Ruthenium-Catalyzed Ionic Hydrogenation of Aziridinium Cations

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Hydride transfer from CpRu(dppm)H (dppm = bis(diphenylphosphino)methane) to asymmetrically substituted aziridinium cations occurs at the less substituted carbon when the substituents are alkyl, but at the more substituted carbon when the substituent is phenyl. Some of the phenyl-substituted aziridinium cations react with the amine resulting from H^- transfer; the reaction of the same phenyl-substituted cation with Cp*Ru(dppf)H (dppf = 1,1′-bis(diphenylphosphino)ferrocene) shows evidence of electron transfer. CpRu(dppm)H can catalyze the hydrogenation of the same aziridinium cations to ammonium cations; this reaction occurs with the same regioselectivity as the stoichiometric H^- transfer reactions.

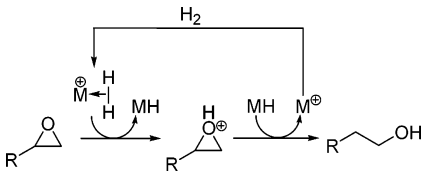
Introduction

There are relatively few reports of the homogeneous hydrogenation of epoxides, particularly terminal epoxides,[1−3] and there is no general method for preparing primary alcohols from terminal epoxides and hydrogen (although 2-phenylethanol can be prepared from styrene oxide and hydrogen with several catalysts).[2]

The Fujitsu group obtained only a 44% yield of 3-buten-1-ol when the hydrogenation of 3,4-epoxy-1-butene was catalyzed by various cationic rhodium complexes.[3a] The transfer hydrogenation (with isopropyl alcohol as the hydrogen source) of 1,2-epoxyalkanes gave branched (secondary) alcohols with several catalysts derived from $Rh_2(OAc)_4$.[3b] Ikariya and co-workers have recently reported secondary alcohols as the dominant products with the ternary catalyst system Cp*Ru(1,5-cyclooctadiene)Cl/2-(diphenylphosphino)ethylamine/KOH.[3c]

One approach to obtaining terminal alcohols from the catalytic hydrogenation of epoxides would be an *ionic* mechanism, with H^- transferred to the internal carbon of the protonated epoxide (Scheme 1).

Scheme 1



However, the instability of protonated epoxides at ambient temperature (although they can be spectroscopically observed at low temperatures[4]) makes it inconvenient to examine their reactions with transition-metal hydrides M−H. We have therefore examined instead the regiochemistry of H^- transfer to aziridinium cations, which are isoeletronic with prontonated epoxides.

Aziridinium cations are themselves important in the synthesis of biologically active compounds,[5] and their ring-opening reactions with nucleophiles, such as amines,[6] hydrazine hydrate,[7] alcohols,[6f,n] naphthols,[8] halide ions,[6m,9] CN^-,[9d] SCN^-,[10] AcO^-,[11] RS^-,[6o,11] and several organometallic anions,[12] have been studied. However, the reaction of aziridinium cations with transition-metal hydrides has not been studied, and, to the best of our knowledge, the catalytic hydrogenation of aziridinium cations has not been reported.

In this paper we report H^- transfer from ruthenium hydrides to aziridinium cations and the observation of one-electron transfer with one ruthenium hydride, Cp*Ru(dppf)H (dppf = 1,1′-bis(diphenylphosphino)ferrocene).[13] We also demonstrate that the hydrogenation of aziridinium cations can be catalyzed by other ruthenium hydrides.

Results and Discussion

Synthesis of Aziridinium Cations. Although some aziridinium cations are unstable in regard to dimeriza-

(1) Hydrogenation of internal epoxides: (a) Shimizu, I.; Oshima, M.; Nisar, M.; Tsuji, J. *Chem. Lett.* **1986**, 1775−1776. (b) Oshima, M.; Yamazaki, H.; Shimizu, I.; Nisar, M.; Tsuji, J. *J. Am. Chem. Soc.* **1989**, *111*, 6280−6287. (c) Shimizu, I.; Hayashi, K.; Ide, N.; Oshima, M. *Tetrahedron* **1991**, *47*, 2991−2998. (d) Shimizu, I.; Omura, T. *Chem. Lett.* **1993**, 1759−1760. (e) Torii, S.; Okumoto, H.; Nakayasu, S.; Kotani, T. *Chem. Lett.* **1989**, 1975−1978. (f) Chan, A. S. C.; Coleman, J. P. *J. Chem. Soc., Chem. Commun.* **1991**, 535−536. (g) Bakos, J.; Orosz, Á.; Cserépi, S.; Tóth, I.; Sinou, D. *J. Mol. Catal. A* **1997**, *116*, 85−97. (h) Noguchi, Y.; Yamada, T.; Uchiro, H.; Kobayashi, S. *Tetrahedron Lett.* **2000**, *41*, 7493−7497. (i) Kakei, H.; Nemoto, T.; Ohshima, T.; Shibasaki, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 317−320.

(2) Hydrogenation of styrene oxide: (a) Kwiatek, J.; Mador, I. L.; Seyler, J. K. *J. Am. Chem. Soc.* **1962**, *84*, 304−305. (b) Love, C. J.; McQuillin, F. J. *J. Chem. Soc., Perkin Trans. 1* **1973**, 2509−2512. (c) Fujitsu, H.; Shirahama, S.; Matsumura, E.; Takeshita, K.; Mochida, I. *J. Org. Chem.* **1981**, *46*, 2287−2290.

(3) Hydrogenation of other terminal epoxides: (a) Fujitsu, H.; Matsumura, E.; Shirahama, S.; Takeshita, K.; Mochida, I. *J. Chem. Soc., Perkin Trans. 1* **1982**, 855−859. (b) Ricci, M.; Slama, A. *J. Mol. Catal.* **1994**, *89*, L1−L4. (c) Ito, M.; Hirakawa, M.; Osaku, A.; Ikariya, T. *Organometallics* **2003**, *22*, 4190−4192.

(4) Olah, G. A.; Szilagyi, P. J. *J. Org. Chem.* **1971**, *36*, 1121−1126.

(5) (a) Dahanukar, V. H.; Zavialov, L. A. *Curr. Opin. Drug Discovery Dev.* **2002**, *5*, 918−927. (b) Cossy, J.; Pardo, D. G. *Targets Heterocycl. Syst.* **2002**, *6*, 1−26.

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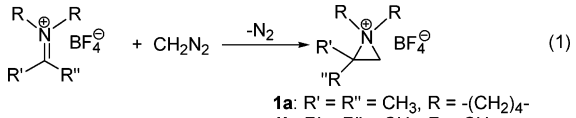
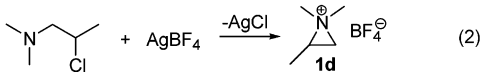
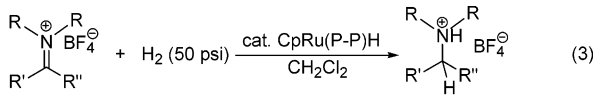
tion to piperazinium cations,[14] most can be isolated after their preparation by (1) the reaction of diazomethane with iminium cations, (2) the treatment of β-haloethylamines with silver salts, or (3) the quaternization of aziridines.[15] We prepared the cations **1a**−**c** according to eq 1, and **1d** according to eq 2.

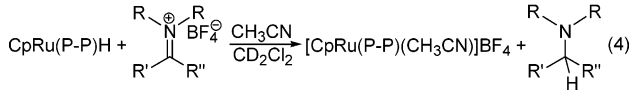


1a: R' = R'' = CH_3, R = $-(CH_2)_4-$
1b: R' = R'' = CH_3, R = CH_3
1c: R' = Ph, R'' = H, R = $-(CH_2)_4-$

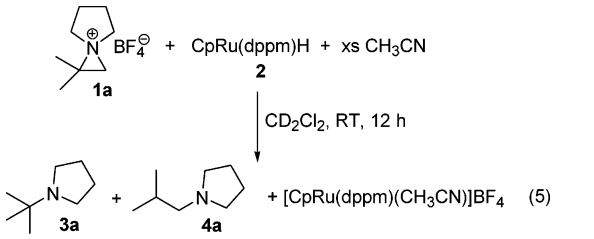


Stoichiometric Hydride Transfer from Ruthenium Hydrides to Aziridinium Cations. While investigating the ionic hydrogenation of iminium cations according to eq 3, catalyzed by CpRu(P−P)H (where P−P is a chelating diphosphine),[16] we learned that the efficiency and enantioselectivity of the catalyst could be inferred from the rate constant and the enantioselectivity of the stoichiometric hydride transfer reaction in eq 4.

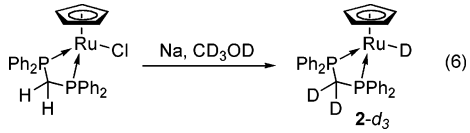




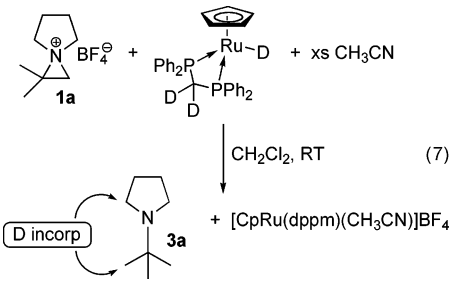
We therefore examined the reaction of the aziridinium cation **1a** with CpRu(dppm)H (**2**) under conditions similar to those in eq 4, i.e., in CD_2Cl_2 in the presence of the coordinating ligand CH_3CN. The amine products **3a**[17] and **4a**[18] were formed smoothly in a ratio of 70:1 (eq 5). The regiochemical preference (attack on the less substituted carbon) is the same as that reported for attack on alkyl-substituted aziridinium cations by other nucleophiles, i.e., amines,[6k,o−q] PhS^-,[6o] and CN^-.[9d,19]



We attempted to prepare CpRu(dppm)D, in an effort to confirm the site of hydride transfer in eq 5. However, treatment of CpRu(dppm)Cl with $NaOCD_3/CD_3OD$ resulted in deuteration of the methylene of the diphosphine as well as the hydride ligand (eq 6), yielding **2**-d_3. Presumably the methylene is easily deprotonated because the resulting carbanion is stabilized by two phosphorus atoms.[20]



Reaction of **1a** with **2**-d_3 (eq 7) led to deuterium incorporation into the *tert*-butyl group of the amine **3a**, confirming that the less substituted carbon of the aziridinium ring had received the transferred D^-/H^-. There was also incorporation into the α position of the pyrrolidinium ring, reflecting the acidity of that C−H bond[20] and the basicity of the D^- ligand.



The reaction of the *N*,*N*-dimethyl aziridinium cation **1b** with the hydride **2** (eq 8) was much faster than that of **1a**. The same preference for attack on the less-substituted carbon was observed with **1b**, although the

(6) (a) Dieter, R. K.; Deo, N.; Lagu, B.; Dieter, J. W. *J. Org. Chem.* **1992**, *57*, 1663−1671. (b) Miao, G.; Rossiter, B. E. *J. Org. Chem.* **1995**, *60*, 8424−8427. (c) O'Brien, P.; Poumellec, P. *Tetrahedron Lett.* **1996**, *37*, 5619−5622. (d) Saravanan, P.; Singh, V. K. *Tetrahedron Lett.* **1998**, *39*, 167−170. (e) de Souse, S. E.; O'Brien, P.; Poumellec, P. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1483−1492. (f) Anderson, S. R.; Ayers, J. T.; DeVries, K. M.; Ito, F.; Mendenhall, D.; Vanderplas, B. C. *Tetrahedron: Asymmetry* **1999**, *10*, 2655−2663. (g) Colman, B.; de Sousa, S. E.; O'Brien, P.; Towers, T. D.; Watson, W. *Tetrahedron: Asymmetry* **1999**, *10*, 4175−4182. (h) Chuang, T.-H.; Sharpless, K. B. *Org. Lett.* **1999**, *1*, 1435−1437. (i) Chuang, T.-H.; Sharpless, K. B. *Org. Lett.* **2000**, *2*, 3555−3557. (j) Curthbertson, E.; O'Brien, P.; Towers, T. D. *Synthesis* **2001**, 693−695. (k) O'Brien, P.; Towers, T. D. *J. Org. Chem.* **2002**, *67*, 304−307. (l) Couturier, M.; Tucker, J. L.; Andresen, B. M.; DeVries, K. M.; Vanderplas, B. C.; Ito, F. *Tetrahedron: Asymmetry* **2003**, *14*, 3517−3523. (m) Piotrowska, D. G.; Wróblewski, A. E. *Tetrahedron* **2003**, *59*, 8405−8410. (n) Couty, F.; Evano, G.; Prim, D. *Tetrahedron Lett.* **2005**, *46*, 2253−2257. (o) Richardson, P. F.; Nelson, L. T. J.; Sharpless, K. B. *Tetrahedron Lett.* **1995**, *36*, 9241−9244. (p) Liu, Q.; Marchington, A. P.; Boden, N.; Rayner, C. M. *J. Chem. Soc., Perkin Trans. 1* **1997**, 511−525. (q) McKay, C.; Wilson, R. J.; Rayner, C. M. *Chem. Commun.* **2004**, 1080−1081. (r) Carter, C.; Fletcher, S.; Nelson, A. *Tetrahedron: Asymmetry* **2003**, *14*, 1995−2004. (s) Katagiri, T.; Takahashi, M.; Fujiwara, Y.; Ihara, H.; Uneyama, K. *J. Org. Chem.* **1999**, *64*, 7323−7329.

(7) Chuang, T.-H.; Sharpless, K. B. *Helv. Chim. Acta* **2000**, *83*, 1734−1743.

(8) Periasamy, M.; Seenivasaperumal, M.; Rao, V. D. *Tetrahedron: Asymmetry* **2004**, *15*, 3847−3852.

(9) (a) Bottini, A. T.; Dowden, B. F.; Sousa, L. *J. Am. Chem. Soc.* **1965**, *87*, 3249−3250. (b) Somekh, L.; Shanzer, A. *J. Am. Chem. Soc.* **1982**, *104*, 5836−5837. (c) Gmeiner, P.; Junge, D.; Kärtner, A. *J. Org. Chem.* **1994**, *59*, 6766−6776. (d) Weber, K.; Kuklinski, S.; Gmeiner, P. *Org. Lett.* **2000**, *2*, 647−649. (e) Nagle, A. S.; Salvatore, R. N.; Chong, B.-D.; Jung, K. W. *Tetrahedron Lett.* **2000**, *41*, 3011−3014. (f) Sekar, G.; Nishiyama, H. *Chem. Commun.* **2001**, 1314−1315. (g) Back, T. G.; Parvez, M.; Zhai, H. *J. Org. Chem.* **2003**, *68*, 9389−9393.

(10) Abe, H.; Aoyagi, S.; Kibayashi, C. *J. Am. Chem. Soc.* **2005**, *127*, 1473−1480.

(11) Verhelst, S. H. L.; Martinez, B. P.; Timmer, M. S. M.; Lodder, G.; van der Marel, G. A.; Overkleeft, H. S.; van Boom, J. H. *J. Org. Chem.* **2003**, *68*, 9598−9603.

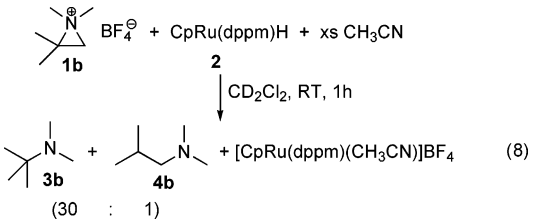
(12) (a) Overman, L. E.; Sharp, M. J. *J. Org. Chem.* **1992**, *57*, 1035−1038. (b) Graham, M. A.; Wadsworth, A. H.; Thornton-Pett, M.; Carrozzini, B.; Cascarano, G. L.; Rayner, C. M. *Tetrahedron Lett.* **2001**, *42*, 2865−2868. (c) Andrews, D. R.; Dahanukar, V. H.; Eckert, J. M.; Gala, D.; Lucas, B. S.; Schumacher, D. P.; Zavialov, I. A. *Tetrahedron Lett.* **2002**, *43*, 6121−6125.

(13) Hembre, R. T.; McQueen, J. S.; Day, V. W. *J. Am. Chem. Soc.* **1996**, *118*, 798−803.

(14) Leonard, N. J.; Klainer, J. A. *J. Heterocycl. Chem.* **1971**, *8*, 215−219.

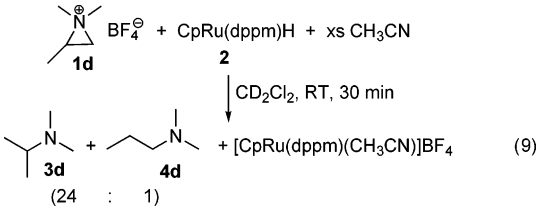
(15) Crist, D. R.; Leonard, N. J. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 962−974.

selectivity was less than in eq 5: the amines **3b**[21] and **4b**[18] were formed in a 30:1 ratio in eq 8.



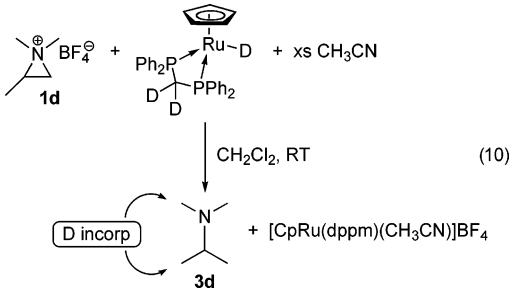
(8)

With the monomethyl aziridinium cation **1d** hydride transfer from **2** was even faster (eq 9). Attack on the less-substituted carbon still predominated, although the selectivity decreased further: the amines **3d**[22] and **4d**[18] were formed in a ratio of 24:1.



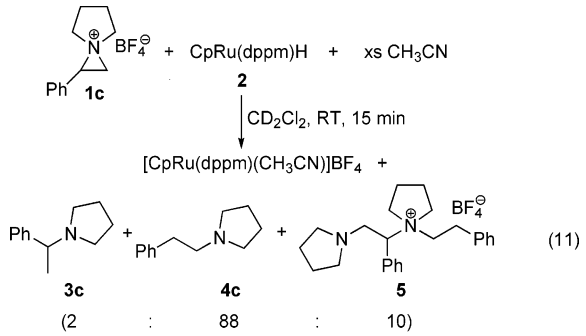
(9)

Treatment of **1d** with **2**-d_3 (eq 10) led to deuterium incorporation into the isopropyl group of the amine **3d**, confirming that the less substituted carbon of the aziridinium ring had received the transferred D^-/H^-. There was also, by analogy with the pyrrolidinium result in eq 7, some incorporation into the methyl substituents of **3d**.

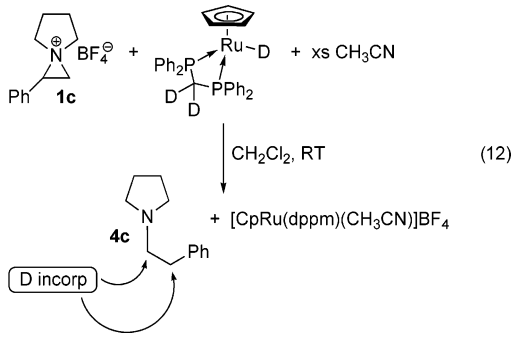


(10)

Reaction of the aryl-substituted aziridinium cation **1c** with the hydride **2** was also fast, but the principal product, **4c**, arose from transfer to the *more substituted* carbon (eq 11): the same regiochemistry generally observed for attack by nucleophiles on aryl-substituted aziridinium cations.[6a–n,7,12c] However, treatment of **1c** with **2**-d_3 led to deuterium incorporation into the α as well as the β carbon of the phenethyl substituent in the amine **4c** (eq 12)!

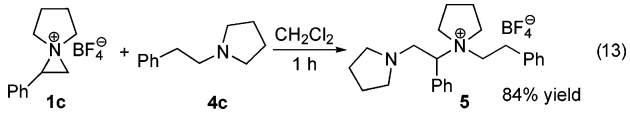


(11)



(12)

The ammonium salt **5** must arise from the opening of the aziridinium cation **1c** by the product amine **4c** (eq 13). An authentic sample of **5** can be prepared from equimolar amounts of **1c** and **4c**. In similar experiments there is no reaction within 1 h between **1c** and the more hindered product amine **3c**. In eq 11 the amines **3c**[23] and **4c**[24] and the ammonium salt **5** were formed in a ratio of 2:88:10.



(13)

When the reaction of **2** with **1c** was examined at low temperature (−64 °C) with concentrations of **1c** high enough to keep [**1c**] constant despite the operation of eq 13, the disappearance of **2** was straightforwardly second order (eq 14). (Details are given in the Supporting Information.) The value of k at −64 °C proved to be $1.30(2) \times 10^{-3}$ M^{-1} s^{-1}.

$$-\frac{d[\mathbf{2}]}{dt} = k[\mathbf{2}][\mathbf{1c}] \qquad (14)$$

Finally, the product ratios arising from reaction with **1c** were examined over the series of ruthenium hydrides in Table 1. The product distributions agree with the relative rates already observed for hydride transfer to iminium cations:[25] when transfer to **1c** is slower (as in entry 4), the amine **4c** can compete

(16) (a) Magee, M. P.; Norton, J. R. *J. Am. Chem. Soc.* **2001**, *123*, 1778−1779. (b) Guan, H.; Iimura, M.; Magee, M. P.; Norton, J. R.; Janak, K. E. *Organometallics* **2003**, *22*, 4084−4089. (c) Guan, H.; Iimura, M.; Magee, M. P.; Norton, J. R.; Zhu, G. *J. Am. Chem. Soc.* **2005**, *127*, 7805−7814.

(17) Bottini, A. T.; Roberts, J. D. *J. Am. Chem. Soc.* **1958**, *80*, 5203−5208.

(18) Taniguchi, Y.; Horie, S.; Takaki, K.; Fujiwara, Y. *J. Organomet. Chem.* **1995**, *504*, 137−141.

(19) Unimolecular ring opening of **1a** (in the fashion shown for **1c** in Scheme 2) would give predominantly the tertiary carbocation and lead (after hydride transfer) to the formation of **4a**.

(20) Stabilization of carbanions by adjoining N or P atoms is well known. For examples see: Reutov, O. A.; Beletskaya, I. P.; Butin, K. P. *CH-Acids*; Pergamon: New York, 1978; pp 69−71; translation editor, T. R. Crompton.

(21) Bushweller, C. H.; O'Neil, J. W.; Bilofsky, H. S. *Tetrahedron* **1971**, *27*, 5761−5766.

(22) Brown, J. H.; Bushweller, C. H. *J. Am. Chem. Soc.* **1992**, *114*, 8153−8158.

(23) Lee, N. E.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 5985−5986.

(24) Katritzky, A. R.; Hughes, C. V.; Rachwal, S. *J. Heterocycl. Chem.* **1989**, *26*, 1579−1588.

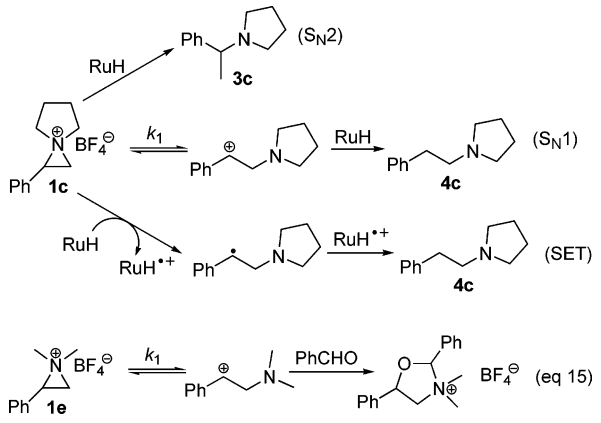
(25) For the ionic hydrogenation of iminium cations catalyzed by series of ruthenium hydrides, the relative activities are in the order **2** > **6** > **7** > **8**.[16c]

Table 1. Product Ratios for Stoichiometric Hydride Transfers from Various LRu(P−P)H to the Aziridinium Cation 1c

entry	LRu(P−P)H	**3c**:**4c**:**5**[a]
1	CpRu(dppm)H (**2**)	2:88:10
2	CpRu(dppe)H (**6**)	3:75:22
3	(CpMe)Ru(dppe)H (**7**)	2:73:25
4	Cp*Ru(dppe)H (**8**)	3:13:84

[a] Determined by the integration of ^{1}H NMR.

Scheme 2



efficiently with Cp*Ru(dppe)H (**8**) for nucleophilic attack on **1c** and ring opening, and the dominant product becomes **5**.

Electron Transfer Reaction between Cp*Ru(dppf)H and Aziridinium Cation 1c. The preference for attack at the more substituted carbon in eq 11 requires discussion. The regioselectivity can be explained as the result of an S_N1 process: unimolecular ring opening by the aziridinium **1c** forms the more stable carbocation, and subsequent H^- transfer gives **4c** (Scheme 2). However, as the rate law in eq 14 shows, eq 11 is second order and occurs too rapidly ($t_{1/2}$ < 98 min at −64 °C) for k_1 to be rate determining. From experiments in which the carbocation from **1e** is trapped with excess benzaldehyde (eq 15)[26] we know that k_1 for **1e** is $<10^{-4}$ s^{-1} at room temperature,[27] and we observe little reaction (<10% at room temperature after 2 days) when **1c** is treated with excess benzaldehyde.

It is *possible* that the H^- transfer in eq 11 *may* occur through a single-electron-transfer (SET) mechanism: a *two-step* H^- transfer, with electron transfer followed by $H^•$ transfer.[28] Electrochemistry studies have shown that aryl aziridinium salts are more easily reduced than alkyl aziridinium salts by 0.6−0.9 V.[29]

In an attempt to observe electron transfer and $H^•$ transfer separately, we treated the aziridinium cation

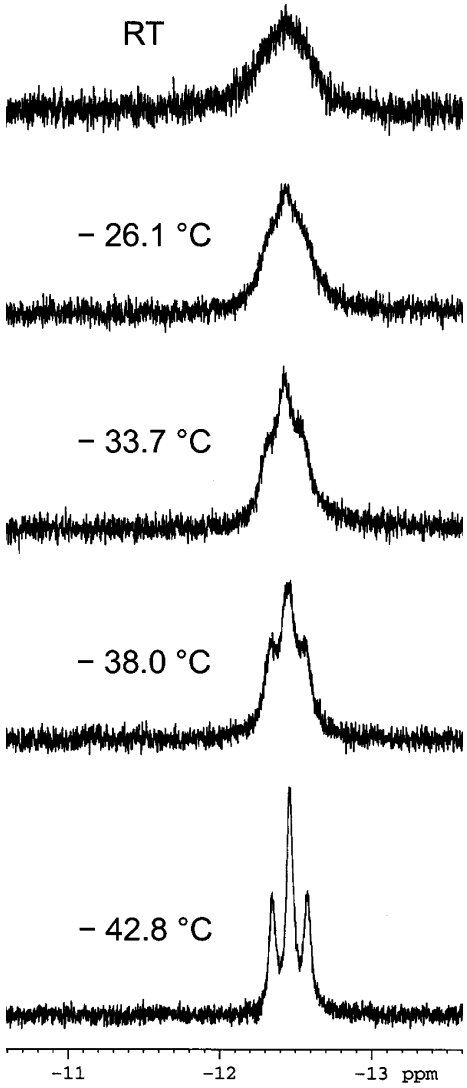
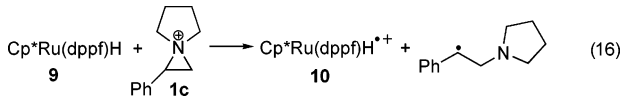


Figure 1. ^{1}H NMR hydride resonance from eq 16 as a function of temperature.

1c at room temperature with Cp*Ru(dppf)H (**9**) (known to undergo facile one-electron oxidation[13]). Most of the hydride remained unchanged, but there was clear evidence for the electron transfer in eq 16.[30] The hydride ^{1}H NMR resonance of **9** broadened a great deal, while its Cp* and ferrocenyl resonances broadened significantly. The line width, as illustrated for the hydride resonance in Figure 1, decreased at lower temperatures.



This differential broadening implies rapid e^- self-exchange (eq 17) between **9** and its radical cation $Cp^*Ru(dppf)H^{•+}$ (**10**) (which has been prepared by Hembre and characterized by near-infrared spectroscopy[13]). The temperature dependence of the broadening confirms the exchange and implies that this system is

(26) Keenan, T. R.; Leonard, N. J. *J. Am. Chem. Soc.* **1971**, *93*, 6567−6574.

(27) A value of 3.8×10^{-4} s^{-1} has been measured at 50 °C for the k_1 in eq 15,[26] which would suggest a $t_{1/2}$ > 1.9 h at room temperature for eq 11 if ring opening were the rate-determining step.

(28) Some evidence for an SET mechanism is offered by the observation of a small hump at δ −6.9 as we monitored the kinetics of reaction 11 at −64 °C. This signal is probably due to some $[CpRu(dppm)(H_2)]^+$ (Jia, G.; Morris, R. H. *Inorg. Chem.* **1990**, *29*, 581−582), the formation of which (from CpRu(dppm)H) would require the presence of some of the strongly acidic cation radical $CpRu(dppm)H^{+•}$.

(29) Crist, D. R.; Borsetti, A. P.; Kass, M. B. *J. Heterocycl. Chem.* **1981**, *18*, 991−995.

(30) Several years ago we reported similar ^{1}H NMR line broadening from rapid self-exchange between an azazirconacyclobutene and its radical cation: Harlan, C. J.; Hascall, T.; Fujita, E.; Norton, J. R. *J. Am. Chem. Soc.* **1999**, *121*, 7274−7275.

in the "large hyperfine" or "slow exchange" limit of the de Boer−MacLean equation for NMR line broadening due to e^- exchange.[30,31] A simplified form (eq 18) of that equation thus applies; the line width (T_{2ex}^{-1}) now depends only on the rate constant for e^- exchange (k_R) and the concentration of the radical cation **10**.

$$\underset{\mathbf{10}}{\text{Cp*Ru(dppf)H}^{\bullet+}} + \underset{\mathbf{9}}{\text{Cp*Ru(dppf)H}} \overset{k_R}{\rightleftharpoons} \underset{\mathbf{9}}{\text{Cp*Ru(dppf)H}} + \underset{\mathbf{10}}{\text{Cp*Ru(dppf)H}^{\bullet+}} \quad (17)$$

$$\Delta(T_{2ex}^{-1}) = k_R[\mathbf{10}] \quad (18)$$

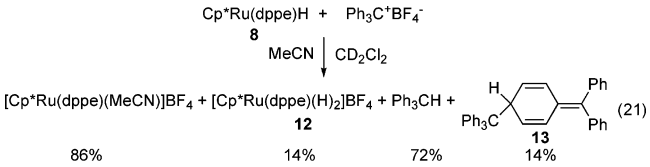
The persistence of the line broadening at room temperature implies that **10** is unable to transfer H•, presumably as the result of the steric congestion around its hydride ligand. Hydride radical cations such as **10** have been implicated in many reactions[13,33] but seldom isolated, although Lapinte has characterized the PF_6^- salt of an iron hydride radical cation, [Cp*Fe(dppe)H]-PF_6, by X-ray crystallography.[32] These radical cations are known for their kinetic acidity[33] and frequently protonate the neutral hydride from which they are formed. In the reaction of **1c** and **9** we observed (in the ^{1}H NMR) a small amount of the [Cp*Ru(dppf)$(H)_2$]BF_4 (**11**),[13] surely the result of the proton transfer reaction in eq 19. The formation of **11** offers indirect but persuasive evidence that the radical cation **10** has been formed.

$$\underset{\mathbf{10}}{\text{Cp*Ru(dppf)H}^{\bullet+}} + \underset{\mathbf{9}}{\text{Cp*Ru(dppf)H}} \longrightarrow \text{Cp*Ru(dppf)}^{\bullet} + \underset{\mathbf{11}}{\text{Cp*Ru(dppf)(H)}_2^{+}} \quad (19)$$

The addition of cobaltocene to the **9**/**1c** reaction mixture provided further evidence of the electron transfer in eq 17. The Cp_2Co reduced the radical cation **10** (eq 20) and, by suppressing the self-exchange in eq 18, restored the ^{1}H NMR spectrum of **9** to its original appearance.

$$\underset{\mathbf{10}}{\text{Cp*Ru(dppf)H}^{\bullet+}} + \text{Cp}_2\text{Co} \longrightarrow \underset{\mathbf{9}}{\text{Cp*Ru(dppf)H}} + \text{Cp}_2\text{Co}^{+} \quad (20)$$

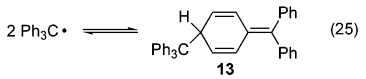
A related SET mechanism explains the formation of trityl radical as a byproduct of the reaction between trityl cation and the hydride **8** (eq 21). The dihydride cation **12**[34] is presumably formed by H^+ transfer to **8** (eq 23) from the radical cation Cp*Ru(dppe)H$^{\bullet+}$ formed by the initial electron transfer (eq 22).[35] Oxidation of the resulting Cp*Ru(dppe)$^{\bullet}$ by Cp*Ru(dppe)H$^{\bullet+}$ gives [Cp*Ru(dppe)(MeCN)]$^+$ (eq 24).[36] Gomberg's dimer **13**[37] is in equilibrium (eq 25) with the $Ph_3C^{\bullet}$ produced by the e^- transfer; subsequent H$^{\bullet}$ transfer (eq 26) gives Ph_3CH and [Cp*Ru(dppe)(MeCN)]$^+$.



$$\underset{\mathbf{8}}{\text{Cp*Ru(dppe)H}} + \text{Ph}_3\text{C}^{+} \longrightarrow \text{Cp*Ru(dppe)H}^{\bullet+} + \text{Ph}_3\text{C}^{\bullet} \quad (22)$$

$$\text{Cp*Ru(dppe)H}^{\bullet+} + \underset{\mathbf{8}}{\text{Cp*Ru(dppe)H}} \longrightarrow \text{Cp*Ru(dppe)}^{\bullet} + \underset{\mathbf{12}}{\text{[Cp*Ru(dppe)(H)}_2\text{]}^{+}} \quad (23)$$

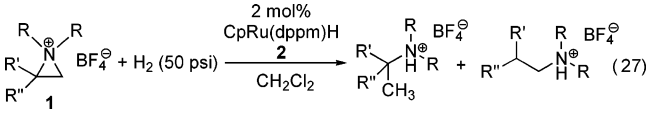
$$\text{Cp*Ru(dppe)}^{\bullet} + \text{Cp*Ru(dppe)H}^{\bullet+} \longrightarrow \text{[Cp*Ru(dppe)]}^{+} + \underset{\mathbf{8}}{\text{Cp*Ru(dppe)H}} \quad \xrightarrow{\text{MeCN}} \quad \text{[Cp*Ru(dppe)(MeCN)]}^{+} + \underset{\mathbf{8}}{\text{Cp*Ru(dppe)H}} \quad (24)$$



$$\text{Cp*Ru(dppe)H}^{\bullet+} + \text{Ph}_3\text{C}^{\bullet} + \text{MeCN} \rightarrow \text{[Cp*Ru(dppe)(MeCN)]}^{+} + \text{Ph}_3\text{CH} \quad (26)$$

It is *possible* that all the **1c**/RuH reactions in Table 1 occur through an SET mechanism, even though the subsequent H$^{\bullet}$ transfer step is too fast to prevent the identification of the radical intermediates.

Catalytic Ionic Hydrogenation of Aziridinium Cations. Given the established relationship between turnover in catalytic ionic hydrogenations and the rate of stoichiometric H^- transfers,[16] the success of the stoichiometric H^- transfers in eqs 5, 8, 9, and 11 and Table 1 suggested that the catalytic hydrogenation of aziridinium cations should be possible. We therefore treated various aziridinium cations with 50 psi H_2 in the presence of 2 mol % of ruthenium catalyst **2**. The results (eq 27) are given in Table 2.



As expected from the stoichiometric hydride transfer reactions (eqs 5, 8, 9, 11), alkyl-substituted aziridinium cations gave the more branched ammonium cations (entries 1−3), while the aryl-substituted aziridinium cation **1c** gave the less branched ammonium cation (entry 4). *To our knowledge this is the first report of the catalytic hydrogenation of aziridinium cations*. We believe, in light of our studies on the mechanism of the ionic hydrogenation of iminium cations,[16] that the aziridinium cations undergo hydrogenation by the mechanism in Scheme 3 (in which **1c** is shown as a representative substrate). H^- transfer from the hydride complex to the aziridinium cation (**1c** in this case) generates the amine (**4c** in this case) and a 16-electron ruthenium complex; coordination of H_2 (dihydrogen complexes are known to be kinetically acidic[38]) leads to protonation of the amine (**4c** here), giving the ammonium salt (**15c** here), and regeneration of the ruthenium hydride catalyst.

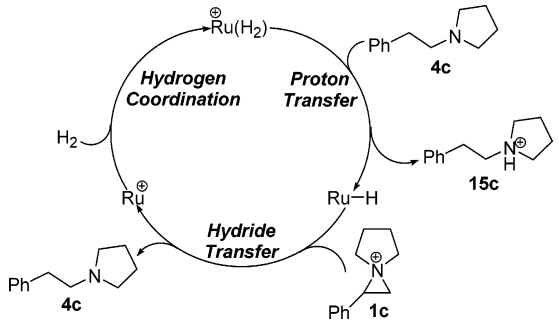
(31) de Boer, E.; MacLean, C. *J. Chem. Phys.* **1966**, *44*, 1334−1342.
(32) Hamon, P.; Toupet, L.; Hamon, J.-R.; Lapinte, C. *Organometallics* **1992**, *11*, 1429−1431.
(33) Ryan, O. B.; Tilset, M.; Parker, V. D. *J. Am. Chem. Soc.* **1990**, *112*, 2618−2626.
(34) Jia, G.; Ng, W. S.; Chu, H. S.; Wong, W.-T.; Yu, N.-T.; Williams, I. D. *Organometallics* **1999**, *18*, 3597−3602.
(35) The equivalent of eq 22 has been reported for Cp*Ru(dppf)H by: Hembre, R. T.; McQueen, J. S. *Angew. Chem., Int. Ed, Engl.* **1997**, *36*, 65−67.
(36) A case similar to eq 24 has been reported. See Scheme 1 in: Smith, K.; Rømming, C.; Tilset, M. *J. Am. Chem. Soc.* **1993**, *115*, 8681−8689.
(37) McBride, J. M. *Tetrahedron* **1974**, *30*, 2009−2022.
(38) (a) Jessop, P. G.; Morris, R. H. *Coord. Chem. Rev.* **1992**, *121*, 155−284. (b) Heinekey, D. M.; Oldham, W. J. *Chem. Rev.* **1993**, *93*, 913−926.

Table 2. Ionic Hydrogenation of Aziridinium Cations Catalyzed by CpRu(dppm)H (2)[a]

entry	aziridinium	time	hydrogenation products	regioselectivity [b]	yield [c]
1	**1a**	17 h	**14a** **15a**	(70 : 1)	85%
2	**1b**	20 h	**14b** **15b**	(30 : 1)	76%
3	**1d**	20 h	**14d** **15d**	(24 : 1)	77%
4	**1c**	1 h	**14c** **15c**	(1 : 50)	73%

[a] Reaction conditions: [**1**] = 0.1 mol/L, [**2**] = 0.002 mol/L, H_2 pressure 50 psi, in CH_2Cl_2, room temperature. [b] Determined by ^1H NMR integration of the crude product. [c] Isolated yield.

Scheme 3



In the catalytic hydrogenation of **1c** (entry 4, Table 2) we did not observe the formation of **5** (or its protonated dication). Presumably in the catalytic cycle the protonation of **4c** is much faster than the reaction of **4c** with the aziridinium cation **1c** (as in eq 13).

Experimental Section

General Procedures. All air-sensitive compounds were prepared and handled under a N_2/Ar atmosphere using standard Schlenk and inert-atmosphere box techniques. CH_2Cl_2 and Et_2O were deoxygenated and dried over two successive activated alumina columns under argon. Benzene was distilled from Na and benzophenone under a nitrogen atmosphere. CD_2Cl_2 was dried over CaH_2, degassed by three freeze−pump−thaw cycles, and then purified by vacuum transfer at room temperature. An ether solution of CH_2N_2 was prepared from Diazald using an Aldrich Diazald kit with Clear-Seal joints. **Caution:** CH_2N_2 is explosive when heated. It should be handled with care in a well-ventilated fume hood. CpRu(dppm)H (**2**),[39] CpRu(dppe)H (**6**),[39] (CpMe)Ru(dppe)H (**7**),[16c] Cp*Ru(dppe)H (**8**),[40] Cp*Ru(dppf)H (**9**),[13] 1-isopropylidenepyrrolidinium tetrafluoroborate,[41] *N*-methyl-*N*-(1-methylethylidene)-methanaminium tetrafluoroborate,[42] and 1-(2-phenylethyl)-pyrrolidine (**4c**)[43] were prepared as described in the literature.

1,1-Dimethyl-3-azoniaspiro[2.4]heptane Tetrafluoroborate (1a). Under a nitrogen atmosphere CH_2N_2 ether solution was added dropwise to a cold (0 °C) solution of 1-isopropylidenepyrrolidinium tetrafluoroborate (1.59 g, 8.0 mmol) in 80 mL of CH_3CN. When a yellow color persisted in the solution, the addition was stopped. The reaction mixture was stirred at 0 °C for another 15 min before a few drops of acetic acid were added to remove the excess CH_2N_2. The volume of the solution was reduced to 30 mL, then 170 mL of Et_2O was carefully poured down the sides of the flask. The mixture was kept at −30 °C for 2 days. The resulting colorless crystals were filtered, washed with Et_2O, and dried under vacuum to give a white solid (1.41 g, 83% yield). ^1H NMR (400 MHz, CD_3CN): δ 1.58 (s, CH_3, 6H), 2.05−2.20 (m, NCH$_2$CH_2, 4H), 2.92 (s, NCH_2C(CH$_3$)$_2$, 2H), 3.07−3.15 (m, NCH_2 CH$_2$, 2H), 3.48−3.57 (m, NCH_2CH$_2$, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, CD_3CN): δ 20.81, 24.85, 54.03, 54.27, 57.32. Anal. Calcd for $C_8H_{16}NBF_4$: C, 45.11; H, 7.57; N, 6.58. Found: C, 45.21; H, 7.63; N, 6.53.

1,1,2,2-Tetramethylaziridinium Tetrafluoroborate (1b). The cation has been previously reported with perchlorate as the counterion.[44] Its tetrafluoroborate salt was prepared from *N*-methyl-*N*-(1-methylethylidene)methanaminium tetrafluoroborate in 46% yield by a procedure similar to that used for **1a**. ^1H NMR (300 MHz, CD_2Cl_2): δ 1.72 (s, NC(CH_3)$_2$, 6H), 3.01 (s, NCH_2, 2H), 3.11 (s, N(CH_3)$_2$, 6H). $^{13}C\{^1H\}$ NMR (75 MHz, CD_2Cl_2): δ 20.04, 46.00, 52.87, 56.02. Anal. Calcd for $C_6H_{14}NBF_4$: C, 38.54; H, 7.55; N, 7.49. Found: C, 38.56; H, 7.57; N, 7.50.

1-Phenyl-3-azoniaspiro[2.4]heptane Tetrafluoroborate (1c). This compound has been previously prepared;[45] however, no NMR data were reported. ^1H NMR (400 MHz, CD_2Cl_2): δ 1.89−2.01 (m, NCH$_2$CH_2, 1H), 2.13−2.25 (m, NCH$_2$CH_2, 2H), 2.27−2.36 (m, NCH$_2$CH_2, 1H), 2.71−2.78 (m, NCH_2, 1H), 3.09−3.18 (m, NCH_2, 1H), 3.67−2.81 (m, NCH_2, 4H), 4.56 (t, NC*H*Ph, J_{H-H} = 8.1 Hz, 1H), 7.45−7.61 (m, *Ar*, 5H). $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$): δ 23.89, 24.29, 41.74, 53.56, 55.13, 61.74, 125.99, 129.69, 130.29, 131.43. Anal. Calcd for $C_{12}H_{16}NBF_4$: C, 55.21; H, 6.18; N, 5.37. Found: C, 54.89; H, 6.27; N, 5.29.

1,1,2-Trimethylaziridinium Tetrafluoroborate (1d). The cation has been previously reported with perchlorate as the counterion.[46] Its tetrafluoroborate salt was prepared as follows: to a cold (5−10 °C) solution of 1-(dimethylamino)-2-chloropropane (2.43 g, 20 mmol) in 60 mL of benzene was slowly added a suspension of $AgBF_4$ (3.9 g, 20 mmol) in 5 mL of benzene. The mixture was warmed to room temperature and stirred overnight. The brown solid was filtered and washed with acetone several times. The combined acetone filtrate was pumped to dryness, and the residue was recrystallized from acetone/Et_2O to afford a white solid (2.47 g, 71% yield). ^1H NMR (400 MHz, CD_3COCD_3): δ 1.67 (d, NCHCH_3, J_{H-H} = 6.2 Hz, 3H), 2.99−3.02 (m, NCH_2, 1H), 3.14 (s, NCH_3, 3H), 3.21 (s, NCH_3, 3H), 3.20−3.24 (m, NCH_2, 1H), 3.39−3.45 (m, NC*H*CH$_3$, 1H). $^{13}C\{^1H\}$ NMR (100 MHz, CD_3COCD_3): δ 11.65, 42.81, 46.91, 49.68, 50.84. Anal. Calcd for $C_5H_{12}NBF_4$: C, 34.72; H, 6.99; N, 8.10. Found: C, 34.99; H, 7.03; N, 8.01.

Stoichiometric Hydride Transfer from Ruthenium Hydrides to Aziridinium Cations. In a typical experiment, a ruthenium hydride (20 μmol), CH_3CN (2.1 μL, 40 μmol), and CD_2Cl_2 (ca. 0.8 mL) were mixed in a vial under an inert atmosphere. The aziridinium cation **1** (20 μmol) was added to the mixture in one portion. The resulting solution was transferred to a J. Young NMR tube. The reaction was monitored by ^1H NMR, and the product ratio was measured by ^1H NMR integration.

1-(2-Phenylethyl)-1-(1-phenyl-2-pyrrolidinylethyl)pyrrolidinium Tetrafluoroborate (5). 1-(2-Phenylethyl)pyrro-

(39) Bruce, M. I.; Humphrey, M. G.; Swincer, A. G.; Wallis, R. C. *Aust. J. Chem.* **1984**, *37*, 1747−1755.
(40) Lee, D.-H. *J. Korean Chem. Soc.* **1992**, *36*, 248−254.
(41) Leonard, N. J.; Paukstelis, J. V. *J. Org. Chem.* **1963**, *28*, 3021−3024.
(42) Bao, J.; Park, S.-H. K.; Geib, S. J.; Cooper, N. J. *Organometallics* **2003**, *22*, 3309−3312.
(43) Shapiro, S. L.; Soloway, H.; Freedman, L. *J. Am. Chem. Soc.* **1958**, *80*, 6060−6064.
(44) Leonard, N. J.; Paukstelis, J. V.; Brady, L. E. *J. Org. Chem.* **1964**, *29*, 3383−3386.
(45) Kass, M. B.; Borsetti, A. P.; Crist, D. R. *J. Am. Chem. Soc.* **1973**, *95*, 959−961.
(46) Tyssee, D. A.; Baizer, M. M. *J. Electrochem. Soc.* **1971**, *118*, 1420−1425.

lidine (39 μL, 0.21 mmol) was added dropwise to the aziridinium cation **1c** (52 mg, 0.20 mmol) in 10 mL of CH_2Cl_2, and the resulting solution stirred at room temperature for 1 h. Et_2O was added until a white precipitate formed. After filtration the solid was washed with Et_2O (3 × 20 mL) and dried under vacuum to afford the ammonium product **5** (73 mg, 84% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.72−1.78 (m, NCH_2CH_2, 4H), 1.95−2.18 (m, $N^+CH_2CH_2$, 4H), 2.53−2.57 (m, NCH_2CH_2, 2H), 2.63−2.70 (m, NCH_2CH_2, 2H), 2.99−3.04 (m, NCH_2CHPh, 1H), 3.08−3.13 (m, NCH_2CHPh, 1H), 3.14−3.21 (m, $N^+CH_2CH_2Ph$, 1H), 3.27−3.34 (m, $N^+CH_2CH_2Ph$, 1H), 3.52−3.71 (m, $N^+CH_2CH_2$, 4H), 3.73−3.81 (m, $N^+CH_2CH_2Ph$, 1H), 3.98−4.05 (m, $N^+CH_2CH_2Ph$, 1H), 4.82−4.85 (m, N^+CHPh, 1H), 7.19−7.53 (m, *Ar*, 10H). ^{13}C{^{1}H} NMR (100 MHz, CD_2Cl_2): δ 22.32, 22.98, 24.02, 30.11, 54.62, 57.51, 60.65, 61.02, 61.36, 73.34, 127.65, 128.84, 129.17, 129.71, 130.56, 130.89, 132.23, 135.16. Anal. Calcd for $C_{24}H_{33}N_2BF_4$: C, 66.06; H, 7.62; N, 6.42. Found: C, 65.72; H, 7.55; N, 6.43.

Deuterium Transfer and Exchange Experiments (eqs 7, 10, 12). Typically **2**-d_3 (11.1 mg, 20 μmol), CH_3CN (2.1 μL, 40 μmol), and CH_2Cl_2 or CD_2Cl_2 (ca. 0.8 mL) were mixed in a vial under an inert atmosphere. The aziridinium salt (20 μmol) was added in one portion, and the resulting solution was transferred to a J. Young tube. The reaction was monitored by either ^{1}H or ^{2}D NMR.

Kinetics of Hydride Transfer from CpRu(dppm)H (2) to the Aziridinium Cation 1c. Under an inert atmosphere, the aziridinium salt **1c** (24.2 mg, 92.7 μmol) was dissolved in 800 μL of CD_2Cl_2 and transferred to a screw-cap NMR tube with a Teflon-coated septum insert; 1.5 μL of a hexamethylcyclotrisiloxane standard (0.0557 M in benzene) was added and the NMR tube frozen in liquid nitrogen while its contents were under an atmosphere of nitrogen connected to a bubbler. Separately a stock solution was prepared from CpRu(dppm)H (22.1 mg, 40.0 μmol) and CH_3CN (6 μL, 115 μmol) in 1000 μL of CD_2Cl_2; 200 μL of this solution was added to the NMR tube with a microliter syringe. The tube was then thawed at −70 °C (with its contents still under N_2 connected to the bubbler) and its contents were mixed; then it was inserted into an NMR probe precooled to −64 °C. The disappearance of the hydride signal was monitored via ^{1}H NMR (by comparison to the height of the hexamethylcyclotrisiloxane standard) for at least three half-lives. The NMR probe temperature was calibrated with a Wilmad chemical shift thermometer (99.97% methanol + 0.03% HCl).[47] This experiment was repeated with varying amounts of **1c** (129.5, 154.0, and 191.5 μmol).

Low-Temperature NMR of the Reaction of Cp*Ru(dppf)H (9) with the Aziridinium Salt 1c. Under an inert atmosphere, Cp*Ru(dppf)H (15.8 mg, 20.0 μmol) and aziridinium salt **1c** (5.2 mg, 20.0 μmol) were dissolved in 800 μL of CD_2Cl_2 and transferred to a J. Young NMR tube. The ^{1}H NMR spectrum was recorded at room temperature and at lower temperatures (−26.1, −33.7, −38.0, and −42.8 °C). The NMR probe temperature was calibrated with a Wilmad chemical shift thermometer (99.97% methanol + 0.03% HCl).[47]

Reaction of Cp*Ru(dppe)H (8) with $[Ph_3C]BF_4$. Under a nitrogen atmosphere, the hydride **8** (12.7 mg, 20 μmol) and $[Ph_3C]BF_4$ (6.6 mg, 20 μmol) were placed in a vial, followed by the addition of CD_2Cl_2 (ca. 0.8 mL) containing CH_3CN (4.2 μL, 80 μmol). The resulting solution was transferred to a J. Young NMR tube. The reaction was complete within 10 min at room temperature, and the product ratios were measured by ^{1}H NMR integration.

Hydrogenation of Aziridinium Cations by Ruthenium Hydrides. A solid aziridinium cation (1.0 mmol) and the ruthenium hydride catalyst (0.02 mmol) were added to a Fischer−Porter bottle under a nitrogen atmosphere. The bottle was flushed several times with hydrogen gas. Then 10 mL of CH_2Cl_2 was added by syringe under a flow of hydrogen, and the resulting solution stirred under 50 psi of hydrogen. When the hydrogenation of aziridinium cation was complete (monitored by ^{1}H NMR), the reaction mixture was transferred to a Schlenk flask and the solvent removed under vacuum. The product ratio was measured by ^{1}H NMR integration of the crude product. The residue was washed with Et_2O several times and dried under vacuum.

1-(*tert*-Butyl)pyrrolidinium Tetrafluoroborate (14a): white solid (183 mg, 85% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.42 (s, CH_3, 9H), 2.05−2.11 (m, NCH_2CH_2, 2H), 2.12−2.22 (m, NCH_2CH_2, 2H), 3.05−3.17 (m, NCH_2CH_2, 2H), 3.54−3.62 (m, NCH_2CH_2, 2H), 7.66 (br, N*H*, 1H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 23.59, 24.84, 49.03, 61.96. Anal. Calcd for $C_8H_{18}NBF_4$: C, 44.68; H, 8.44; N, 6.51. Found: C, 44.92; H, 8.38; N, 6.33.

***N*,*N*-Dimethyl-*tert*-butylammonium Tetrafluoroborate (14b):** white solid (143 mg, 76% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.46 (s, $NC(CH_3)_3$, 9H), 2.87 (d, $N(CH_3)_2$, J_{H-H} = 5.2 Hz, 6H), 7.32 (br, N*H*, 1H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 24.57, 38.99, 63.83. Anal. Calcd for $C_6H_{16}NBF_4$: C, 38.13; H, 8.53; N, 7.41. Found: C, 38.28; H, 8.50; N, 7.25.

***N*,*N*-Dimethylisopropylammonium Tetrafluoroborate (14d):** white solid (135 mg, 77% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.38 (d, $NCH(CH_3)_2$, J_{H-H} = 6.7 Hz, 6H), 2.87 (d, $N(CH_3)_2$, J_{H-H} = 5.2 Hz, 6H), 3.60 (dsept, $NCH(CH_3)_2$, J_{H-H} = 3.0 Hz, 6.7 Hz, 1H), 7.38 (br, N*H*, 1H). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 16.82, 39.99, 59.18. Anal. Calcd for $C_5H_{14}NBF_4$: C, 34.32; H, 8.06; N, 8.00. Found: C, 34.37; H, 8.29; N, 7.86.

1-(2-Phenylethyl)pyrrolidinium Tetrafluoroborate (15c): white solid (194 mg, 73% yeild). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.10−2.22 (m, NCH_2CH_2, 4H), 2.95−3.05 (m, NCH_2CH_2, 2H), 3.06−3.13 (m, $PhCH_2$, 2H), 3.36−3.42 (m, NCH_2CH_2Ph, 2H), 3.81−3.88 (m, NCH_2CH_2, 2H), 7.21−7.31 (m, *Ar*, 5H), 7.82 (br, N*H*, 1H). ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$): δ 22.93, 32.33, 55.33, 57.34, 127.46, 128.73, 129.04, 135.42. Anal. Calcd for $C_{12}H_{18}NBF_4$: C, 54.78; H, 6.90; N, 5.32. Found: C, 54.92; H, 6.93; N, 5.34.

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Note Added after ASAP Publication. In the version of this paper published on the Web on Nov. 12, 2005, eq 26 was incorrect. The version of this equation that now appears is the correct one.

Supporting Information Available: Rate constants and plot for pseudo-first-order kinetics of **2** with **1c** at −64 °C. This material is available free of charge via the Internet at http://pubs.acs.org.

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(47) (a) van Geet, A. L. *Anal. Chem.* **1970**, *42*, 679−680. (b) Raidford, D. S.; Fisk, C. L.; Becker, E. D. *Anal. Chem.* **1979**, *51*, 2050−2051.