Reactions of Iodoalkane and Diiodoalkane Complexes of Ruthenium(II) with Fluoride

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The η^1-iodoalkane complexes $[CpRu(CO)(PPh_3)(IR)]PF_6$ react very rapidly with the fluoride sources $[(Me_2N)_3S][Me_3SiF_2]$, $[Bu_4N]F\cdot 3H_2O$, $[Ph_3PNPPh_3]F$, and KF/18-crown-6 in CD_2Cl_2 at 20 °C to give the corresponding fluoroalkanes (FR) and $CpRuI(CO)(PPh_3)$ as the major products. Reaction of the η^1-iodomethane rhenium complex $[CpRe(NO)(PPh_3)(IMe)]BF_4$ with fluoride in CD_2Cl_2 gave $CpReCl(NO)(PPh_3)$, $CpReF(NO)(PPh_3)$, and IMe as the major products. Carbon–fluorine bond formation (production of CH_3F) accounted for less than 1% of the overall reaction products. A series of η^1-α,ω-diiodoalkane complexes of the general form $[CpRu(CO)(PR_3)\{I(CH_2)_nI\}]PF_6$(R = Ph, n = 1, 3, 4; R = Cy, Me, n = 3) and the η^2-1,3-diiodopropane complex $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ have been prepared. $[CpRu(CO)(PPh_3)(ICH_2I)]PF_6$ reacts with $[(Me_2N)_3S][Me_3SiF_2]$ to give $CpRuF(CO)(PPh_3)$ and CH_2I_2. The complexes $[CpRu(CO)(PR_3)\{I(CH_2)_nI\}]PF_6$ (n = 3, 4) react with $[(Me_2N)_3S][Me_3SiF_2]$ to give varying amounts of $F(CH_2)_nI$, $CH_2{=}CH(CH_2)_{n-2}I$, $I(CH_2)_nI$, $CpRuI(CO)(PR_3)$, and $[\{CpRu(CO)(PR_3)\}_2(\mu\text{-}I)]PF_6$. The diruthenium cation $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ reacts rapidly with 2 equiv of fluoride to give allyl fluoride as the major organic product.

Introduction

Simple analogy with the extensive studies of the addition of oxygen and nitrogen based nucleophiles to organic ligands bound to transition metals[1] suggests the potential for the selective generation of C–F bonds via similar reactions with fluoride ion in aprotic solvents. However reactions involving fluoride addition to organotransition metal compounds are very few. Addition of fluoride ion to cationic carbyne ligands results in the formation of the fluorocarbene complexes $(CO)_5Cr\{CF(NEt_2)\}$[2] and $Cp(CO)_2M\{CF(Ph)\}$ (M = Mn, Re).[3] Recently, we have shown that addition of $[(Me_2N)_3S][Me_3SiF_2]$ to $[(\eta^5\text{-}C_6H_7)Fe(CO)_3]BF_4$ under dry conditions gives $(\eta^4\text{-}C_6H_7F)Fe(CO)_3$ which is rather unstable with respect to C–F bond cleavage reactions.[4] Of particular significance to this paper is the recent report by Crabtree and Faller in which a range of nucleophiles *including fluoride ion* were shown to be *rapidly* methylated by the η^1-methyl iodide complex $[(\eta^5\text{-}C_5H_5)Ru(CO)(PPh_3)(ICH_3)]PF_6$.[5] No experimental details or yields were given for the fluoride reaction (eq 1).

$$[(\eta^5\text{-}C_5H_5)Ru(CO)(PPh_3)(ICH_3)]^+ + F^- \rightarrow (\eta^5\text{-}C_5H_5)Ru(CO)(PPh_3)I + CH_3F \quad (1)$$

In addition, Gladysz has observed the formation of cyclohexyl fluoride in 24% yield when the cationic Re(I)–cyclohexyl iodide complex $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(IC_6H_{11})]^+BF_4^-$ is reacted with PPh_3. Other products included cyclohexene and $[Ph_3P(C_6H_{11})]^+BF_4^-$. The evidence suggested BF_4^- participation in carbon–iodine bond cleavage.[6] Because of its rapidity, the formation of C–F bonds from the reaction of cationic iodoalkane complexes with fluoride ion could find utility in the synthesis of ^{18}F-labeled radiopharamaceuticals where synthetic speed and efficiency are a major consideration.[7] In this paper we report upon the synthesis of a series of iodoalkane complexes of ruthenium(II) and their reactions with fluoride ion. A brief study of the reaction of $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(ICH_3)]BF_4$[8] with F^- is also included.

Experimental Section

General Considerations. All manipulations were carried out under an atmosphere of dry N_2 or argon, using dry and degassed solvents. Deuterated solvents were dried over 4-Å molecular sieves and freeze–thaw degassed. IR spectra were recorded in CH_2Cl_2. ^1H NMR spectra (CD_2Cl_2 solution) were referenced to tetramethylsilane and recorded at either 200 or 400 MHz. ^{19}F and $^{31}P\{^1H\}$ NMR spectra (CD_2Cl_2 solution) were recorded at 300 MHz and chemical shifts were referenced to $CFCl_3$ and 85% H_3PO_4, respectively. Mass spectra were conducted on a VG 70-250S/SE mass spectrometer. Microanalyses were carried out by Canadian Microanalytical Laboratories.

Starting Materials. $AgPF_6$, ICH_2I, $I(CH_2)_3I$, $I(CH_2)_4I$, $[(Me_2N)_3S][Me_3SiF_2]$, $[Bu_4N]F\cdot 3H_2O$, "spray dried" KF, 18-crown-6, 1,4-diaminobutane, $[Ph_3P{=}N{=}PPh_3]Cl$, and AgF were purchased from Aldrich Chemical Co. $RuCl_3\cdot xH_2O$ was purchased from Digital Specialty Chemicals Inc. $Re_2(CO)_{10}$ was purchased from Strem Chemical Co. $[Ph_3P{=}N{=}PPh_3]F$,[9] 1-fluoro-3-iodopropane,[10] and the complexes $CpRu(CO)(PR_3)Cl$ (R = Me, Cy, Ph),[11] $[CpRe(NO)(PPh_3)(IMe)]BF_4$,[8] and $[CpRu(CO)(PPh_3)(IR)]PF_6$[5] (R = Me, Et, *n*-propyl, isopropyl, cyclohexyl, and

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p-tolyl) were prepared according to literature methods. The complexes $[CpRu(CO)(PPh_3)\{I(CH_2)_nI\}]PF_6$ (n = 1, 3, 4), $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$, $[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]PF_6$, and $[CpRu(CO)(PR_3)\{I(CH_2)_3I\}]PF_6$ (R = Me, Cy), unless otherwise specified, were prepared following the method of Crabtree et al.[5]

$[CpRu(CO)(PPh_3)(ICH_2I)]PF_6 \cdot {}^1/_6ICH_2I$ (1g): orange microcrystals (85% yield); IR (ν_{CO}, cm^{-1}) 1996; ^1H NMR (δ, ppm) 7.6–7.2 (15H, m, phenyl H's), 5.32 (5H, s, Cp H's), 4.06 (1H, d, ICH_2I, $J_{^1H-^1H}$ = 6.23 Hz), 3.97 (1H, d, ICH_2I, $J_{^1H-^1H}$ = 6.20 Hz), 3.91 (s, free ICH_2I); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e of parent ion $[CpRu(CO)(PPh_3)(ICH_2I)]^+$ 767 (calcd), 766 (found). Anal. Calcd (found) for $C_{25}H_{22}F_6I_2OP_2Ru \cdot {}^1/_6ICH_2I$: C, 33.07 (33.13); H, 2.46 (2.46).

(*RR,SS*)/(*RS,SR*)-$[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ (2a): pale yellow powder (76% yield); IR (ν_{CO}, cm^{-1}) 1991; ^1H NMR (δ, ppm) 7.6–7.2 (30H, m, phenyl H's), 5.26 (10H, s, CpH's), 3.32 (4H, br t, $-ICH_2$), 2.09 (2H, m, $-CH_2-$); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e for parent ion $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}]PF_6^+$ 1355 (calcd), 1354 (found). Anal. Calcd (found) for $C_{51}H_{46}F_{12}I_2O_2P_4Ru_2$: C, 40.87 (40.77); H, 3.09 (3.09).

$[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]PF_6$ (1j): dull orange microcrystals (69% yield); IR (ν_{CO}, cm^{-1}) 1991; ^1H NMR (δ, ppm) 7.6–7.2 (15H, m, phenyl H's), 5.25 (5H, s, CpH's), 4.45 (2H, d of t, $J_{^{19}F-^1H}$ = 46.9 Hz, $-CH_2F$), 3.45 (2H, m, $-ICH_2$), 2.06 (2H, m, $-CH_2-$); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e for parent ion $[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]^+$ 645 (calcd), 645 (found).

$[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]PF_6$ (1h). To an orange solution containing 0.356 g (0.434 mmol) of $[CpRu(CO)(PPh_3)(p\text{-iodotoluene})]PF_6$ in 6 mL of CH_2Cl_2 was added 1.0 mL (8.7 mmol) of 1,3-diiodopropane. The resultant orange solution was allowed to stand overnight and then transferred via cannula into a Schlenk frit and filtered in order to remove a small amount of a gray precipitate. Slow addition of pentane (15 mL) to the clear orange filtrate afforded an orange oil. When allowed to stand, the oil crystallized to a yellow solid. After washing with pentane (2 × 10 mL), the yellow solid was dried in vacuo (0.24 g, 62% yield). Recrystallization from CH_2Cl_2/pentanes/excess $I(CH_2)_3I$ afforded an analytically pure sample of **1h**: IR (ν_{CO}, cm^{-1}) 1991; ^1H NMR (δ, ppm) 7.6–7.2 (15H, m, phenyl H's), 5.26 (5H, s, Cp H's), 3.43 (2H, m, Ru–ICH_2), 3.32 (4H, m, $-ICH_2CH_2CH_2I-$, dinuclear complex **2a**), 3.28 (4H, t, free $ICH_2CH_2CH_2I$), 3.15 (2H, t, $-CH_2I$), 2.23 (2H, quintet, free $ICH_2CH_2CH_2I$), 2.08 (br quintet, $-CH_2-$ of both the mono- and dinuclear complexes **1h** and **2a**); mass spectrum (FAB, nitrobenzyl alcohol matrix): m/e for parent ion $[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]^+$ 753 (calcd), 752 (found). Anal. Calcd (found) for $C_{27}H_{26}F_6I_2OP_2Ru$: C, 36.14 (36.42); H, 2.92 (2.92).

The following compounds were similarly prepared. **$[CpRu(CO)(PPh_3)\{I(CH_2)_4I\}]PF_6$ (1i)**: Yellow powder (54% yield); IR (ν_{CO}, cm^{-1}) 1989; ^1H NMR (δ, ppm, 400 MHz) 7.6–7.3 (15H, m, phenyl H's), 5.25 (5H, s, Cp H's), 3.35 (m, $-ICH_2-$, mono- and dinuclear complexes), 3.21 (4H, m, free $ICH_2CH_2CH_2CH_2I$), 3.19 (2H, t, $-CH_2I$), 1.93 (4H, m, free $ICH_2CH_2CH_2CH_2I$), 1.8 (m, $-CH_2CH_2-$, mono- and dinuclear complexes); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e for parent ion $[CpRu(CO)(PPh_3)\{I(CH_2)_4I\}]^+$ 767 (calcd), 766 (found). **$[CpRu(CO)(PCy_3)\{I(CH_2)_3I\}]PF_6$ (1k)**: dull yellow powder (61% yield); IR (ν_{CO}, cm^{-1}) 1977; ^1H NMR (δ, ppm) 5.43 (10H, s, Cp H's, dinuclear complex), 5.41 (5H, s, Cp H's, mononuclear complex), 3.52 (m, $-ICH_2$, mono- and dinuclear complexes), 3.29 (t, free $ICH_2CH_2CH_2I$), 3.25 (2H, t, $-CH_2I$), 2.23 (2H, quintet, free $ICH_2CH_2CH_2I$), 2.16 (m, $-CH_2-$, mono- and dinuclear complexes), 2.1–1.15 (br m, cyclohexyl H's); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e for parent ion $[CpRu(CO)(PCy_3)]^+$ 475 (calcd), 475 (found). Anal. Calcd (found) for $C_{27}H_{44}F_6I_2OP_2Ru$: C, 35.42 (34.76); H, 4.84 (4.61). **$[CpRu(CO)(PMe_3)\{I(CH_2)_3I\}]PF_6$ (11)**: as an impure dull yellow powder (40% yield); IR (ν_{CO}, cm^{-1}) 1983; ^1H NMR (δ, ppm) 5.37 (s, Cp H's, mononuclear complex), 5.36 (s, Cp H's dinuclear complex), 3.55 (m, $-ICH_2$), 3.47 (m, $-ICH_2$, dinuclear complex), 3.28 (t, free $ICH_2CH_2CH_2I$), 3.24 (d of t, $-CH_2I$, mononuclear complex), 2.23 (quintet, free $ICH_2CH_2CH_2I$), 2.18 (br quintet, $-CH_2-$ of mono- and dinuclear complexes), 1.74 (d, PMe_3, dinuclear complex), 1.73 (d, $-PMe_3$, mononuclear complex); mass spectrum (FAB, nitrobenzyl alcohol matrix) m/e for parent ion $[CpRu(CO)(PMe_3)\{I(CH_2)_3I\}]^+$ 567 (calcd), 567 (found).

(*RR,SS*)/(*RS,SR*)-$[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]PF_6$ (4). A 10-mL aliquot of CH_2Cl_2 was added to a solid mixture containing 0.176 g (0.227 mmol) of $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$ and 0.139 g (0.238 mmol) of $CpRu(CO)(PPh_3)I$. The resultant orange solution was left to stand overnight in order to ensure complete reaction. After the solution was concentrated to dryness, the residual orange oil was triturated with pentanes to afford an orange solid which was air dried (yield 0.21 g, 78%). An analytical sample of **4** was obtained as an air stable orange powder from CH_2Cl_2/ether. IR (ν_{CO}, cm^{-1}): 1976. ^1H NMR (δ, ppm): 7.55–7.23 (30H, m, phenyl H's), 5.04, 4.90 (10H, s, Cp H's of the (*RR,SS*)/(*RS,SR*) diastereomers). $^{31}P\{^1H\}$ NMR (CH_2Cl_2): δ 46.97 (s), 47.26 (s). Mass spectrum (FAB, nitrobenzyl alcohol matrix): m/e for parent ion $[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]^+$ 1041 (calcd), 1040 (found). Anal. Calcd (found) for $C_{48}H_{40}F_6IO_2P_3Ru_2$: C, 48.66 (48.28); H, 3.40 (3.52).

^1H, ^{19}F, and $^{31}P\{^1H\}$ NMR Studies of the Reactions of Fluoride Ion with Cationic Iodoalkane and Diiodoalkane Complexes of Ru(II) (See Table) and Re(I). These were performed in a N_2 atmosphere drybox by adding a yellow to pale orange CD_2Cl_2 solution of the organometallic complex (30–50 mg) to a slight excess (5–15%) of the solid fluoride reagent, $\{[Ph_3PNPPh_3]F, [Bu_4N]F\cdot 3H_2O, [(Me_2N)_3S][Me_3SiF_2]\}$, filtering the resultant deep orange solution into an NMR tube, and recording the ^1H, ^{19}F and $^{31}P\{^1H\}$ NMR spectra. In the case of the diiodoalkane complexes, 3–4 drops of the appropriate diiodoalkane was added to the solution prior to mixing with the fluoride source. The reaction of $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$ with KF/18-crown-6 was carried out by stirring 0.030 g (0.510 mmol) of KF together with 0.005 g (0.019 mmol) of 18-crown-6 in CD_2Cl_2 for 5 min followed by the addition of 0.036 g (0.046 mmol) of the complex as a solid. The resultant orange mixture was rapidly stirred for 5 min and filtered into an NMR tube and its ^1H NMR spectrum recorded.

Rapid and Efficient Synthesis of *N*-(3-Fluoropropyl)putrescine. A yellow CD_2Cl_2 solution containing 0.034 g (0.043 mmol) of $[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]PF_6$ was added to 0.004 g (0.043 mmol) of 1,4-diaminobutane. After the resultant orange solution was analyzed for its ^1H and ^{19}F NMR spectra, HCl gas was passed through the solution for 1 min. The white precipitate which formed was separated from the orange solution, washed with CH_2Cl_2, and air dried. ^1H and ^{19}F NMR spectra obtained for the white solid in CD_3OD were in agreement with spectral data reported for the $[F(CH_2)_3NH_2(CH_2)_4NH_3]^{2+}$ dication.[12]

Results and Discussion

The cationic η^1-iodoalkane complexes required in this study were prepared by following the general procedures reported by Crabtree, Faller, and Gladysz as outlined in eqs 2–5. The η^1-iodoalkane complexes **1a-f** and **3** have been previously characterized. New iodoalkane complexes were isolated as yellow-orange powders and characterized by spectroscopic methods and by elemental analyses. The 1,3-diiodopropane complexes $[CpRu(CO)(PR_3)\{I(CH_2)_3I\}]PF_6$ were frequently contaminated with small amounts of $[Ag\{I(CH_2)_3I\}_2]PF_6$[13] when prepared by the $AgPF_6$ route (eq 2). Pure samples of these complexes could be more easily obtained using the iodide displacement

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$$CpRuCl(CO)(PR_3) \xrightarrow[\text{i. } AgPF_6]{CH_2Cl_2} [CpRu(CO)(PR_3)(CH_2Cl_2)]PF_6 + AgCl$$

$$\downarrow \text{ii. } +R'I$$

$$[CpRu(CO)(PR_3)(R')]PF_6 \quad (2)$$

1a–j

1a–j: $PR_3 = PPh_3$; R' = (a) Me, (b) Et, (c) *n*-Pr, (d) *i*-Pr, (e) Cy, (f) tolyl, (g) CH_2I, (h) $(CH_2)_3I$, (i) $(CH_2)_4I$, (j) $(CH_2)_3F$

$$[CpRu(CO)(PR_3)(tolI)]PF_6 + I(CH_2)_3I \longrightarrow [CpRu(CO)(PR_3)\{I(CH_2)_3I\}]PF_6 + tolI \quad (3)$$

1h

1i: $PR_3 = PPh_3$, $I(CH_2)_4I$
1k: $PR_3 = PCy_3$
1l: $PR_3 = PMe_3$

$$2[CpRuCl(CO)(PPh_3)] + 2AgPF_6 \xrightarrow[\text{ii. } +I(CH_2)_3I]{\text{i. } -AgCl} [\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2 \quad (4)$$

2a

$$CpReMe(NO)(PPh_3) + HBF_4 + MeI \longrightarrow [CpRe(NO)PPh_3)(MeI)]BF_4 + CH_4 \quad (5)$$

3

reaction (eq 3). In solution the α,ω-diiodoalkane complexes $[CpRu(CO)(PR_3)\{I(CH_2)_nI\}]PF_6$ ($n = 3$, $PR_3 = PPh_3$, PCy_3, PMe_3; $n = 4$, $PR_3 = PPh_3$) were found to undergo disproportionation and an equilibium with free α,ω-diiodoalkane and the (*RR,SS*)/(*RS,SR*) diruthenium cations of $[\{CpRu(CO)(PR_3)\}_2\{I(CH_2)_nI\}](PF_6)_2$ was rapidly established (e.g. eq 6 and Figure 1). Addition of a few

$$2[CpRu(CO)(PR_3)\{I(CH_2)_3I\}]PF_6 \rightleftarrows I(CH_2)_3I + [\{CpRu(CO)(PR_3)\}_2\{I(CH_2)_3I\}](PF_6)_2 \quad (6)$$

drops of $I(CH_2)_nI$ to these solutions forced the equilibrium position to the left (diruthenium cation of **2** no longer observed in the ^1H NMR). The observed equilibrium ratio $[Ru]I(CH_2)_3I^+$:$[Ru]I(CH_2)_3I[Ru]^{2+}$ of 77:23 ($PR_3 = PPh_3$) is close to that expected statistically (i.e. 67:33) assuming that the ligating ability of the "free iodide" in $[Ru]I(CH_2)_3I^+$ is essentially unchanged from that of uncomplexed 1,3-diiodopropane. Consistent with this variation of the coordinated PR_3 ligand (PCy_3, PPh_3, PMe_3) had only a small effect on the equilibrium ratios. Similarly, in solution the 1,4-diiodobutane complex $[CpRu(CO)(PPh_3)\{I(CH_2)_4I\}]PF_6$ equilibrates with free diiodobutane and the (*RR,SS*)/(*RS,SR*) dication $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_4I\}](PF_6)_2$.

The reaction of $CpRuI(CO)(PPh_3)$ with $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$ in CH_2Cl_2 results in displacement of propyl iodide and formation of the cationic μ-iodo complex $[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]PF_6$ (**4**) which was isolated as an orange powder and fully characterized as a 50:50 (*RR,SS*)/(*RS,SR*) diastereomeric mixture (eq 7). Complex **4** is structurally similar to the cationic Re(I)

$$CpRuI(CO)(PPh_3) + [CpRu(CO)(PPh_3)(n\text{-}PrI)]PF_6 \rightarrow [\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]PF_6 + n\text{-}PrI \quad (7)$$

4

complex (*RR,SS*)-$[\{(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)\}_2I]^+BF_4^-$ previously prepared by Gladysz *et al.*[14] In addition, complex **4** had been previously observed spectroscopically to be one of the possible products from the decomposition of

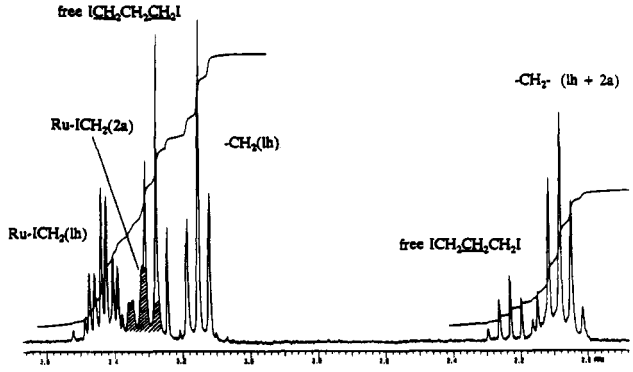
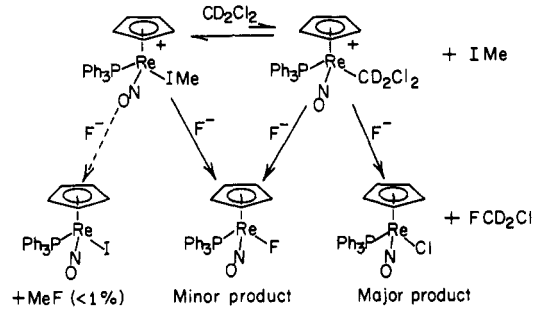


Figure 1. ^1H NMR spectrum showing the equilibrium established between the complex $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_2I)]PF_6$ (**1h**), free $I(CH_2)_3I$, and the dinuclear complex (**2a**) when **1h** is dissolved in CD_2Cl_2 at 20 °C (phenyl and Cp region not shown). The shaded region corresponds to Ru–ICH_2 protons of the (*RR,SS*)/(*RS,SR*) dinuclear complex $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ (**2a**).

Scheme I



$[CpRu(CO)(PPh_3)(IR)]^+$ cations in CD_2Cl_2 solution but, prior to this study, had not been isolated.[5]

Reaction of [CpRe(NO)(PPh$_3$)(IMe)]BF$_4$ with Fluoride. The results of an NMR study of the reaction of the rhenium methyl iodide complex $[CpRe(NO)(PPh_3)(IMe)]BF_4$ (**3**) with $[(Me_2N)_3S][Me_3SiF_2]$ in CD_2Cl_2 are summarized in Scheme I. Whilst Gladysz *et al.*[15] have previously shown that **3** will rapidly methylate bromide, reaction of **3** with fluoride proceeds mainly via displacement of methyl iodide and the formation of a mixture of the known halide complexes $CpReF(NO)(PPh_3)$[16] and $CpReCl(NO)(PPh_3)$.[17] Formation of $(\eta^5\text{-}C_5H_5)ReCl(NO)(PPh_3)$ is thought to involve an initial equilibrium exchange between CD_2Cl_2 and ICH_2I at Ru(II) followed by F^- attack at the coordinated CD_2Cl_2 ligand (Scheme I). Support for this process is given by Gladysz *et al.* who proposed a similar ligand exchange reaction between CH_2Cl_2 and secondary alkyl iodides at Re(I) in order to account for the BF_4^- promoted production of the chloride bridged cation $[\{(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)\}_2(\mu\text{-}Cl)]^+$.[6] Substitution at C to give methyl fluoride accounts for less than 1% of the overall reaction products. Because of the low yield of methyl fluoride (the reaction of interest) we turned our attention to the corresponding reactions using the ruthenium iodoalkane complexes $[CpRu(CO)(PPh_3)(IR)]PF_6$.

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(15) Winter, C. H.; Veal, W. R.; Garner, C. M.; Arif, A. M.; Gladysz, J. A. *J. Am. Chem. Soc.* **1989**, *111*, 4766.
(16) Agbossou, S. K.; Roger, C.; Igau, A.; Gladysz, J. A. *Inorg. Chem.* **1992**, *31*, 419.
(17) Merrifield, J. H.; Fernández, J. M.; Buhro, W. E.; Gladysz, J. A. *Inorg. Chem.* **1984**, *23*, 4022.

Table I. Results of a ^1H, ^{19}F, and $^{31}P\{^1H\}$ NMR Study of the Reactions of F^- with the Cationic Ru(II)–Iodoalkane Complexes $[CpRu(CO)(PPh_3)(IR)]PF_6$ (See Scheme II)

R in $[CpRu(CO)(PPh_3)(IR)]PF_6$	fluoride source	fluoride substitution R—F	% yield	ligand substitution[a] R—I	% yield	other products (% yield)
Me	$[(Me_2N)_3S][Me_3SiF_2]$	CH_3F	91	CH_3I	9	
Et	$[(Me_2N)_3S][Me_3SiF_2]$	CH_3CH_2F	99	CH_3CH_2I	1	
n-propyl	$[(Me_2N)_3S][Me_3SiF_2]$	$CH_3CH_2CH_2F$	99	$CH_3CH_2CH_2I$	1	
n-propyl	$[Ph_3P{=}N{=}PPh_3]F$	$CH_3CH_2CH_2F$	63	$CH_3CH_2CH_2I$	23	$CH_3CH_2CH_2Cl$ (9) + $CH_3CH_2CH_2OH$ (5)
n-propyl	KF/18-crown-6	$CH_3CH_2CH_2F$	57	$CH_3CH_2CH_2I$	43	
n-propyl	$[Bu_4N]F{\cdot}3H_2O$	$CH_3CH_2CH_2F$	85	$CH_3CH_2CH_2I$	1	$CH_3CH_2CH_2OH$ (14)
isopropyl	$[(Me_2N)_3S][Me_3SiF_2]$	$(CH_3)_2CHF$	65	$(CH_3)_2CHI$	2	$CH_3CH{=}CH_2$ (33)
cyclohexyl	$[(Me_2N)_3S][Me_3SiF_2]$	$C_6H_{11}F$	0	$C_6H_{11}I$	2	cyclohexene (98)

[a] % yields are based on the amount of Ru(II)–iodoalkane complex consumed. [b] Displacement of RI is by $CpRuI(CO)(PPh_3)$ to give an equimolar amount of the diruthenium cation $[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]^+$ (see eq 7).

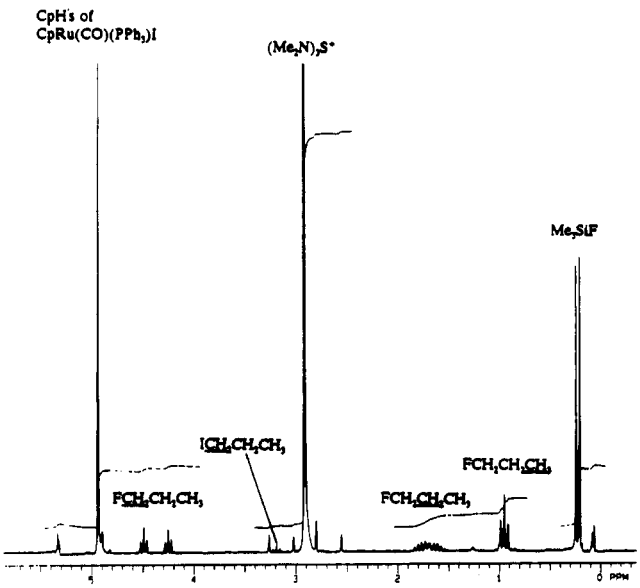
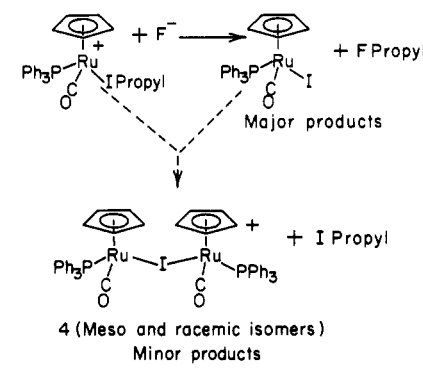


Figure 2. ^1H NMR spectrum showing the efficient production of *n*-propyl fluoride from the reaction of $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$ (**1c**) with $[(Me_2N)_3S][Me_3SiF_2]$ in CD_2Cl_2 at 20 °C (phenyl region now shown).

Reactions of $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$ (1c) with the fluoride sources $[Ph_3PNPPh_3]F$, KF/18-crown-6, $[Bu_4N]F{\cdot}3H_2O$, and $[(Me_2N)_3S][Me_3SiF_2]$ were investigated stoichiometrically (5–15% excess fluoride) by ^1H NMR in CD_2Cl_2 at 20 °C. The reactions were essentially complete within the time of mixing (<1 min). Major products of the reactions were identified by ^1H NMR spectroscopy and are listed in Table I. Propyl fluoride, the most dominant product in all cases, and $CpRuI(CO)(PPh_3)$ were readily identified (Figure 2). Other products included equal quantities of propyl iodide and $[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]PF_6$ (**4**) resulting from the reaction of the initially formed iodo complex $CpRuI(CO)(PPh_3)$ with **1c** (see Scheme II). Significant quantities of **4** were obtained when KF/18 crown-6 was used, presumably due to the low solubility of this fluoride source in CD_2Cl_2. 1-Propanol (14%), presumably formed from reaction of **1c** with water was observed when $[Bu_4N]F{\cdot}3H_2O$ was the fluoride source, and minor amounts of PrCl and PrOH were seen when $[Ph_3PNPPh_3]F$ (prepared following the procedure of Douglas and Ruff[9]) was used. This latter observation suggested Cl^- and OH^-/H_2O contamination of this reagent. The data (Table I) clearly showed $[(Me_2N)_3S][Me_3SiF_2]$ to be the most effective fluoride reagent for the production of propyl fluoride (99%).

Scheme II



The reagent $[(Me_2N)_3S][Me_3SiF_2]$ was very effective for fluorination at carbon when reacted with the EtI complex **1b** (99% EtF) and the MeI complex **1a** (91% MeF, 9% MeI + 9% **4**). Reaction with the isopropyl iodide complex **1d** gave isopropyl fluoride (65%) together with the deprotonation product propene (33% eq 8). Deprotonation to give cyclohexene (98%) and substitution to give cyclohexyl iodide and **4** (2%) were observed when $[(Me_2N)_3S][Me_3SiF_2]$ was reacted with the cyclohexyl iodide complex **1e**. No C–F bond formation was observed. The 3-fluoroiodopropane complex **1j** reacted with a slight excess of $[(Me_2N)_3S][Me_3SiF_2]$ to give 1,3-difluoropropane (56%), allyl fluoride (deprotonation, 34%), 3-fluoroiodopropane, and the cation of **4** (10%).

$$[Ru]ICH(Me)_2 + [(Me_2N)_3S][Me_3SiF_2] \rightarrow \underset{65\%}{FCH(Me)_2} + \underset{33\%}{CH_2{=}CHMe} + [Ru]I + HF \quad (8)$$

Reactions of the η^1-Diiodoalkane Complexes $[CpRu(CO)(PR_3)\{I(CH_2)_nI\}]PF_6$ (n = 1, 3, 4) with $[(Me_2N)_3S][Me_3SiF_2]$. A frequently used method for the synthesis of ^{18}F-labeled radiopharmaceuticals involves the initial formation of $^{18}FCH_2CH_2CH_2I$ which is then used to alkylate the biologically active molecule of interest via substitution of the iodide.[18] Consequently, the reaction of the cation of the α,ω-diiodoalkane complexes $[CpRu(CO)(PR_3)\{I(CH_2)_nI\}]PF_6$ with fluoride is of particular interest as it represents a potentially fast and efficient means of obtaining fluoroiodoalkanes of the type $I(CH_2)_nF$.

Addition of $[(Me_2N)_3S][Me_3SiF_2]$ to a CD_2Cl_2 solution of the diiodomethane complex $[CpRu(CO)(PPh_3)(ICH_2I)]PF_6$ resulted solely in substitution of ICH_2I

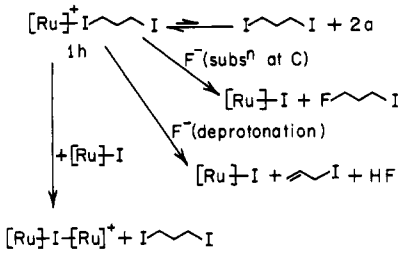
(18) (a) Shiue, C.-Y.; Bai, L.-Q.; Teng, R.-R.; Wolf, A. P. *J. Labelled Compds. Radiopharm.* **1987**, *24*, 55. (b) Chesis, P. L.; Griffeth, L. K.; Mathias, C. J.; Welch, M. J. *J. Nucl. Med.* **1990**, *31*, 192.

Table II. Results of ^1H, ^{19}F, and $^{31}P\{^1H\}$ NMR Studies of the Reactions of $[(Me_2N)_3S][Me_3SiF_2]$ with Some Cationic Ru(II)–Diiodoalkane Complexes[a] (See Scheme III and IV)

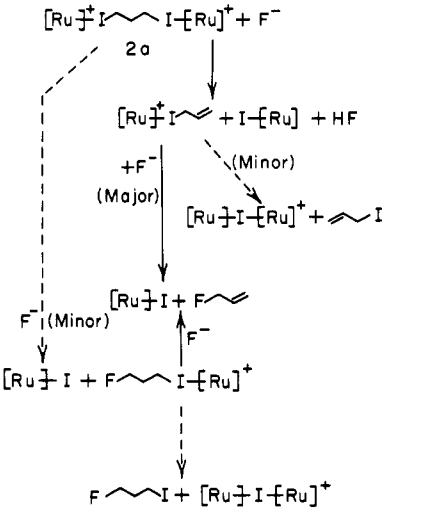
	obsd product distribution (% yield)		
complex	fluoride substitution at carbon	fluoride promoted deprotonation	ligand substitution
$[CpRu(CO)(PPh_3)(ICH_2I)]PF_6$			$CpRu(CO)(PPh_3)F + ICH_2I$ (100)
$[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]PF_6$	$F(CH_2)_3I$ (33) + $FCH_2CH{=}CH_2$ (11)	$ICH_2CH{=}CH_2$ (44)	$I(CH_2)_3I$ (11)
$[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]PF_6$[b]	$F(CH_2)_3I$ (33) + $FCH_2CH{=}CH_2$ (7)	$ICH_2CH{=}CH_2$ (55)	$I(CH_2)_3I$ (5)
$[CpRu(CO)(PPh_3)\{I(CH_2)_4I\}]PF_6$[b]	$F(CH_2)_4I$ (60)	$ICH_2CH_2CH{=}CH_2$ (40)	
$[CpRu(CO)(PMe_3)\{I(CH_2)_3I\}]PF_6$[b]	$F(CH_2)_3I$ (19) + $FCH_2CH{=}CH_2$ (57)	$ICH_2CH{=}CH_2$ (24)	$I(CH_2)_3I$ (24)
$[CpRu(CO)(PCy_3)\{I(CH_2)_3I\}]PF_6$[b]	$F(CH_2)_3I$ (14) + $FCH_2CH{=}CH_2$ (10)	$ICH_2CH{=}CH_2$ (50)	$I(CH_2)_3I$ (26)
$[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$[c]	$F(CH_2)_3I$ (5) + $FCH_2CH{=}CH_2$ (85)	$ICH_2CH{=}CH_2$ (5)	
$[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]PF_6$	$F(CH_2)_3F$ (56)	$FCH_2CH{=}CH_2$ (34)	$F(CH_2)_3I$ (10)

[a] % yields are based on the amount of Ru(II)–diiodoalkane complex consumed. Ru(II) products are $CpRuI(CO)(PPh_3)$ and $[\{CpRu(CO)(PPh_3)\}_2(\mu\text{-}I)]PF_6$. [b] 3–4 drops of free diiodoalkane ligand added prior to the reaction with $[(Me_2N)_3S][Me_3SiF_2]$. [c] 2 equiv of $[(Me_2N)_3S][Me_3SiF_2]$ used.

Scheme III. Reaction Products and Proposed Pathways for the Reaction of $[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]PF_6$ with $[(Me_2N)_3S][Me_3SiF_2]$ ([Ru] = $CpRu(CO)(PPh_3)$)



Scheme IV. Reaction Products and Proposed Pathways for the Reaction of $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ with $[(Me_2N)_3S][Me_3SiF_2]$ ([Ru] = $CpRu(CO)(PPh_3)$)



(100%) and formation of the fluoro complex $[CpRuF(CO)(PPh_3)]$, the structure of which was assigned on the basis of the diagnostic $^2J_{^{19}F-^{31}P}$ value of 16.6 Hz.[19] {^1H NMR δ 4.88 (s), Cp H's; $^{31}P\{^1H\}$ NMR (recorded on both a 300- and a 400-MHz spectrometer) δ 46.39 ($J_{^{19}F-^{31}P}$ = 16.6 Hz)}.

Addition of $[(Me_2N)_3S][Me_3SiF_2]$ to a CD_2Cl_2 solution of the 1,3-diiodopropane complex **1h** {an equilibrium mixture consisting of **1h** (77%), $I(CH_2)_3I$, and the dication of **2a** (23%)—see eq 6} resulted in the rapid formation of the desired product 3-fluoroiodopropane (33%) and $CpRuI(CO)(PPh_3)$ together with allyl iodide (44%), allyl fluoride (11%, formed from the dication **2a**), and equimolar quantities of 1,3-diiodopropane and complex **4** (11%) (see Table II and Scheme III). Since the dication of **2a** reacts essentially via deprotonation pathways (see below and Scheme IV), it suggests that the yield of 3-fluoroiodopropane based on the initial solution concentration of the η^1-1,3-diiodopropane complex **1h** is *ca.* 43%. However, addition of $[(Me_2N)_3S][Me_3SiF_2]$ to a CD_2Cl_2 solution of **1h** in the presence of several added drops of 1,3-diiodopropane (added to suppress the formation of the cation of **2a**—see eq 6) did not markedly change the product distribution {3-fluoroiodopropane (33%), allyl iodide (55%), and allyl fluoride (7%). Formation of the allyl fluoride suggests that dication formation was not fully suppressed}. Addition of $[(Me_2N)_3S][Me_3SiF_2]$ to $[CpRu(CO)(PR_3)\{I(CH_2)_3I\}]PF_6$ {in CD_2Cl_2 + a few drops of $I(CH_2)_3I$} gave for PR_3 = PCy_3 (i.e. **1k**) 3-fluoroiodopropane (14%), allyl iodide (50%), and allyl fluoride (10%) together with $I(CH_2)_3I$ and $[\{CpRu(CO)(PCy_3)\}_2I]PF_6$ (26%). For PR_3 = PMe_3 (**1l**) the organic products were 3-fluoroiodopropane (19%), allyl fluoride (57%), and allyl iodide (24%).

Reaction of the diruthenium cation of $[\{CpRu(CO)(PPh_3)\}_2\{I(CH_2)_3I\}](PF_6)_2$ with 2 equiv of $[(Me_2N)_3S][Me_3SiF_2]$ resulted in the rapid and efficient formation of allyl fluoride (85%) together with very minor amounts of 3-fluoroiodopropane and allyl iodide (Table II and Scheme IV).

The addition of $[(Me_2N)_3S][Me_3SiF_2]$ to $[CpRu(CO)(PPh_3)\{I(CH_2)_4I\}]PF_6$ in CD_2Cl_2 in the presence of an excess of 1,4-diiodobutane (added to suppress dication formation) gave 4-fluoroiodobutane (substitution at C, 60%) and 4-iodobut-1-ene (deprotonation, 40%).

Comments and Conclusions

The reactions of simple η^1-iodoalkane complexes of ruthenium(II) with fluoride represent one of the fastest as well as efficient methods of achieving C–F bond formation when a nucleophilic fluoride source is used. Furthermore the results when $[Bu_4N]F{\cdot}3H_2O$ is used indicate that the presence of a small amount of water has only a small detrimental effect on C–F bond formation, the yield of propyl fluoride being 85% *vs* 99% when $[(Me_2N)_3S][Me_3SiF_2]$ is used (reaction with $[CpRu(CO)(PPh_3)(ICH_2CH_2CH_3)]PF_6$, Table I). The stoichiometric reactions with difunctional systems such as the 1,3-diiodopropane and 3-fluoroiodopropane complexes are less effective with respect to C–F bond formation. The synthesis of 3-fluoroiodopropane using $[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]PF_6$ is more rapid, but the yield is certainly no better than other rapid synthetic procedures.[18a] It should be noted, however, that the chemistry and yields obtained by working with nanogram

(19) Doherty, N. M.; Hoffman, N. W. *Chem. Rev.* **1991**, *91*, 553.

quantities, as is the case in ^{18}F-labeling procedures, can be considerably different from those experienced in conventional synthetic studies.[7a] As such, a question yet to be resolved, and one that requires an ^{18}F-labeling study, is "what is the yield of 3-fluoroiodopropane based on fluoride when nanogram quantities of the fluoride source are reacted with a large excess of the cation $[CpRu(CO)(PPh_3)\{I(CH_2)_3I\}]^+$?". It is conceivable that HF produced in the deprotonation pathway (Scheme III) may also function as a fluoride source, thereby leading to increased yields of 3-fluoroiodopropane, based on fluoride. However, before undertaking such a study, it will be necessary to synthesize cationic η^1-iodoalkane complexes with noncoordinating anions that do not contain fluoride so as to avoid unwanted ^{19}F contamination of the required ^{18}F-labeled 3-fluoroiodopropane. While many labeling procedures have utilized a three carbon linkage, successful labels may also be accessible using a four carbon chain. In this regard the rapid formation of 4-fluoroiodobutane in 60% yield suggests considerable potential for these ruthenium iodoalkane complexes in ^{18}F labeling procedures.

Finally, it is conceivable that η^1-iodoalkane complexes of ruthenium(II) could be useful in the attachment of a [^{18}F]-3-fluoropropyl group to a biologically active reagent. In this respect it is noteworthy that capture of iodoalkanes by $[CpRu(CO)(PPh_3)(CH_2Cl_2)]^+$ (generated *in situ*—see eq 2) is reasonably fast—a time frame of a few minutes. As an indication of this potential we have found that the complex $[CpRu(CO)(PPh_3)\{I(CH_2)_3F\}]PF_6$ reacts very rapidly with 1,4-diaminobutane (putrescine) to give the protonated form of *N*-(3-fluoropropyl)putrescine in high yield. ([^{18}F]-3-fluoropropyl)putrescine has recently been shown to have potential as a prostate imaging agent.[12]

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