Supporting Information

An Ambient-Pressure and Base-Free Aldehyde Hydrogenation Catalyst Supported by a Bifunctional Abnormal NHC Ligand

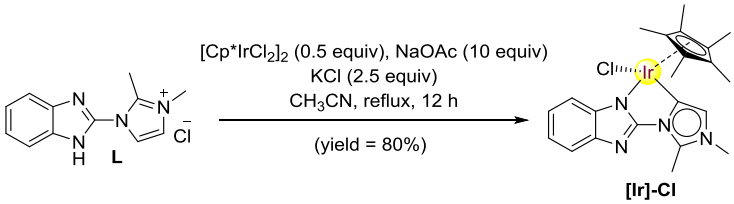
Subhash Garhwal, Babulal Maji, Shrivats Semwal, and Joyanta Choudhury*

Organometallics & Smart Materials Laboratory
Department of Chemistry
Indian Institute of Science Education and Research Bhopal
Bhopal 462066, India
E-mail: joyanta@iiserb.ac.in

I. 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 standard $CDCl_3$: δ = 7.26 ppm for ^{1}H spectra, 77.16 ppm for $^{13}C\{^{1}H\}$ spectra; CD_3OD: δ = 3.31 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), and 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 99.999%) gas was purchased from INOX Air Products Pvt. Ltd. 2-chloro-1-H-benzimidazole was purchased from Sigma Aldrich. 1,2-dimethyl-1H-imidazole was purchased from Spectrochem.

II. Synthesis of [Ir]-Cl



Scheme S1. Synthesis of Complex [Ir]-Cl

The ligand precursor **L** was synthesized by stirring neat reaction of 2-chloro-1-H-benzimidazole (1 mmol) and 1,2-dimethyl-1H-imidazole (3 mmol) in a pressure tube at 135 °C for 8 h. After the end of the reaction, the residue was washed with dry THF three times followed by washing with chloroform. The resulting off-white powder was isolated and dried in vacuum. Yield: 150 mg (60 %). ^{1}H NMR (400 MHz, DMSO-d_6): δ 14.10 (bs, 1H), 8.30 (d, *J* = 2.1 Hz, 1H), 7.95 (d, *J* = 2.1 Hz, 1H), 7.70 (dd, *J* = 5.9, 3.3 Hz, 2H), 7.35 (dd, *J* = 6.0, 3.2 Hz, 2H), 3.91 (s, 3H), 2.96 (s, 3H) ppm. $^{13}C\{^{1}H\}$ NMR (126 MHz, DMSO-d_6) δ 146.44, 141.19, 123.50, 123.39, 120.38, 35.28, 11.71 ppm (*few peaks due to quaternary carbons were not observed!*). LRMS (positive ion): 213.1 (calcd 213.1 for $[C_{12}H_{13}N_4]^+$). Anal. Calcd for $C_{12}H_{13}N_4Cl$: C, 57.95; H, 5.27; N, 22.53. Found: C, 57.79; H, 5.34; N, 22.41. A mixture of the ligand precursor **L** (42.5 mg, 0.125 mmol), $[IrCp^*Cl_2]_2$ (50 mg, 0.063 mmol), CH_3COONa (102.53 mg, 1.25 mmol), and KCl (23.4 mg, 0.314 mmol) was refluxed in CH_3CN (20 mL) for 12 h. After cooling to room temperature, the reaction mixture was filtered through *Celite* and all volatiles were removed under reduced pressure. Complex **[Ir]-Cl** was obtained as a yellow-red solid by precipitation from CH_2Cl_2/Et_2O. Yield: 57.4 mg (80%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.66 – 7.64 (d, *J* = 8 Hz, 1H, CH_{Benz}), 7.46 – 7.44 (d, *J* = 8 Hz, 1H, CH_{Benz}), 7.14 – 7.09 (dtd, *J* = 16.5, 7.1, 1.4 Hz, 2H, CH_{Benz}), 6.66 (s, 1H, CH_{imid}), 3.67 (s, 3H, CH_{methyl}), 3.17 (s, 3H, CH_{methyl}), 1.85 (s, 15H, (CH_3)$_5$Cp*)) ppm. $^{13}C\{^{1}H\}$ NMR (126 MHz, $CDCl_3$) δ 156.06 (Ir-C_{aNHC}), 145.91, 141.40, 140.58, 139.27, 120.53, 120.45, 119.91, 118.49, 113.65, 87.85, 33.84 (N-$CH_{3imidazole}$), 10.46 $(CH_3)_5$Cp*), 9.93 (C-$CH_{3imidazole}$) ppm. HRMS (ESI, positive ion) $[M\text{-}Cl]^+$=539.1800 (calcd for $[C_{22}H_{26}N_4Ir]^+$ =539.1782). Anal. Calcd for $C_{22}H_{26}N_4IrCl$: C, 46.02; H, 4.56; N, 9.76. Found: C, 45.98; H, 4.63; N, 9.88.

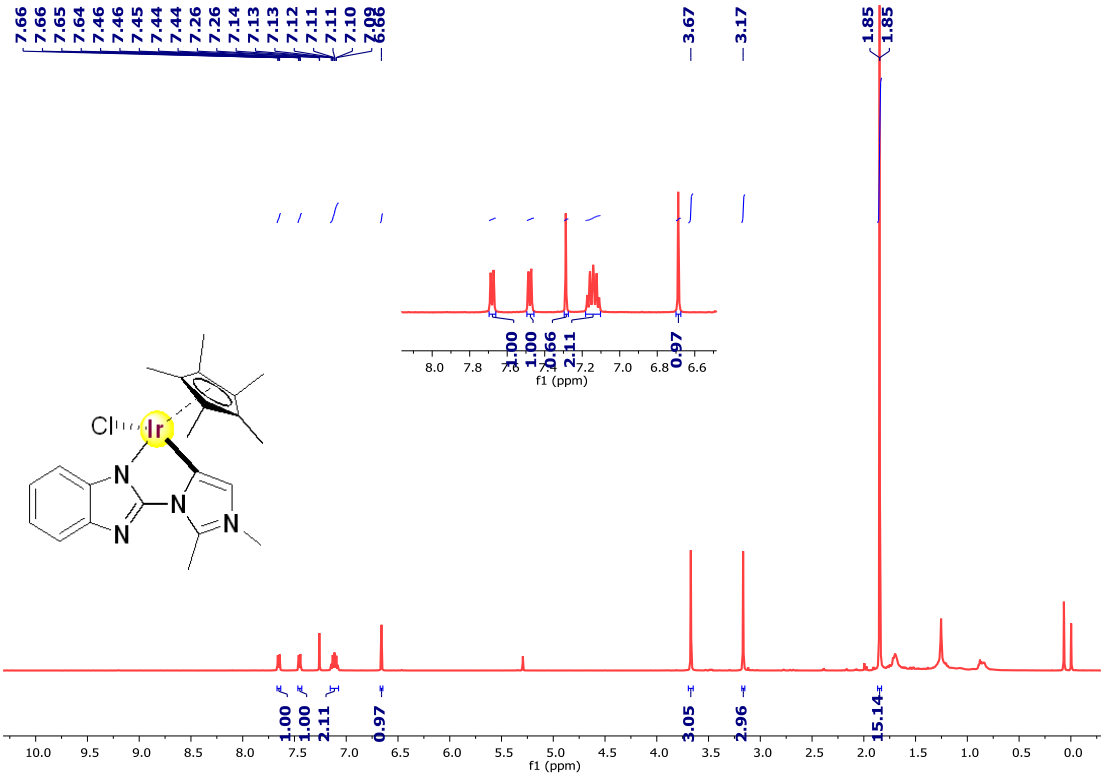


Figure S1. ^{1}H NMR spectrum of **[Ir]-Cl** in $CDCl_3$.

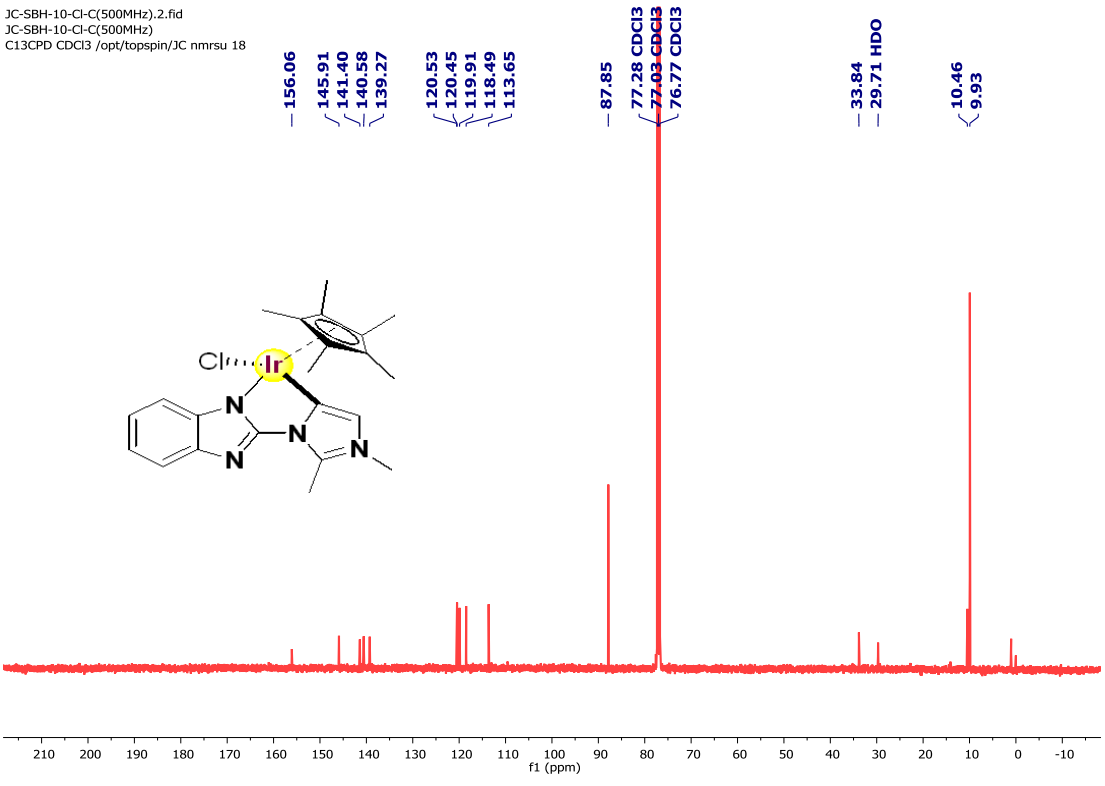


Figure S2. $^{13}C\{^{1}H\}$ NMR spectrum of **[Ir]-Cl** in $CDCl_3$.

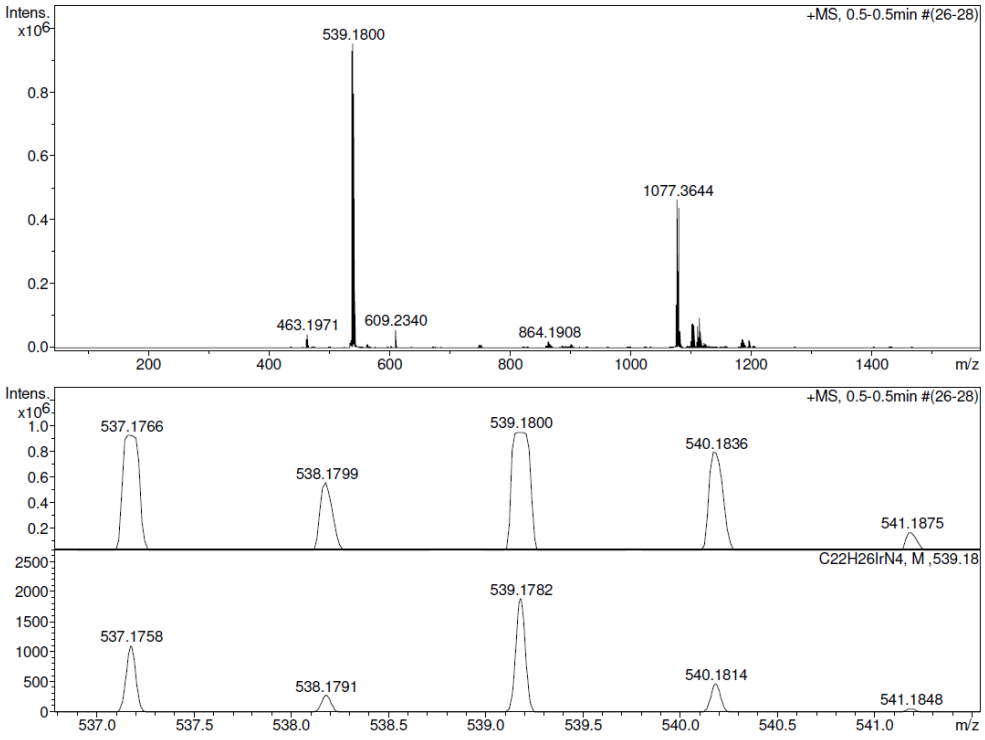


Figure S3. ESI-MS (positive mode) spectrum of **[Ir]-Cl**.

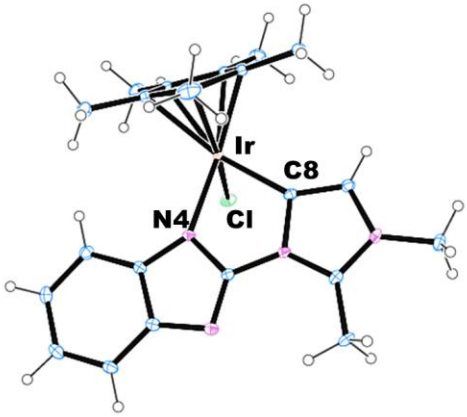


Figure S4. Crystal structure of **[Ir]-Cl**. Selected bond lengths (Å) and angles (°): Ir-Cl = 2.4350(9), Ir-N4 = 2.084(3), Ir-C8 = 2.030(3), C8−Ir−N4 = 77.22(12).

III. General procedure for catalytic aldehyde hydrogenation

(a) Optimization table: A 25 mL two-neck round-bottom (RB) flask was charged with benzaldehyde (0.4 mmol) and the catalyst (0.002 mmol). To this mixture, a known amount of 1,3,5-trimethoxy benzene (TMB) was added as an internal standard. Next, vacuum was applied to the flask followed by filling with H_2 gas and keeping the flask attached to a balloon filled with H_2 gas. After adding the solvent (1 mL) to the flask via a syringe, the resulting reaction mixture was stirred at the desired temperature. After the desired reaction time, 40 µL of reaction mixture aliquot was withdrawn for gas chromatographic (GC) analysis. If solvent contains water, then 100 µL of ethyl acetate was added and the upper layer was injected into GC. The yield was calculated with the help of calibration curves.

(b) Isolation of product: After desired time, the reaction was stopped and the product was separated by extraction with ethyl acetate using a separating funnel. The ethyl acetate layer was concentrated under reduced pressure and the product was dried under vacuum. The dried product was dissolved in a desired deuterated solvent for ^{1}H NMR spectroscopy.

(c) Reaction without H_2 gas: The same procedure was followed as described above but H_2 gas was not applied to the reaction. Instead the reaction was conducted under nitrogen environment. No product was formed as confirmed by GC.

(d) Substrate scope: Similar procedure was followed as described above but with different aldehydes.

(e) Intermolecular chemoselectivity: Similar procedure was followed as described above but with equimolar benzalaldehyde and the competing unsaturated substrate.

IV. Mechanistic investigation

(a) ^{1}H NMR spectroscopic monitoring of a stoichiometric reaction of the catalyst with aldehyde and H_2 at ambient temperature: A Wilmad® low pressure/vacuum (LPV) NMR tube was charged with a CD_3OD (500 µL) solution of catalyst **[Ir]-Cl** (0.002 mmol) and benzaldehyde (0.002 mmol). The tube containing the mixture was frozen under liquid nitrogen and vacuum was applied for few minutes from a Schlenk line. After this, a hydrogen balloon was attached to the tube. The reaction was monitored periodically by ^{1}H NMR spectroscopy at ambient temperature with occasional charging of H_2 gas. A hydride signal at −14.6 ppm was observed just after 10 min along with the signals due to benzyl alcohol (a broad singlet at 4.60 ppm for Ph*CH*$_2$OH and a broad triplet at 4.58 ppm for Ph*CH*$_2$OD) which was generated in small amount. After another 10 min, upon the disappearance of the hydride signal, the mixture was again charged with H_2 gas, and the reaction was followed at 10 min intervals. A gradual decrease of the benzaldehyde signals at 10.0 ppm (a singlet) with concomitant increase of the benzyl alcohol signals was observed. No other intermediate was observed in this experiment.

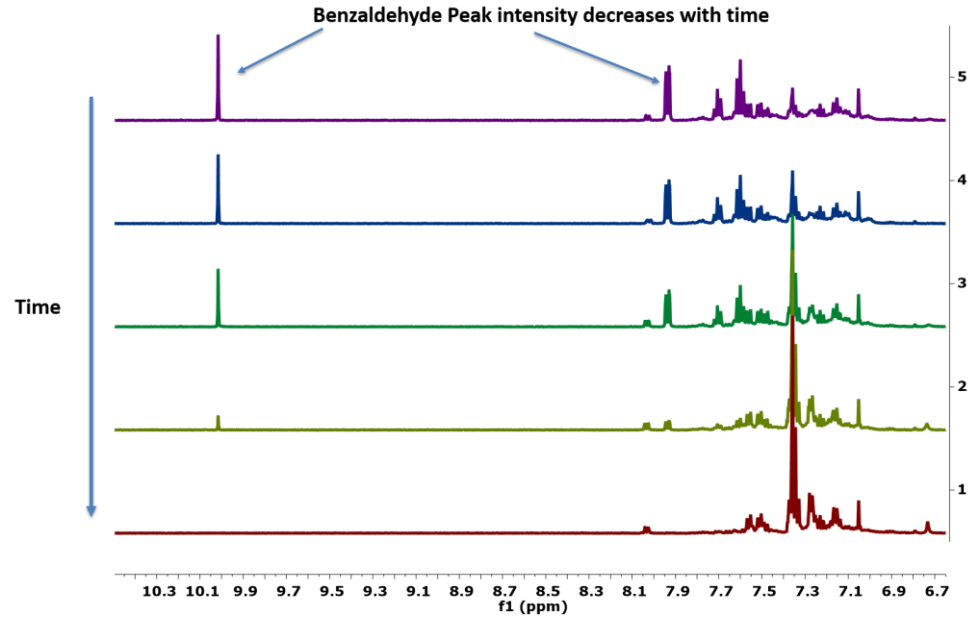


Figure S5a. Partial (6.7-10.4 ppm region) ^{1}H NMR spectral overlay plot of a stoichiometric reaction of **[Ir]-Cl** with aldehyde and H_2 in CD_3OD at ambient temperature

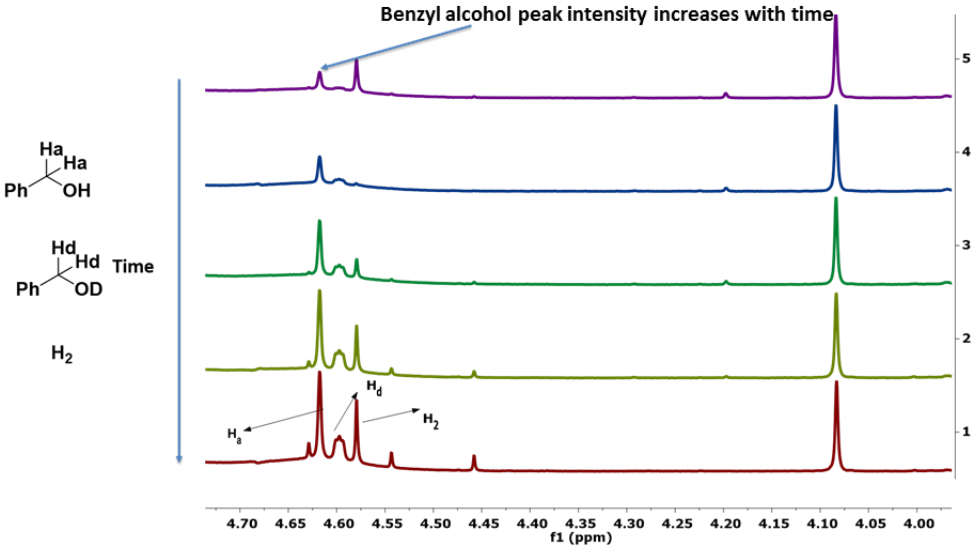


Figure S5b. Partial (4.0-4.7 ppm region) ^{1}H NMR spectral overlay plot of a stoichiometric reaction of **[Ir]-Cl** with aldehyde and H_2 in CD_3OD at ambient temperature

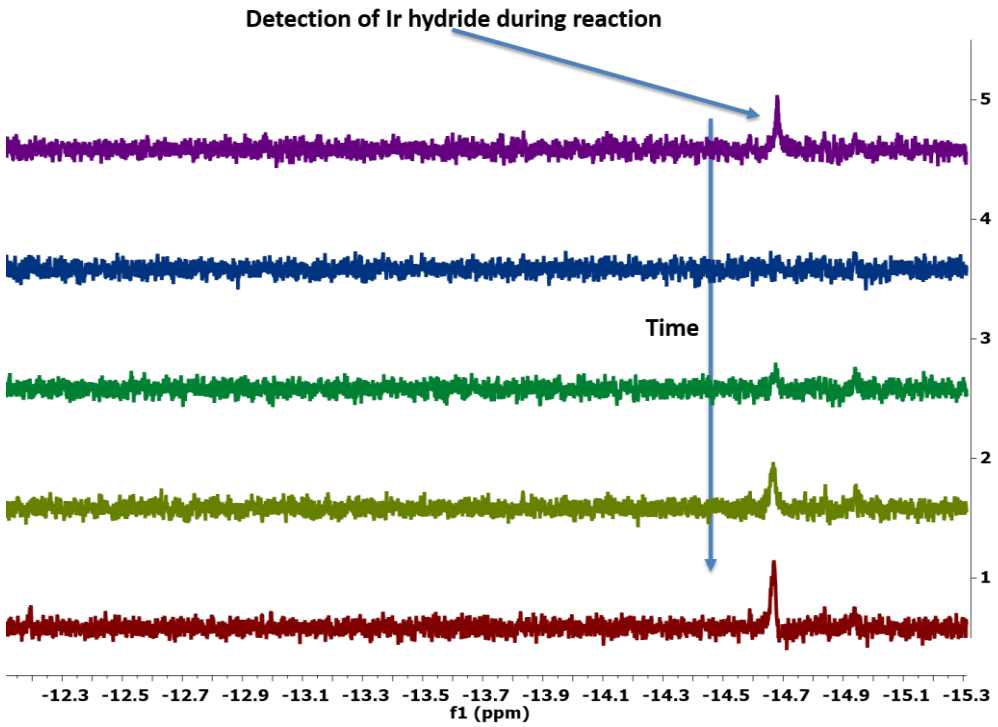


Figure S5c. Partial (−15.3 – −12.3 ppm region) ^{1}H NMR spectral overlay plot of a stoichiometric reaction of **[Ir]-Cl** with aldehyde and H_2 in CD_3OD at ambient temperature

(b) Variable temperature (VT) ^{1}H NMR spectroscopic monitoring of a stoichiometric reaction of the catalyst with aldehyde and H_2: To investigate the above stoichiometric reaction further, a similar experiment as described in *Section IV (a)*, was set-up following the same procedure. This reaction was monitored by variable temperature ^{1}H NMR (VT ^{1}H NMR) spectroscopy from 263 K to 313 K in CD_3OD. Upon increasing the temperature, a gradual decrease of hydride and benzaldehyde peaks along with increase of benzyl alcohol peak was recorded. Interestingly, the intensity of the methyl peaks of the catalyst backbone remained unchanged throughout the experiment, suggesting the integrity of the catalyst. In this VT ^{1}H NMR experiment, signal due to H_2 gas at 4.57 ppm was also observed along with the Ir–H peak at −14.6 ppm at the lower temperatures while both the peaks disappeared at higher temperatures, suggesting a plausible reversibility of the H_2-cleavage step.

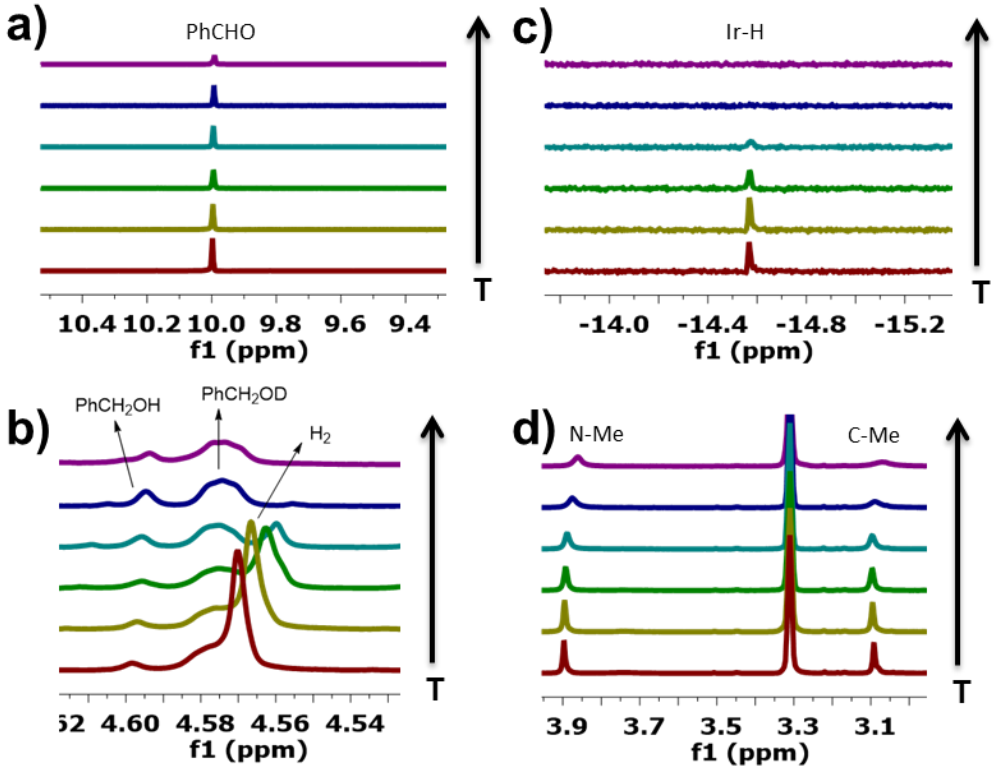


Figure S6. VT (263 K–313 K) ^{1}H NMR spectral overlay plot of a stoichiometric reaction of **[Ir]-Cl** with aldehyde and H_2 in CD_3OD: (a) monitoring of PhC*H*O peak; (b) monitoring of PhCH_2OH, PhCH_2OD and H_2 peaks; (c) monitoring of Ir–*H* peak; (d) monitoring of ligand N-*Me* and C-*Me* peaks.

(c) Variable temperature (VT) ^{1}H NMR spectroscopic monitoring of a reaction of the catalyst with H_2 only:
To probe the plausible reversibility of the H_2-cleavage step as suggested from the above experiment, a similar VT ^{1}H NMR experiment as described in *Section IV (b)*, but without introducing benzaldehyde into the NMR tube, was monitored from 233 K to 313 K in CD_3OD (see SI). Indeed, the appearance of the sharp Ir–H peak along with a broad H_2 peak at lower temperature regime and slow, gradual disappearance of the same with increasing temperature supported such a hypothesis of reversible cleavage of H_2 by the catalyst generating a fast equilibrium of the type (Ir-solvento + H_2) ⟷ Ir–H species. The broadening effect of the ligand backbone protons (along with Cp* protons) with increasing temperature was also observed as expected for a fast equilibrium between two Ir-species.

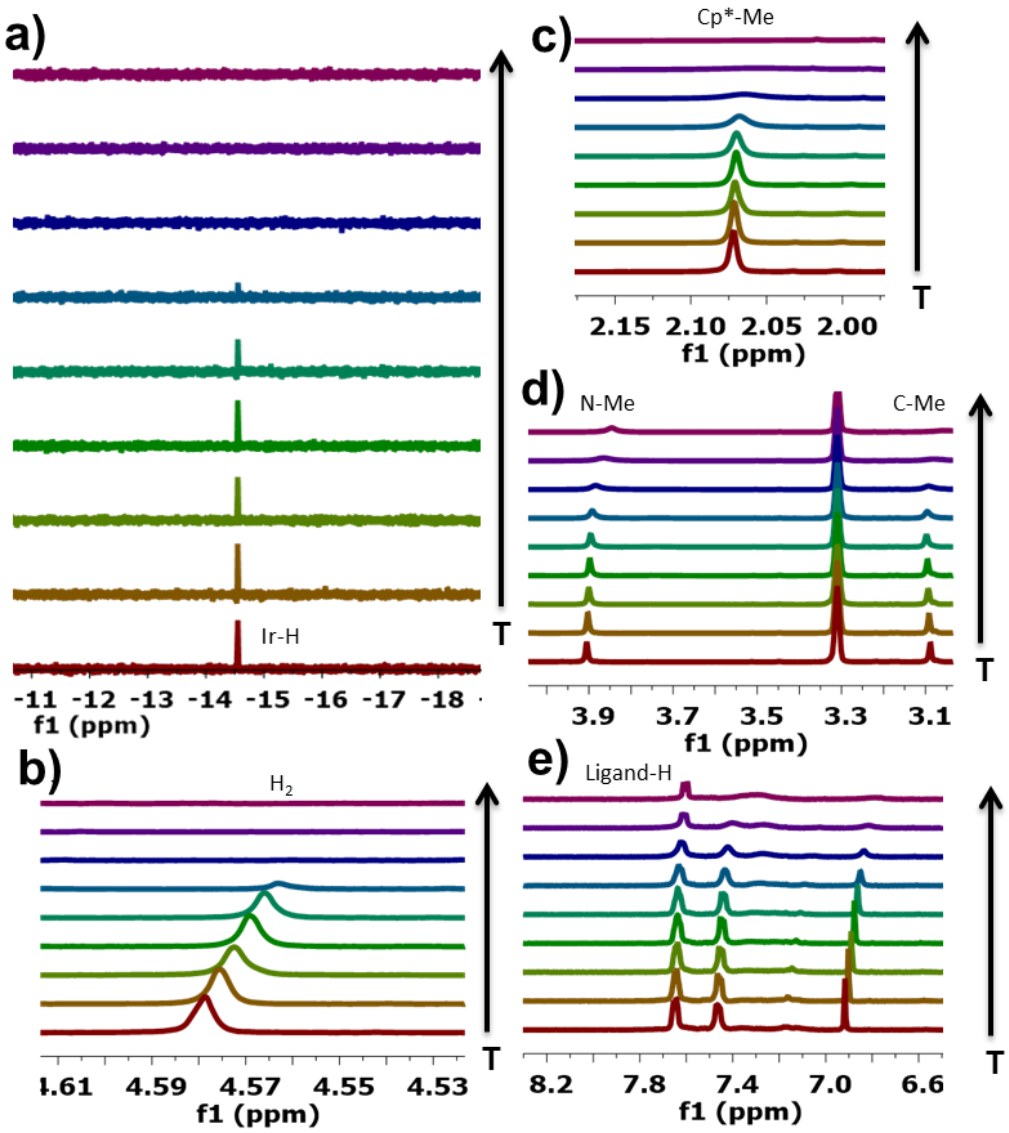


Figure S7. VT (233 K–313 K) ^{1}H NMR spectral overlay plot of a reaction of **[Ir]-Cl** with H_2 in CD_3OD: (a) monitoring of Ir–*H* peak; (b) monitoring of *H_2* peak; (c) monitoring of Cp*-*Me* peak; (d) monitoring of ligand N-*Me* and C-*Me* peaks; (e) monitoring of ligand aromatic backbone peaks.

(d) Effect of added chloride ligand: A general procedure as described in *Section III (a)* was followed. A 25 mL two-neck round-bottomed flask was charged with benzaldehyde (0.4 mmol) and catalyst (0.002 mmol). 3 mL of ethanol was added to the flask, and a balloon filled with H_2 gas was fixed to it. Excess KCl (0.02 mmol) was added to the reaction mixture. After stirring for a specific time at 35^0 C, known volume of aliquot was withdrawn and analysed with GC to calculate the yield of product. The following rate plots were obtained, suggesting an inhibition effect of reaction rate by added chloride ligand.

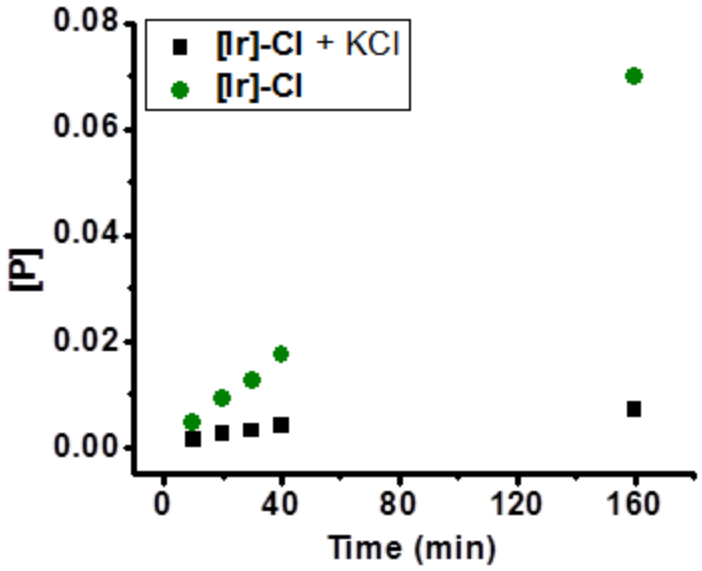


Figure S8. Reaction-time profile for a reaction catalyzed by **[Ir]-Cl** and a reaction catalyzed by **[Ir]-Cl** in the presence of excess KCl.

(e) Initial rate kinetics study for the determination of rate-law:

(i) Order with respect to aldehyde: A general procedure as described in *Section III (a)* was followed. A 25 mL two-neck round bottomed flask was charged with catalyst (0.002 mmol) and benzaldehyde (in different concentrations). After that 3 mL of ethanol was added to the flask, and a balloon filled with H_2 gas was fixed to it. After stirring for a specific time at 35^0 C, a known volume of the aliquot was withdrawn and analyzed with GC to calculate the yield of product. The following plots were used to calculate the order according to reported procedure.[S1]

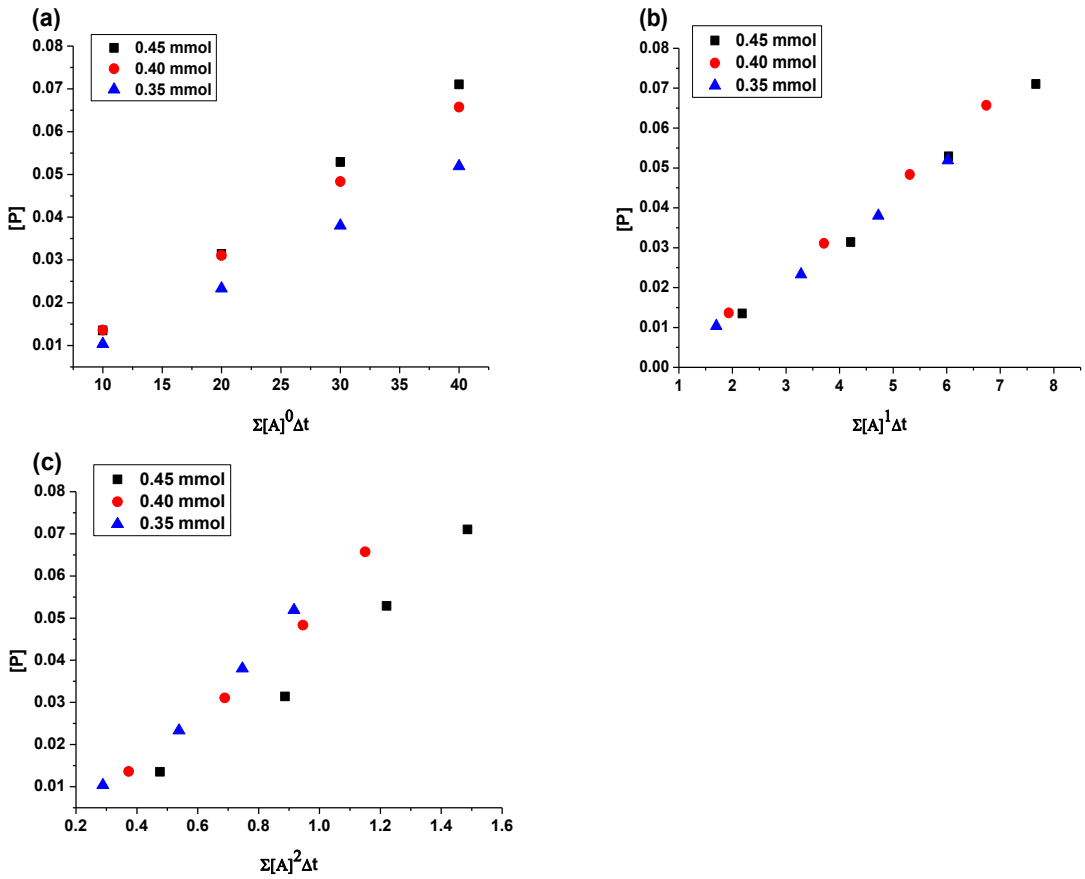


Figure S9. Order with respect to the aldehyde: (a) Plot of [P] vs. $\Sigma[A]^0\Delta t$, (b) Plot of [P] vs. $\Sigma[A]^1\Delta t$, (c) Plot of [P] vs. $\Sigma[A]^1\Delta t$.[S1]

(ii) Order with respect to hydrogen: A general procedure as described above was followed. A 25 mL two-neck round bottomed flask was charged with benzaldehyde (0.4 mmol) and catalyst (0.002 mmol). 3 mL of ethanol was added to the flask, and vacuum was applied to the flask. After that the flask was attached to a low-pressure Parr hydrogenator and pressurized with H_2 (at different pressures of 0.75 atm, 1 atm, and 1.25 atm). After stirring for a specific time at 35^0 C, a known volume of the aliquot was withdrawn and analyzed with GC to calculate the yield of product. The following plots were used to calculate the order according to reported procedure. [S2]

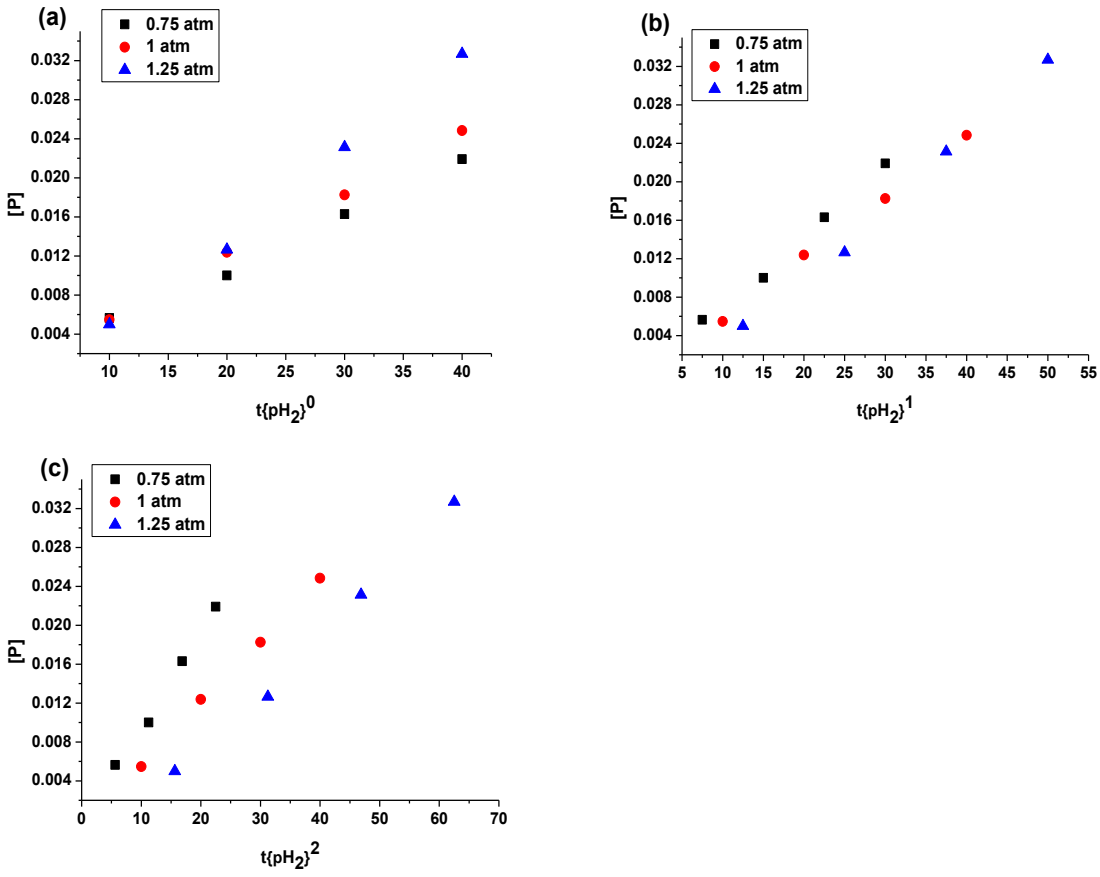


Figure S10. Order with respect to H_2: (a) Plot of [P] vs. $t[H_2]^0$, (b) Plot of [P] vs. $t[H_2]^1$, (c) Plot of [P] vs. $t[H_2]^2$.[S2]

(iii) Order with respect to catalyst: A general procedure as described above was followed. A 25 mL two-neck round bottomed flask was charged with benzaldehyde (0.4 mmol) and catalyst (in different concentrations). 3 mL of ethanol was added to the flask, and a balloon filled with H_2 gas was fixed to it. After stirring for a specific time at 35^0 C, a known volume of the aliquot was withdrawn and analyzed with GC to calculate the yield of product. The following plots were used to calculate the order according to reported procedure.[S2]

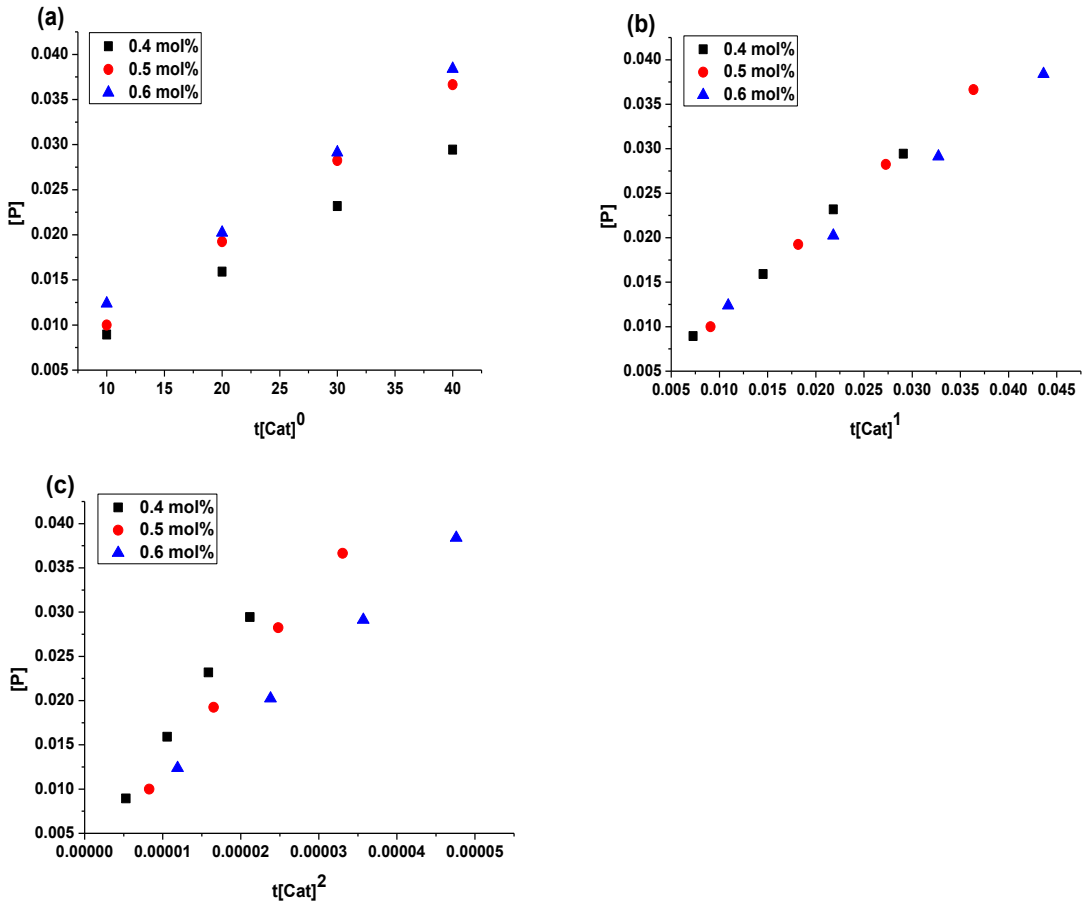


Figure S11. Order with respect to catalyst: (a) Plot of [P] vs. t[cat]^0, (b) Plot of [P] vs. t[cat]^1 (c) Plot of [P] vs. t[cat]^2.[S2]

(f) DKIE studies: A general procedure was followed as described in *Section III (a)*. The following reaction conditions were applied to study the deuterium kinetic isotope effect (DKIE). The results were based on three experiments in each study.

Experiment 1: Benzaldehyde = 0.4 mmol; catalyst = 0.002 mmol; H_2O = 2 mL; H_2 balloon; Temp. = 30 °C
Experiment 2: Benzaldehyde = 0.4 mmol; catalyst = 0.002 mmol; D_2O = 2 mL; H_2 balloon; Temp. = 30 °C
Experiment 3: Benzaldehyde = 0.4 mmol; catalyst = 0.002 mmol; H_2O = 2 mL; D_2 balloon; Temp. = 30 °C
Experiment 4: Benzaldehyde = 0.4 mmol; catalyst = 0.002 mmol; D_2O = 2 mL; D_2 balloon; Temp. = 30 °C

The DKIE values were evaluated from the generated plots as shown below.

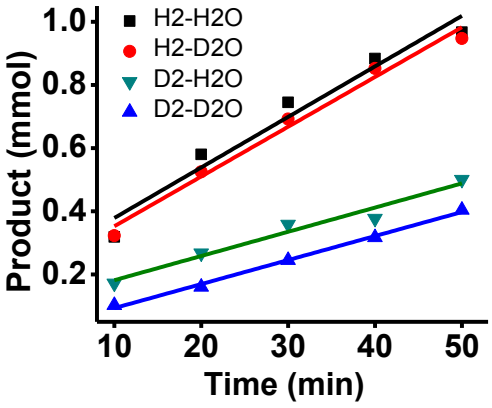


Figure S12. DKIE plots.

(g) Hammett study: A general procedure was followed as described in *Section III (a)*. A 25 mL two-neck round-bottomed flask was charged with the desired aldehyde (0.4 mmol) and catalyst (0.002 mmol). 3 mL of ethanol was added to the flask and a balloon filled with H_2 gas was fixed to it. After stirring for specific time at 35^0 C, known volume of aliquot was withdrawn and analyzed with GC to calculate the yield of product. The following plots were used to calculate ρ (reaction constant) value.

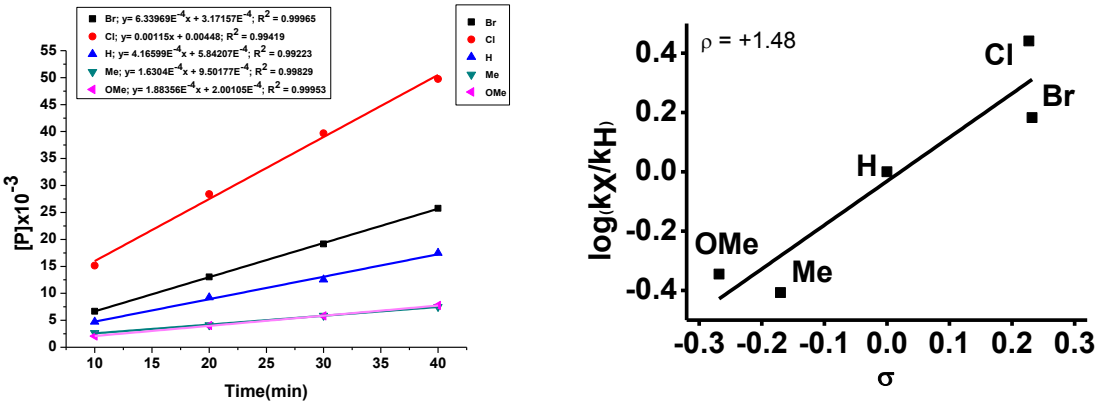


Figure S13. Hammett plots.

V. ^{1}H NMR spectra of the alcohol products

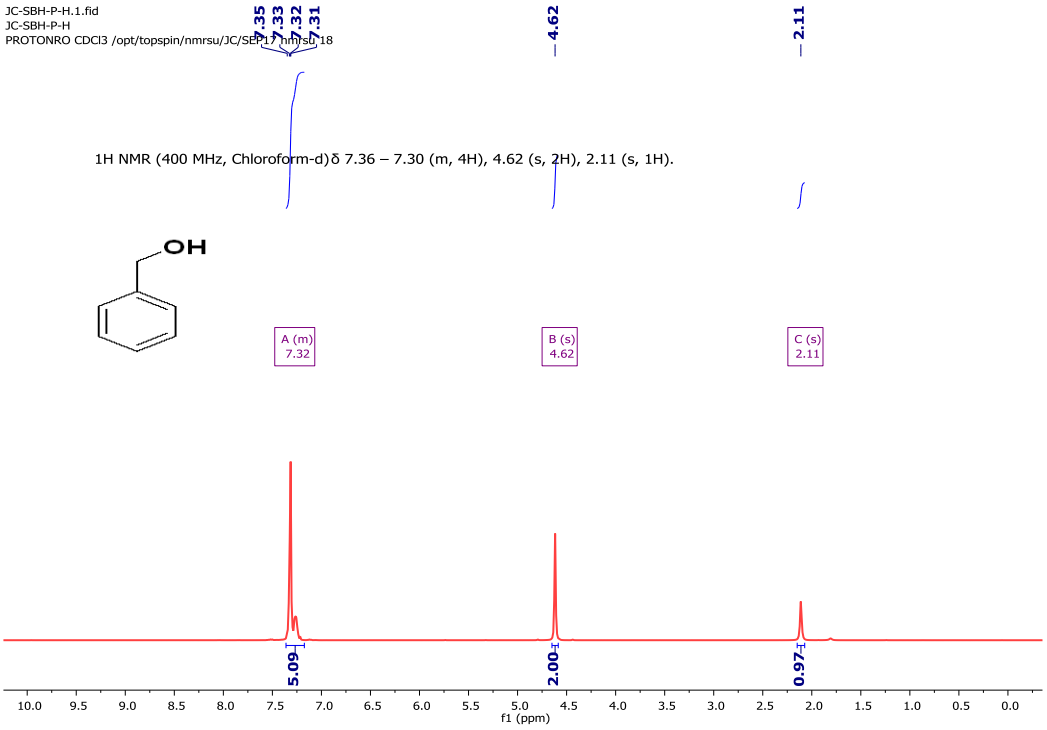


Figure S14. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of benzyl alcohol.

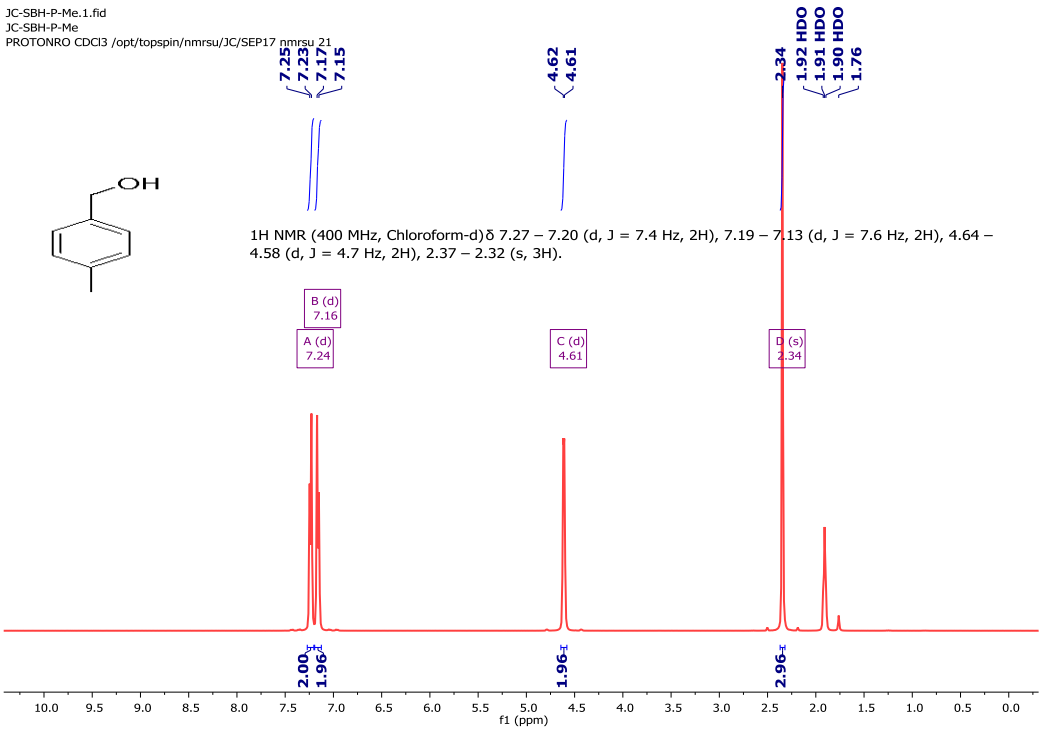


Figure S15. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-methylbenzyl alcohol.

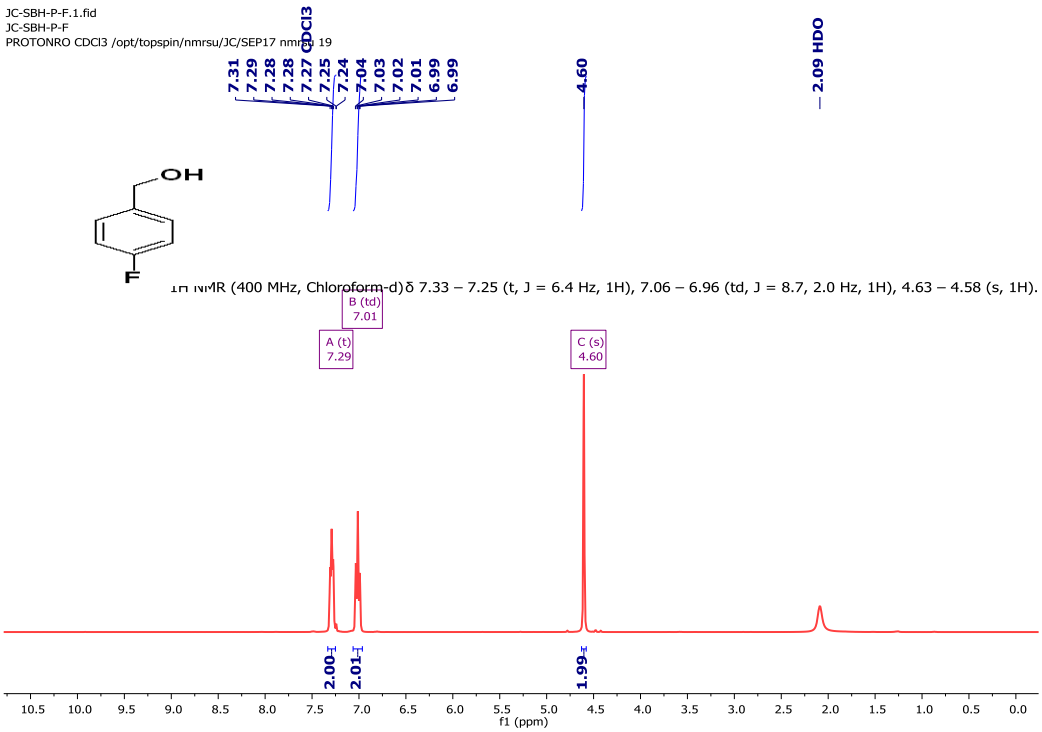


Figure S16. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-fluorobenzyl alcohol.

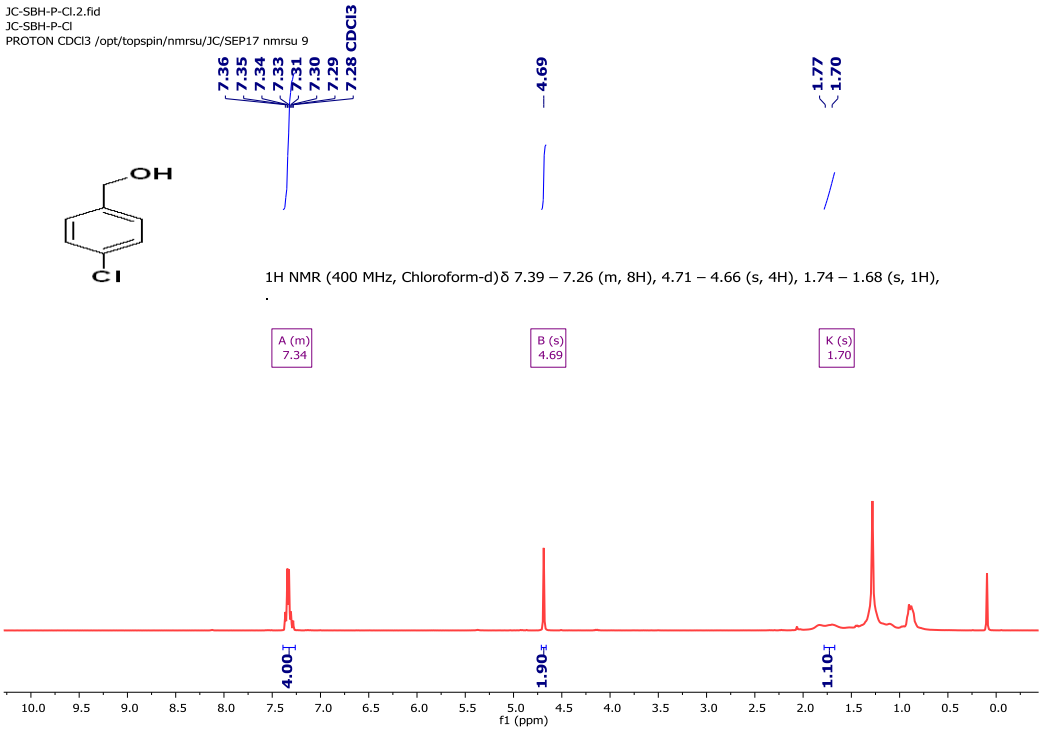


Figure S17. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-chlorobenzyl alcohol.

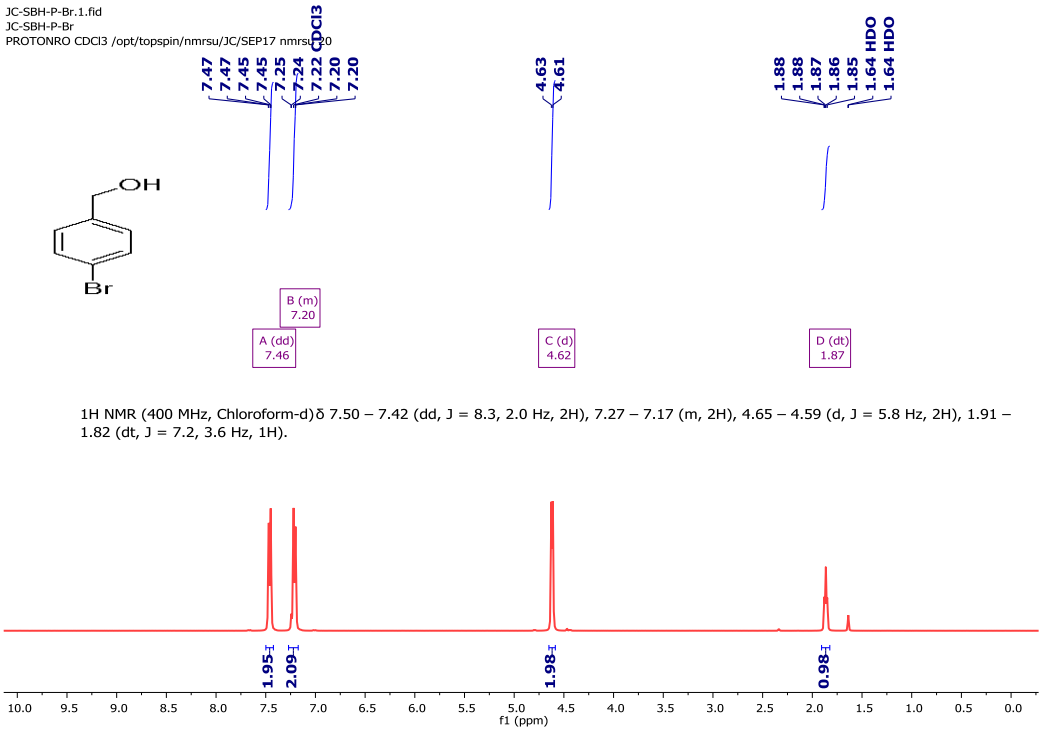


Figure S18. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-bromobenzyl alcohol.

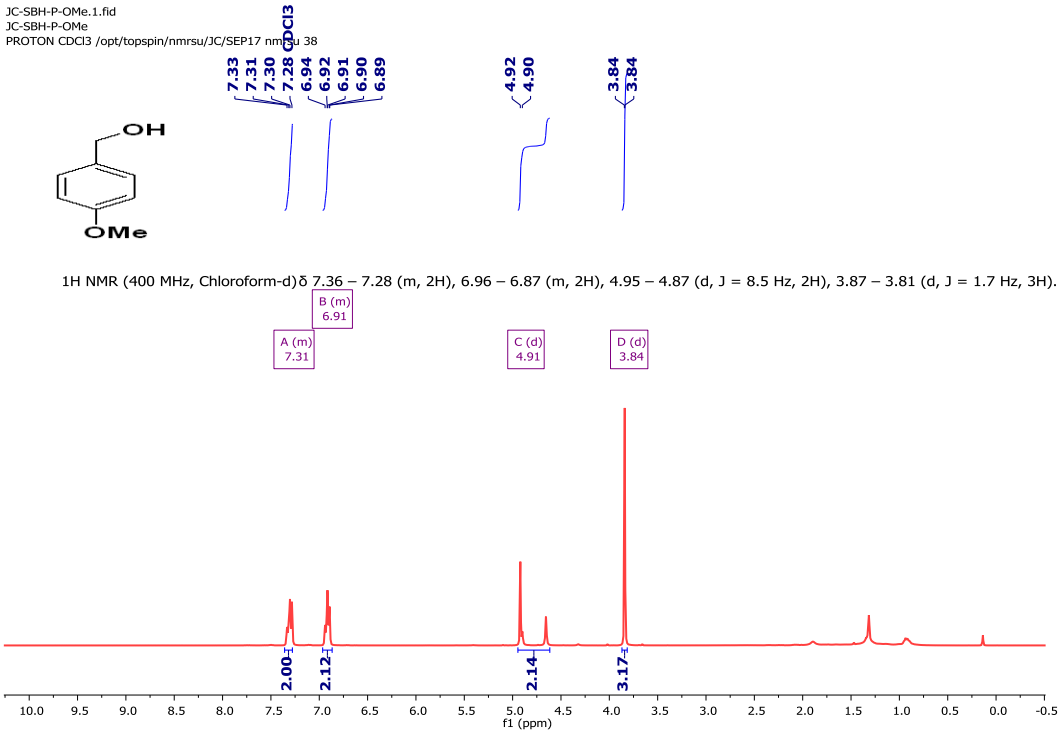


Figure S19. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-methoxybenzyl alcohol.

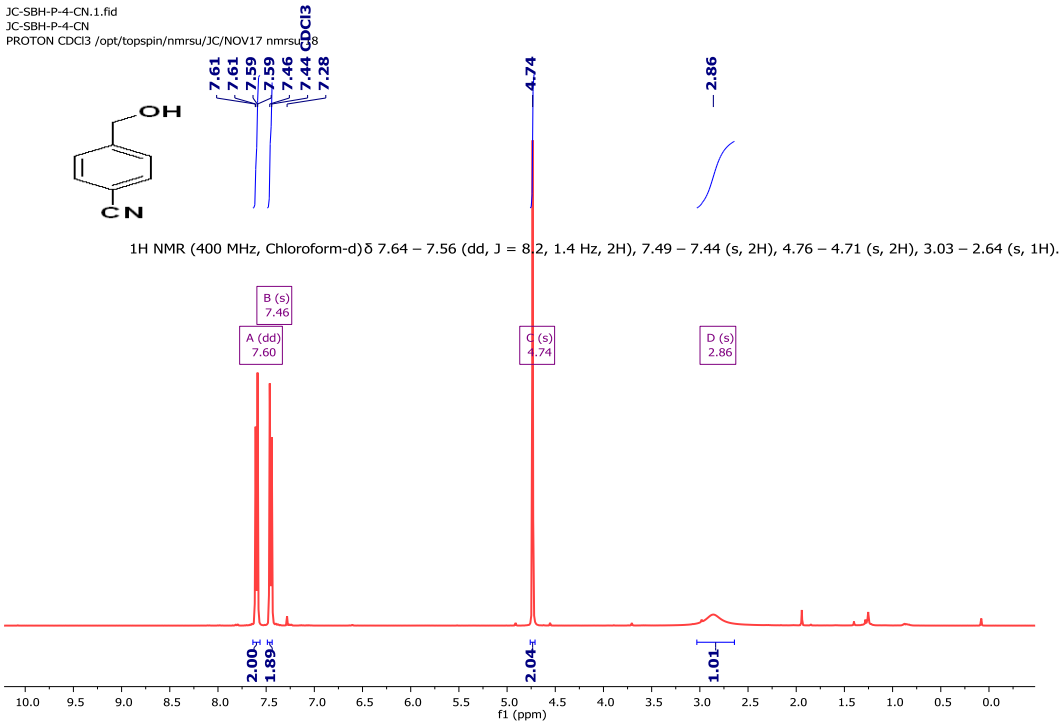


Figure S20. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-cyanobenzyl alcohol.

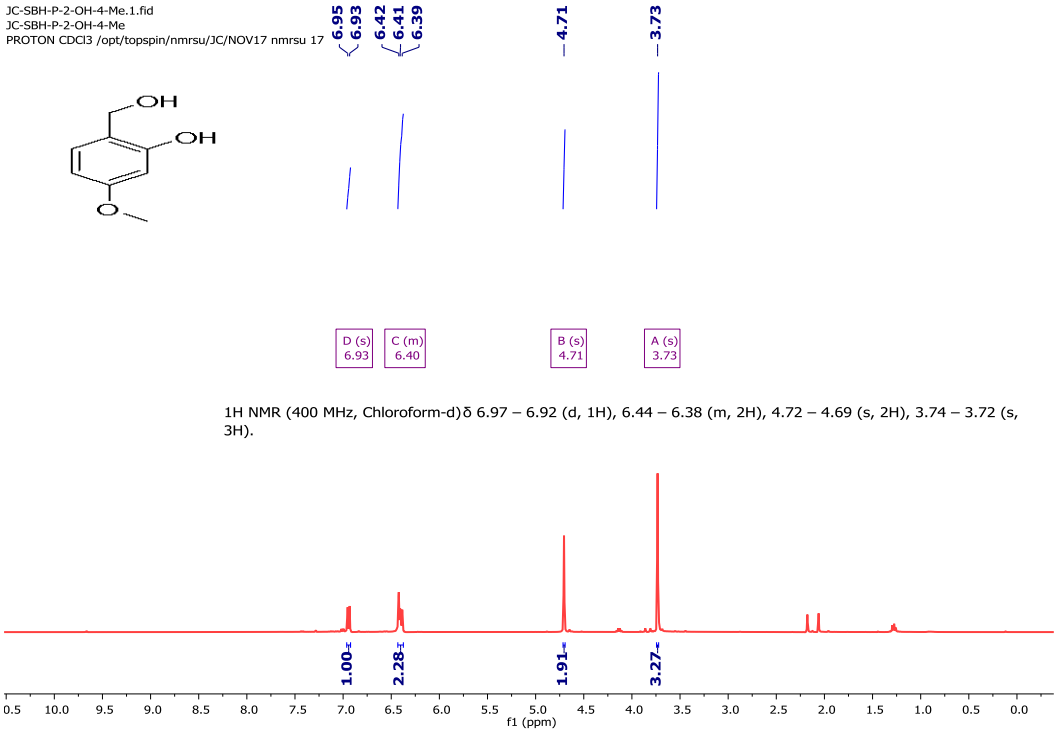
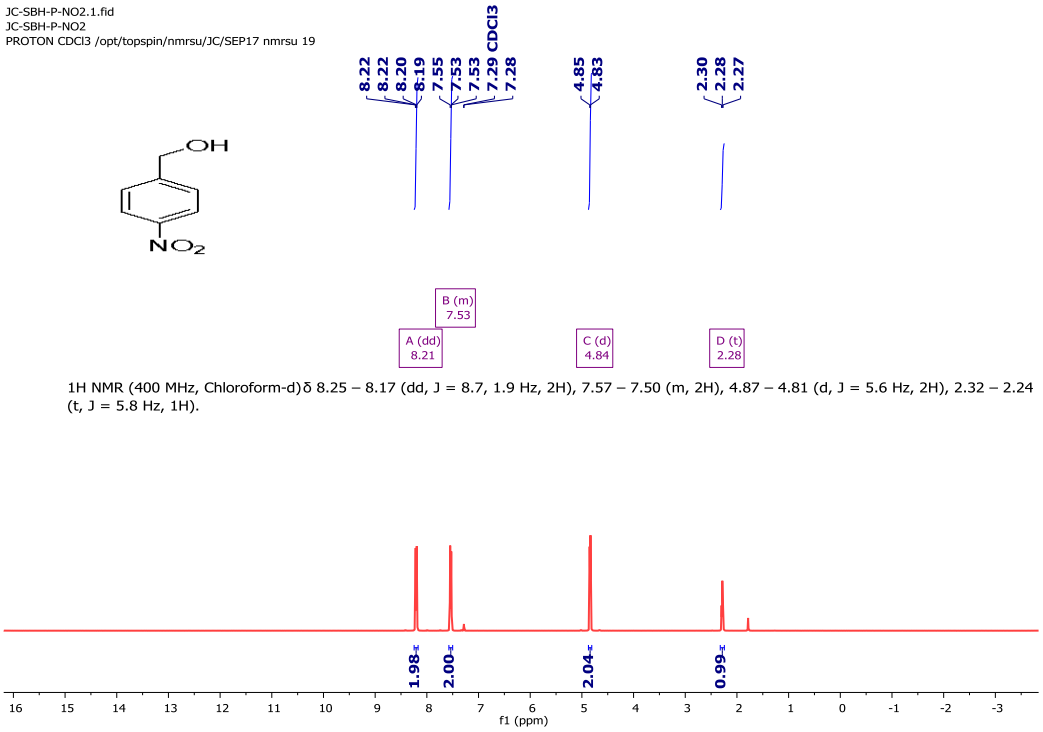
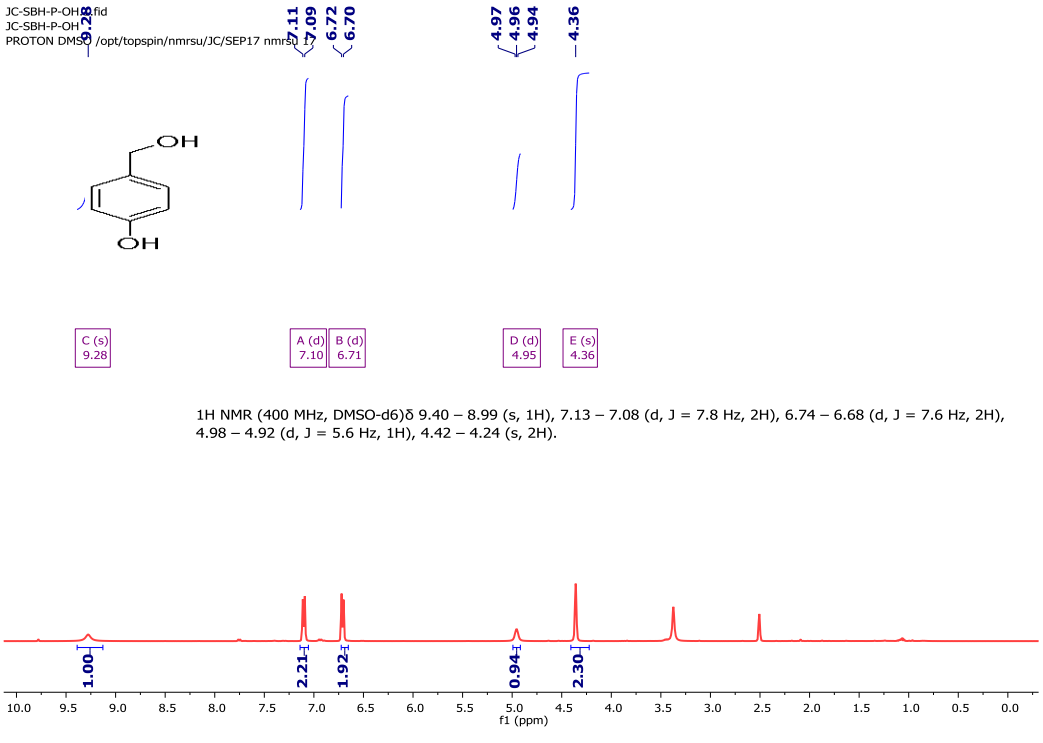


Figure S21. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 2-hydroxy-4-methoxybenzyl alcohol.



1H NMR (400 MHz, Chloroform-d) δ 8.25 – 8.17 (dd, J = 8.7, 1.9 Hz, 2H), 7.57 – 7.50 (m, 2H), 4.87 – 4.81 (d, J = 5.6 Hz, 2H), 2.32 – 2.24 (t, J = 5.8 Hz, 1H).

Figure S22. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-nitrobenzyl alcohol.



1H NMR (400 MHz, DMSO-d6) δ 9.40 – 8.99 (s, 1H), 7.13 – 7.08 (d, J = 7.8 Hz, 2H), 6.74 – 6.68 (d, J = 7.6 Hz, 2H), 4.98 – 4.92 (d, J = 5.6 Hz, 1H), 4.42 – 4.24 (s, 2H).

Figure S23. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-hydroxybenzyl alcohol.

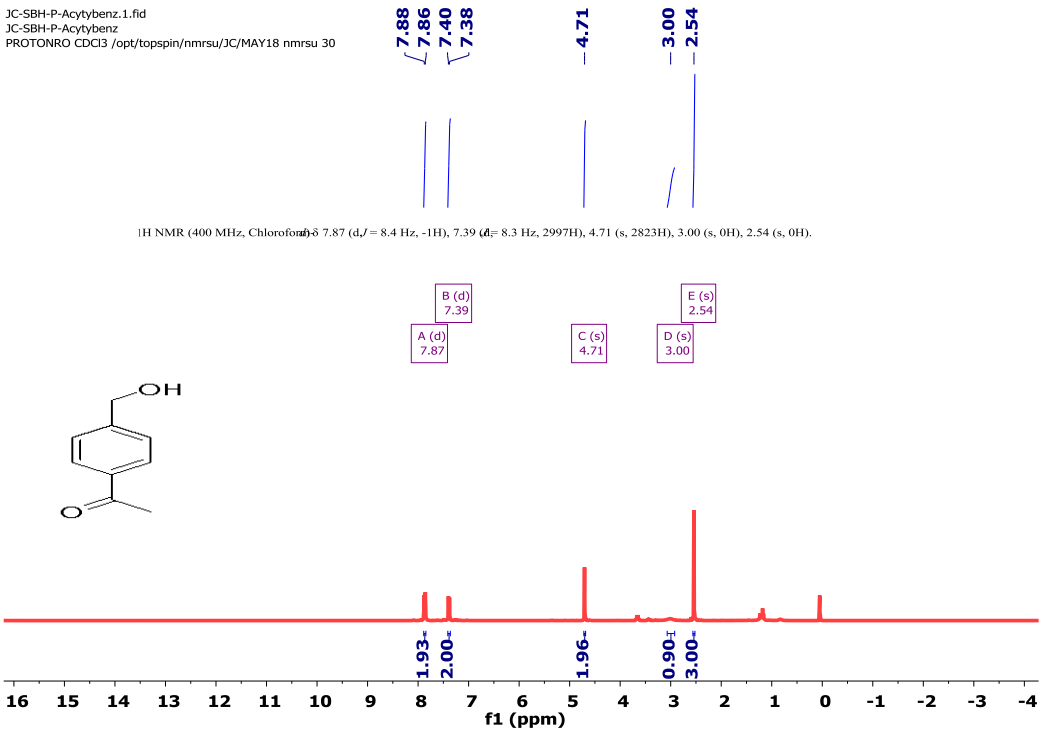


Figure S24. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 1-(4-(hydroxymethyl)phenyl)ethan-1-one.

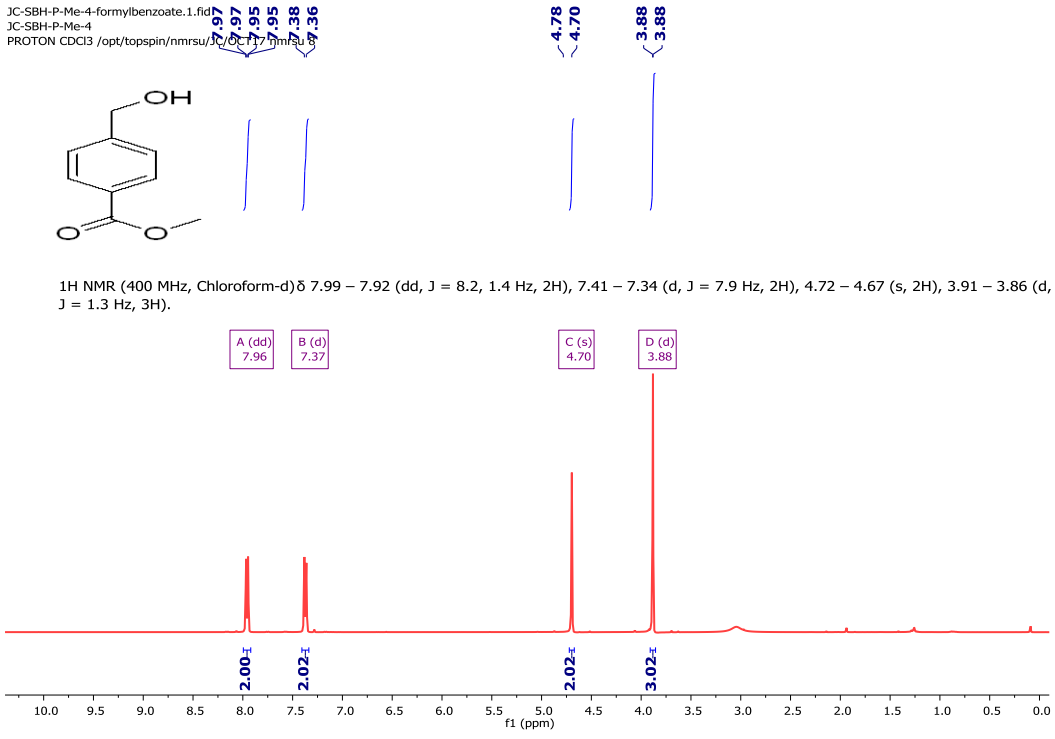


Figure S25. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of methyl 4-(hydroxymethyl)benzoate.

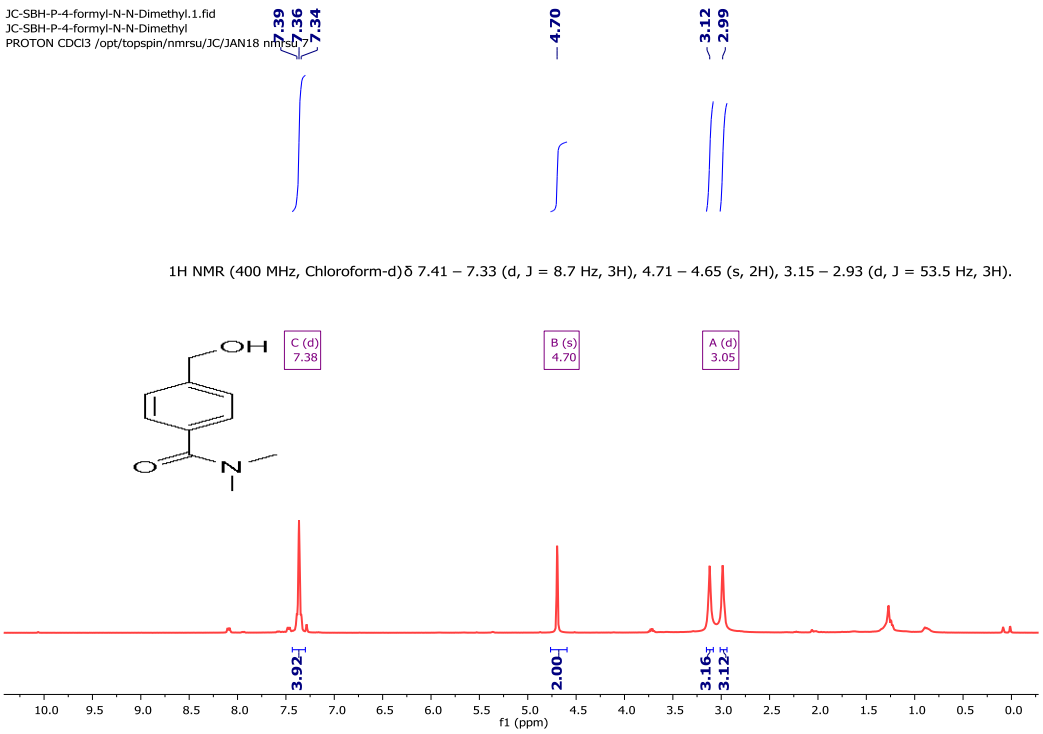


Figure S26. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of 4-(hydroxymethyl)-N,N-dimethylbenzamide.

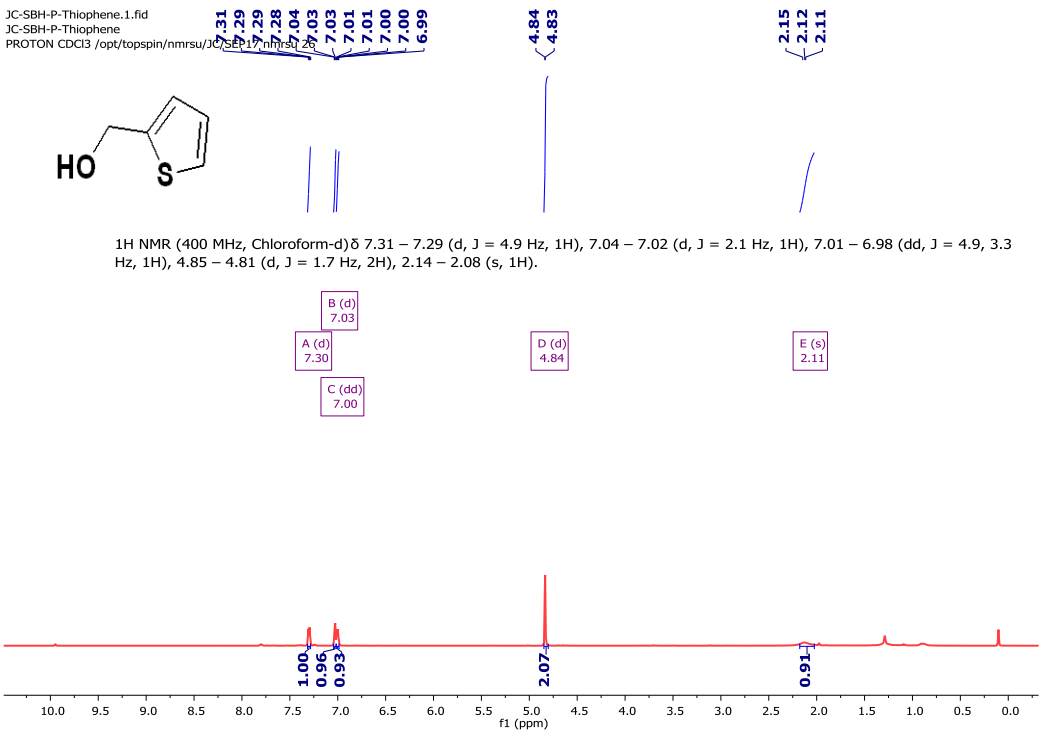


Figure S27. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of thiophen-2-ylmethanol.

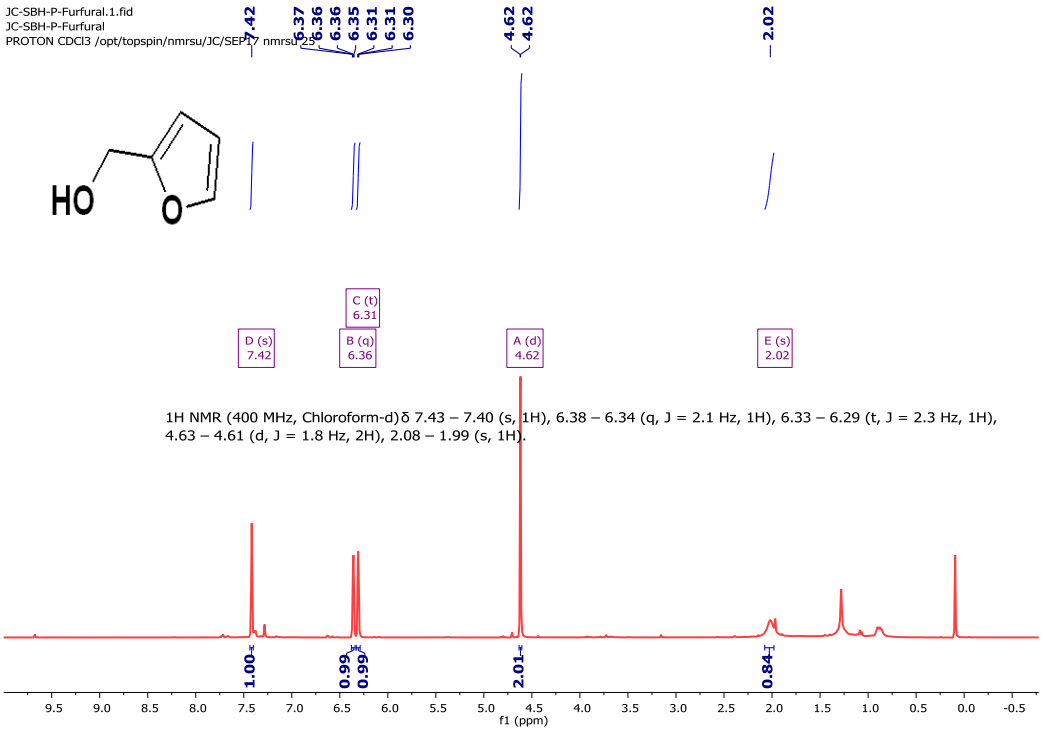


Figure S28. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of furan-2-ylmethanol.

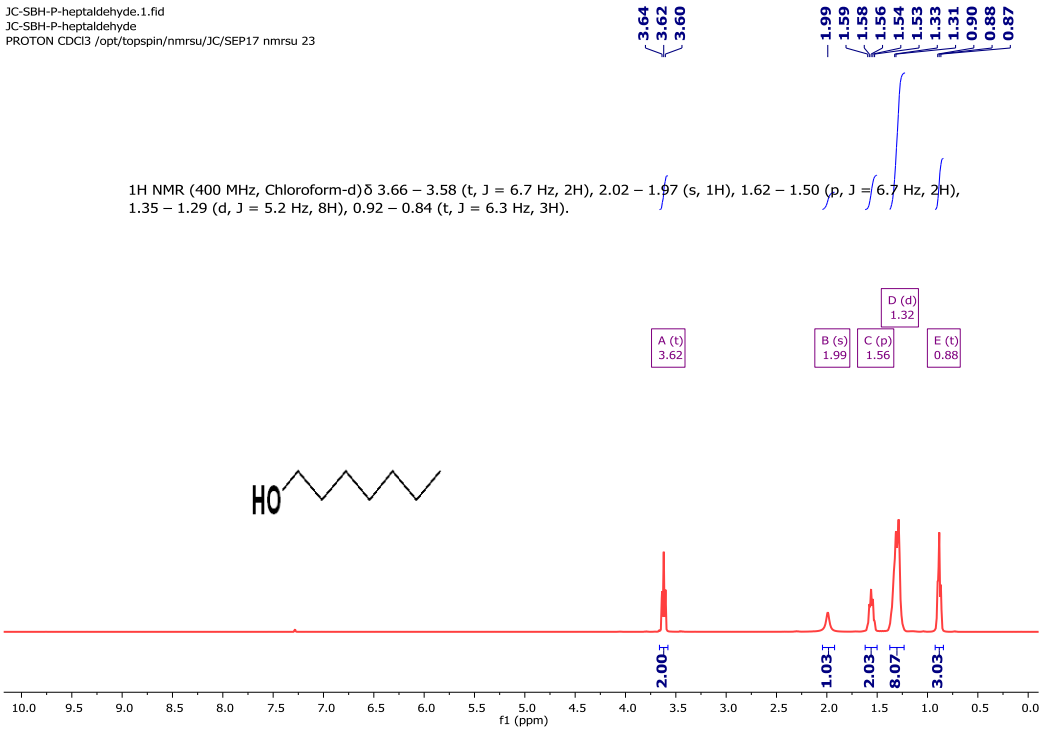


Figure S29. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of n-heptanol.

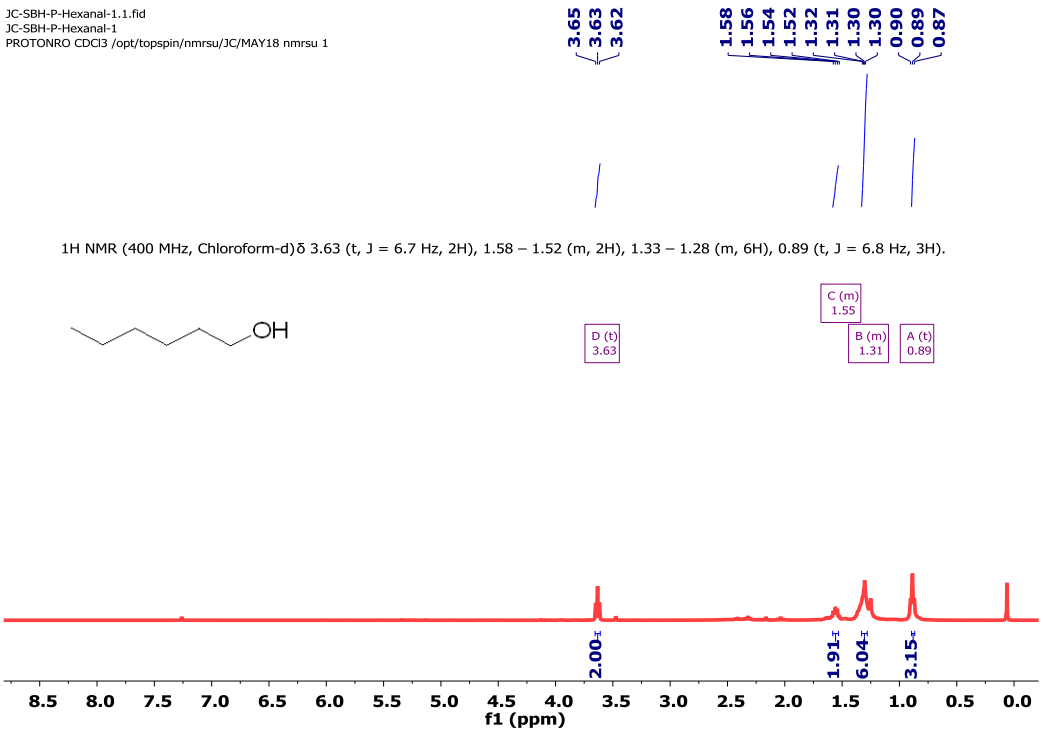


Figure S30. ^{1}H NMR spectrum ($CDCl_3$, 400 MHz) of n-hexanol.

VI. References

S1. Burés, J. Variable Time Normalization Analysis: General Graphical Elucidation of Reaction Orders from Concentration Profiles. *Angew. Chem. Int. Ed*. **2016**, *55*, 16084-16087.

S2. Burés, J. A Simple Graphical Method to Determine the Order in Catalyst. *Angew. Chem. Int. Ed*. **2016**, *55*, 2028-2031.