Electronic Supplementary Information

Photo-Ejected Ligands Hyperpolarized by Parahydrogen in Reversible Exchange

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Synthesis

Synthesis of [Ir(IMes)(COD)Cl]

The SABRE pre-catalyst [Ir(IMes)(COD)Cl] (IMes = 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene, COD = 1,5-cyclooctadiene), was synthesized according to methods previously described in the literature.[1]

Synthesis and characterization of $[Ru(bpy)_2(pyd)_2]^{2+}$ and $[Ru(tpy)(biq)(pyz)]^{2+}$

$[Ru(bpy)_2(pyd)_2]^{2+}$ (**1**) $Ru(bpy)_2Cl_2$ (0.15 g, 0.288 mmol) (bpy = 2,2'-bipyridine) and 10-fold excess (2.88 mmol) of pyridazine (pyd = pyridazine) were added to 10 mL of degassed ethanol:water (1:1) in a pressure tube. The mixture was stirred at 100°C for 12 hours. The reaction was allowed to cool to room temperature, excess starting material was extracted into dichloromethane, and a saturated aqueous solution of KPF_6 (1–2 mL) was added to the aqueous fraction, producing a red precipitate. The precipitate was then extracted into dichloromethane, and the solvent was removed under reduced pressure. The solid was purified using flash chromatography (SiO_2, 0.3% saturated KNO_3, 5% water in CH_3CN, ramped to 15% H_2O) to give the pure complex. After column purification, the NO_3-salt was dissolved in minimal water and converted to the PF_6-salt upon adding a saturated solution of KPF_6. The precipitate was isolated by extraction into dichloromethane, and the solvent was removed under reduced pressure. Yield: 230 mg (92%). ^{1}H NMR (CD_3CN): δ 8.97 (d, *J* = 5.6 Hz, 2H, 6'-bpy), 8.93-8.96 (m, 2H, α-pyd), 8.80 (dt, *J* = 5.8, 1.2 Hz, 2H, δ-pyd), 8.36 (d, *J* = 7.9 Hz, 2H, 3'-bpy), 8.23 (d, *J* = 8.1 Hz, 2H, 3-bpy), 8.15 (td, *J* = 8.0, 1.5 Hz, 2H, 4'-bpy), 7.89 (td, *J* = 8.0, 1.5 Hz, 2H, 4-bpy), 7.84 (d, *J* = 5.8 Hz, 2H, 6-bpy), 7.76 (ddd, *J* = 8.0, 5.7, 1.4 Hz, 2H, 5'-bpy), 7.63 (ddd, *J* = 8.8, 5.0, 1.4 Hz, 2H, β-bpy), 7.48 (ddd, *J* = 8.0, 5.8, 2.0 Hz, 2H, γ-pyd), 7.31 (ddd, *J* = 8.0, 5.6, 1.3 Hz, 2H, 5-bpy); ^{13}C NMR (CD_3CN): δ 158.62, 158.47, 158.13, 154.53, 153.86, 153.70, 139.08, 138.74, 131.31, 128.45, 127.81, 124.65, 124.09; purity by HPLC = 98 %; ESI MS calcd for $C_{28}H_{24}N_8Ru$ $[M]^+$ PF_6^- 719.08, $[M]^{2+}$ 287.06; found 719.2 $[M]^+$ PF_6^-, 287.0 $[M]^{2+}$; UV/Vis (CH_3CN): λ_{max} (ε × 10^{-3}) 420 nm (12.5).

$[Ru(tpy)(biq)(pyz)]^{2+}$ (**2**) $[Ru(tpy)(biq)Cl]PF_6$ (0.13 mmol) (tpy = 2,2',2"-terpyridine, biq = 2,2'-biquinoline) and 10-fold excess of pyrazine (1.3 mmol) (pyz = pyrazine) were added to 8 mL of degassed EtOH : H_2O (1:1) in a pressure tube. The mixture was stirred at 80 °C for 12 hours. The reaction mixture was transferred into 50 ml of H_2O. The addition of a saturated aqueous KPF_6 solution (ca. 1 mL) produced a red precipitate that was collected by vacuum filtration and washed with ether. The solid was purified using flash chromatography (SiO_2, 0.3% saturated KNO_3, 2% water in CH_3CN, ramped to 8% H_2O) to give the pure complex. After

column purification, the NO_3-salt was dissolved in minimal water and converted to the PF_6-salt upon adding a saturated solution of KPF_6. The precipitate was isolated by extraction into dichloromethane, and the solvent was removed under reduced pressure. Yield: 72 mg (58%). ^{1}H NMR (CD_3CN): δ 8.97 (dd, *J* = 15.6, 8.9 Hz, 2H), 8.70 (d, *J* = 8.8 Hz, 1H), 8.57 (d, *J* = 8.1 Hz, 2H), 8.27-8.42 (m, 5H), 8.09 (d, *J* = 3.2 Hz, 2H), 8.01 (t, *J* = 7.9 Hz, 2H), 7.93 (d, *J* = 5.4 Hz, 2H), 7.85 (d, *J* = 8.1 Hz, 1H), 7.76 (t, *J* = 7.7 Hz, 1H), 7.63 (d, *J* = 3.1 Hz, 2H), 7.50 (d, *J* = 7.7 Hz, 1H), 7.27-7.41 (m, 4H), 7.16 (d, *J* = 8.8 Hz, 1H), 6.67 (d, *J* = 8.8 Hz, 1H). Purity by HPLC = 95 %. ESI MS calcd for $C_{38}H_{27}N_7Ru$ $[M]^+$ PF_6^- 816.1; found 816.1. UV/Vis (CH_3CN): λ_{max} (ε × 10^{-3}) 510 nm (9.9).

Table S1. Absorbance maximum and quantum yield of ligand loss (Φ_{PS}) upon irradiation.

Compound	λ_{max} abs (nm)		ϕ_{PS}	
	A	B	(1)	(2)
$[Ru(bpy)_2(pyd)_2]^{2+}$	420	450	0.11	0.0005
$[Ru(tpy)(biq)(pyz)]^{2+}$	510	-	0.14	-

ϕ_{PS} in water with 470 nm light, where 1 is the first ligand photolysis, and 2 is the second, if applicable.

Photolysis

Preliminary photolysis experiments were performed with 2.68 mM **1**, and 2.67 mM **2** in acetone-d_6 using a 9.4 T, 400 MHz, Bruker NMR spectrometer with an Advance NEO console. The LED source described below was utilized. The photolysis measurements proceeded *in situ* with a 20 s delay (approximating a very long T_1 delay), irradiation for 0.1–10 s, and acquisition of one scan, 45-degree pulse for 2 s, with light, see Figure S1. The light was turned off after the acquisition, and the measurements continued. Ambient temperature and pressure were utilized for these measurements.

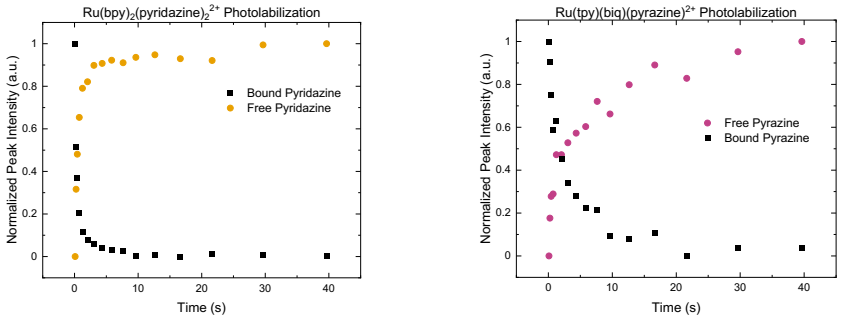

Figure S1. *Photolabilization driven by 455 nm light at 135 mW, measured in acetone-d_6. The loss of the peak indicating bound substrate and the growth of the peak indicating free substrate was quantified.*

Quantitative Photolysis

To measure the actual concentration of free substrate, pyridazine or pyrazine, at the time points of interest, quantitative NMRs with an internal standard of 1,3,5-trimethoxybenzene were measured. Concentrations averaged 6.29 mM for **1** and 2.38 mM for **2** and were performed in triplicate in acetone-d_6. Samples were irradiated with 455 nm light at 135 mW, at several time intervals: **1**: 0 s, 30 s, 60 s, 90 s, 270 s, and 390 s, and **2**: 0 s, 30 s, 60 s, 90 s, and 150 s (16 scans, 5 s delays). As one of the previously described peaks of **2**, half of a doublet overlapped with the pyrazine peak; a correction was applied to spectra, assuming the integral of the obscured portion of the doublet would correlate with the integral of the measurable portion of the doublet. The exposed doublet to obscured doublet ratio was calculated at the 0 s time point when no free pyrazine was present. Once calculated, the exposed portion of the doublet was measured, and the corresponding computed integral of the obscured doublet was subtracted from the integral of the pyrazine.

Table S2. Quantitative NMR Sample 1 with **1**.

Time (s)	**1** Integral (a.u.)	Pyridazine Integral (a.u.)	Trimethoxy benzene Integral	Pyridazine Concentration (M)	% Formation of Pyridazine
0	1.18618E+12	33464017920	6.47571E+12	0.000243	2.82
30	-	2.31834E+11	6.4588E+12	0.00169	19.6
90	-	4.30704E+11	6.45072E+12	0.00314	36.5
270	-	5.91904E+11	6.39066E+12	0.00436	50.6
390	-	5.73067E+11	6.36089E+12	0.00424	49.2
Concentration (M)	0.00863		0.0105		

Table S3. Quantitative NMR Sample 2 with **1**.

Time (s)	**1** Integral (a.u.)	Pyridazine Integral (a.u.)	Trimethoxy benzene Integral	Pyridazine Concentration (M)	% Formation of Pyridazine
0	1.39282E+12	3.7E+10	7.72536E+12	0.00023	2.65
30		2.45E+11	7.64488E+12	0.00155	17.8
90		4.45E+11	7.67594E+12	0.00279	32.2
270		6.22E+11	7.50164E+12	0.00340	46.0
390		5.64E+11	7.49442E+12	0.00362	41.7*
Concentration (M)	0.00868		0.0107		

* Point excluded from calculation as a long wait preceded the acquisition of the NMR.

Table S4. Quantitative NMR Sample 3 with **1**.

Time (s)	**1** Integral (a.u.)	Pyridazine Integral (a.u.)	Trimethoxy benzene Integral (a.u.)	Pyridazine Concentration (M)	% Formation of Pyridazine
0	1.34766E+12	5.83E+10	9.02169E+12	0.000298	4.33
30		2.48E+11	9.20562E+12	0.00124	18.0
90		4.31E+11	9.13822E+12	0.00217	31.6
270		5.86E+11	9.05421E+12	0.00298	43.3
390		4.47E+11	9.03374E+12	0.00226	33.1*
Concentration (M)	0.00687		0.0102		

* Point excluded from calculation as a long wait preceded the acquisition of the NMR.

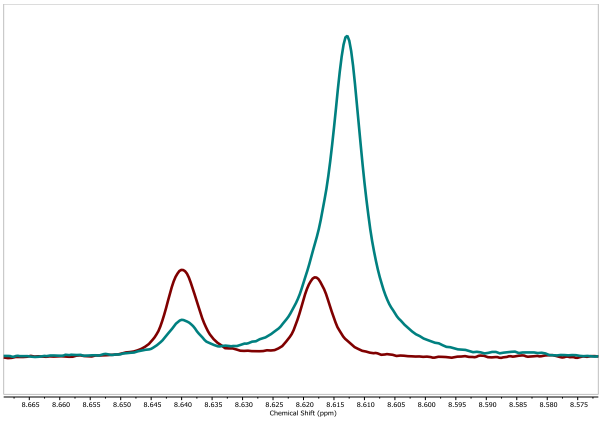

Figure S2. *Compound **2**'s qNMR, at time points 0 s (red) and 30 s (teal), where the doublet at 0 s demonstrates the starting material and the 30 s time point shows the overlapped spectra of the remaining starting material and the newly formed pyrazine.*

Table S5. Quantitative NMR Sample 1 with **2**.

Time (s)	**2** Integral (a.u.)	Pyrazine Integral (a.u.)	Exposed Portion of Doublet (a.u.)	Corrected Pyrazine Integral (a.u.)	Trimethoxy benzene Integral (a.u.)	Pyrazine Concentration (M)	% Formation of Pyrazine
0	5.71018E+11	1.524E+11	1.2839E+11	0	1.00786E+13	0	0.00
30		5.74495E+11	79487093760	4.80143E+11	1.01368E+13	0.00103	41.8
60		7.144E+11	62800574464	6.39856E+11	1.02722E+13	0.00136	55.0
90		7.48909E+11	57693176832	6.80427E+11	1.02267E+13	0.00145	58.7
150		8.01668E+11	58355957760	7.324E+11	1.02795E+13	0.00156	62.9

Concentration (M)	0.00247				0.00970		

Table S6. Quantitative NMR Sample 2 with **2**.

Time (s)	**2** Integral (a.u.)	Pyrazine Integral (a.u.)	Exposed Portion of Doublet (a.u.)	Corrected Pyrazine Integral (a.u.)	Trimethoxy benzene Integral (a.u.)	Pyrazine Concentration (M)	% Formation of Pyrazine
0	4.0843E+11	1.11464E+11	97234038784	0	9.22175E+12	0	0.00
30		4.57856E+11	54111021056	3.95826E+11	9.11089E+12	0.000877	49.1
60		5.3285E+11	47536871424	4.78356E+11	9.13072E+12	0.00106	59.1
90		5.47014E+11	46748906496	4.93423E+11	9.19232E+12	0.00108	60.6
150		5.73525E+11	41835420672	5.25567E+11	9.22114E+12	0.00115	64.3
Concentration (M)	0.00179				0.00900		

Table S7. Quantitative NMR Sample 3 with **2**.

Time (s)	**2** Integral (a.u.)	Pyrazine Integral (a.u.)	Exposed Portion of Doublet (a.u.)	Corrected Pyrazine Integral (a.u.)	Trimethoxy benzene Integral (a.u.)	Pyrazine Concentration (M)	% Formation of Pyrazine
0	4.19118E+11	1.16491E+11	94281403392	0	8.45455E+12	0	0.00
30		4.83564E+11	50593694720	4.21052E+11	8.31463E+12	0.00147	51.1
60		5.54646E+11	39333065728	5.06047E+11	8.34397E+12	0.00176	61.2
90		5.61616E+11	39450373120	5.12872E+11	8.25835E+12	0.00181	62.6
150		5.67522E+11	39843004416	5.18294E+11	8.15921E+12	0.00185	64.1
Concentration (M)	0.00289				0.0129		

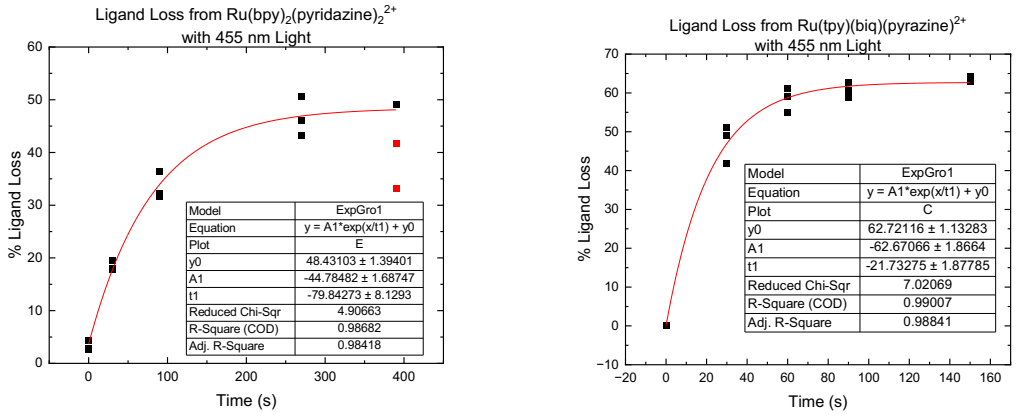

Figure S3. *The qNMR monitored loss of pyridazine from* ***1*** *and* ***2*** *in acetone-d_6, with 455 nm light at 135 mW.*

Table S8. Ligand loss at time point of interest.

Sample	Time Point of Interest (s)	Loss of Ligand (%)
1	180	43.7
2	60	58.8

Conditions of the Hyperpolarization Experiments

Parahydrogen

For experiments, *p*-H_2 was generated using an Advanced Research Systems *p*-H_2 generator in combination with a Lakeshore 335 Cryogenic temperature controller, which flows hydrogen gas over an iron oxide catalyst at 28 K. We achieved an output *p*-H_2 percentage of 93.1% under these experimental conditions.

Light Irradiation and Bubbling Setup Conditions

The polarization transfer field (PTF) was chosen based on well-established studies involving the hyperpolarization of free pyridazine and pyrazine at 6.5 mT induced by a mT field solenoid coil. [2,3] An IDR-329 kilogauss meter was used to verify the field before each experiment.

The samples were excited with a 135 mW 455 nm LED in a Prizmatix Five Fiber Coupled LED System for NMR Spectroscopy, with the light presented via a polymer optical fiber (POF). The POF had a high numerical aperture and a diameter of 1000 µm, was 4 m long, and the cladding had been stripped 23 cm before the end. To ensure irradiation in the detection region of the NMR, the final 5 cm was sanded as described previously.[4] Unless otherwise specified, the samples were pressurized with 50 psi, 3.4 atm, *p*-H_2 at a 45 sccm flow rate set using a Bronkhorst EL-FLOW MFC (mass flow controller).

To ensure bubbling and irradiation simultaneously, a custom-made Teflon cap was utilized with an inlet with a capillary tube for *p*-H_2 bubbling, an outlet, and an inner tube to separate the POF fiber optic from the sample. The NMR tube and inner tube were made by New Era, specifically the PhotoNMR Sampling Device-5mm. The Teflon cap was screwed into the NMR tube, utilizing an O-ring, and utilized Idex connectors to secure the inflow tubing, outflow tubing, and inner tube for the fiber optic. The "para-cube," previously described by Austin Browning, supplied the p-H2 from a connected tank. [5]

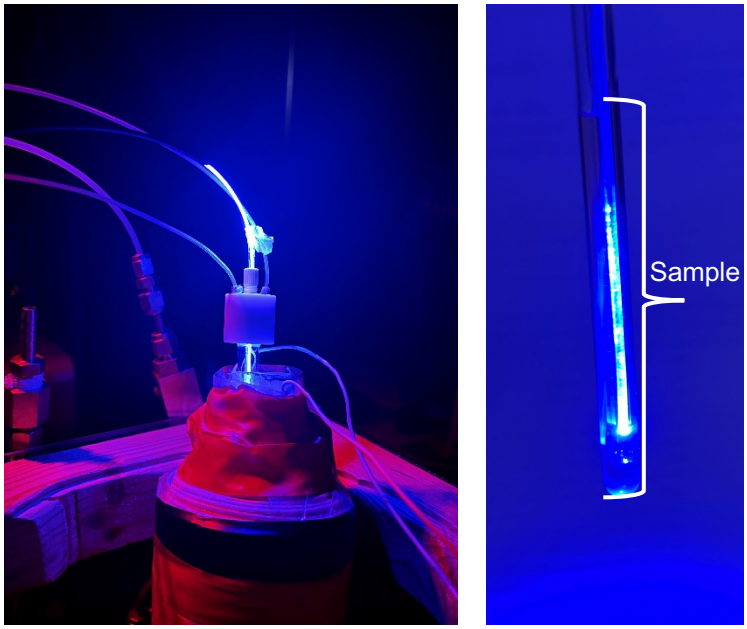

Figure S4. *Left, the NMR tube, with the Teflon cap and LED fiber optic, in the PTF, placed within the para-cube. Right, the sample within the NMR tube with the sanded section of the LED fiber optic within the inner tube.*

To polarize the sample, *p*-H_2 was bubbled for 30 s while the sample was irradiated or kept in the dark in the PFT. After the bubbling time had elapsed, the sample was manually transferred into the Oxford Instruments 1.4 T NMR, and a 90-degree pulse was acquired. As previously noted, the NMR maintains a temperature of 40 ℃. Thus, the sample was, following the acquisition, removed from the NMR and placed into a water bath at ~21 ℃ for a minimum of 1.5 minutes. A scan after the relaxation and cooling period was performed to ensure that the signal measured only originated from the current scan. If hyperpolarization remained, the sample was placed back in the water bath for a longer delay. If the signal had relaxed to thermal polarization, another 1.5-minute delay in the water bath was performed, followed by bubbling and signal acquisition.

NMR Sample Concentration and Conditions

All samples were prepared in the dark, as much as possible, and under an inert atmosphere. The concentrations utilized were 8.2 mM **1**, $Ru(bpy)_2(pyridazine)_2^{2+}$ and 7.3 mM **2**, $Ru(tpy)(biq)(pyridazine)^{2+}$, with an average of 4.0 mM Ir(IMes)(COD)(Cl), the SABRE catalyst precursor, in 0.5 mL air free acetone-d_6. A 90-degree pulse was applied to the samples, with one scan for NMR spectral acquisition. The highest enhancement formed in **1** at 3 min of total irradiation and for **2** at 1 min total irradiation with 455 nm light.

Enhancement Calculations

Temperature Measurements

The temperature is essential to measure the polarization successfully, and the experimental transfer methodology between the 40℃ benchtop NMR and the 21℃ water bath made it challenging to assess at the moment of acquisition. Measurement of the temperature of the NMR sample was then necessary and performed utilizing an air-free methanol thermometer, using the equation described by Karschin et al.[6] The regular procedure (1.5 minutes in water bath, 30 s in the coil) was followed to best approximate the temperature, albeit without bubbling H_2 or irradiating the sample. Unfortunately, the two methanol peaks could not be resolved with one scan upon immediate transfer to the NMR, likely due to the lack of a net magnetic moment within the NMR before signal acquisition. The immediate transfer and measurement would have provided the closest comparison to the temperature of the sample after hyperpolarization. This necessitated acquiring more measurements to create a curve to extrapolate the temperature at 0 s. The sample was then transferred into the NMR and left within the NMR for increasing amounts of time. Therefore, after 30 s of the methanol sample in the coil had elapsed, it was transferred to the magnet, and after a 10–30 s wait, the signal was acquired. Four measurements were obtained per time interval. Once the temperature of methanol at 0 s had been extrapolated (21.11 ± 0.72℃) the temperature of acetone-d_6 could be determined, 21.04 ± 0.80℃ using heat capacities at 298.15 K described previously.[7,8]

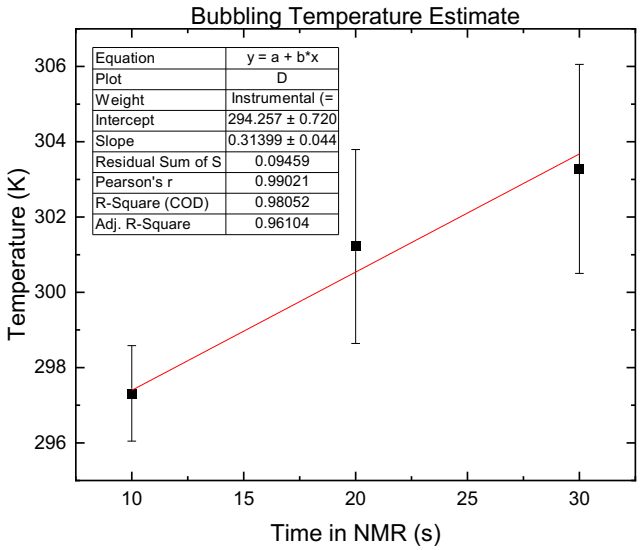

Figure S5. *Temperature was measured as a function of time in the benchtop NMR, using a methanol-d_4 thermometer, with four measurements per data point.*

External NMR Standard

Similar to the challenge of measuring methanol peak shifts without allowing for the build up of net magnetization, the thermal polarization of **1** and **2** after excitation proved challenging to resolve by comparison of the thermally polarized spectra to the hyperpolarized spectra. To address this, an external standard was utilized: 0.021 M 1,3,5-trimethoxybenzene in acetone-d_6. The same acquisition parameters and methodology were used as the hyperpolarization experiments, and the linewidth was less than the linewidth used for the SABRE measurements by 0.17–0.07 Hz. Fourteen measurements were acquired, each comprised one scan, with an exponential apodization applied, here using MestReNova version 14.1.2-25024. After the measurements concluded, the signal was averaged, and the concentration and number of protons accounted for, resulting in a value of 6400 signal M^{-1} $protons^{-1}$.

Calculation of Hyperpolarization and Enhancement Values

Enhancement values for ^{1}H NMR signals were calculated using the following equation:

$$\frac{\rho_{HP}}{\rho_{Thermal}} = enhancement$$

Where $\rho_{Thermal}$ is the thermal polarization and ρ_{HP} is the polarization of the hyperpolarized sample.

$$\rho_{Thermal} = \tanh\left(\frac{\gamma B_0 \hbar}{2k_B T}\right)$$

Where $\gamma_{(^1H)}$ is the gyromagnetic ratio of ^{1}H (2.67522 x 10^8 rad*$s^{-1}T^{-1}$), B_0 is the magnetic field (1.4 T), $\hbar$ is reduced Planck's constant, and k_B is Boltzmann's constant.

$$\rho_{HP} = \tanh\left(\frac{\gamma B_0 \hbar}{2k_B T}\right) * \frac{S_{Substrate}}{S_{Standard}} * \frac{SD_{Standard}}{SD_{Substrate}}$$

Where $S_{Substrate}$ is the NMR signal for pyridazine/pyrazine substrates, corresponding to the absolute integral, and $S_{Standard}$ is the NMR signal of the external standard.

SD is equal to the spin density, quantifying the relationship between the number of protons and the concentration of substrate/standard.

$$SD = C * n_p$$

Where C is concentration, and n_p is the number of protons the signal of substrate or standard contains.

Table S9. Enhancement calculations and hyperpolarization of pyridazine and pyrazine.

Target	Conditions	|S|	C (M)	n_p	Enhancement (fold)	ρ_{HP} (%)[a]
1,3,5-Trimethoxy benzene	External Standard	1224.6	0.0213	9	-	-
Pyridazine	**1**, 180 s 455 nm Light, IrIMes, *p*-H_2	147694.3	0.00358[b]	2	3229	1.6
Pyrazine	**2**, 60 s 455 nm Light, IrIMes, *p*-H_2	50134.6	0.00429[c]	4	457	0.22

[a] 21.04°C and 1.41 T, [b] 43.7% of 8.2 mM of **1**, [c] 58.8% of 7.3 mM of **2**

Stability in Protonated Acetone

A small amount of each was dissolved in protonated acetone to quantify the thermal stability of **1** and **2** in acetone. Initial UV-visible spectra were measured with a Cary UV-Vis Spectrophotometer. Following measurement, the cuvettes were sealed: **1** in an air-free cuvette, although the sample was aerated, and **2** in a non-air-free cuvette. Samples were left in a water bath at 40 ℃ for 24 (**1**) and 21 (**2**) hours, covered in aluminum foil. After the delay, the spectra were again compared to the initial measurement. Some increase in the absorbance of the spectra of **1** is likely due to minimal evaporation of the solvent. After 24 hours, 98% of **1** remained, and after 21 hours, 18% of **2** remained.

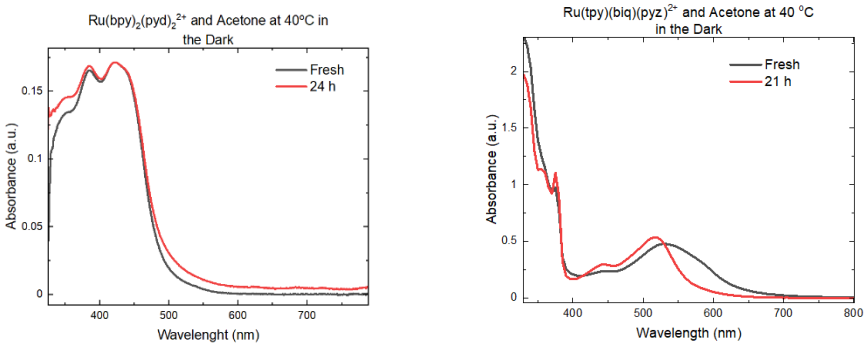

Figure S6. *UV-Vis spectra illustrating the relative thermal stabilities of* ***1*** *and* ***2*** *at 40°C in the dark in acetone.*

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