Supplementary Information

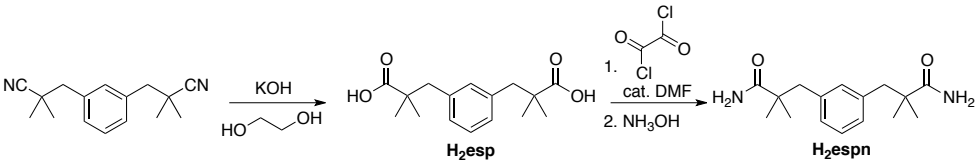
"A Mixed-Valent Dirhodium (II,III) Catalyst with Increased Longevity in Intramolecular C-H Amination"

Katherine P. Kornecki and John F. Berry

General

All reagents were obtained commercially and used without further purification unless otherwise noted. Acetonitrile (CH_3CN), ether (Et_2O), tetrahydrofuran (THF) and toluene were obtained from a VAC solvent system and degassed prior to use. Dichloromethane was dried over CaH_2 and distilled prior to use. Reactions were performed using oven-dried glassware under an atmosphere of nitrogen. 4Å sieves used in catalytic reactions were activated in a 400°C oven overnight prior to use. Thin layer chromatography (TLC) was performed using EM Reagent 0.25 mm silica gel 60-F plates. Visualization was performed by UV absorbance or cerium ammonium molybdate. Flash chromatography was performed using EM Silica Gel 60 in the indicated solvents. ^{1}H NMR spectra were recorded in $CDCl_3$, unless otherwise noted, on a Bruker AV-300 spectrometer at room temperature. Chemical shifts are reported on a ppm scale referenced to TMS at 0.0 ppm. Electrochemical measurements were performed with a 1 mM analyte concentration and 0.1 M concentration of tetrabutylammonium hexafluorophosphate supporting electrolyte. The reference electrode was a non-aqueous $Ag/AgNO_3$ cell contained by a Vycor tip; the working electrode was a glassy carbon disk, and the auxiliary electrode was a platinum wire. All cyclic voltammetry data is referenced to the ferrocene/ferrocenium couple with $E_{1/2}$ = 0 V. UV-Visible spectra were obtained using a StellarNet miniature BLUE-wave UV-Vis dip probe with Tungsten-Krypton lightsource and a 10 mm path length tip. X-Ray crystal diffraction was performed on a Bruker APEX diffractometer with a Mo-Kα radiation. Elemental analyses were measured at Midwest Microlab, LLC.

H_2espn



H_2espn is made by converting the previously reported dicarboxylate ligand, H_2esp, to the diamide. H_2esp was synthesized according to the literature[1] from a dinitrile precursor. The procedure for the dinitrile was modified in two ways: the formation of lithium diisopropylamide was performed at -78°C rather than at 0°C. Also, once the α,α,α',α'-dichloroxylene solution was added to deprotonated isobutyronitrile, the reaction was quenched after 5 minutes rather than

after 10h. Additionally, the dinitrile was purified by recrystallizing from a 98:2 solution of hexanes:DCM rather than by column chromatography. Hydrolysis of the dinitrile was unmodified.

Converting the diacid to the diamide was done by forming the diacylchloride *in situ*. H_2esp (1.80 g, 6.47 mmol, 1 eq) was added to a Schlenk flask and freshly distilled DCM (30 mL) was added via syringe. Oxalyl chloride (1.65 mL, 19.4 mmol, 3 eq.) was added by syringe, followed by 3 drops of dry DMF. Vigorous bubbling occurred and the solution slowly became a homogenous clear yellow. The reaction was stopped after 4h, and the solvent was removed *in vacuo*. The flask was kept under vacuum for an additional 1h to ensure that excess oxalyl chloride was removed. The residue was redissolved in fresh DCM and the reaction was cooled to 0°C. Concentrated aqueous NH_3OH (7 mL) was added to the reaction and a white precipitate immediately precipitated from solution, which was collected by filtration. The residue was extracted with acetone until only NH_4Cl remained on the filter. The filtrate was dried over $MgSO_4$ and filtered a second time. The filtrate was concentrated by rotary evaporation, and the residue recrystallized from chloroform. Filtering yields a bright white paper-like solid (1 g, 56%). δ_H(300 MHz; $CDCl_3$; TMS) 1.198 (12H, s), 2.803 (4H, s), 5.417 (4H, br s), 7.024 (3H, m), 7.194 (1H, t). ESI EMM^+ m/z: (calc.) 267.1838; (found) 299.3610 (M+Na). mp 172 °C. CHN Elemental Analysis (calc.) C 69.53, H 8.75, N 10.14; (found) C 68.96, H 8.50, N 10.14.

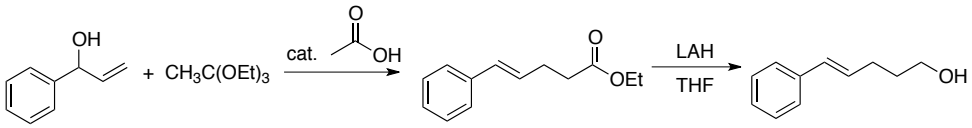
$Rh_2(espn)_2Cl$ (Catalyst **2**)

H_2espn (450 mg, 1.6 mmol, 4 eq.) and crystalline $Rh_2(OAc)_4$•2MeOH (210 mg, 0.40 mmol, 1 eq.) were added to a 250 mL Schlenk flask, which was evacuated for 1h. Anhydrous, degassed chlorobenzene (150 mL) was added to the starting materials and the flask was equipped with a Soxhlet extraction head containing a thimble with a 3:1 mixture of $NaCO_3$ and sand that had been oven-dried overnight, and reflux condenser. The reaction was slowly heated to 140°C. The solution became a homogeneous clear indigo at ~90°C, but eventually became opaque and lime green at higher temperatures. The reaction was heated for 12h before being cooled to 80°C. The Soxhlet head was removed and N-chlorosuccinimide (54 mg, 0.40 mmol, 1 eq.) was added to the reaction. The reaction mixture was heated for 20 minutes at 80°C until the solution became bright red. The solution was then cooled to room temperature and the solvent was removed by rotary evaporation. The residue was dissolved in acetone and subjected to column

chromatography with gradient elution (5% to 30% acetone in DCM) yielding two distinct bands. The first to elute is orange (the [4,0] isomer, **2b**, ~9% yield), the second is red (the [2,2] isomer, **2a**). Both isomers can be recrystallized from their DCM/acetone solutions. Recrystallization of **2a** gives burgundy twinned crystals, (Figures 1 and SI-1) (125 mg, 39%). $\lambda_{max}(CH_3CN)$/nm 472, 1004 (see Figure S5). MALDI-MS m/z (calc.) 789.116 (found) 789.211. CHN Elemental Analysis (calc.) C 48.65, H 5.61, N 7.09; (found) C 48.52, H 5.40, N 7.01.

Competition substrates

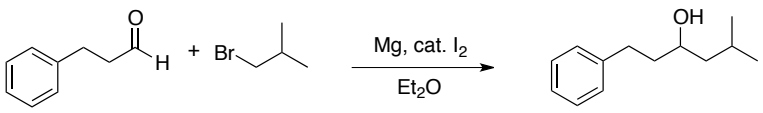
Sulfamate esters used for intramolecular catalytic cyclization reactions are readily obtained from corresponding alcohols using Procedure A described in Espino et al.[2] Each sulfamate ester and C−H functionalization product described herein has previously been reported and fully characterized in the literature (respective references below). Thus, sulfamate ester and product ^{1}H NMR spectra were compared with known literature values to confirm identity. Starting alcohols for sulfamate esters **S1**, **S2** and **S3** are commercially available from Sigma-Aldrich and were used without further purification. Preparations for starting alcohols **S4-alcohol** and **S5-alcohol** are described below.



S4-alcohol

***S4*-alcohol**. Triethyl orthoacetate (14 mL, 74.5 mmol), α-vinyl benzyl alcohol (5 g, 37.2 mmol) and acetic acid (0.1 mL) were added to a flask equipped with a short-path distillation head and heated to 160°C for 3h. Ethanol was distilled out of the reaction at ~140°C after ~3h. The reaction mixture was then cooled to room temperature and diluted with an equal volume of ethyl acetate. An equal volume of 1 M aqueous HCl was added and the mixture was stirred vigorously for 1h. The phases were separated and the organic phase was washed with brine (~30 mL). The organic phase was then dried over $MgSO_4$ and concentrated. The **ethyl-ester** of **S4-alcohol** was purified by vacuum distillation. Yield = 3.5 g (46%) δ_H(300 MHz; $CDCl_3$; TMS) 1.55 (3H, t), 2.49 (4H, m), 4.16 (2H, q), 6.18-6.33 (1H, m), 6.42 (1H, dt), 7.31-741 (5H, m). ESI EMM^+ m/z: (calc.) 204.1150; (found) 204.1161.

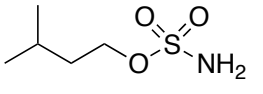
The ethyl ester of **S4-alcohol** was then reduced by reacting the neat oil with a 1 M THF solution of lithium aluminum hydride (10 eq.) at 0°C. The reaction was allowed to warm up to room temperature and react for 2h. The reaction was quenched by cooling to 0°C and slowly adding cold water dropwise. Once bubbling ceased, the reaction was poured into a beaker with 200 mL of water and acidified w/ 50 mL of 2 M aqueous HCl. The mixture was extracted into ethyl acetate three times, followed by a wash with brine. The organic phase was dried over $MgSO_4$ and concentrated. **S4-alcohol** was purified by column chromatography on silica gel with gradient elution 0 → 20% EtOAc in hexanes, R_f = 0.15. Purification yields a clear oil, 1.3 g (50%). δ_H(300 MHz; $CDCl_3$; TMS) 1.68-1.82 (2H, m), 1.85-1.96 (2H, m), 2.71 (1H, t), 3.63-3.75 (2H, m), 6.23 (1H, dt), 6.36-6.45 (1H, m), 7.14-7.37 (5H, m). ESI EMM^+ m/z: (calc.) 162.1045; (found) 162.1050.



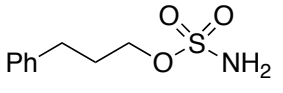
S5-alcohol

***S5*-alcohol**. A solution of 1-bromo-2-methyl propane (1.42 mL, 0.013 mmol) in 20 mL Et_2O was slowly added to a Schlenk flask containing magnesium turnings (350 mg, 0.014 mmol, 1.1 eq.) that had been activated with a crystal of iodine. Once the magnesium was consumed, a solution of hydrocinnemaldehyde (1.7 mL, 0.013 mmol) in 20 mL Et_2O was added dropwise over twenty minutes. The reaction was heated to reflux for 3h and monitored by TLC. Once the hydrocinnemaldehyde was consumed, the reaction mixture was cooled to 0°C and then quenched with 2 M aqueous HCl (20 mL) and extracted into ~50 mL of Et_2O three times. The organic layer was washed with saturated $NaHCO_3$ (20 mL), followed by a wash with brine (20 mL). The organic layer was dried over $MgSO_4$ and concentrated. The **S5**-alcohol was purified by column chromatography using isocratic elution 10% ethyl acetate in hexanes, R_f = 0.48. Purification yields a clear oil, 1 g (40%). δ_H(300 MHz; $CDCl_3$; TMS) 0.906 (6H, d), 1.28-1.31 (2H, m), 1.39-1.47 (1H, m), 1.565 (2H, m), 1.72-1.81 (2H, m), 2.67-2.80 (1H, m), 3.7 (1H, br s), 7.19-7.31 (5H, m). ESI EMM^+ m/z: (calc.) 192.1514; (found) 192.1519.

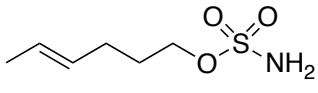
Sulfamate Esters


(S1)

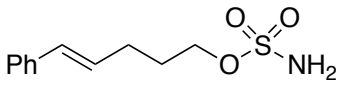
δ_H(300 MHz; $CDCl_3$; TMS) 0.945 (6H, d), 1.64 (2H, q), 1.71-1.82 (1H, m), 4.25 (2H, m), 4.81 (2H, br d). Lit. ref[1]


(S2)

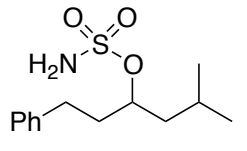
δ_H(300 MHz; $CDCl_3$; TMS) 2.04-2.13 (2H, m), 2.75 (2H, t), 4.21 (2H, t), 4.86 (2H, br s), 7.16-7.35 (5H, m). Lit. ref[2]


(S3)

δ_H(300 MHz; $CDCl_3$; TMS) 1.65 (3H, ddd), 1.80 (2H, tt), 2.14-2.08 (2H, m), 4.21 (2H, t), 4.68 (2H, br s), 5.32-5.52 (2H, m). Lit. ref[3]


(S4)

δ_H(300 MHz; $CDCl_3$; TMS) 1.95 (2H, tt), 2.36 (2H, dtd), 4.28 (2H, t), 4.64 (2H, br s), 6.18 (1H, dt), 6.44 (1H, dt), 7.19-7.36 (5H, m). Lit. ref[3]

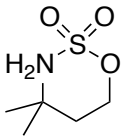

(S5)

δ_H(300 MHz; $CDCl_3$; TMS) 0.92 (3H, d), 0.95 (3H, d), 1.46-1.55 (1H, m), 1.75-1.81 (2H, m), 2.09-2.03 (m, 2H), 2.75 (2H, t), 4.59 (2H, br s), 4.73 (1H, tt), 7.18-7.32 (5H, m). Lit. ref[3]

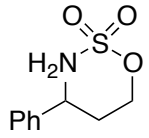
Prototypical catalytic conditions

All catalytic reactions were conducted on a 20 mg (sulfamate ester) scale in 2 mL of freshly distilled DCM or benzene with ~20 mg of 4 Å molecular sieves. Stock solutions of **2** were prepared and the appropriate catalyst loading was delivered by micropipette. In intermolecular reactions, C-H substrate was also delivered by micropipette, unless the reaction was run neat in substrate. $PhI(OAc)_2$ was added last as a solid (one equivalent in intramolecular reactions, two equivalents in intermolecular reactions). Reactions were stopped after 12h and the solvent was evaporated. The reaction mixture was then redissolved in $CDCl_3$ with and product conversion was determined by ^1H NMR integration of starting materials versus products. Product ratios were also determined by this method. Relaxation delays were increased to 10 seconds for the acquisition of spectra related to catalytic reactions to ensure integration accuracy.

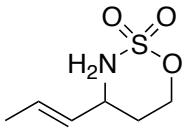
Amination Products



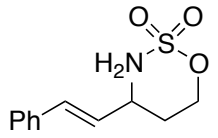
δ_H(300 MHz; $CDCl_3$; TMS) 1.42 (6H, s), 1.77 (2H, t), 4.46 (1H, br s), 4.67 (2H, t). Lit. ref [1]



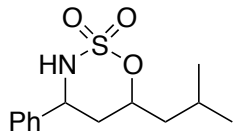
δ_H(300 MHz; $CDCl_3$; TMS) 1.99-2.09 (1H, m), 2.18-2.32 (1H, m), 4.34 (1H, d), 4.66 (1H, ddd), 4.87 (2H, td), 7.31-7.46 (5H, m). Lit. ref[2]



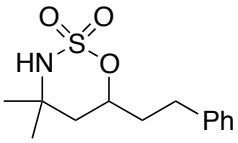
δ_H(300 MHz; $CDCl_3$; TMS) 1.73 (3H, ddd), 1.75-1.92 (2H, m), 3.92 (1H, br d), 4.20-4.32 (1H, m), 4.55 (1H, ddd), 4.75 (1H, dt), 5.44 (1H, m), 5.78 (1H, m). Lit. ref[3]



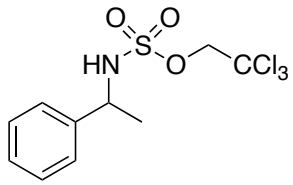
δ_H(300 MHz; $CDCl_3$; TMS) 1.90-2.05 (2H, m), 4.04 (1H, br d), 4.49-4.57 (1H, m), 4.62 (1H, ddd), 4.79-4.85 (1H, m), 6.12 (1H, dd), 6.66 (1H, dd), 7.28-7.39 (5H, m). Lit. ref[3]



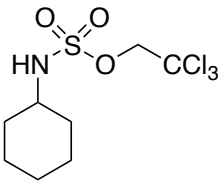
δ_H(300 MHz; $CDCl_3$; TMS) 0.96 (3H, d), 0.98 (3H, d), 1.42 (1H, ddd), 1.76-1.84 (1H, m), 1.86-1.96 (1H, m), 2.06 (1H, ddd), 4.12 (1H, br d), 4.82 (1H, ddd), 4.93-5.00 (1H, m), 7.33-7.43 (5H, m). Lit. ref[3]



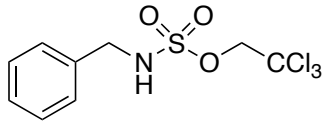
δ_H(300 MHz; $CDCl_3$; TMS) 1.30 (3H, s), 1.47 (3H, s), 1.62 (1H, d), 1.63 (1H, s), 1.84-1.93 (1H, m), 2.02-2.11 (1H, m), 2.75 (1H, ddd), 2.86 (1H, ddd), 3.94 (1H, br s), 4.81-4.87 (1H, m), 7.17-7.34 (5H, m). Lit. ref[3]



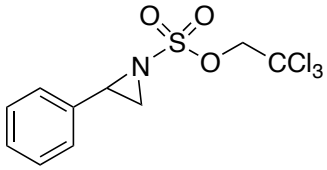
δ_H(300 MHz; $CDCl_3$; TMS) 1.63 (3H, d), 4.43 (1H, d), 4.44 (1H, d), 4.74 (1H, quint), 4.89 (1H, br d), 7.30-7.41 (5H, m). Lit. ref[4]



δ_H(300 MHz; $CDCl_3$; TMS) 1.12-1.41 (5H, m), 1.56-1.64 (1H, m), 1.71-1.79 (2H, m), 2.04-2.12 (2H, m), 3.39-3.49 (1H, m), 4.46 (1H, br d), 4.63 (2H, s). Lit. ref[4]

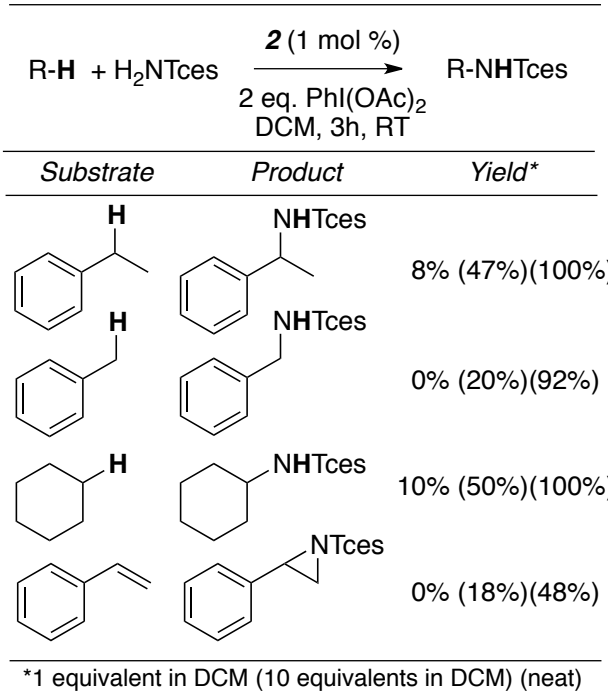


δ_H(300 MHz; $CDCl_3$; TMS) 4.38 (2H, d), 4.56 (2H, s), 4.92 (1H, br s), 7.32-7.35 (5H, m). Lit. ref [5]



δ_H(300 MHz; $CDCl_3$; TMS) 2.63 (1H, d), 3.09 (1H, d), 3.88 (1H, dd), 4.81 (1H, d), 4.88 (1H, d), 7.29 – 7.39 (5H, m). Lit. ref[6]

Table SI-1. Intermolecular reactivity of **2**.



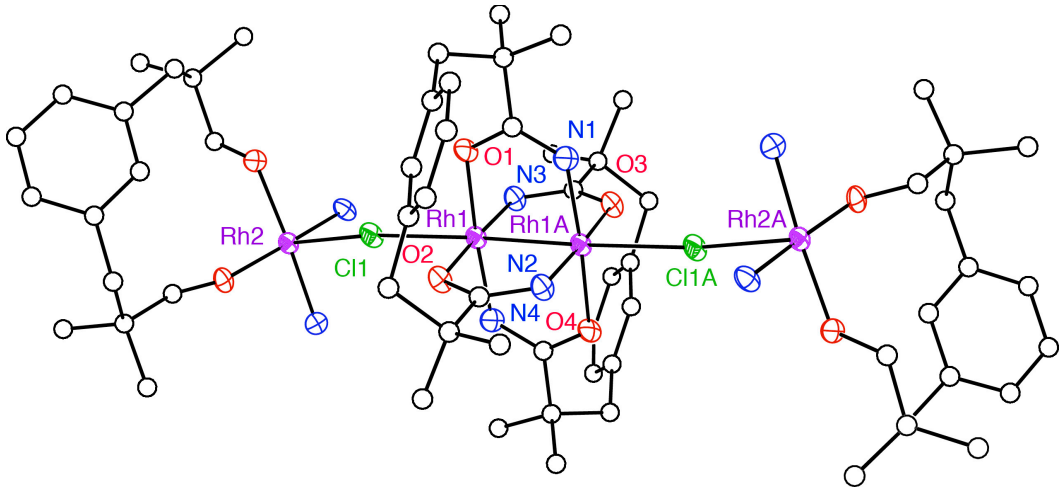


Figure SI-1. Grown structure of **2a**. This complex crystallizes in polymeric chains with three dichloromethane molecules (not shown for clarity). $C_{35}H_{50}Cl_{17}N_4O_4Rh_2$, M = 1044.76, triclinic, a = 12.6948(6), b = 13.6859(6), c = 14.8577(7), U = 2129.04(18) Å^3, T = 100 K, space group *P-1*, Z = 2, R = 0.0613, wR2 = 0.1857. Relevant bond distances (Å): Rh-Rh = 2.4155(9), Rh-Cl = 2.617(2), Rh-N = 1.970[6], Rh-O = 2.033[5]. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif with CCDC#900048.

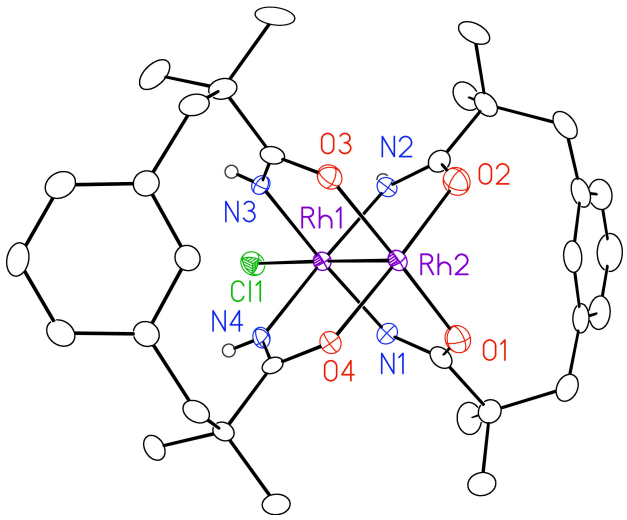


Figure SI-2. The [4,0] isomer of $Rh_2(espn)_2Cl$, **2b**. Thermal ellipsoids drawn at 50% probability. Hydrogen atoms omitted for clarity. This compound crystallizes with two dichloromethane molecules in the asymmetric unit (not shown for clarity). $C_{34}H_{44}Cl_{15}N_4O_4Rh_2$, M = 959.83, monoclinic, a = 13.2750(3), b = 12.8783(3), c = 23.4841(5), U = 3884.71(15) Å^3, T = 100 K,

space group $P2_1/c$, Z = 4, R = 0.0296, wR2 = 0.0568. Relevant bond distances (Å): Rh-Rh = 2.4136(4), Rh-Cl = 2.4165(9), Rh-N = 2.003[3], Rh-O = 1.998[2]. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif with CCDC#900049.

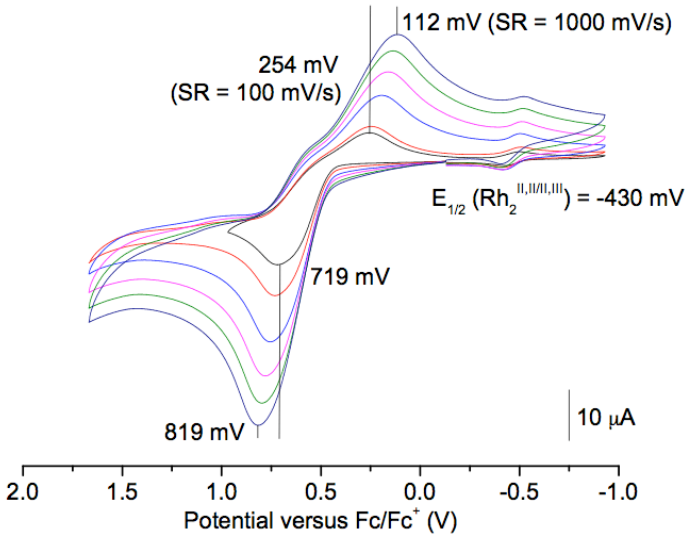
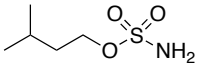
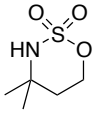
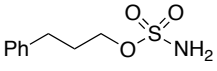
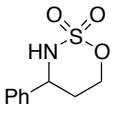


Figure SI-3. **2** (1 mM in CH_3CN/100 mM tetrabutylammonium hexafluorophosphate) in the presence of 10 mM tetrabutylammonium chloride at different scan rates.

Table SI-2. Simple cyclization reactions at 0.05 mol% loading for catalysts **2a** and **2b**

	Substrate	Product	Catalyst ***2a*** **TON (Yield)**	*Catalyst* ***2b*** **TON (Yield)**
S1			1400 (70%)	1460 (73%)
S2			1450 (72%)	1420 (71%)

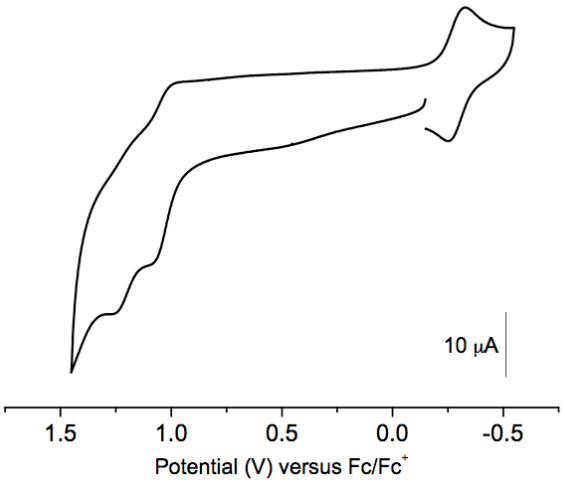


Figure SI-4. **2** (1 mM in CH_3CN/100 mM tetrabutylammonium hexafluorophosphate) with two equivalents K(BAr^f) (Figure 2 in manuscript), plus 2 equivalents $PhI(OAc)_2$. The oxidant causes changes in the electrochemistry of **2**; this is not the case when $PhI(OAc)_2$ is added to **1**. [7]

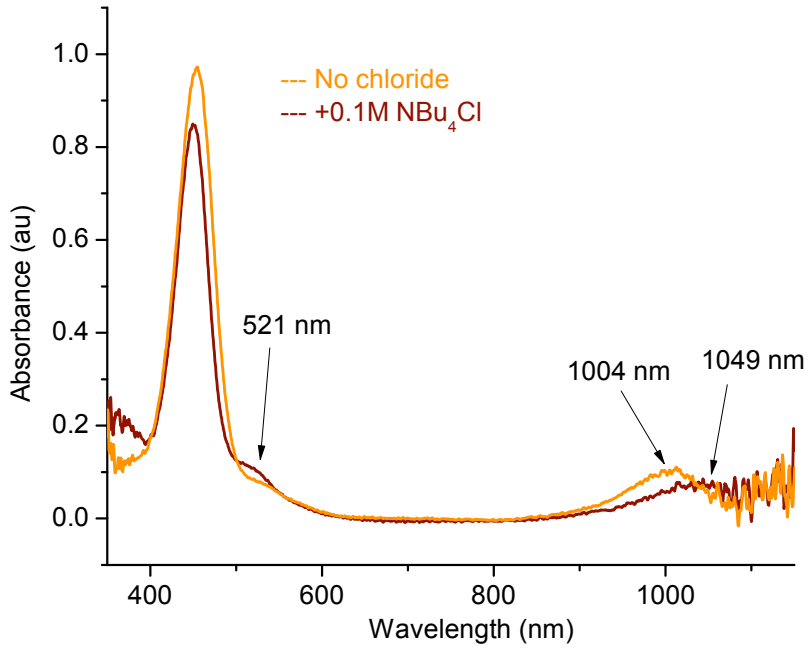


Figure SI-5. UV-Visible spectrum of **2** (orange); in the presence of excess chloride (red). A slight bathochromic shift is observable upon chloride addition.

1. C. G. Espino, K. W. Fiori, M. Kim and J. Du Bois, *J. Am. Chem. Soc.*, 2004, **126**, 15378-15379.
2. C. G. Espino and J. A. DuBois, *Angew. Chem. Int. Edn Engl.*, 2001, **40**, 598-600.
3. M. E. Harvey, D. G. Musaev and J. Du Bois, *J. Am. Chem. Soc.*, 2011, **133**, 17207-17216.
4. K. W. Fiori and J. Du Bois, *J. Am. Chem. Soc.*, 2007, **129**, 562-568.
5. L. J. Ingram, A. Desoky, A. M. Ali and S. D. Taylor, *The Journal of Organic Chemistry*, 2009, **74**, 6479-6485.
6. K. Guthikonda and J. Du Bois, *J. Am. Chem. Soc.*, 2002, **124**, 13672-13673.
7. K. P. Kornecki and J. F. Berry, *Chem.-Eur. J.*, 2011, **17**, 5827-5832.