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Reaction of metal diethylnitroxides with pentafluoropyridine, pentafluorobenzene, octafluorotoluene and 2-chloro-3- or 5-nitropyridine ☆

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Abstract

Treatment of the nitroxides Et_2NO^- M^+ (**2a–c**) (M = Na, Li, K) and $(Et_2NO^-)_2$ Ba^{2+} (**2d**) with pentafluoropyridine (**3**) at room temperature (1 d) gave in all cases the compounds Py–NEt_2 (**8**), Py–$ONEt_2$ (**9**), Py–NHEt (**10**) and Py–$O^-H_2\overset{+}{N}Et_2$ (**11**) (where Py = tetrafluoro-4-pyridyl) in the approximate ratio 1:30:30:35. The radical traps, 1,4-dinitrobenzene or galvinoxyl, retarded the reaction (5 d required for complete consumption of **3**), but the same products were formed in a similar ratio and compounds **8–11** were also formed by decomposition of the amine oxide Py–$\overset{+}{N}(\bar{O})Et_2$ (**20**) [synthesised by the route: **3** + $Et_2NH \rightarrow$ **8** (57%); **8** + $(CF_3CO)_2O/H_2O_2 \rightarrow$ **20** (81%) as the monohydrate]. It is proposed that the products **8–11** arose mainly via an $S_{RN}1$ mechanism involving single electron transfer (SET) from the nitroxide **2** to the substrate **3** leading to the radical anion (**21**) and hence the tetrafluoro-4-pyridyl radical (**22**) which reacted with **2** at nitrogen to afford the amine oxide **20**. Major Meisenheimer rearrangement of **20** gave hydroxylamine **9**, while minor rearrangement afforded the hydroxylamine Py–N(Et)OEt (**23**) which eliminated ethanal to yield the secondary amine **10**. Competing deoxygenation of **20** gave the tertiary amine **8** and the salt **11** [synthesised by reaction of Py–OH (**26**) with Et_2NH] was formed via decomposition of **8** in light (or on heating) involving homolytic fission of the weak N–O bond. Treatment of **9** with the acids AHF or CF_3SO_3H resulted in exothermic reaction and gave compounds **8** (27%, 11%), **10** (16%, 18%) and **11** (13%, 25%) via competing protonation at oxygen and nitrogen.

The corresponding reactions of nitroxide **2a** with the substrates C_6HF_5 (**4**) and $C_6F_5CF_3$ (**5**) afforded the salt 4-H-C_6F_4–O^- $H_2\overset{+}{N}Et_2$ (**12**) (15%) and a mixture of the compounds 4-CF_3–C_6F_4–R [R = $ONEt_2$ (**13**) (23%); R = NHEt (**14**) (2%); R = O^- $H_2\overset{+}{N}Et_2$ (**15**) (12%)], respectively, while treatment of **2a** with 2-chloro-3-nitropyridine (**6**) and 2-chloro-5-nitropyridine (**7**) gave the tertiary amines 2-*N,N*-diethylamino-3-nitropyridine (**16**) (35%) or 2-*N,N*-diethylamino-5-nitropyridine (**18**) (25%) together with *N*-(2-chloro-3-pyridyl)-*N*-(3-nitro-2-pyridyl)amine (**17**) (13%) or *N*-(2-chloro-5-pyridyl)-*N*-(5-nitro-2-pyridyl)amine (**19**) (27%) via presumed $S_{RN}1$ pathways.

Keywords: Metal diethylnitroxides; Pentafluoropyridine; Pentafluorobenzene; Octafluorotoluene; 2-chloro-3-nitropyridine; 2-chloro-5-nitropyridine

1. Introduction

Hydroxylamines and their salts are ambident nucleophiles and it has been reported that reaction of the salt $(CF_3)_2NO^-$ Na^+ with chloronitrobenzenes [2], 2- and 4-halogenopyridines [3,4], polyfluoropyridines [3,5] and octafluorotoluene [3] gave, in all cases, the corresponding trisubstituted hydroxylamines $(CF_3)_2NOAr$ or $(CF_3)_2NOPy$, via a presumed S_NAr pathway involving nucleophilic attack by the oxygen atom. Treatment of 2-chloro-pyridine, -pyrimidine and -pyrazine with mercurials derived from bis-(trifluoromethyl)amino-oxyl, $(CF_3)NO\cdot$, resulted analogously in replacement of chlorine by the $(CF_3)_2NO$ group [6].

In contrast to these observations, trapping of benzyne (generated from anthranilic acid and isoamyl nitrite) with the parent hydroxylamine $(CF_3)_2NOH$ afforded the novel amine oxide $(CF_3)_2\overset{+}{N}(\bar{O})Ph$ and the tertiary amine $(CF_3)_2NPh$, formed presumably via nucleophilic attack involving the nitrogen atom [2].

A number of *N*-fluoropyridyl- and *N*-fluoroaryl-hydroxylamines have been prepared [7–9]. However, *O*-fluoropyridyl- and *O*-fluoroaryl-hydroxylamines [apart from those containing the $(CF_3)_2NO$ group] have not been reported in the chemical literature and the major aim of the present study was to synthesise certain such compounds. To this end *N,N*-diethylhydroxylamine (**1**) was converted into its sodium salt **2a** and reactions of the nitroxide **2a** with pentafluoropyridine

☆ Reported in part, in a preliminary communication; see Ref. [1].

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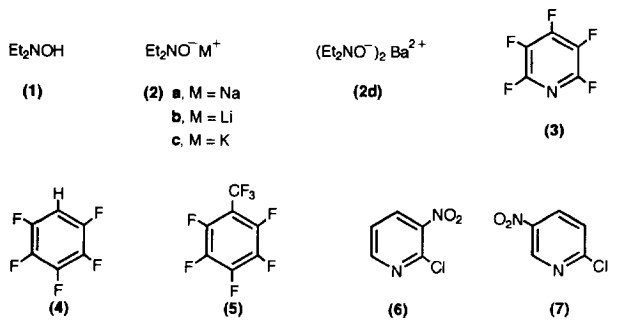
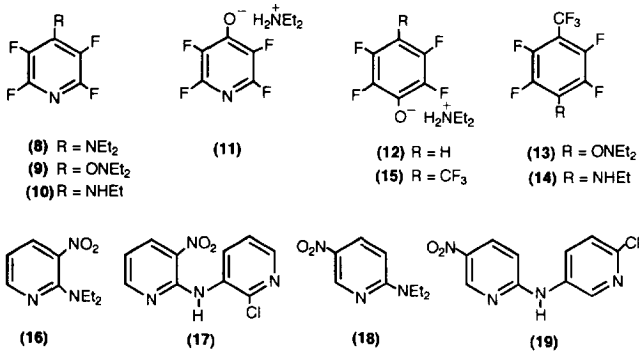
(3), pentafluorobenzene (4) and octafluorotoluene (5) were carried out. The reactions of the corresponding lithium (**2b**), potassium (**2c**) and barium (**2d**) nitroxides with **3** were then investigated to compare the results with those obtained for the sodium nitroxide **2a**. Finally, the reactions of the nitroxide **2a** with 2-chloro-3-nitropyridine (**6**) and 2-chloro-5-nitropyridine (**7**) were also studied for comparison with the reported reactions of the sodium nitroxide $(CF_3)_2NO^-\ Na^+$ with these substrates [2].



2. Results and discussion

The results obtained from the reactions of the metal nitroxides **2** with the substrates **3–7** are summarised in Table 1.



2.1. Reactions of nitroxides 2 with pentafluoropyridine (3)

In contrast to the reaction of the nitroxide $(CF_3)_2NO^-\ Na^+$ with pentafluoropyridine (**3**), which gave the hydroxylamine 4-$(CF_3)_2NOC_5F_4N$ as the sole isolated product [3], the reactions of the nitroxides **2** were more complex and, besides the 4-substituted tetrafluoropyridylhydroxylamine (**9**), the 4-pyridylamines **8** and **10**, and diethylammonium tetrafluoro-4-pyridinolate **11** were also isolated; compound **11** was shown to have arisen by decomposition **9** (see later).

Nucleophilic attack on **3**, including that of the nitroxide $(CF_3)_2NO^-\ Na^+$ [3], in general results in initial substitution of the 4-fluorine and a satisfactory rationale for this has been put forward [10]. However, with certain nucleophiles, i.e. HO^- in ^{t}BuOH [11], oximate salts $R^1R^2C{=}N{-}O^-\ M^+$ ($R^1 = R^2 = Me$ or Ph; $R^1 = Me$, $R^2 = Ph$; M = Li, Na or K) [12,13] and hydrazone salts $Ph_2C{=}NNR\ Li^+$ (R = H or Ph) [12,13], 2-substitution can compete with 4-substitution. All of the isolated products **8–11** in the present work were 4-substituted tetrafluoropyridines.

For reaction at room temperature (1 d), the ratios of the products **8–11** were very similar regardless of the metal nitroxide **2a–d** used, or whether heterogeneous (solvent Et_2O) or homogeneous (solvent PhH) conditions were employed. However, reaction involving nitroxide **2a** at −78 °C in Et_2O gave a higher yield of the hydroxylamine **9** at the expense of compounds **10** and **11**.

The hydroxylamine **9** could have arisen (i) by a conventional S_NAr mechanism involving nucleophilic attack by an oxygen lone pair in **2** on the 4-position of **3** (Scheme 1) as proposed for the corresponding reaction of the nitroxide $(CF_3)_2NO^-\ Na^+$ [3], (ii) by an S_NAr mechanism involving nucleophilic attack by the nitrogen lone pair in **2** to give the amine oxide **20** which then rearranged to **9** (Scheme 2) or (iii) via an $S_{RN}1$ mechanism involving a single electron transfer (SET) from the nitroxide **2** to **3** to afford the radical anion **21** and hence the 4-tetrafluoropyridyl radical **22** and leading to **9** and/or the amine oxide **20** (Scheme 3).

Experiments were then undertaken to try to determine whether an SET reaction was involved and whether the amine oxide **20** was formed as an intermediate.

The presence of radical species in the reaction of nitroxide **2a** in Et_2O solvent was shown by electron paramagnetic resonance (EPR) studies and a preliminary heterogeneous reaction of **2a** with **3** in Et_2O solvent in the presence of the radical trap 1,4-dinitrobenzene (**1d**), which resulted in a much slower consumption of nitroxide **2a** than in the absence of the trap and gave the hydroxylamine **9** as the only detected product together with unchanged **3** (ratio 25:75) [12,13]. This observation was interpreted on the basis that two mechanisms were operative in the reaction: (i) an SET mechanism leading to all the isolated products and (ii) an S_NAr mechanism leading to hydroxylamine **9** and the salt **11** (by decomposition of **9**). However, a later investigation [14] failed to confirm this result and it was found that heterogeneous reaction of nitroxide **2a** (in solvent Et_2O) or homogeneous reaction of nitroxide **2c** (in solvent PhH) with **3** in the presence of the radical traps 1,4-dinitrobenzene or galvinoxyl at room temperature was much slower (5 d required for complete conversion to **3** as shown by ^{19}F NMR spectroscopy as compared to 1 d in the absence of the radical trap), but the same products **8–11** were formed in similar ratio to that obtained in the absence of the trap.

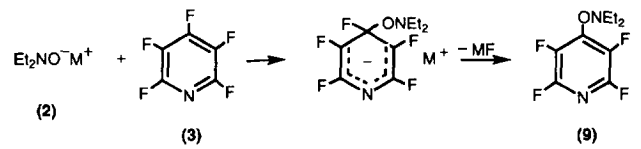
The retardation of the reactions in the presence of the radical traps is evidence for a contribution from an SET mechanism, but it does not preclude a competing S_NAr mechanism.

The amine oxide **20** was then synthesised by reaction of diethylamine with pentafluoropyridine (**3**) in solvent Et_2O at 0 °C to give 4-(diethylamino)tetrafluoropyridine (**8**) (57%), which, on treatment with trifluoroacetic anhydride and hydrogen peroxide (85%) in solvent $CHCl_3$, gave the monohydrate of compound **20** (81%). The structure of the

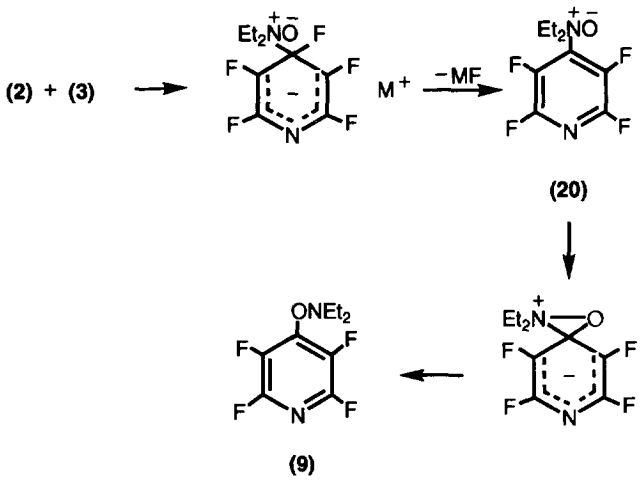
Table 1
Reactions of metal *N,N*-diethylnitroxides **2** with halogenopyridines and polyfluorobenzenes (ca. 1:1 molar ratio)

Substrate	Nitroxide	Solvent	Conditions		Products (%) [e]	Entry 3.3 [h]
			Temp. (°C)	Time (d)		
3	**2a**	Et_2O	−78	0.625	**8** (<1); **9** (33); **10** (8); **11** (4)	(a) (i)
3	**2a**	Et_2O		1	**8** (<1); **9** (23); **10** (21); **11** (24) ratio = 1:33:31:35 [f]	(a) (ii)
3	**2a**	C_6H_6	20	1	**8** (<1); **9** (24); **10** (23); **11** (27) ratio = 1:32:30:37 [f]	(a) (iii)
3 [a]	**2a**	Et_2O	20 [d]	1	ratio **3/9** = 75:25 [f]	(c) (i)
3 [b]	**2a**	Et_2O	20	5		(c) (i)
3 [c]	**2a**	Et_2O	20	5		(c) (ii)
3	**2b**	C_6H_6	20	1		(b)
3	**2c**	C_6H_6	20	1	Ratio **8/9/10/11** = 1:31 ± 4:32 ± 4:36 ± 4 [f]	(b)
3 [a]	**2c**	C_6H_6	20	5		(c) (iii)
3 [c]	**2c**	C_6H_6	20	5		(c) (iv)
3	**2d**	C_6H_6	20	1		(b)
4	**2a**	Et_2O	20	8	**12** (15)	(d)
5	**2a**	Et_2O	−78	0.33	**13** (23); **14** (2); **15** (12)	(e)
6	**2a**	THF	20	3	**16** (35); **17** (13) [g]	(f)
7	**2a**	Et_2O	20	1	**18** (25); **19** (27)	(g)

[a] In the presence of 1,4-dinitrobenzene (0.10 mol equiv.).
[b] In the presence of 1,4-dinitrobenzene (0.50 mol equiv.).
[c] In the presence of galvinoxyl (0.10 mol equiv.).
[d] Initiated at −78 °C (1 h).
[e] Yields based on substrate reacted, i.e. not recovered.
[f] Ratios as determined by ^{19}F NMR spectroscopy.
[g] Unchanged **6** (10% recovered) also isolated.
[h] Experimental section sub-headings.



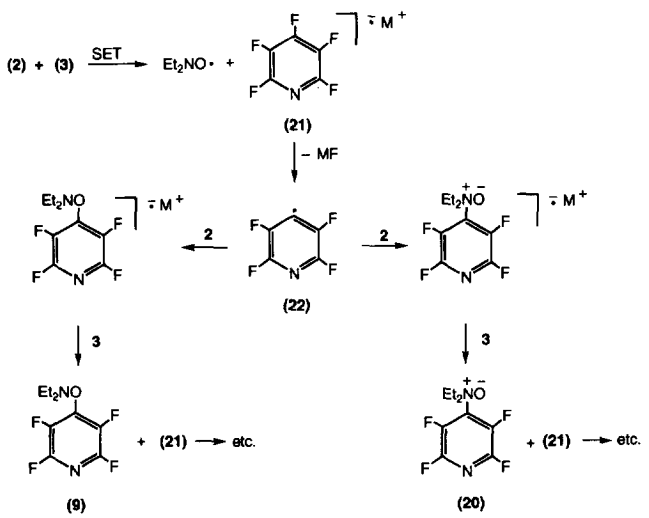
Scheme 1.



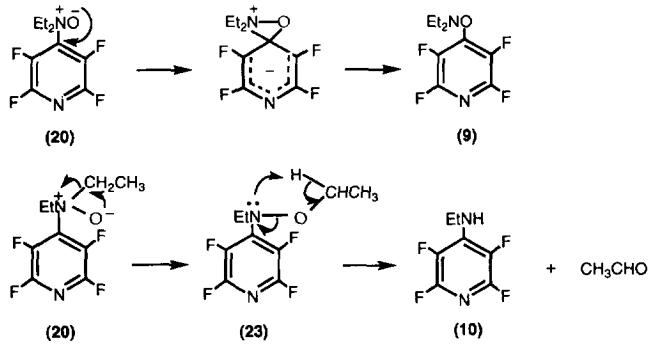
Scheme 2.

product was confirmed by the following spectral data: [δ_H: 13.8 (br., 2H, H_2O); 4.40 (q, 4H, $2CH_2N$, J=7 Hz); 1.50 (t, 3H, $2CH_3CH_2$, J=7 Hz) ppm. δ_F: −5.2 (mult., 2F, F-2/6); −60.0 (mult., 2F, F-3/5) ppm. MS m/z: 238 (M^+ for anhydrous **20**). IR ν_{max} (cm^{-1}): 3400 (br., hydrogen-bonded O–H str., i.e. –Ō----H–OH)]. The ^{19}F NMR chemical shifts were at considerably lower field than those observed in the spectra of the parent amine **8** [δ_F: −17.8 (F-2/6); −79.5 (F-3/5) ppm] and the hydroxylamine **9** [δ_F: −16.0 (F-2/6); −77.6 (F-3/5) ppm] in agreement with the presence of the strong electron-withdrawing $Et_2\overset{+}{N}(\bar{O})$ group in the 4-position.

On gentle warming (40 °C) in vacuo with continuous pumping, the monohydrate of compound **20** afforded hydrox-



Scheme 3.



Scheme 4.

ylamine **9** (58%) (which underwent partial decomposition to salt **11** on storage with the decomposition being accelerated by light) and the secondary amine **10** (12%) after separation by dry column flash chromatography (DCFC); a weak TLC spot with the same R_F value as that of the tertiary amine **8** was observed on examination of the crude product mixture and a tar was also formed in the reaction.

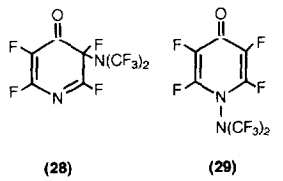
On heating, amine oxides have been reported to decompose by *syn*-elimination of an alkene to afford *N,N*-disubstituted hydroxylamines [15–18] or to undergo Meisenheimer rearrangement to give *N,N,O*-trisubstituted hydroxylamines [2,15,16,19]. Certain tertiary amines give the parent tertiary amines and secondary amines on thermolysis [20].

The products **9** and **10** can be explained by two competing Meisenheimer rearrangements of the monohydrate of amine oxide **20**, i.e. a major rearrangement involving oxide attack on the 4-position of the pyridyl ring leading to **9** and a minor rearrangement involving oxide attack on a methylene carbon in an ethyl group to give the intermediate *O*-ethylhydroxylamine (**23**) from which elimination of ethanal afforded the secondary amine **11** (Scheme 4). Comparable aldehyde eliminations from *O*-allyl and *O*-benzyl-*N*-methyl-*N*-phenylhydroxylamines have been reported [15,21].

The trace of tertiary amine **8** detected in the crude product mixture was formed presumably by deoxygenation of the amine oxide **20**.

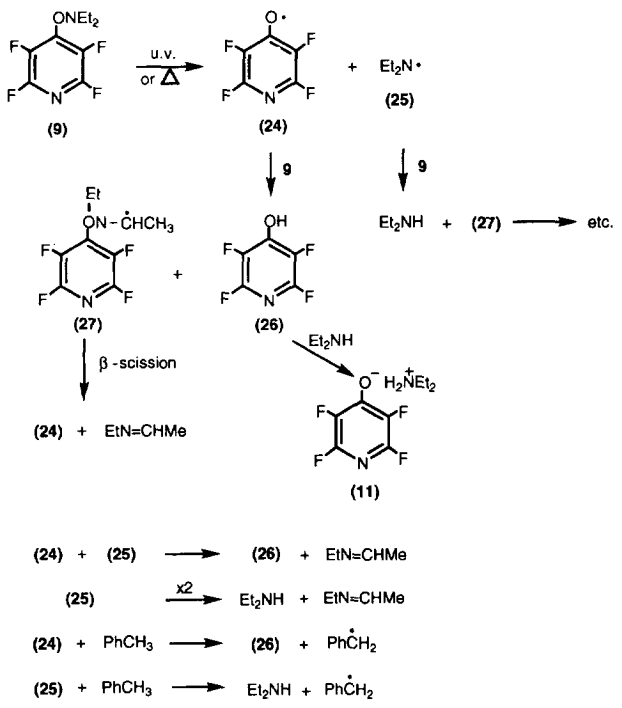
The observation that hydroxylamine **9** was unstable on storage in light and decomposed to afford salt **11** and tar showed that **9** is the precursor of **11**. Hydroxylamine **9** was also thermally unstable and, on heating in the absence of light at 90–110 °C (3 d), unchanged **9** (76% recovered), **11** (33%) and tar were formed; rearrangement of **9** to the amine oxide **20** did not take place since amine **10**, a decomposition product of **20**, was not detected. The yield of salt **11** was increased greatly by thermolysis of **9** in the presence of an excess of toluene at 100 °C (4 d) which gave unchanged **9** (21% recovered) and **11** (78%).

It is proposed that salt **11** is formed from **9** via homolytic fission of the weak N–O bond in light or on heating to give tetrafluoropyridine-4-oxy (**24**) and diethylamino (**25**) radicals. Hydrogen abstraction by these radicals afforded 4-hydroxytetrafluoropyridine (**26**) and diethylamine, respectively, which then interacted to yield salt **11**. In the absence of other molecules which contain C–H bonds, the hydrogen abstractions can occur by disproportionation reactions of radicals **24** and **25** or, more likely, by reaction of **24** and **25** with unchanged **9** to produce the radical **27**. When **9** was decomposed in toluene, benzylic hydrogen abstraction from toluene by the radicals **24** and **25** took place (Scheme 5). Pyrolysis of the hydroxylamine 4-$(CF_3)_2NOC_5F_4N$ at 125 °C also resulted in N–O bond cleavage, but the resulting radicals **24** and $(CF_3)_2N\cdot$ recombined *meta* to the ring nitrogen and at the ring nitrogen to give the dienones **28** and **29**, respectively [3].



Salt **11** was synthesised in 90% yield by treatment of the 4-hydroxypyridine **26** [prepared from reaction of aqueous sodium hydroxide with pentafluoropyridine (**3**) in 26% yield] with diethylamine in diethyl ether at 0 °C, and its structure was confirmed by X-ray crystallography [22]. Hydrolysis of **11** with aqueous hydrochloric acid gave the 4-hydroxypyridine **26** (83%).

In conclusion, all of the products **8**–**11** isolated from reaction of the nitroxides **2** with pentafluoropyridine (**3**) can be explained by the intermediacy of the amine oxide **20**. The results obtained indicate that compound **20** arose mainly by an $S_{RN}1$ mechanism involving the formation of the radical



Scheme 5.

anion **21** and hence the tetrafluoro-4-pyridyl radical **22** which reacted with the nitroxides **2** at nitrogen (Scheme 3). However, it was not possible to discount competing contributions from (i) an $S_{RN}1$ mechanism involving reaction of the radical **22** with the nitroxides **2** at oxygen leading to the hydroxylamine **9** (Scheme 3) or (ii) S_NAr mechanisms in which compounds **9** and **20** were formed by attack on **3** by oxygen and nitrogen lone pairs in **2**, respectively (Schemes 1 and 2).

In contrast to these results, reaction of the nitroxide $(CF_3)_2NO^-\ Na^+$ with **3** is reported to afford only the trisubstituted hydroxylamine 4-$(CF_3)_2NOC_5F_4N$ via a presumed S_NAr mechanism involving attack by an oxygen lone pair on **3**. In $(CF_3)_2NO^-$ the availability of the nitrogen lone pair is reduced considerably by the two electron-withdrawing CF_3 groups relative to that in the nitroxides **2**, which have two electron-releasing ethyl groups bonded to nitrogen. Therefore, nucleophilic attack involving the nitrogen lone pair is less favoured in the nitroxide $(CF_3)_2NO^-$ than in the nitroxides **2**. Furthermore, the amine oxide 4-$(CF_3)_2\overset{+}{N}(\bar{O})C_5F_4N$ is destabilised by three electron-withdrawing groups and its formation would be less favoured than formation of amine oxide **20**, which contains two stabilising ethyl groups and only one destabilising tetrafluoropyridyl group. The electron-withdrawing CF_3 groups would also render electron transfer (SET) from the nitroxide $(CF_3)_2NO^-$ to **3** less favourable and therefore an $S_{RN}1$ reaction involving this nitroxide would be less likely than with the nitroxides **2**.

A study of the reactions of hydroxylamine **9** with acids was also carried out. Treatment of **9** with anhydrous hydrogen fluoride (AHF) at 20 °C (4 h) or with trifluoromethanesulphonic acid at 20 °C (1 h) gave compounds **8** (27%; 11%), **10** (16%; 18%) and **11** (13%; 25%), together with tar, and the reactions were extremely exothermic. It is proposed that the products were formed as shown in Scheme 6.

Protonation of **9** can take place at oxygen or nitrogen to give the cations **30** and **31**, respectively. Homolytic fission of the N–O bonds in **30** and **31**, favoured by light and the heat generated in the reactions, followed by hydrogen abstraction by the resulting radicals or radical cations from available C–H bonds afforded diethylamine and 4-hydroxytetrafluoropyridine (**26**), either as the neutral compounds or their protonated counterparts. Reaction between diethylamine and **26** gave the salt **11**, while nucleophilic attack of diethylamine on protonated **26** at the carbon bearing the good leaving group H_2O led to the tertiary amine **8**. Competing rearrangement of **30** gave the amine oxide **20** and hence the secondary amine **10** via Meisenheimer rearrangement and elimination of ethanal.

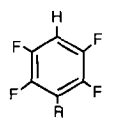
2.2. Reaction of the sodium nitroxide 2a with pentafluorobenzene (4) and octafluorotoluene (5)

The products isolated from reaction of the nitroxide **2a** with the substrates **4** and **5** in Et_2O solvent, i.e. the diethylammonium salt **12** from **4** and the hydroxylamine **13**, the secondary amine **14** and the diethylammonium salt **15** from **5**, were analogous to those obtained from the corresponding reaction with pentafluoropyridine (**3**). In the absence of other evidence, it is proposed that these products arose mainly via the intermediacy of the amine oxides **32** and **33**, which then underwent Meisenheimer rearrangement and further reaction as outlined in Schemes 2–5 for the products from the reaction of the nitroxides **2** with **3**.

It was perhaps surprising that the hydroxylamine **34**, the precursor of salt **12**, and the secondary amine **35** were not detected in the products from the reaction of pentafluorobenzene (**4**), but considerable tar formation was observed and the yield of salt **12** was very low.

The compounds **12–15** were all *para*-disubstituted tetrafluorobenzenes as shown by their ^{19}F NMR spectra which contained only two absorptions for the ring fluorines, i.e. F-2/6 and F-3/5. If S_NAr processes compete with an $S_{RN}1$ pathway, then nucleophilic attack would be expected *para* to the H or CF_3 substituent as observed for the reaction of other nucleophiles with compounds **4** and **5** [3,23,24].

(32) R=H
(33) R=CF_3

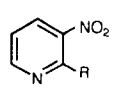


(34) R=$ONEt_2$
(35) R=NHEt

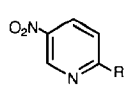
2.3. Reaction of the sodium nitroxide 2a with the chloronitropyridines 6 and 7

The bis(pyridyl) amines **17** and **19** were unexpected products from these reactions and the tertiary amines **16** and **18** were obtained in reasonable yield in contrast to the traces of tertiary amine **8** isolated from the corresponding reaction involving pentafluoropyridine (**3**). Expected products, such as the hydroxylamine (**36a/b**) and the secondary amine (**37a/b**), were not detected and considerable tar formation was observed. These results contrast the reaction of the nitroxide $(CF_3)_2NO^-\ Na^+$ with the substrates **6** and **7** which afforded the tertiary hydroxylamine (**38a/b**) by a presumed S_NAr mechanism [3,4].

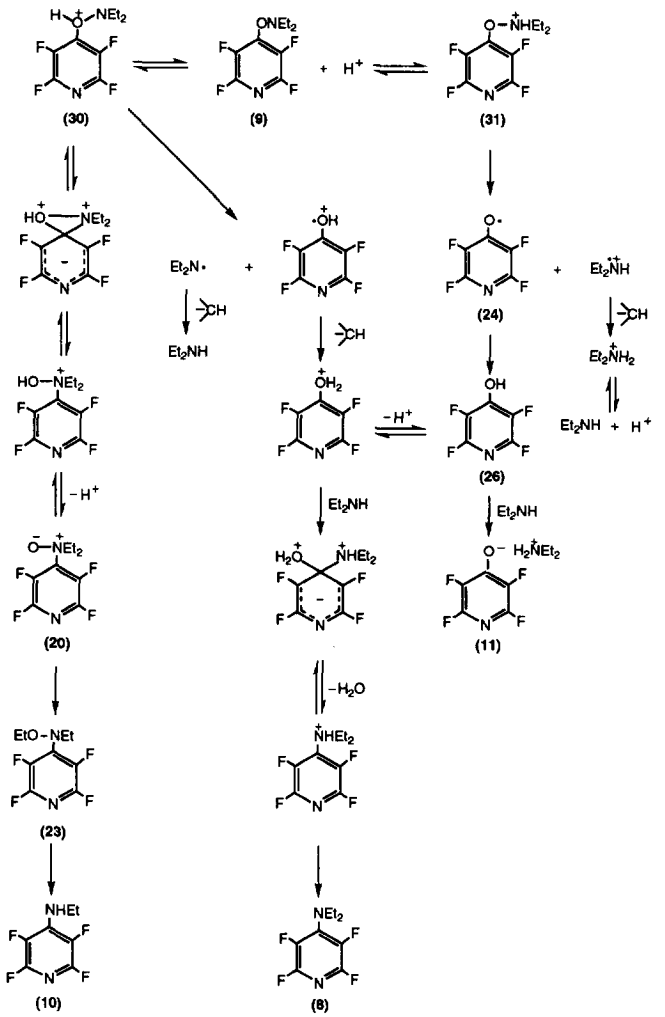
It has been reported that monochloropyridines can undergo $S_{RN}1$ reaction with nucleophiles, e.g. treatment of 2-chloropyridine with the thiophenoxide ion gave phenyl 2-pyridyl sulphide [25]. Therefore, it is considered probable that an $S_{RN}1$ pathway is involved in the present reactions and that the tertiary amines **16** and **18** are formed by deoxygenation of intermediate amine oxides **39a** and **39b**, respectively, as has been reported for certain tertiary amine oxides on thermolysis [20].



(36a) R=$ONEt_2$
(37a) R=NHEt
(38a) R=$ON(CF_3)_2$
(39a) R=$\overset{+}{N}(Et_2)\bar{O}$



(36b) R=$ONEt_2$
(37b) R=NHEt
(38b) R=$ON(CF_3)_2$
(39b) R=$\overset{+}{N}(Et_2)\bar{O}$



Scheme 6.

A reaction pathway which explains both the deoxygenation of the amine oxides **39a** and **39b** and the formation of the bis(pyridyl) amines **17** and **19** is shown in Scheme 7.

An $S_{RN}1$ mechanism involving single electron transfer (SET) from the nitroxide **2a** to the chloronitropyridine **6** or **7** afforded the amine oxide **39a/b** via the 2-pyridyl radical (**40a/b**) derived from the radical anion (**41a/b**). Further reaction of the radical **40a/b** with the amine oxide **39a/b** resulted in deoxygenation to give the tertiary amine **16** or **18** and the resonance-stabilised pyridyl-2-oxy radical (**42a/b**). Competing reaction of radical **40a/b** with the substrate **6** or **7** at oxygen in the nitro group led to intermediate oxyl radical (**43a/b**) which underwent β-scission to afford the chloronitrosopyridine (**44a/b**) and the radical **42a/b**. Reaction of the nitrosopyridine **44a/b** with the pyridyl radical **40a/b** gave first the bis(pyridyl)oxyl radical (**45a/b**) and then the tris(pyridyl)oxyl radical (**46a/b**), which underwent N–O bond scission to regenerate substrate **6** or **7** together with the bis(pyridyl) amino radical (**47a/b**). Hydrogen abstraction by radical **47a/b** from suitable C–H bonds then gave the observed bis(pyridyl) amine **17** or **19**. The fate of the pyridyl-2-oxy radical **42a/b** is not known, although it would be expected to function as an efficient radical trap at the ring nitrogen, C-3 or C-5 positions.

The sequence of steps initiated by reaction of the chloronitrosopyridine **44a/b** with the oxyl radical **45a/b**, and culminating in formation of the amino radical **47a/b** and regeneration of the substrate **6** or **7**, is analogous to the steps considered to occur in the reaction of the amino-oxyl $(CF_3)_2NO\cdot$ with the nitrosoalkane CF_3NO to afford the nitroalkane CF_3NO_2 and the amino radical $(CF_3)_2N\cdot$ [26].

If the above pathway is correct then the preferred deoxygenation of the amine oxides **39a/b** indicates that Meisenheimer rearrangement of these amine oxides to afford the hydroxylamines **36a/b** and the secondary amines **37a/b** is less favourable than the corresponding rearrangement of the amine oxide **20** formed from pentafluoropyridine (**3**).

The products **16–19** were identified by elemental analysis (for C, H, N), molecular ion peaks in their mass spectra (*m/z* 195 for **16/18**; 250/252 for **17/19**), IR bands [ν_{max} (cm^{-1}): 1480–1460 (s) (asym. NO_2 str.); 1350–1325 (s) (sym. NO_2 str.) for **16–19**; ca. 3300 (m) (N–H str.) for **17/19**] and their ^1H NMR spectra {absorptions for $-N(CH_2CH_3)_2$ [δ_H: 1.12/1.22 (t, 6H, $2CH_3$); 3.35/3.70 (q, 4H, $2NCH_2$) ppm] in **17/19** and pyridine ring protons with identical substitution patterns to those in the substrates **6** and **7** and having the appropriate chemical shifts, multiplicities and coupling constants (Table 2).

3. Experimental details

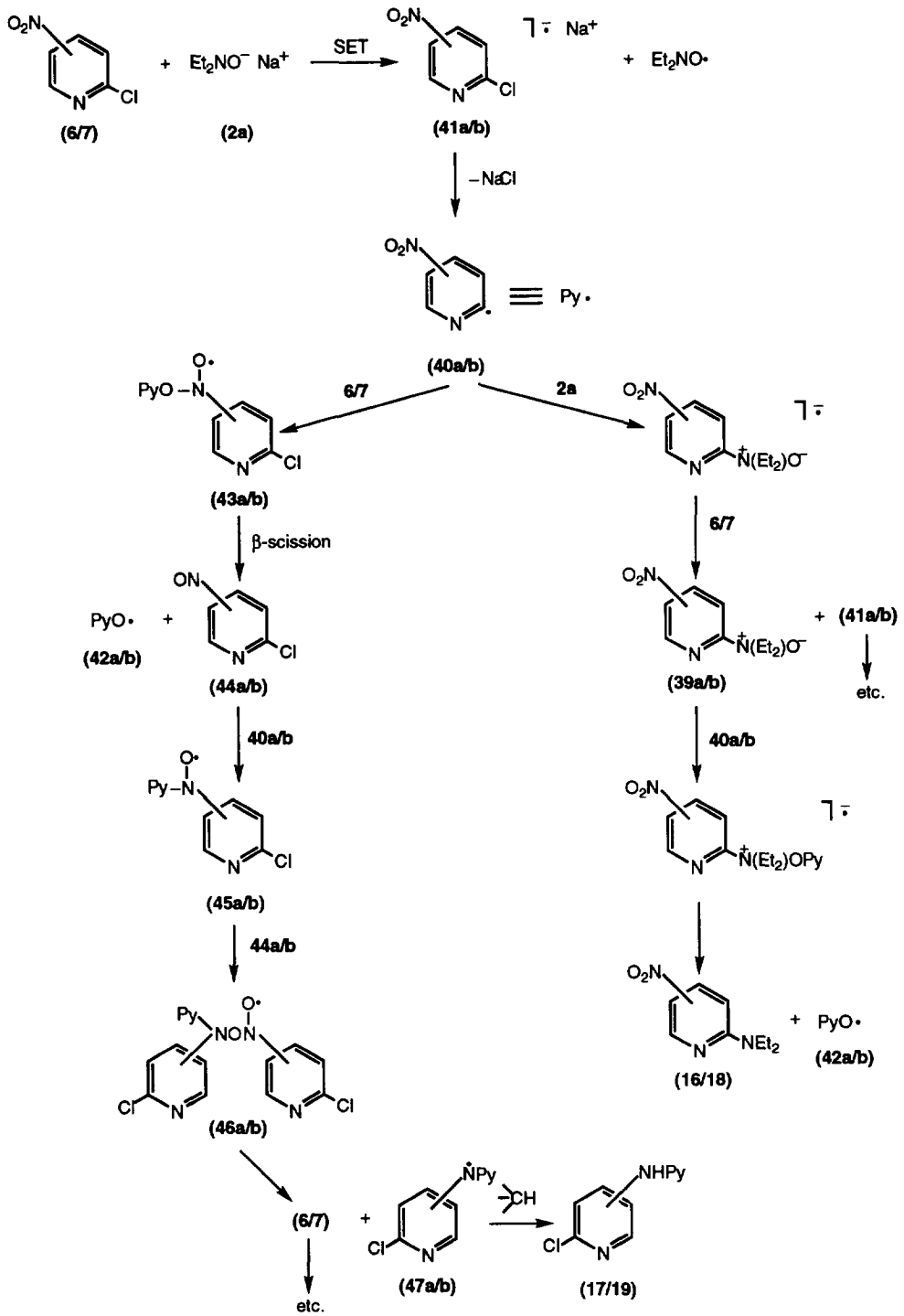
3.1. Starting materials

The substrates **3–7** were commercial samples and the purity of each was checked (NMR spectroscopy) before use.

The nitroxides **2** were prepared by addition of a slight excess (5%–10%) of *N,N*-diethylhydroxylamine (**1**) to a stirred mixture of small slices of the appropriate metal (Na, Li, K or Ba) in a solvent (Et_2O, THF or PhH) under a nitrogen atmosphere with stirring being continued at room temperature until the metal had been consumed completely (1–4 d for Na, K and Li; ca. 10 d for Ba); in benzene as the solvent at a temperature (70 °C) above the melting point of potassium (64 °C), the preparation of the potassium nitroxide **2c** was complete in 3 h. The salts **2** were soluble in benzene, but were present as white slurries in the ether solvents and were used in situ without isolation.

3.2. General techniques

The reactions of the salts **2** were carried out under nitrogen in the solvents described in the text. The products from all the reactions were either separated (or purified) by dry column flash chromatography (DCFC) using silica gel (Fluka 60 GF_{254}) and eluants as given in the text, or sublimation under reduced pressure, or their relative ratios were determined by ^{19}F NMR spectroscopy.



Scheme 7.

The pure products were examined by IR spectroscopy (Perkin-Elmer DE783 instrument), ^{1}H NMR spectroscopy [Perkin-Elmer R34 (220 MHz) spectrometer; external reference Me_4Si], ^{19}F NMR spectroscopy [Perkin-Elmer R32 (84.6 MHz) instrument; external reference CF_3CO_2H], ^{13}C NMR spectroscopy [Bruker AC-300 (75.0 MHz) spectrometer with broad-band proton decoupling and D_2O as the deuterium lock signal; external reference Me_4Si] and mass spectrometry (Kratos MS 45 spectrometer operating with an electron beam energy of 70 eV under electron impact conditions). The NMR spectra were run on solutions in $CDCl_3$ (unless stated to the contrary) and chemical shifts to low field of reference are designated positive.

Boiling points were determined by Siwoloboff's method and melting points are uncorrected.

Table 2
^1H, ^{19}F and ^{13}C NMR spectral data

Compound	NMR δ (ppm) [a]
8	δ_H: 3.30 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.05 (t, 3H, $2CH_3$, $J=7$ Hz). δ_F: −17.8 (mult., 2F, F-2/6); −79.5 (mult., 2F, F-3/5). δ_C: 144.9 (d mult., C-2/6, $^1J=236$ Hz); 139.1 (tt, C-4, $^2J=7.7$ Hz, $^3J=5.3$ Hz); 133.8 (d mult., C-3/5, $^1J=257$ Hz); 46.2 (t, NCH_2, $^4J=5.1$ Hz); 13.1 (s, CH_3).
9	δ_H: 3.42 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.15 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: −16.0 (mult., 2F, F-2/6); −77.6 (mult., 2F, F-3/5). δ_C: 145.1 (d mult., C-2/6, $^1J=242$ Hz); 139.3 (tt, C-4, $^2J=8.1$ Hz, $^3J=5.0$ hz); 132.4 (d mult., C-3/5, $^1J=248$ Hz); 46.4 (t, NCH_2, $^5J=5.1$ Hz); 13.7 (s, CH_3).
10	δ_H: 4.52 (br., 1H, NH); 3.50 (q, 2H, NCH_2, $J=7$ Hz); 1.22 (t, 3H, CH_3, $J=$Hz). δ_F: −16.0 (mult., 2F, F-2/6); −86.0 (mult., 2F, F-3/5). δ_C: 144.2 (d mult., C-2/6, $^1J=235$ Hz); 137.7 (tt, C-4, $^2J=10.2$ Hz, $^3J=5.4$ Hz); 130.7 (d mult., C-3/5, $^1J=244$ Hz); 39.6 (t, NCH_2, $^4J=4.2$ Hz); 15.9 (s, CH_3).
11 [b]	δ_H: 3.25 (q, 4H, $2NCH_2$, $J=7$ Hz); 2.00 (br., 2H, NH_2); 1.50 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: −23.4 (mult., 2F, F-2/6); −94.2 (mult., 2F, F-3/5). δ_C: 160.0 (mult., C-4); 146.0 (d mult., C-2/6, $^1J=230$ Hz); 137.2 (d mult., C-3/5, $^1J=245$ Hz); 42.5 (s, NCH_2); 11.8 (s, CH_3).
12 [b]	δ_H: 7.90 (br., 1H, arom., 4-H); 3.68 (q, 4H, $2NCH_2$, $J=7$ Hz); 2.00 (br., 2H, NH_2); 1.25 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: −70.5 (mult., 2F, F-3/5); −94.0 (mult., 2F, F-2/6).
13	δ_H: 3.14 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.20 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: +22.8 (t, 3F, CF_3, $J=22.5$ Hz); −64.0 (mult., 2F, F-3/5); −83.2 (mult., 2F, F-2/6).
14	δ_H: 4.10 (br., 1H, NH); 3.50 (q, 2H, NCH_2, $J=7$ Hz); 1.25 (q, 3H, CH_3, $J=7$ Hz). δ_F: +23.8 (t, 3F, CF_3, $J=22.5$ Hz); −65.6 (mult., 2F, F-3/5); −83.2 (mult., 2F, F-2/6).
15 [b]	δ_H: 4.10 (q, 4H, $2NCH_2$, $J=7$ Hz); 2.02 (br., 2H, NH_2); 1.30 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: +24.0 (t, 3F, CF_3, $J=22.5$ Hz); −73.0 (mult., 2F, F-3/5); −91.5 (mult., 2F, F-2/6).
16	δ_H: 8.22 (dd, 1H, H-6, $J_{5-6}=5$ Hz, $J_{4-6}=2.5$ Hz); 7.96 (dd, 1H, H-4, $J_{5-4}=8$ Hz, $J_{6-4}=2.5$ Hz); 6.56 (dd, 1H, H-5, $J_{4-5}=8$ Hz, $J_{6-5}=5$ Hz); 3.35 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.12 (t, 6H, $2CH_3$, $J=7$ Hz).
17	δ_H: 10.40 (br., 1H, NH); 8.75 (dd, 1H, H-6, $J_{5-6}=9$ Hz, $J_{4-6}=2.5$ Hz); 8.40 (dd, 1H, H-6′, $J_{5'-6'}=8$ Hz, $J_{4'-6'}=2.5$ Hz); 8.35 (dd, 1H, H-4, $J_{5-4}=5$ Hz, $J_{6-4}=2.5$ Hz); 7.95 (dd, 1H, H-4′, $J_{5'-4'}=5$ Hz, $J_{6'-4'}=2.5$ Hz); 7.10 (dd, 1H, H-5, $J_{6-5}=9$ Hz, $J_{4-5}=5$ Hz); 6.80 (dd, 1H, H-5′, $J_{6'-5'}=8$ Hz, $J_{4'-5'}=5$ Hz).
18	δ_H: 8.90 (d, 1H, H-6, $J_{4-6}=2.5$ Hz); 8.05 (dd, 1H, H-4, $J_{3-4}=10$ Hz, $J_{6-4}=2.5$ Hz); 6.72 (d, 1H, H-3, $J_{4-8}=10$ Hz); 3.70 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.22 (t, 6H, $2CH_3$, $J=7$ Hz). δ_C: 159.2 (s, C-5); 146.7 (s, C-6); 133.9 (s, C-4); 132.3 (s, C-3); 103.9 (s, C-2); 43.3 (s, NCH_2); 12.5 (s, CH_3).
19	δ_H: 9.50 (br., 1H, NH); 9.05 (d, 1H, H-6, $H_{4-6}=2.5$ Hz); 8.70 (d, 1H, H-6′, $J_{4'-6'}=3$ Hz); 8.38 (dd, 1H, H-4, $J_{3-4}=10$ Hz, $J_{6-4}=2.5$ Hz); 8.34 (dd, 1H, H-4′, $J_{3'-4'}=10$ Hz, $J_{6'-4'}=3$ Hz); 7.24 (d, 1H, H-3, $J_{4-3}=10$ Hz); 7.02 (d, 1H, H-3′, $J_{4'-3'}=10$ Hz).
20	δ_H: 13.80 (br., 2H, H_2O); 4.40 (q, 4H, $2NCH_2$, $J=7$ Hz); 1.50 (t, 6H, $2CH_3$, $J=7$ Hz). δ_F: −5.2 (mult., 2F, F-2/6); −60.0 (mult., 2F, F-3/5).

[a] In $CDCl_3$ solvent.
[b] In acetone-d_6 solvent.

3.3. Reactions of alkali metal and alkaline earth metal N,N-diethylnitroxides 2

(a) Sodium N,N-diethylnitroxide (2a) with pentafluoropyridine (3)

(i) Experiment 1. In diethyl ether at −78 °C

Pentafluoropyridine (**3**) (7.50 g, 44.4 mmol) was added slowly (1 h) to a cold (−78 °C) stirred slurry of the sodium salt **2a** [prepared from sodium (1.00 g, 43.5 mmol) and *N,N*-diethylhydroxylamine (**1**) (4.10 g, 46.0 mmol) in anhydrous diethyl ether (ca. 50 cm^3)] and stirring was continued at −78 °C (15 h). After warming to room temperature, the brown precipitate was removed by filtration and the solvent removed in vacuo to give a high-boiling residue (8.10 g) which was shown by TLC (eluant: chloroform/n-hexane 1:3 v/v) and ^{19}F NMR spectroscopy to contain four major components ($R_F=0.85$, 0.80, 0.65 and 0.0) in the ratio 1:73:17:19. The mixture was separated by DCFC to afford the following products.

(i) 4-(Diethylamino)tetrafluoropyridine (**8**) (trace) (eluant: chloroform/n-hexane 1:4 v/v), which was identified by a comparison of its ^1H, ^{13}C and ^{19}F NMR and mass spectra with those of an authentic sample prepared in the present work.

(ii) 4-(*N,N*-Diethylamino-oxy)tetrafluoropyridine (**9**) (nc) (eluant: chloroform/n-hexane 1:2 v/v) (3.30 g, 14.7 mmol, 33%) (Analysis: Found: C, 45.1; H, 4.2; N, 11.8; F, 32.2%; M^+, 238. $C_9H_{10}F_4N_2O$ requires: C, 45.4; H, 4.2; N, 11.8; F, 32.0%; M, 238).

(iii) 4-(Ethylamino)tetrafluoropyridine (**10**) (nc) (eluant: chloroform) (0.70 g, 3.6 mmol, 8%) (Analysis: Found: C, 43.2; H, 3.1; N, 14.3; F, 39.8%; M^+, 194. $C_7H_6F_4N_2$ requires: C, 43.3; H, 3.1; N, 14.4; F, 39.2%; M, 194), m.p. 40–42 °C.

(iv) Diethylammonium tetrafluoro-4-pyridinolate (**11**) (nc) (eluant: methanol/chloroform 1:20 v/v) (0.35 g, 1.5 mmol, 4%) (Analysis: Found: C, 45.3; H, 5.2; N, 11.7%. $C_9H_{12}F_4N_2O$ requires: C, 45.0; H, 5.0; N, 11.7%), m.p. 240 °C (with decomposition), which was identified by X-ray crystallography [23].

(ii) Experiment 2. In diethyl ether at room temperature

Reaction between pentafluoropyridine (**3**) (15.00 g, 89.0 mmol), the sodium salt **2a** [prepared from sodium (2.00 g, 87.0 mmol) and *N,N*-diethylhydroxylamine (**1**) (8.00 g, 90.0 mmol) in diethyl ether (ca. 100 cm^3)] with the mixture stirred (18 h), gave a brown precipitate (9.10 g) which was removed by filtration and treated with boiling ethyl acetate (100 cm^3). After filtration, the ethyl acetate solution was cooled and the solvent removed in vacuo to afford the salt **11** (4.50 g, 19.0 mmol, 21%).

The solvent was also removed in vacuo from the filtrate of the reaction mixture to give a brown high-boiling residue (12.0 g) which was shown by TLC to contain the same four major components as in the previous experiment. These were separated by DCFC (as in Experiment 1) to afford **8** (trace),

9 (4.80 g, 20.0 mol, 23%), **10** (3.60 g, 19.0 mmol, 21%) and **11** (0.58 g, 2.4 mmol, 3%).

(iii) Experiment 3. In benzene at room temperature

Treatment of the sodium salt **2a** [prepared from sodium (0.92 g, 40.0 mmol) and **1** (4.00 g, 44.0 mmol) in benzene (ca. 200 cm^3)] with pentafluoropyridine (**3**) (6.76 g, 40.0 mmol) with the reaction stirred (1 d) and the solvent then removed in vacuo gave a residue (11.52 g) which was shown (^{19}F NMR spectroscopy) to contain compounds **8–11** in the ratio 1:32:30:37. The products were separated by DCFC (as in Experiment 1) to afford **8** (trace), **9** (2.29 g, 9.6 mmol, 24%), **10** (1.79 g, 9.2 mmol, 23%) and **11** (2.59 g, 10.8 mmol, 27%).

(b) Other metal N,N-diethylnitroxides 2 with pentafluoropyridine (3)

The stirred reactions between pentafluoropyridine (**3**) (40.0 mmol) and (i) the lithium nitroxide **2b** (ca. 40 mmol), (ii) the potassium nitroxide **2c** (ca. 40 mmol) and (iii) the barium nitroxide **2d** (ca. 20 mmol) in benzene (ca. 200 cm^3) at room temperature (1 d), with the solvent then removed in vacuo, gave compounds **8–11** in the ratio $1:31\pm4:32\pm4:36\pm4$ as shown by ^{19}F NMR spectroscopy.

(c) The sodium (2a) and potassium (2c) nitroxides with pentafluoropyridine (3) in the presence of free-radical trapping agents

(i) The sodium nitroxide 2a with 1,4-dinitrobenzene

In an initial experiment, pentafluoropyridine (**3**) (1.69 g, 10.0 mmol) was added to a cold (−78 °C) stirred mixture of 1,4-dinitrobenzene (0.16 g, 1.0 mmol) and the sodium salt **2a** [prepared from sodium (0.24 g, 1.4 mmol) and **1** (0.84 g, 11.5 mmol) in diethyl ether (30 cm^3)] and stirring was continued at −78 °C (1 h) and then at room temperature (1 d). The resulting brown mixture was shown (^{19}F NMR spectroscopy) to contain unchanged **3** and the hydroxylamine **9** in the ratio 75:25.

A second experiment was carried out using pentafluoropyridine (**3**) (3.8 g, 20.0 mmol), 1,4-dinitrobenzene (1.68 g, 10.0 mmol) and the sodium nitroxide **2a** [prepared from sodium (0.46 g, 20.0 mmol) and **1** (1.87 g, 20.6 mmol) in diethyl ether (10 cm^3)] with the reaction stirred at room temperature and monitored by TLC and ^{19}F NMR spectroscopy. When the reaction was complete (5 d), the solvent was removed in vacuo and the residue (7.26 g) was shown by ^{19}F NMR spectroscopy to contain compounds **8–11** in the ratio 1:32:31:36.

(ii) The sodium nitroxide 2a with galvinoxyl

Pentafluoropyridine (**3**) (3.38 g, 20.0 mmol) was added to a stirred mixture of galvinoxyl (0.84 g, 2.0 mmol) and the sodium nitroxide **2a** [prepared from sodium (0.46 g, 20.0 mmol) and **1** (1.87 g, 20.6 mmol) in diethyl ether (60 cm^3)], and stirring was continued at room temperature until the reaction was complete (5 d) as shown by ^{19}F NMR spectroscopy. Removal of the solvent in vacuo gave a residue containing compounds **8–11** in the ratio 1:33:31:35 (^{19}F NMR spectroscopy).

(iii) The potassium nitroxide 2c with 1,4-dinitrobenzene

The reaction between pentafluoropyridine (**3**) (3.38 g, 20.0 mol) and a solution of 1,4-dinitrobenzene (1.68 g, 10.0 mmol) and the potassium salt **2c** [prepared from potassium (0.78 g, 20.0 mmol) and **1** (0.48 g, 20.2 mmol) in benzene (200 cm^3)], with the mixture stirred at room temperature (5 d) and the solvent then removed in vacuo, gave a residue containing compounds **8–11** in the ratio 1:32:31:36 (^{19}F NMR spectroscopy).

(iv) The potassium nitroxide 2c with galvinoxyl

The reaction of pentafluoropyridine (**3**) (3.35 g, 10.0 mmol) with a solution of galvinoxyl (0.84 g, 2.0 mmol) and the potassium nitroxide **2c** [prepared from potassium (0.78 g, 20.0 mmol) and **1** (0.50 g, 20.4 mmol) in benzene (100 cm^3)], with the mixture stirred at room temperature (5 d) and the solvent then removed in vacuo, gave a residue containing compounds **8–11** in the ratio 1:29:30:40 (^{19}F NMR spectroscopy).

(d) Sodium N,N-diethylnitroxide 2a with pentafluorobenzene (4)

Pentafluorobenzene (**4**) (8.30 g, 49.0 mmol) was added slowly to a stirred slurry of the sodium salt **2a** [prepared from sodium (1.10 g, 48.5 mmol) and **1** (4.40 g, 49.0 mmol) in diethyl ether (ca. 50 cm^3)] and the mixture was stirred at room temperature (8 d), filtered and the solvent removed in vacuo to afford a high-boiling residue (4.80 g).

The only product isolated by DCFC (eluant: methanol/chloroform 1:20 v/v) was diethylammonium 2,3,5,6-tetrafluorophenolate (**12**) (nc) (1.80 g, 7.5 mmol, 15%) (Analysis: Found: C, 50.4; H, 5.2; N, 5.7%. $C_{10}H_{13}F_4NO$ requires: C, 50.2; H, 5.4; N, 5.9%), m.p. 190–192 °C (with decomposition).

(e) Sodium N,N-diethylnitroxide (2a) with octafluorotoluene (5)

Octafluorotoluene (**5**) (10.00 g, 42.4 mmol) in diethyl ether (ca. 50 cm^3) was added slowly to a cold (−78 °C), stirred slurry of the sodium salt **2d** [prepared from sodium (0.96 g, 41.7 mmol) and **1** (4.10 g, 46.0 mmol) in diethyl ether (ca. 50 cm^3)] and stirring continued at −78 °C (8 h). After warming to room temperature, the resulting material was filtered and the solvent removed in vacuo to give a high-boiling residue (12.0 g) which was shown by TLC (eluant: chloroform/n-hexane 1:3 v/v) to contain three major components (R_F = 0.75, 0.50 and 0.00). The mixture was separated by DCFC to afford the following products.

(i) *N,N*-Diethyl-*O*-(heptafluoro-*p*-tolyl)hydroxylamine (**13**) (nc) (eluant: chloroform/n-hexane 1:1 v/v) (3.00 g, 9.8 mmol, 23%) (Analysis: Found: C, 43.1; H, 3.6; N, 4.3%; M^+, 305. $C_{11}H_{10}F_7NO$ requires: C, 43.3; H, 3.3; N, 4.5%; M, 305).

(ii) *N*-Ethyl-heptafluoro-*p*-toluidine (**14**) (nc) (eluant: chloroform/n-hexane 1:1 v/v) (0.20 g, 0.8 mmol, 2%) (Analysis: Found: M^+, 261. $C_9H_6F_7N$ requires: M, 261).

(iii) Diethylammonium heptafluoro-*p*-cresolate (**15**) (nc) (eluant: methanol/chloroform 1:20 v/v) (1.50 g, 5.0 mmol, 12%) (Analysis: Found: C, 42.8 ; H, 4.1; N, 4.7%. $C_{11}H_{12}F_7NO$ requires: C, 43.0; H, 3.9; N, 4.6%), m.p. 196–198 °C (with decomposition).

*(f) Sodium N,N-diethylnitroxide (**2a**) with 2-chloro-3-nitropyridine (**6**)*

2-Chloro-3-nitropyridine (**6**) (3.00 g, 19.0 mmol) in THF (ca. 20 cm^3) was added slowly (1 h) to a stirred slurry of the sodium salt **2a** [prepared from sodium (0.43 g, 18.7 mmol) and **1** (2.49 g, 28.0 mmol) in THF (ca. 50 cm^3)] and stirring continued (3 d). The black precipitate was filtered off and the solvent removed in vacuo to give a black residue which was shown by TLC (eluant: chloroform) to contain three major components (R_F = 0.80, 0.50 and 0.32). The mixture was separated by DCFC which gave the following compounds.

(i) 2-Diethylamino-3-nitropyridine (**16**) (nc) (eluant: chloroform) (1.30g, 6.7 mmol, 35%) (Analysis: Found: C, 55.4; H, 7.0; N, 21.3%; M^+, 195. $C_9H_{13}N_3O_2$ requires: C, 55.4; H, 6.7; N, 21.5%; M, 195).

(ii) Unchanged 2-chloro-3-nitropyridine (**6**) (eluant: chloroform) (0.30 g, 1.9 mmol, 10% recovered).

(iii) *N*-(2-Chloro-3-pyridyl)-*N*-(3-nitro-2-pyridyl)-amine (**17**) (nc) (eluant: methanol/chloroform 1:20 v/v) (0.30 g, 1.2 mmol, 13%) (Analysis: Found: C, 47.6; H, 2.7; N, 22.0%; M^+, 250/252. $C_{10}H_7ClN_4O_2$ requires: C, 47.5; H, 2.8; N, 22.3%; M, 250.5), m.p. 158–160 °C.

*(g) Sodium N,N-diethylnitroxide (**2a**) with 2-chloro-5-nitropyridine (**7**)*

2-Chloro-5-nitropyridine (**7**) (3.00 g, 19.0 mmol) in diethyl ether (ca. 50 cm^3) was added slowly (1 h) to a stirred slurry of the sodium salt **2a** [prepared from sodium (0.43 g, 18.7 mmol) and **1** (2.40 g, 27.0 mmol) in diethyl ether (ca. 50 cm^3)] and stirring was continued (24 h). Work-up as in the previous experiment gave a brown residue (2.80 g) which contained two major components (R_F = 0.60 and 0.20) as shown by TLC (eluant: chloroform). Separation of the major components by DCFC gave the following products.

(i) 2-Diethylamino-5-nitropyridine (**18**) (nc) (eluant: chloroform) (0.90 g, 4.6 mmol, 25%) (Analysis: Found: C, 55.6; H, 7.0; N, 21.7%; M^+, 195. $C_9H_{13}N_3O_2$ requires: C, 55.4; H, 6.7; N, 21.5%; M, 195), m.p. 72–74 °C.

(ii) *N*-(2-Chloro-5-pyridyl)-*N*-(5-nitro-2-pyridyl)amine (**19**) (nc) (eluant: methanol/chloroform 1:10 v/v) (0.65 g, 2.58 mmol, 27%) (Found: C, 47.6; H, 2.8; N, 2.5%; M^+, 250/252. $C_{10}H_7ClN_4O_2$ requires: C, 47.5; H, 2.8; N, 22.3%; M, 250.5), m.p. 200 °C (with decomposition).

*3.4. Reactions of 4-(N,N-diethylamino-oxy)-tetrafluoropyridine (**9**)*

(a) With anhydrous hydrogen fluoride (AHF)

AHF (20 cm^3, 1.0 mmol) was added in one portion to the hydroxylamine **9** (1.50 g, 6.3 mmol) contained in a polyethylene bottle (ca. 50 cm^3) fitted with a cap. An exothermic reaction took place and the colour changed to deep violet then to dark brown. After stirring the mixture at room temperature (4 h), the AHF was allowed to evaporate in a fume cupboard overnight to afford a brown oil (1.40 g) which was shown by TLC (eluant: chloroform/n-hexane 1:3 v/v) to contain three major components (R_F = 0.90, 0.80 and 0.00). The mixture was separated by DCFC to afford the tertiary amine **8** (eluant: chloroform/n-hexane 1:1 v/v) (0.41 g, 1.8 mmol, 27%), the secondary amine **10** (eluant: chloroform) (0.20 g, 1.0 mmol, 16%) and the ammonium salt **11** (eluant: methanol/chloroform 1:10 v/v) (0.20 g, 0.8 mmol, 13%).

(b) With triflic acid

Addition of triflic acid (2.00 g, 13.3 mmol) to the hydroxylamine **9** (1.00 g, 4.2 mmol) resulted in an exothermic reaction and the solution turned dark brown. After stirring at room temperature (1 h), diethyl ether (ca. 20 cm^3) was added and the resulting material shown by TLC to contain the same three major components as in the previous experiment. Separation by DCFC (using the same eluants as in the previous experiment) afforded the tertiary amine **8** (0.10 g, 0.45 mmol, 11%), the secondary amine **10** (0.15 g, 0.77 mmol, 18%) and the ammonium salt **11** (0.25 g, 1.04 mmol, 25%).

(c) Thermolysis in a Pyrex flask

The hydroxylamine **9** (1.21 g, 5.0 mmol), heated at 90–110 °C (3 d) in a Pyrex flask (ca. 10 cm^3) fitted with a condenser surmounted with a drying tube ($CaCl_2$), gave dark brown material which was shown by TLC (eluant: chloroform) to contain two major components (R_F = 0.92 and 0.00). Separation of these by DCFC gave unchanged hydroxylamine **9** (eluant: chloroform) (0.90 g, 3.8 mmol, 76% recovered) and the ammonium salt **11** (eluant: methanol/chloroform 1:10 v/v) (0.10 g, 0.40 mmol, 33%).

(d) Thermolysis in the presence of toluene

A mixture of the hydroxylamine **9** (1.50 g, 6.3 mmol) and toluene (20 cm^3) was heated under reflux in a Pyrex flask (4 h) and after cooling the solvent removed in vacuo to afford a high-boiling residue (1.70 g) shown by TLC (eluant: chloroform/n-hexane 1:3 v/v) to contain unchanged starting material **9** (R_F = 0.85) and one major product (R_F = 0.00). Separation by DCFC gave unchanged hydroxylamine **9** (0.60 g, 2.5 mmol, 40% recovered) (eluant: chloroform) and the ammonium salt **11** (0.40 g, 1.7 mmol, 46%) (eluant: methanol/chloroform 1:10 v/v).

A second experiment using hydroxylamine **9** (1.47 g, 6.2 mmol) and toluene (2.25 g, 24.4 mmol), with the mixture heated in vacuo in a sealed Pyrex tube (ca. 33 cm^3) at 100

°C (4 d), gave a white precipitate which was filtered off and identified as the ammonium salt **11** (0.91 g, 3.8 mmol, 78%). Removal of the solvent from the filtrate afforded a brown liquid residue (1.30 g) which was shown by TLC (eluant: chloroform) to contain one major component. This was separated by DCFC (same eluant) and identified as unchanged hydroxylamine **9** (0.30 g, 1.3 mmol, 21% recovered).

3.5. Synthesis and thermal decomposition of N,N-diethyl-N-(tetrafluoro-4-pyridyl)amine oxide (20)

(a) Preparation of 4-(diethylamino)tetrafluoropyridine (8)

Pentafluoropyridine (**3**) (10.00 g, 59.1 mmol) in diethyl ether (ca. 15 cm^3) and diethylamine (10.00 g, 137.0 mmol) in diethyl ether (ca. 15 cm^3) were cooled (0 °C) separately and then mixed. After stirring at 0 °C (1 h), the resulting material was filtered and the solvent removed from the filtrate in vacuo to give a high-boiling oil (9.25 g). This was purified by DCFC (eluant: diethyl ether) to afford 4-(diethylamino)tetrafluoropyridine (**8**) (nc) (7.50 g, 33.8 mmol, 57%) (Analysis: Found: C, 48.8; H, 4.4; N, 12.5; F, 34.0%; M^+, 222. $C_9H_{10}F_4N_2$ requires: C, 48.6; H, 4.5; N, 12.6; F, 34.2%; M, 222).

(b) Oxidation of 4-(diethylamino)tetrafluoropyridine (8)

The tertiary amine **8** (3.00 g, 13.5 mmol) in chloroform (20 cm^3) was added dropwise (1 h) to a stirred mixture of trifluoroacetic anhydride (6.00 g, 28.1 mmol) and hydrogen peroxide (85%, 3.0 cm^3) in chloroform (ca. 25 cm^3) and the mixture heated under reflux (2 h), then cooled to room temperature and stored (12 h). The small aqueous layer was separated and the organic layer dried ($MgSO_4$) and then filtered through silica gel (10.0 g, TLC grade). The silica gel was washed with chloroform (50 cm^3) and then with a mixture of chloroform and methanol (9:1 v/v, 100 cm^3). The latter fraction was collected and the solvent removed in vacuo to afford a straw-coloured syrup shown by TLC (eluant: methanol/chloroform 1:9 v/v) to consist of one component ($R_F = 0.75$). The syrup was identified as *N,N*-diethyl-*N*-(tetrafluoro-4-pyridyl)amine oxide monohydrate (**20**) (nc) (2.80 g, 10.9 mmol, 81%) (Analysis: Found: M^+, 238. $C_9H_{10}F_4N_2O$ requires: M, 238).

(c) Thermolysis of N,N-diethyl-N-(tetrafluoro-4-pyridyl)-amine oxide monohydrate (20)

Compound **20** (2.80 g, 10.9 mmol) when heated in vacuo at 40 °C (2 h) gave a yellow viscous oil which was shown by TLC (eluant: chloroform/n-hexane) to contain two major components ($R_F = 0.80$ and 0.63). These were separated by DCFC to afford the hydroxylamine **9** (1.50 g, 6.3 mmol, 58%) (eluant: chloroform/n-hexane 1:3 v/v) and the secondary amine **10** (0.25 g, 1.3 mmol, 12%) (eluant: chloroform). A minor component was also present with the same retention time as the tertiary amine **8**.

Table 3
Mass spectral data

Compound	MS: *m/z* (%, assignment) [a]
8	222 (33, M^+); 207 [100, $(M-Me)^+$]; 179 [85, $(M-C_3H_7)^+$]; 178 [4, $(M-C_3H_8)^+$]; 177 [10, $(M-C_3H_9)^+$]; 150 [6, $(M-Et_2N)^+$]; 29 (81, $C_2H_5^+$ / CH_3N^+).
9	238 (4, M^+); 223 [42, $(M-Me)^+$]; 222 [36, $(M-CH_4)^+$]; 193 [12, $(M-C_3H_9)^+$]; 179 (100, $C_6HF_4NO^+$); 29 (62).
10	194 (23, M^+); 193 [6, $(M-H)^+$]; 179 [100, $(M-Me)^+$]; 44 (19, $C_2H_6N^+$); 29 (98).
11	167 (65, $C_5HF_4NO^+$); 148 (11, $C_5HF_3NO^+$); 119 (60, $C_4F_3N^+$); 92 (11, $C_4H_{11}FN^+$); 74 (100, $C_4H_{12}N^+$); 44 (23); 30 (70, CH_3N^+); 29 (44).
12	166 (23, $C_6H_2F_4O^+$); 147 (2, $C_6H_2F_3O^+$); 118 (23, $C_5HF_3^+$); 105 (23, $C_4F_3^+$); 104 (4, $C_4H_2F_2O^+$); 87 (100, $C_4HF_2^+$); 74 (3); 73 (2, $C_4H_{11}N^+$); 72 (20, $C_4H_{10}N^+$); 29 (99).
13	305 (3, M^+); 290 [1, $(M-Me)^+$]; 285 (1, $(M-HF)^+$]; 234 (75, $C_7HF_7O^+$); 217 (4, $C_7F_7^+$); 215 (100, $C_7HF_6O^+$); 69 (24, CF_3^+); 29 (99).
14	261 (22, M^+); 260 [6, $(M-H)^+$]; 246 [100, $(M-Me)^+$]; 242 [24, $(M-F)^+$]; 69 (13); 44 (67); 29 (98).
15	234 (54, $C_7HF_7O^+$); 215 (100, $C_7HF_6O^+$); 186 (17, $C_6F_6^+$); 184 (42, $C_6HF_5O^+$); 74 (6); 69 (23); 29 (89).
16	196 [100, $(M+H)^+$]; 195 (2, M^+); 180 [30, $(M-Me)^+$]; 178 (28, $C_8H_8N_3O_2^+$); 166 (23, $C_7H_8N_3O_2^+$); 162 (11, $C_8H_8N_3O^+$); 152 (17, $C_7H_8N_2O_2^+$); 136 (21, $C_8H_{12}N_2^+$); 134 (37, $C_8H_{10}N_2^+$); 133 (20, $C_8H_9N_2^+$); 121 (14, $C_5H_3N_2O_2^+$); 120 (11, $C_7H_8N_2^+$); 119 (76, $C_7H_7N_2^+$); 79 (29, $C_5H_5N^+$); 29 (20).
17	250/252 (18, M^+); 215 [100, $(M-Cl)^+$]; 169 (92, $C_{10}H_7N_3^+$); 168 (17, $C_{10}H_6N_3^+$); 112/114 (18, $C_5H_3ClN^+$); 78 (11, $C_5H_4N^+$); 76 (23, $C_5H_2N^+$).
18	196 [22, $(M+H)^+$]; 195 (51, M^+); 180 [80, $(M-Me)^+$]; 179 [10, $(M-CH_4)^+$]; 166 [69, $(M-Et)^+$]; 152 [100, $(M-C_3H_7)^+$]; 134 (48); 120 (53); 106 (33, $C_6H_6N_2^+$).
19	250/252 (68, M^+); 249/251 [76, $(M-H)^+$]; 215 [100, $(M-Cl)^+$]; 203/205 [27, $(M-H-NO_2)^+$]; 169 (54); 168 (12); 112/114 (18).
20	238 (21, M^+); 223 [4, $(M-Me)^+$]; 210 [4, $(M-C_2H_4)^+$]; 195 [8, $(M-C_3H_7)^+$]; 167 (12, $C_5HF_4NO^+$); 88 (2, $C_4H_{10}NO^+$); 69 (72, $C_2H_6NO^+$); 57 (35, $C_3H_7N^+$); 56 (37, $C_3H_6N^+$); 45 (98, CH_4NO^+); 44 (100, CH_3NO^+); 42 (43, $C_2H_4N^+$); 29 (48).

[a] Expressed as a percentage of the base peak.

3.6. Hydrolysis of diethylammonium tetrafluoro-4-pyridinolate (11)

Hydrochloric acid (32%, 10 cm^3) was added to a solution of the ammonium salt **11** (0.70 g, 2.9 mmol) in water (10 cm^3), cooled to 5 °C, the mixture stirred at 5 °C (1 h) and then extracted with dichloromethane (3 × 15 cm^3). The extract was dried ($MgSO_4$) and the solvent removed in vacuo

to afford 4-hydroxytetrafluoropyridine (**26**) (0.40 g, 2.4 mmol, 83%), m.p. 98 °C; lit. value [27] m.p. 73–75 °C, which was identified by a comparison of its R_F value (0.20; eluant: chloroform) and NMR spectra with those of an authentic sample prepared as described below.

3.7. Preparation of 4-hydroxyltetrafluoropyridine (26) [28]

A mixture of pentafluoropyridine (**3**) (2.00 g, 11.8 mmol) and sodium hydroxide (1.00 g, 25.0 mmol) in water (20 cm^3) was heated under reflux (4 h). The resulting solution was cooled (10 °C), acidified with hydrochloric acid (32%, 10 cm^3) and then extracted with dichloromethane. The extract was dried ($MgSO_4$) and the solvent removed in vacuo to afford a white solid (0.86 g), which on sublimation (10 mmHg) gave 4-hydroxytetrafluoropyridine (**26**) (0.50 g, 3.0 mmol, 26%), m.p. 96–98 °C; lit. value [27] m.p. 73–75 °C; ^1H NMR ($CDCl_3$) δ: 6.25 (br., OH) ppm. Lit. value [28] ^{19}F NMR δ: −17.0 (2F); −86.1 (2F) ppm.

3.8. Preparation of diethylammonium tetrafluoro-4-pyridinolate (11)

Diethylamine (2.00 g, 27.0 mmol) was added dropwise to a cold (0 °C) solution of 4-hydroxytetrafluoropyridine (**26**) (1.00 g, 6.0 mmol) in diethyl ether (15 cm^3). The heavy precipitate which formed immediately was filtered off and washed with diethyl ether (2×5 cm^3) to afford diethylammonium tetrafluoro-4-pyridinolate (**11**) (1.30 g, 5.4 mmol, 90%), m.p. 240–242 °C (with decomposition).

The ^1H, ^{19}F and ^{13}C NMR spectra of the new compounds **8–20** are recorded in Table 2 and the MS data are summarised in Table 3.

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