Redox Chemistry

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Reversible Hydride Generation and Release from the Ligand of $[Ru(pbn)(bpy)_2](PF_6)_2$ Driven by a pbn-Localized Redox Reaction**

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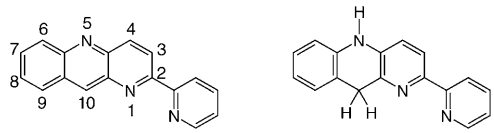
Metal hydrides such as $LiAlH_4$ and $NaBH_4$ have been widely employed in organic synthesis as fundamental reducing agents, and numerous modified forms have been developed for specific purposes. In biological reactions, on the other hand, the NAD^+/NADH redox couple, in which the oxidized form (NAD^+) with a pyridinium structure is reversibly converted into the reduced form (NADH) with two electrons and one proton, plays a key role in reversible hydride transfer reactions. Chemists have focused much attention on the function of NADH as an *organic hydride*. A number of kinetic studies of the hydride transfer,[1] asymmetric reductions of carbonyl compounds,[2] electron and hydrogen-atom transfer[3] with NADH and its model compounds have been carried out. However, as far as we know, all the reactions so far reported using NAD^+/NADH model compounds are stoichiometric.[2,4]

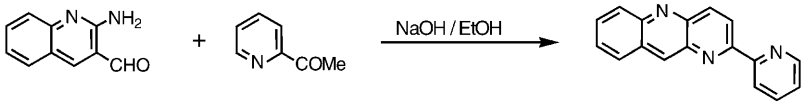
Recently, we revealed that the electrochemical reduction of *cis*-$[Ru(napy\text{-}\kappa N)(CO)(bpy)_2](PF_6)_2$ (napy = 1,8-naphthyridine) at −1.34 V (versus the ferrocene/ferrocenium (Fc/Fc^+) couple) in H_2O results in bond formation between the noncoordinating N atom of napy and the carbonyl carbon atom as well as the subsequent hydrogenation of the napy ring. Reoxidation of the solution at 0.06 V fully regenerated *cis*-$[Ru(napy\text{-}\kappa N)(CO)(bpy)_2]^{2+}$ (Scheme 1).[5] The reversible formation of a C–H bond in a pyridinium ring by two electrons and one proton (Scheme 1) is in good agreement with the NAD^+/NADH redox couple. This observation has driven us to construct a catalytic system that is able to generate and release hydride ions from a ligand of a transition-metal complex, because until now there has been no report of transition-metal complexes operating in the same way as the NAD^+/NADH system. Herein we describe the synthesis and electrochemical behavior of $[Ru(pbn)(bpy)_2](PF_6)_2$ (**1**, pbn = 2-(2-pyridyl)benzo[*b*]-1.5-naphthyridine, bpy = 2,2′-bipyridine; Scheme 2). The electrochemical



Scheme 2. Ligands used to form a catalytic system.

reduction of **1** under aqueous acidic conditions induces formation of the hydrogenated product $[Ru(pbnH_2)(bpy)_2](PF_6)_2$ (**2**). We also report the electrochemical reduction of acetone by using complex **1** as a precatalyst.

2-(2-Pyridyl)benzo[*b*]-1.5-naphthyridine (pbn) was prepared by coupling 3-aminoquinaldehyde[6] with 2-acetylpyridine in ethanol in the presence of NaOH[7] [Eq. (1)]. $[RuCl_2(bpy)_2]$ was treated with two equivalents of $AgPF_6$ in

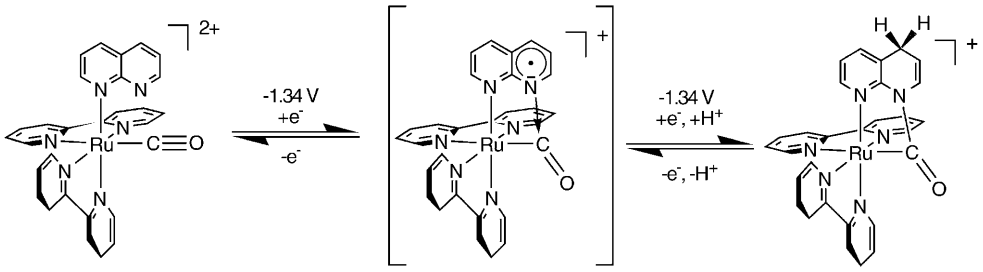


(1)

2-methoxyethanol, followed by addition of one equivalent of pbn to give $[Ru(pbn)(bpy)_2](PF_6)_2$ (**1**) as a red-purple powder [Eq. (2)]. The structure of complex **1** was determined by X-ray crystallographic analysis (Figure 1)[8] and NMR spectroscopy.

The addition of hydrochloric acid to a solution of **1** in acetonitrile resulted in a dramatic change from orange-brown to green. The UV/Vis spectra show there is a bathochromic shift of the absorption band of the metal-to-ligand charge transfer (MLCT) based on the pbn ligand from 529 to 604 nm. The extent of the decrease in the energy of the π* orbital of pbn upon protonation of the ligand would be larger than that of the dπ orbital of the Ru(II) atom. As a result, the MLCT band of **1** showed a red-shift as a result of a narrowing of the Ru(dπ)–L(π*) energy gap under acidic conditions. A similar green color has been observed in some ruthenium complexes containing quaternary polypyridine-type ligands.[9]

The cyclic voltammogram of **1** measured in MeCN in the presence of 0.1 M Me_4NBF_4 exhibited one reversible (Ru^{II}/Ru^{III}) redox couple at $E_{1/2} = +1.09$ V (versus Fc/Fc^+) and



Scheme 1. Electrochemical reduction of *cis*-$[Ru(napy\text{-}\kappa N)(CO)(bpy)_2]^{2+}$.

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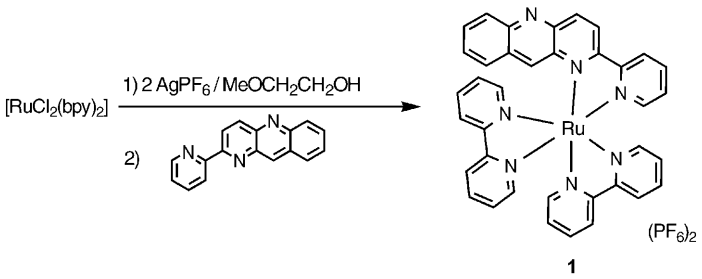
[**] pbn = 2-(2-pyridyl)benzo[*b*]-1,5-naphthyridine, bpy = 2,2′-bipyridine.



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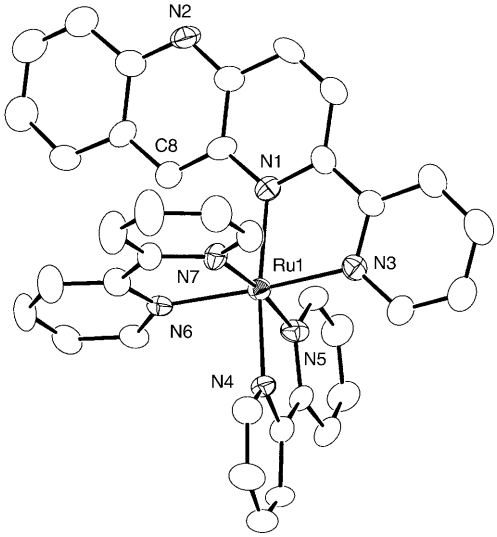


Figure 1. ORTEP drawing of the cationic part of **1** with 50% thermal ellipsoids. Hydrogen atoms are omitted for simplicity. Selected bond length [Å] and angles [°]: Ru1-N1 2.116(5), Ru1-N3 2.051(5), Ru1-N4 2.038(5), Ru1-N5 2.057(6), Ru1-N6 2.082(5), Ru1-N7 2.058(5), N1-Ru1-N3 78.0(2), N1-Ru1-N4 173.1(2); N1-Ru1-N5 98.9(2), N1-Ru1-N6 101.3(2), N1-Ru1-N7 86.4(2), N3-Ru1-N4 95.3(2), N3-Ru1-N5 89.7(2), N3-Ru1-N6 173.9(2), N3-Ru1-N7 95.9(2), N4-Ru1-N5 79.2(2), N4-Ru1-N6 85.5(2), N4-Ru1-N7 96.0(2), N5-Ru1-N6 96.4(2), N5-Ru1-N7 173.0(2), N6-Ru1-N7, 78.0(2).

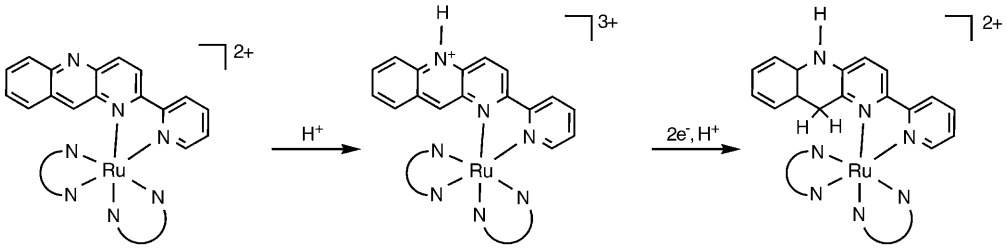
three ligand-based redox processes at $E_{1/2} = -1.03$, -1.65, and -1.92 V. The first of the ligand-based redox processes is assigned to the pbn ligand, and other two waves to bpy redox processes. The first reduction wave appeared at -0.37 V after the addition of 50 equivalents of HCl to the solution. Thus, the protonation of the pbn ligand shifts the redox potentials towards the positive region by approximately 700 mV relative to **1**. The fact that the pbn-based redox reaction takes place reversibly ($\Delta E = 68$ mV) indicates that the radical species generated by the one-electron reduction is stable and does not undergo further reactions, for example, abstraction or dimerization of the H radical by radical coupling.

The potentiostatic electrolysis of **1** in a 1:1 mixture of MeCN and 0.1M AcOH/AcONa buffer solution at -1.14 V (versus Fc/Fc^+) under N_2 consumed electrons corresponding to two electrons per molecule, and then the reaction stopped. The solution turned from red-purple to orange-brown. The ESI-MS spectrum of the resulting solid **2** obtained after drying showed a parent signal at m/z 336.5 with a divalent cation pattern, which is increased by one mass number relative to **1** (m/z 335.5), thus indicating that two hydrogen atoms were added to **1**.

The ^{1}H NMR spectrum of **2** in [D$_6$]acetone displayed 19 different signals with a total intensity of 27 protons in the aromatic region, which are assigned to two bpy and reduced pbn ligands, including the NH proton. Two characteristic doublets appeared at $\delta = 4.19$ and 3.18 ppm while the singlet peak at $\delta = 8.55$ ppm assigned to the proton on C10 disappeared (Scheme 3).[10]

Dissolving complex **2** in [D$_6$]acetone resulted in the solution turning from orange-brown to red-orange quite slowly at room temperature. The time-dependent ^{1}H NMR spectrum showed a new signal at $\delta = 3.75$ ppm, which is assigned to the hydrogen atom on the C2 carbon atom of $(CD_3)_2CHOH$. This result indicates that acetone was reduced by **1** to generate 2-propanol, as shown in Scheme 4. Controlled potential electrolysis of **1** (1 mM) was performed in the presence of 0.1M AcOH/AcONa buffer and 0.1M NaCl in an aqueous acetone solution (1:1 v/v, 10 mL) at -1.14 V (versus Fc/Fc^+) with a glassy carbon working electrode. The reaction progressed slowly, and about 20 μmol of 2-propanol formed in 48 h with a current efficiency of approximately 90%. To our knowledge, this is the first example of the electrochemical catalytic reduction of organic molecules by using a NAD^+/NADH model system.

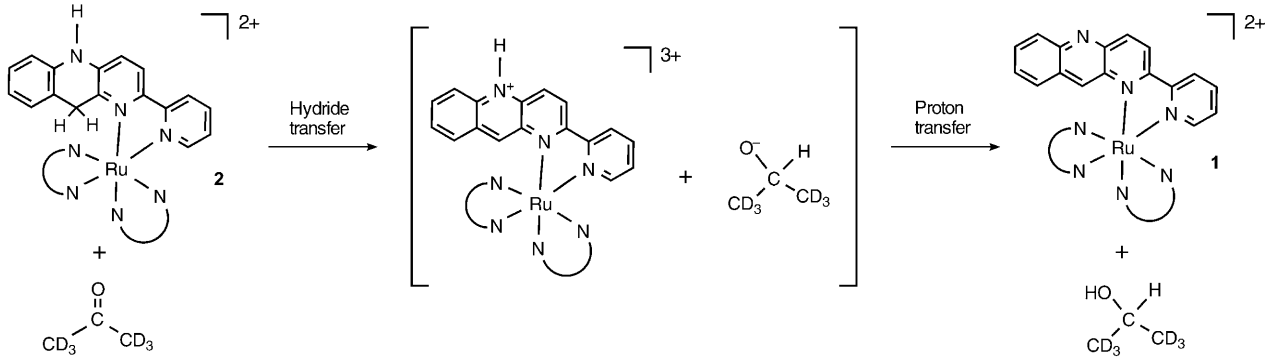
In summary, we have demonstrated the synthesis of a novel ruthenium complex with a ligand that behaves in the same way as the NAD^+/NADH redox couple. We have succeeded in the catalytic reduction of acetone with two electrons and H_2O as a proton source for the first time. The key points of this catalytic system are "hydride" generation and transfer, similar to the function of the NAD^+/NADH redox couple.



Scheme 3. Electrochemical reduction of $[Ru(pbn)(bpy)_2]^{2+}$.

Experimental Section

1: A solution of $AgPF_6$ (60 mg, 0.24 mmol) in $CH_3OCH_2CH_2OH$ (5 mL) was added to a solution of $[RuCl_2(bpy)_2]$ (53 mg, 0.11 mmol)



Scheme 4. Mechanism for the reduction of acetone.

in $CH_3OCH_2CH_2OH$ (20 mL) and this mixture was stirred at 70 °C for 2 h. The resulting gray solid was removed by filtration through celite, and then the red-orange filtrate was added to a solution of pbn (28 mg, 0.11 mmol) in $CH_3OCH_2CH_2OH$ (5 mL) and the solution changed immediately from red-orange to red-purple. The reaction mixture was stirred at 70 °C for 12 h. The solution was concentrated to ca. 1 mL and poured into aqueous NH_4PF_6 solution. The reddish purple solid formed was collected and dried in vacuo (92 mg, 88 % yield). Elemental analysis calcd for $C_{37}H_{29}F_{12}N_7OP_2Ru$ (**1**·H_2O): C 45.41, H 2.99, N 10.02; found; C 45.48, H 3.18, N 9.70. ^{1}H NMR (500 MHz, [D_6]acetone): $\delta = 9.15$ (d, J(H,H) = 7.8 Hz, 1 H), 9.09 (d, J(H,H) = 9.3 Hz, 1 H, pbn-H^4), 8.91 (d, J(H,H) = 1.0 Hz, 1 H), 8.90 (d, J(H,H) = 7.8 Hz, 1 H), 8.81 (d, J(H,H) = 9.3 Hz, 1 H, pbn-H^3), 8.71 (d, J(H,H) = 8.3 Hz, 1 H), 8.55 (s, 1 H, pbn-H^{10}), 8.54 (d, J(H,H) = 6.3 Hz, 2 H), 8.47 (d, J(H,H) = 5.4 Hz, 1 H), 8.35 (dt, J(H,H) = 7.8, 1.0 Hz, 1 H), 8.32 (dt, J(H,H) = 7.8, 1.0 Hz, 1 H), 8.27 (dt, J(H,H) = 9.3, 1.0 Hz, 1 H), 8.23 (dt, J(H,H) = 9.3, 1.0 Hz, 1 H), 8.16 (d, J(H,H) = 8.8 Hz, 1 H, pbn-H^6), 8.12 (d, J(H,H) = 4.9 Hz, 1 H), 8.02 (dt, J(H-H) = 7.8, 1.0 Hz, 1 H), 7.99 (d, J(H-H) = 5.4 Hz, 1 H), 7.93 (dt, J(H,H) = 8.3, 1.0 Hz, 1 H, pbn-H^7), 7.85 (dt, J(H,H) = 7.8 1.0 Hz, 1 H), 7.83 (d, J(H,H) = 5.6 Hz, 1 H), 7.67 (dt, J(H,H) = 5.4, 1.0 Hz, 1 H), 7.59 (t, J(H,H) = 7.3 Hz, 1 H, pbn-H^8), 7.56 (dt, J(H,H) = 5.9, 1.0 Hz, 1 H), 7.48 (dt, J(H-H) = 6.3, 1.0 Hz, 1 H), 7.42 (dt, J(H,H) = 7.3, 1.0 Hz, 1 H), 7.33 ppm (d, J(H,H) = 8.3 Hz, 1 H, pbn-H^9). ESI-MS: $m/z = 335.5$ $[M-2PF_6]^{2+}$.

Electrolytic reduction of **1**: Reduction of **1** was performed in a solution of DMF/0.1 M aqueous AcOH/AcONa buffer (1:9, 10 mL) and supporting electrolyte (NaCl, 0.1 M) under controlled potential electrolysis at −1.14 V (versus Fc/Fc$^+$) by using an electrolysis cell consisting of three components: the working (glassy carbon) and counter (platinum plate) electrode compartments were separated by an anion-exchange membrane (AMP). An Ag/Ag$^+$ reference electrode was separated from the working compartment by a luggin capillary. N_2 was bubbled through the solution in the cell for 1 h followed by pre-electrolysis at −1.2 V, then a solution of **1** (19 mg, 20 μmol) in DMF (1 mL) was added. The solution changed from red-purple to orange-brown after about 3 C consumed. After consuming 4.2 C, the solution was transferred to a Schlenk tube, and the solvent was removed by evaporation to give a brown solid. ^{1}H NMR (500 MHz, [D_6]acetone): $\delta = 8.83$ (t, J(H,H) = 7.8 Hz, 2 H), 8.82 (d, J(H,H) = 7.8 Hz, 2 H), 8.68 (s, 1 H, pbnH_2-N*H*), 8.64 (d, J(H,H) = 5.4 Hz, 1 H), 8.52 (d, J(H,H) = 8.3 Hz, 1 H), 8.44 (d, J(H,H) = 8.8 Hz, 1 H, pbnH_2-H^3), 8.17–8.24 (m, 5 H), 8.07 (t, J(H,H) = 7.8 Hz, 1 H), 7.98 (d, J(H,H) = 5.4 Hz, 1 H), 7.84 (d, J(H,H) = 4.9 Hz, 1 H), 7.68 (d, J(H,H) = 5.4 Hz, 1 H), 7.60–7.66 (m, 3 H), 7.52 (t, J(H,H) = 6.8 Hz, 1 H), 7.41 (d, J(H,H) = 8.8 Hz, 1 H, pbnH_2-H^4), 7.33 (t, J(H,H) = 6.3 Hz, 1 H), 7.00 (t, J(H,H) = 7.3 Hz, 1 H, pbnH_2-H^8), 6.71 (d, J(H,H) = 7.8 Hz, 1 H, pbnH_2-H^9), 6.67 (t, J(H,H) = 7.8 Hz, 1 H, pbnH_2-H^7), 6.18 (d, J(H,H) = 7.3 Hz, 1 H, pbnH_2-H^6), 4.19 (d, J(H,H) = 21 Hz, 1 H, pbnH_2-H^{10}), 3.18 ppm (d, J(H,H) = 21 Hz, 1 H, pbnH_2-H^{10}). ESI-MS: $m/z = 336.5$ $[M-2PF_6]^{2+}$.

Electrolytic reduction of acetone: Acetone reduction was performed in a 1:1 solution of acetone/0.1 M aqueous AcOH/AcONa buffer containing **1** (1 mM) and supporting electrolyte (NaCl, 0.1 M) under controlled potential electrolysis at −1.14 V (versus Fc/Fc$^+$) by using an electrolysis cell similar to that used in the reduction of **1**. The analysis of the solution was carried out by sampling 0.1 mL portions from the solution after appropriate intervals of time. Qualitative and quantitative analyses of the product were conducted by using GC-MS and GC, respectively.

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[8] Crystallographic data for **1**·acetone: monoclinic, $P2_1/n$ (no. 14), $a = 13.761(10)$, $b = 18.05(1)$, $c = 16.67(1)$ Å, $\beta = 101.558(9)°$, $V = 4056(4)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.668\ g\,cm^{-3}$, $\mu(Mo_{K\alpha}) = 5.65\ cm^{-1}$, $R1(R_w) = 0.098$ (0.234) for 8963 unique data with $I > 2\sigma(I)$ and 568 parameters. A suitable single crystal for the measurement was mounted on a glass fiber. Data were collected at −100 °C on a Rigaku/MSC Mercury CCD diffractometer by using graphite-monochromated $Mo_{K\alpha}$ radiation ($\lambda = 0.71070$ Å). All data were collected and processed using the Crystal Clear program (Rigaku). All the calculations were carried out by using the teXsan software package.[11] All structures were solved by direct methods and expanded using Fourier techniques. Refinements were performed anisotropically for all non-hydrogen atoms by the full-matrix least-squares method. Hydrogen atoms were placed at the calculated positions and were included in the structure calculation without further refinement of the parameters. CCDC-248968 (**1**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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[10] We tried to isolate and recrystallize complex **2**. However, good single crystals of **2** were not obtained, since recrystallization of **2** gave a mixture of **1** and **2**. Complex **2** is unstable in air and in solution under inert atmosphere, and slowly changed into complex **1**. ESI-MS analysis showed **2** at first, but the parent signal of **1** gradually appeared with time. Since the recrystallization has not resulted in purification of **2**, the elemental analysis was not completely satisfactory.

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