Communication

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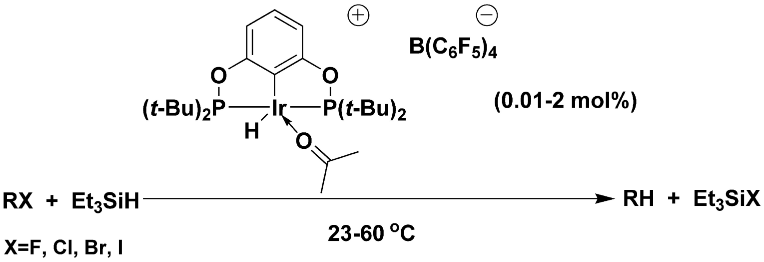

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Iridium-Catalyzed Reduction of Alkyl Halides by Triethylsilane

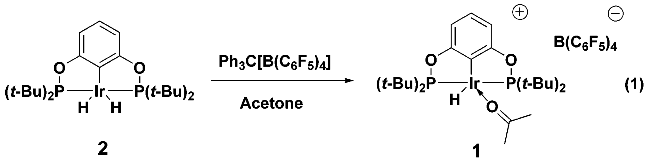
Jian Yang and Maurice Brookhart*

Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290

Received July 31, 2007; E-mail: mbrookhart@unc.edu

Alkyl halides are generally reduced with trialkyl tin hydrides via a radical chain mechanism.[1] Alternative reduction procedures are desired owing to the toxicity of the tin reagents and problems separating tin byproducts from reduction products. Silanes are thermodynamically capable of such reductions, but the Si−H bond is too strong to support a radical chain reaction.[2] Use of $(TMS)_3SiH$ possessing a weak Si−H bond circumvents this problem but is not economically attractive.[2] High loadings of Pd(II) salts have been shown to induce Et_3SiH reduction of certain classes of alkyl halides.[3] Strong Lewis acids (e.g., $AlCl_3$) have been used in combination with Et_3SiH; skeletal rearrangements accompanying reduction support a mechanism involving carbocation-like intermediates.[4] The combination of $Et_3SiH/Ph_3C^+BAr^-_4$ ($Ar- = C_6F_5-$) can reduce alkyl fluorides via a mechanism involving generation of carbocations through fluoride abstraction by Et_3Si^+ (formed from Ph_3C^+ and Et_3SiH) followed by hydride transfer to the carbocation by Et_3SiH.[5] Similar chemistry has been described using a bissilylated onium salt.[6] We report here a cationic Ir(III) hydride complex, **1**, which is a versatile and highly active catalyst for reduction of a broad spectrum of alkyl halides by Et_3SiH.

Synthesis of **1** is achieved in 94% isolated yield by treatment of dihydride **2**[7] with $Ph_3C^+BAr^-_4$ in acetone (eq 1). Complete characterization including a single-crystal X-ray structural analysis is in hand.[8] Reductions of halides (eq 2) are conveniently carried out either in chlorobenzene or in neat alkyl halide. Catalyst loadings of 0.5 mol % are generally used (but can be much lower, see below) together with 3 equiv of Et_3SiH; temperatures of 23−60 °C are employed depending on substrate.



(1)

$$RX + Et_3SiH \xrightarrow[23^{o}C\text{-}60^{o}C]{0.5\ mol\%\ \mathbf{1}} RH + Et_3SiX \qquad (2)$$

X=F, Cl, Br, I

Table 1. Reduction of Alkyl Halides Catalyzed by **1**[a]

entry	catalyst mol %	halide	solvent[b]	*T*, °C	*t* h	conversion[c] %
1	0.5	benzyl bromide	A	23	0.3	>99
2	0.5	benzyl chloride	A	23	0.3	>99
3	0.075	benzyl bromide	A	23	2.5	>99
4	0.01	benzyl chloride	B	23	29	32
5	0.5	1-chloropentane	A	60	7	>99
6	0.5	1-bromopentane	A	60	1.5	>99
7	0.5	1-iodopentane	A	60	48	>99
8	2.0	1-fluoropentane	A	60	50	92[d]
9	0.5	1-chloropentane	C	23	20	86
10	0.5	1-bromopentane	C	23	3.3	98
11	0.5	2-chloropentane	A	60	2.3	>99[e]
12	0.5	2-bromopentane	A	60	0.7	>99[e]
13	0.5	chlorocyclohexane	A	60	16	>99[e]
14	0.5	bromocycloheptane	A	23	0.3	>99[e]
15	0.5	2-chloropentane	C	23	9	99[e]
16	0.5	2-bromopentane	C	23	3.3	98[e]
17	0.5	trityl chloride	A	23	0.3	>99
18	0.5	*tert*-pentyl chloride	A	23	0.3	>99[e]
19	1.0	CD_2Cl_2	D	23	168	>99[f]

[a] Reaction conditions: 3 equiv. of Et_3SiH. [b] Solvent: A, C_6D_5Cl; B, $C_6D_4Cl_2$; C, neat; D, CD_2Cl_2. [c] Determined by loss of alkyl halides by NMR. [d] Products in addition to pentane are observed. [e] In addition to alkane, traces of olefin and H_2 were observed and converted to alkanes at longer reaction times. [f] Catalyst loading and conversion refer to Et_3SiH. The reduction product is CD_2H_2; only traces of CD_2HCl are observed at 50% reaction.

Results of typical reductions are illustrated in Table 1. Conversions are determined by NMR spectroscopy. Entries 1−2 show that benzyl chloride and benzyl bromide are rapidly reduced at 23 °C, 0.5% catalyst loading. With 0.075% loading, complete reduction of benzyl bromide (1330 TOs) is accomplished in 2.5 h at 23 °C. At 0.01% loading 3200 TOs for reduction of benzyl chloride are achieved after 29 h. Results of reduction of simple primary alkyl halides are shown in entries 5−10. Rapid reduction of 1-bromopentane occurs at 60 °C (0.5% **1**) while under similar conditions 1-chloropentane requires ca. 7 h for complete reduction. Reduction of 1-iodopentane is slow, requiring 48 h for complete conversion. 1-Fluoropentane can be reduced but exhibits only 92% conversion at 2% catalyst loading after 50 h. Results of reductions of neat 1-bromopentane and 1-chloropentane at 23 °C are shown in entries 9 and 10. Again, the bromide is more reactive than the chloride.

Reductions of simple secondary halides are shown in entries 11−16. Like the primary halides, efficient reductions can be accomplished in chlorobenzene or in neat alkyl halide at either 60 or 23 °C and bromides are reduced more rapidly than chlorides. The tertiary chlorides, trityl chloride as well as *tert*-pentyl chloride are reduced rapidly at 23 °C (entries 17 and 18).

To determine relative reactivities of primary and secondary halides, competition experiments were run by treating a 1:1 molar ratio of the two pentyl halides in $C_6D_4Cl_2$ with 6 equiv Et_3SiH and 1% **1** and monitoring initial rates of reduction of the halides at 23 °C. The following relative rates were determined: 1-chloropentane/2-chloropentane = 2.6:1.0, 1-bromopentane/2-bromopentane = 2.0:1.0, and 1-iodopentane/2-iodopentane = 1.6:1.0.

Results in Table 1 show that, qualitatively, reactivities follow the order RBr > RCl > RI when reductions are carried out in separate flasks. Quite different results are seen when two different halides compete for reduction in the same flask. The experimental protocol is summarized in eq 3 and results are shown in Table 2. In a representative experiment, 1-iodoheptane (1 equiv) and 1-bromohexane (80 equiv) were treated with 30 equiv of Et_3SiH and 5% **1**. Analysis of heptane and hexane very early in the reaction (less than 12.5% conversion of 1-iodoheptane) established a relative reactivity ratio of 80:1 for primary iodide/primary bromide. Bromide versus chloride and iodide versus chloride values are shown in the

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Table 2. Competition Experiments to Determine the Relative Reactivities of Primary Chloride, Bromide, and Iodide

entry	RX	R′X′	R′X′/RX	relative reactivies (RX/R′X′)
1	1-iodoheptane	1-chlorohexane	250	1200
2	1-bromoheptane	1-chlorohexane	200	260
3	1-iodoheptane	1-bromohexane	80	80

Table 2 and establish that in head-to-head competition RI > RBr > RCl. These results show that highly chemoselective reductions can be achieved.

$$\underset{\text{1 equiv.}}{\text{RX}} + \underset{\text{80 to 250 equiv.}}{\text{R'X'}} \xrightarrow[\text{C}_6\text{H}_5\text{F},\ 23^{\circ}\text{C}]{5\ \%\ \mathbf{1},\ 30\ \text{equiv. Et}_3\text{SiH}} \text{RH} + \text{R'H} \quad (3)$$

$$(\text{X, X}' = \text{Cl, Br, I})$$

Substantial mechanistic details were uncovered by in situ ^1H and ^{31}P NMR monitoring of working catalyst systems, with ^{31}P NMR data being the more useful. First, potential intermediates were generated independently and their ^{31}P NMR spectra recorded. The ^{31}P chemical shifts for these species are summarized in Figure 1 and the means of generating them are described in Supporting Information.

Exposure of the acetone complex **1** to Et_3SiH results in rapid formation of $(CH_3)_2CHOSiEt_3$ and a highly reactive solvated complex which initiates the reaction. Following the in situ reduction of CH_3I at 23 °C shows that the only Ir species present is the CH_3I complex, **3**. However, following the reduction of either 1-chloropentane or 1-bromopentane shows that the Ir species exist as a mixture of the halide complex (**6** or **7**) and the σ-silane complex **4** with the ratio depending on the ratio of silane/halide and the nature of the halide (the bromide binds tighter than the chloride). Low-temperature NMR experiments show that the σ-silane complex is in rapid equilibrium with the halide complexes and this equilibrium is established rapidly relative to reduction.[9] These results support the catalytic cycle shown in Scheme 1.

The reactivity order, RI < RCl < RBr (separate flasks) and the observation that CD_2HCl is reduced much faster than CD_2Cl_2 are inconsistent with a radical mechanism. Reduction of iridium halide complex **A** by Et_3SiH is also inconsistent with the order RI < RCl < RBr. Kinetic studies of the reduction of CH_3I show that the turnover frequency is zero-order in $[CH_3I]$ and first-order in $[Et_3SiH]$, consistent with the proposed catalytic cycle where **A**, $[Ir]H(ICH_3)^+$, is the dominant resting state. Data collected to date cannot distinguish between step I or step II as the turnover-limiting step, and this may well vary with the nature of the substrate. The proposed mechanism also explains the differing relative reactivities of halides in separate flasks versus the same flask. Alkyl iodides bind tightly to Ir and result in very low equilibrium concentrations of the σ-silane complex thus retarding the overall rate, but the silane complex reacts preferentially with iodides when offered the "same flask" experiments.

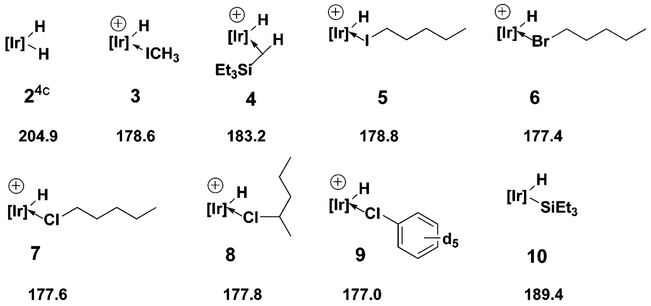
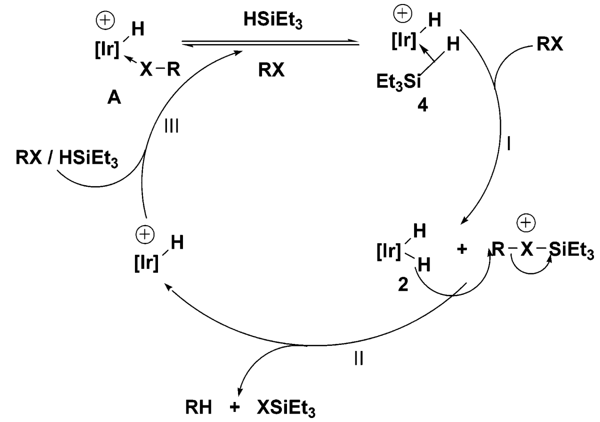


Figure 1. Characteristic ^{31}P NMR shifts used to identify key Ir species.

Scheme 1. Proposed Catalytic Cycle for Iridium-Catalyzed Reduction of Alkyl Halides by Triethylsilane



In summary, iridium complex **1** is a highly effective catalyst for reduction of a wide class of alkyl halides by triethylsilane. The catalytic cycle appears to operate by a unique process in which an electrophilic iridium silane complex acts as a silylating reagent to produce a silyl-substituted halonium ion which is then readily reduced by the nucleophilic dihydride formed following silyl transfer. This mechanism has parallels to that proposed by Piers for hydrosilylation of ketones using $(C_6F_5)_3B/Et_3SiH$ wherein the silane is activated by $(C_6F_5)_3B$ and transfers Et_3Si^+ to ketone.[10] Indeed complex **1** catalyzes the reduction of other functional groups and will be the subject of future publications.

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Supporting Information Available: CIF files containing X-ray crystallographic data for complex **1**, experimental details, and kinetics. This material is available free of charge via the Internet at http://pubs.acs.org.

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(8) Details are reported in Supporting Information.
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