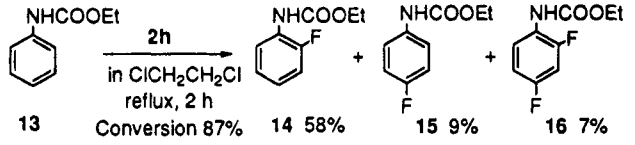
Scheme 4



Scheme 5



Scheme 6



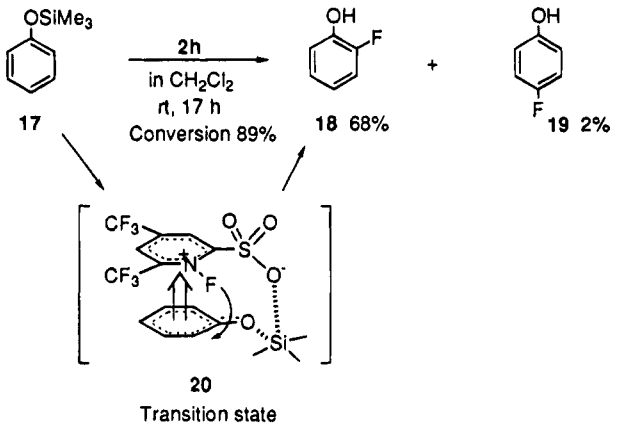
o/p ratio (3.5/1, run 9). The polar solvents or the acid may destroy the hydrogen bonding and thus the exclusive *o*-fluorination may disappear.

As is evident from a comparison with run 6, hexafluoro-2-propanol and triflic acid greatly shortened reaction time, since the fluoro alcohol freely dissolved the *N*-fluoro salt **2h** and triflic acid activates **2h** by protonating the sulfonate counteranion, as will be discussed later. The fluoro alcohol may also activate **2h** to some extent, being weakly acidic.

1-Naphthol was fluorinated exclusively at *o*-position to give 2-fluoro-1-naphthol (**11**) and 2,2-difluoro-1(2*H*)-naphthalenone (**12**) (Scheme 5).

As shown in Scheme 6, phenylurethane, an aniline derivative, was fluorinated with **2h** to give *o*-fluoro isomer **14** highly selectively (*o/p* = 6.4/1). Fluorination with **2g** gave similar selectivity and yields (*o/p* = 7.8/1: *o*-F **14**, 70%; *p*-F **15**, 9%; 2,4-di-F **16**, 2%; conversion 64%) under the same conditions except for longer reaction time (15.5 h). This high selectivity may be explained by hydrogen bonding interactions between SO_3^- and NH in the transition state through the π-complexation.[6d] The use of 1,1,1,3,3,3-hexafluoro-2-propanol solvent for the fluorination with **2h** gave low selectivity (*o/p* = 2.5/1: **14**, 48%; **15**, 19%; **16**, 8%; conversion 88%), and reaction time was greatly shortened (rt, 2.5 h).

Scheme 7



As mentioned above, OH and NH groups have great influence on selectivity. In regard to silicon atoms, the fluorination of a trimethylsilyl ether of phenol was found to bring about highly selective *o*-fluorination (*o/p* = 34/1, Scheme 7). This may indicate interactions between SO_3^- and silicon atoms in transition state **20** through the π-complexation. This π-complexation results in a great decrease in electron density of the silyl phenol rings, which may activate the silyl atoms. Thus, the close sulfonate anions can interact with the silyl atoms. These may be coordinating interactions of SO_3^- with silicon, since activated tetrasubstituted silicon atoms have the capacity to form a pentacovalent element.[16]

The SO_3^- substituent of *N*-fluoropyridiniumsulfonates can act as a proton acceptor. A strong acid should possibly accelerate fluorination because protonation converts the *N*-fluoropyridinium-2-sulfonate into the more reactive *N*-fluoro-2-sulfopyridinium salt **21** as shown in Scheme 8. The electron-withdrawing effect of SO_3H should be much greater than that of SO_3^-.

Table 3 shows the acid-catalyzed fluorination of anisole. With **2h**, the addition of an equivalent amount of triflic acid resulted in fast fluorination and preferential *p*-fluorination (0.3 h, *o/p* = 26/54), compared to the case without triflic acid (29.5 h, *o/p* = 30/46). A catalytic amount of triflic acid was effective (run 2). These findings support catalytic protonation to the SO_3^-. Re-

(16) (a) Bassindale, A. R.; Taylor, P. G. In *The Chemistry of Organic Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons, Ltd.: Chichester, 1989; Part 1, pp 839–892. (b) Corriu, R. J. P.; Young, J. C. In *The Chemistry of Organic Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons, Ltd.: Chichester, 1989; Part 2, pp 1241–1288.

Scheme 8

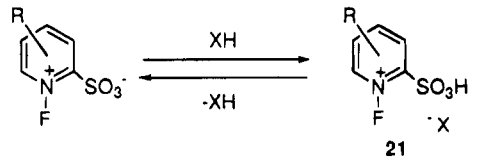


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Table 3. Acid-Catalyzed Fluorination of Anisole with *N*-Fluoropyridiniumsulfonates

run[a]	"F+"	additive	time[b] (h)	convn[c] (%)	product[d] (%) *o*-fluoroanisole	*p*-fluoroanisole
1	**2h**	TfOH (1 equiv)	0.3	85	26	54
2	**2h**	TfOH (0.1 equiv)	5.5	81	30	53
3	**2h**	none	29.5	80	30	46
4	**2g**	TfOH (1 equiv)	3	79	35	44

[a] Each reaction was carried out in 4 mL of anhyd dichloromethane under reflux using 1 mmol of anisole and 1 mmol of *N*-fluoropyridiniumsulfonate. [b] Each reaction time was the time when *N*-fluoropyridiniumsulfonate was consumed. [c] See *b* in Table 2. [d] Determined by GC on the basis of the consumed anisole.

Table 4. Fluorination of Enol Silyl Ether 23a–d with *N*-Fluoropyridiniumsulfonates 2 and 2b–e and *N*-Fluoropyridinium Triflate (22)

run	"F+"	substrate	solvent	time[a] (h)	product[b] (%) **24** (α/β)[c]	**25**[d]	ratio[b] **24/25**
1	**2b**	**23a**	CH_2Cl_2	20	72 [69][e] (1/3.5)	5[1][e]	14/1
2	**2b**	**23a**	CH_3CN	11	83 (1/3.4)	11	7.5/1
3	**2b**	**23a**	DMF	3.5	88 (1/3.9)	12	8/1
4	**2b**	**23b**	CH_2Cl_2	48	92 (1/3.8)	1	92/1
5	**2b**	**23c**	CH_2Cl_2	66	90 (1/3.5)	<1	>92/1
6	**2b**	**23d**	CH_2Cl_2	90	93 (1/3.8)	0	infinite
7	**2c**	**23a**	CH_2Cl_2	24	67 (1/3.8)	5	13/1
8	**2d**	**23a**	CH_2Cl_2	24	70 (1/4)	7	10/1
9	**2e**	**23a**	CH_2Cl_2	30	30 (1/5)	5	6/1
10	**2**	**23a**	CH_2Cl_2	47	24 (1/3.8)	2	12/1
11	**22**	**23a**	CH_2Cl_2	4	36 (1/1.8)	15	2.4/1
12	**22**	**23d**	CH_2Cl_2	2.5	33 (1/1.5)	8	4.1/1

[a] Each reaction time was the time when **23a**, **b**, **c**, or **d** was consumed. [b] Determined by ^{19}F-NMR on the basis of the enol silyl ethers used, unless otherwise noted. [c] α and β mean 6α- and 6β-fluoro isomers, respectively. [d] Product **25** was one isomer, but its configuration of 4-position was not determined.[6d] [e] Isolated yields.

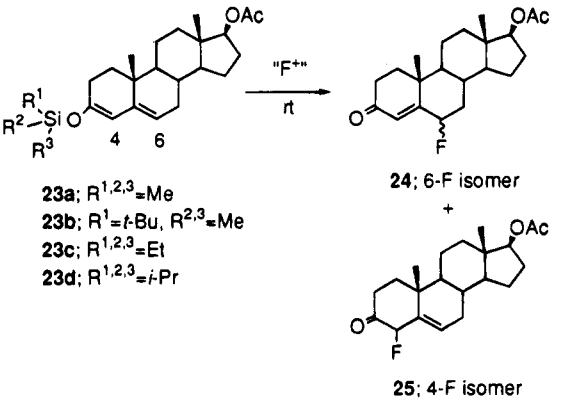
sults obtained with **2g** may be explained similarly (run 4). Preferential *p*-fluorination by **2h** may be due to the bulkiness around the N–F part of the protonated *N*-fluoro salt **21** with consequent repulsion of the methoxy group of anisole.

Table 4 shows the fluorination of conjugated enol trialkylsilyl ethers **23a–d** of a steroid with *N*-fluoropyridinium-2-sulfonates **2b–e** and **2** and the non-counteranion-bound salt, *N*-fluoropyridinium triflate (**22**).

As seen in run 1, **2b** reacted with trimethylsilyl ether **23a** in dichloromethane at room temperature to give high regioselectivity and yield of 6-fluoro isomer **24** (**24/25** = 14/1). Lipophilic methyl-substituted salt **2b** greatly improved the yield, compared with unsubstituted salt **2** (run 10). Runs 1, 4, 5, and 6 showed its regioselectivity to greatly increase with bulkiness of the silyl part. The most bulky triisopropylsilyl group exclusively gave **24** in high yield (run 6). In contrast, non-counteranion-bound salt, *N*-fluoropyridinium triflate (**22**) (runs 11 and 12) gave low regioselectivity and yield of **24**, even in the case of the most bulky silyl group (run 12) (Scheme 9).

As shown in Scheme 10, the above high regioselectivity of 6-fluoro isomer **24** with counteranion-bound salts may

Scheme 9



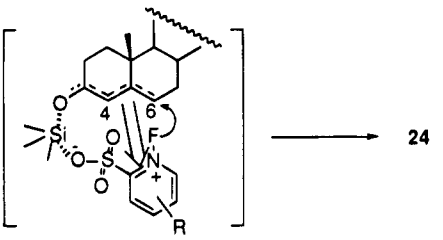
23a; $R^{1,2,3}$=Me
23b; R^1=*t*-Bu, $R^{2,3}$=Me
23c; $R^{1,2,3}$=Et
23d; $R^{1,2,3}$=*i*-Pr

24; 6-F isomer

+

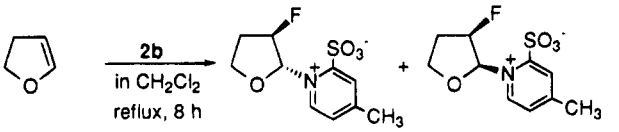
25; 4-F isomer

Scheme 10



26

Scheme 11



27 **28** 59% **29** 16%

be explained by interactions between SO_3^- and silicon atoms in transition state **26** through π-complexation between the π-electron-deficient pyridinium ring and the π-electron-rich conjugated enol silyl ether moiety, similar to the case of the trimethylsilyl ether of phenol, discussed above. Thus, the silicon–oxygen interactions facilitate fluorination at the 6-position. This was supported by the fact that polar solvents, acetonitrile and dimethylformamide, decreased the selectivity (runs 2 and 3). The observed shorter reaction time may be attributed to high or free solubilization of **2b** by these polar solvents.

Regarding α/β-stereoselectivity of the 6-position of **24**, these conteranion-bound salts produced the thermodynamically less stable 6β isomer more preferentially (α/β = 1/3.4–1/5) than non-counteranion-bound salt **22** (α/β = 1/1.5–1/1.8) (Table 4). More bulky 6-methyl salt **2e** gave the highest β-stereoselectivity (α/β = 1/5, run 9). The explanation for this is not clear at present.

2,3-Dihydrofuran, an enol alkyl ether, was fluorinated with **2b** to give a 3.7:1 mixture of trans **28** and cis adduct **29** (Scheme 11). Non-counteranion-bound salt **22** gave a 1:1 mixture of the corresponding trans and cis adducts.[6d]

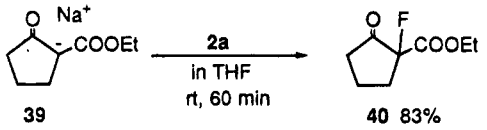
As shown in Table 5, β-dicarbonyl compounds were easily fluorinated with the most powerful **2h**. **2h** reacted with 2-acetylcyclohexanone (**30**) in THF to give fluoride **31** in high yield. The fluorination of 1,3-diphenyl-1,3-propanedione (**32**) gave the corresponding monofluoride **33** almost exclusively (run 2). Difluoride **34** was obtained in only trace amounts. Similar exclusive monofluorination by *N*-fluorobis[(trifluoromethyl)sulfonyl]imide in dichloromethane–water has been reported.[8e,f] When

Table 5. Fluorination of β-Dicarbonyl Compounds with *N*-Fluoro-4,6-bis(trifluoromethyl)pyridinium-2-sulfonate (2h)

run	β-dicarbonyl compd	solvent	*T* (°C)	time (h)	product	yield[a] (%)
1	$CH_2(CH_2)_2CH_2COCHCOCH_3$ (**30**)	THF	rt	1	$CH_2(CH_2)_2CH_2COCFCOCH_3$ (**31**)[b]	83
2	$PhCOCH_2COPh$ (**32**)	THF	rt	16	PhCOCHFCOPh (**33**)	66
					$PhCOCF_2COPh$ (**34**)	trace
3	**32**	$(CF_3)_2CHOH$	rt	0.33	**33**	46
					34	17
4	$CH_2CH_2CH_2COCHCOOEt$ (**35**)	THF	rt	46	$CH_2CH_2CH_2COCFCOOEt$ (**36**)	84
5	$CH_2(CH_2)_2CH_2COCHCOOEt$ (**37**)	$(CF_3)_2CHOH$	rt	0.5	$CH_2(CH_2)_2CH_2COCFCOOEt$ (**38**)	98

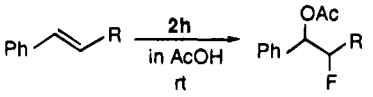
[a] Determined by ^{19}F NMR. [b] Lerman, O.; Rozen, S. *J. Org. Chem.* **1983**, *48*, 724.

Scheme 12



39 40 83%

Scheme 13



41; R=H; 24%
42; R=CH_3; 51%

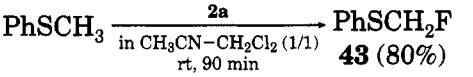
1,1,1,3,3,3-hexafluoro-2-propanol was used as a solvent, a 2.7:1 mixture of mono- and difluorides **33** and **34** was obtained (run 3), possibly since the fluoro alcohol activated **2h** to some extent as discussed above or enolized monofluoride **33**. β-Keto esters **35** and **37** were fluorinated to give fluorides **36** and **38** in high yields, respectively.

The sodium salts of dicarbonyl compounds were fluorinated with the least powerful **2a**, as also noted for *N*-fluoro-2,4,6-trimethylpyridinium triflate.[6c] **2a** reacted with sodium salt **39** to give fluoro product **40** in high yield (Scheme 12).

Sulfonate **2h** reacted with styrene in acetic acid for 18 h to give fluoro acetoxy adduct **41** in low yield (Scheme 13). The fluorination of β-methylstyrene occurred more smoothly (1.5 h) to give adduct **42** in fairly good yield. Product **42** was a 1:1 mixture of threo and erythro isomers. The reactivity of **2h** is lower than that of *N*-fluoropentachloropyridinium triflate or tetrafluoroborate because the latter reacts with styrene more smoothly than **2h** to give a high yield of adduct **41**.[6d]

Sulfonate **2a** reacted with thioanisole in a 1:1 mixture of acetonitrile and dichloromethane to give α-fluoro sulfide **43** in high yield (Scheme 14). This reaction was

Scheme 14



greatly dependent on the solvent. Thus, acetonitrile gave 42% of **43**, while dichloromethane yielded no **43**. In contrast, non-counteranion-bound salt *N*-fluoro-2,4,6-trimethylpyridinium triflate gave a 87% yield of **43** in dichloromethane.[6c]

Conclusion

We have developed a new series of power-variable *N*-fluoropyridinium salts, alkyl or (trifluoromethyl)-substituted *N*-fluoropyridinium-2-sulfonates, which make possible the highly selective fluorination of a wide range of nucleophiles. The present study demonstrates not only the high effectiveness of the lipophilic alkyl and trifluoromethyl substituents but also the novel function of the 2-sulfonate anion to act as a hand, so to speak, for fixing the *N*-fluoropyridinium salt system in fluorination. The sulfonate anion substituent also changes into the strongly electron-withdrawing substituent SO_3H by protonation, which greatly increases fluorinating capability. In addition, compared to non-counteranion-bound *N*-fluoropyridinium salts, these counteranion-bound salts facilitate the separation of fluorinated products from pyridinesulfonic acids reproduced, because the pyridinesulfonic acids are soluble in an aqueous layer. The recovered pyridinesulfonic acids reproduce *N*-fluoropyridinium-sulfonates. The counteranion-bound *N*-fluoropyridinium salts should thus be useful as fluorinating agents in the preparation of numerous organofluorine compounds.

Experimental Section

General Methods. Melting points were uncorrected. ^1H and ^{19}F NMR spectra were recorded at 200 or 500 MHz and 188 or 470 MHz, respectively. The solvents for ^{19}F NMR were the same as for ^1H NMR, unless otherwise noted, and ^{19}F chemical shifts were given in ppm downfield from $CFCl_3$ as an internal standard. Mass spectra were obtained at 70 eV by the EI method. The fluorination apparatus was reported previously.[6e,g]

Materials. Enol trialkylsilyl ethers **23a–d** were prepared by reported methods.[17] 4- and 6-Methyl-, 4-ethyl-, 4-*tert*-butyl-, and 4,6-dimethylpyridine-2-sulfonic acids were prepared according to known methods.[18,19] The solvents used for the reactions were dried by usual methods before use.

Synthesis of Pyridine-2-sulfonic Acids 1f (M = H), 1g (M = H), and 1h (M = H). Chloropyridine **5** (500 mmol) and Na_2SO_3 (600 mmol) were added to 400 mL of EtOH and H_2O (1:3), and the mixture was heated in an autoclave for 10.5 h at 140 °C. Chloropyridine **6** (500 mmol) and Na_2SO_3 (600 mmol) were added to 400 mL of EtOH and H_2O (1:3), and the mixture was heated in an autoclave for 10.5 h at 130 °C. Chloropyridine **7** (80 mmol) and Na_2SO_3 (88 mmol) were added to 72 mL of EtOH and H_2O (1:5), and the mixture was heated in an autoclave for 6.5 h at 180 °C. Sodium pyridine-2-sulfonate **1f** (M = Na) or **1g** (M = Na) separated from the reaction mixture as a precipitate, which was collected by filtration after standing. If needed, the filtrate was concen-

(17) Larson, G. L. In *The Chemistry of Organic Silicon Compounds*; Patai, S.,Rappoport, Z., Eds.; John Wiley & Sons, Ltd.: Chichester, 1989; Part 1, pp 763–808.

(18) Delarge J. *Il Farmaco, Ed. Sc.* **1967**, *22*, 1069.

(19) Data of new compounds are as follows. **4-Ethyl-2-pyridinesulfonic acid**: mp 221–223 °C (EtOH); ^1H NMR (D_2O) δ 1.32 (3H, t, *J* = 7.6 Hz, CH_3), 2.98 (2H, q, *J* = 7.6Hz, CH_2), 7.92 (1H, dd, *J* = 5.9, 1.8 Hz, 5-H), 8.18 (1H, d, *J* = 1.8 Hz, 3-H), 8.62 (1H, d, *J* = 5.9 Hz, 6-H); IR (KBr) 1310 (SO_2) cm^{-1}; MS *m/z* 188 ($M^+ + 1$). Anal. Calcd for $C_7H_9NO_3S$: C, 44.91; H, 4.85; N, 7.48. Found: C, 44.93; H, 4.85; N, 7.55. **4-*tert*-Butyl-2-pyridinesulfonic acid**: mp 296–297 °C (CH_3CN); ^1H NMR (D_2O) δ 1.41 (9H, s, CH_3), 8.08 (1H, dd, *J* = 6.1, 2.0 Hz, 5-H), 8.30 (1H, dd, *J* = 2.0, 0.6 Hz, 3-H), 8.65 (1H, dd, *J* = 6.1, 0.6 Hz, 6-H); IR (Nujol) 1265 (SO_2) cm^{-1}; MS *m/z* 216 (M^++1). Anal. Calcd for $C_9H_{13}NO_3S$: C, 50.22; H, 6.09; N, 6.51. Found: C, 50.22; H, 6.06; N, 6.47.

trated, giving an additional precipitate. Total yields of **1f** (M = Na) and **1g** (M = Na) were 88 and 92%, respectively. In the case of **7**, the resulting reaction mixture was evaporated to dryness under reduced pressure. The residue was extracted with MeOH, and the extract was filtered and evaporated to dryness under reduced pressure to give **1h** (M = Na) in 97% yield. Each sodium pyridine-2-sulfonate, which was dried at 120 °C for 4–5 h in vacuo, was mixed with concd hydrochloric acid [40 mL per gram of **1f** (M = Na) or **1g** (M = Na); 10–20 mL per gram of **1h** (M = Na)]. The resulting NaCl precipitate was removed by filtration, and the filtrate was evaporated to dryness under reduced pressure to give pyridine-2-sulfonic acid **1f** (M = H), **1g** (M = H), or **1h** (M = H) quantitatively.

5-(Trifluoromethyl)-2-pyridinesulfonic acid [1f (M = H)]: mp 290–315 °C (with dec) (recrystallization solvent, CH_3CN); ^1H NMR (D_2O) δ 8.11 (1H, dm, J = 8.3Hz, 3-H), 8.38 (1H, dm, J = 8.3Hz, 4-H), 8.96 (1H, m, 6-H); ^{19}F NMR (DMSO-d_6) −60.4 (s, CF_3); IR (KBr) 1229 (SO_2) cm^{-1}; MS m/z 228 ($M^+ + 1$). Anal. Calcd for $C_6H_4F_3NO_3S$: C, 31.72; H, 1.77; N, 6.17. Found: C, 31.71; H, 1.68; N, 6.13.

3-Chloro-5-(trifluoromethyl)-2-pyridinesulfonic acid [1g (M = H)]: mp 310–325 °C (with dec) (CH_3CN); ^1H NMR (D_2O) δ 8.47 (1H, m, 4-H), 8.83 (1H, m, 6-H); ^{19}F NMR −60.3 (s, CF_3); IR (KBr) 1287 (SO_2) cm^{-1}; MS m/z 260 ($M^+ + 1$), 262 ($M^+ + 1$). Anal. Calcd for $C_6H_3ClF_3NO_3S$: C, 27.55; H, 1.16; N, 5.35. Found: C, 27.42; H, 1.08; N, 5.27.

4,6-Bis(trifluoromethyl)-2-pyridinesulfonic acid [1h (M = H)]: mp 205–207 °C (with dec) ($ClCH_2CH_2Cl$); ^1H NMR (CD_3CN) δ 8.30 (1H, bs, 5-H), 8.44 (1H, bs, 3-H); ^{19}F NMR −63.9 (3F, s, 6-CF_3), −67.2 (3F, s, 4-CF_3); IR (KBr) 3447 (br) (OH), 1283 (SO_2) cm^{-1}; MS m/z ($M^+ + 1$). Anal. Calcd for $C_7H_3F_6NO_3S \cdot 1/2H_2O$: C, 27.64; H, 1.33; N, 4.60. Found: C, 27.63; H, 1.20; N, 4.86.

Synthesis of *N*-Fluoropyridinium-2-sulfonates. General Procedure. A reaction flask was charged with a pyridinesulfonic acid, a solvent, and, if necessary, an additive. The amounts of pyridinesulfonic acids, solvents, and additive used are shown in Table 1. The charged flask was purged with N_2 and placed on a cooling bath of the temperature shown in Table 1. A 10% F_2-90% N_2 mixture gas was then introduced at a flow rate of 2–15 mL min^{-1} per 1 mmol of the pyridinesulfonic acid, just above the surface of the rapidly stirred reaction mixture. The amount of F_2 used was 3 equiv to the pyridinesulfonic acid. After the flow of F_2 was stopped, N_2 only was passed through the flask at rate of 15–30 mL min^{-1} for 30 min, while keeping the reaction mixture at the same temperature. The post-treatment for run 1 (Table 1) was as follows. The reaction mixture was evaporated to dryness under reduced pressure, and the residue was extracted with CH_3CN. The extract was filtered and evaporated to dryness under reduced pressure to give **2a**. For runs 2, 3, 8, and 9, large amounts of Et_2O, THF and Et_2O, THF, and THF and EtOAc, respectively, were added to the reaction mixtures to give the *N*-fluoropyridinium-sulfonates as precipitates, which were collected by filtration. For runs 4–7 and 10–15, the reaction mixtures were evaporated to dryness and the residue was washed with some AcOEt to give crystals of the *N*-fluoropyridinium sulfonates. The product yields are shown in Table 1. *N*-Fluoropyridinium-sulfonates recrystallized from solvents shown below were used as fluorinating agents in the present study.

***N*-Fluoro-4,6-dimethylpyridinium-2-sulfonate (2a)**: mp 207–212 °C (with dec) (recrystallization solvent; CH_3CN–Et_2O); ^1H NMR (CD_3CN) δ 2.60 (3H, m, 4-CH_3), 2.79 (3H, d, J = 4.1 Hz, 6-CH_3), 7.75 (1H, dd, J = 6.2, 2.7 Hz, 5-H), 8.12 (1H, dd, J = 5.4, 2.7 Hz, 3-H); ^{19}F NMR 19.8 (bs, NF); IR (Nujol) 1263 (SO_2) cm^{-1}; MS m/z 206 ($M^+ + 1$). Anal. Calcd for $C_7H_8FNO_3S$: C, 40.97; H, 3.93; N, 6.83. Found: C, 40.69; H, 3.84; N, 6.90.

***N*-Fluoro-4-methylpyridinium-2-sulfonate (2b)**: mp 203–208 °C (with dec) (CH_3CN); ^1H NMR (CD_3CN) δ 2.67 (3H, m, 4-CH_3), 7.88 (1H, m, 5-H), 8.31 (1H, ddm, J = 6.1, 2.7 Hz, 3-H), 8.86 (1H, dd, J = 14.4, 7.2 Hz, 6-H); ^{19}F NMR 32.6 (bs, NF); IR (Nujol) 1285 (SO_2) cm^{-1}; MS m/z 192 ($M^+ + 1$). Anal. Calcd for $C_6H_6FNO_3S$: C, 37.70; H, 3.16; N, 7.33. Found: C, 37.87; H, 2.92; N, 7.40.

***N*-Fluoro-4-ethylpyridinium-2-sulfonate (2c)**: mp 196.5–198.5 °C (with dec) (CH_3CH_2CN); ^1H NMR (CD_3CN) δ 1.31 (3H, t, J = 7.5 Hz, CH_3), 2.99 (2H, q, J = 7.5 Hz, CH_2), 7.94 (1H, m, 5-H), 8.31 (1H, ddm, J = 6.1, 2.8 Hz, 3-H), 8.92 (1H, dd, J = 14.4, 7.2 Hz, 6-H); ^{19}F NMR 32.9 (bs, NF); IR (Nujol) 1255 (SO_2) cm^{-1}; MS m/z 206 ($M^+ + 1$). Anal. Calcd for $C_7H_8FNO_3S$: C, 40.97; H, 3.93; N, 6.83. Found: C, 41.10; H, 3.84; N, 6.90.

***N*-Fluoro-4-*tert*-butylpyridinium-2-sulfonate (2d)**: mp 237–240 °C (CH_3CN); ^1H NMR (CD_3CN) δ 1.41 (9H, s, CH_3), 8.07 (1H, ddd, J = 7.4, 6.4, 3.0 Hz, 5-H), 8.38 (1H, dd, J = 6.0, 3.0 Hz, 3-H), 8.93 (1H, dd, J = 14.2, 7.4 Hz, 6-H); ^{19}F NMR 33.0 (bs, NF); IR (Nujol) 1260 (SO_2) cm^{-1}; MS m/z 234 ($M^+ + 1$). Anal. Calcd for $C_9H_{12}FNO_3S$: C, 46.34; H, 5.19; N, 6.00. Found: C, 46.12; H, 5.43; N, 6.22.

***N*-Fluoro-6-methylpyridinium-2-sulfonate (2e)**: mp 192–195 °C (CH_3CN); ^1H NMR (CD_3CN) δ 2.86 (3H, d, J = 4.2 Hz, 6-CH_3), 7.94 (1H, ddd, J = 7.8, 7.8, 2.1 Hz, 5-H), 8.28 (1H, ddd, J = 7.8, 5.8, 2.1 Hz, 3-H), 8.42 (1H, ddd, J = 7.8, 7.8, 0.7 Hz, 4-H); ^{19}F NMR 27.7 (bs, NF); IR (Nujol) 1260 (SO_2) cm^{-1}; MS m/z 192 ($M^+ + 1$). Anal. Calcd for $C_6H_6FNO_3S$: C, 37.70; H, 3.16; N, 7.33. Found: C, 37.87; H, 2.95; N, 7.39.

***N*-Fluoro-5-(trifluoromethyl)pyridinium-2-sulfonate (2f)**: mp 190–220 °C (with dec) (CH_3CN); ^1H NMR (CD_3CN) δ 8.69 (1H, ddm, J = 8.2, 6.2 Hz, 3-H), 8.90 (1H, dm, J = 8.2 Hz, 4-H), 9.66 (1H, dd, J = 13.5, 0.9 Hz, 6-H); ^{19}F NMR 44.5 (1F, bs, NF), −61.9 (3F, s, CF_3); IR (Nujol) 1262 (SO_2) cm^{-1}; MS m/z 246 ($M^+ + 1$). Anal. Calcd for $C_6H_3F_4NO_3S$: C, 29.40; H, 1.23; N, 5.71. Found: C, 29.21; H, 1.09; N, 5.85.

***N*-Fluoro-3-chloro-5-(trifluoromethyl)pyridinium-2-sulfonate (2g)**: mp 220–250 °C (with dec) (CH_3CN); ^1H NMR (CD_3CN) δ 9.03 (1H, m, 4-H), 9.62 (1H, dm, J = 13.4 Hz, 6-H); ^{19}F NMR 53.5 (1F, bs, NF), −61.8 (3F, s, CF_3); IR (Nujol) 1276 (SO_2) cm^{-1}; MS m/z 276 ($M^+ + 1$), 278 ($M^+ + 1$). Anal. Calcd for $C_6H_2ClF_4NO_3S$: C, 25.77; H, 0.72; N, 5.01. Found: C, 25.49; H, 0.79; N, 4.87.

***N*-Fluoro-4,6-bis(trifluoromethyl)pyridinium-2-sulfonate (2h)**: mp 172–174 °C (with dec) (CF_3COOH–EtOAc); ^1H NMR (CD_3CN) δ 8.91 (1H, m, 5-H), 9.04 (1H, m, 3-H); ^{19}F NMR 35.5 (1F, d, J = 21.0 Hz, NF), −62.2 (3F, d, J = 21.0 Hz, 6-CF_3), −63.7 (3F, s, 4-CF_3); IR (Nujol) 1281 (SO_2) cm^{-1}; MS m/z 314 ($M^+ + 1$). Anal. Calcd for $C_7H_2F_7NO_3S$: C, 26.85; H, 0.64; N, 4.47. Found: C, 26.60; H, 0.85; N, 4.43.

Synthesis of *N*-Fluoropyridinium-3-sulfonate (3). A flask was charged with 3.18 g (20 mmol) of 3-pyridinesulfonic acid, 10 g (20 mmol) of Amberlite IRA-94S, and 40 mL of $(CF_3)_2CHOH$, purged with N_2, and placed on a cooling bath of 0 °C. A 10% F_2-90% N_2 mixture gas was then introduced at a flow rate of 45 mL min^{-1}, just above the surface of the rapidly stirred reaction mixture. The amount of F_2 used was 61.5 mmol. After the flow of F_2 was stopped, N_2 was passed through the flask at rate of 45 mL min^{-1} for 30 min at the same temperature. The reaction mixture was filtered, and the filtrate was evaporated to dryness to give 3.07 g (87%) of **3**: mp 201–202 °C (with dec) ($(CF_3)_2CHOH$–Et_2O); ^1H NMR ($(CF_3)_2CDOD$) δ 8.25 (1H, ddd, J = 7.8, 4.2, 4.2 Hz, 5-H), 8.95 (1H, ddd, J = 12.8, 6.9, 2.2 Hz, 6-H), 9.04 (1H, d, J = 7,8 Hz, 4-H) 9.40 (1H, d, J = 12 Hz, 2-H); ^{19}F NMR 55.0 (bs, NF); IR (Nujol) 1251 (SO_2) cm^{-1}; MS m/z 178 ($M^+ + 1$). Anal. Calcd for $C_5H_4FNO_3S$: C, 33.90; H, 2.28; N, 7.91. Found: C, 33.76; H, 2.01; N, 7.78.

Synthesis of *N*-Fluoropyridinium-4-sulfonate (4). A flask was charged with 1.84 g (10.2 mmol) of sodium 4-pyridinesulfonate and 40 mL of $(CF_3)_2CHOH$, purged with N_2, and placed on a cooling bath of 0 °C. A 10% F_2-90% N_2 mixture gas was then introduced in the same manner as for **3** above. The amount of F_2 used was 30.8 mmol. TFA (20 mL) was added to the reaction mixture and the reaction mixture was evaporated to dryness under reduced pressure. The residue was washed with some CH_3CN to yield 1.34g (74%) of **4**: mp 230–260 °C (with dec) ($(CF_3)_2CHOH$–EtOAc); ^1H NMR ($(CF_3)_2CDOD$) δ 8.58 (2H, dd, J = 3.6, 3.6 Hz, 3-H, 5-H), 9.00 (2H, dd, J = 13.1, 7.0 Hz, 2-H, 6-H); ^{19}F NMR 52.6 (bs, NF); IR (Nujol) 1244 (SO_2) cm^{-1}; MS m/z 178 ($M^+ + 1$). Anal. Calcd for $C_5H_4FNO_3S$: C, 33.90; H, 2.28; N, 7.91. Found: C, 33.63; H, 2.24; N, 7.63.

Fluorination of Aromatics. General Procedure. Under an argon atmosphere, 1 mmol of a *N*-fluoropyridiniumsulfonate was added to a solution of 1 mmol of a substrate in 2–4 mL of a solvent. The solvents, the reaction conditions, and the yields are shown in Tables 2 and 3. Each reaction time was the time when the *N*-fluoropyridiniumsulfonate was consumed. Each reaction was monitored with aqueous KI solution. Yields were determined by ^{19}F NMR or GC of the reaction mixtures. The spectral data of the products agreed with those of authentic samples.[6d]

Fluorination of Enol Silyl Ethers 23a–d. General Procedure. Under an argon atmosphere, 1 mmol of a *N*-fluoropyridinium salt was added to a solution of 1 mmol of an enol silyl ether in 4 mL of a solvent, and the mixture was stirred at rt. The solvents, the reaction conditions and the yields are shown in Table 4. The reaction mixture was poured into 2 N HCl aqueous solution and extracted with CH_2Cl_2. The extract was washed with saturated NaCl aqueous solution, dried with anhyd $MgSO_4$, filtered, and evaporated. The yield was determined by ^{19}F NMR of the resulting residue using fluorobenzene as an internal standard. The spectral data of the products agreed with those of authentic samples.[6d] In run 1, the products were isolated by column chromatography of the residue on silica gel using a 10:1 mixture of hexane and EtOAc as an eluent. The isolation yields are shown in Table 4.

Fluorination of 2,3-Dihydrofuran. Under an argon atmosphere, 1 mmol of 2,3-dihydrofuran was stirred with 1 mmol of **2b** in 4 mL of CH_2Cl_2 at reflux temperature for 8 h. Then the reaction solution was evaporated. Products **28** and **29** were separated by column chromatography on silica gel using a 4:1 mixture of CH_2Cl_2 and CH_3CN as an eluent.

***N*-(*trans*-3′-Fluoro-2′,3′,4′,5′-tetrahydro-2′-furanyl)-4-methylpyridinium-2-sulfonate (28)**: 59%; mp 140–141 °C (EtOAc); ^1H NMR (CD_3CN) δ 2.14 (1H, m, 4′-H), 2.34 (1H, dddm, J = 15.4, 15.4, 6.0 Hz, 4′-H), 4.41 (1H, ddd, J = 11.8, 8.7, 6.1 Hz, 5′-H), 4.76 (1H, ddd, J = 9.6, 9.6, 1.1 Hz, 5′-H), 5.57 (1H, dd, J = 48.1, 3.9 Hz, 3′-H), 7.53 (1H, d, J = 13.4 Hz, 2′-H), 7.82 (1H, dd, J = 6.6, 2.0 Hz, 5-H), 8.40 (1H, d, J = 2.0 Hz, 3-H), 8.49 (1H, d, J = 6.6 Hz, 6-H); ^{19}F NMR −179.5 (dddd, J = 48.1, 44.0, 21.2, 13.4 Hz); IR (KBr) 1268 (SO_2) cm^{-1}; MS m/z 262 ($M^+ + 1$). Anal. Calcd for $C_{10}H_{12}FNO_4S$: C, 45.97; H, 4.63; N, 5.36. Found: C, 45.87; H, 4.68; N, 5.36.

***N*-(*cis*-3′-Fluoro-2′,3′,4′,5′-tetrahydro-2′-furanyl)-4-methylpyridinium-2-sulfonate (29)**:16%; mp 160–180 °C (with dec) (EtOAc); ^1H NMR (CD_3CN) δ 2.45 (1H, m, 4′-H), 2.60 (1H, m, 4′-H), 4.37 (1H, ddd, J = 8.6, 8.6, 2.2 Hz, 5′-H), 4.52 (1H, ddd, J = 10.8, 8.5, 5.9 Hz, 5′-H), 5.79 (1H, dddd, J = 53.0, 3.3, 3.3, 0.9 Hz, 3′-H), 7.56 (1H, dd, J = 17.8, 3.3 Hz, 2′-H), 7.82 (1H, dd, J = 6.6, 2.0 Hz, 5-H), 8.39 (1H, d, J = 2.0 Hz, 3-H), 8.69 (1H, dd, J = 6.6, 2.6 Hz, 6-H); ^{19}F NMR −190.2 (m); IR (KBr) 1256 (SO_2) cm^{-1}; MS m/z 262 ($M^+ + 1$). Anal. Calcd for $C_{10}H_{12}FNO_4S$: C, 45.97; H, 4.63; N, 5.36. Found: C, 46.02; H, 4.61; N, 5.30.

Fluorination of Active Methylene Compounds. General Procedure. Under an argon atmosphere, 1 mmol of a substrate was stirred with 1 mmol of **2h** in 2 mL of a solvent at rt. The solvents, the reaction conditions, and the yields are shown in Table 5. Yields were determined by ^{19}F NMR of the concentrated reaction mixtures using fluorobenzene as an internal standard. The spectral data of the products agreed with those of authentic samples.[6d]

Fluorination of Sodium Salt (39) of Ethyl 1-Oxocyclopentane-2-carboxylate. Under an argon atmosphere, 3.6 mmol of **2a** was added in several portions to a THF solution at rt of **39**, which was prepared in situ by treating 3 mmol of ethyl 1-oxocyclopentane-2-carboxylate with 3 mmol of 60% NaH in oil in 24 mL of THF at 0 °C. After 1 h, the reaction mixture was poured into dilute hydrochloric acid and extracted with Et_2O. The extract was washed with aqueous $NaHCO_3$ solution and then with H_2O, dried with anhyd $MgSO_4$, filtered, and evaporated. ^{19}F NMR of the resulting residue using fluorobenzene as an internal standard showed that **40** was obtained in 83% yield. The spectral data of the product agreed with those of an authentic sample.[6d]

Fluorination of Olefins. General Procedure. Under an argon atmosphere, 313 mg (1 mmol) of **2h** was added to a solution of 1 mmol of an olefin in 4 mL of AcOH. The mixtures for styrene and β-methylstyrene as olefins were stirred at rt for 18 and 1.5 h, respectively. Then the reaction mixture was poured into H_2O and extracted with Et_2O. The extract was washed with aqueous $NaHCO_3$ solution and then with H_2O, dried with anhyd $MgSO_4$, filtered, and evaporated. Yields (**41**, 24%; **42**, 51%) were determined by ^{19}F NMR of the residue using fluorobenzene as an internal standard. The spectral data of the products agreed with those of authentic samples.[6d]

Fluorination of Thioanisole. Under an argon atmosphere, 246 mg (1.2 mmol) of **2a** was added to a solution of 124 mg (1 mmol) of thioanisole in 4 mL of a 1:1 mixture of CH_3CN and CH_2Cl_2. The mixture was stirred at rt for 80 min. In order to stabilize the product, Et_3N (170 mL, 1.2 mmol) was added and the mixture was stirred for an additional 10 min. ^{19}F NMR of the reaction mixture using fluorobenzene as an internal standard showed that **43** was produced in 80% yield. The spectral data of the product agreed with those of an authentic sample.[6c]

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