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Novel Reactivity of Ruthenium Alkylidenes in Protic Solvents: Degenerate Alkylidene Proton Exchange

David M. Lynn[†] **and Robert H. Grubbs***

Contribution from the Arnold and Mabel Beckman Laboratories of Chemical Synthesis, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91125

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Abstract: A novel organometallic transformation is reported in which the alkylidene protons of water-soluble ruthenium alkylidenes **1** and **2** undergo nondestructive, degenerate exchange with solvent-derived deuterons in perdeuterated protic solvents such as D_2O and CD_3OD. Deuterated alkylidene complex (**1-D**) was isolated from a solution of alkylidene **1** in D_2O, and the new alkylidene was fully characterized by ^1H, ^2H, ^{13}C, and ^{31}P NMR spectroscopy and fast-atom bombardment mass spectroscopy (FAB-MS). The rate of alkylidene proton exchange for this transformation was found to correlate with the bulk dielectric constant of the solvent or solvent mixtures employed. The data support a mechanism for proton exchange involving the dissociation of a chloride ion from the ruthenium metal center. The rate of alkylidene H/D exchange for alkylidene **2** was faster than the rate of exchange for alkylidene **1**, demonstrating that relative rates of exchange are influenced by the electron densities at the metal centers of these complexes. Several additional ruthenium alkylidenes were found to undergo analogous alkylidene H/D exchange reactions, including parent alkylidene $(Cy_3P)_2Cl_2Ru{=}CHPh$ (**3**) in CD_2Cl_2/CD_3OD mixtures. These data suggest that this novel reactivity may be general for an entire class of ruthenium alkylidenes provided that protic species are available in solution and that the dielectric constant of the reaction medium is sufficiently high to ionize the halide ligands.

Introduction

We recently described the synthesis of ruthenium alkylidenes **1** and **2** bearing charged phosphine ligands.[1] These alkylidenes are soluble and stable in protic, high-dielectric solvents such as methanol and water and initiate ring-opening metathesis polymerization (ROMP)[1a,b] and ring-closing metathesis (RCM)[1c] in these solvents. During the synthesis and isolation of these new alkylidenes, we discovered an additional and unexpected mode of reactivity. Specifically, the alkylidene protons of complexes **1** and **2** were found to undergo nondestructive exchange with solvent deuterons when they were dissolved in perdeuterated protic solvents such as D_2O and CD_3OD (eq 1). The protonation of nucleophilic early-transition metal alkylidene complexes is well-known,[2] and the protonation of ruthenium dihaloalkylidenes and rhenium alkylidene complexes has been reported.[3] However, in these cases protonation generally results in alkylidene decomposition or a well-defined, irreversible transformation to a metal−alkyl (nonalkylidene) intermediate or product. The reversible, nondestructive solvent/alkylidene proton exchange reaction represented in eq 1 appears to be

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[†] Current address: Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139.

(1) (a) Lynn, D. M.; Mohr, B. M.; Grubbs, R. H.; Henling, L. M.; Day, M. W. *J. Am. Chem. Soc.* **2000**, *122*, 6601. (b) Lynn, D. M.; Mohr, B.; Grubbs, R. H. *J. Am. Chem. Soc.* **1998**, *120*, 1627. (c) Kirkland, T. A.; Lynn, D. M.; Grubbs, R. H. *J. Org. Chem.* **1998**, *63*, 9904. (d) Mohr, B.; Lynn, D. M.; Grubbs, R. H. *Organometallics* **1996**, *15*, 4317.

(2) Schrock, R. R. *Acc. Chem. Res.* **1979**, *12*, 98.

(3) (a) Casey, C. P.; Vosejpka, P. C.; Askham, F. R. *J. Am. Chem. Soc.* **1990**, *112*, 3713. (b) Clark, G. R.; Hoskins, S. V.; Jones, T. C.; Roper, W. R. *J. Chem. Soc., Chem. Commun.* **1983**, 719. (c) Brothers, P. J.; Roper, W. R. *Chem. Rev.* **1988**, *88*, 1293.

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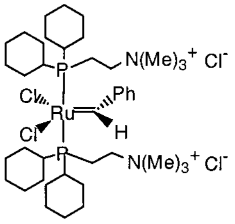

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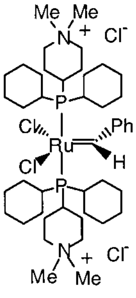

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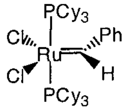

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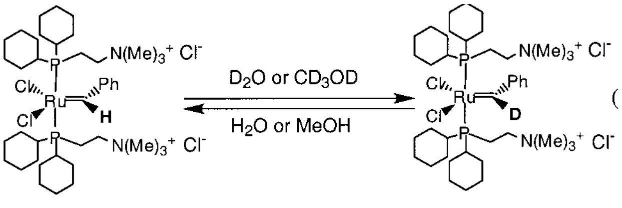
unique to ruthenium alkylidene[1] and vinylidene[4] complexes dissolved in protic, high-dielectric environments.



1 **1-D** (1)

The alkylidene H/D exchange behavior observed for these complexes in protic solvents is of fundamental interest in the context of understanding and developing new organometallic transformations. This novel activity could also bear practical consequences in view of the growing use of ruthenium alkylidenes in the fields of organic,[5] polymer,[6] and organometallic[7] chemistry. In addition to alkylidenes **1** and **2**, we have found that several other ruthenium alkylidenes undergo this exchange phenomenon, including parent alkylidene **3**[8] in CD_3OD/CD_2Cl_2 mixtures, suggesting that this novel activity may be general for an entire family of ruthenium alkylidenes. In addition to our observations with ruthenium alkylidenes, Saoud et al. recently identified an analogous example of proton−solvent exchange occurring with a new water-soluble ruthenium vinylidene complex.[4] Herein, we detail our investigations into the nature of this exchange reaction employing alkylidene **1**.

Results and Discussion

Characterization of Deuterated Alkylidene Complex 1-D. ^1H NMR spectroscopic analysis revealed that the alkylidene proton resonances of alkylidene **1** decayed over time when these complexes were dissolved in either D_2O or CD_3OD. All other characteristics of the ^1H and ^{31}P NMR spectra of these complexes remained unchanged, and no new resonances were observed even after the alkylidene resonances had completely disappeared. These data suggested that alkylidene **1** was not decomposing in solution, but was converted to deuterated alkylidene complex **1-D**, shown in eq 1. This alkylidene proton−deuteron exchange reaction was completely reversible when **1-D** was dissolved in nondeuterated protic solvents−dissolution of **1-D** in either H_2O or MeOH regenerated protio-alkylidene **1**, and this cycle could be repeated up to three times with no observable decomposition as determined by ^1H, ^{13}C, and ^{31}P NMR spectroscopy.

Analysis of complex **1-D** by high-resolution FAB mass spectrometry yielded an observed mass of m/z 868.3646. This value is in excellent agreement with the predicted mass of the [M − Cl] fragment of deuterated alkylidene **1-D** (predicted m/z 868.3648).[9] The incorporation of deuterium at the alkylidene carbon in **1-D** was further confirmed via direct observation of this species by ^2H NMR spectroscopy. The ^2H NMR spectrum of this complex consisted of a single deuterium resonance, which appeared as a very broad singlet at a diagnostic chemical shift of 20.00 ppm. The expected C−D coupling at the alkylidene carbon of **1-D** was observed by ^{13}C NMR spectroscopy (500 MHz, CD_3OD, 301.89 ppm, $J = 19.4$ Hz), although the peaks were broad in this experiment and the splitting pattern for this resonance was additionally complicated by unresolved coupling to phosphorus. In the deuterium-decoupled ^{13}C NMR spectrum, the carbon resonance was considerably sharper.

Influence of Solvent Dielectric on Reaction Rates. The rates for the proton−deuteron exchange in the above experiments varied with solvent composition, suggesting that rates were dramatically influenced by the differences in the dielectric constants of these two solvents (32.7 and 78.5 for methanol and water, respectively).[10] For example, the exchange was complete in 20 min for alkylidene **1** in D_2O, while the reaction required three weeks in CD_3OD under otherwise equivalent conditions ($[\mathbf{1}] = 0.022$ M, room temperature). Although we cannot conclusively rule out H−D exchange due to residual D_2O in CD_3OD, the use of rigorously dry CD_3OD (99.999%) suggested that CD_3OD itself was capable of facilitating this reaction. The rate of the exchange reaction shown in eq 1 was investigated by monitoring the disappearance of the alkylidene proton resonance in the ^1H NMR spectrum of alkylidene **1**. Mixtures of D_2O and CD_3OD were used as solvents in these initial experiments, as the rate of exchange proceeded too rapidly in D_2O, and too slowly in CD_3OD, to be experimentally feasible. The exchange reaction in a 30% D_2O/70% CD_3OD (v/v) solvent mixture at 30 °C exhibited pseudo-first-order kinetics and the rate constant, k_{obs}, for this reaction was calculated to be $17.2(\pm 0.2) \times 10^{-3}$ min^{-1} (Figure 1). The analysis of these data was simplified by the initial assumption that the rates of exchange due to CD_3OD in the reaction mixture were negligible relative to the rates of exchange due to D_2O.

The rate of the H/D exchange reaction for alkylidene **1** was investigated as a function of D_2O concentration in various D_2O/CD_3OD solvent mixtures. As shown in Figure 2, the observed

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[4] For a recent report of a ruthenium vinylidene complex that undergoes vinylidene H/D exchange in CD_3OD in analogy to alkylidenes **1** and **2**, see: Saoud, M.; Romerosa, A.; Peruzzini, M. *Organometallics* **2000**, *19*, 4005−4007.

[5] For leading references to the application of ruthenium alkylidenes in organic chemistry, see: (a) Furstner, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3013. (b) Blackwell, H. E.; O'Leary, D. J.; Chatterjee, A. K.; Washenfelder, R. A.; Bussmann, D. A.; Grubbs, R. H. *J. Am. Chem. Soc.* **2000**, *122*, 58. (c) Grubbs, R. H.; Chang, S. *Tetrahedron* **1998**, *54*, 4413.

[6] For examples of the application of ruthenium alkylidenes in polymer synthesis, see: (a) Bielawski, C. W.; Grubbs, R. H. *Angew. Chem., Int. Ed.* **2000**, *39*, 2903. (b) Maynard, H. D.; Okada, S. Y.; Grubbs, R. H. *Macromolecules* **2000**, *33*, 6239. (c) Weck, M.; Jackiw, J. J.; Rossi, R. R.; Weiss, P. S.; Grubbs, R. H. *J. Am. Chem. Soc.* **1999**, *121*, 4088.

[7] For recent developments in the synthesis of ruthenium alkylidenes, see: (a) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 953. (b) Huang, J.; Stevens, E. D.; Nolan, S. P.; Peterson, J. L. *J. Am. Chem. Soc.* **1999**, *121*, 2674. (c) Weskamp, T.; Schattenmann, W. C.; Spiegler, M.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **1998**, *37*, 2490.

[8] (a) Belderrain, T. R.; Grubbs, R. H. *Organometallics* **1997**, *16*, 4001. (b) Schwab, P. E.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, *118*, 100. (c) Schwab, P. E.; France, M. B.; Grubbs, R. H.; Ziller, J. W. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2039.

[9] Although it is possible that this result represents the observation of an [M − Cl + H] fragment resulting from protio-alkylidene **1**, the analysis of **1** by FAB mass spectrometry from the same ionization matrix yielded the mass of the [M − Cl] ion. This suggests that the observed ionized species in the present FAB mass spectrometry experiment is also the [M − Cl] species and not the protonated [M − Cl + H] fragment. Unfortunately, this complex could not be examined by electron impact (EI) mass spectrometry.

[10] Lowry, T. H.; Richardson, S. S. *Mechanism and Theory in Organic Chemistry*; Harper and Row: New York, 1987.

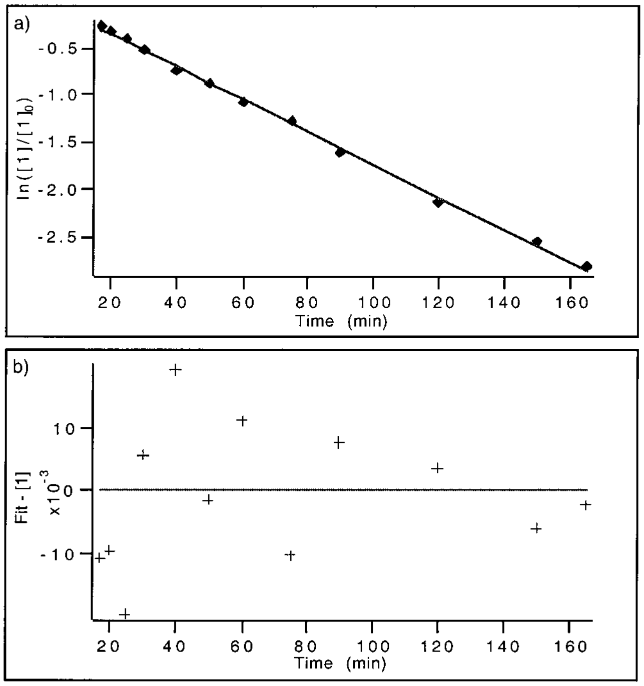

Figure 1. (a) Representative plot of ln([**1**]/[**1**]$_0$) vs time for alkylidene **1**. The reaction was carried out with [**1**]$_0$ = 0.022 M, in a 30% D_2O/70% CD_3OD solvent mixture at 30 °C. The filled diamonds are the data points and the solid line is the best linear fit to the data. (b) Plot of the residuals from the fit in a) found by taking the difference between the data and the curve fit at each point.

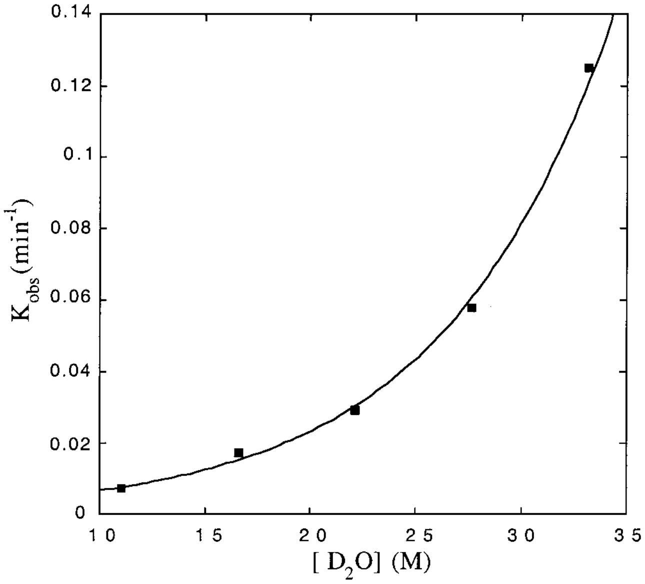

Figure 2. Plot of k_{obs} vs [D_2O] for alkylidene **1**. Reactions were carried out in mixtures of D_2O and CD_3OD as solvent at 30 °C. The filled squares are the data points, and the solid curve represents the best calculated exponential fit (R^2 = 0.997).

rate constants varied exponentially with increasing concentrations of D_2O in the solvent mixture. A plot of ln(k_{obs}) vs ln[D_2O] derived from these data did not permit the extraction of a reliable value for the order of D_2O in these reactions.[11] However, a plot of ln(k_{obs}) vs 1/*D* yielded a linear relationship,[12] revealing a direct correlation between reaction rates and the dielectric constant of the reaction medium (Figure 3).[13]

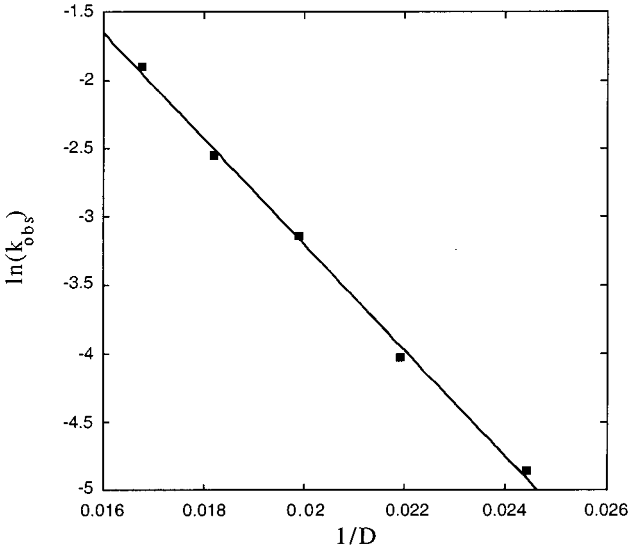

Figure 3. Plot of ln(k_{obs}) vs 1/*D* for alkylidene **1** (*D* = dielectric constant of solvent). Reactions were carried out in mixtures of D_2O and CD_3OD as solvent at 30 °C. The filled squares are the data points, and the solid line represents the best calculated linear fit. Intercept = 4.56(±0.24); slope = −388.01(±11.64); linear correlation coefficient (R^2) = 0.997.

To separate contributions to the rate in the above experiments resulting from increasing D_2O volume fractions from potential contributions due to changes in the bulk solvent dielectric constant, we performed a series of analogous experiments in THF-d_8/D_2O mixtures. The dielectric constant of THF is considerably lower than that of methanol, and mixtures of THF and water have lower dielectric constants than methanol/water mixtures at equivalent water concentrations.[14] When alkylidene **1** was dissolved in THF-d_8/D_2O mixtures, rates of exchange were much slower (relative to rates observed in D_2O/CD_3OD mixtures) at equivalent concentrations of D_2O (Figure 4).[15] These results suggested that the rates of proton−deuteron exchange were primarily dictated by solvent dielectric, and not the actual concentration of D_2O present in the solvent mixture. These results could also indicate, however, that the initial assumption that the rate of exchange due to methanol in D_2O/CD_3OD mixtures may not be as negligible as originally assumed. An overlayed plot of k_{obs} versus *D* for both series of experiments (in both D_2O/CD_3OD and THF-d_8/D_2O solvent mixtures) suggests that both conclusions may be true. For example, Figure 5 expresses the rate data shown in Figure 4 as a function of solvent dielectric constant. As shown, the differences between the rates of exchange in both solvent mixtures are negligible with respect to dielectric constant at lower D_2O concentrations ([D_2O] < 40% (v/v), bulk solvent dielectric (*D*) < 50). The deviation in the curves at higher D_2O concentrations ([D_2O] > 40% (v/v), *D* > 50), however, suggests that the contribution to the rate from methanol may become significant at higher dielectric constants.

The rates of alkylidene proton exchange in alkylidene **1** were determined to be independent of phosphine concentration. For

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[11] Although the plot of ln(k_{obs}) vs ln[D_2O] derived this relationship as linear, the order of D_2O derived from this relationship was calculated to be 2.50 ± 0.23.

[12] Laidler, K. J. *Chemical Kinetics*; Harper and Row: New York, 1987.

[13] Values for the dielectric constants for various mixtures of methanol and water at 30 °C were taken from: Åkerlof, G. *J. Am. Chem. Soc.* **1932**, *54*, 4125.

[14] (a) Renard, E.; Justice, J.-C. *J. Solution Chem.* **1974**, *3*, 633. (b) Justice, M.-C.; Justice, J.-C.; Kay, R. L. *J. Solution Chem.* **1990**, *19*, 1211.

[15] Values for the dielectric constants for various mixtures of THF and water at 30 °C were taken from ref 14.

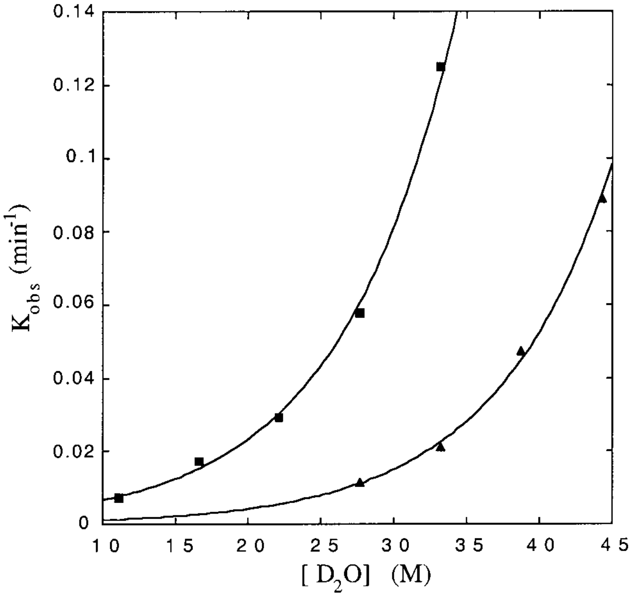

Figure 4. Plot of k_{obs} vs [D_2O] for the deuterium exchange in alkylidene **1** in mixtures of D_2O/THF-d_8 and D_2O/CD_3OD. Reactions were carried out at 30 °C. The filled squares are the data points for the reactions in D_2O/CD_3OD, the filled triangles are the data points for the reactions in D_2O/THF-d_8. The solid curves represent the best calculated exponential fits to these data.

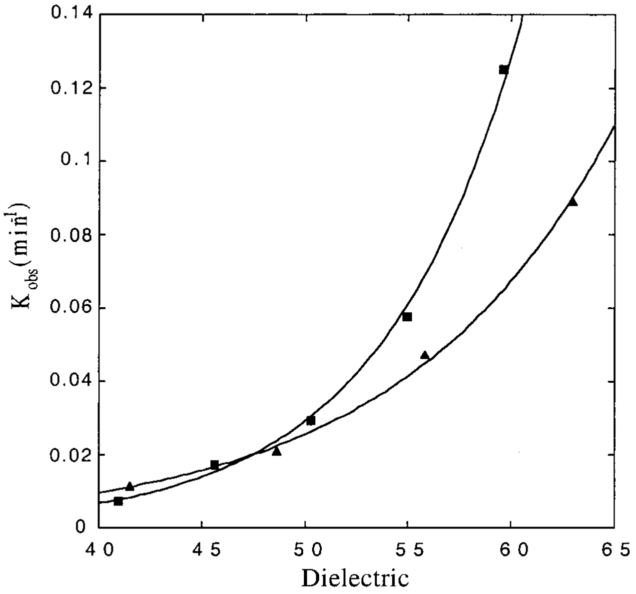

Figure 5. Overlayed plot of k_{obs} vs D for the deuterium exchange in alkylidene **1** in mixtures of D_2O/THF-d_8 and D_2O/CD_3OD. Reactions were carried out at 30 °C. The filled squares are the data points for the reactions in D_2O/CD_3OD, and the filled triangles are the data points for the reactions in D_2O/THF-d_8. The solid curves represent the best calculated exponential fits to these data.

example, the half-life of the reaction in the presence of 1.0 equiv of added phosphine was 13.41(±1.48) min [$k_{obs} = 52.0(\pm 6.0) \times 10^{-3}$ min^{-1}] in a 50% D_2O/50% CD_3OD solvent mixture at 30 °C. The half-life of that reaction did not differ significantly from the half-life for the same reaction in the absence of added phosphine [12.01(±0.28) min, $k_{obs} = 58.0(\pm 1.0) \times 10^{-3}$ min^{-1}] within the estimated errors for these measurements. The estimated error for the experiment conducted in the presence of added phosphine is large, as the magnitude of the proton resonances arising from the methyl groups on the added phosphine introduced significant uncertainty to the integration of the alkylidene protons in this experiment. A similar experiment was performed employing 5.0 equiv of added phosphine. The alkylidene proton of **1** could not be reliably integrated under these conditions. However, a qualitative assessment of reaction rate provided further evidence that the rate of this reaction was independent of phosphine concentration.

The experiments above indicated that the rates of the H/D exchange reaction for alkylidene **1** were directly influenced by the dielectric constants of the solvents employed. Given the proton-transfer nature of this reaction and the protic nature of both methanol and water, we investigated the rate of the exchange reaction as a function of the solution pH. Unfortunately, a quantitative investigation of the influence of added acid on H−D exchange rate could not be conducted because Brønsted acids react to protonate the phosphine ligands of **1**, perturbing the structures of these complexes.[1a,b] As outlined above, the alkylidene H/D exchange reaction occurs too rapidly in aqueous solution to be quantitatively investigated by NMR. However, a qualitative evaluation of data obtained through the addition of 0.3 equiv of DCl to a solution of alkylidene **1** in D_2O suggested that the addition of acid did not significantly influence the rate of the exchange reaction. For example, the alkylidene proton was completely exchanged for deuterium in D_2O solution after 20 min, as determined by ^1H NMR spectroscopy ([**1**] = 0.022 M, room temperature). The two alkylidene resonances[16] observed in the experiment employing DCl were observed to disappear over the same time period.

We also investigated the exchange reaction in d_6-succinate buffer (5 mM, pH 5.4) to determine the effect of reduced pH under more mild conditions. In analogy to the above experiment, we observed two alkylidene protons immediately upon dissolution of alkylidene **1** in the aqueous buffer, and a new unidentified peak was observed by ^{31}P NMR spectroscopy during this experiment. In contrast to the experiment employing DCl, the two alkylidene resonances observed in this experiment disappeared over a 45 min period. However, the structural perturbations in the alkylidene structure that occur under acidic conditions, which include the potential coordination of buffer ions to the metal center,[17] prevented the extraction of substantive conclusions from this experiment.

The direct addition of an equivalent of NaOD to a solution of alkylidene **1** results in alkylidene decomposition.[1a] The reactions discussed above carried out in the presence of excess weakly basic phosphine ligand (1 and 5 equiv in a D_2O/CD_3OD solvent mixture), however, suggested that the H/D exchange rates in these reactions were also independent of added base. To determine the effect of added base in aqueous solution, we investigated the rate of H/D exchange in deuterated phosphate buffer (5 mM, pH 7.8). The alkylidene proton of complex **1** completely exchanged with solvent-derived deuterons over a period of 20 min, suggesting that the rate of exchange was not influenced by this increase in solution pH. In contrast to the experiments carried out under acidic conditions, we observed no changes in the ^1H NMR spectrum of alkylidene **1** during this experiment. However, a small unidentified peak was observed in the ^{31}P NMR spectrum (singlet, 1.7 ppm, ≈5% relative to **1**) during this experiment. As such, we cannot

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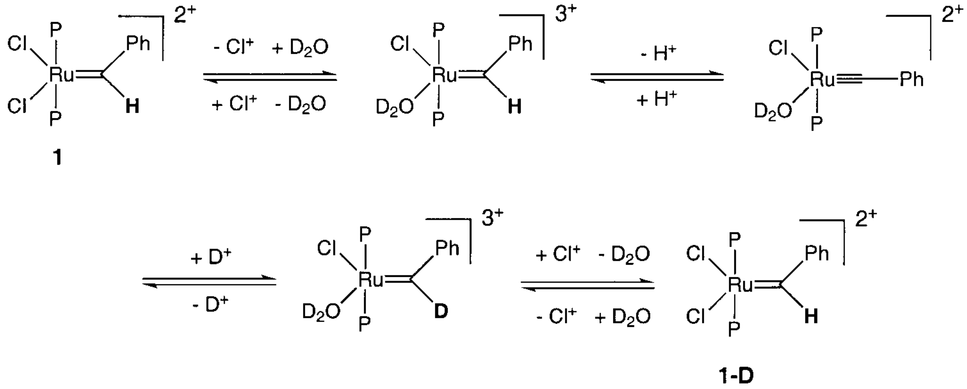
(16) The addition of 0.3 equiv of DCl to solutions of alkylidene **1** in D_2O results in the protonation of a phosphine ligand and the generation of two alkylidene resonances in the ^1H NMR spectrum of this complex. The two alkylidene resonances correspond to bisphosphine alkylidene **1** and a monophosphine derivative. See refs 1a and 1b.

(17) Carboxylate species have been found to coordinate to ruthenium alkylidenes under certain conditions, with concomitant attenuation of the metathesis activities of the resulting complexes. See: Dias, E. L.; Nguyen, S. T.; Grubbs, R. H. *J. Am. Chem. Soc.* **1997**, *119*, 3887.

Scheme 1. Proposed Mechanism for Alkylidene H/D Exchange for Alkylidene **1**



conclusively rule out the possibility that a small amount of the alkylidene was modified in the presence of buffer ions during this experiment. In addition to potential changes in alkylidene structure, it should be noted that changes in pH and the addition of buffer salts result in changes in the ionic strength and the dielectric constants of these solutions. Because the rate of alkylidene proton exchange is strongly dependent on the dielectric constant of the employed medium (as described above), conclusions based on these experiments should also be made with discretion.

The rate of alkylidene proton exchange was inversely proportional to the concentration of added chloride in aqueous solution. As described above, the alkylidene proton of complex **1** is completely exchanged with solvent-derived deuterons after 20 min ([**1**] = 0.022 M, room temperature). In the presence of 1.0 equiv of NaCl, however, the alkylidene proton of **1** exchanged more slowly over a period of 30 min ([NaCl] = 0.022 M, [**1**] = 0.022 M). The reaction was even slower in the presence of 4.0 equiv of NaCl, requiring 90 min for the alkylidene proton to exchange completely ([NaCl = 0.088 M, [**1**] = 0.022 M). The solubility of alkylidene **1** in D_2O was reduced in the presence of NaCl, and a fine light green precipitate was observed during the exchange reaction carried out in the presence of 4 equiv of NaCl.[18] The observation of an equilibrium involving the solvolysis of a chloride ligand in alkylidene **1** is consistent with earlier observations that the ruthenium−chloride bonds in this complex are labile, and that anionic ligand exchange reactions with alkylidene **1** are relatively facile in aqueous solvents.[1]

In general, exchange rates were also influenced by the nature of the alkylidene substituents. While exchange occurred rapidly for phenyl-substituted benzylidene **1** in D_2O, the rates of this reaction for *alkyl*-substituted complexes were much slower. For example, the alkylidene proton of a ruthenium ethylidene complex derived from **1** could be observed for hours in aqueous solution.[19] Likewise, alkyl-substituted propagating species in ring-opening metathesis polymerization (ROMP) reactions initiated by **1** and **2** can be observed for up to three months under certain conditions.[1a,b]

Scheme 1 outlines a proposed mechanism for the exchange of the alkylidene proton in complex **1** in which a chloride ion dissociates from the metal center. This mechanism is consistent with the rate data obtained in the presence of excess chloride and explains the influence of solvent dielectric on the rate of the exchange reaction. Dissociation of a chloride ion from the ruthenium metal center would yield a cationic metal center (and an overall charge of +3 on the complex considering the charges on pendant phosphines). In a coordinating solvent such as water, this complex is likely coordinated by at least one stabilizing water molecule. The generation of a cationic metal center would render the alkylidene proton more acidic via inductive withdrawal of electron density from the alkylidene carbon. Subsequent deprotonation of the alkylidene carbon would yield a ruthenium carbyne species with a neutral metal center (overall charge = +2). Protonation of this intermediate by a solvent-derived deuteron, followed by coordination of chloride, would yield deuterated alkylidene **1-D**.

We favor the mechanism in Scheme 1 over an alternative mechanism in which the cationic monochloro-alkylidene complex is protonated at the alkylidene carbon (subsequent deprotonation would give **1-D**), because this alternative would require the generation of a higher energy dicationic ruthenium alkyl species bearing an overall +4 charge. In contrast, the intermediates proposed in Scheme 1 alternate between complexes having either a neutral or a cationic metal center (either +2 or +3 considering charges on pendant phosphines). Additionally, an initial deprotonation step is consistent with qualitative observations that the rate of H/D exchange occurs more rapidly for benzylidene complexes than for ethylidene complexes, as inductive withdrawal of electron density in the benzylidene complex would render the alkylidene proton more acidic. Our data do not rule out the formation of a cationic carbyne-hydride intermediate as an elementary step in the alkylidene H/D exchange reaction. (In such a scheme, deprotonation/reprotonation of the metal center would be assumed to account for proton−deuteron exchange.) Several cationic ruthenium carbyne-hydride species have been isolated from ruthenium vinylidene complexes in organic solvents under certain conditions.[20] However, we believe that a more direct deprotonation/protonation scheme is consistent with the high dielectric constant of the solvent, the amphoteric and coordinating nature of water, and the cationic nature of the metal center upon dissociation of chloride.

Additional Examples. The rate of exchange of the alkylidene proton in complex **2** was pseudo-first order with respect to alkylidene, but rates were generally faster than the rates of exchange observed for **1**. For example, in a 30% D_2O/70% CD_3OD (v/v) solvent mixture, the observed rate of the exchange for the alkylidene proton in **2** [$k_{obs} = 200.0(\pm 7.0) \times 10^{-3}$ min^{-1}]

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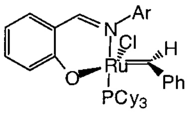
[18] Peaks in the ^{1}H NMR spectrum were very broad in this experiment. The nature of the precipitate is not known.

[19] A qualitative analysis of the rate of this reaction could not be made due to the instability of the ruthenium alkylidene complex. See refs 1a and 1c.

[20] For examples of cationic ruthenium carbyne−hydride species formed from ruthenium vinylidene complexes, see: (a) González-Herrero, P.; Weberndörfer, B.; Ilg, K.; Wolf, J.; Werner, H. *Angew. Chem., Int. Ed.* **2000**, *39*, 3266. (b) Stuer, W.; Wolf, J.; Werner, H.; Schwab, P.; Schulz, M. *Angew. Chem., Int. Ed.* **1998**, *37*, 3421.

was nearly 12 times faster than the rate of exchange in alkylidene **1**. The rate of the reaction was influenced by the dielectric constant of the solvent, but an analysis of the rate as a function of D_2O concentration in D_2O/CD_3OD solvent mixtures did not yield a straightforward exponential relationship as observed for alkylidene **1**. As the phosphines coordinated to **2** are more electron-rich than the phosphines coordinated to **1**,[1d] these results suggest that the rates of exchange for alkylidenes **1** and **2** are significantly influenced by the electron density at the metal centers of these complexes. Presumably, the substantially more electron-rich phosphines coordinated to alkylidene **2** increase the rate of the overall reaction through stabilization of the resulting cationic metal center after chloride dissociation (Scheme 1), although phosphine sterics should also play a role.[21]

We have also found that methanol-soluble ruthenium alkylidenes **4**[22] and **5**[23] undergo alkylidene proton exchange in CD_3OD and D_2O/CD_3OD mixtures. In the case of alkylidene **4**, the rate of H/D exchange in methanol is approximately 54 times faster than the rate of exchange for alkylidene **1** under equivalent conditions, further illustrating the influence of coordinated ligands on the rate of the exchange reaction. The alkylidene proton of complex **6**, a dimethylvinyl analogue of benzylidene **1**, undergoes alkylidene H/D exchange at the alkylidene H_α position when dissolved in either D_2O or CD_3OD.[24] Coupling between the incorporated deuterium atom and the adjacent vinyl proton (H_β) was manifest as a broad singlet at 7.85 ppm [the H_β proton in protio-**6** is observed as a doublet (7.85 ppm, $J = 8.25$ Hz)]. Finally, we have also observed alkylidene H/D exchange during experiments conducted with parent benzylidene **3** in CD_2Cl_2/CD_3OD mixtures (eq 2). These examples suggest that degenerate alkylidene proton exchange may be general for an entire family of ruthenium alkylidenes, provided that protic species are available in solution and that the dielectric constant of the reaction medium is sufficiently high. As outlined above, Saoud et al. have reported the extension of this exchange behavior to the vinylidene proton of a new water-soluble ruthenium vinylidene complex dissolved in CD_3OD.[4]



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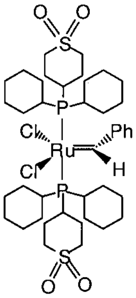

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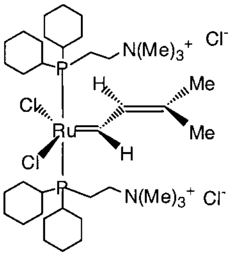

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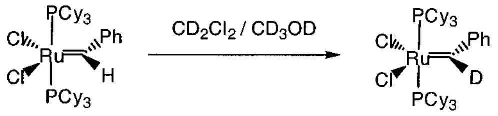

3 **3-D** (2)

Summary

Ruthenium alkylidenes **1** and **2** represent the first examples of isolable alkylidenes that are soluble and stable in protic, high-dielectric solvents such as water and methanol. During the synthesis and isolation of these complexes, we discovered that the alkylidene protons in these complexes **1** and **2** exchanged with solvent-derived deuterons when they were dissolved in perdeuterated protic solvents such as D_2O and CD_3OD. This behavior has not been observed for other alkylidenes in organic solvents. The rate of the exchange reaction was influenced primarily by the dielectric constants of the solvents employed, and the data support a mechanism in which a chloride ion dissociates from the ruthenium center. In addition to our initial observations, we have identified several other alkylidenes that undergo analogous alkylidene H/D exchange reactions in protic solvents, including parent alkylidene **3** in CD_2Cl_2/CD_3OD mixtures. This mode of reactivity may therefore be general for an entire class of ruthenium alkylidenes, provided that protic species are available in solution and that the dielectric constant of the reaction medium is sufficiently high to ionize the halide ligands.

We believe that the continuous, fluxional activity occurring at the alkylidene carbon in complexes **1** and **2** may be partially responsible for the reduced stabilities of these complexes. As previously described, alkylidenes **1** and **2** are dramatically less stable in aqueous solution as compared to alkylidenes such as **3** in organic solvents.[1] The alkylidene exchange reaction is not itself a decomposition reaction. However, the dissociation of chloride and the generation of higher energy intermediates may contribute to the instability of these complexes and introduce alternate modes of decomposition.[25] The stability of ruthenium alkylidenes in protic environments is a practical concern given the growing application of olefin metathesis to highly functionalized, biologically inspired substrates which are preferably or exclusively soluble in protic, high-dielectric solvent mixtures.[26] We continue to investigate the nature of this new reaction with a view to designing alkylidenes with enhanced stabilities in protic media.

Experimental Section

General Considerations. All manipulations involving ruthenium alkylidene complexes were performed by using standard Schlenk techniques under argon or in a nitrogen-filled drybox. Argon was purified by passage through columns of BASF R3-11 catalyst (Chemalog) and 4 Å molecular sieves (Linde). ^1H NMR (300.1 MHz) were recorded on a GE QE-300 spectrometer. ^{31}P NMR (161.9 MHz) spectra were

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(21) A reviewer has noted that the cone angle of the phosphine coordinated to alkylidene **2** should be greater than the cone angles of the phosphine coordinated to **1**, and that these steric parameters could influence chloride dissociation and the rate of H/D exchange. We have been unable to measure a difference in the cone angles of these cationic phosphines (see ref 1d). However, experimental evidence has shown that the phosphine coordinated to **2** is substantially more electron donating than the phosphine coordinated to **1** (ref 1d). While steric and electronic factors undoubtedly both play a role, we attribute the disparities in the metathesis activities and the H/D exchange rates of these complexes primarily to differences in phosphine electronics.

(22) Chang, S.; Jones, L.; Wang, C. M.; Henling, L. M.; Grubbs, R. H. *Organometallics* **1998**, *17*, 3460.

(23) Rölle, T. R.; Grubbs, R. H. Unpublished results.

(24) Dimethylvinyl alkylidene **6** was synthesized through direct exchange of the triphenylphosphine ligands in $(Ph_3P)_2Cl_2Ru{=}CHCH{=}CMe_2$, in analogy to the synthesis of alkylidene **1** (see refs 1a and 1d). Alkylidene **6** was not obtained as an analytically pure complex, and qualitative observations of alkylidene H/D exchange in D_2O and CD_3OD were made on a sample of alkylidene **6** containing a 10% excess of the cationically charged phosphine ligand. For a reference describing the synthesis of $(Ph_3P)_2Cl_2Ru{=}CHCH{=}CMe_2$, see: Wilhelm, T. E.; Belderrain, T. R.; Brown, S. N.; Grubbs, R. H. *Organometallics* **1997**, *16*, 3867.

(25) For a recent investigation into the various routes through which ruthenium alkylidene complexes decompose, see: Ulman, M.; Grubbs, R. H. *J. Org. Chem.* **1999**, *64*, 7202.

(26) (a) Gordon, E. J.; Sanders, W. J.; Kiessling, L. L. *Nature* **1998**, *392*, 30. (b) Kanai, M.; Mortell, K. H.; Kiessling, L. L. *J. Am. Chem. Soc.* **1997**, *119*, 9931. (c) Mortell, K. H.; Weatherman, R. V.; Kiessling, L. L. *J. Am. Chem. Soc.* **1996**, *118*, 2297.

recorded on a JEOL GX-400 spectrometer. ^{13}C NMR (125.78 MHz) spectra were recorded on a Varian Inova 600 spectrometer. All chemical shift values are given in ppm and are referenced with respect to residual protons in the solvent for proton spectra, or to phosphoric acid for phosphorus spectra.

Materials. D_2O, D_2O/DCl solutions, THF-d_8, KD_2PO_4, K_2DPO_4, and d_6-sucinnic acid was purchased from Cambridge Isotope Laboratories (Cambridge, MA). Rigorously dried CD_3OD (certified 99.999%) was purchased directly from Acros Organics (Lot No. A010250901). CD_3OD, D_2O, THF-d_8, and deuterated buffer solutions were degassed by purging with argon and stirring under vacuum prior to use. Alkylidenes **1** and **2** were prepared as previously reported.[1a,d] All other reagents were reagent grade and used without further purification.

$RuCl_2(=CDPh)[Cy_2PCH_2CH_2N(CH_3)_3{}^+Cl^-]_2$ (1-D). Alkylidene **1** (20 mg) was placed in a Schlenk flask equipped with a stirbar and capped with a rubber septum. D_2O (1 mL) was added via syringe, and the solution was stirred for 30 min at room temperature. Solvent was removed under vacuum to yield the deuterated alkylidene in quantitative yield as a red/brown solid. A singlet (corresponding to the alkylidene deuteron) was observed at δ 20.00 ppm in the ^2H NMR spectrum (d_4-MeOH). ^1H, ^{13}C, and ^{31}P NMR spectra for this compound were identical to alkylidene **1**,[1d] with the following exceptions: In the ^1H NMR spectrum, no alkylidene resonance was observed. In the ^{13}C NMR spectrum, the expected C−D coupling at the alkylidene carbon of **1-D** was observed (500 MHz, CD_3OD, 301.89 ppm, $J = 19.4$ Hz), although peaks were broad and the splitting pattern for this resonance was additionally complicated by unresolved coupling to phosphorus. This carbon resonance sharpened considerably upon analysis by deuterium-decoupled ^{13}C NMR spectroscopy. High-resolution FAB MS: calculated for $[M - Cl^-]$ 868.3648, found 868.3646. The observed isotopic abundance for the corresponding $[M - Cl^-]$ peaks identically matched the predicted isotope pattern for the $[M - Cl^-]$ fragment of the title compound.

Kinetic Investigation of Alkylidene Proton−Deuteron Exchange. Reactions for kinetic studies were performed in NMR tubes capped with rubber septa. All reactions were conducted at a constant temperature (30.0 °C), constant volume (500 μL), and constant catalyst concentration (0.022 M). Reactions were conducted in the following general manner. In a drybox, alkylidene (0.011 mmol) was weighed into an NMR tube and dissolved in a desired amount of CD_3OD [up 500 μL, dependent on the volume ratio of methanol to water to be investigated (see below)], and the NMR tube was capped with a rubber septum. The NMR tube was removed from the drybox, wrapped with Parafilm, and lowered into the NMR probe (preheated at 30 °C) for 2 min to allow the solution of alkylidene to reach thermal equilibrium. The sample was ejected from the NMR probe, and a volume of D_2O (the amount necessary to bring the total volume of the reaction to 500 μL) was injected via gastight syringe. The NMR tube was shaken vigorously and immediately lowered back into the NMR probe for data collection. The disappearance of the alkylidene proton resonances in these experiments was monitored by integrating the alkylidene proton versus methylene chloride as an internal standard or the ortho protons on the alkylidene substituent.

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