

Highly Stereoselective Proton/Hydride Exchange: Assistance of Hydrogen Bonding for the Heterolytic Splitting of H₂Anja Friedrich,[†] Markus Drees,[†] Jörn Schmedt auf der Gönne,^{*,‡} and Sven Schneider^{*,†}

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The heterolytic activation of H₂ is of great importance in both biological systems (e.g., hydrogenases) and catalytic ionic hydrogenations.¹ For hydrogenations of carbonyl groups, Ru catalysts with primary amino ligands have been found to exhibit extraordinary activities.² This “NH effect” was attributed to a bifunctional mechanism with rate-determining heterolytic hydrogen splitting by intramolecular proton transfer from an η^2 -H₂ ligand to a basic amido ligand, but calculated barriers for this step turned out to be too high in comparison with experimental results.³ Furthermore, the acceleration of catalytic rates by alkali alkoxide cocatalysts, protic solvents, and hydrogenation products points toward the involvement of hydrogen bridging in bifunctional H₂ activation,⁴ which was confirmed computationally.^{5,4h} However, the body of experimental data, which allows for the quantification and precise mechanistic interpretation of this observation, remains very limited,⁶ and most recently, kinetic studies have suggested direct proton transfer as originally proposed to be operative in the absence of base.⁷

Ir and Ru complexes with the PNP pincer ligand HN(CH₂CH₂PⁱPr₂)₂ (HPNP) have been utilized as catalysts for hydrogenation of ketones and imines,⁸ and cooperative, pyridine-based PNP ligands are active catalysts in acceptorless alcohol dehydrogenation.⁹ Recently, we presented the dehydrocoupling of borane–amine adducts catalyzed by the amido complex [Ru(H)PMe₃(PNP)] (**1**).¹⁰ Complex **1** reversibly both eliminates and adds H₂, forming equilibria with [Ru(H)PMe₃{N(CHCHPⁱPr₂)(CH₂CH₂PⁱPr₂)}] (**2**) and [Ru(H)₂PMe₃(HPNP)] (**3**), respectively.^{10a} Amino complex **3** features a trans-dihydride configuration with only one hydride in close proximity to the internal N–H acid, representing an ideal probe for studying hydrogen exchange processes of the syn H–N–Ru–H moiety referenced against the second hydride.

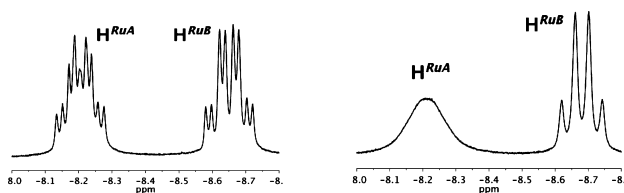
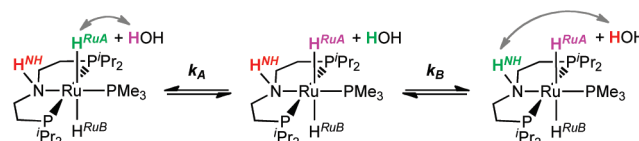


Figure 1. Hydride regions of the ¹H NMR spectra of (left) **3** and (right) **3** with 2 equiv of H₂O.

The ¹H NMR spectrum of complex **3** in THF-*d*₈ (Figure 1, left) exhibits two sharp signals in the hydride region at –8.20 (H^{RuA}) and –8.65 ppm (H^{RuB}). H^{RuA} can be assigned to the hydride adjacent to the PNP N–H proton (H^{NH}) using ¹H nuclear Overhauser effect NMR spectroscopy (NOESY). To account for possible chemical

exchange of H^{RuA} with H^{NH}, the NOE signals were calibrated with proton distances obtained from a density functional theory (DFT) model of **3**. In the calculated structure, the H^{RuA}...H^{NH} distance (*d*_A = 2.64 Å) is very close to the distances between H^{RuB} and two C–H protons on the pincer backbone (*d*_{B1} = 2.60 Å; *d*_{B2} = 2.81 Å), which are equivalent on the NMR time scale. A comparison of the distances (*d*_A^{–6}/*d*_B^{–6} = 1.14)¹¹ with the integrals of the respective NOESY (τ_m = 1 s) cross peaks (*I*_A/*I*_B = 1.13) suggests negligible H^{RuA}/H^{NH} chemical exchange on the experimental time scale. Accordingly, H₂ elimination from **3** proceeds very slowly, and full dehydrogenation toward **1** under vacuum at room temperature takes several hours.

Scheme 1. Exchange of H₂O with H^{RuA} and H^{NH} in Amino Dihydride Complex **3**

The addition of 2 equiv of water to a sample of **3** in THF-*d*₈ results in broadening of the hydride signals and breakdown of the H^{RuA}–H^{RuB} *J*-coupling (Figure 1, right).¹² The hydride chemical shift differences with respect to dry samples were very small [Δδ(H^{RuA}) = 0.01 ppm; Δδ(H^{RuB}) = 0.03 ppm], which would be in agreement with Ru–H/H₂O proton exchange via short-lived dihydrogen complexes.¹³ Accordingly, below –50 °C, exchange was slow on the NMR time scale, giving two sharp hydride signals with similar *T*₁^{min} values [154 ms (191 K) for H^{RuA} and 172 ms (191 K) for H^{RuB} at 400 MHz] that are typical of terminal hydride ligands.¹⁴ Addition of molecular sieves to this NMR sample resulted in full restoration of the “dry” ¹H NMR spectrum. Most significantly, at room temperature, the broadening of the H^{RuA} signal was considerably larger than for H^{RuB}, pointing toward very different exchange rates, as was further substantiated using *T*₁ measurements: above –50 °C, the apparent *T*₁ values derived from inversion recovery for H^{RuA} dropped as a result of rapid exchange, contrasting sharply with H^{RuB} (see the Supporting Information).

Proton exchange rates of H₂O (4.25 equiv) with H^{RuA} [*k*_A = 337(20) L mol^{–1} s^{–1}] and H^{NH} [*k*_B = 8.0(4) L mol^{–1} s^{–1}] in THF-*d*₈ were derived using ¹H 2D NMR exchange spectroscopy (EXSY) combined with simultaneous fitting of several 2D spectra at different mixing times (Scheme 1).^{15,16} This method offers the opportunity to study simultaneous multisite exchange over a wide dynamic range of exchange rates without the isotope effect inherent in H/D exchange kinetics. The *k*_A value is surprisingly high, considering the low acidity of water in such a nonpolar solvent. Most intriguingly, within experimental error, no direct exchange of H₂O

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with H^{RuB} was found. Stereoselective dihydrogen bonding has been observed previously, e.g., for $[\text{Re}(\text{cis-H})_2(\text{CO})(\text{NO})(\text{trans-PR}_3)_2]$ with alcohols, and was attributed to different relative ligand hydricities and steric effects.¹⁷ However, H^{RuA} and H^{RuB} are in very similar steric environments, and the trans dihydride configuration suggests comparable basicities of the hydride ligands. Therefore, the highly site-selective hydride/ H_2O exchange and large exchange rate for H^{RuA} can best be rationalized in terms of directing $\text{H}^{\text{NH}}/\text{OH}_2$ hydrogen bonding. To further probe for the influence of the amine proton, the nitrogen atom was blocked by methylation (see the Supporting Information). Addition of 2 equiv of H_2O to $[\text{Ru}(\text{H})_2\text{PMe}_3(\text{MePNP})]$ [**5**; $\text{MePNP} = \text{MeN}(\text{CH}_2\text{CH}_2\text{P}^i\text{Pr}_2)_2$] in THF-d_8 did not result in considerable broadening of either of the two hydride signals, and the mutual J -coupling was retained. Finally, the H_2O exchange rates with the hydrides of **5** as derived using ^1H 2D EXSY [0.07(3) and 0.03(2) $\text{L mol}^{-1} \text{s}^{-1}$] were very similar to each other and ~ 4 orders of magnitude smaller than k_{A} , supporting the idea that stereoselective H^+/H^- exchange in **3** is directed by H^{NH} .¹⁸

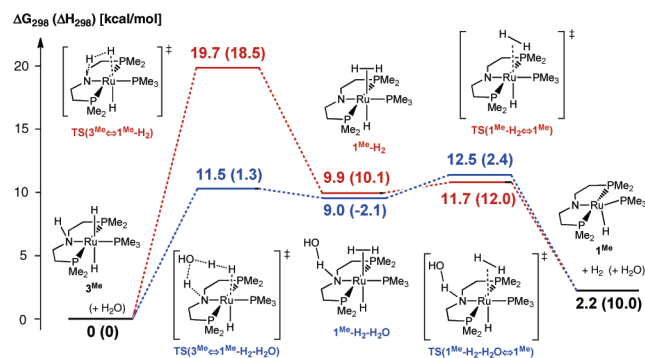


Figure 2. DFT calculations (B3LYP/6-31+G**) for heterolytic hydrogen splitting in THF (blue) with and (red) without water assistance.¹⁹

Since the intermediate dihydrogen complex that accounts for H^+/H^- exchange should be on the reaction path of H_2 activation by **1** as well, these results suggest that water lowers the barrier for heterolytic hydrogen splitting. Therefore, H_2 addition to model complex **1**^{Me} with and without H_2O was examined using DFT calculations (Figure 2). Addition of H_2 to amide **1**^{Me} is slightly exergonic ($\Delta G = -2.2$ kcal/mol). The water-free mechanism exhibits a barrier of $\Delta G^\ddagger = 9.8$ kcal/mol for rate-determining proton transfer from the H_2 ligand to N in the four-membered-ring transition state $\text{TS}(3^{\text{Me}} \leftrightarrow 1^{\text{Me}}\text{-H}_2)$. In contrast, hydrogen bonding of the amido and H_2 ligands with water via six-membered-ring transition state $\text{TS}(3^{\text{Me}} \leftrightarrow 1^{\text{Me}}\text{-H}_2\text{-H}_2\text{O})$ lowers this barrier by $\Delta\Delta G^\ddagger = 8.2$ kcal/mol, in agreement with our proton exchange experiments.¹⁹ Overall, the computed reaction profile compares well with calculations by Brandt, Andersson, and co-workers⁵ on alcohol-assisted hydrogen activation in the diamine diphosphine model system $[\text{Ru}(\text{trans-H})_2(\text{cis-PR}_3)_2(\text{H}_2\text{NCH}_2\text{CH}_2\text{NH}_2)]$.

The unusual stereoselectivity of H^+/H^- exchange and the computational results strongly emphasize the role of hydrogen-bonding networks with Brønsted acids as weak as H_2O for heterolytic H_2 splitting by Ru–amide hydrogenation catalysts. In view of the ubiquitous availability of water, this mechanism might be relevant for both catalysis and biological heterolytic H_2 activation.

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Supporting Information Available: Full preparative, analytical, and computational details. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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- (19) $3^{\text{Me}}\text{-H}_2\text{O}$ with water hydrogen-bonded to H^{NH} was found to be slightly endergonic with respect to 3^{Me} ($\Delta G = +2.0$ kcal/mol, $\Delta H = -7.5$ kcal/mol; see the Supporting Information).

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