

Supporting Information

Carbon-nitrogen and nitrogen-nitrogen bond formation from nucleophilic attack at coordinated nitrosyls in Fe and Ru heme models

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General experimental

All reactions, except when noted otherwise, were performed anaerobically using Schlenk techniques under an atmosphere of N₂. Air-sensitive reagents and chemical precursors were handled inside a glove box. Solvents used in the reactions were collected under N₂ from a PureSolv 400-5-MD Solvent Purification System (Innovative Technology) or distilled from appropriate drying agents under an atmosphere of N₂. Nitric oxide (NO) gas was passed through a KOH column and through a cold trap (dry ice/acetone) to minimize the introduction of NO_x impurities. (OEP)Ru(CO), NOBF₄, PhLi (1.8 mM in Et₂O), cobaltocene, and PhNO (>97%) were purchased from Sigma-Aldrich. ¹⁵NO (Icon Isotopes Inc., 99% ¹⁵N) was used as received. ¹⁵NOBF₄ was synthesized following a published procedure.¹ FT-IR spectra were recorded on a Bruker Tensor 27 spectrometer. Gas chromatography was performed on a 7890A Agilent gas chromatograph equipped with Varian VF-5ms capillary column (30 m x 0.25 mm x 0.25 μm). GC conditions: initial temperature of 40 °C for 5 min, ramped to 250 °C at a rate of 20 °C/min and temperature maintained at 250 °C for 20 min, with inlet temperature and pressure of 280 °C and 35.531 psi, respectively. GC-mass spectral analysis of the sample in cyclohexane employed a 5975C Agilent Triple-axis EI MS detector.

X-ray diffraction was performed on a Bruker diffractometer equipped with APEX ccd area detector using graphite monochromated Mo K α radiation ($\lambda = 0.71073$ Å). The single-crystal X-ray crystal structure of (OEP)Ru(PhNO)(5-MeIm) has been deposited with the Cambridge Crystallographic Data Center with the identifier CCDC 1545442.

Synthesis of the {MNO}⁶ (M = Fe, Ru) precursors

The Fe compounds [(OEP)Fe(NO)(5-MeIm)]OTf² and [(OEP)Fe(NO)(1-MeIm)]OTf³ were synthesized as described previously, in 60% and 64% isolated yields, respectively.

i. [(OEP)Ru(NO)(5-MeIm)]BF₄. This compound was prepared in a similar manner as described for the preparation of [(TTP)Ru(NO)(1-MeIm)]BF₄ with slight modifications.⁴ To a CH₂Cl₂ (10 mL) solution of (OEP)Ru(CO) (43.1 mg, 0.065 mmol) was added 5-MeIm (6.0 mg, 0.07 mmol) and the mixture stirred for 1 h, during which time the ν_{CO} band of the precursor at 1939 cm⁻¹ (NaCl plate) shifted to 1892 cm⁻¹ indicative of the formation of the adduct (OEP)Ru(CO)(5-MeIm). NOBF₄ (8.0 mg, 0.068 mmol) was added and the solution was stirred for another 1 hr during which time the red solution changed to red-brown characterized by the disappearance of the ν_{CO} band of (OEP)Ru(CO)(5-MeIm) at 1892 cm⁻¹ with concomitant formation of a new band at 1849 cm⁻¹ assigned to ν_{NO} of [(OEP)Ru(NO)(5-MeIm)]BF₄ ($\nu_{15\text{NO}}$ 1815 cm⁻¹; ν_{BF_4} = 1080 cm⁻¹). The product was isolated in 67% yield. ¹H NMR (CDCl₃, 400 MHz; δ , ppm): 11.41 (br, 1H, 5-MeIm N-H), 10.51 (s, 4H, methine C-H), 7.26 (s, CHCl₃), 5.31 (s, CH₂Cl₂), 4.21 (br, 16H, ethyl-CH₂), 2.01 (br, 24H, ethyl-CH₃), 1.00 (s, 1H, 5-MeIm-H), 0.33 (s, 3H, 5-MeIm-CH₃), and 0.18 (s, 1H, 5-MeIm-H).

ii. [(OEP)Ru(NO)(1-MeIm)]BF₄. This 1-MeIm derivative was obtained similarly in 70% isolated yield. IR (KBr): ν_{NO} 1852 cm⁻¹ ($\nu_{15\text{NO}}$ 1814 cm⁻¹; ν_{BF_4} = 1080 cm⁻¹).

Reactions of the {MNO}⁶ (M = Fe, Ru) compounds with PhLi

i. Reaction of [(OEP)Fe(NO)(5-MeIm)]OTf with PhLi. To a THF (5 mL) solution of [(OEP)Fe(NO)(5-MeIm)]OTf (18.9 mg, 0.022 mmol) at 0 °C was added 40 μ L of PhLi (1.8 mM in Et₂O). The mixture was stirred for 30 min at this temperature during which time the color of the solution changed from red-purple to red. IR monitoring of this reaction (using dried aliquots on NaCl plates) revealed an associated disappearance of the precursor ν_{NO} band at 1894 cm⁻¹ and formation of new bands at 1336(w), 1346 (w), and 1556 cm⁻¹(m). The solution was filter-cannulated (to remove the Li salt by-product). The filtrate was concentrated to *ca.* 2mL and then dry *n*-hexane (10 mL) was added to result in the precipitation of a product. The solvent was then decanted from the suspension, and the solid washed with *n*-hexane (3x10 mL) and subsequently dried completely under reduced pressure under vacuum. The IR spectrum of the solid as a KBr pellet revealed bands at 1336 cm⁻¹ assigned to the ν_{NO} of (OEP)Fe(PhNO)(5-MeIm) (minor product), at 1346 cm⁻¹ assigned to ν_{NO} of (OEP)Fe(PhNO)₂ (minor product; $\nu_{15\text{NO}}$ 1319 cm⁻¹), and at 1556 cm⁻¹ assigned to $\nu_{\text{C-C}}$ of (OEP)Fe(Ph). This reaction was reproducible over several (~50x) trials.

ii. Reaction of [(OEP)Fe(NO)(1-MeIm)]OTf with PhLi. This reaction was performed in a similar manner as that described above. To a THF (5 mL) solution of [(OEP)Fe(NO)(1-MeIm)]OTf (25.5 mg, 0.03 mmol) at 0 °C was added 25 μ L of PhLi (1.8 mmol/mL in Et₂O). The mixture was stirred for 30 min at this temperature during which time the color of the solution changed from red-purple to red. IR monitoring of this reaction (using dried aliquots on NaCl plates) revealed an associated disappearance of the precursor ν_{NO} band at 1888 cm⁻¹ and formation of new bands at 1337(w), 1346 (w), and 1557 cm⁻¹(m). The solution was filter-cannulated (to remove the Li salt by-product). The IR spectrum of the solid obtained after work-up (as a KBr pellet) revealed bands at ν_{NO} 1337 cm⁻¹ assigned to (OEP)Fe(PhNO)(1-MeIm) (minor product), ν_{NO} 1346 cm⁻¹ ($\nu_{15\text{NO}}$ 1319 cm⁻¹) assigned to (OEP)Fe(PhNO)₂ (minor product), and 1557 cm⁻¹ assigned to $\nu_{\text{C-C}}$ of (OEP)Fe(Ph). This reaction was reproducible over several (~50 x) trials.

iii. Reaction of [(OEP)Ru(NO)(5-MeIm)]BF₄ with PhLi. To a THF (5 mL) solution of [(OEP)Ru(NO)(5-MeIm)]BF₄ (53.3 mg, 0.064 mmol) at 0 °C was added 55 μ L of PhLi (1.8 mM in Et₂O). The mixture was stirred for 2-3 h at this temperature during which time the color changed from brown-red to purple-red. IR monitoring of the reaction (using dried aliquots on NaCl plates) revealed the disappearance of the ν_{NO} band of the precursor [(OEP)Ru(NO)(5-MeIm)]BF₄ at 1849 cm⁻¹, with concomitant formation of new bands at 1309 cm⁻¹ and 1839 cm⁻¹. The mixture was then cannula filtered (to remove the Li salt byproduct) and the filtrate subsequently dried under vacuum. The product associated with new ν_{NO} band at 1309 cm⁻¹ was isolated from the product mixture via neutral alumina column chromatography using CH₂Cl₂:acetone (9:1) as the eluent. The eluent was dried in vacuo and the resulting solid washed with *n*-hexane (3x) and subsequently dried in vacuo. IR (KBr); ν_{NO} 1309 cm⁻¹ ($\nu_{15\text{NO}}$ 1283 cm⁻¹) assigned to (OEP)Ru(PhNO)(5-MeIm) (27% isolated yield). ¹H NMR (CDCl₃, 400 MHz; δ , ppm): 9.5 (s, 4H, methine-H), 7.26 (s, CHCl₃), 6.12 and 5.67 (m, Ar-H), 5.30 (s, CH₂Cl₂), 3.86 (overlapping q, 16H, ethyl-CH₂), 1.77 (t, 24H, ethyl-CH₃), 1.27 and 0.90 (hexane impurity), 0.65 (s, 1H 5-MeIm-H), 0.23 (s, 1H 5-MeIm-H), and 0.21 (s, 3H, 5-MeIm-CH₃). The identity of this compound as (OEP)Ru(PhNO)(5-MeIm) was confirmed by X-ray crystallography.

iv. Reaction of [(OEP)Ru(NO)(1-MeIm)]BF₄ with PhLi. The reaction of [(OEP)Ru(NO)(1-MeIm)]BF₄ with PhLi was performed similarly. To a THF (5 mL) solution of [(OEP)Ru(NO)(1-MeIm)]BF₄ (20.2 mg, 0.024 mmol) at 0 °C was added 20 μ L of PhLi (1.8 mM in Et₂O). The mixture was stirred for 2-3 h at this temperature during which time the color changed from brown-red to purple-red. IR monitoring of the reaction revealed the disappearance of the ν_{NO} band of the precursor [(OEP)Ru(NO)(1-MeIm)]BF₄ at 1851 cm⁻¹, with concomitant formation of new bands at 1306 cm⁻¹ and 1818 cm⁻¹ (as NaCl plate) The mixture was then cannula filtered (to remove the Li salt byproduct) and the filtrate subsequently dried in vacuo. The product associated with new ν_{NO} band at 1306 cm⁻¹ was isolated from the product mixture via neutral alumina column chromatography using

CH₂Cl₂:acetone (9:1) as the eluent. The eluent was dried in vacuo and the resulting solid washed with *n*-hexane (3x) and subsequently dried in vacuo. IR (KBr); ν_{NO} 1306 cm⁻¹ ($\nu_{15\text{NO}}$ 1283 cm⁻¹) assigned to (OEP)Ru(PhNO)(1-MeIm) (33% isolated yield).

Independent synthesis of the nitrosobenzene compounds (OEP)M(PhNO)(5-MeIm) (M = Fe, Ru); control experiments

i. (OEP)Fe(PhNO)₂ and (OEP)Fe(PhNO)(5-MeIm). The (OEP)Fe(PhNO)₂ compound was obtained in a manner similar to that used for the preparation of (TPP)Fe(PhNO)₂ with slight modifications.⁵ To a Schlenk tube charged with (OEP)FeCl (19.2 mg, 0.031 mmol) in THF was added Cp₂Co (8.0 mg, 0.04 mmol) and the solution stirred for 30 min at room temperature during which time the starting pale purple solution changed to a bright red color. The solution was filtered (to remove the Cp₂CoCl by-product) and the filtrate subsequently dried in vacuo. The resulting solid was dissolved in CH₂Cl₂, and PhNO (5.1 mg, 0.05 mmol) was added. The solution was stirred for 1 h. The volume of the solution was then reduced to *ca.* 2 mL followed by the addition of anhydrous *n*-hexane to induce the precipitation of a solid. The solvent was then decanted from the suspension, and the remaining solid was washed with anhydrous *n*-hexane (3x10 mL) and subsequently dried in vacuo. IR (KBr): ν_{NO} 1346 cm⁻¹ of (OEP)Fe(PhNO)₂.

The ¹H NMR spectrum at 25 °C suggests the formation of five-coordinate mono-nitrosobenzene complex (OEP)Fe(PhNO) based on ligand signal integrations. ¹H NMR (CDCl₃, 25 °C, 400 MHz; δ , ppm): 9.53 (s, 4H, methine C-*H*), 7.26 (s, CHCl₃), 6.13 and 5.64 (br, 5H, phenyl-*H*), 5.30 (s, CH₂Cl₂), 3.83 (br, 16H, ethyl-CH₂), 1.74 (t, 24H, ethyl-CH₃).

The bis-nitrosobenzene compound in solution can be stabilized at low temperature in the presence of excess PhNO. ¹H NMR (CDCl₃, -20 °C, 400 MHz; δ , ppm): 9.86 (s, 4H, methine C-*H*), 7.26 (s, CHCl₃), 6.36–5.92 (br, 10H, phenyl-*H*), 5.27 (s, CH₂Cl₂), 3.95 (br, 16H, ethyl-CH₂), 1.80 (t, 24H, ethyl-CH₃).

The solid (OEP)Fe(PhNO)₂ product was redissolved in CH₂Cl₂ and 1 equiv. 5-MeIm was added, and the mixture was stirred for another 30 min during which time the 1346 cm⁻¹ in the IR spectrum (as a NaCl plate) was replaced by a new band at 1336 cm⁻¹. The solvent was removed under reduced pressure and the remaining solid washed with anhydrous *n*-hexane (3x10 mL) and dried in vacuo. IR (KBr): 1336 cm⁻¹ assigned to the ν_{NO} of (OEP)Fe(PhNO)(5-MeIm). ¹H NMR (CDCl₃, 400 MHz; δ , ppm): 9.55 (s, 4H, methine C-*H*), 7.26 (s, CHCl₃), 6.1–5.25 (br, 5H, phenyl-*H*), 5.31 (s, CH₂Cl₂), 3.86 (overlapping q, 16H, ethyl-CH₂), 1.72 (t, 24H, ethyl-CH₃), 1.28 and 0.86 (hexane impurity), 0.49 (s, 1H, 5-MeIm-H), 0.05 (s, 1H, 5-MeIm-H), and -1.03 (s, 3H, 5-MeIm-CH₃).

ii. (OEP)Ru(PhNO)(5-MeIm). This compound was prepared in a similar manner as described for (TTP)Ru(PhNO)(1-MeIm) with slight modifications.⁶ To a CH₂Cl₂ (10 mL) solution of (OEP)Ru(CO) (24.9 mg, 0.038 mmol) was added an excess of PhNO (19.5 mg,

0.182 mmol) and the solution stirred at room temperature for 30 min during which time the color changed from pink-red to brown. The IR spectrum of the solution (as a NaCl plate) revealed the disappearance of the precursor ν_{CO} band at 1936 cm^{-1} with a concomitant formation of a strong band at 1337 cm^{-1} assigned to the ν_{NO} of the bis-nitrosobenzene (OEP)Ru(PhNO)₂ complex.⁷ The volume of the solution was reduced to *ca.* 2 mL and followed by the addition of anhydrous *n*-hexane (15 mL) to induce the precipitation of the (OEP)Ru(PhNO)₂ product. The solvent was decanted from the suspension. The remaining solid was washed with dry *n*-hexane (3x10 mL) and dried in vacuo. The solid was then dissolved in CH₂Cl₂ (10 mL) and excess 5-MeIm was added. The solution was stirred at room temperature for 30 min during which time the solution changed color from brown to a bright red-purple. Dry *n*-hexane was added to precipitate a solid. The supernatant solution was decanted and the residue washed with *n*-hexane and dried in vacuo. IR (KBr): ν_{NO} 1308 cm^{-1} of the (OEP)Ru(PhNO)(5-MeIm) product. ¹H NMR (CDCl₃, 400 MHz; δ , ppm): 9.45 (s, 4H, methine-H), 7.26 (s, CHCl₃), 6.10 and 5.64 (m, Ar-H), 5.30 (s, CH₂Cl₂), 3.84 (overlapping q, 16H, ethyl-CH₂), 1.74 (t, 24H, ethyl-CH₃), 1.27 and 0.87 (hexane impurity), 0.40 (s, 1H 5-MeIm-H), 0.04 (s, 1H 5-MeIm-H), and -0.1 (s, 3H, 5-MeIm-CH₃). Anal. Calcd for C₄₆H₅₅RuN₇O: C, 67.12; H, 6.74; N, 11.91; Found: C, 67.01; H, 6.83; N, 11.73.

Reaction of [(OEP)Fe(NO)(5-MeIm)]OTf with LiNEt₂

To a THF solution of [(OEP)Fe(NO)(5-MeIm)]OTf (20.1 mg, 0.024 mmol) at 0 °C was added LiNEt₂ (3.8 mg, 0.048 mmol) and the mixture was stirred for 5 min at this temperature. The solution was then slowly warmed to room temperature and stirred for additional 30 min during which time the color of the solution changed from purple-red to red accompanied by the disappearance of the ν_{NO} band of the precursor at 1890 cm^{-1} (NaCl plate). The THF was removed in vacuo, and the residue was redissolved in CDCl₃ (2 mL) for ¹H NMR spectroscopic analysis. The formation of ~13.0% unoptimized yield of Et₂NNO was determined by ¹H NMR spectroscopy against a C₆H₆ standard; the identity of Et₂NNO was confirmed by GC-MS (Figure S1). IR spectroscopy of the residue (in CH₂Cl₂) revealed the formation of (OEP)Fe(NO) in ~71% unoptimized yield as the major inorganic product of this reaction.

¹H NMR of the reaction mixture (CDCl₃, 400 MHz, δ ppm): 7.26 (s, CHCl₃), 4.14 (q, Et-CH₂ of Et₂NNO), 3.61 (q, Et-CH₂ of Et₂NNO), 1.41 (t, Et-CH₃ of Et₂NNO), 1.11 (t, Et-CH₃ of Et₂NNO), in addition to other peaks due to the presence of iron-porphyrin inorganic products. The assignment of the ¹H NMR chemical shifts was confirmed by (i) spiking the sample with an authentic Et₂NNO (the assigned peaks increased in intensity), and (ii) comparing the ¹H NMR spectral signals from the reaction mixture with those of authentic Et₂NNO (Fig. S1, top right).

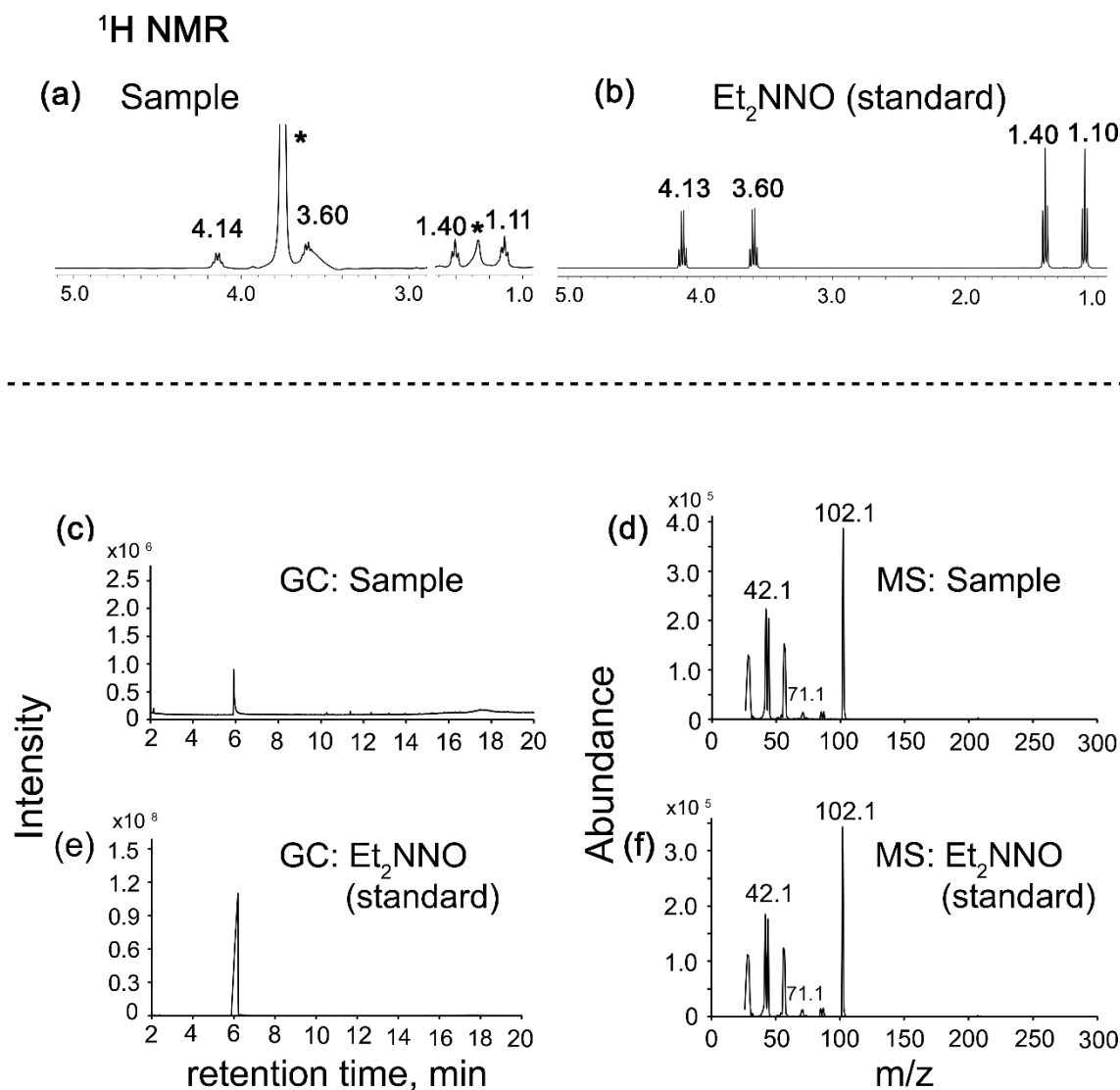


Figure S1. Figure S1: ^1H NMR spectroscopic and GC-MS identification of Et_2NNO as a product of the reaction of $[(\text{OEP})\text{Fe}(\text{NO})(5\text{-MeIm})]\text{OTf}$ with LiNEt_2 . (a) ^1H NMR spectroscopic detection of free *N*-nitrosodiethylamine (in CDCl_3) from the reaction of $[(\text{OEP})\text{Fe}(\text{NO})(5\text{-MeIm})]\text{OTf}$ with LiNEt_2 , (b) ^1H NMR spectrum of an authentic sample of *N*-nitrosodiethylamine. (c) Gas chromatogram of the sample product mixture from the reaction of $[(\text{OEP})\text{Fe}(\text{NO})(5\text{-MeIm})]\text{OTf}$ with LiNEt_2 showing elution of *N*-nitrosodiethylamine (*c.f.*, the gas chromatogram of an authentic sample shown in (e) below), (d) mass spectrum of the eluted peak from the GC run showing the identity of the product as *N*-nitrosodiethylamine (*c.f.*, an authentic sample shown in (f) below).

Reactions of the {MNO}⁶ (M = Fe, Ru) compounds with sodium azide (NaN₃)

i. Reaction of [(OEP)Fe(NO)(5-MeIm)]OTf with NaN₃. To a THF/DMF (4:1 mL) solution of [(OEP)Fe(NO)(5-MeIm)]OTf (17.9 mg, 0.021 mmol) was added 1.5 equiv. of NaN₃ and the mixture stirred for 2–3 h inside a sealed Schlenk tube. The headspace gases were then vacuum-transferred to an IR gas cell (10 cm path length) for IR spectral data collection. IR (gas): $\nu_{\text{as}}(\text{N}_2\text{O})$ 2237/2211 cm⁻¹ of the N₂O gas formed.⁸ When the ¹⁵N-labeled [(OEP)Fe(¹⁵NO)(5-MeIm)]OTf precursor was used, bands at 2189/2165 cm⁻¹ assigned to $\nu_{\text{as}}^{14}\text{N}^{15}\text{NO}$ were evident, with no unlabeled N₂O or ¹⁵N¹⁴NO being present. An IR spectrum of the product solution shows no ¹⁵N-isotope sensitive FeNO-containing by-product remaining in solution.

ii. Reaction of [(OEP)Ru(NO)(5-MeIm)]BF₄ with NaN₃. To a THF/DMF (4:1 mL) solution of [(OEP)Ru(NO)(5-MeIm)]BF₄ (37.7 mg, 0.045 mmol) was added 1.5 equiv. of NaN₃ and stirred for 5 h in a sealed Schlenk tube. The headspace gases were vacuum-transferred to the IR gas cell for gas-phase IR spectral data collection. IR (gas): $\nu_{\text{as}}(\text{N}_2\text{O})$ 2237/2211 cm⁻¹ of the N₂O gas formed.⁸ When the ¹⁵N-labeled [(OEP)Ru(¹⁵NO)(5-MeIm)]OTf precursor was used, bands due to unlabeled N₂O (237/2211 cm⁻¹; major) and singly-labeled ¹⁴N¹⁵NO (ν_{as} 2189/2165 cm⁻¹) were present. IR (THF/DMF): ν_{NO} = 1825 cm⁻¹ ($\nu_{^{15}\text{NO}}$ = 1790 cm⁻¹).

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