Electronic Supplementary Information (ESI)

Switchable hydrogenation with betaine–derived bifunctional Ir–NHC catalyst

Babulal Maji and Joyanta Choudhury*

Organometallics & Smart Materials Laboratory, Department of Chemistry,
Indian Institute of Science Education and Research (IISER) Bhopal, Bhopal 462 066, India.

E-mail: joyanta@iiserb.ac.in.

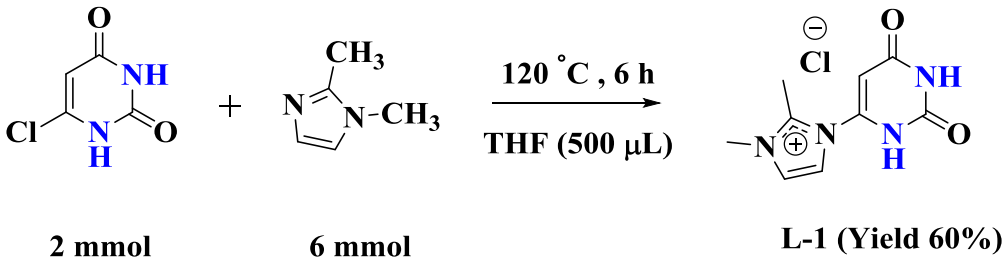
1. General information

^{1}H and $^{13}C\{^{1}H\}$ NMR spectra were recorded on Bruker AVANCE III 400 and 500 MHz NMR spectrometers at 25 °C unless mentioned otherwise. Chemical shifts (δ) are expressed in ppm using the residual proton resonance of the solvent as an internal reference as applicable – $CDCl_3$: δ = 7.26 ppm for ^{1}H spectra, 77.16 ppm for ^{13}C $\{^{1}H\}$ spectra; DMSO-d_6: δ = 2.50 ppm for ^{1}H spectra, 39.50 ppm for $^{13}C\{^{1}H\}$ spectra; D_2O: δ = 4.79 ppm CD_3CN δ= 1.94 ppm for ^{1}H spectra. All coupling constants (*J*) are expressed in hertz (Hz) and only given for $^{1}H–^{1}H$ couplings unless mentioned otherwise. The following abbreviations were used to indicate multiplicity: s (singlet), d (doublet), t (triplet), q (quartet), dd (doublet of doublets), m (multiplet), bs (broad singlet). ESI mass spectrometry was performed on a Bruker microTOF QII spectrometer. Single crystal X-ray diffraction measurements were performed with Bruker APEX-II CCD instrument. Dry solvents and reagents were obtained from commercial suppliers and used without further purification. Deuterated solvents were purchased from Sigma Aldrich. H_2 (purity 99.99%) gases was purchased from INOX Air Products Pvt. Ltd.

2. Synthesis of complex Ir-U_{NH}

a) Step-1: Synthesis of ligand (L-1): 6-(2,3-dimethyl-1H-3,4-imidazol-1-yl)pyrimidine-2,4(1H,3H)-dione.

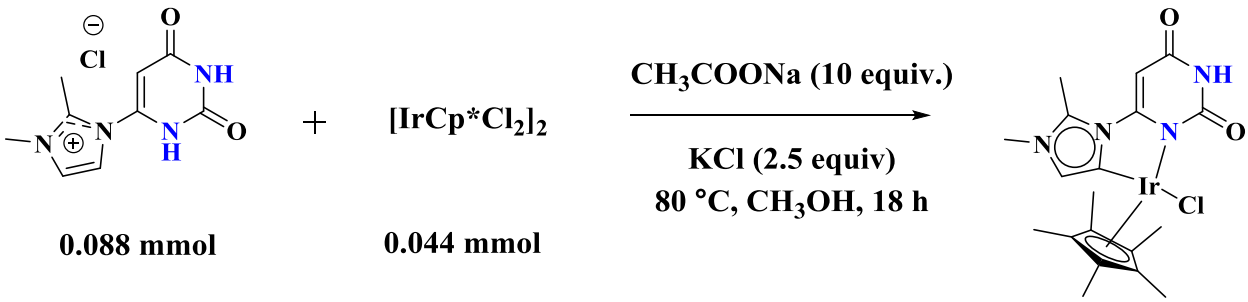
Ligand **L-1** was synthesized by stirring neat reaction of 6-chloropyrimidine-2,4 (1H,3H)-dione (293.6 mg, 2 mmol) and 1,2-dimethyl-1H-imidazole (532 μL, 6 mmol) in a pressure tube at 120 °C for 6 h in the presence of 500 μL of dry THF. After the end of the reaction, the residue was dissolved in dry MeOH and precipitated out with dry THF. The precipitate was washed three times with dry THF (30 mL) and finally one time with Et_2O (10 mL). The resulting off-white powder was dried in high vacuum. Yield 291 mg (60 %). ^{1}H NMR (400 MHz, D_2O) δ 7.63 (s, 1H), 7.47 (s, 1H), 5.78 (s, 1H), 2.74 (s, 3H), 3.8 (s, 3H). $^{13}C\{^{1}H\}$ (126 MHz, D_2O) δ 169.1, 160.3, 157.3, 144.9, 122.7, 120.0, 93.1, 34.7, 10.4. HRMS (ESI positive ion) *m/z*= 207.0853 (calculated=207.0852 for $[C_9H_{11}N_4O_2]^+$).



Scheme S1. Synthesis of the ligand **L-1**

b) Step-2: Complexation

A mixture of ligand **L-1** (21.4 mg, 0.088 mmol), $[IrCp^*Cl_2]_2$ (35.1 mg, 0.044 mmol), CH_3COONa (72.0 mg, 0.8 mmol), and KCl (16.3 mg, 0.22 mmol) was refluxed in MeOH (8 mL) for 18 h. After cooling to room temperature, the solvent was evaporated under reduced pressure. After that the residue was dissolved in DCM and filtered through a syringe filter. The remaining solution was concentrated under vacuum. Addition of diethyl ether to this concentrated solution resulted into a large amount of precipitate. This precipitate was filtered and washed with diethyl ether to afford the desired product as a light yellow solid. After that the powder complex as obtained was set for recrystallization in $CH_3OH+CH_2Cl_2/Et_2O$. Yield 31 mg (62%). ^{1}H NMR (400 MHz, D_2O) δ 7.08 (s, 1H), 6.02 (s, 1H), 3.83 (s, 3H), 2.85 (s, 3H), 1.71 (s, 15H). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.27 (s, 1H), 6.65 (s, 1H), 5.75 (s, 1H), 3.78 (s, 3H), 2.82 (s, 3H), 1.79 (s, 15H) .^{13}C{^{1}H} NMR (126 MHz, DMSO-d_6): δ 164.8 (Ir-*C*) 155.9, 145.0, 128.9, 122.8, 95.8, 87.50, 34.9, 12.5, 8.6. HRMS (ESI, positive ion) *m/z*= 533.1507 (calculated= 533.1505 for $[C_{19}H_{24}N_4IrO_2]^+$).

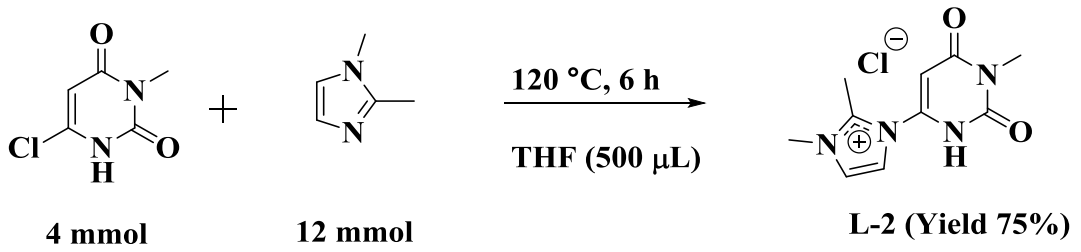


Scheme S2. Synthesis of the complex **Ir-U$_{NH}$**

3. Synthesis of complex Ir-U_{NMe}

a) Step 1: Synthesis of ligand L-2: 6-(2,3-dimethyl-1H-3l4-imidazol-1-yl)-3-methylpyrimidine-2,4(1H,3H)-dione

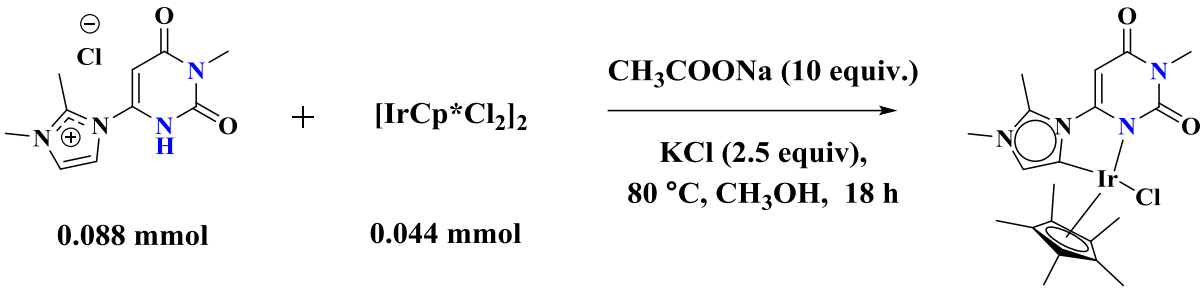
Ligand **L-2** was synthesized by stirring neat reaction of 6-chloro-3-methylpyrimidine-2,4(1H,3H)-dione (586.2 mg, 4 mmol,) and 1,2-dimethyl-1H-imidazole (1.06 mL, 12 mmol) in a pressure tube at 120 °C for 6 h in the presence of 500 µL THF. After the end of the reaction, the residue was dissolved in dry MeOH and precipitated out with dry THF. The precipitate was washed three times with THF (30 mL) and finally one time with Et_2O (10 mL). The resulting off-white powder was dried in high vacuum. Yield: (530 mg, 75 %). ^{1}H NMR (500 MHz, D_2O) δ 7.72 (s, 1H), 7.61 (s, 1H), 6.12 (s, 1H), 3.91 (s, 3H), 3.33 (s, 3H), 2.74 (s, 3H). $^{13}C\{^1H\}$ (126 MHz, D_2O) δ 167.1, 156.9, 149.8, 145.5, 123.1, 120.3, 95.4, 34.9, 27.6, 10.2. HRMS (ESI, positive ion) *m/z*= 221.1007 (calculated= 221.1033 for $[C_9H_{11}N_4O_2]^+$).



Scheme S3 Synthesis of the ligand **L-2**

b) Step 2: Complexation

A mixture of ligand **L-2** (22.5 mg, 0.088 mmol), $[IrCp^*Cl_2]_2$ (35.1 mg, 0.044 mmol) CH_3COONa (72 mg, 0.8 mmol), and KCl (16.3 mg, 0.22 mmol) was refluxed in methanol (8 mL) for 18 h. After cooling to room temperature, the reaction mixture was filtered through Celite and all volatiles were removed under reduced pressure. The complex was obtained as a light yellow solid by precipitation from CH_2Cl_2/Et_2O. After that the powdered complex as obtained was set for recrystallization in CH_2Cl_2/Et_2O.Yield (31 mg, 60%). ^{1}H NMR (500 MHz, D_2O) δ 7.02 (s, 1H), 6.08 (s, 1H), 3.83 (s, 3H), 3.35 (s, 3H), 2.84 (s, 3H), 1.70 (s, 15H). ^{1}H (400 MHz, $CDCl_3$) 6.64 (s, 1H), 6.11 (s, 1H), 3.78 (s, 3H), 3.42 (s, 3H), 2.85 (s, 3H), 1.79 (s, 15). $^{13}C\{^1H\}$ NMR (126 MHz, D_2O) δ 167.7, 157.0, 156.3, 143.5, 122.1, 89.4, 85.2, 66.0, 34.4, 28.5, 11.8, 8.6. HRMS (ESI, positive ion) *m/z*= 547.1672 (calculated= 547.1685 for $[C_{20}H_{26}N_4IrO_2]^+$).



Scheme S4. Synthesis of **Ir-U$_{NMe}$**

4. General procedure for hydrogenation reaction

In a 10 mL two-neck round bottom flask fitted with a condenser, quinoxaline (0.2 mmol, 100 μL, stock solution in TFE) and catalyst (0.002 mmol, 90 μL, stock solution in TFE) were taken. After that the air inside the reaction vessel was evacuated by applying vacuum and then the flask was refilled with H_2 gas from a balloon attached at the top of the condenser. This process was repeated thrice. Then 3 mL of a mixture of 2, 2, 2 trifluoroethanol (TFE, 75%) and water (H_2O, 25%) (or only 3 mL of H_2O) were added to this reaction vessel. Then the reaction mixture was stirred for desired time at 50 °C. The yield of the product was calculated by withdrawing the aliquot (100 μL) at different time intervals, followed by extracting with ethyl acetate and analysing by gas chromatography. The same procedure was followed for the hydrogenation catalysis in presence of base K_2CO_3, by addition of required amount of K_2CO_3 in the reaction mixture.

5. Additional figures

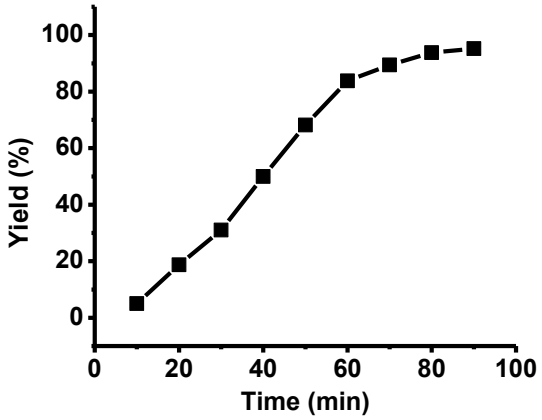


Fig. S1 Hydrogenation of quinoxaline with 0.5 mol% **Ir-U$_{NH}$** at 50 °C.

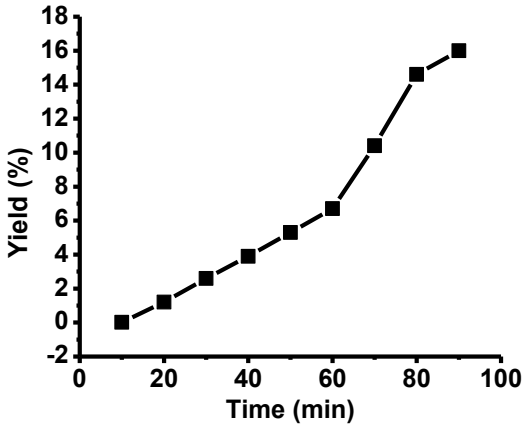


Fig. S2 Hydrogenation of quinoxaline with 0.1 mol% **Ir-U$_{NH}$** at 50 °C.

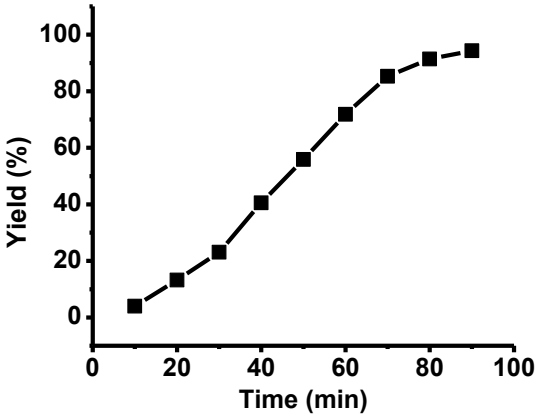


Fig. S3 Hydrogenation of quinoxaline with 1.0 mol% **Ir-U$_{NH}$** at 30 °C.

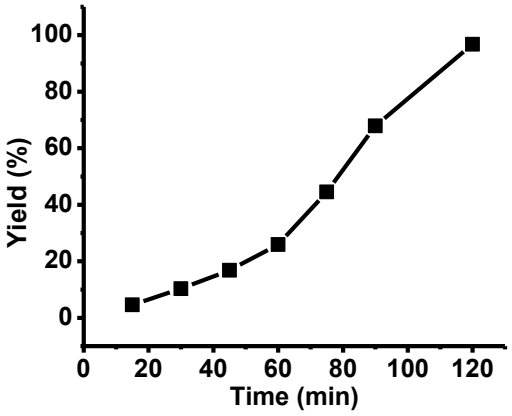


Fig. S4 Hydrogenation of quinoline with 1.0 mol% **Ir-U$_{NH}$** at 50 °C.

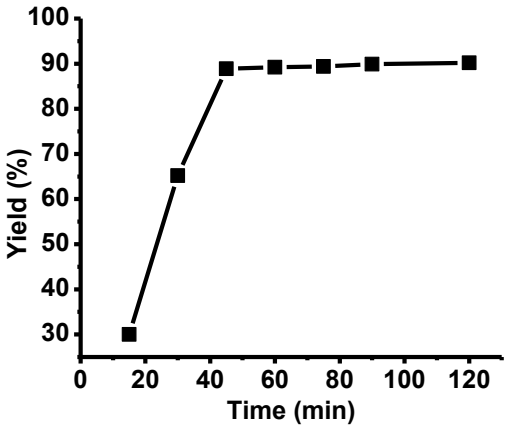


Fig. S5 Hydrogenation of 2-methyl quinoline with 1.0 mol% **Ir-U$_{NH}$** at 50 °C.

6. General procedure for the dehydrogenation of 2-methyl-1,2,3,4-tetrahydroquinoxaline

A 10 mL two-neck round-bottomed flask containing a stirring bar was sequentially charged with 1,2,3,4- tetrahydroquinoxaline (0.4 mmol) or 2-methyl 1,2,3,4- tetrahydroquinoxaline (0.4 mmol), catalyst **Ir-U$_{NH}$** (1.0 mol%) and H_2O (25%)+TFE (75%) (3 mL) as solvent. Afterwards, a condenser was placed in and the reaction mixture was heated at 95 ºC. After 24 h, the reaction mixture was extracted with Et_2O and analyzed by GC. The dehydrogenated products i.e., the corresponding quinoxalines were characterized by ^{1}H NMR spectroscopy.

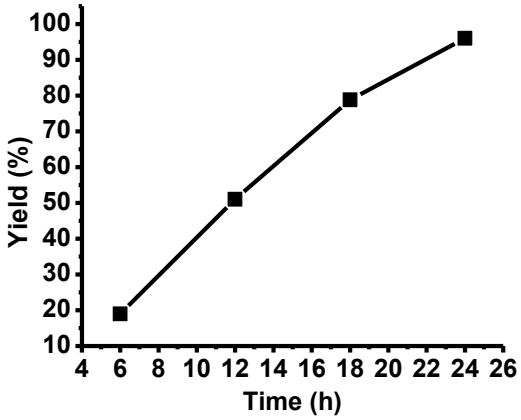


Fig. S6 Dehydrogenation of 1,2,3,4-tetrahydroquinoxaline with **Ir-U$_{NH}$** catalyst.

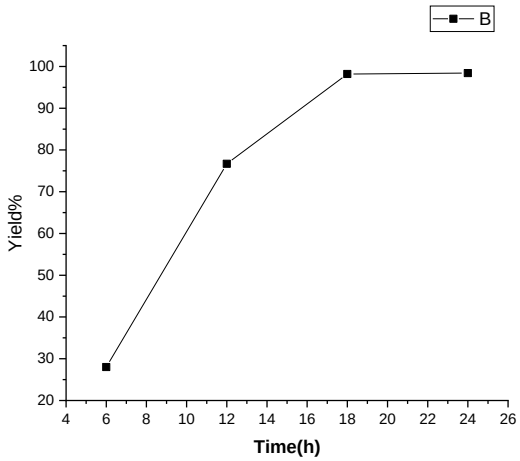


Fig. S7 Dehydrogenation of 2-methyl 1,2,3,4-tetrahydroquinoxaline with **Ir-U$_{NH}$** catalyst.

7. In situ ^{1}H NMR spectroscopic study for the reaction of H_2 with Ir-U$_{NH}$

A J-Young NMR tube was charged with **Ir-U$_{NH}$** (0.0052 mmol; 3.0 mg), H_2O (20 μL), TFE (50 μL) and CD_3CN (500 μL). After this, the tube was shaken well at room temperature for 5 min. Then an H_2 balloon was attached to the tip of the NMR tube. After 15 min ^{1}H NMR spectrum was recorded at ambient temperature. After addition of H_2 balloon color changed from light yellow to orange-red. After that, quinoxaline (0.0051 mmol, taken from a stock solution) was added to the same NMR tube and ^{1}H NMR spectrum was recorded.

Similar procedure was followed for the reaction in the presence of base (K_2CO_3) but in the presence of K_2CO_3 (0.205 mmol, 28.3 mg).

8. Catalytic hydrogenation with D_2 balloon

The general hydrogenation procedure was followed but by applying a balloon (~ 0.5 L) filled with D_2 gas. The corresponding D-incorporated product was analyzed by ^{1}H NMR spectroscopy.

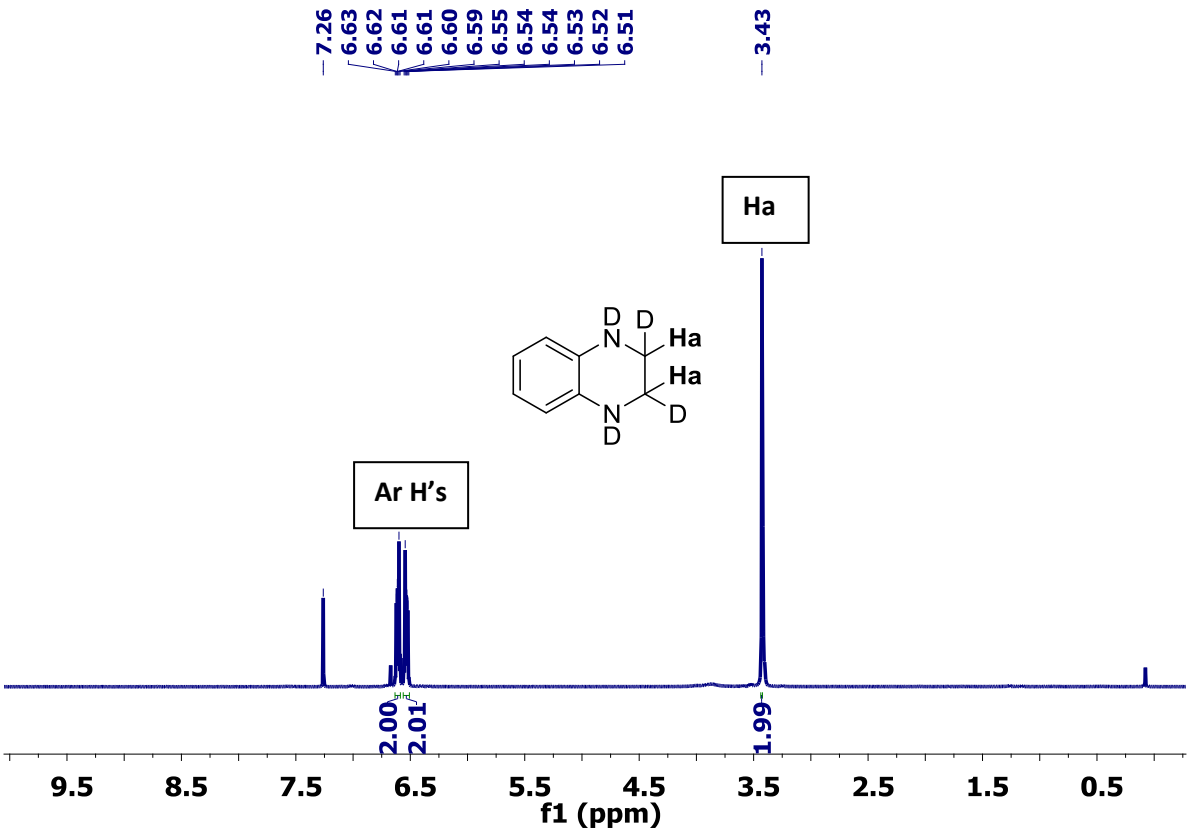


Fig. S8 ^{1}H NMR (500 mHz, $CDCl_3$) spectrum of the D-labelled hydrogenated quinoxaline.

9. Switchable catalysis experiment

The general hydrogenation procedure as described above was followed for this experiment as well with 1 mol% **Ir-U$_{NH}$** as catalyst. After 10 min of reaction 10 mol% of base (K_2CO_3, 2.7 mg; 0.02 mmol) was added to the flask. Aliquot was taken out after 10 min interval. Afterward, 20 mol% of HCl (100 μL from an aqueous stock solution, 0.4 mmol) was added and again aliquot was withdrawn after 10 min of reaction. These cycles were repeated and the aliquots were analyzed by gas chromatography to calculate the yield of the product.

Similar switcging experiment was also performed by using KOH (80 mol%) and HCl (80 mol%) consecutively. The aliquots withdrawn in every 15 min were analyzed by the same procedure as above.

10. Copy of the NMR/mass spectra

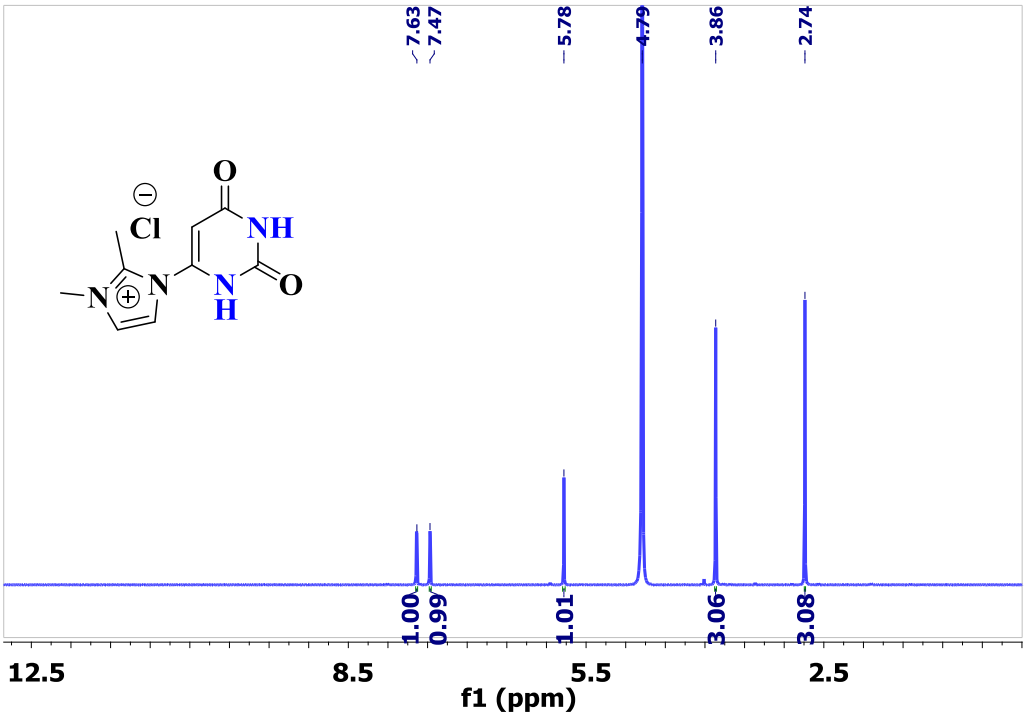


Fig. S9 ^{1}H NMR spectrum Ligand **L-1** (400 MHz, D_2O, 300 K).

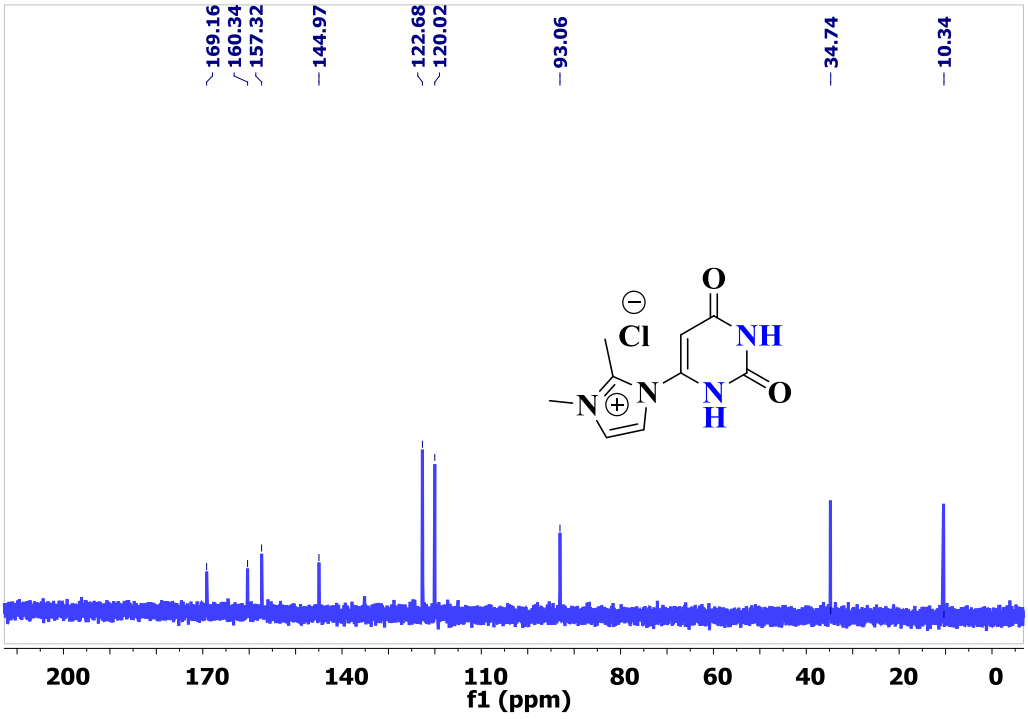


Fig. S10 $^{13}C\{^{1}H\}$ NMR spectrum of **L-1** (126 MHz, D_2O, 300 K).

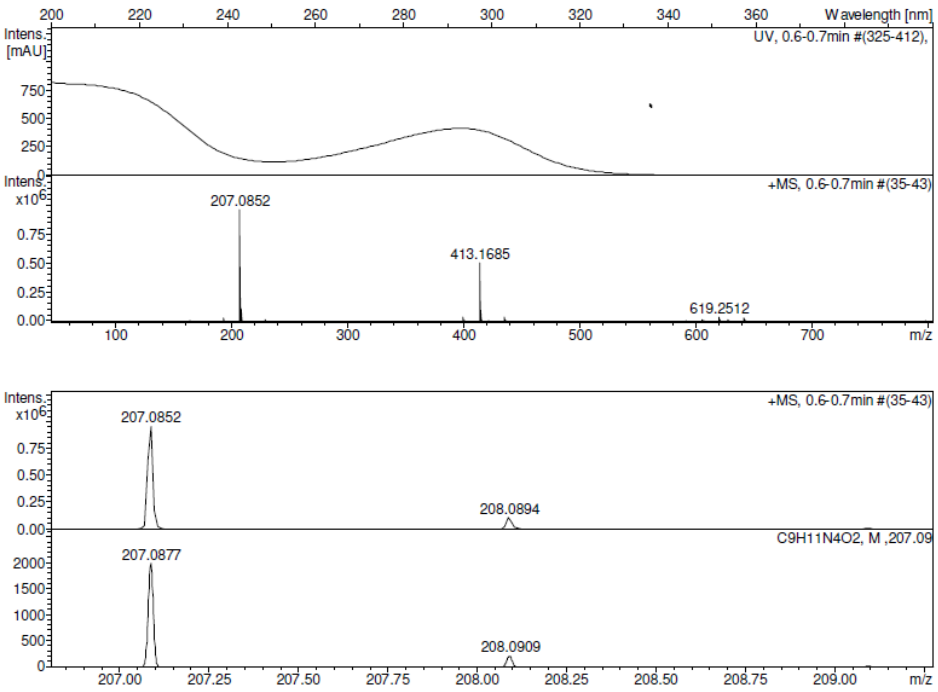


Fig. S11 ESI-MS (positive ion mode) spectrum of **L-1.**

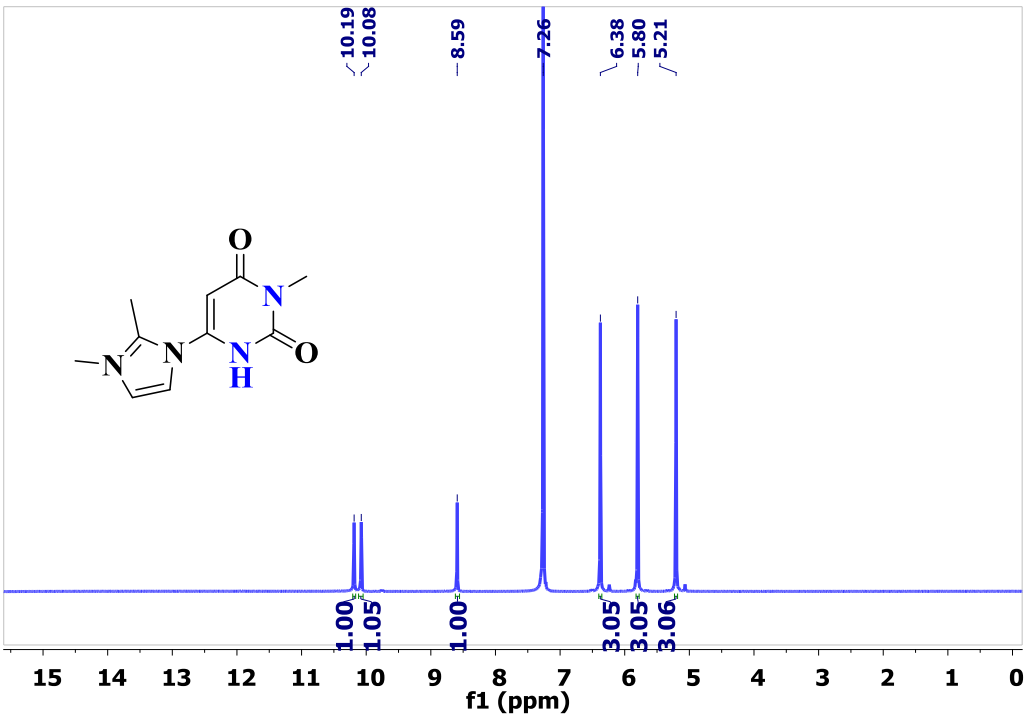


Fig S12 ^{1}H NMR spectrum Ligand **L-2** (400 MHz, D_2O, 300 K).

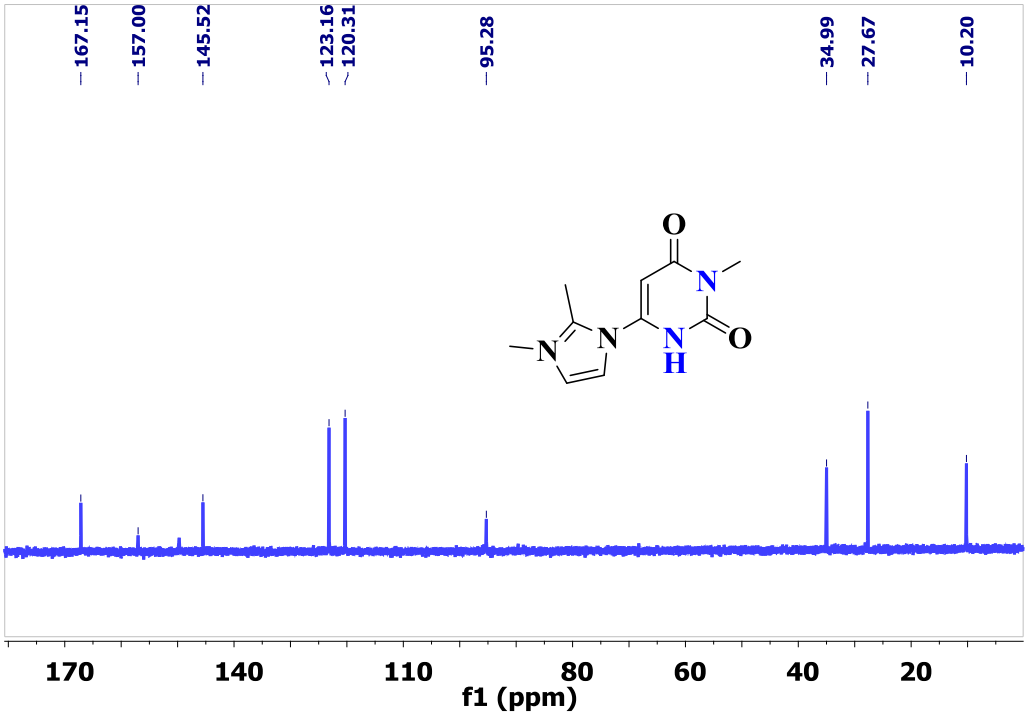


Fig S13 $^{13}C\{^{1}H\}$ NMR spectrum of **L-2** (126 MHz, D_2O, 300 K).

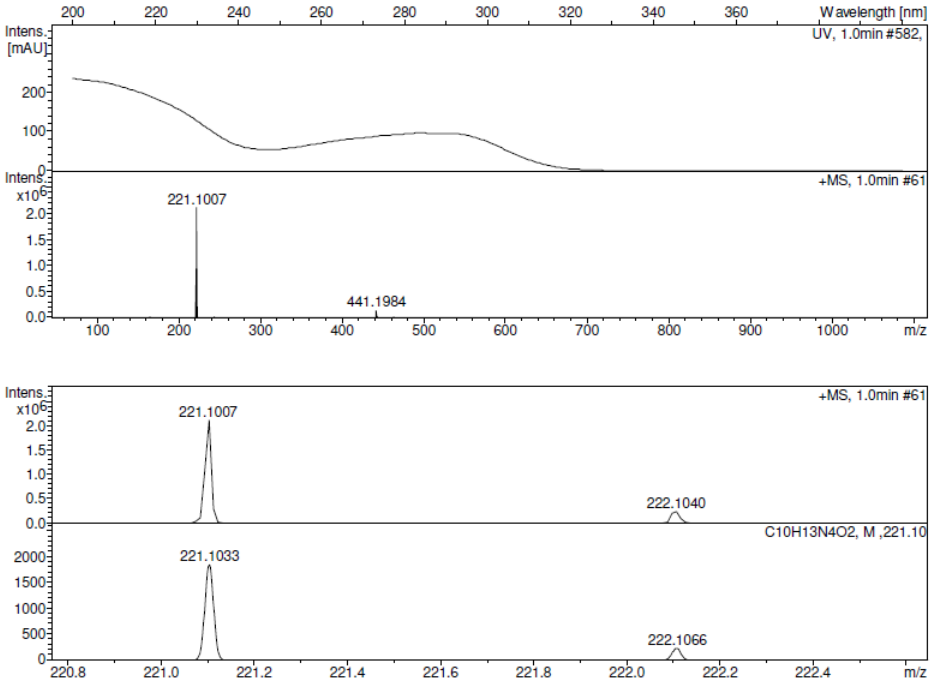


Fig S14 ESI-MS (positive ion mode) spectrum of **L-2.**

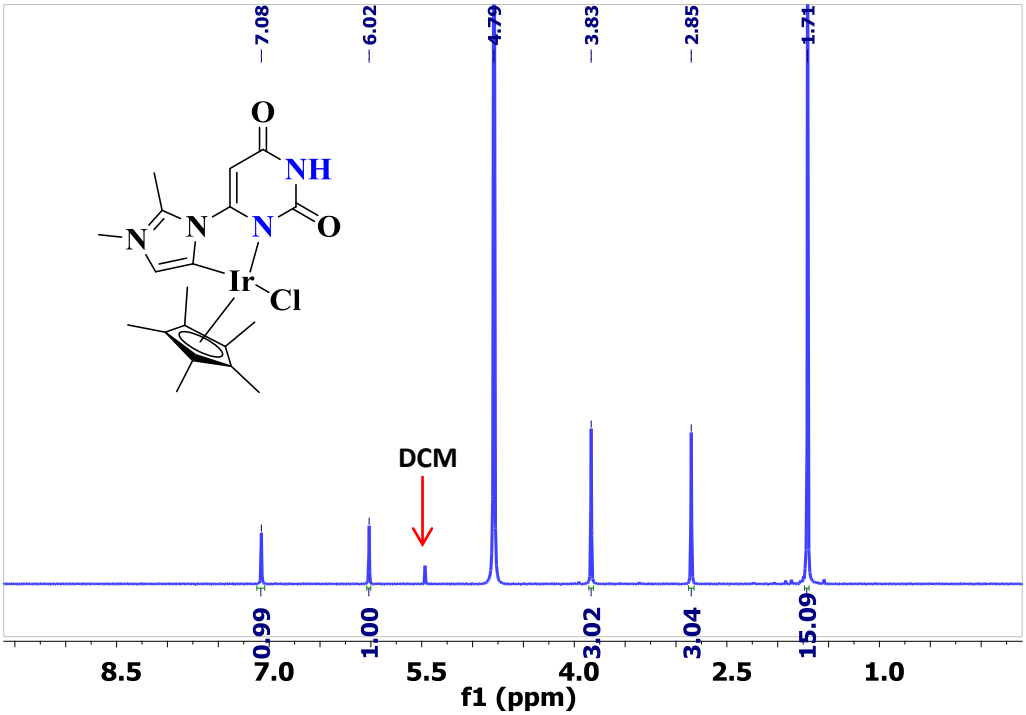


Fig S15 ^{1}H NMR spectrum of **Ir-U$_{NH}$** (400 MHz, D_2O, 300 K)

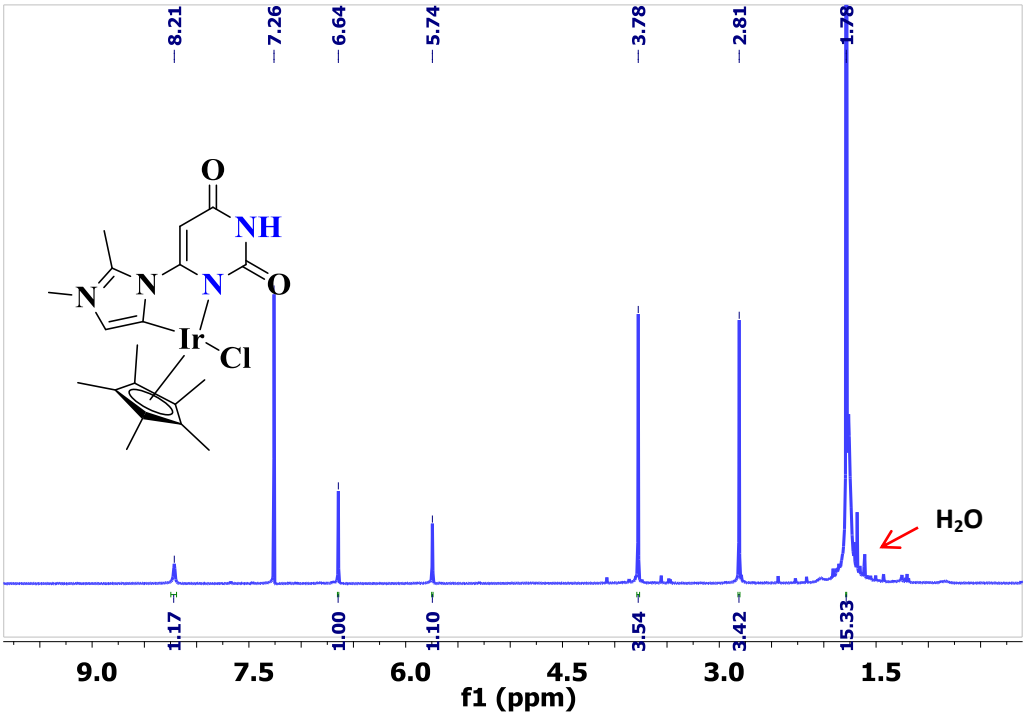


Fig S16 ^{1}H NMR spectrum of **Ir-U$_{NH}$** (400 MHz, $CDCl_3$, 300 K)

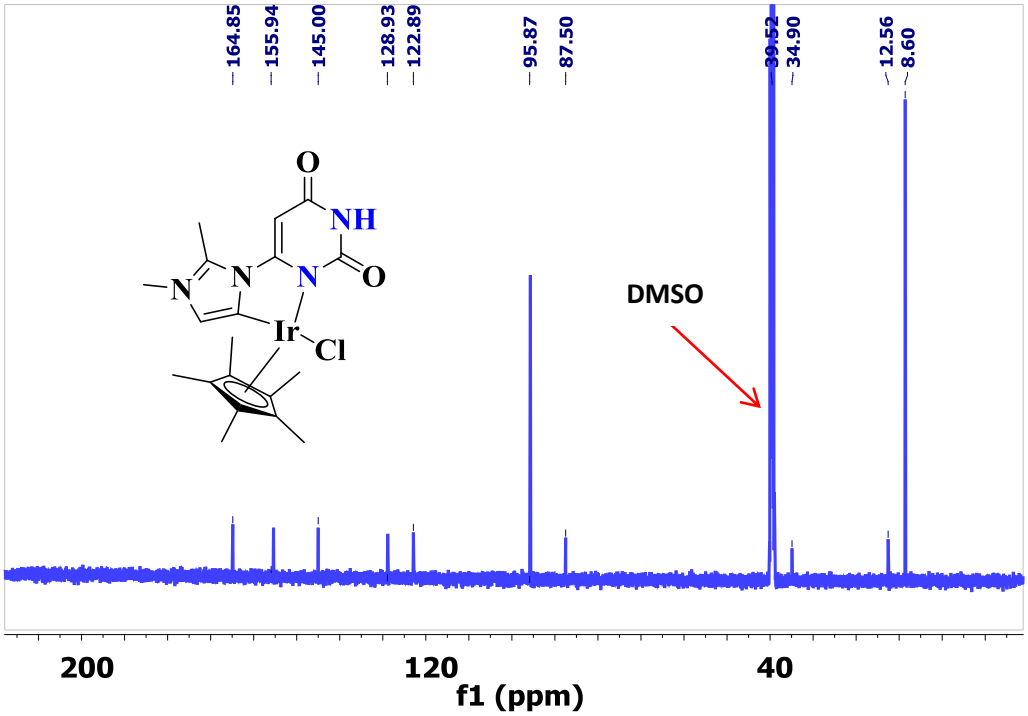


Fig S17 $^{13}C\{^{1}H\}$ NMR spectrum of **Ir-U$_{NH}$** (126 MHz, DMSO-d6, 300 K).

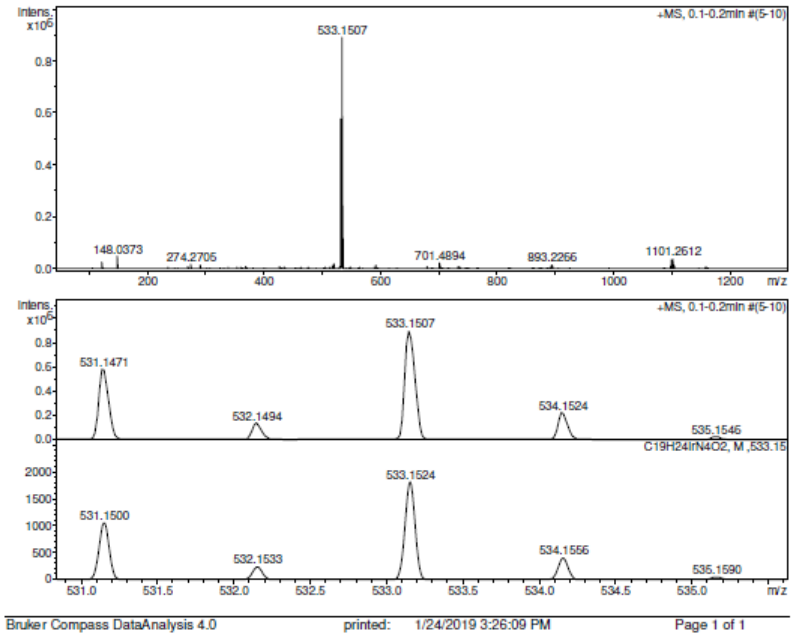


Fig S18 ESI-MS (positive ion mode) spectrum of **Ir-U$_{NH}$**

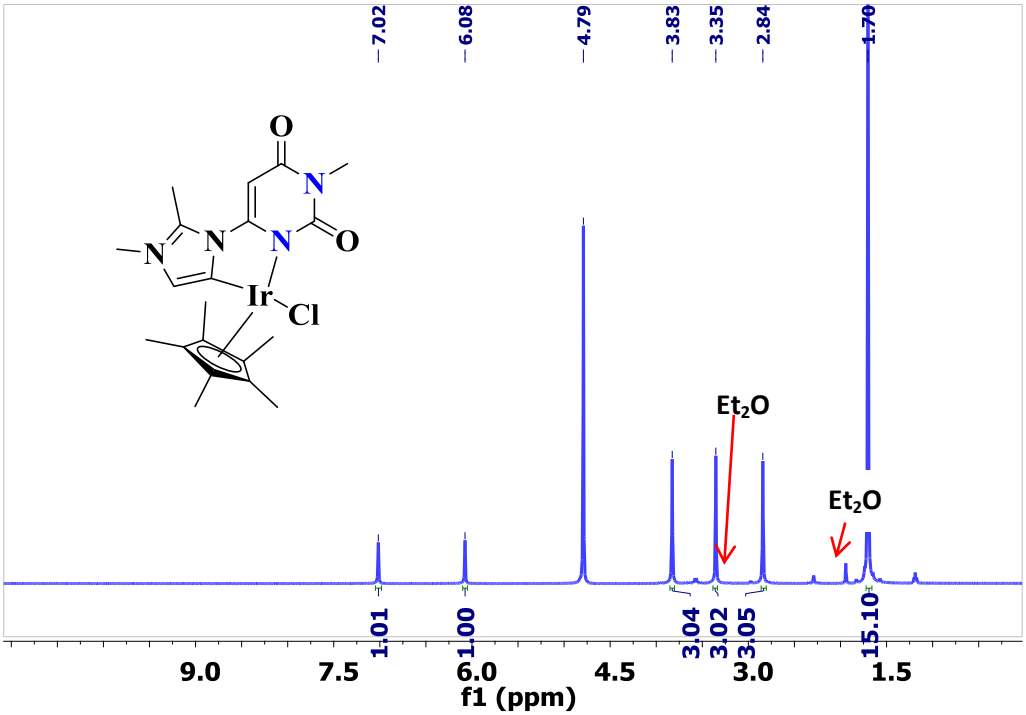


Figure S19 ^{1}H NMR spectrum of **Ir-U$_{NMe}$** (500 MHz, D_2O, 300 K)

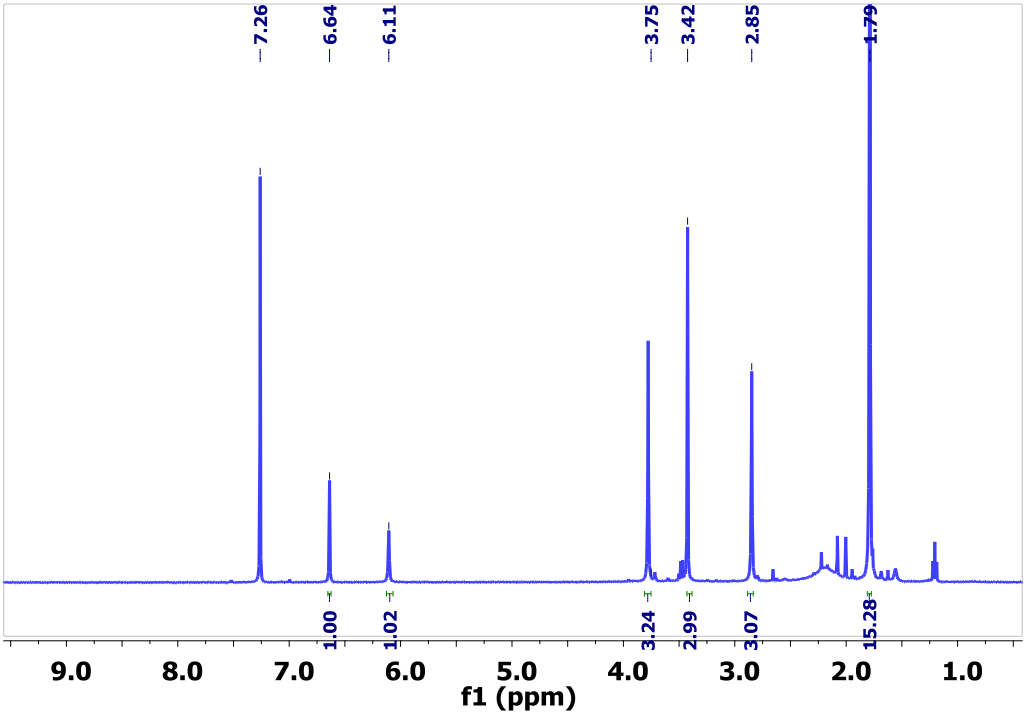


Figure S20 ^{1}H NMR spectrum of **Ir-U$_{NMe}$** (400 MHz, $CDCl_3$, 300 K

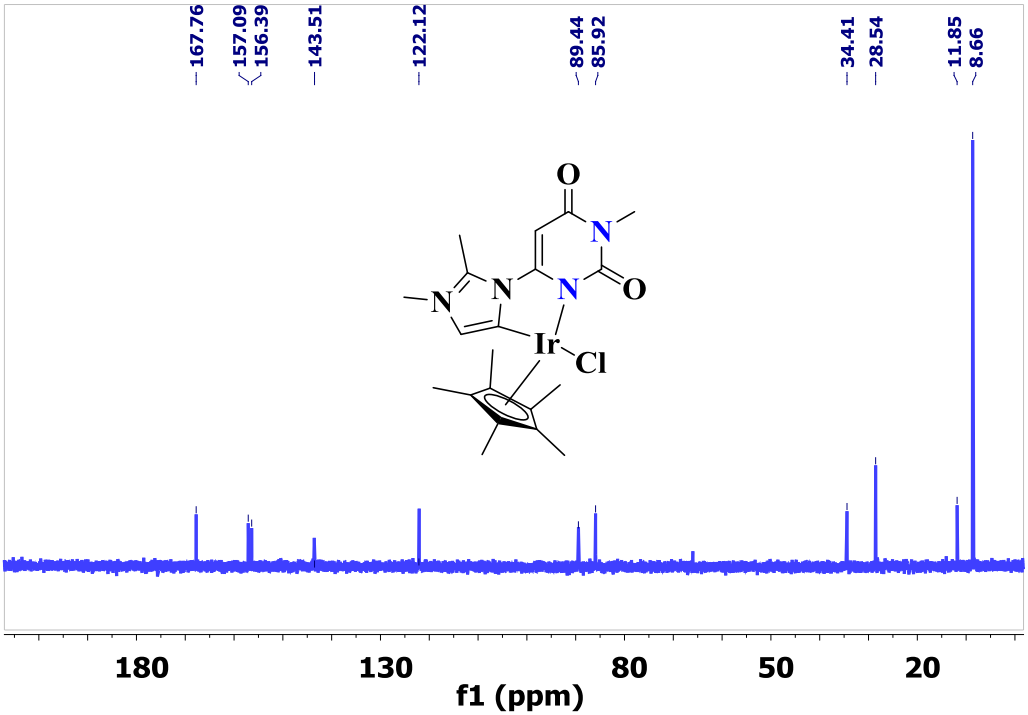


Fig S21 ^{13}C {^{1}H} NMR spectrum of **Ir-U$_{NMe}$** (126 MHz, D_2O, 300 K)

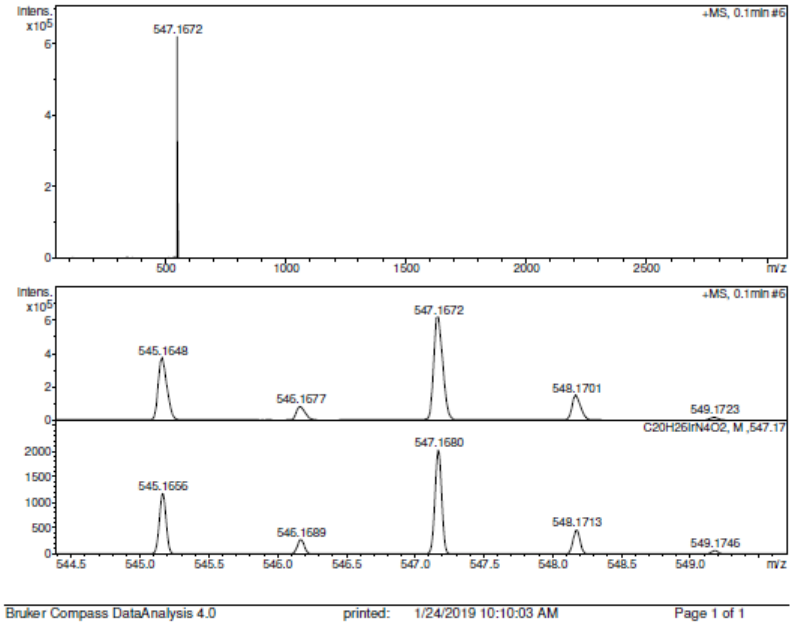


Fig. S22 ESI-MS (positive ion mode) spectrum of **Ir-U$_{NMe}$**

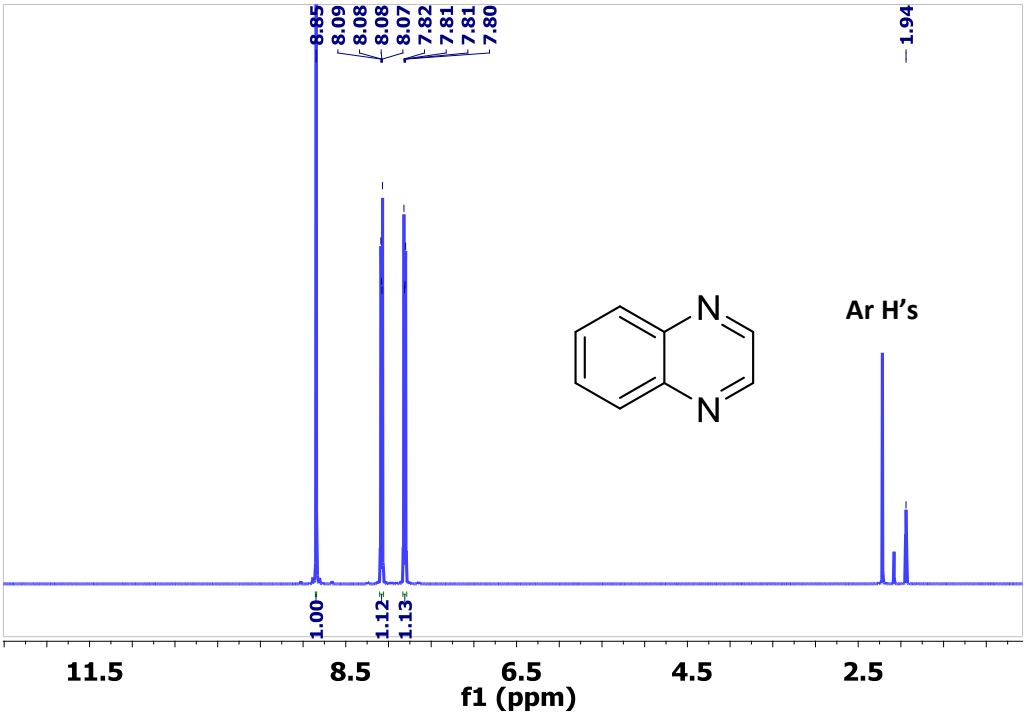


Fig. S23 ^{1}H NMR spectrum (500 MHz, CD_3CN, 300 K) of quinoxaline.

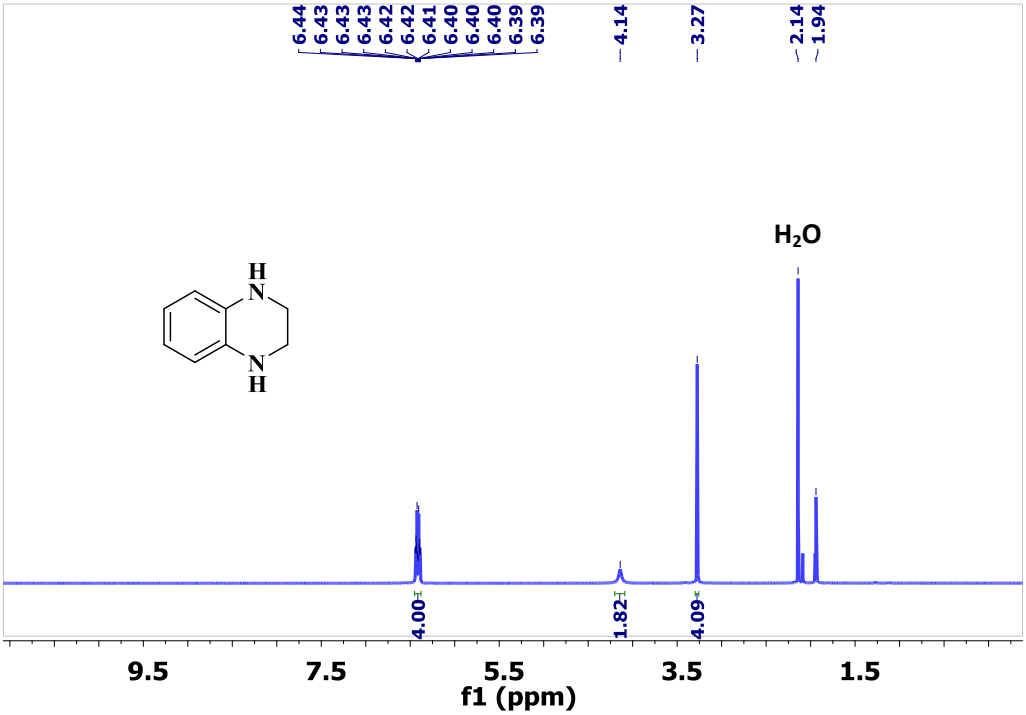


Fig. S24 ^{1}H NMR spectrum (500 MHz, CD_3CN, 300 K) of tetrahydro quinoxaline

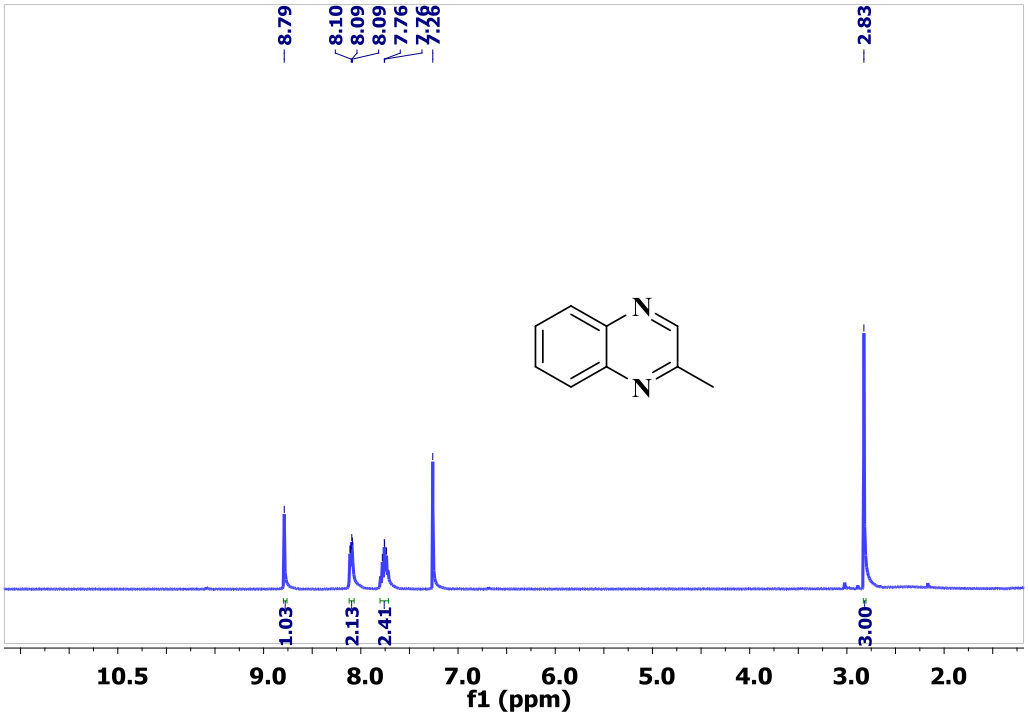


Fig. S25 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 2-methylquinoxaline.

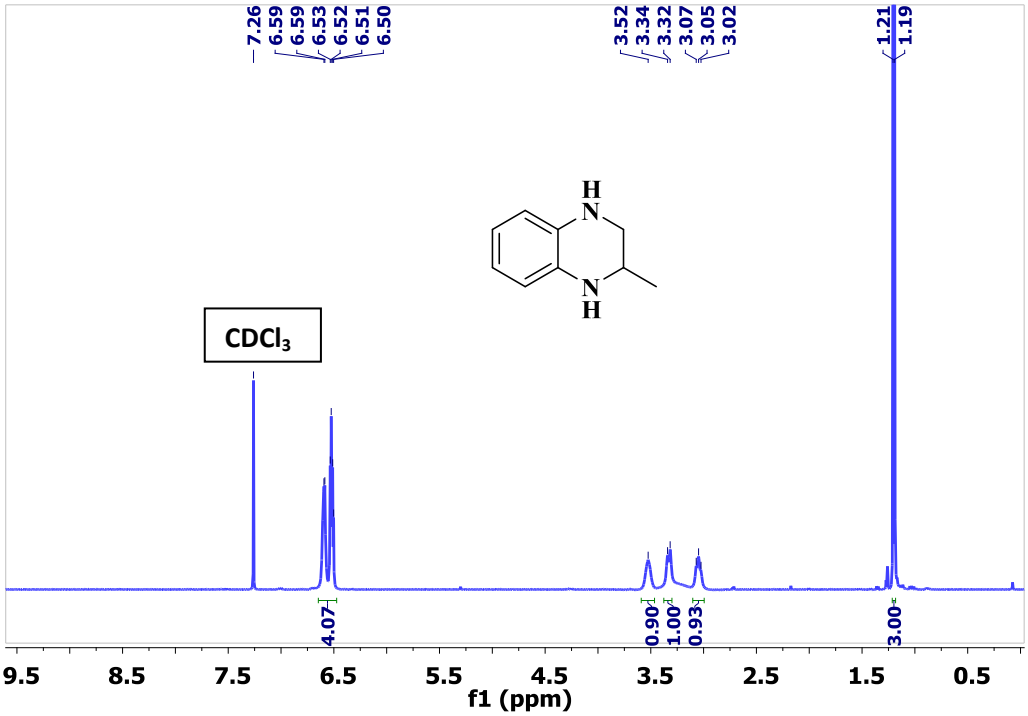


Fig. S26 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 2-methyl-1,2,3,4-tetrahydroquinoxaline.

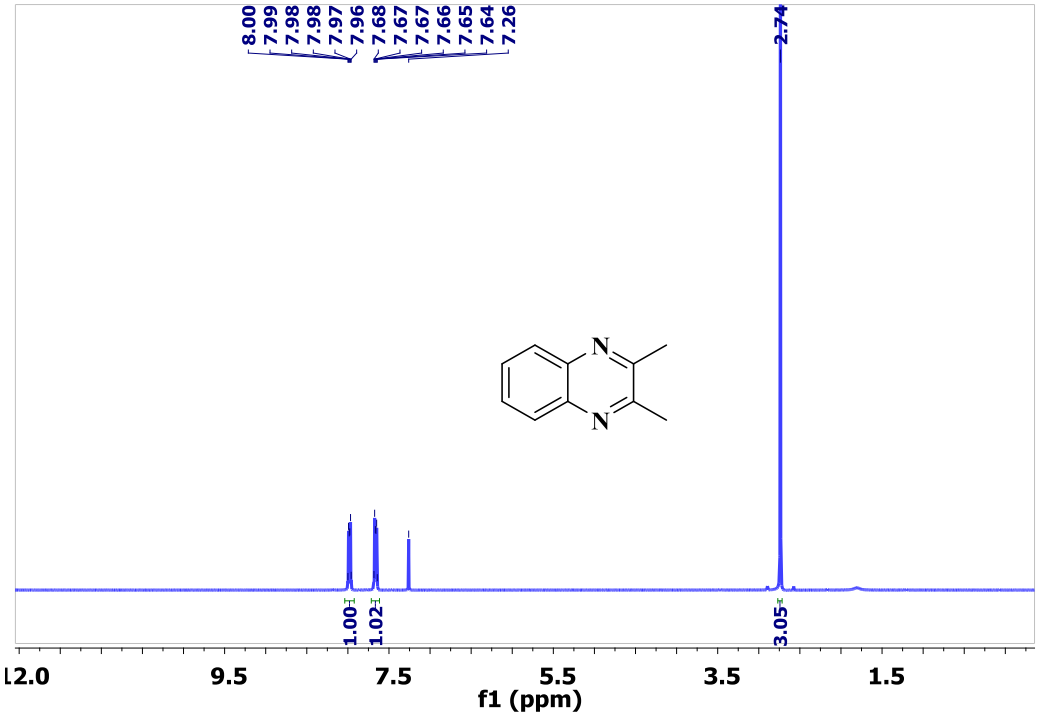


Fig. S27 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 2,3 di-methyl quinoxaline.

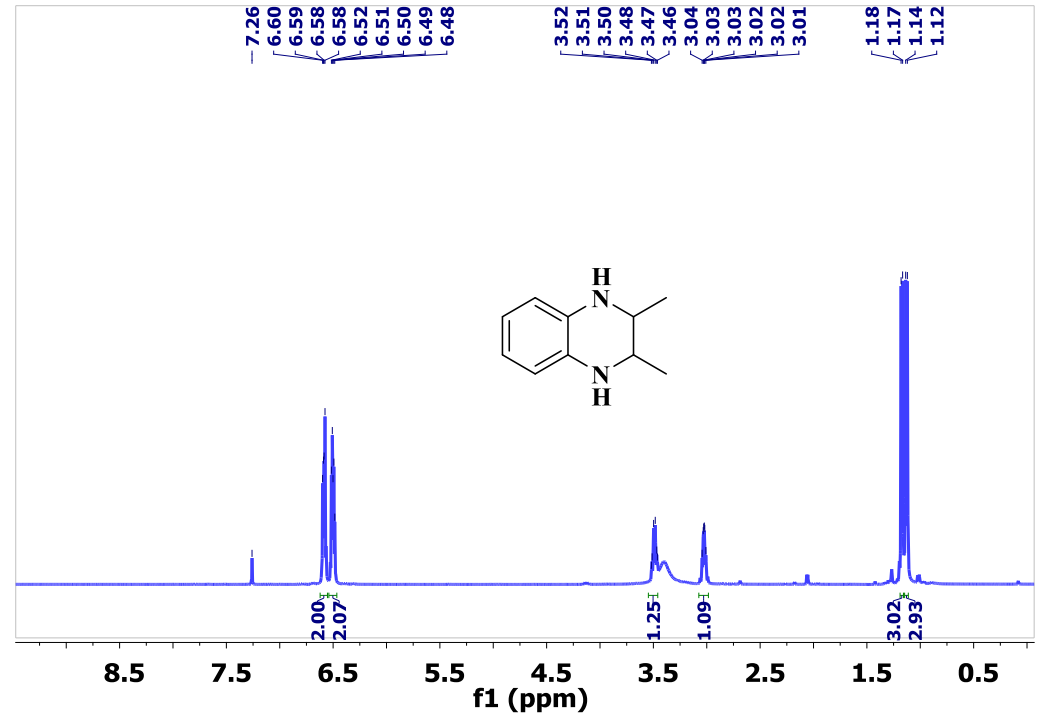


Fig. S28 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of tetrahydro 2,3-dimethyl-1,2,3,4-tetrahydroquinoxaline.

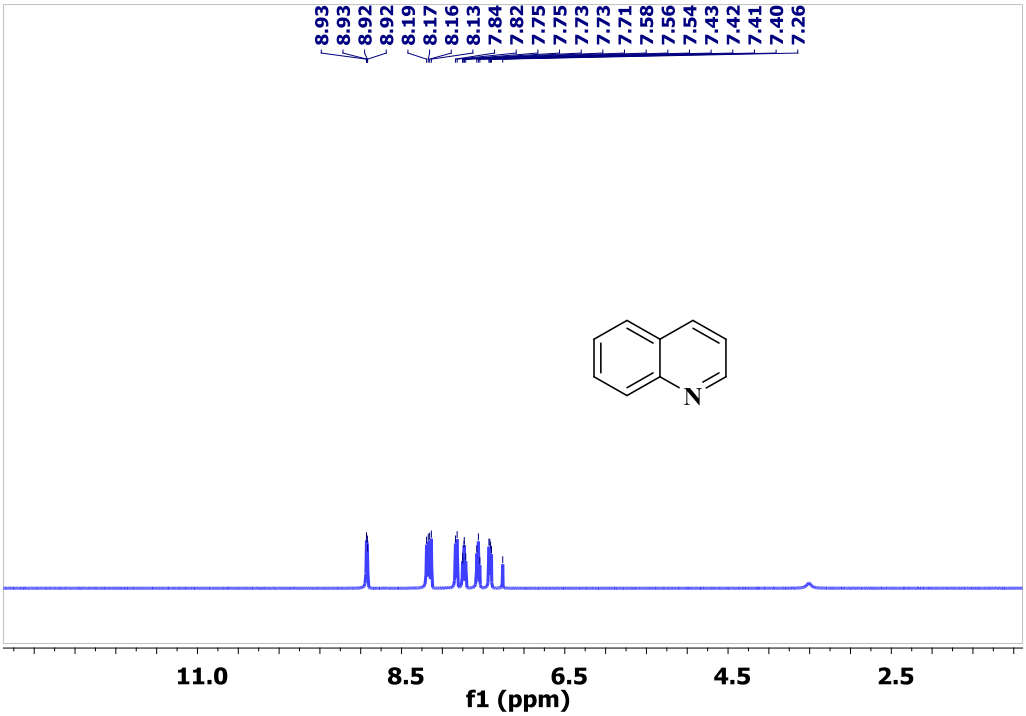


Fig. S29 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of quinolone.

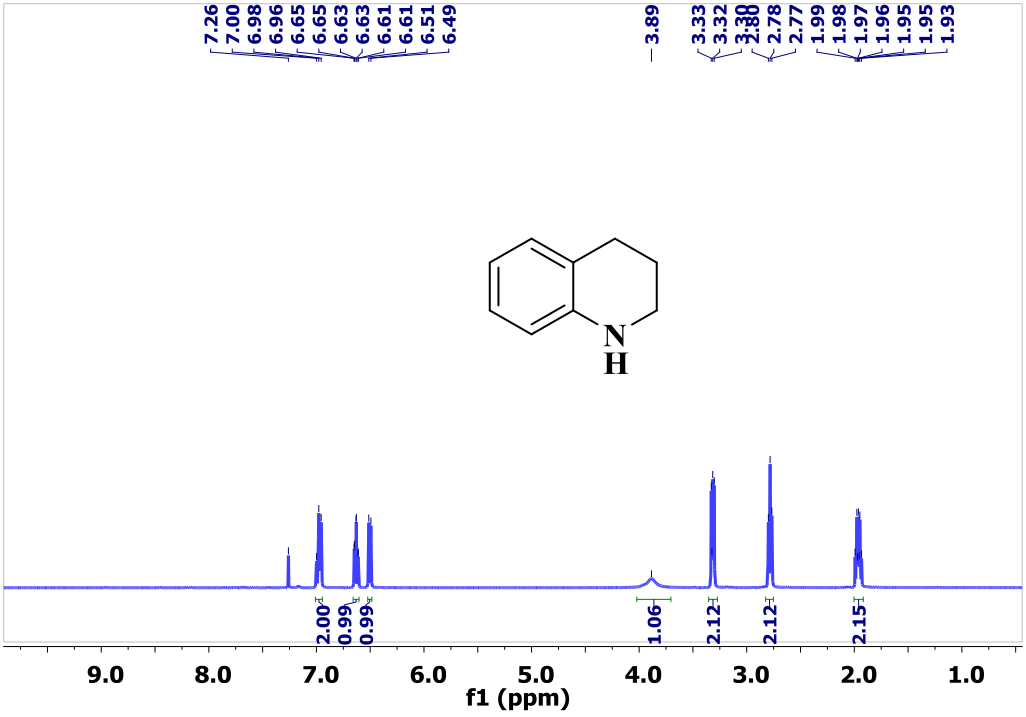


Fig. S30 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 1,2,3,4-tetrahydroquinoline.

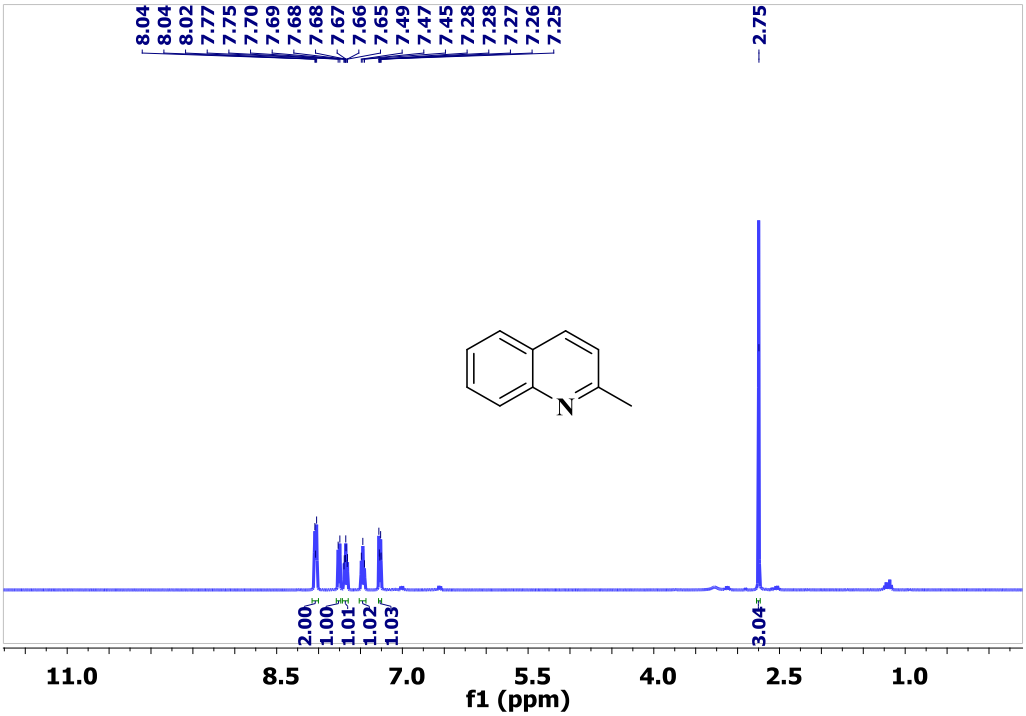


Fig. S31 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 2-methylquinoline.

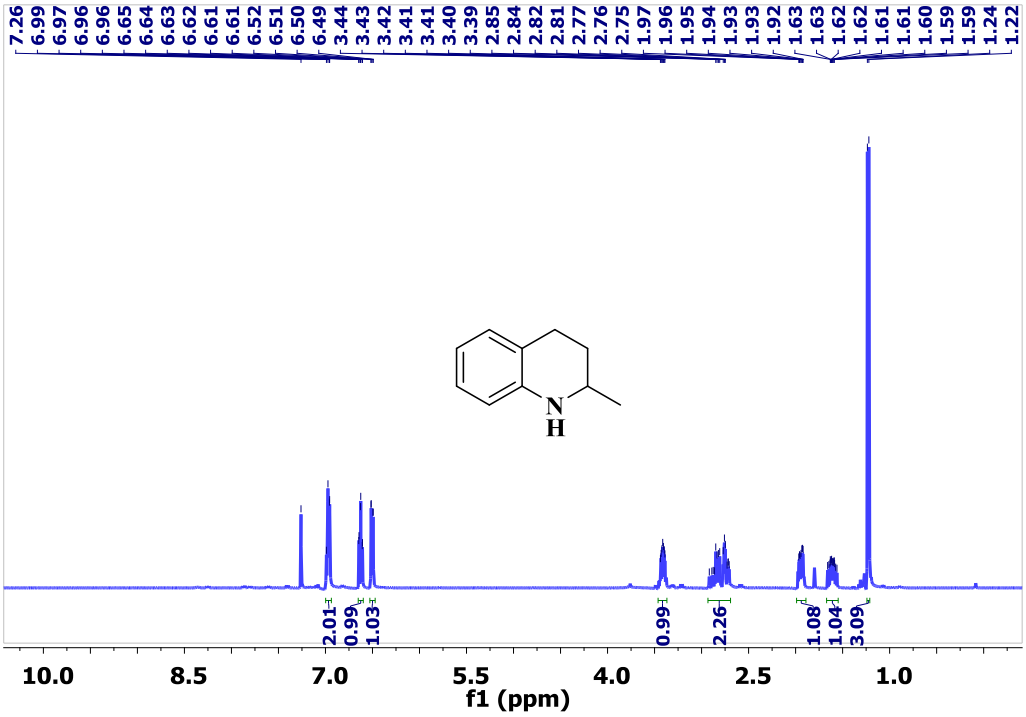


Fig. 32 ^{1}H NMR spectrum (400 MHz, $CDCl_3$, 300 K) of 2-methyl-1,2,3,4-tetrahydroquinoline.

11. Additional images

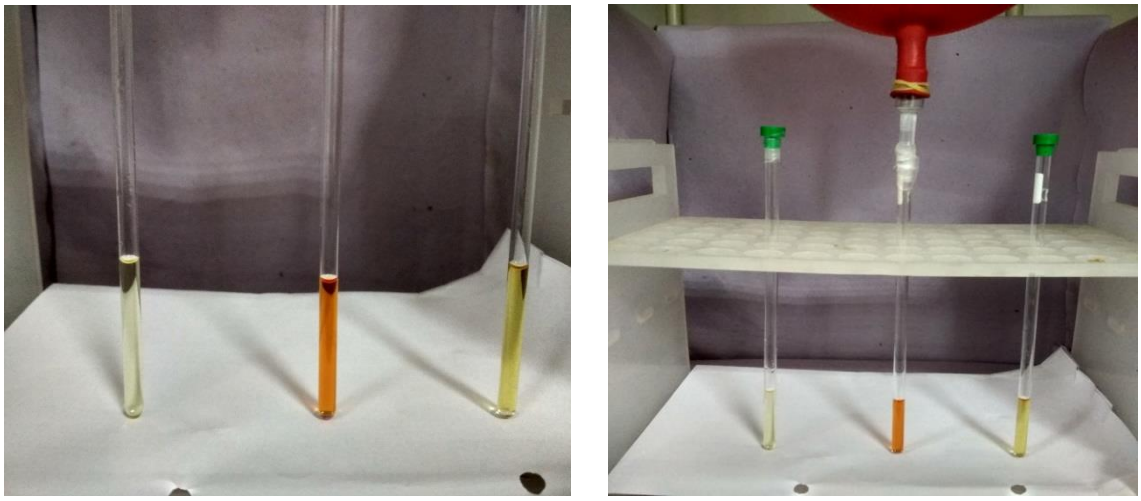


Fig S33 Images of color change of the solution of **Ir-U$_{NH}$** at different conditions:

[from left to right: a) only complex in (TFE 50 μL, H_2O 20 μL, CD_3CN 500 μL), b) complex in (TFE 50 μL, H_2O 20 μL, CD_3CN 500 μL)+H_2 balloon, and c) complex in (TFE 50 μL, H_2O 20 μL, CD_3CN 500 μL)+H_2 balloon +equivalent amount of quinoxaline with respect to complex]

12. Crystal structure of Ir-U$_{NH}$

Single crystals suitable for diffraction were grown from DCM/CH_3OH and ether solvent combination by vapor diffusion method, and data were collected at low temperature. For details please see the cif file (CCDC No. 1895154).

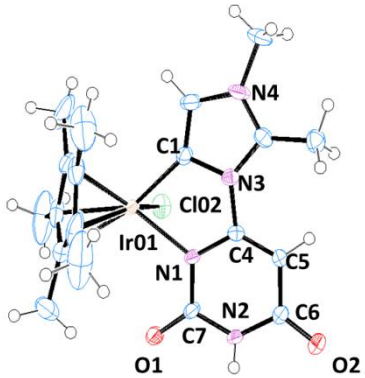


Fig. S34 ORTEP plot of the crystal structure of **Ir-U$_{NH}$** (thermal ellipsoids are at the 50% probability level). Solvent molecules were not shown. Selected bond lengths (Å) and angles (deg): C1−Ir01 = 2.005(5), Ir01-Cl02= 2.411(15), N1−Ir01 = 2.140(4), C6-O2 = 1.238(6),C7-O1 =1.235(6), C5-C6 = 1.432(7), C4-C5 = 1.357(6), N1-C7 = 1.367(6), N2-C7 = 1.378(6), N2-C6 = 1.379(6), C1-N1-Ir = 117.7(3), N3-C1-Ir01 =116.7(3), C1-Ir-N1 = 76.40(17), O2-C6-N2=119.6(5), O_2-C6-C5 = 126.3(5).