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Direct Observation of Reductive Elimination of MeX (X = Cl, Br, I) from Rh^{III} Complexes: Mechanistic Insight and the Importance of Sterics

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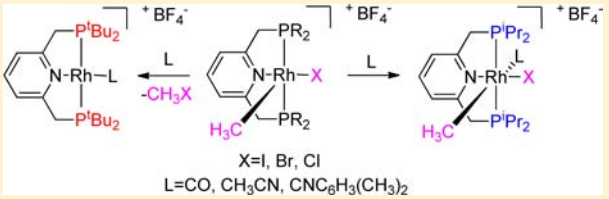
Supporting Information

ABSTRACT: Rare cases of directly observed reductive elimination (RE) of methyl halides from Rh^{III} complexes are described. Treatment of the coordinatively unsaturated complexes $[(^tBuPNP)Rh(CH_3)X][BF_4]$ (**1**–**3**, X = I, Br, and Cl; ^tBuPNP = 2,6-bis-(di-*tert*-butylphosphinomethyl)pyridine) with coordinating and noncoordinating compounds results in the formation of the corresponding free methyl halides and Rh^I complexes. The rate increase of CH_3I and CH_3Br RE in the presence of polar aprotic solvents argues in favor of an S_N2 RE mechanism. However, the RE of CH_3Cl is faster in polar protic solvents, which argues in favor of a concerted C–Cl RE. The RE of methyl halides from complexes **1**–**3** is induced by steric factors, as treatment of the less bulky complexes $[(^iPrPNP)Rh(CH_3)X][BF_4]$ (**19**–**21**; X = I, Br, Cl, respectively) with coordinating compounds leads to the formation of the adducts complexes rather than RE of the methyl halides. The accumulated evidence suggests that the RE process is nonassociative.



INTRODUCTION

While oxidative addition of carbon–halide bonds (C–X) to late transition metal complexes is well-known, the microscopic reverse, C–X reductive elimination (RE), which is normally thermodynamically uphill, is rare.[1] However, this process can play an important role in the formation of organic halides, which are fundamental starting materials in organic and organometallic chemistry. The RE of alkyl halides is rarely reported, while reports on aryl halide RE are more prevalent. The reports on alkyl halide RE include the pyrolysis of a Pt^{IV} complex[2] to give methyl chloride and methyl iodide RE from $(dppe)Pt(CH_3)_3I$ (dppe = $Ph_2PCH_2CH_2PPh_2$).[3] $C(sp^3)$–F RE from Pd^{IV} complexes was also reported.[4] RE of CH_3Cl was reported as a byproduct in Shilov's methane oxidation process.[5] In a later case, the RE is assumed to take place by an S_N2 mechanism, involving initial halide dissociation followed by its nucleophilic attack on the methyl ligand.[6] The Wilkinson complex was reported to catalyze a halogen-exchange reaction between allyl and alkyl halides by oxidative addition and RE of the $C(sp^3)$–X (X = Cl, Br) bonds.[7,8] RE of alkyl halides was also reported for Au^{III} complexes.[9] Alkyl iodide reductive elimination from the Pd^{II} complex is the product-forming step in the cycloisomerizations of 1-iodo-6-ene compounds.[10] A reversible oxidative addition-RE of methyl chloride and iodide based on IR analysis was reported from an Ir^{III} complex.[11] Recently, we reported two cases of RE of CH_3I from Rh^{III} complexes, involving $[(^tBuPNP)Rh(CH_3)(CN)][I]$ in aprotic solvents[12] and a Rh^{III} naphthyl–PCP pincer complex.[13] The RE process in the latter case takes place in a concerted manner and not by an S_N2 mechanism. In addition, CH_3I elimination is promoted by sterics and takes place only from the ^tBu–PCP complex, while the less bulky ^iPr–PCP Rh^{III} complex is stable. A similar effect was reported by Hartwig and co-workers for the RE of aryl halides upon addition of bulky phosphines to arylpalladium^{II} halide complexes[14] and in the catalytic conversion of aryl and vinyl triflates to aryl and vinyl halides.[15]

RE of aryl halides is more common than the RE of alkyl halides[1c,d] and is often reported for Pd^{IV}[16,17] and Pt^{IV}[18] complexes. Pd^{III},[19] Pd^{II},[15a,b] and Ni^{III}[20] were also reported to eliminate aryl halides. Reductive elimination of aryl halides is proposed to take place also in catalytic halide exchange mediated by copper and nickel.[1d] The Monsanto process involves reductive elimination of acyl iodide in the final step from the complex $[Rh(COCH_3)(CO)_2I_3]^-$.[21,22] The rarer carbon-fluoride reductive elimination was recently highlighted[23] due to its potential importance in pharmaceutical and agrochemical industries, and a few catalytic fluorinations of unactivated compounds have been reported.[24]

Here we report the direct observation of facile, quantitative RE of methyl halides from Rh^{III} complexes at ambient temperature upon addition of coordinative and noncoordinative agents. This report explores all of the following aspects of the rarely observed RE of alkyl halides in one system: (a) the reactivity of different halides (I, Br, and Cl), (b) the effect of polar protic versus polar aprotic solvents, (c) the influence of coordinative and noncoordinative agents in inducing the RE process, and (d) the importance of steric over electronic effects in promoting alkyl halide RE. On the basis of the experimental

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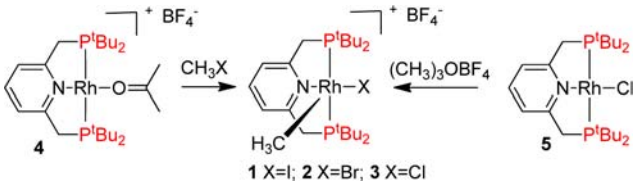
evidence, a plausible mechanism is proposed, providing new insights into this important fundamental transformation.

RESULTS AND DISCUSSION

Synthesis and Characterization of [(^{t}BuPNP)Rh(CH_3)X][BF_4] Complexes. Complexes **1**[12] and **2** were obtained in quantitative yields by addition of CH_3I and CH_3Br, respectively, to the Rh^I complex **4**[25] (Scheme 1). The reaction

Scheme 1



of complex **4** with an excess of CH_3Cl (1 M solution in *t*-butyl methyl ether) was sluggish and unselective, leading to a mixture of unidentified complexes in low yields after 3 days at ambient temperature. Nevertheless, the methyl chloride complex **3** can be obtained by the addition of $[(CH_3)_3O][BF_4]$ to **5**[26] (Scheme 1). Complexes **1**−**3** exhibit sharp doublets at δ = 51.20, 48.71, and 46.68 ppm, respectively, in the $^{31}P\{^1H\}$ NMR spectra with $^1J_{RhP}$ = 100 Hz. The methyl ligand exhibits doublet of triplets patterns in the $^{13}C\{^1H\}$ NMR spectra at 8.97, 9.99, and 10.47 ppm, respectively, with $^1J_{RhC}$ = 25 Hz and $^2J_{PC}$ = 4 Hz. The X-ray structures of complexes **1**−**3** (Figure 1) exhibit

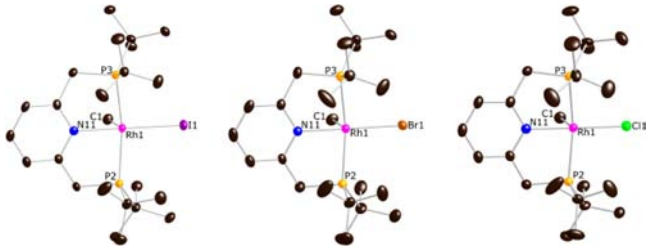


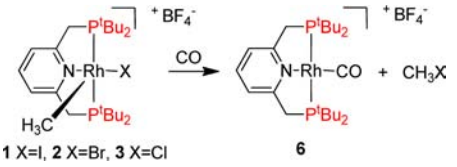
Figure 1. Crystal structures of complexes **1** (left), **2** (middle), and **3** (right) at 50% probability level. Hydrogen atoms and the counterions are omitted for clarity. For bond distances and angles see Supporting Information.

square pyramidal geometries with the methyl ligand in the apical position. The Rh−CH_3 bond length is identical in complexes **1** and **2** (2.060(3) Å) and slightly shorter in complex **3** (2.051(3) Å). The Rh−X bond varies as expected, with bond lengths of 2.6352(8), 2.4566(5), and 2.3276(9) Å for X = I, Br, and Cl, respectively. The Rh−N bond lengths (2.077(2), 2.066(2), and 2.055(3) Å for **1**−**3**, respectively) correlate with the *trans* influence of the halides (I > Br > Cl), respectively.[1b]

Reductive Elimination of CH_3X by the Addition of Ancillary Ligands. Upon reaction of complexes **1**−**3** with CO, 2,6-dimethylphenyl isonitrile (dmpin), or acetonitrile, RE of CH_3X (X = I, Br, Cl) takes place, and the Rh^I complexes **6**,[25] **7**,[25] and **8**,[26] respectively, are formed (Schemes 2−5). The generated CH_3X was detected by gas chromatography−mass spectrometry (GCMS) and NMR.

Reaction with CO. The RE of the methyl halides from complexes **1**−**3** in the presence of CO is irreversible (Scheme 2). Adduct complexes of the type $Rh^{III}(CO)(CH_3)X$ were not observed in methylene chloride, neither at ambient nor at low

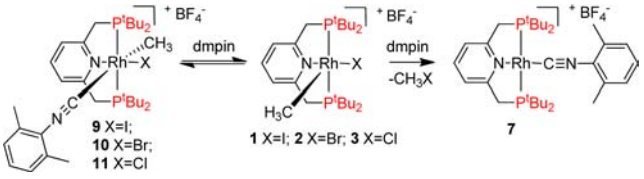
Scheme 2



temperatures (200−273 K). Performing the reactions in screw-cap NMR tubes with vigorous shaking to avoid a CO diffusion effect on the reaction rates, it was clearly observed that the reaction rate followed the trend I > Br > Cl. In addition, the rate of the RE is strongly influenced by the solvent. In the case of complex **1** the reaction is faster in polar aprotic solvents than in polar protic solvents. Thus, reaction of complex **1** (0.007 mmol) with CO (1 mL, about 0.04 mmol) in acetone reached completion after 25 min and in the (less polar) methylene chloride after 3.5 h, while in a mixture of acetone/water (1:1), full conversion to complex **6** was observed after 7 h, and in the methanol/methylene chloride mixture (1:1), only 50% conversion was observed after 4.5 h. Interestingly, the rate of RE of CH_3Cl from complex **3** follows a markedly different trend: in the polar protic solvents (acetone/water and methanol/methylene chloride) the reaction reached completion after 6 h, while in the polar aprotic solvents (acetone and methylene chloride) the reaction reached 50% conversion after 8 h. The rate of CH_3Br RE from complex **2** followed the trend acetone > polar protic solvents > methylene chloride with 50% conversion after 3, 6.5, and 8.5 h, respectively.

Reaction with Isonitriles. In the reaction of **1**−**3** with 2,6-dimethylphenyl isonitrile (dmpin), the adduct intermediates **9**−**11** were observed (Scheme 3). Complexes **9**−**11** exhibit

Scheme 3



sharp doublets at 293 K at δ = 62 ppm, in the $^{31}P\{^1H\}$ NMR spectra with $^1J_{RhP}$ = 90 Hz. The methyl ligand signals are shifted high field at about 10 ppm in the $^{13}C\{^1H\}$ NMR and at about 1 ppm in the ^1H NMR as compared with the unsaturated complexes **1**−**3**, in which the methyl ligand is located *trans* to a vacant coordination site. The X-ray structure of complex **9** (Figure 2) exhibits a slightly distorted octahedral geometry with

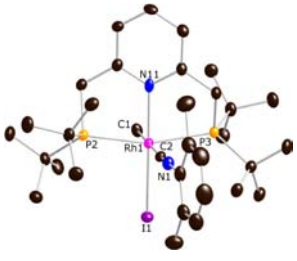


Figure 2. Crystal structure of complex **9** at 50% probability level. The hydrogen atoms and the counteranion are omitted for clarity. For bond distances and angles see Supporting Information.

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the dmpin ligand positioned *trans* to the methyl ligand and the iodide located *trans* to the pyridine moiety. The Rh−CH_3 and Rh−I bond lengths are elongated by 0.059 and 0.048 Å, respectively, as compared to the corresponding bonds of complex **1**. The $^{31}P\{^1H\}$ NMR spectra of **9**−**11** are temperature dependent (Figure 3). In ^1H and $^{13}C\{^1H\}$ NMR,

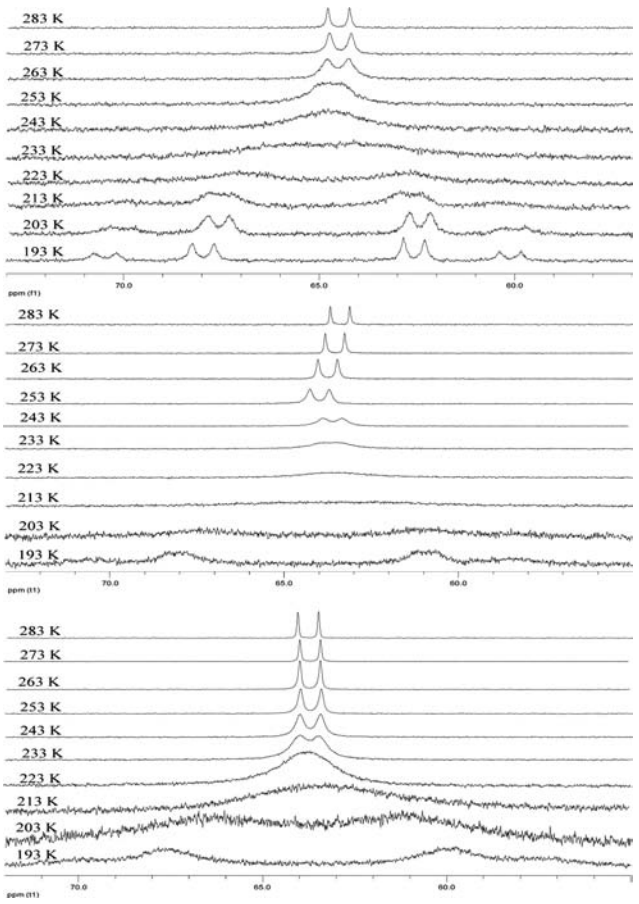


Figure 3. Temperature dependence of $^{31}P\{^1H\}$ NMR spectrum of [(^{t}BuPNP)Rh(CH_3)(dmpin)X][BF_4] (**9**, X = I, top), (**10**, X = Br, middle), and (**11**, X = Cl, bottom) in methylene chloride-d_2.

the signals of the ^{t}Bu−P and the CH_2P groups are broadened at lower temperatures, while those of Rh−CH_3 and isonitrile ligands do not exhibit temperature dependence. This temperature dependence was observed in all three solvents (acetone, methylene chloride, and methanol) and also in the presence of an excess of isonitrile. The iodide complex **9** exhibits signal broadening already at 273 K, while the bromide and the chloride complexes (**10** and **11**, respectively) exhibit broad signals only at 253 K. This observation, along with the fact that the methyl and dmpin ligands do not exhibit fluxionality, may suggest that the temperature dependence is due to halide dissociation, which is expected to be most facile with the iodide complex **9** and least favored with the chloride complex **11**.

In addition, equilibria were observed between complexes **1**−**3** and the dmpin−adduct complexes **9**−**11** (Scheme 3). For example, addition of 2-methylphenyl isonitrile (mpin) to reaction mixtures of the dmpin−adduct complexes (in the absence of complexes **1**−**3**) resulted in the formation of [(^{t}BuPNP)Rh(CH_3)X(mpin)][BF_4] (**12**, X = I; **13**, X = Br; **14**, X = Cl) and [(^{t}BuPNP)Rh(mpin)][BF_4] (**15**). The rates of CH_3X RE from complexes **1**−**3** in the presence of dmpin

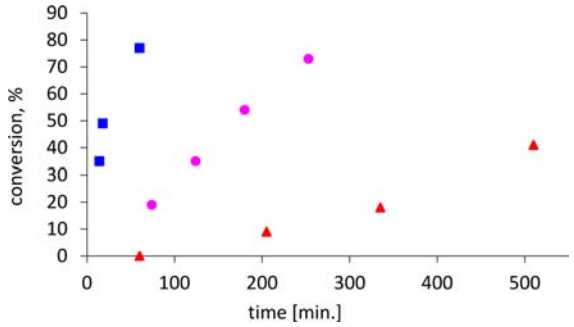
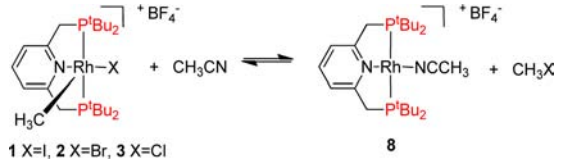


Figure 4. Rates of CH_3I RE from complex **1** in acetone at ambient temperature with 1 (blue ■), 10 (pink ●), and 30 (red ▲) equiv of dmpin.

Scheme 4



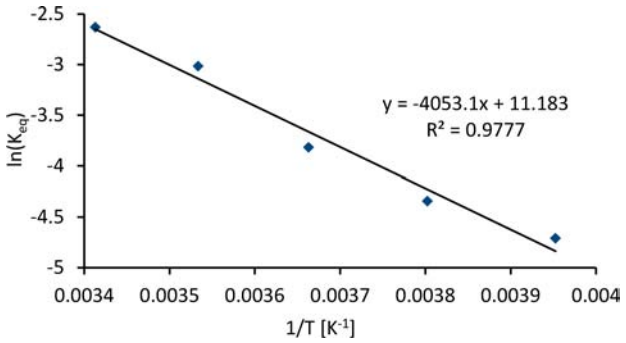


Figure 5. van't Hoff plot for **1** + CH_3CN ⇌ **8** + CH_3I.

decrease with increasing concentration of dmpin (Figure 4). This fact implies that the RE takes place from the unsaturated starting complexes **1**−**3** and not from the adduct complexes **9**−**11** (Scheme 3). The RE rate in acetone in the presence of dmpin followed the trend of I > Br > Cl.

Reaction with Acetonitrile. The addition of an excess of acetonitrile to acetone solutions of **1**−**3** leads to the formation of the reported cationic acetonitrile complex **8**[26] and the free methyl halides (Scheme 4). In contrast to the reaction with CO, the reactions of **1**−**3** with acetonitrile were found to be reversible as observed by variable-temperature $^{31}P\{^1H\}$ NMR experiments. Equilibrium constants (K_{eq} = ([**8**]$_{eq}$[CH_3I]$_{eq}$)/([**1**]$_{eq}$[CH_3CN]$_{eq}$)) were obtained for temperatures between 293 and 253 K, yielding ΔH^0 = 8.06 ± 0.70 kcal/mol, ΔS^0 = 22.24 ± 2.58 eu, and $\Delta G^0_{298} \approx$ 1.6 kcal/mol, derived from the van't Hoff plot shown in Figure 5. The adduct complexes [Rh^{III}(CH_3CN)(CH_3)X] were not observed.

Reaction with Noncoordinating CH_3X Trapping Agents. Addition of ^{t}Bu$_3$P or [(^{i}PrPNP)Rh(COE)][BF_4] (**16**), which can act as noncoordinating "trapping agents" of methyl halides, also afforded RE of CH_3X from complexes **1**−**3** (Scheme 5).

The bulky phosphine ^{t}Bu$_3$P does not coordinate to complexes **1**−**3** or even to complex **4**. Addition of ^{t}Bu$_3$P (an equivalent or excess) to complexes **1**−**3** in acetone gave the

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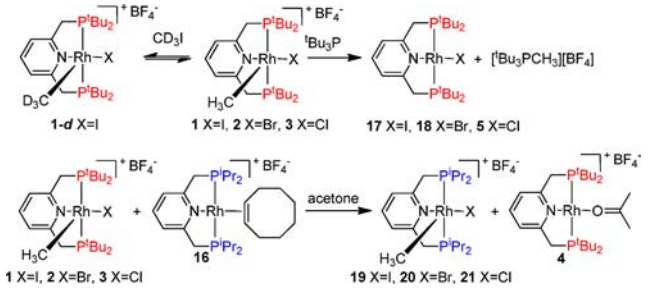
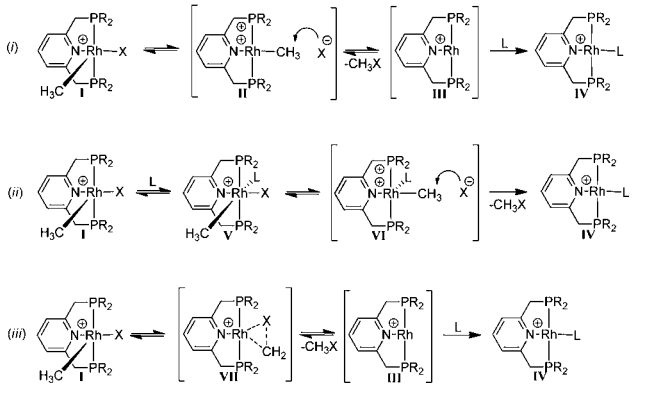
Scheme 5



Scheme 6



phosphonium salt [^{t}Bu$_3$PCH$_3$][BF$_4$] and [(^{t}BuPNP)RhX] (**17**, X = I;[11] **18**, X = Br; **5**, X = Cl), respectively. Complexes **17** and **18** were obtained also by addition of NaI or NaBr, respectively, to an acetone solution of **4**. The reaction progress of complexes **1**−**3** with ^{t}Bu$_3$P was followed by ^{1}H NMR and was performed with an equivalent or an excess of the phosphine. The reaction of complexes **1**−**3** with ^{t}Bu$_3$P in acetone followed the trend I > Br > Cl, as illustrated in Figure 6. As expected, reactions were accelerated by increasing concentrations of the complexes.[27] The reactions of complexes **1**−**3** with an excess of ^{t}Bu$_3$P were found to be pseudo first-order in the complexes (Figure 6).[28]

Addition of [(^{i}PrPNP)Rh(COE)][BF$_4$] (**16**) to an acetone solution of **1**−**3** resulted in the oxidative addition of the generated CH$_3$X to **16** to give [(^{i}PrPNP)Rh(CH$_3$)X][BF$_4$] (**19**, X = I; **20**, X = Br; **21**, X = Cl) and complex **4**. As in the case of ^{t}Bu$_3$P, the reaction rates followed the trend I > Br > Cl. Thus, under similar conditions (14 mM of complexes **1**−**3** and **16** at ambient temperature) 100%, 65%, and 4% conversions, respectively, were observed after 4 h.

Methyl iodide formation can also be demonstrated by the addition of CD$_3$I to **1** (Scheme 5). CH$_3$/CD$_3$ exchange in **1** was observed by ^{1}H and ^{13}C{^{1}H} NMR. This exchange is very fast in acetone, equilibrium being reached in a few minutes, while the reaction in methylene chloride was much slower and equilibrium was obtained only after 20 h (with 1 equiv of CD$_3$I at 293 K).

Possible Mechanism for the RE. Possible mechanisms for the methyl halide RE from complexes **1**−**3** are described in Scheme 6. Pathway (*i*) represents a nonassociative S$_N$2-type RE mechanism, in which halide dissociation from complex **I** generates a dicationic species (**II**), followed by nucleophilic attack of the halide on the methyl ligand. The resulting Rh^I 14e$^-$ complex (**III**) is stabilized by coordination of ligand L.[29] Pathway (*ii*) represents an associative S$_N$2-type RE mechanism, in which preliminary coordination of L generates a saturated 18e$^-$ complex (**V**) and promotes halide dissociation. The resulting dication specie **VI** is stabilized by the ancillary ligand L; however, it may reduce the electrophilicity of the methyl ligand as compared to specie **II**. An S$_N$2 mechanism was suggested for CH$_3$Cl RE in Shilov's system[6] and CH$_3$I RE from [(Ph$_2$PCH$_2$CH$_2$PPh$_2$)Pt(CH$_3$)$_3$I].[3] The latter is assumed to take place from an unsaturated five-coordinate intermediate, which is generated by halide dissociation. While polar protic solvents may increase the halide dissociation step in pathways (*i*) and (*ii*) by hydrogen-bonding interaction, such an interaction should also be expected to decrease the nucleophilicity of the dissociated halide.[30] Indeed, through studies of S$_N$2 C−X (X = O, N) RE by Pt^{IV}[31] and Pd^{IV}[32] complexes, the retardation of RE in the presence of protic solvents has been indicated. We have reported the competitive RE from a [Rh^{III}(CH$_3$)(CN)][I] complex to give exclusively CH$_3$CN in protic solvents and CH$_3$I in aprotic solvents.[12] Pathway (*iii*) represents a concerted RE, in which RE takes via a three-centered transition state (**VII**). Since octahedral Rh^{III}

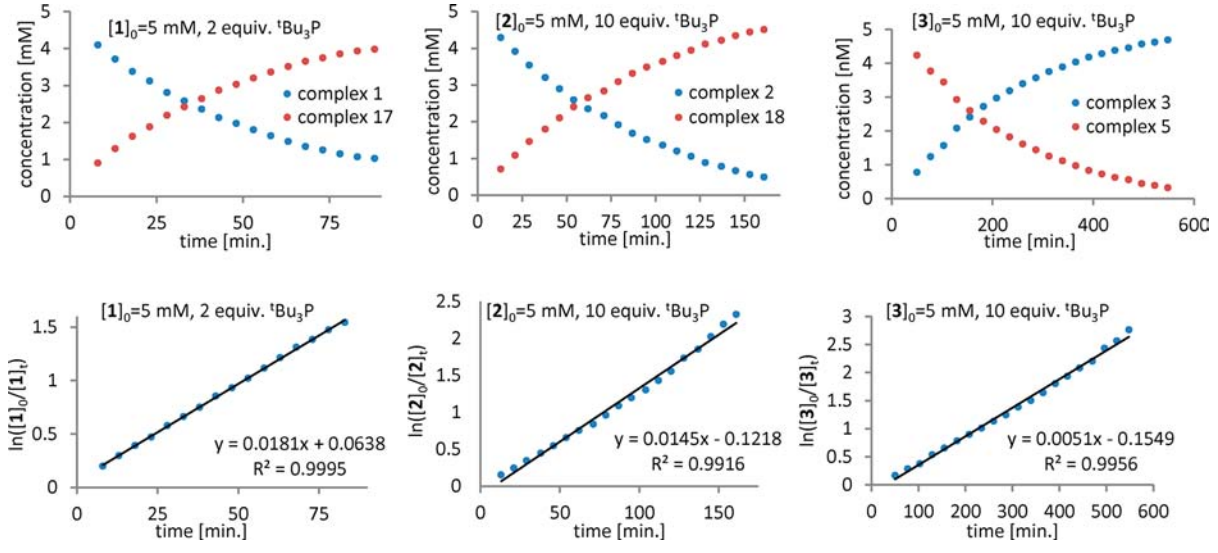


Figure 6. Reaction profiles for the reactions of complexes **1**−**3** with excess of ^{t}Bu$_3$P (top) and first-order kinetic plots (bottom).

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complexes tend to undergo concerted RE by a dissociative mechanism, in which a five-coordinated intermediate is the active specie,[1b] an associative concerted RE mechanism was excluded. A concerted RE of CH_3I was described for a Rh^{III} naphthyl pincer complex.[12] Concerted RE was demonstrated for $C(sp^3)$−Cl by the Pt^{IV} complex[33] and for $C(sp^3)$−F by the Pd^{IV} complex.[4a]

The observed increase in the rate of CH_3I and CH_3Br RE in the presence of the more polar aprotic solvent (acetone) and mildly polar (methylene chloride) argues in favor of an S_N2 -type RE mechanism in the case of complexes **1** and **2**, involving iodide or bromide dissociation followed by nucleophilic attack of the halide on the methyl ligand. The RE rate of CH_3Cl from complex **3** exhibits an opposite trend, in which elimination was faster in polar protic solvents, suggesting that in this case a concerted RE is operative rather than an S_N2 mechanism.[34] Evidence for a nonassociative mechanism, in which the RE takes place directly from the unsaturated complexes **1**−**3**, is the CH_3X RE in the presence of noncoordinating "trapping agents" and the observed CD_3I/CH_3I exchange. Thus, a nonassociative S_N2-type mechanism (pathway (*i*), Scheme 6) is suggested for the RE from complexes **1** and **2** and a concerted RE from the five-coordinate complex **3** (pathway (*iii*)).The reason for the latter might be related to the observation that the Rh−Cl bond length in complex **3** is shorter by 0.308 and 0.129 Å as compared to the corresponding bond of complexes **1** and **2**, respectively. The proximity of the Cl and the methyl ligands to the metal center in complex **3** enables better overlapping of their orbitals, promoting a concerted reductive elimination.

Synthesis and Characterization of [(^{i}PrPNP)Rh(CH_3)-X][BF_4] Complexes. To explore the influence of sterics on the RE process, the ^{i}PrPNP analogues **19**−**20** were synthesized from the Rh^I complex **16**, in analogy to complexes **1** and **2** (Scheme 7). Unfortunately, the reaction of CH_3Cl with **16** was

Scheme 7

very slow and resulted in a low yield (10%) of **21**. In addition, [(^{i}PrPNP)RhCl] (**22**) did not react with $[(CH_3)_3O][BF_4]$, in contrast to its ^{t}Bu analogue (vide supra). Finally, we obtained complex **21** (in 80% purity according to $^{31}P\{^1H\}$NMR) by the reaction of complex **19** with LiCl in acetone, followed by abstraction of the iodide with 1 equiv of $AgBF_4$ (Scheme 7). Complexes **19**−**21** exhibit sharp doublets in the $^{31}P\{^1H\}$ NMR spectra at 41.76, 41.60, and 38.24 ppm, respectively, with $^1J_{RhP}$ = 100 Hz. The methyl ligands exhibit doublets of triplets (or a broad doublet) in the $^{13}C\{^1H\}$ NMR spectra at 3.96, 5.21, and 5.69 ppm, respectively, with $^1J_{RhC}$ = 25 Hz. The structures of **19**−**21**, which are very similar to their ^{t}Bu analogues, were confirmed by X-ray crystallography (Figure 7). The Rh−CH_3 bond lengths in complexes **19**−**21** are longer than in complexes **1**−**3** by 0.013, 0.01, and 0.06 Å, respectively. The Rh−N bond lengths in complexes **19**−**21** are similar to those in complexes **1**−**3**, respectively. Surprisingly, the Rh−I bond length in complex **19** is shorter than in complex **1** by 0.013 Å, while the Rh−Br and Rh−Cl bond lengths are longer by 0.026 and

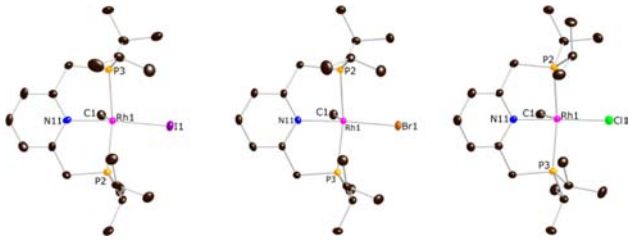
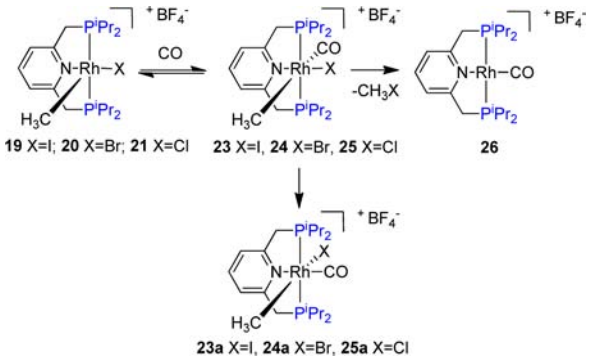


Figure 7. Crystal structures of complexes **19** (left), **20** (middle), and **21** (right) at 50% probability level. Hydrogen atoms and counterions are omitted for clarity. For bond distances and angles see Supporting Information.

0.0392 Å in complexes **20** and **21** than in complexes **2** and **3**, respectively, as expected.

Reactivity of [(^{i}PrPNP)Rh(CH_3)X][BF_4] Complexes. In sharp contrast to the ^{t}BuPNP complexes **1**−**3**, the reaction of the less sterically hindered ^{i}PrPNP complexes **19**−**21** with CO, dmpin, or acetonitrile resulted in the adduct complexes [(^{i}PrPNP)Rh(CH_3)X(L)][BF_4] (X = I, Br, Cl; L = CO, dmpin, CH_3CN) (Schemes 8−10). Addition of CO to

Scheme 8



complexes **19**−**21** resulted in the saturated Rh^{III} complexes [(^{i}PrPNP)Rh(CH_3)X(CO)][BF_4] (**23**, X = I; **24**, X = Br; **25**, X = Cl) (Scheme 8). Complexes **23**−**25** exhibit doublets at 47 (±1) ppm ($^1J_{RhP}$ = 87 Hz) in the $^{31}P\{^1H\}$ NMR. The methyl ligand of **23** and **24** gives rise to sharp signals at 0.97 ppm (dt, $^2J_{PC}$ = 14.5, $^1J_{RhC}$ = 6.3 Hz) and 4.95 ppm (dt, $^1J_{RhC}$ = 15.2 Hz, $^2J_{PC}$ = 6.1 Hz), respectively, and the CO ligand gives rise to sharp signals at 184.21 ppm (dt, $^1J_{RhC}$ = 31.4 Hz, $^2J_{PC}$ = 9.2 Hz) and 184.19 (dt, $^1J_{RhC}$ = 38.8 Hz, $^2J_{PC}$ = 9.6 Hz), respectively.

Complex **25** exhibits a broad signal for the methyl and the CO ligands at 293 K; however, at 243 K, the methyl ligand exhibits a multiplet at 6.45 ppm, and the CO ligand exhibits a sharp signal at 184.50 (dt, $^1J_{RhC}$ = 38.3 Hz, $^2J_{PC}$ = 8.8 Hz).

Equilibria were observed between complexes **19**−**21** and the CO−adduct complexes **23**−**25** (Scheme 8). Upon addition of ^{13}CO to a methylene chloride solution of **23**−**25**, fast exchange with the CO ligand was observed according to $^{13}C\{^1H\}$ NMR.

The isolated complexes **23**−**25** slowly eliminate CH_3X to give the complex [(^{i}PrPNP)Rh(CO)][BF4] (**26**).[35] The rate of the methyl iodide RE is decelerate in the presence of CO. For example, complex **23** under CO (one atmosphere) in methylene chloride solution gave complex **26** in 28% yield according to $^{31}P\{^1H\}$ NMR after 3 days at ambient temperature, while in the absence of CO complex **26** was obtained in 59% yield under the same conditions (time, temperature,

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solvent, and concentration). This observation, in addition to the observed equilibria between complexes **19**–**21** and **23**–**25**, respectively, is in line with the observed reductive elimination of methyl halides from complexes **1**–**3** in the presence of dmpin, and in accordance with a nonassociative RE mechanism. In addition, when methanol was used as a solvent, RE of methyl halide from **23** was retarded, while slightly accelerated in the case of **25**, as was observed in the case of complexes **1** and **3** and in accordance with an S_N2-type RE mechanism for methyl iodide and methyl bromide, and with a concerted mechanism for the RE of methyl chloride.

Following the RE of CH_3X from complexes **23**–**25** by $^{31}P\{^1H\}$ NMR spectroscopy, new complexes were observed, which were assigned as the isomers of complexes **23**–**25** (**23a**–**25a**), in which the CO ligand is *cis* to the methyl ligand (Scheme 8). The methyl ligand in complex **23a** is shifted to a higher field in the $^{13}C\{^1H\}$ NMR spectrum by 2.8 ppm, while the CO ligand is shifted to a lower field by 2.8 ppm. The $^{13}C\{^1H\}$ NMR spectrum of the double-labeled complex $[(^i\text{PrPNP})Rh(^{13}CH_3)X(^{13}CO)][BF_4]$ (**23**) exhibits a $^2J_{CC}$ of 31.2 Hz for the methyl and CO ligands, while in complex **23a** the $^2J_{CC}$ is only 2.1 Hz, in line with CO *cis* to the methyl ligand (Figure 8). The isomerization rate of complexes **23**–**25** to

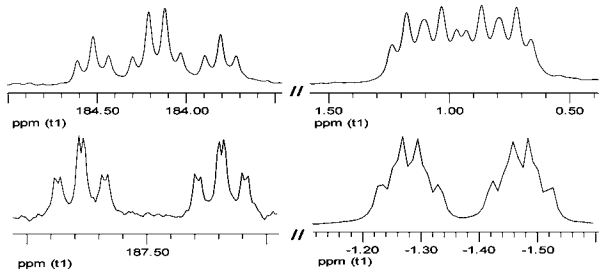


Figure 8. $^{13}C\{^1H\}$ NMR spectrum of complexes **23** (top) and **23a** (bottom); signals of the labeled ligands ^{13}CO–Rh and $^{13}CH_3$–Rh.

23a–**25a** is slower under CO atmosphere. For example, complex **23a** was obtained in 8% and 41% yields in the presence and absence of CO, respectively, under ambient temperature in methylene chloride. Addition of a large excess of methyl iodide to complex **26** resulted in formation of complex **23a** in 16% yield according to $^{31}P\{^1H\}$ NMR after 10 days at ambient temperature. Since complex **23a** was obtained in a higher yield by isomerization of complex **23** (in the absence of CO) than from the direct oxidative addition of methyl iodide to the Rh^I carbonyl complex **26**, it may be assumed that **26** is not an intermediate in the isomerization process.

An X-ray structure of complex **23a** (Figure 9) was obtained by layering a methylene chloride solution of complex **23** with pentane under nitrogen. The Rh–CH_3, Rh–N, and Rh–P bond lengths in complex **23a** are elongated by 0.040, 0.043, and 0.047 (average) Å, respectively, as compared to the corresponding bonds of complex **19**, while the Rh–I bond length is extensively elongated by 0.172 Å.

Addition of dmpin to complexes **19**–**21** resulted in formation of the saturated Rh^{III} complexes $[(^i\text{PrPNP})Rh(CH_3)X(\text{dmpin})][BF_4]$ (**27**, X = I; **28**, X = Br; **29**, X = Cl) exclusively (Scheme 9). Complexes **27**–**29** are stable and do not eliminate methyl halide. In addition, while dynamic behavior was observed for **9**–**11** (vide supra), this was not observed for **27**–**29** (Figure 10). Complexes **27**–**29** exhibit sharp doublets at δ = 46 (±1) ppm, in the $^{31}P\{^1H\}$ NMR

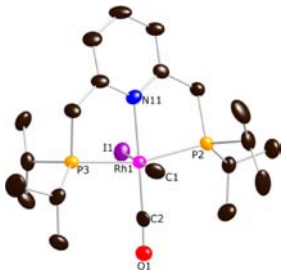
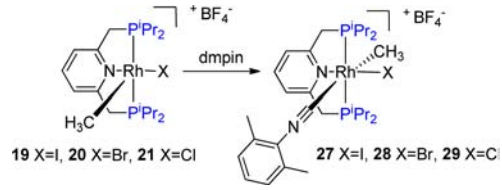


Figure 9. Crystal structure of complex **23a** at 50% probability level. Hydrogen atoms and counterions are omitted for clarity. For bond distances and angles see Supporting Information.

Scheme 9



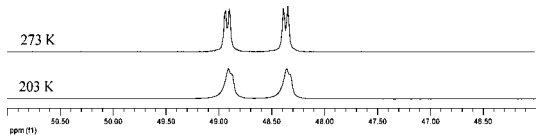
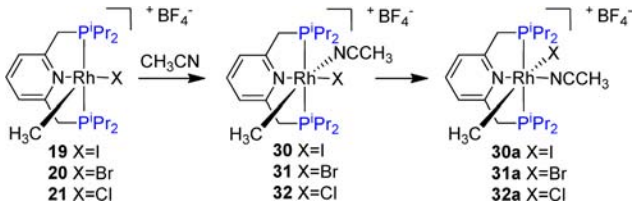


Figure 10. Variable-temperature $^{31}P\{^1H\}$ NMR spectra of $[(^i\text{PrPNP})Rh(CH_3)(\text{dmpin})I][BF4]$ (**27**) in methylene chloride-d_2.

spectra with $^1J_{RhP}$ = 90 (±1) Hz. The methyl ligand signals are shifted highfield by 7.6, 5.6, and 4.6 ppm for complexes **27**–**29**, respectively, in the $^{13}C\{^1H\}$ NMR and by about 0.2 ppm in the ^1H NMR as compared with the unsaturated complexes **19**–**21**.

Upon addition of acetonitrile to complexes **19**–**21**, mixtures of two isomers of the complexes $[(^i\text{PrPNP})Rh(CH_3)X(CH_3CN)][BF_4]$ (**30**, X = I; **31**, X = Br; **32**, X = Cl) were obtained with acetonitrile *cis* or *trans* to the methyl ligand (Scheme 10). While the reaction of complexes **20** and **21** with

Scheme 10



acetonitrile resulted in a single product after 18 h at ambient temperature (**31a** and **32a**, respectively), equilibrium of the *cis*/*trans* isomers was observed for complexes **30** and **30a**. The isolated complexes **31a** and **32a** are *cis* isomers according to NMR data and give rise to a sharp doublet at 48.31 ppm ($^1J_{RhP}$ = 92.2 Hz) and 50.39 ppm ($^1J_{RhP}$ = 92.2 Hz), respectively, in the $^{31}P\{^1H\}$ NMR, slightly shifted to lower field as compared to the *trans* isomers by 5 and 7.5 ppm, respectively. The acetonitrile ligand in complexes **31a** and **32a** is shifted to a lower field by 0.45 ppm in the ^1H NMR and by 2.4 (CH_3CN) and 9 ppm (CH_3CN) in $^{13}C\{^1H\}$ NMR as compared with free acetonitrile. Moreover, distinguished signals of the acetonitrile ligand were observed in the presence of free acetonitrile. The

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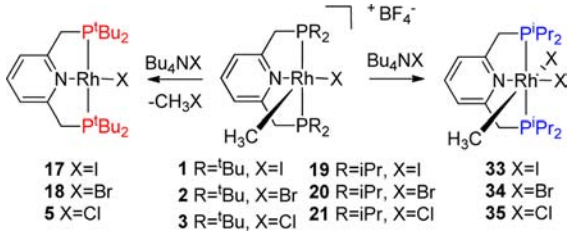
methyl ligand in complexes **31a** and **32a** is significantly shifted high field in the $^{13}C\{^1H\}$ NMR as compared to complexes **20** and **21** and gives rise to signals at −3.00 (dt, $^1J_{RhC}$ = 20.8 Hz, $^2J_{PC}$ = 4.5 Hz) and −5.63 (dt, $^1J_{RhC}$ = 10.5 Hz, $^2J_{PC}$ = 5.0 Hz), respectively. The reaction mixture of complex **19** with acetonitrle in methylene chloride reveals two signals in the $^{31}P\{^1H\}$ NMR corresponding to the *cis* and *trans* isomers: a sharp signal at 45.00 ppm for the *cis* isomer (**30a**) (dd, $^1J_{RhP}$ = 91.8 Hz, $^1J_{PC}$ = 4.6 Hz) and a broad signal, which upon cooling to 253 K appears as a doublet of doublet at 44.68 ppm ($^1J_{RhP}$ = 95.7 Hz, $^1J_{PC}$ = 3.9 Hz), for the *trans* isomer (**30**). The $^{13}C\{^1H\}$ NMR of the mixture reveals two signals for the methyl ligand at 0.72 ppm (dt, $^1J_{RhC}$ = 21.0 Hz, $^2J_{PC}$ = 4.7 Hz) for the *trans* isomer (**30**) and at −7.60 (dt, $^1J_{RhC}$ = 20.3 Hz, $^2J_{PC}$ = 6.3 Hz) for the *cis* isomer (**30a**). Addition of acetonitrile to a methylene chloride solution of **19** at 253 K resulted in the *trans* isomer (**30**) exclusively, indicating that it is the kinetic product. The kinetic *trans* isomer is stable at 243 K but isomerizes to **30a** at ambient temperature.

While the $^tBu_2$−PNP complexes **1**−**3** reductively eliminate methyl halides in the presence of Bu_4NX (excess or 1 equiv; X = I, Br, Cl, respectively) to give complexes **17**, **18**, and **5**, respectively, the $^iPr_2$−PNP complexes **19**−**21** react with Bu_4NX to give the saturated complexes $[(^iPrPNP)Rh(CH_3)X_2]$ (**33**, X = I; **34**, X = Br; **35**; X = Cl, respectively) (Scheme 11).

Scheme 11



The methyl ligand in complexes **33**−**35** is shifted downfield by 4.6, 8.3, and 10.7 ppm as compared to complexes **19**−**21**, respectively, and similar in trend and magnitude to the methyl chemical shift of complexes **30a**−**32a**, in which the methyl ligand is assumed to be *trans* to the halide. The X-ray structure of complex **33** (Figure 11) reveals hexagonal geometry around the Rh center, and the Rh−CH_3 bond length is longer than in complex **19** by 0.058 Å. The Rh−I(1) bond which is located *trans* to the pyridine moiety is longer than in complex **22** by 0.057 Å, and it is shorter by 0.205 Å than the Rh−I(2) bond, which is *trans* to the methyl ligand.

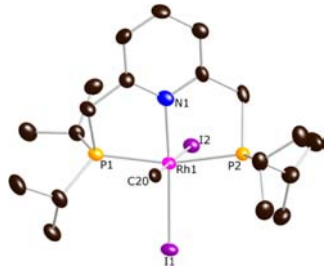


Figure 11. Crystal structure of complex **33** at 50% probability level. Hydrogen atoms and counterion are omitted for clarity. For bond distances and angles see Supporting Information.

Addition of an equivalent of CD_3I to complex **19** in methylene chloride did not result in CH_3/CD_3 exchange as indicated by NMR. However, when a large excess of CD_3I was added to complex **19** in acetone, traces of free CH_3I could be observed after 18 h.

Thus, the RE of methyl halides from the ^{t}BuPNP complexes **1**−**3** is much easier than in the case of the ^{i}PrPNP analogues **19**−**21**, even though the lower electron density on the metal in **19**−**21** relative to **1**−**3** should promote RE. This demonstrates the importance of steric effects in this reaction. A similar effect was observed for the naphthyl-based PCP-type complex $[(C_{10}H_5(CH_2{-}PR_2)_2)Rh(CH_3)I]$ (R = ^{t}Bu), where RE of CH_3I occurs upon reaction with CO, while the less bulky complex (R = ^{i}Pr) did not eliminate CH_3I.[13] Steric factors were found to facilitate also RE from Pd^{II} aryl halide[14] and methyl halide[36] complexes.

CONCLUSIONS

A series of cationic methyl halide Rh^{III} complexes based on the electron-rich ^{t}BuPNP (**1**−**3**) and ^{i}PrPNP (**19**−**21**) ligands were synthesized. A rare case of directly observed RE of methyl halides from complexes **1**−**3** in the presence of coordinating and noncoordinating potential ligands is described.

On the basis of solvent effects on the RE rate, an S_N2 mechanism is suggested for the RE of CH_3X (X = I, Br) from complexes **1** and **2**, while CH_3Cl probably eliminates in a concerted fashion. In both mechanisms the RE is more facile from a five-coordinate complex as compared with the saturated 18 e^- complex; thus a nonassociative rather than an associative mechanism is suggested (Scheme 6, pathways (*i*) and (*iii*), respectively).

The RE is induced by sterics, as RE was retarded in the case of the less sterically hindered complexes **19**−**21**, which react with coordinating substrates to give the saturated Rh^{III} adduct complexes.

ASSOCIATED CONTENT

Supporting Information

Experimental procedures and characterization of complexes **2**, **3**, **8**, **9**−**15**, **18**, **20**−**25**, and **27**−**35**; NMR spectra of complexes **9**−**14**, **21**, **24**, **25**, and **29**−**35**; and X-ray data for **3**, **9**, **20**, **21**, **23a**, and **33** (tables of selected bond distances and angles and CIF files). This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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REFERENCES

(1) (a) Atwood, J. D. *Inorganic and Organometallic Reaction Mechanisms*, 2nd ed.; VCH Publishers: New York, 1997. (b) Crabtree, R. H. *The Organometallic Chemistry of the Transition Metals*, 4th ed.; Wiley Interscience: New York, 2005. For a recent review on RE of carbon-halogen see: (c) Vigalok, A. *Chem.—Eur. J.* **2008**, *14*, 5102. (d) Vigalok, A.; Kaspi, A. W. *Top. Organomet. Chem.* **2010**, *31*, 19. (e) Jiang, X.; Liu, H.; Gu, Z. *Asian J. Org. Chem.* **2012**, *1*, 16.

(2) Ruddick, J. D.; Shaw, B. L. *J. Chem. Soc. A* **1969**, 2969.

(3) (a) Goldberg, K. I.; Yan, J. Y.; Winter, E. L. *J. Am. Chem. Soc.* **1994**, *116*, 1573. (b) Goldberg, K. I.; Yan, J. Y.; Breitung, E. M. *J. Am. Chem. Soc.* **1995**, *117*, 6889.

(4) (a) Racowski, J. M.; Gary, J. B.; Sanford, M. S. *Angew. Chem., Int. Ed.* **2012**, *51*, 3414. (b) McMurtrey, K. B.; Racowski, J. M.; Sanford, M. S. *Org. Lett.* **2012**, *14*, 4094.

(5) Shilov, A. E.; Shul'pin, G. B. *Chem. Rev.* **1997**, *97*, 2879.

(6) (a) Luinstra, G. A.; Wang, L.; Stahl, S. S.; Labinger, J. A.; Bercaw, J. E. *J. Organomet. Chem.* **1995**, *504*, 75. (b) Luinstra, G. A.; Labinger, J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **1993**, *115*, 3004.

(7) Wang, J.; Tong, X.; Xie, X.; Zhang, Z. *Org. Lett.* **2010**, *12*, 5370.

(8) For an example of CH_3Cl RE by the Rh^{III} complex, see: Lindner, E.; Wang, Q.; Mayer, H. A.; Fawzi, R.; Steimann, M. *Organometallics* **1993**, *12*, 1865.

(9) (a) Scott, V. J.; Labinger, J. A.; Bercaw, J. E. *Organometallics* **2010**, *29*, 4090. (b) Mankad, N. P.; Toste, F. D. *Chem. Sci.* **2012**, *3*, 72.

(10) (a) Liu, H.; Li, C.; Qiu, D.; Tong, X. *J. Am. Chem. Soc.* **2011**, *133*, 6187. (b) Petrone, D. A.; Malik, H. A.; Clemenceau, A.; Lautens, M. *Org. Lett.* **2012**, *14*, 4806.

(11) Vickers, P. W.; Pearson, J. M.; Ghaffar, T.; Adams, H.; Haynes, A. *J. Phys. Org. Chem.* **2004**, *17*, 1007.

(12) Feller, M.; Iron, A. M.; Shimon, L. J. W.; Diskin-Posner, Y.; Leitus, G.; Milstein, D. *J. Am. Chem. Soc.* **2008**, *130*, 14374.

(13) Frech, C. M.; Milstein, D. *J. Am. Chem. Soc.* **2006**, *128*, 12434.

(14) (a) Roy, A. H.; Hartwig, J. F. *J. Am. Chem. Soc.* **2001**, *123*, 1232. (b) Roy, A. H.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 13944. (c) Roy, A. H.; Hartwig, J. F. *Organomettalics* **2004**, *23*, 1533.

(15) (a) Shen, X.; Hyde, A. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **2010**, *132*, 14076. (b) Pan, J.; Wang, X.; Zhang, Y.; Buchwald, S. L. *Org. Lett.* **2011**, *13*, 4974. (c) Imazaki, Y.; Shirakawa, E.; Ueno, R.; Hayashi, T. *J. Am. Chem. Soc.* **2012**, *134*, 14760.

(16) (a) Yahav-Levi, A.; Goldberg, I.; Vigalok, A.; Vedernikov, A. N. *J. Am. Chem. Soc.* **2008**, *130*, 724. (b) Kaspi, A. W.; Yahav-Levi, A.; Goldberg, I.; Vigalok, A. *Inorg. Chem.* **2008**, *47*, S. (c) Whitfield, S. W.; Sanford, M. S. *J. Am. Chem. Soc.* **2007**, *129*, 15142. (d) Furuya, T.; Ritter, T. *J. Am. Chem. Soc.* **2008**, *130*, 10060. (e) Arnold, P. L.; Sanford, M. S.; Pearson, S. M. *J. Am. Chem. Soc.* **2009**, *131*, 13912.

(17) Ettorre, R. *Inorg. Nucl. Chem. Lett.* **1969**, *5*, 45.

(18) (a) Yahav-Levi, A.; Goldberg, I.; Vigalok, A. *J. Am. Chem. Soc.* **2006**, *128*, 8710. (b) Yahav-Levi, A.; Goldberg, I.; Vigalok, A.; Vedernikov, A. N. *Chem. Commun.* **2010**, *46*, 3324.

(19) Powers, D. C.; Benitez, D.; Tkatchouk, E.; Goddard, W. A., III; Ritter, T. *J. Am. Chem. Soc.* **2010**, *132*, 14092.

(20) Higgs, A. T.; Zinn, P. J.; Simmons, S. J.; Sanford, M. S. *Organometallics* **2009**, *28*, 6142.

(21) (a) Dekleva, T. W.; Forster, D. *Adv. Catal.* **1986**, *34*, 81. (b) Maitlis, P. M.; Haynes, A.; Sunley, G. J.; Howard, M. J. *J. Chem. Soc., Dalton Trans.* **1996**, 2187 and references therein.

(22) The reductive elimination of acetyl iodide was also reported to take place from the related complex $[Rh(CO(CH_3))(CO)_{I2}(PEt_3)_2]^-$: Rankin, J.; Benyei, A. C.; Poole, A. D.; Cole-Hamilton, D. J. *J. Chem. Soc., Dalton Trans.* **1999**, 3771.

(23) (a) Ball, N. D.; Sanford, M. S. *J. Am. Chem. Soc.* **2009**, *131*, 3796. (b) Furuya, T.; Ritter, T. *Org. Lett.* **2009**, *11*, 2860. (c) Furuya, T.; Benitez, D.; Tkatchouk, E.; Strom, A. E.; Tang, P.; Goddard, W. A., III; Ritter, T. *J. Am. Chem. Soc.* **2010**, *132*, 3793. (d) Grushin, V. V. *Acc. Chem. Res.* **2010**, *43*, 160. (e) Kaspi, A. W.; Goldberg, I.; Vigalok, A. *J. Am. Chem. Soc.* **2010**, *132*, 10626. (f) Furuya, T.; Benitez, D.; Tkatchouk, E.; Strom, A. E.; Tang, P.; Goddard, W. A.; Ritter, T. *J. Am. Chem. Soc.* **2010**, *132*, 3793. (g) Lee, E.; Kamlet, A. S.; Powers, D. C.; Neumann, C. N.; Boursalian, G. B.; Furuya, T.; Choi, D. C.; Hooker, J. M.; Ritter, T. *Science* **2011**, *334*, 639. (h) Zhao, S. −B.; Becker, J. J.; Gagné, M. R *Organometallics* **2011**, *30*, 3926. (i) Lee, E.; Hooker, J. M.; Ritter, T. *J. Am. Chem. Soc.* **2012**, *134*, 17456. (j) Mankad, N. P.; Toste, F. D. *Chem. Sci.* **2012**, *3*, 72.

(24) (a) Watson, D. A.; Su, M.; Teverovskiy, G.; Zhang, Y.; García-Fortanet, J.; Kinzel, T.; Buchwald, S. L. *Science* **2009**, *325*, 1661. (b) Katcher, M. H.; Doyle, A. G. *J. Am. Chem. Soc.* **2010**, *132*, 17402. (c) Akana, J. A.; Bhattacharyya, K. X.; Müller, P.; Sadighi, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 7736. (d) Hollingworth, C.; Hazari, A.; Hopkinson, M. N.; Tredwell, M.; Benedetto, E.; Huiban, M.; Gee, A. D.; Brown, J. M; Gouverneur, V. *Angew. Chem., Int. Ed.* **2011**, *50*, 2613. (e) Hull, K. L.; Anani, W. Q.; Sanford, M. S. *J. Am. Chem. Soc.* **2006**, *128*, 7134. (f) Wang, X.; Mei, T. -S.; Yu, J. −Q. *J. Am. Chem. Soc.* **2009**, *131*, 7520. (g) Casitas, A.; Canta, M.; Solà, M.; Costas, M.; Ribas, X. *J. Am. Chem. Soc.* **2011**, *133*, 19386. (h) Chan, C. S. L.; Wasa, M.; Wang, X.; Yu, J. Q. *Angew. Chem., Int. Ed.* **2011**, *50*, 9081.

(25) Feller, M.; Ben-Ari, E.; Gupta, T.; Shimon, L. J. W.; Leitus, G.; Diskin-Posner, G.; Weiner, L.; Milstein, D. *Inorg. Chem.* **2007**, *46*, 10479.

(26) Hermann, D.; Gandelman, M.; Rozenberg, H.; Shimon, L. J. W.; Milstein, D. *Organometallics* **2002**, *21*, 812.

(27) See Supporting Information.

(28) The kinetic studies of the reactions of complexes **1**−**3** with one equivalent of $^tBu_3P$ were not conclusive. Reactions of complexes **2** and **3** with 5 equiv of $^tBu_3P$ also exhibit first-order kinetics, but at a lower rate, as a result of slower trapping of the formed methyl halide as phosphonium salt (see Supporting Information).

(29) The structures of the complexes as drawn are not meant to confer any geometrical relationships and do not represent the actual solvated structures.

(30) (a) Reichardt, C. *Pure Appl. Chem.* **1982**, *54*, 1867. (b) Reichardt, C. *Solvents and Solvent Effects in Organic Chemistry*, 2nd ed.; VCH: Weinheim, Germany, 1988.

(31) (a) Williams, B. S.; Holland, A. W.; Goldberg, K. I. *J. Am. Chem. Soc.* **1999**, *121*, 252. (b) Williams, B. S.; Goldberg, K. I. *J. Am. Chem. Soc.* **2001**, *123*, 2576.

(32) Ye, Y.; Ball, N. D.; Kampf, J. W.; Sanford, M. S. *J. Am. Chem. Soc.* **2010**, *132*, 14682.

(33) (a) Crosby, S. H.; Thomas, R. H.; Clarkson, G. J.; Rourke, J. P. *Chem. Commun.* **2012**, *48*, 5775. (b) Crosby, S. H.; Clarkson, G. J.; Rourke, J. P. *Organometallics* **2012**, *31*, 7256.

(34) Acceleration of RE of CH_3Cl in polar protic solvents by itself does not necessarily indicate a concerted mechanism. We have suggested a concerted RE for the methyl chloride complex since unlike the iodide and the bromide complexes the RE was not retarded in polar protic solvents.

(35) Feller, M.; Diskin-Posner, Y.; Shimon, L. J. W.; Ben-Ari, E.; Milstein, D. *Organometallics* **2012**, *31*, 4083.

(36) Lan, Y.; Liu, P.; Newman, S. G.; Lautens, M.; Houk, K. N. *Chem. Sci.* **2012**, *3*, 1987.