Selective fluorination of pyridine and its derivatives in the presence of high-oxidation-state transition metals*

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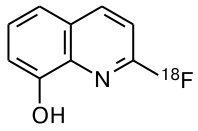
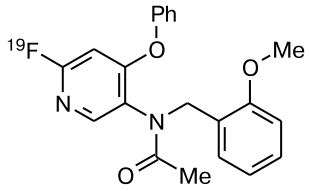
The oxidative fluorination of pyridine and 4-ethylpyridine under chemical and electrochemical conditions in the presence of transition metal (high-oxidation-state nickel, cobalt, and silver) salts was studied. The chemical fluorination affords 2-fluoropyridine in all cases, while the electrochemical fluorination results in 2-fluoro- or 3-fluoropyridine depending on the catalyst used.

Key words: C—H functionalization, oxidation, fluorination, electrosynthesis, pyridine, 4-ethylpyridine, potassium hexafluoronickelate, cobalt trifluoride, silver nitrate.

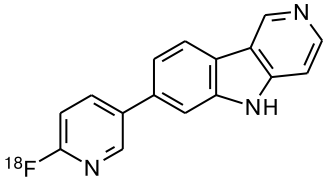
2-[^{18}F]-Fluoro-substituted pyridines are widely used as the fragments of radiotracers for positron emission tomography,[1] which is explained by simple (although often inefficient) methods of their radiochemical synthesis and their restricted defluorination *in vivo*.[2]



[^{18}F]CABS13



6-[^{18}F]PBR-28



[^{18}F]AV-1451 ([^{18}F]T807)

In addition, nonradioactive fluorinated heterocycles are extensively used in medicinal chemistry as both target compounds and synthetic intermediates.[3,4] Conventionally, 2-fluoropyridines are synthesized by nucleophilic substitution of fluoride for a suitable leaving group in the 2 position (Scheme 1, Eq. (1)). Substitution of 2-chloro- and 2-bromopyridines with fluorine requires high temperatures or using anhydrous tetrabutylammonium fluoride (TBAF).[5a] The synthesis of fluoropyridines from aminopyridines by the Balz—Schiemann reaction uses potentially explosive diazonium intermediates.[5b] It was shown that 2-nitro- and 2-trialkylammonium pyridines can be good precursors of 2-fluoropyridines,[5c,6] although their wide application is limited by the complexity of their synthesis (Scheme 1, Eq. (2)).[7] Recently, a new approach to the synthesis of 2-fluoropyridine based on the Chichibabin reaction, which consists in direct fluorination of the pyridine C—H bond using AgF_2 (Scheme 1, Eq. (3)), was proposed.[4] This method is applied successfully for substrates with different functional groups and provides access to a wide range of 2-fluoropyridines, which in some cases considerably improves the synthetic approaches to clinically significant compounds. It was shown that some 2-substituted pyridines can be obtained by the C—H bond activation of pyridine *N*-oxides with metal complex catalysts in the presence of different nucleophiles (Cl, Br, CN, amine, *etc.*).[8,9] Several examples of preparation of 2-pyridyltrimethylammonium salts from pyridine *N*-oxides were described.[10] The use of 2-pyridyltrialkylammonium salts for the synthesis of fluoropyridines was described in Ref. 11 (Scheme 1, Eq. (4)). The reaction is performed under moderately mild conditions; however, this method is multistep and requires a large volume of solvents (including explosive THF), as well as the excess of the activating electrophile (3 equiv.), trifluoroacetic anhydride (TFAA) or *p*-toluenesulfonic anhydride (Ts_2O). In addition, the use of 2- and 3-phenylpyridines allows obtaining ammonium salts in good yields (100% and 58%, respectively), but the use of 4-phenylpyridine does not afford the desired result.[11]

The electrochemical fluorination of pyridine proceeds inefficiently under severe conditions, typically, at high an-

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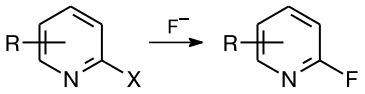
Scheme 1

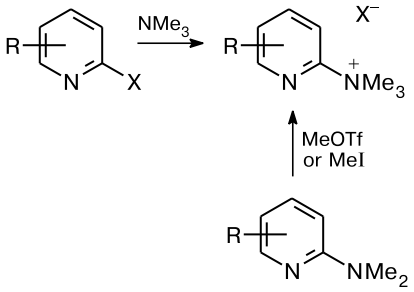
Nucleophilic aromatic substitution



(1)

X = Cl, Br, $^+N_2$, NO_2, $^+NR_3$

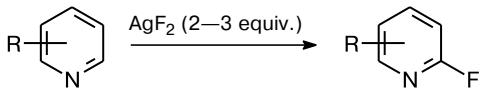
Formation of pyridyltrimethylammonium salt



(2)

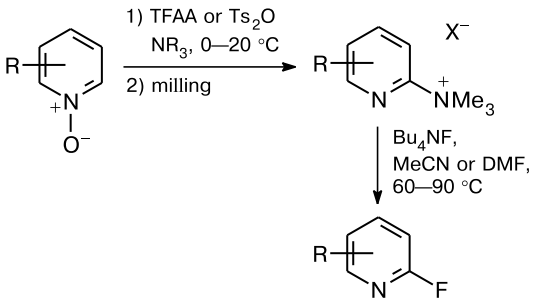
R is an electron-withdrawing group.
X = Cl, Br, $^+N_2$, NO_2, $^+NR_3$

Fluorination of the C—H bond involving AgF_2



(3)

Synthesis *via* pyridyltrialkylammonium salts



(4)

ode potentials and a high power consumption; the product yields being at best 22% based on pyridine and 10% based on the current in a concentrated fluoride solution (0.5 *M* $Me_4NF \cdot 2HF$ in acetonitrile, 70-fold excess of fluoride compared to pyridine).[12]

As is known, chemical oxidative fluorination of organic compounds can proceed with the assistance of nickel fluorides (in hydrofluoric acid) and high-oxidation-state silver or cobalt fluorides.[13] The redox-active NiF_2/NiF_3 film formed in a solution of HF and its salts was shown to play a key role in some electrochemical fluorination processes.[14]

The development of reliable synthetic methods, which would allow fast (at the final step of the synthesis) and regioselective introduction of the fluorine atom into the pyridine ring, is still of great significance for the search of new drugs and the design of radiotracers. In addition, a general synthetic method which would provide access to both nonradioactive fluoropyridines and ^{18}F-radioligands *via* a common intermediate is in demand.

The aim of the present work was to regenerate electrochemically the catalytic amounts of high-oxidation-state nickel and cobalt fluorides on the anode and to use them for regioselective one-step monofluorination of pyridine under mild conditions excluding the conventional excess of oxidant (high-oxidation-state metal fluoride or other oxidant) and agressive hydrofluoric acid.

Results and Discussion

In the present work, we considered approaches to fluorination of pyridine and 4-ethylpyridine under different conditions using different fluorinating agents and transition metal salts. The following fluorinating reagents, catalysts and fluorine sources, were studied by cyclic voltammetry (CV): K_2NiF_6, CsF, AgF, and CoF_3, as well as Me_4NF in MeCN and a paste electrode (Figs 1 and 2, Table 1). Since the solubility of many fluorides in acetonitrile is low, carbon paste electrode (CPE) based on the phosphonium salt[15] was used to specify their oxidation potentials (see Fig. 2, Table 1). The oxidation potentials of fluorides in solution and in the solid state are either close or in some cases coincide.

Pyridine and 4-ethylpyridine in the available potential range do not oxidize on glassy carbon electrode (up to 3.0 V). All fluorides under study oxidize at high anode potentials of about 2 V and higher. Since the oxidation potentials of fluorides differ slightly (only Me_4NF is nota-

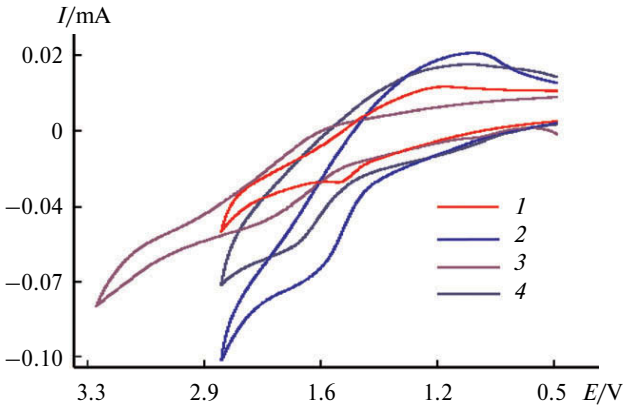


Fig. 1. CV curves for oxidation of K_2NiF_6 (*1*), CsF (*2*), AgF (*3*), and CoF_3 (*4*) in MeCN. Conditions: 0.1 V s^{-1}, Bu_4NBF_4, a glassy carbon (GC) working electrode, and an $Ag/AgNO_3$ reference electrode.

Note. Figures 1 and 2 are available in full color on the web page of the journal (http://www.link.springer.com).

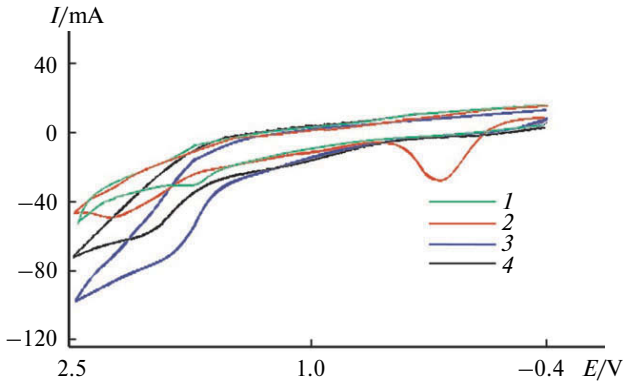


Fig. 2. CV curves for oxidation of K_2NiF_6 (*1*), AgF (*2*), CsF (*3*), and CoF_3 (*4*) in carbon paste electrode. Conditions: 0.1 V s^{-1}, Bu_4NBF_4, a platinum auxiliary electrode, an $Ag/AgNO_3$ reference electrode, MeCN.

bly more difficult to oxidize), one can assume that all of them correspond to oxidation of fluoride ions proceeding *via* the formation of fluorine radical.

High-oxidation-state metal fluorides under certain conditions can fluorinate organic compounds;[13,14] therefore, it is necessary to consider the earlier unstudied chemical oxidative fluorination of pyridine, as well as to try regeneration of the active form of metal fluoride, for example, nickel or cobalt fluoride, on the anode under catalytic reaction conditions.

First, potassium hexafluoronickelate was studied as the fluorinating agent. The CV curve for a solution of the salt under study shows oxidation to occur at a high anode potential of 1.85 V in both acetonitrile and a paste (see Figs 1 and 2). Potassium hexafluoronickelate (K_2NiF_6) was studied also by ESR spectroscopy. The commercial reagent (Sigma-Aldrich, 99% purity), which is formally a Ni^{IV} compound, was found to contain Ni^{III} impurities. The ESR signal for the K_2NiF_6 powder is a homogeneously broadened line with $g = 2.25$ and $\Delta H = 230$ Gs (Fig. 3). Apparently, the signal belongs to impurity Ni^{III} centers in

Table 1. Oxidation peak potentials of fluorides acting as the fluorine sources in the synthesis of fluoropyridine[a]

Fluorine source	E_p^{ox}/V	
	GC	CPE
K_2NiF_6	1.85 (1.33 in Py)	1.9
CsF	1.91	2.0
AgF	2.06	2.2
CoF_3	2.10 (1.40 in Py)	2.1
Me_4NF	2.90	—[b]
NiF_2Py_4	1.30	—[c]
CoF_2Py_4	1.40	—[c]

[a] Relative to $Ag/AgNO_3$, the solvent was MeCN.
[b] No oxidation. [c] Not recorded.

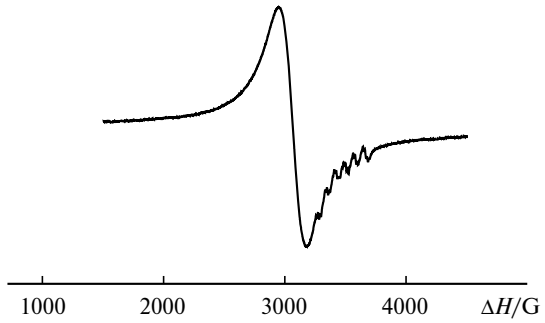


Fig. 3. ESR spectrum for the K_2NiF_6 powder.

the crystal lattice. The signal intensity corresponds to the Ni^{III} content of about 5—10% in the sample. The ESR spectrum also contains an additional signal, presumably, from the high-spin ($S = 5/2$) $3d^5$ Mn ions with splitting from the fluorine nuclei. The intensity of the second signal is lower by about two orders of magnitude than that of the first signal. Upon addition of pyridine to the K_2NiF_6 powder, the intensity of Ni^{3+} signal decreases with time (Fig. 4). No new signals, including those belonging to the pyridine radical cation, appear.

The performed electrochemical CV studies revealed that upon addition of pyridine to potassium hexafluoronickelate the oxidation peak of the latter shifts to the cathode region (Fig. 5), perhaps, due to the formation of nickel(II) fluorides oxidizing at the earlier stages.

As noted above, substituted cyclohexanes can be fluorinated completely on exposure to the fluorinating reagents generated from potassium hexafluoronickelate in the presence of BF_3 or anhydrous HF (in fact, $RNiF_3$ and NiF_4).[16] We assumed that the electrochemical oxidation of nickel(II) fluorides which must form as the final products from nickel(III) and nickel(IV) compounds after oxidative fluorination of an aromatic compound, for example, pyridine,

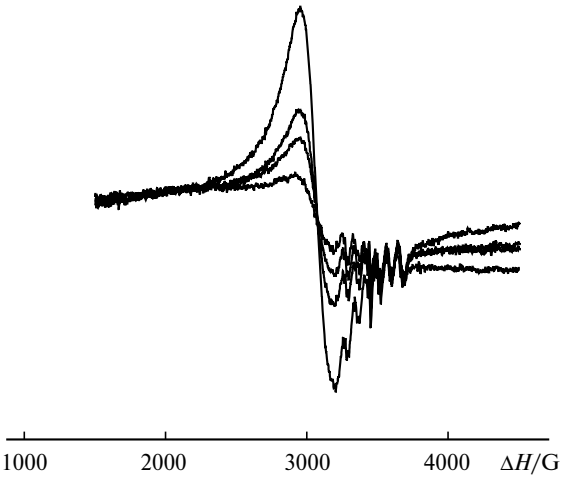


Fig. 4. Decrease in the intensity of the ESR signal for the Ni^{3+} ions of K_2NiF_6 upon addition of pyridine.

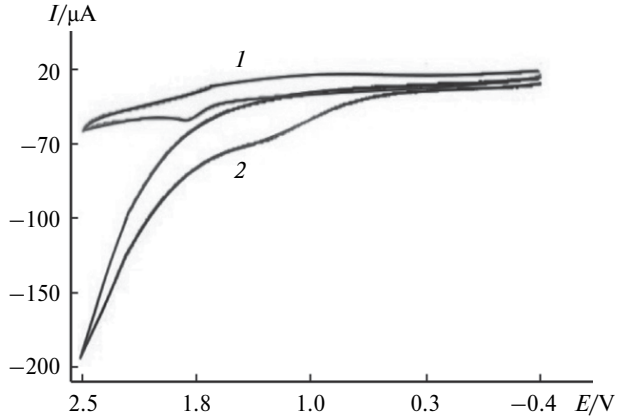
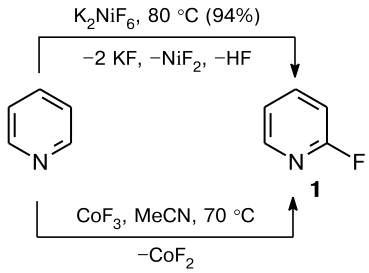


Fig. 5. CV curves for oxidation of K_2NiF_6 in MeCN (*1*) and pyridine (*2*). Conditions: 0.1 V s^{-1}, Bu_4NBF_4, a platinum auxiliary electrode, an $Ag/AgNO_3$ reference electrode, MeCN.

will make the process catalytic by nickel, for which the available non-aggressive salt, for example, CsF and thereto similar salt, can be selected as the source of the major fluorine portion. This helps one to avoid the use of aggressive HF or BF_3 as coreagents. We found that chemical fluorination of pyridine using potassium hexafluoronickelate proceeds selectively at 80 °C to form a single reaction product, 2-fluoropyridine (**1**) whose ^{19}F NMR spectrum contains a singlet signal at δ_{19F} −65.88. The reaction was performed in the excess of pyridine, which served as both a substrate and a solvent (Scheme 2). The crimson color of the solution suggesting the presence of the starting potassium hexafluoronickelate in the reaction mixture disappears after several hours; at the same time, bright-blue crystals and a beige crystalline powder form.

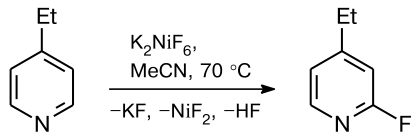
Scheme 2



The beige crystalline powder is potassium fluoride. The resulting blue crystals are the earlier described[17] nickel fluoride coordinated to pyridine, nickel tetrapyridine difluoride NiF_2Py_4. The oxidation peak of NiF_2Py_4 on the CV curve is close to that of K_2NiF_6 in pyridine (see Table 1), *i.e.*, the reaction of the latter compounds, coordination, and oxidation start quite fast. The above-described reaction does not proceed in dichloromethane. Perhaps, this reaction requires a higher temperature (b.p. of CH_2Cl_2 is 40 °C); in acetonitrile, the complete conversion requires heating at 70 °C for a long time.

Fluorination of 4-ethylpyridine with potassium hexafluoronickelate using either the excess of the starting pyridine (80 °C) or acetonitrile (70 °C, 3 days) proceeds analogously (the ratio of EtPy : K_2NiF_6 = 3 : 1). The yield of 2-fluoro-4-ethylpyridine (**2**) was 46% (Scheme 3).

Scheme 3

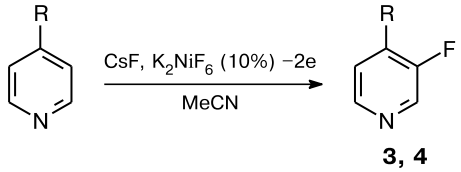


(δ_{19F} −69.82)

As the fluorinating agent, CoF_3 was also studied. The reaction between pyridine and cobalt trifluoride was performed in acetonitrile at 70 °C (24 h) at the 1 : 1 ratio of the starting reagents. In this case, pyridine is also fluorinated at the 2 position (see Scheme 2); however, the reaction under these conditions proceeds slower: according to the data from ^1H NMR spectroscopy, the degree of pyridine conversion within 24 h is about 30%. The ^{19}F NMR spectrum displays a singlet at δ_{19F} −67.4. The ^1H NMR spectrum ($CDCl_3$) coincides completely with that of 2-fluoropyridine obtained using K_2NiF_6 as the fluorinating agent (see Scheme 2). The reaction in the excess of pyridine also proceeds selectively to form 2-fluoropyridine. During the synthesis, precipitation of pink crystals which, as in the case of K_2NiF_6, correspond to the complex of cobalt difluoride and four pyridine ligands (the analogous structure was described[18] only for Co^{III}). We failed to obtain the spectral characteristics of this complex, since the signals are much broadened due to the presence of paramagnetic cobalt species.

The electrooxidative fluorination of pyridine and 4-ethylpyridine was performed in order to regenerate electrochemically the catalytic amounts of high-oxidation-state nickel and cobalt fluorides on the anode followed by their use for selective one-step monofluorination of pyridine under mild conditions. The electrolysis was performed in a divided cell in acetonitrile at room temperature. The source of fluoride ions was cesium fluoride and tetramethylammonium fluoride. Electricity 2 F per 1 mol of pyridine was passed. When potassium hexafluoronickelate was used as the catalyst (the ratio of the starting reagents was Py : K_2NiF_6 : CsF = 1 : 0.1 : 2), the electrolysis was performed at a potential of 2.07 V (*vs.* $Ag/AgNO_3$). In contrast to the chemical reaction, the ^{19}F NMR spectrum of the reaction mixture contains a singlet at δ_{19F} −128.8. According to the spectral data, in contrast to products described in Ref. 12, the main fluorination product in this case is 3-fluoropyridine (**3**) (Scheme 4).

Scheme 4



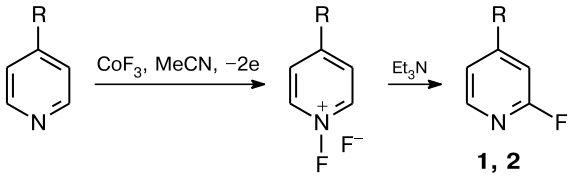
3, 4

X = H (**3**), Et (**4**)

The electrooxidative fluorination of 4-ethylpyridine using potassium hexafluoronickelate as the catalyst proceeds analogously to form 3-fluoro-4-ethylpyridine (**4**) (δ_{19F} –127.4). It should be noted that functionalization of pyridine typically proceeds at the 2 position.[4–7] The C—H substitution reactions at the 3 position, for example, upon catalytic olefination of pyridine in the presence of palladium complexes[19] or classical electrophilic substitution,[20] are known.

The electrocatalytic fluorination of pyridine and 4-ethylpyridine was studied also in the presence of CoF_3 (the ratio of the starting reagents was 1 : 1). In contrast to the above-described electrolysis, cobalt trifluoride acted in this case as both the source of fluoride ions and the catalyst. After passing 2 F of electricity per 1 mol of metal fluoride at a potential of 1.92 V, the ^{19}F NMR spectrum of the reaction mixture displayed two singlet signals at δ_{19F} –34.8 and –152.2 with identical intensities, which can suggest the formation of the pyridinium salt **6**.[21] Subsequent treatment of salt **6** with triethylamine affords 2-fluoropyridine **1** (δ_{19F} –69.8) (Scheme 5).

Scheme 5

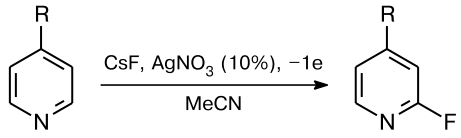


5, 6 **1, 2**

R = H (**1**, **5**), Et (**2**, **6**)

Pyridine underwent electrocatalytic fluorination using $AgNO_3$ as the catalyst and cesium fluoride as the fluorine source (Py : $AgNO_3$: CsF = 1 : 0.1 : 2). The electrolysis was performed without a supporting electrolyte at an anode potential of 0.98—1.10 V. The isolated product was 2-fluoropyridine (**1**) (Scheme 6, Table 2). 4-Ethylpyridine under these conditions is fluorinated analogously.

Scheme 6



1, 2

X = H (**1**), Et (**2**)

The use of tetramethylammonium fluoride as the source of fluoride ions upon electrocatalytic fluorination of pyridine and 4-ethylpyridine in the presence of potassium hexafluoronickelate results a dramatic decrease in the yield of fluorinated products. The reason for such difference is not obvious. It seems that in this case a higher quantity of electricity is required. It should be noted that without catalysts, such as nickel, cobalt, or silver salts, in the presence of CsF the electrocatalytic fluorination do not occur under these conditions.

Thus, the electrocatalytic fluorination of pyridine and 4-ethylpyridine depending on the catalyst used proceeds selectively under mild condtions at the 2 and 3 positions, the used source of fluoride ions has no effect on the regiochemistry of fluorination, but influences the yield of the final product. The dependence of the reaction regioselectivity on the nature of the catalyst metal and the synthesis method (chemical or electrochemical) is likely caused by different mechanisms of oxidative fluorination whose clarification require additional studies.

Experimental

Acetonitrile was distilled successively over P_2O_5, $KMnO_4$, and molecular sieves 4 Å. Benzene was purified by distillation

Table 2. Electrochemical fluorination of pyridine and 4-ethylpyridine

Substrate	Catalyst (10%)	Source F^-	Potential/V	Fluorinated product	Yield (%)
Pyridine	K_2NiF_6	CsF	2.07	**3**	43
4-Ethylpyridine	K_2NiF_6	CsF	1.89	**4**	45
Pyridine	CoF_3	CoF_3	2.08	**1**	49
4-Ethylpyridine	CoF_3	CoF_3	2.12	**2**	57
Pyridine	$AgNO_3$	CsF	1.02	**1**	48
4-Ethylpyridine	$AgNO_3$	CsF	0.76	**2**	20
Pyridine	K_2NiF_6	Me_4NF	2.04	**3**	—*
4-Ethylpyridine	K_2NiF_6	Me_4NF	1.59	**4**	7

* Trace amounts.

over sodium metal. After purification, the solvents were stored under dry argon atmosphere. The supporting salt Et_4NBF_4 was recrystallized from ethanol and dried for 2 days in a vacuum cabinet at 100 °C. Pyridine and 4-ethylpyridine, potassium hexafluoronickelate, and tetramethylammonium fluoride were obtained from Aldrich, boron trifluoride was obtained from Alfa Aesar, silver nitrate and cesium fluoride were obtained from Strem Chemicals. All syntheses were performed under dry argon atmosphere.

Preparative electrolyses were performed using a B5-49 direct-current power supply in a 40-mL three-electrode cell. The potential of the working electrode was recorded using a V7-27 direct-current voltmeter versus an Ag/0.01 *M* $AgNO_3$ reference electrode in acetonitrile. The working surface of a platinum cylindrical anode serving as the working electrode was equal to 20.0 cm^2. The diaphragm was a ceramic plate with a pore size of 900 nm. The cathode was a platinum gauze and the catholyte was a saturated solution of $PyHBF_4$ in acetonitrile. During the electrolysis, the electrolyte was magnetically stirred under the constant stream of argon passed through a drying system.

NMR spectra were recorded on a Bruker AVANCE-400 (400.1 MHz (^{1}H) and 376.5 MHz (^{19}F)) spectrometers. Proton chemical shifts were recorded using residual protons of a deuterated solvent as the internal standard and ^{19}F chemical shifts were recorded relative to C_6F_6 ($\delta_{^{19}F}$ −164.9).

In voltammetric studies, the working electrode was a stationary disc glassy carbon electrode with a working surface area of 8 mm^2 and a platinum electrode with a working surface area of 3.14 mm^2. Voltammograms were recorded on a BASi Epsilon potentiostat. The curves were recorded at the potential linear scan rate of 100 mV s^{-1}. The reference electrode upon voltammetric measurements was Ag/0.01 *M* $AgNO_3$ in acetonitrile. The auxiliary electrode was a platinum wire with a diameter of 1 mm and a length of 10 mm. The measurements were performed in a temperature-controlled (25 °C) cell in argon atmosphere. Cyclic voltammograms were recorded in MeCN at the substrate concentration of $5 \cdot 10^{-3}$ mol L^{-1} against Bu_4NBF_4 ($1 \cdot 10^{-1}$ mol L^{-1}).

Electrolysis (general procedure). Pyridine or 4-ethylpyridine (6.2 mmol), the source of F^- ions (CsF, Me_4NF, or CoF_3, 6.2 mmol), and the catalyst (K_2NiF_6, CoF_3, or $AgNO_3$, 0.62 mmol) in acetonitrile (20 mL) were placed in an electrochemical cell. The electrolysis was performed with division of the anode and cathode compartments with stirring on a magnetic stirrer under the constant flow of argon. Electricity of 2 F per 1 mol of the starting pyridine (333 mA h) was passed through the electrolyte. Once the electrolysis has been completed, the reaction mixture was passed through silica gel and the solvent was removed. The residue was purified by column chromatography on silica gel (the eluents were CH_2Cl_2 and pentane).

2-Fluoropyridine (1). ^{1}H NMR (DMSO-d_6), δ: 8.29 (d, 1 H, $^3J_{HH}$ = 5.85 Hz); 8.02 (dt, 1 H, $^3J_{HH}$ = 7.98 Hz, $^4J_{HF}$ = 1.25 Hz); 7.38 (dd, 1 H, $^3J_{HH}$ = 7.28 Hz, $^3J_{HH}$ = 4.91 Hz); 7.20 (dd, 1 H, $^3J_{HH}$ = 7.54 Hz, $^3J_{HF}$ = 2.58 Hz) (*cf.* Ref. 22). ^{19}F NMR (DMSO-d_6), δ: −65.88 (*cf.* Ref. 23: $\delta_{^{19}F}$ −69.5).

4-Ethyl-2-fluoropyridine (2). ^{1}H NMR ($CDCl_3$), δ: 8.10 (d, 1 H, $^3J_{HH}$ = 5.05 Hz); 6.97 (m, 1 H); 6.72 (s, 1 H); 2.67 (q, 2 H, CH_2, $^3J_{HH}$ = 7.61 Hz); 1.24 (t, 3 H, CH_3, $^3J_{HH}$ = 7.61 Hz) (*cf.* Ref. 24). ^{19}F NMR ($CDCl_3$), δ: −69.8.

3-Fluoropyridine (3). ^{1}H NMR (DMSO-d_6), δ: 8.61 (d, 1 H, $^3J_{HF}$ = 5.85 Hz); 8.49 (d, 1 H, $^3J_{HH}$ = 4.98 Hz); 7.72 (dd, 1 H, $^3J_{HH}$ = 8.58 Hz, $^3J_{HF}$ = 9.24 Hz); 7.52 (d, 1 H, $^3J_{HH}$ = 7.54 Hz). ^{19}F NMR (DMSO-d_6), δ: −128.4 (*cf.* Ref. 25: $\delta_{^{19}F}$ −125.6).

4-Ethyl-3-fluoropyridine (4). ^{1}H NMR ($CDCl_3$), δ: 8.37 (d, 1 H, $^3J_{HH}$ = 5.05 Hz); 8.29 (m, 1 H); 7.27 (d, 1 H, $^3J_{HF}$ = 7.12 Hz); 2.74 (q, 2 H, CH_2, $^3J_{HH}$ = 7.63 Hz); 1.26 (t, 3 H, CH_3, $^3J_{HH}$ = = 7.63 Hz) (*cf.* Ref. 26). ^{19}F NMR ($CDCl_3$), δ: −128.4.

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References

1. F. Dollé, *Curr. Pharm. Des.*, 2005, **11**, 3221.
2. (a) J. A. McCarron, V. W. Pike, C. Halldin, J. Sandell, J. Sóvágó, B. Gulyas, Z. Cselényi, H. V. Wikström, S. Marchais-Oberwinkler, B. Nowicki, F. Dollé, L. Farde, *Mol. Imaging Biol.* 2004, **6**, 17; (b) V. W. Pike, *Trends Pharmacol. Sci.*, 2009, **30**, 431.
3. V. A. Petrov, *Fluorinated Heterocyclic Compounds: Synthesis, Chemistry, and Applications*; John Wiley & Sons, Hoboken, 2009, 533 p.
4. (a) P. S. Fier, J. F. Hartwig, *Science*, 2013, **342**, 956; (b) P. S. Fier, J. F. Hartwig, *J. Am. Chem. Soc.*, 2014, **136**, 10139.
5. (a) H. Sun, S. G. DiMagno, *Angew. Chem., Int. Ed.*, 2006, **45**, 2720; (b) T. Fukuhara, N. Yoneda, A. Suzuki, *J. Fluorine Chem.*, 1988, **38**, 435; (c) S. D. Kuduk, R. M. DiPardo, M. G. Bock, *Org.Lett.*, 2005, **7**, 577.
6. (a) L. Dolci, F. Dollé, S. Jubeau, F. Vaufrey, J. Crouzel, *J. Labelled Compd. Radiopharm.*, 1999, **42**, 975; (b) M. Karramkam, F. Hinnen, F. Vaufrey, F. Dollé, *J. Labelled Compd. Radiopharm.*, 2003, **46**, 979.
7. (a) D. E. Olberg, J. M. Arukwe, D. Grace, O. K. Hjelstuen, M. Solbakken, G. M. Kindberg, A. Cuthbertson, *J. Med. Chem.*, 2010, **53**, 1732; (b) F. Dollé, L. Dolci, H. Valette, F. Hinnen, F. Vaufrey, I. Guenther, C. Fuseau, C. Coulon, M. Bottlaender, C. Crouzel, *J. Med. Chem.*, 1999, **42**, 2251; (c) Y.-S. Ding, N. Liu, T. Wang, J. Marecek, V. Garza, I. Ojima, J. S. Fowler, *Nucl. Med. Biol.*, 2000, **27**, 381.
8. (a) J. A. Bull, J. J. Mousseau, G. Pelletier, A. B. Charette, *Chem. Rev.*, 2012, **112**, 2642; (b) C. Liu, J. Luo, L. Xu, Z. Huo, *ARKIVOC*, 2013, Part (i), 154; (c) J. J. Yin, B. P. Xiang, M. A. Huffman, C. E. Raab, I. W. Davies, *J. Org. Chem.*, 2007, **72**, 4554; (d) J. M. Keith, *J. Org. Chem.*, 2008, **73**, 327; (e) J. M. Keith, *J. Org. Chem.*, 2010, **75**, 2722; (f) A. T. Londregan, S. Jennings, L. Q. Wei, *Org. Lett.*, 2010, **12**, 5254; (g) A. T. Londregan, S. Jennings, L. Q. Wei, *Org. Lett.*, 2011, **13**, 1840; (h) S. E. Wengryniuk, A. Weickgenannt, C. Reiher, N. A. Strotman, K. Chen, M. D. Eastgate, P. S. Baran, *Org. Lett.*, 2013, **15**, 792; (i) R. P. Farrell, M. V. Silva Elipe, M. D. Bartberger, J. S. Tedrow, F. Vounatsos, *Org. Lett.*, 2013, **15**, 168.
9. Pat. EU EP0619307, 1994; https://www.google.com/patents/EP0619307A1?cl=en&hl=ru.
10. (a) E. Rivadeneira, K. Jelich, Eur. Pat. EP 556683, 1993; https://www.google.com/patents/EP0556683A1?cl=en; (b) E. Rivadeneira, K. Jelich, Pat. US 5502194, 1996; http://www.google.com/patents/US5502194; (c) A. Johansson, T. Svensson, Pat. WO/2001/070730, 2001; http://www.google.com/patents/WO2001070730A1?cl=en.

11. H. Xiong, A. T. Hoye, K.-H. Fan, X. Li, J. Clemens, C. L. Horchler, N. C. Lim, G. Attardo, *Org. Lett.*, 2015, **17**, 3726.
12. J. R. Ballinger, F. W. Teare, B. M. Bowen, E. S. Garnett, *Electrochim. Acta*, 1985, **30**, 1075.
13. (a) A. Lin, C. B. Huehls, J. Yang, *Org. Chem. Front.*, 2014, **1**, 434; (b) T. Liang, C. N. Neumann, T. Ritter, *Angew. Chem., Int. Ed.*, 2013, **52**, 8214; (c) N. Bartlett, R. D. Chambers, A. J. Roche, R. C. H. Spink, L. Chaconb, J. M. Whalen, *Chem. Commun.*, 1996, 1049; (d) B. Zenva, K. Lutor, L. Chacon, M. Fele-Beuermann, J. Allman, C. Shen, N. Bartlett, *J. Am. Chem. Soc.*, 1995, **117**, 10025; (e) N. Bartlett, R. D. Chambers, A. J. Roche, R. C. H. Spink, L. Chacon, J. M. Whalen, *J. Chem. Soc.*, *Chem. Commun.*, 1996, 1049; (f) S.-J. Lou, D.-Q. Xu, A.-B. Xia, Y.-F. Wang, Y.-K. Liu, X.-H. Du, Z.-Y. Xu, *Chem. Commun.,* 2013, **49**, 6218.
14. (a) P. Sartori, N. Ignat´ev, *J. Fluorine Chem.*, 1998, **87**, 157; (b) F. G. Drakesmith, in *Topics in Current Chemistry*, Springer, Berlin, 1997, Vol. **193**, p. 197.
15. M. N. Khrizanforov, D. M. Arkhipova, R. P. Shekurov, T. P. Gerasimova, V. V. Ermolaev, D. R. Islamov, V. A. Miluykov, O. N. Kataeva, V. V. Khrizanforova, O. G. Sinyashin, Y. H. Budnikova., *J. Solid State Electrochem.*, 2015, **19**, 2883.
16. N. Bartlett, R. Chambers, A. J. Roche, R. C. H. Spink, L. Chacyn, J. M. Whalen, *Chem. Commun.*, 1996, 1049.
17. J. Holzbock, W. Sawodny, L. Walz, *Z. Kristallogr.*, 1997, **212**, 115.
18. J. Holzbock, W. Sawodny, U. Thewalt, *Z. Anorg. Allg. Chem.*, 2000, **626**, 2563.
19. M. Ye, G.-L. Gao, J.-Q. Yu, *J. Am. Chem. Soc.*, 2011, **133**, 6964.
20. J. A. Joule, R. Mills, *Heterocyclic Chemistry*, 4th ed., Blackwell Sci., Oxford, 2000, 589 pp.
21. (a) T. Umemoto, K. Harasawa, G. Tomizawa, *J. Fluorine Chem.*, 1991, **53**, 369; (b) T. Umemoto, K. Harasawa, G. Tomizawa, K. Kawada, K. Tomita, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 1081.
22. A. Y. Denisov, V. I. Mamatyuk, O. P. Shkuro, *Magn. Reson. Chem.*, 1985, **23**, 482.
23. P. Tang, W. Wang, T. Ritter, *J. Am. Chem. Soc.*, 2011, **133**, 11482.
24. R. D. Chambers, M. Parsons, G. Sandford, Ch. J. Skinner, M. J. Atherton, J. S. Moilliet, *J. Chem. Soc.*, *Perkin Trans. 1*, 1999, 803.
25. T. Furuya, T. Ritter, *Org. Lett.*, 2009, **11**, 2860.
26. Eur. Pat. Appl. EP 1595881 (A1); https://worldwide.espacenet.com.

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