Homogeneous Metal-Catalyzed Hydrogenolysis of C−F Bonds

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*Inter*molecular activation of the strong C−F bonds[1] by soluble transition-metal complexes[2−13] is an area of major current interest. Remarkable results achieved in the field include metal-assisted C−F activation reactions of aromatic[2−10] and olefinic[11,12] substrates, synthesis in solution of η^2- and η^4-C_6F_6 complexes of rhodium and iridium, some of which are proposed as intermediates in C−F activation of fluoroarenes,[8,14−16] and, finally, recent activation of aliphatic perfluorinated substrates by Fe, Co[13], and U[9] complexes. Despite this obvious progress, which has also resulted in publication of a review on the topic,[17] it was not until only recently that first examples of **homogeneous transition-metal-catalyzed** C−F activation reactions were reported.[18,19] After we discovered that rhodium silyl complexes can catalyze F/H exchange between hydrosilanes and hexa- or pentafluorobenzene under mild conditions,[18] we set ourselves a task to try to generalize this approach. Here we report that C−F bonds of C_6F_6 and C_6F_5H can be efficiently and selectively hydrogenolyzed in a simple reaction with H_2 and a base with trimethylphosphine complexes of rhodium as catalysts.

Heating of $L_3RhC_6F_5$[18] (**1**) or L_4RhH[20] (**2**) (L = PMe_3) at 95−100 °C in C_6F_6 or C_6F_5H in presence of a base (Et_3N or a mixture of Et_3N and K_2CO_3) under 85 psi of hydrogen leads to the substitution of F by H and capturing of the released HF by the base (eq 1).

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$$C_6F_5X + H_2 + Et_3N \xrightarrow{\text{1 or 2}} C_6F_4HX + Et_3N\cdot HF \quad (1)$$
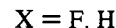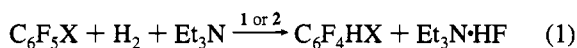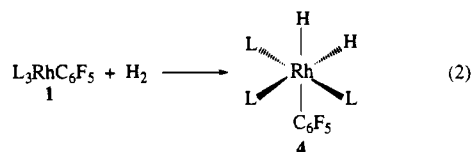
$$X = F, H$$

Table 1 gives details on amounts of reagents and conditions of catalytic runs. As seen from the table, **1** is slightly more effective than **2**, which in turn is much more effective than $HRh(PPh_3)_4$[21] (**3**) (entries 1−3). The reaction is chemo- and regioselective: C_6F_6 is more reactive than C_6F_5H (entries 4 *vs* 8 and 6 *vs* 9); C_6F_5H undergoes C−F activation at para position producing 1,2,4,5-$C_6F_4H_2$ as a major isomer. The reaction works even without a base (entry 11), albeit much less efficiently, probably, because of the fast decay of catalytically active species.[22] In the absence of rhodium complexes no reaction was observed under the same conditions (entries 12 and 13). The nature of the base taken also affects the reaction's efficiency: when K_2CO_3, which is insoluble under reaction conditions, is used together with Et_3N (which serves as a phase-transfer agent), the yield significantly increases (entries 5−7, 9, and 10).

To gain some mechanistic understanding of the catalysis that operates in these systems we carried out the following experiments. Complex **1** reacts smoothly with H_2 even at atmospheric pressure and room temperature, cleanly producing *mer,cis*-L_3-$RhH_2C_6F_5$ (**4**) (eq 2). The disposition of ligands in **4** unequivo-

$$L_3RhC_6F_5 + H_2 \longrightarrow \text{(structure 4)} \quad (2)$$

cally follows from its spectral data[23] and is analogous to that of the $HSi(OEt)_3$−adduct for which we reported[18] an X-ray crystal structure. This configuration is crucial for the reactivity of **4**. The hydride, which is trans to C_6F_5 and which has a strong trans influence,[24] weakens the otherwise fairly strong Rh−C_6F_5 bond, while the second hydride, which is cis to the pentafluorophenyl group is required for C_6F_5−H reductive elimination to occur. Indeed, **4** slowly eliminates pentafluorobenzene even at room temperature (eq 3).

$$\text{(structure 4)} \longrightarrow [L_3RhH] + C_6F_5H \quad (3)$$
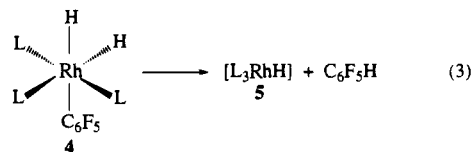
We probed reactivity of the resulting unsaturated L_3RhH (**5**) by reacting *at room temperature* its saturated homologue L_4-RhH (**2**) with C_6F_6 in presence of Et_3N as a base. Although the reaction is more complicated than it is shown in eq 4,[25] we have been able after the removal of all volatile components

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(23) $^{31}P\{^1H\}$-NMR (C_6F_6, ext. 85% H_3PO_4) δ −25.3 dtt ($^1J_{P−Rh}$ = 86.5 Hz; $^2J_{P−P}$ = 29.2 Hz; $^4J_{P−F}$ = 37.3 Hz); −7.3 dd ($^1J_{P−Rh}$ = 102.2 Hz; $^2J_{P−P}$ = 29.1 Hz); ^1H-NMR (C_6F_6, ext. TMS) δ = 1.18 vt (*J* = 3.1 Hz), 18H, PMe_3; 1.37 d ($^2J_{H−P}$ = 6.2 Hz), 9H, PMe_3; −10.3 dm ($^2J_{H−P,trans}$ = 176 Hz), 1H, Rh−H; −12.7 m, 1H, Rh−H; $^{19}F\{^1H\}$-NMR (C_6F_6) δ = −99.2 "t" (*J* = 35 Hz), 2F_{ortho}; −164.7 m, 2F_{meta}; −165.2 t (*J* = 18.6 Hz), 1F_{para}.

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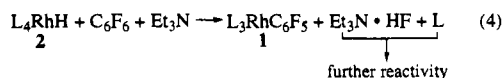
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Table 1. Rhodium-Catalyzed Hydrogenolysis of C_6F_6 and C_6F_5H[a]

		initial conditions				product distribution			
						C_6F_5H		1,2,4,5-$C_6F_4H_2$	
no.	substrate[b]	catalyst, mmol	Et$_3$N, mmol	K$_2$CO$_3$, mmol	time, h	mmol	turnovers	mmol	turnovers
1	C_6F_6	1, 0.02	2.0	no	17	0.332	16.6	0.004	0.20
2	C_6F_6	2, 0.02	2.0	no	17	0.252	12.6	1.6×10^{-3}	0.08
3	C_6F_6	3, 0.02	2.0	no	17	0.062	3.1	$<1 \times 10^{-3}$	
4	C_6F_6	1, 0.02	2.0	no	54	0.400	20.0	5.2×10^{-3}	0.26
5	C_6F_6	1, 0.02	0.2	2.0	36	2.28	114	0.1	5.0
6	C_6F_6	1, 0.02	0.2	2.0	1.83	0.95	47.5	2.8×10^{-2}	1.4
7	C_6F_6[c]	1, 0.02	0.2	4.0	20	1.95	97.5	0.172	8.6
8	C_6F_5H	1, 0.02	2.0	no	54			0.132	6.6
9	C_6F_5H	1, 0.02	0.2	2.0	1.83			0.146	7.3
10	C_6F_5H	1, 0.02	0.2	2.0	20			1.11	55.5
11	C_6F_6	1, 0.02	no	no	36	0.103	5.15	$<3 \times 10^{-3}$	<0.15
12	C_6F_6	no	2.0	no	24	<0.01		$<1 \times 10^{-3}$	
13	C_6F_6	no		0.2	40	0.011		$<1 \times 10^{-3}$	

[a] The catalytic reactions were run at 95−100 °C in the corresponding polyfluorobenzene as a solvent under 85 psi H_2 in a 90 mL Fischer−Porter pressure flask. Yields were determined by ^{19}F-NMR using 0.1 mmol of C_6H_5F as an internal standard which was added to reaction mixtures after the reactions were interrupted. [b] The substrate (0.8 mL) was used that corresponds to 6.96 and 7.24 mmol for C_6F_6 and C_6F_5H, respectively. [c] C_6F_6 (1.0 mL, 8.70 mmol) was used.
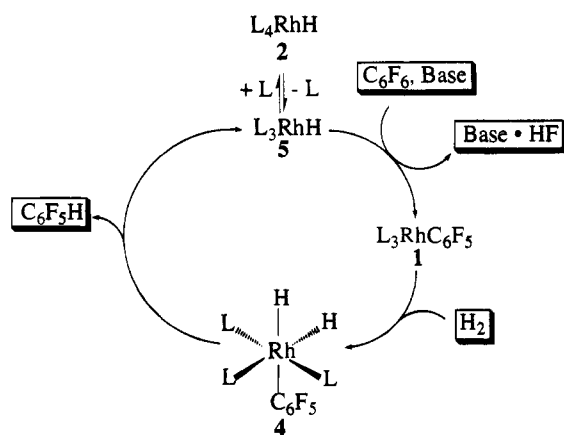
Figure 1. Catalytic cycle for the hydrogenolysis of C_6F_6 in presence of PMe$_3$ complexes of rhodium.

under vacuum and extraction of the residue with pentane to isolate **1** in 52% yield. Taken together, the stoichiometric

$$L_4RhH + C_6F_6 + Et_3N \longrightarrow L_3RhC_6F_5 + Et_3N \bullet HF + L \quad (4)$$
$$\mathbf{2} \qquad\qquad\qquad\qquad \mathbf{1}$$

further reactivity

reactions depicted in eqs 2−4 allow us to propose the following cycle for catalytic hydrogenolysis of C_6F_6 and C_6F_5H (Figure 1).

Except for the C−F activation step all other reactions depicted in Figure 1, namely **1** → **4** and **4** → **5**, are normal H−H

oxidative addition and C−H reductive elimination. As for the transformation **5** → **1**, which we have also demonstrated to occur readily, and which is the central step in the cycle, we believe that it proceeds via electron transfer from the complex to the substrate[4,7,18,19] with subsequent release of fluoride ion. Still, we cannot exclude regular C−F oxidative addition[2,3,26] either. It is also unclear at present exactly how the base acts. We know, however, that transformations **1** → **4** and **4** → **5** do not require a base.

We believe that the cycle with C_6F_5H as a substrate is completely analogous to the one depicted in Figure 1. The difference between the two is the participation of the analogs of **1** and **4** which have C_6F_4H−rather than C_6F_5− group bound to the rhodium center and correspondingly produce $C_6F_4H_2$. We have spectroscopic evidence that the mentioned analog of **4** is formed (along with C_6F_5H and $C_6F_4H_2$) in the reaction of **1** with H_2 under 90 psi pressure in C_6D_6 at room temperature.[27]

In summary, we have demonstrated here a rare case of **homogeneous transition-metal-catalyzed** C−F ativation. Trimethylphosphine complexes of rhodium efficiently catalyze homogeneous hydrogenolysis of the strong C−F bonds of polyfluorinated benzenes under mild conditions in the presence of a base.[28] We have also shown that the reaction exhibits chemo- and regioselectivity. The proposed catalytic cycle for the hydrogenolysis involves electron-rich hydridorhodium(I) phosphine complexes as the species that induce cleavage of C−F bonds. This implies that other complexes which can serve as a good source of such species are also likely to be active. Studies aimed at further clarification of the reaction mechanism and at generalization of the reactions reported here with respect to catalysts, substrates, and bases are underway.

This work suggests that the emerging field of metal-catalyzed homogeneous C−F activation may be developed quite generally and may be of significant synthetic potential.

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(27) ^{19}F-NMR of the mixture formed contains in addition to the signals due to **4**, C_6F_5H, and 1,2,4,5-$C_6F_4H_2$ two multiplets of equal intensity at δ = −102.2 and −141.4, whose chemical shifts are characteristic for fluorines bound to an aromatic ring and located ortho to a metal center and ortho to a hydrogen substituent, respectively. The multiplet at δ = −141.4 simplifies upon proton decoupling in full analogy with the corresponding signals of C_6F_5H and 1,2,4,5-$C_6F_4H_2$. See: (a) Bruce, M. I. *J. Chem. Soc. A* **1968**, 1459−1464. (b) Bennett, R. L.; Bruce, M. I.; Gardner, R. C. F. *J. Chem. Soc., Dalton Trans.* **1973**, 2653−2657.

(28) Heterogeneously catalyzed hydrogenolysis of carbon−fluorine bonds is known; the reaction of polyfluorobenzenes requires very high temperatures and is nonselective: (a) Hudlicky, M. *Chemistry of Organic Fluorine Compounds*, 2nd ed.; Prentice-Hall: New York, 1992; p 175. (b) Florin, R. E.; Pummer, W. J.; Wall, L. A. *J. Res. Natl. Bur. Stand.* **1959**, *62*, 119−122.