A low-valent dinuclear ruthenium diazadiene complex catalyzes the oxidation of dihydrogen and reversible hydrogenation of quinones†

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The dinuclear ruthenium complex [Ru₂H(H)(Me₂dad)(dbcot)]₂ contains a 1,4-dimethyl-diazabuta-1,3-diene (Me₂dad) as a non-innocent bridging ligand between the metal centers to give a [Ru₂(Me₂dad)] core. In addition, each ruthenium is bound to one dibenzo[a,e]cyclooctatetraene (dbcot) ligand. This Ru dimer converts H₂ to protons and electrons. It also catalyzes reversibly under mild conditions the selective hydrogenation of vitamins K₂ and K₃ to their corresponding hydroquinone equivalents without affecting the C=O double bonds. Mechanistic studies suggest that the [Ru₂(Me₂dad)] moiety, like hydrogenases, reacts with H₂ and releases electrons and protons stepwise.

Hydrogenase enzymes are the most efficient biological catalysts for the mutual interconversion of hydrogen to protons and electrons, H₂ ⇌ H⁺ + H⁻.1–4 A detailed understanding of the mechanisms of these reactions is necessary for the development of efficient artificial catalytic systems for the use of H₂ as a renewable energy source.5 Currently, there are three classes of hydrogenases known which either contain a bimetallic core, [Fe₂Fe] or [Fe₂Ni], or a single Fe center as active sites.6–8 Intensive spectroscopic investigations, including the determination of the structures of several hydrogenases by single-crystal X-ray diffraction methods,6–8 allowed extraction of the essential features needed for activity: (i) redox active metal centers; (ii) an electron reservoir; (iii) a cooperating ligand9–11 participating reversibly in the heterolytic cleavage/formation of H₂; and (iv) a free coordination site for substrate binding (see a simplified sketch of the active [Fe₂Fe] core at the top of Fig. 1).

All hydrogenases contain CO and some CN as archetypical σ-donor/π-acceptor ligands that keep iron in a low spin state and link these enzymes to classical organometallic chemistry. Consequently, the synthesis of hydrogenase model complexes is an intensively investigated topic of organometallic chemistry and some recent relevant examples A–G are shown in Fig. 1. Complexes A and B employ redox non-innocent ligands like biphenyl12 or phosphole13 in order to mimic Fe₄S₄ ferredoxines as ubiquitous electron reservoirs in enzymes.14,15 Both complexes, A and B, are active electrocatalysts for the production of H₂ from acidic media. To date, the closest model to natural [Fe₂Fe] hydrogenases is complex C, which can catalyze the oxidation of H₂ to H⁺ in the presence of an oxidant and a base.16 The discovery that basic sites in a chelating diphosphane ligand greatly enhance the efficiency of heterolytic H₂ splitting and the electrochemical oxidation of H₂ has led to the development of iron or nickel complexes like D as functional hydrogenase models which achieve truly impressive turnover frequencies (TOFs) of up to 100 000 s⁻¹ for the electrocatalytic production of H₂.19–21 When tethered to conducting support materials, derivatives of D allow fabrication of membrane-electrode assemblies at which H₂ is produced at a very low overpotential.18 The structural and functional model E for [Ni₄Fe] hydrogenase was reported, which likewise generates H₂ from mildly acidic solutions with high rates.24 The mononuclear iron model complex F in combination with an apoenzyme was used to prepare an [Fe] hydrogenase model.25 Remarkably, this semiartificial enzyme, like its natural counterpart, is able to reversibly hydrogenate methylene tetrahydromethanopterin. Due to the enhanced stability of Ru hydrides, the replacement of Fe with Ru in artificial enzymes has also been investigated.26–29 Several dinuclear ruthenium complexes were proposed as hydrogenase mimics.30–34 For example, Rauchfuss et al. achieved the photochemical addition of H₂ across the Ru–Ru bond in complex G and moreover could demonstrate that the terminal hydride ligand in the resulting diruthenium dihydride complex is more easily protonated than the bridging hydride.30

Recently, diazadiene olefin complexes [M(trop₂dad)] with low-valent iron or ruthenium centers became accessible
In these complexes, the trop2dad ligand combines the well-established chemical and redox non-innocence of diazadienes (dads) and related ligands with the σ-donor/p-acceptor properties of olefins. Some of these low-valent metal complexes have remarkable properties. For example, [Ru0(trop2dad)] was found to be an efficient catalyst for the clean conversion of aqueous basic methanol or formaldehyde solutions into H2 and carbonate. Herein we report the synthesis of the dinuclear complex [Ru2(Me2dad)(dbcot)2](3) which under 1 bar of H2 is converted to [Ru2H(m-H)(Me2dad)(dbcot)2](3(m-H)H) as a fully artificial but functional [Fe,Fe] hydrogenase model (Fig. 2). This complex catalyzes the oxidation of hydrogen to protons and electrons as well as the reversible and selective hydrogenation of vitamin K3 (VK3) or vitamin K2 (VK2) forming dihydrovitamin K3 (VK3H2) or VK2 hydroquinone (VK2H2) without affecting the C=C double bonds of these vitamins.

Refluxing dbcot with ruthenium(III) chloride trihydrate in ethanol and THF quantitatively produces the brown coordination polymer [RuCl2(dbcot)]1, which reacts further with N,N'-dimethyldiaminoethane (Me2en) in THF and forms the mononuclear complex [RuCl2(Me2en)(dbcot)]2 in 92% yield (Fig. 2). The deprotonation of 2 by 2.05 eq. of KOTBu produced a tetranuclear complex, [K][Ru4(m-H)(Me2dad)]2(dbcot)4 ([K][32(m-H)]) in 40% yield as the major species (for detailed spectroscopic data of all isolated complexes reported in this work see the ESI†). Reducing the tetranuclear [K][32(m-H)] with 3.4 equivalents of KC8 generates the dianionic dinuclear [K]2[Ru2(Me2dad)(dbcot)]2([K]2[3]) in 85% yield. The 2 : 1 ratio of dbcot to Me2dad and lack of hydride signals in the 1H NMR spectrum suggests the presence of a Ru dimer complex with no hydrides. The low-frequency shift of the Me2dad and olefinic protons in [K]2[3] compared to [K][32(m-H)] is consistent with a more electron rich complex (see ESI Table 2†). The oxidation of [K]2[3] with 2 eq. of [Fe][PF6] gives a neutral dinuclear complex Ru3(Me2dad)(dbcot)3(3) in 77% yield. The 1H NMR spectra of 3 show sharp resonances at 0 °C, indicating the structure shown in Fig. 2, in which one Ru center is coordinated in a cis,N,N fashion, and the other in an η1 fashion by the bridging Me2dad ligand. But broad signals for the aromatic and olefinic protons are observed at room temperature, indicating molecular dynamics phenomena. Various NMR experiments show that two dynamic processes occur: (i) exchange of the cis,N,N/η1
coordination mode of the Me2dad ligand between the two Ru centers and (ii) rotation of the dbcot ligands (see ESI Fig. 3 for details). Finally, exposure of 3 to 1 bar of H2 quickly forms a dinuclear dihydride complex, Ru2H(μ-H)(Me2dad)(dbcot)2 (3(μ-H)H), in quantitative yield. The two Ru–H resonances at −0.74 ppm and −2.74 ppm in THF-d8 show a coupling of 2JHH = 8.7 Hz, which suggests that both hydrides coordinate to the same Ru atom. The NOESY spectrum allows us to propose the structure of 3(μ-H)H as shown in Fig. 2 with a bridging hydride (δ = −0.74 ppm) and a terminal hydride (δ = −2.74 ppm) (see ESI Fig. 5†).

Single crystals of [K]2[3(μ-H)] and [K]2[3] were obtained from a THF/DME/hexane mixture in the presence of 18-crown-6. Crystals of 3(μ-H)H were grown by slow evaporation of a saturated benzene solution. All structures were investigated by X-ray diffraction methods and plots are shown in Fig. 3. [K]2[3(μ-H)] is a tetranuclear complex which contains two bimetallic ruthenium moieties bridged by a hydride. The complex [K]2[3] is best described as an ion pair [K]4[3]− in which the [K]4− anion consists of a sandwich complex with a (dbcot)Ru2C2 unit as the central deck to which a Ru(dbcot) fragment binds in an η1-fashion to one side and a K(18-crown-6) fragment to the other side. The dinuclear dihydride 3(μ-H)H contains a bridging and a terminal hydride located on a plane of symmetry including also the two Ru centers, similar to the complex Ru2(S2C2H4)(μ-H)(H)(CO)4(PCy3)2 G reported by Rauchfuss et al. Note that in the Ru2 complex fragments, the κ24,κNη4 coordination mode of the diazadiene ligand centers is retained in all complexes. This structural motif is known for related dimeric [Ru2(CO)5(R2dad)] complexes.42

The Ru–Ru distances in [K]2[3(μ-H)], [K]2[3] and 3(μ-H)H are 2.6947(5), 2.8239(8) and 2.7300(3) Å, respectively, similar to the ones observed in the Ru(r) dimer complexes (2.632–2.937 Å), suggesting the presence of Ru–Ru bonds. The longer Ru–Ru distance in [K]2[3] (2.8239(6) Å) reflects the highly reduced state of this species. Also, the olefinic bonds in [K]2[3] (average of 1.450(3) Å) are longer than the ones in [K]2[3(μ-H)] (average of 1.433(3) Å) and 3(μ-H)H (average of 1.424(3) Å), indicating strong back donation from the Ru–Ru unit into the π* orbitals of the coordinated C=Cdbcot bonds. This effect increases with increasing anionic charge of the complex (in free dbcot, the average olefin bond length is 1.321 Å). Note that the C=Cdbcot bond lengths coordinated to Ru2 are longer than those bound to Ru1, indicating a higher electron density at Ru2. Of special interest are the C–N and C–C bond lengths of the diazadiene ligand because they reflect the oxidation state of the ligand and consequently also of the metal. The neutral diimine form, RN=CH–CH=NR, binds to a low-valent metal center, M0, and is characterized by short C–N bonds (∼1.29 Å) and a long C–C bond (∼1.46 Å). With increasing shift of electron density from the metal center to the ligand, the C–N bonds are lengthened while the C–C bond shortens: in the diazadiene radical anion [RN=CH–CH=NR]−, coordinated to M+*, C–N = 1.33 Å and C–C = 1.39 Å; in the dianionic bisamido olefin form [RN=CH–CH=NR]−, coordinated to M+**, C–N = 1.38 Å and C–C = 1.35 Å. The C–N and C–C bonds of the Me2dad ligand in [K]2[3(μ-H)], [K]2[3] and 3(μ-H)H are approx. 1.38 Å and 1.39 Å, respectively, indicating a reduced form of the ligand. Consequently, the oxidation states at the Ru centers vary between 0 and +1. These data illustrate the redox non-innocent behavior of the Me2dad ligand in these complexes.43,44 The bridging coordination modes of 2e− reduced dad and the closely related pyridine-diimine ligands have been reported before.45,46

The ability to split H2 into protons and electrons like that of hydrogenases was investigated using the “Rauchfuss test.” In the presence of ten equivalents of PPh3 and [Fe][PF6], 3(μ-H)H catalytically splits hydrogen into protons and electrons under 1 bar H2 at 40 °C, forming protonated triphenylphosphine [Ph3PH][PF6] and Cp2Fe in THF within 1.5 hours (Fig. 4a). More compellingly, 3(μ-H)H is able to catalyze reversibly the hydrogenation of the biologically relevant vitamins VK3 and VK2.47,48 Hydrogenation of VK3 was investigated under 1 bar or 15 bar H2 pressure, at 40 °C or 70 °C (ESI Table 3, entries 1–37). With 1 bar H2, a TON of 252 was achieved. Remarkably, 3(μ-H)H remained active even after 2 months. At 70 °C and 15 bar H2, 0.13 mol% 3(μ-H)H converts 65% of VK3 to VK3H2 to give a TON of 220. Under 15 bar H2, the TOF values at 40 °C and
70 °C are 2.2 and 10 h⁻¹, respectively. VK₂ is a more delicate substrate because it tautomerizes. At room temperature, the dehydrogenation of VK₂ is more selectively achieved (ESI Table 3, entries 5–7). The TON values of VK₃H₂ and VK₂H₂ are 70 (in 48 h) and 24 (in 40 h), respectively. The TOFs for hydrogenation of VK₂ is more selectively achieved (ESI Table 3, entry 4). Our attempts to characterize [3(μ-H)H][OTf] by EPR spectroscopy failed so far and oxidation of [3(μ-H)H] with [Fc][OTf] or reduction of [3(μ-H)H][OTf] with Cp₂Co at 20 K in Me₂THF glass afforded only very weak EPR signals characteristic of a mixture of metal-centered radical species with g-values in the range of 2.6–1.8 and 2.5–1.7, respectively, which are unlikely to stem from any of the paramagnetic on-cycle catalytic intermediates (such as [3(μ-H)H]+ or [3(μ-H)]⁻; vide infra). Note that...
complex [3(μ-H)(OTf)] is catalytically active in both reactions (a) and (b) shown in Fig. 4.

In the next experiment, 3(μ-H)H was oxidized with one equivalent of [Fc][PF6] in the presence of one equivalent of PPh3. Exclusively, [Ru2(μ-H)(Me2dad)(dbcot)]2[PPh3][PF6], [3(μ-H)(PPh3)][PF6].[33] A second equivalent of oxidant is needed to rapidly convert 3(μ-H)H into 3(μ-H)(PPh3)]+.[34] A second equivalent of oxidant is needed to turn over the catalytic cycle to give back [3(μ-H)(PPh3)]+ as the resting state within the catalytic cycle. The complex [3(μ-H)(PPh3)]+ is in equilibrium with [3(μ-H)]† (likely as a solvated adduct [3(μ-H)(solv)]† and present at low concentration), which may coordinate with H2 to give [3(μ-H-H)]+. Deprotonation of [3(μ-H)(H2)]+ by PPh3 (vide infra) gives the phosphonium salt [Ph3PH]+ and regenerates 3(μ-H)H. A second equivalent of oxidant is needed to turn over the catalytic cycle to give back [3(μ-H)(PPh3)]+ as the resting state via the reaction sequence given above.

A slightly different reaction path was observed for the reaction of 3(μ-H)H with quinones. The reaction between 3(μ-H)H and VK3, in the absence of H2, formed a thick suspension, which prevents further characterization by NMR spectroscopy. However, upon addition of a large excess of NaOTf, a signal attributed to complex [3(μ-H)(OTf)] was detected by 1H NMR spectroscopy. No reaction between NaOTf and 3(μ-H)H was observed in the absence of VK3. These data suggest that the terminal hydride of 3(μ-H)H was transferred to VK3, which then formed a protonated semiquinone oxygen bound species [3(μ-H)(VKH)] (see the proposed structure based on DFT calculations in Fig. 8), and that VKH+ is labile enough to be partially displaced by OTf−. When followed by EPR spectroscopy at room temperature, the reaction between 3(μ-H)H and VK3 led to the formation of one organic radical species, which is detected by formation of the EPR silent and sparsely soluble [3(μ-H)(VKH)] as the only product. With the symmetrical benzoquinone 2,5-di-tert-butyl-p-benzoquinone as the model substrate, in situ monitoring of the reaction with 3(μ-H)H afforded immediately the paramagnetic HSO† (protonated semi-quinone) species (doublet, giso = 2.005, Aiso = 10.0 Hz; see ESI part 7.4†).

These observations support the catalytic cycle B shown in red in Fig. 6, in which the neutral semiquinone radical VKH− and the neutral organometallic Ru2 radical [3(μ-H)]+ were formed. It
Proposed mechanisms of H₂ splitting by 3(µ-H)H using PPh₃ and [Fc][PF₆] as the proton and electron acceptors (Cycle A, left), and hydrogenation of vitamin Kₙ (n = 2 or 3) to their hydroquinone analogs by 3(µ-H)H (Cycle B, right).

DFT calculation for the activation of H₂ from [3(µ-H)]⁺ in the presence of PPh₃. The transition state for the deprotonation of the H₂ complex by PPh₃ was not found; however, the direct reaction path from [3(µ-H)(H₂)]⁺ (−3.5 kcal mol⁻¹) to 3(µ-H)H + [Ph₃PH]⁺ (−11.3 kcal mol⁻¹) cannot be excluded.
is still unclear if these radical species are formed via direct hydrogen transfer from \([3(\mu-H)H]^{+}\) to VK, or via initial electron transfer to form the oxidized complex \([3(\mu-H)H]^{+}\) and the reduced quinone \([\text{VK}_n]^{+}\), followed by proton transfer to form \([3(\mu-H)H]^{+}\) and \([\text{VK}_n]^{+}\). Subsequent radical recombination with net reduction of the semiquinone radical forms the observed complex \([3(\mu-H)(\text{VK}_n)H]\). This complex is subsequently hydrogenated by \(H_2\) to give the product \(\text{VK}_nH_2\) and \(3(\mu-H)H\), which is the resting state in this cycle as observed during a single turnover experiment (ESI, Fig. 13†). In this mechanism, the observation of \(3(\mu-H)H\) as the only species present after a single turnover experiment is consistent with a less acidic product \(\text{VK}_nH_2\) compared to \([\text{Ph}_3\text{PH}]^+\).

The activation steps of \(H_2\) by the \(\text{Ru}_2(\text{Me}_2\text{dad})\) core, in both catalytic reactions, were investigated by DFT calculations without using structural simplification (\(\Delta G\) values are given here, see Fig. 7 and ESI part 8†). In the absence of other substrates, \(H_2\) adds to \([3(\mu-H)]^+\) to give \([3(\mu-H)(H_2)]^+\) in a weakly exergonic reaction. This complex can react with a basic substrate like \(\text{PPh}_3\), to give the products \(3(\mu-H)H\) and \([\text{Ph}_3\text{PH}]^+\) in an overall exergonic reaction (\(-11.3 \text{ kcal mol}^{-1}\)) although we did not succeed in finding any transition states for this bimolecular activation. Alternatively, heterolytic cleavage across one Ru–N bond is energetically accessible via TS-1 at 15.8 kcal mol\(^{-1}\) to give \([3(\mu-H)H]_2\]^+. This complex can either rearrange into complex \([3(\mu-H)(H_2)]_2\]^+ to give a hydrogenated C=\(N\) bond of the \(\text{Me}_2\text{dad}\) ligand or the acidic NH group is deprotonated to give the products \(3(\mu-H)H\) and \([\text{Ph}_3\text{PH}]^+\). Note that the direct heterolytic cleavage of \(H_2\) across a Ru C vector via TS-2 and the hydrogenation of one of the C–\(\text{C}_\text{dbco}\) bonds via TS-3 are both highly unfavorable processes. With \([3(\mu-H)]^+\), \(\text{PPh}_3\) forms a stable complex, \([3(\mu-H)(\text{PPh}_3)]^+\) (\(-22.3 \text{ kcal mol}^{-1}\)), which agrees with our assumption that this is the resting state in the catalytic splitting of \(H_2\) with \(\text{PPh}_3\) and \([\text{Fe}][\text{X}]\). The DFT calculations, for the reaction with \(\text{VK}_n\) (Fig. 8), confirm that \(\text{VK}_nH^+\) forms a stable complex, \([3(\mu-H)(\text{VK}_n)H]\) (\(-38.9 \text{ kcal mol}^{-1}\)), in the reaction with \([3(\mu-H)]^+\). But in this case, the final products \(\text{VK}_nH_2\) and \(3(\mu-H)H\) (\(-45.0 \text{ kcal mol}^{-1}\)) are more stable. That is, the adduct \([3(\mu-H)(\text{VK}_n)H]\) is not the resting state in this cycle but \(3(\mu-H)H\). The cleavage of \(H_2\) involves a classical sigma-bond metathesis transition state TS-4 at 32 kcal mol\(^{-1}\) in which hydrogen is activated across the oxygen atom of the coordinated \(\text{VK}_nH\) and the ruthenium metal center. Subsequently, TS-4 collapses in a strongly exergonic reaction to give the products \(\text{VK}_nH_2\) and \(3(\mu-H)H\). This finding agrees with the measured kinetic isotope effect (1.89), which indicates that the cleavage of \(H_2\) is likely involved in the rate determining step. The activation of \(H_2\) may also occur across a Ru–N bond and involves the second Ru center situated far from the Ru–\(\text{VK}_nH\) unit but this activation barrier is significantly higher (\(\Delta G^\ddagger = 42.5 \text{ kcal mol}^{-1}\)).

**Conclusions**

The complex \([\text{Ru}_2(\mu-H)(\text{Me}_2\text{dad})(\text{dbco})_2]\), \(3(\mu-H)H\), can be regarded as a fully artificial mimic of binuclear [Fe,Fe] hydrogenases. The \(\text{Ru}_2(\text{Me}_2\text{dad})\) core serves as an electron reservoir and \([\text{K}]_2[\text{Ru}_2(\text{Me}_2\text{dad})(\text{dbco})_2]\), \([\text{K}]_2[3]\), is the most reduced species and \([\text{Ru}_2(\text{Me}_2\text{dad})(\text{dbco})_2]\), \(3\), is the most oxidized species. The \(\text{Me}_2\text{dad}\) ligand binds in an \(\text{N},\text{N}^\text{N}_{\text{N}}\)-fashion to one Ru center, resulting in a five-membered \(\text{RuN}_2\text{C}_2\) heterocycle with a conjugated \(\pi\)-electron system. Formally, this \(\text{Ru}_2\text{N}_2\text{C}_2\) heterocycle coordinates to a second Ru center as a heteroatom.
analogue of archetypical cyclopentadienyl ligands, a structural feature known for dinuclear Ru2(dad) complexes. However, the Ru2(dad) complexes reported in the literature carry CO as additional ligands and are likely too unstable to serve as efficient catalysts. In this study, the very rigid and concave shaped dibenzocyclooctatriene, dbcot, was used as a neutral four electron π-donor and π*-acceptor ligand, which stabilizes all complexes. A Ru–Ru interaction of about 2.7 Å is observed in all complexes, structurally characterized by single crystal X-ray diffraction methods, which is remarkably invariant. Furthermore, the C=C in dbcot units bound to the Ru centers do not differ much in length (by 0.05 Å between [K][3][longest] and [m(H)][PF6][shortest]), indicating that the electron densities at the Ru centers in the various complexes are rather similar. Small structural and electronic variances at the metal centers are also a feature of [Fe,Fe] and [Ni,Fe] hydrogenases.124,51–58 The complex 3[m(H)]H is a catalyst that splits H2 into protons and electrons in the presence of PPh3 and [Fc][PF6], forming [Ph2PH][PF6] and Cp2Fe (Rauchfuss test for hydrogenase activity), and reversibly and selectively hydrogenates vitamins VK3 or VK2, which are natural substrates for the enzyme hydrogen:quinone oxidoreductase. Spectroscopic data strongly suggest that like in hydrogenases, multiple coupled electron and proton transfer steps might be involved in these reactions. Clearly, the observed activities and efficiencies must be significantly improved. But this investigation demonstrates that redox and chemically non-innocent ligands may be key components and their variation may allow further improvements and uncovering of new bearings in synthesizing small molecular hydrogenase mimics.

Conflicts of interest
There are no conflicts to declare.

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Notes and references


