Selectivity of tungsten mediated dinitrogen splitting vs. proton reduction†

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Mo complexes are currently the most active catalysts for nitrogen fixation under ambient conditions. In comparison, tungsten platforms are scarcely examined. For active catalysts, the control of N₂ vs. proton reduction selectivities remains a difficult task. We here present N₂ splitting using a tungsten pincer platform, which has been proposed as the key reaction for catalytic nitrogen fixation. Starting from [WC13(PNP)] (PNP = N(CH2)2PtBu2), the activation of N₂ enabled the isolation of the dinitrogen bridged redox series (N2)[WC13(PNP)]0/+2+. Protonation of the neutral complex results either in the formation of a nitride [W(N)Cl(HPNN)]+ or H₂ evolution and oxidation of the W₂N₂ core, respectively, depending on the acid and reaction conditions. Examination of the nitrogen splitting vs. proton reduction selectivity emphasizes the role of hydrogen bonding of the conjugate base with the protonated intermediates and provides guidelines for nitrogen fixation.

Introduction

Homogeneous N₂ fixation under ambient conditions has made remarkable progress over the past 15 years.¹ Nishiyabashi and co-workers recently obtained over 4000 equiv. of NH₃ with the proton coupled electron transfer (PCET) reagent H₂O/Sml₂ as H+/e⁻ sources and a molecular Mo pincer catalyst.² Accordingly, nitrogen reduction (NR) via electrochemically or light-driven PCET with related systems has attracted a lot of attention.³ Lindley et al. estimated a suitable overpotential window of 1–1.5 V for selective NR (in MeCN) prior to competing hydrogen reduction (HR) at a glassy carbon cathode.³ However, besides the thermochemical framework, mechanistic models that account for NR vs. HR selectivities of molecular catalysts are generally poorly developed.

Several M(N₂H₂) intermediates relevant to N₂ fixation (Scheme 1) exhibit low N–H bond dissociation free energies (BDFEs) below that of free H₂ (BDFE(H₂, gas) = 97.2 kcal mol⁻¹) as possible branching points into HR.⁵,⁷ Computational evaluation of NR vs. HR selectivities for a series of Fe catalysts pointed at bimolecular H₂ loss from species with low N–H BDFEs.⁸,⁹ Attempts to stabilize such Fe(N₂H₂) species by hydrogen bonding with pendant bases so far resulted in shutdown of catalysis.¹⁰ But, in fact, such secondary interactions might also be relevant for Nishiyabashi’s catalyst as indicated by selectivities obtained with 2,6-lutidinium acids ([LutH]+[X]⁻) as the proton source. These strongly depend on the X⁻ counter anion: NH₃/H₂ (X⁻) = 7.0 (Cl⁻), 0.9 (OTf⁻), and 0.14 (BAR₄⁻).¹¹

In this contribution, we address the role of hydrogen bonding for the selectivity of proton induced N₂ splitting into molecular nitrides vs. proton reduction. N₂ splitting has evolved as an entry into N₂ functionalization for a wide variety of metals¹² and was proposed as the key step in N₂ fixation with Mo pincer catalysts.¹³ Cleavage of Cummins’ seminal complex 1 (Fig. 1) was attributed to the π₂,π₃,π₄,π₅,π₆ configuration of the Mo₂N₂-core, which enables population of

![Scheme 1](image-url)
Fig. 1 Qualitative molecular orbital schemes for 1, 22+, 3 and 4, illustrating the isolobal relationship of 1 (π10)/3 (π10σ8) and 22+ (π8σ4)/4 (π8σ6), respectively.

formation from N2 is surprisingly rare.20 We here report tungsten mediated N2 splitting that competes with proton reduction upon protonation of a {W2N2} pincer complex. Our results provide evidence for the significance of hydrogen bonding for the reaction selectivity.

Results and discussion

Synthesis of the [(N2){WCl(PNP)}2]n+ (n = 0–2) redox series

The reaction of WCl4 with 19PF3 in the presence of NEt3 gives the pincer complex [WCl3(PNP)] (5) in yields of up to 60%. In the absence of a signal in the 31P{1H} NMR spectrum, the paramagnetically shifted 1H NMR signals and the solution magnetic moment derived by Evans’ method (μeff = 2.8 ± 0.1 μB) are in line with a d2 high-spin (S = 1) configuration. The molecular structure obtained by X-ray diffraction closely resembles previously reported compounds [MCl3(PNP)] (M = Re and Mo).18,19

Reduction of 5 with Na/Hg (2 equiv.) under N2 (1 atm) in THF gives the green, N2-bridged dinuclear complex [(N2){WCl(PNP)}2] (6) in up to 66% isolated yield (Scheme 3). In the solid state (Fig. 2) 6 is isostructural with the molybdenum analogue 4, regarding the N2 binding mode, the approximate C2 symmetry due to mutually twisted {WCl(PNP)}-fragments (Cl1-W1-W1#-Cl1#: 89.59°), and the distorted square-pyramidal metal coordination (r = 0.35).21 The short W–N2 bond (1.78(2)/1.82(4) Å) indicates multiple bonding character. In turn, the N–N bond (1.33(4)/1.27(8) Å) is at the higher end for

Table 1 Comparison of the spectroscopic and structural features of Cummins’ Mo–N2-dimer redox series (Ar = C6H3-3,5-Me2)16 with square-pyramidal pincer complexes (M = Re,17 Mo,18 or W, * computed value)

| Compound | n | Configuration | d(NN) [Å] | ν(NN) [cm⁻¹] | S   |
|----------|---|---------------|----------|-------------|-----|
| 1        | 0 | {π10}         | 1.212(2)/1.217(2) | 1630 | 1/2 |
| 2        | +1 | {π8}         | 1.239(4)  | 1503 | 1    |
| 3 (M = Re) | +2 | {π10σ8}      | 1.265(5)  | 1349 | 0    |
| 4 (M = Mo) | 0 | {π8σ4}      | 1.202(10) | 1771* | 1    |
| 5       | 0 | {π8σ4}      | 1.258(9)  | 1343 | 0    |
| 6 (M = W) | 0 | {π8σ4}      | 1.33(4)/1.27(8) | 1392 | 0    |
| 7 (M = W) | +1 | {π6σ2}      | 1.277(5)  | 1414 | 1/2 |
| 8 (M = W) | +2 | {π6σ2}      | 1.266(12) | 1400 | 1    |
N₂-bridged ditungsten complexes. The two ⁴¹P¹[H] NMR signals (δ₀ = 92.9, 87.8 ppm) with large trans-coupling (Jₚᵥ = 147 Hz), the singlet ¹⁵N NMR resonance (δₘ = 31.1 ppm), and the ¹H NMR signature of 6 support a Cₛ symmetric structure also in solution on the NMR timescale.

The N₂ stretching vibration of 6 was assigned to the Raman signal at 1392 cm⁻¹ (λₑₓ = 457 nm, THF solution; ¹⁵N₂ isotope: 1347 cm⁻¹) supporting strong N₂-activation with a formal N–N bond order below the double bonding character (trans-diazene: νₓₓₙ = 1529 cm⁻¹). The closed-shell ground state and degree of N₂ activation are in line with the covalent bonding picture described in Fig. 1. The {π σ̃δ} configuration of the W₂N₂ core can be rationalized to arise from two low-spin WII ions. The twisted conformation enables strong back bonding of each metal ion with one π*-MO of the N₂ bridge, respectively, resulting in net transfer of approximately two electrons as judged from the Raman data. This picture is corroborated by DFT computations, which confirm the {π σ̃δ} configuration of the W₂N₂ core, analogous to the Mo analogue 4 and Cummins’ 2⁺. The blue-shifted N₂ stretching vibration of 6 vs. 4 (Δνₓₓₙ = 49 cm⁻¹; Table 1) indicates slightly reduced back-bonding by the 5d metal.

The redox chemistry of 6 was examined to probe the electronic structure model. Cyclic voltammetry (CV) in THF shows no reduction feature down to −2.9 V (vs. FeCp₂/FeCp₂). In contrast, two reversible oxidation waves (E₁° = −1.39 V; E₂° = −0.91 V) are observed. Both redox events are cathodically shifted by 250 mV with respect to the Mo analogue 4, supporting metal centered oxidation. The oxidation products [(N₂) {WCl(PNP)}₂]⁺ (7⁺) and [(N₂)WCl(PNP)]⁺ (8²⁺) could be isolated in yields beyond 80% upon chemical oxidation of 6 with one and two equivalents of silver salts, respectively (Scheme 3). Stabilization of 8²⁺ requires a weakly coordinating anion, which was introduced with Ag[Al(O(CF₃)₃)]₃ as the oxidant.

In the solid state, 7⁺ and 8²⁺ resemble the twisted conformation found for 6 (Fig. 2). Distinctly different bond lengths around the two tungsten ions of the mixed-valent complex 7⁺ indicate valence localization, which is further supported in solution by the large comproportionation constant (Kᵣ = 10³⁴) and the X-band EPR spectrum at r.t. The isotropic signal (gₑₓ = 1.93) of the low-spin (S = 1/2) complex exhibits hyperfine interaction (HFI) with only one tungsten (A(W183W) = 220 MHz) and two phosphorous nuclei (A(P19P) = 56 MHz), respectively. HFIs with the N₂-bridge are not found and the ¹⁴N₂- and ¹⁵N₂-isotopologues give identical spectra, further supporting metal centered oxidation. In fact, the degree of N₂ activation is almost invariant within the redox series 6⁺⁻7⁺⁻8²⁺ as judged from the invariance of the N–N stretching vibrations and the N–N bond lengths of the W₂N₂ cores (Table 1). Notably, the ¹H NMR spectrum of 7⁺ features four signals assignable to 8Bu groups, in agreement with the averaged C₂ symmetry and therefore valence delocalization on the slow NMR timescale.

The double oxidation product 8²⁺ exhibits paramagnetically shifted, yet relatively sharp ¹H NMR signals. Magnetic characterization by SQUID magnetometry reveals a λₘT product of about 0.6 cm³ mol⁻¹ K⁻¹ at r.t., which gradually drops to 0 at about 20 K. The data can be fitted to a model with two weakly antiferromagnetically coupled (J = −59 cm⁻¹) low-spin (S = 1/2) ions. The g-value (gₑₓ = 1.90) indicates an orbital contribution in the typical range for W⁷⁺ complexes with multiply bound hard ligands, such as oxo or nitrido complexes.

Characterization of the redox series 6⁺⁻7⁺⁻8²⁺ supports the electronic structure picture with {π σ̃δ}/(π σ̃δ)/{π σ̃δ} configurations for the W₃LS/W₃LS (6), W₁₅/W₃LS (7⁺) and W₁₅/W₃LS (8²⁺) complexes, respectively (Fig. 1 and Table 1). The spin orbitals of 7⁺ and 8²⁺ are orthogonal to the W₂N₂ core resulting in weak
Protonation induced N₂ splitting vs. proton reduction

N₂ splitting of 6 into the nitride [W(N)Cl(HPNP)]OTf (9OTf, Scheme 4) as the only detectable tungsten species (NMR/EPR spectroscopy, HR-ESI-MS) was achieved upon adding 2 equiv. of triflic acid at −78 °C and gradual warming to r.t. Complex 9OTf could be isolated in over 60% yield and was fully characterized. The tungsten(v) nitride is NMR silent and features an isotropic signal (gav = 1.93) in the X-band EPR spectrum (THF, r.t.) with HFIs with the tungsten and phosphorous nuclei (Å183W) = 220 MHz; Å19P = 56 MHz. The W=N stretching vibration is found in the IR spectrum at 1058 cm⁻¹ (15N-9OTf: Δν = 29 cm⁻¹). In the solid state (Fig. 3, 9⁺ is isostructural with the molybdenum analogue,²⁹ featuring square-pyramidally coordinated tungsten with the nitride ligand in the apical site. Hydrogen bonding of the amine proton with the triflate anion is indicated by the short NH–O distance (2.03(3) Å). The W≡N bond length (1.679(2) Å) is in the typical range found for the related tungsten nitrides.¹⁴,²⁶

In contrast to the Mo analogue 4 (Scheme 2), the selectivity of protonation induced N₂ splitting strongly varies with the reaction conditions. The addition of HOTf (2 equiv.) to 6 at r.t. results in low nitride yields and substantial amounts of the oxidation products 7⁺ and 8²⁺. Furthermore, 2 equiv. of strong acids with weakly coordinating anions, such as [H(OEt₂)₂]Al[OC(CF₃)₃]₄ and [H(OEt₂)₂]Bar²⁺ (Bar²⁻ = B(C₆H₅-3,5-(CF₃)₂)₃), exclusively gave dicative 8²⁺ both at low (−70 °C) and ambient temperatures (Scheme 4). Concomitant H₂ evolution was confirmed by gas chromatography. Reaction of 6 at r.t. with 1 equiv. of these and other acids [HOTf, (2,6-lutidinium) OTf, [HNEt₃]Bar²⁺, [H(OEt₂)₂]Bar²⁺, and [H(OEt₂)₂]Al[OC(CF₃)₃]₄] selectively gives the oxidation product 7⁺ in all cases.

Next, the influence of the acid counterion on the selectivity was probed. Upon protonation with [HNEt₃]Bar²⁺ (2 equiv.), 7⁺ was found exclusively (Scheme 5). The second oxidation is hampered by the higher pK₅ of this acid vs. HOTf, which prevents protonation of the monocaticonic product. Importantly, this selectivity changes with [HNEt₃]OTf (2 equiv.): in this case, 7⁺ is obtained in spectroscopic yields of up to only 30%. In situ HR-ESI-MS examination indicates that nitride 9⁻ is formed as the only other product. This observation is reminiscent of acid dependent selectivities reported by Nishibayashi for catalytic nitrogen fixation (see above).¹³ For this reason, [HNEt₃]Cl (2 equiv.) was also used. Unfortunately, sluggish mixtures of products were obtained, including substantial amounts of trichloride 5. In the next sections, experimental and computational mechanistic examinations with only [HNEt₃]X (X⁻ = Bar²⁻, OTf⁻) are therefore reported.

Mechanistic examinations

Stoichiometric protonation at low temperatures was carried out to obtain spectroscopic information about intermediates. With 1 equiv. of HOTf at low T (−35 °C), the NMR data are in agreement with pincer protonation to diamagnetic dinuclear
C\textsubscript{1}-symmetric \([\text{HPNP}]\text{ClW(μ-N}_2\text{)WCl(HPNP)]OTf}\) (10\textsuperscript{OTf}), analogous to the respective Mo system ([Scheme 6]).

Notably, immediate formation of the oxidation product 7\textsuperscript{+} was observed with \([\text{H(OEt}_2\text{)}_2]\text{[BARF}_{24}\text{]}\), even at temperatures down to −75 °C. The enhanced stability of 10\textsuperscript{OTf} suggests an interaction of the immediate protonation product with the triflate anion. Contact-ion pair formation is confirmed by \textsuperscript{19}F and \textsuperscript{1}H DOSY NMR spectroscopy at −35 °C. The diffusion coefficient of the triflate anion in 10\textsuperscript{OTf} \((D = 2.29 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1})\) is in the same range as that of the cation \((D = 2.18-2.14 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1})\) and significantly reduced compared to free triflic acid \((D = 5.11 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1})\). We tentatively attribute the solution ion-pairing to hydrogen bonding of the triflate with the pincer N–H proton, as found in the solid state for 9\textsuperscript{OTf} ([Fig. 3]).

Protonation of 6 with 2 equiv. of HOTf at low temperatures in THF is associated with a color change from green to yellow. The absence of a signal in the \textsuperscript{31}P([\text{H}] \text{ NMR spectrum and the broadened and strongly shifted \textsuperscript{1}H NMR signals indicate the formation of a paramagnetic product. The magnetic moment for the presumable product, \([\text{N}_2\text{]}\text{WCl(HPNP)]} \text{OTfs}\) (11\textsuperscript{OTfs}), was estimated with Evans' method at −60 °C \((\mu_{eff} = 4.7 \mu_B)\), i.e. close to the spin-only value for a quintet ground state \((4.9 \mu_B)\). Increasing the temperature leads to fading of the color and disappearance of all \textsuperscript{1}H NMR signals, as expected for selective \textsuperscript{N}_2-splitting into the pale, NMR silent nitride product 9\textsuperscript{OTf}.

Mechanistic information about proton reduction was obtained from kinetic studies. For this purpose, \([\text{HNEt}_3]\text{[BARF}_{24}\text{]}\) was used as the acid, which selectively gives 7\textsuperscript{+} at r.t. within a convenient timescale even under pseudo first-order conditions. Addition of the acid to 6 in THF leads to an immediate drop of absorbance without significant change of the absorption maxima, suggesting only small changes in the electronic structure. The acid concentration dependence of the absorbance allowed for estimating the equilibrium constant and forward rate of the initial protonation of 6 \((K_1 = 1592 \pm 578 \text{ M}^{-1}, k_1 = 163 \pm 47 \text{ M}^{-1} \text{ s}^{-1})\) ([Scheme 7 and Fig. S25 and S26 in the ESI†]). This step is followed by a much slower, monoeponential decay, which was monitored over 5 h (Fig. 4, left). Under pseudo first order conditions in acid \((c(\text{HNEt}_3) + c(\text{6}) = 10–25)\), the rate constant \((k_{obs(2)})\) linearly depends on the acid concentration (Fig. 4, right), which is in agreement with a slow, irreversible second protonation after the initial, fast pre-equilibrium \(K_1\). However, the non-zero intercept indicates the presence of at least one competitive pathway at a low acid concentration. The rate constant \(k_{obs(2)}\) for the formation of 7\textsuperscript{+} was therefore expressed as eqn (1) which results from the minimum kinetic model outlined in Scheme 7:

\[
k_{obs(2)} = \frac{k_2K_1[H^+]^2}{1 + K_1[H^+]} + k_{obs}
\]

The first term accounts for the initial protonation of 6 to give 10\textsuperscript{+}, followed by irreversible H\textsubscript{2} release from acid and 10\textsuperscript{7+}. Rapid, subsequent comproportionation of the resulting 8\textsuperscript{+} with 6 to 2 × 7\textsuperscript{+} is in line with the electrochemical results \((K_c = 10^8\text{, see above})\). The second term in eqn (1) is ascribed to bimolecular decay of 10\textsuperscript{+} as an alternative path at low acid concentrations. The rate constant \(k_3 = 0.018 \pm 0.001 \text{ M}^{-1} \text{ s}^{-1}\) was derived from fitting the experimental data to eqn (1) (with preserved \(K_c\)) under pseudo first order conditions in acid (10–25 equiv.). The rate constant \(k_3 = 0.4 \text{ M}^{-1} \text{ s}^{-1}\) for the bimolecular path at low acid concentrations was obtained from the initial rate of the reaction of 6 and an equimolar amount of \([\text{HNEt}_3]\text{[BARF}_{24}\text{]}\).

Kinetic analysis suggests two pathways for H\textsubscript{2} formation which both go through the spectroscopically characterized common intermediate 10\textsuperscript{+} (as 10\textsuperscript{OTf}). Path B ([Scheme 7]) explains the decay of 10\textsuperscript{+} even in the absence of the acid and reflects a bimolecular H\textsubscript{2} formation route as proposed by Matson and Peters for an iron diazenide N\textsubscript{2} fixation intermediate. However, path A is predominant with excess acid. Besides these routes for hydrogen evolution, splitting of the N\textsubscript{2} bridge is observed in the presence of triflate as the counteranion and is even selective at

![Scheme 6](https://example.com/scheme6.png)

**Scheme 6** Oxidation of 6 with 1 equiv. of acid at different temperatures.

![Scheme 7](https://example.com/scheme7.png)

**Scheme 7** Proposed mechanistic pathways for proton reduction at high (Path A) and low (Path B) acid concentrations.

![Fig. 4](https://example.com/fig4.png)

**Fig. 4** Left: plot of the absorbance at 607 nm vs. time for different concentrations of \([\text{HNEt}_3]\). Results from fitting to the rate law are indicated by red lines. Right: plot of \(k_{obs(2)}\) vs. \([\text{HNEt}_3]\).
lower temperatures. These effects are rationalized computationally in the next section.

**Computational examinations**

Protonation with [NEt₃H][BF₄] was first examined computationally with trimethylammonium as the model acid (Scheme 8). Two different sites, a metal ion and a pincer nitrogen atom, respectively, were considered for the first protonation step. A hydride product [PNP]W{HCl(μ-N₂)WCl(PNP)}₂ (12⁺) adopts an electronic singlet (S = 0) ground state and was found to be the global protonation minimum at ΔG^RESS = −4.7 kcal mol⁻¹ below 6 and [NMe₃H]⁺. Hence, the model computation is in excellent agreement with the experimental equilibrium constant K₁. The computed structure of 12⁺ features a bridging hydride between the metal ion and a pincer phosphorous atom. A similar structure was previously found experimentally by Schrock and co-workers for the protonation of a PCP molybdenum(v) nitride by [NEt₃H][BArF₄]. All efforts to experimentally verify hydride intermediates like 12⁺ were unfortunately unsuccessful. However, pincer protonation to 10⁺ is only slightly less exergonic (ΔG^RESS = −2.9 kcal mol⁻¹). Importantly, this state is further stabilized upon use of [NEt₃H]⁺ as the acid due to hydrogen bonding of the pincer amine moiety with the trflate anion by (ΔG^RESS = −2.1 kcal mol⁻¹). In contrast, the hydride ligand is not involved in hydrogen bonding, rendering 10³⁺⁻ (ΔG^RESS = −5.0 kcal mol⁻¹) the global minimum of the first protonation step. Overall, the metal and pincer protonation products 12⁺ and 10⁺ (and 10³⁺⁻ in the presence of triflate) should be in rapid equilibrium under these conditions, which is slightly shifted towards pincer protonation by hydrogen bonding with the counteranion. Notably, hydrogen bonding with the conjugate base NMe₃ was not observed, presumably for sterical reasons.

Starting from the amine/hydride equilibrium, the second protonation with [NMe₃H]⁺ can ultimately lead to hydrogen evolution or N₂ splitting, respectively. The formation of H₂ and dicaticonic 8²⁺, which represents Path A (Scheme 7), was computed to be exergonic by (ΔG° = −12.8 kcal mol⁻¹) with respect to 6. The most reasonable pathway (Scheme 8, right branch) proceeds via hydride protonation of 12⁺ leading to the dihydrogen intermediate [PNP]W(H₂)Cl(μ-N₂)WCl(PNP)]²⁺ (13²⁺), which is unstable and readily releases H₂ without barriers. While the transition state that leads from 12⁺ to 13²⁺ could not be reliably located due to the flat potential energy profile of protonation, the free energy of 13²⁺ (ΔG° = +19.7 kcal mol⁻¹ with respect to 12⁺) was used as an estimate for the kinetic barrier of hydride protonolysis.⁸ Notably, this value is in excellent agreement with the experimentally derived barrier for Path A (k₂ = 0.018 M⁻¹ s⁻¹; ΔG° = 19 kcal mol⁻¹).

Alternatively, splitting of the dinitrogen bridge (Scheme 8, left branch) was computed to proceed via protonation of the second pincer nitrogen. In the absence of triflate, [(N₂)WCl{HPNP}][OTF]⁻ (11⁻) was located at ΔG° = +5.0 kcal mol⁻¹ vs. 6 (ΔG° = +9.7 kcal mol⁻¹ vs. the global first protonation minimum 12⁺) adopting an electronic quintet (S = 2) ground state in accordance with the experimental findings for 11⁻⁻OTF. From there, N₂ cleavage into the nitrides 9⁻⁻ was computed to be strongly exergonic (ΔG° = −49.7 kcal mol⁻¹) with a kinetic barrier ΔG° = 21.7 kcal mol⁻¹) that is comparable to the experimentally derived barriers for [(N₂)MoCl{HPNP}][OTF]⁻ (ΔG° = 19.5 kcal mol⁻¹) and [(N₂)ReCl(PNP)]²⁻ (ΔG° = 19.8 kcal mol⁻¹), respectively. For the tungsten system, this gives

![Scheme 8](https://example.com/scheme8.png)

Scheme 8: Computed energy profile for protonation induced N₂ splitting (left branch) and hydrogen evolution via Path A (right branch) via double protonation of the dinitrogen complex 6 at room temperature in the absence (solid line) and presence (dashed line) of triflate as the counteranion.
rise to an overall effective barrier for protonation induced N₂ splitting from the most stable monoprotonation intermediate, hydride 1²⁺, of ΔG°₂₉⁸ ≈ 31.4 kcal mol⁻¹. This value is considerably higher than the estimate for the hydrogen evolution pathway (ΔG°₂₉⁸ = +11.5 kcal mol⁻¹), which is in line with selective proton reduction with [NEt₃H][BArF₁₂] as the acid.

Importantly, the relative energetics of these two reaction channels are perturbed in the presence of triflate as the counteranion. As was found for the first pincer protonation (see above), triflate hydrogen bonding stabilizes the pincer diprotonation product 1¹⁰⁻⁻⁻ by −8.8 kcal mol⁻¹. Consequently, the estimated effective barrier for hydrogen evolution (ΔG°₂₉⁸ K⁺ = 20.2 kcal mol⁻¹ vs. the global first protonation minimum in the presence of triflate 1⁰⁻⁻⁻) is slightly raised. On the other hand, the N₂ splitting pathway (ΔG°₂₉⁸ K⁺ = 21.5 kcal mol⁻¹ vs. 1⁰⁻⁻⁻) is almost isoenergetic, in full agreement with the experimental findings. The triflate induced effect on selectivity is therefore attributed to Curtin–Hammett controlled reactivity wherein N–H hydrogen bonding to the counteranion modifies the energetics of the protonation pre-equilibria.

A similar picture evolves for the reaction with triflic acid (see the ESI, Scheme S1†). However, the potential energy of protonation is augmented by the higher driving force with the stronger acid (pKₐ (Et₃NH⁻) – pKₐ (HOTf) = 4.7). This affects the selectivity as the effective barrier for the N₂ splitting branch versus hydrogen evolution is close in energy. Furthermore, all rate determining states are below the starting point 6. In consequence, under these conditions (HOTf as the acid at r.t.), Curtin–Hammett conditions do not apply resulting in the experimentally observed low selectivity. Reduction of the temperature to −80 °C further perturbs the relative energetics of the two reaction pathways with HOTf. The computed amine (ΔG°₂₉₃ K⁺ 1⁰⁻⁻⁻) = 15.1 kcal mol⁻¹) vs. hydride (ΔG°₂₉₃ K⁺ 1²⁺⁻⁻⁻) = −10.3 kcal mol⁻¹) equilibrium is even more shifted towards the amine due to the lower entropic penalty for hydrogen bonding at low T. The negligible population of the hydride tautomer is in agreement with the exclusive experimental observation of 1⁰⁻⁻⁻ and 1¹⁰⁻⁻⁻ upon single and double protonation with HOTF at −80 °C. From 1¹⁰⁻⁻⁻, the dihydrogen complex 1³⁺⁻⁻⁻ (ΔG°₂₉₃ K⁺ 1³⁺⁻⁻⁻) = 12.7 kcal mol⁻¹⁻⁻⁻) is much higher in free energy than the barrier for N₂ splitting (ΔG°₂₉₃ K⁺ = 19.9 kcal mol⁻¹⁻⁻⁻), in line with selective N₂ splitting upon double protonation with HOTF at −80 °C and slow warming.

Concluding remarks

In summary, an anion effect on the selectivity of proton induced dinitrogen splitting (NR) vs. hydrogen evolution (HR) at the N₂ bridged ditungsten complex 6 was demonstrated and rationalized. Our spectroscopic, kinetic and computational studies suggest some guidelines to improve NR over HR yields:

(a) Nitrogen vs. metal protonation offers separate reaction channels with a proposed hydride isomer leading to hydrogen evolution analogous to the highly active Mo-oxo polypyridyl HR catalysts. The tautomerisation equilibrium can be offset by hydrogen bonding with protic N–H hydrogen atoms favoring the use of an acid [BH]⁺X⁻ where the anion X⁻ is prone to form H-bonds for high NR selectivity.

(b) Protonation under Curtin–Hammett control with weak acids can become irreversible with strong acids. Hence, the pKₐ of the acid can have a decisive kinetic effect on the selectivity.

(c) Lower temperatures favour hydrogen bonding interactions due to the reduced entropic penalty as a strategy for increased NR yields.

Besides the immediate application to the current system, these findings might be considered as a model reaction for nitrogen fixation schemes. The studies of Peters and of Nishibayashi have emphasized the importance of proton coupled electron transfer for N₂ fixation under ambient conditions. Our kinetic model might therefore offer some general strategies regarding the choice of acid to improve NR selectivities with respect to unproductive proton reduction.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

† An alternative pathway via reduction of 10⁺ with 6 is less likely based on the derived rate constant (k₁ = 0.12 M⁻¹ s⁻¹⁻¹), which is considerably smaller than k₁.
§ A transition state for the direct protonation of 1²⁺ with HNMe₃⁺ at the hydride ligand was located at 25.4 kcal mol⁻¹ above 6 and two equivalents of [HNMe₃]⁻.

However, this activation free energy is considerably higher than the experimentally determined value (ΔG°₂₉₃ = 19 kcal mol⁻¹). It is not clear if this deviation can be attributed to the computational truncation of the acid or to a lower competing pathway. We therefore prefer to use the experimental value for the discussion of the selectivity. See also the ESI for further discussion.†

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