Mild and Selective Pd-Ar Protonolysis and C-H Activation Promoted by a Ligand Aryloxide Group

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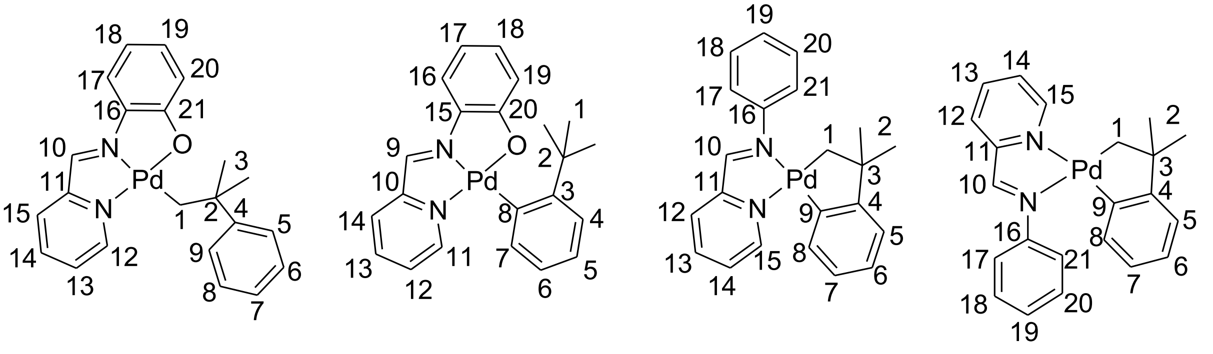
Representative procedure for deuterium labeling to give 1-*d_2* and 2-*d_2*:

H(L1) (0.009 g, 0.046 mmol) was dissolved in CD_3OD (1.5 mL) and stirred for 3 minutes. Then the solution was dried under vacuum to give a yellow powder, **D(L1)**. Next, **D(L1)** was dissolved in CD_2Cl_2 (0.3 mL) and was added to a solution of $[Pd(CH_2CMe_2C_6H_4)(COD)]$ (0.016 g, 0.046 mmol) in CD_2Cl_2 (0.3 mL) and D_2O (140 µL), while stirring. An immediate color change from yellow to dark purple was observed. After 10 minutes, a ^1H NMR experiment was performed of the purple solution identified as **1-*d_2***. Then, the solution was fully dried under vacuum to give **1-*d_2*** as a purple powder. Next, **1-*d_2*** was dissolved in acetone to analyze by ^2H NMR spectroscopy. ^2H NMR for **1-*d_2*** ($(CH_3)_2CO$, 92.0 MHz): δ 7.66 (br, *D*5 and *D*9). **1-*d_2*** was dried under vacuum and dissolved in dry CD_2Cl_2 while stirring. To perform ^2H NMR spectroscopy after 5 days, the solution was fully dried and dissolved in acetone. ^2H NMR for **2-*d_2*** ($(CH_3)_2CO$, 92.0 MHz): δ 7.17(br, *D*4), 1.69 (br, *D*1).

NMR Characterization of Pd(II) Complexes



1 **2** **3b** **3a**

Chart S1 – Atom labeling scheme for the reported compounds **1**, **2**, **3a** and **3b** used for NMR spectroscopy signal assignment.

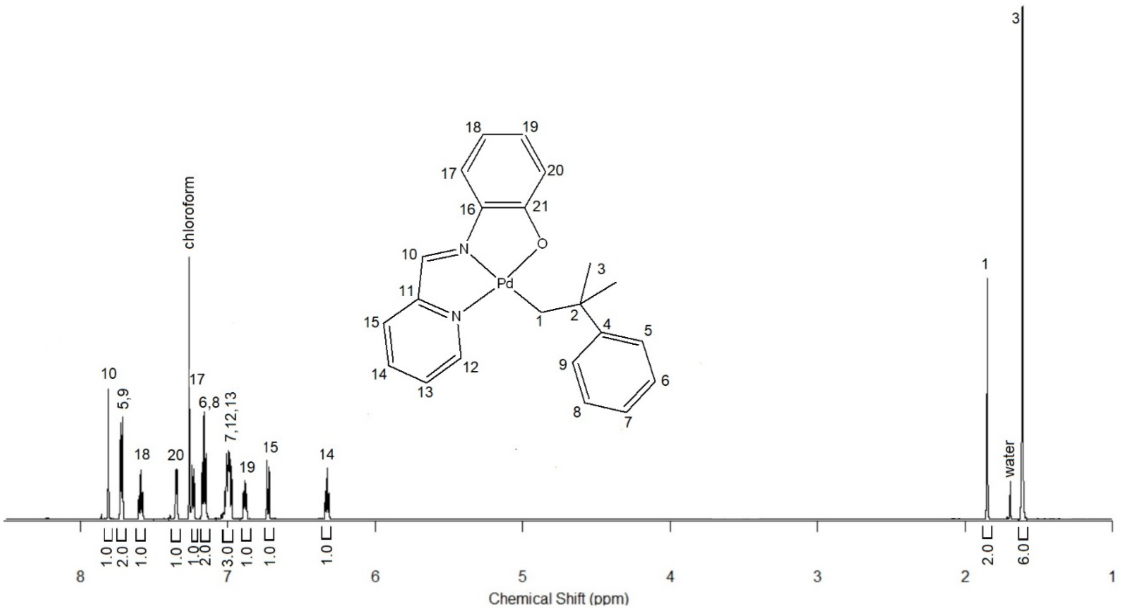


Figure S1- ^{1}H NMR spectrum (CDCl$_3$) of **1**, at 25°C.

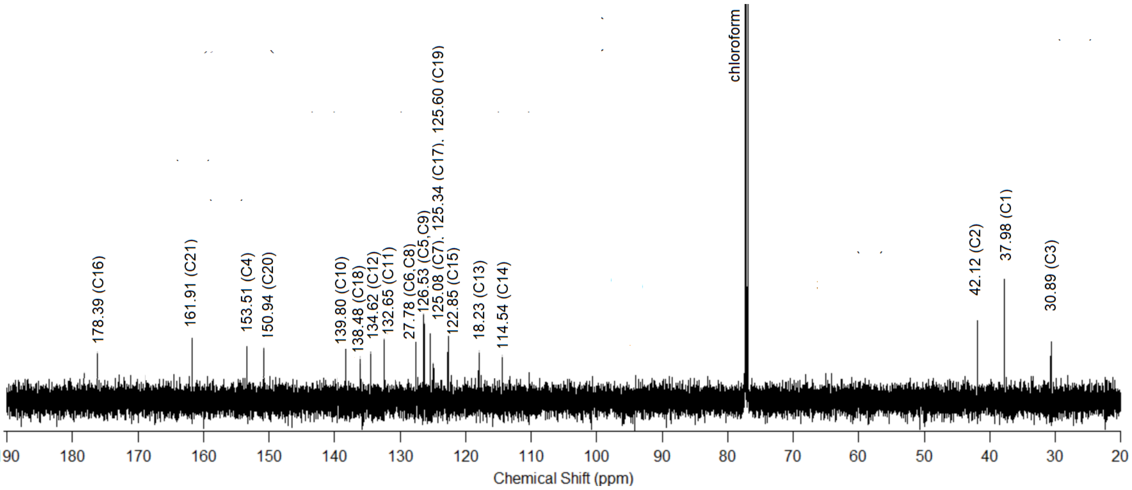


Figure S2- ^{13}C{^{1}H} NMR spectrum (CDCl$_3$) of **1**, at 25°C.

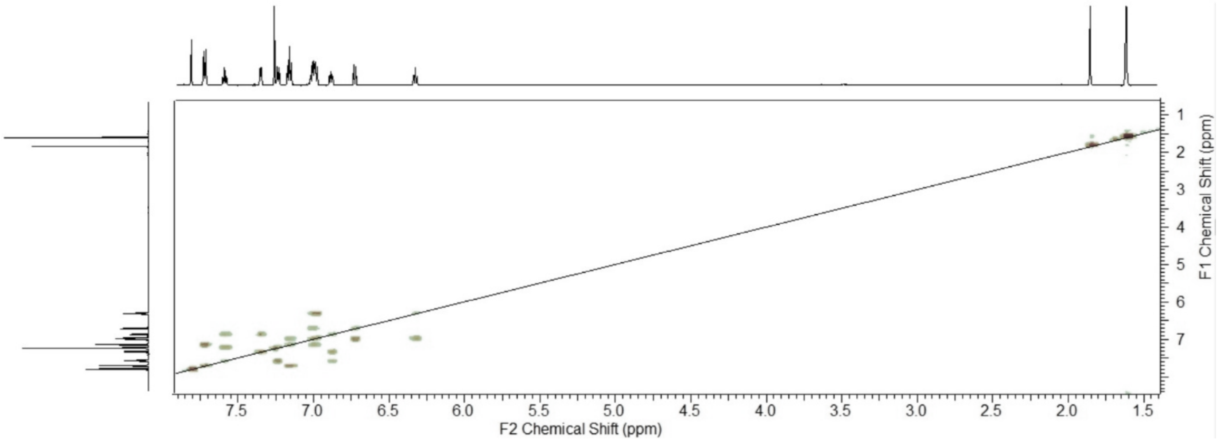


Figure S3- ^1H–^1H gCOSY spectrum ($CDCl_3$) of **1**, at 25°C.

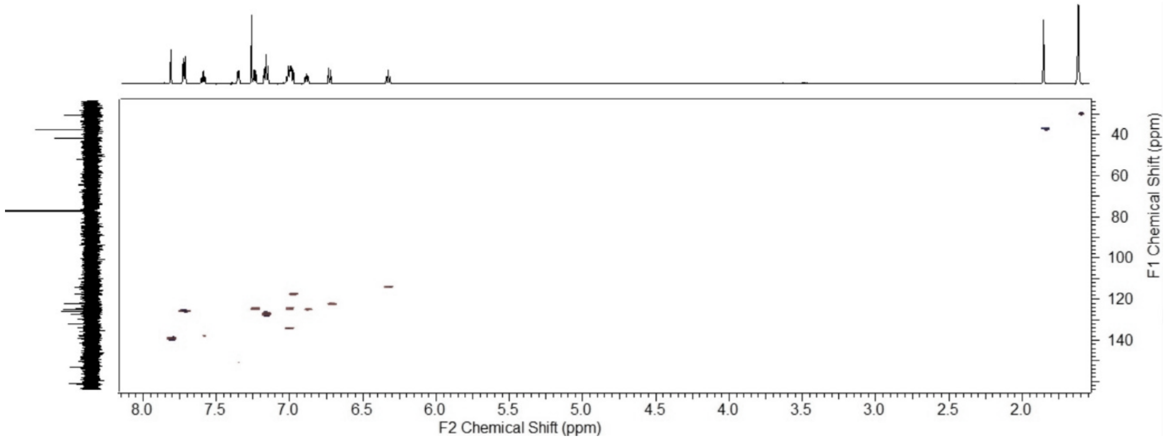


Figure S4- ^1H–^{13}C HSQC spectrum ($CDCl_3$) of **1**, at 25°C.

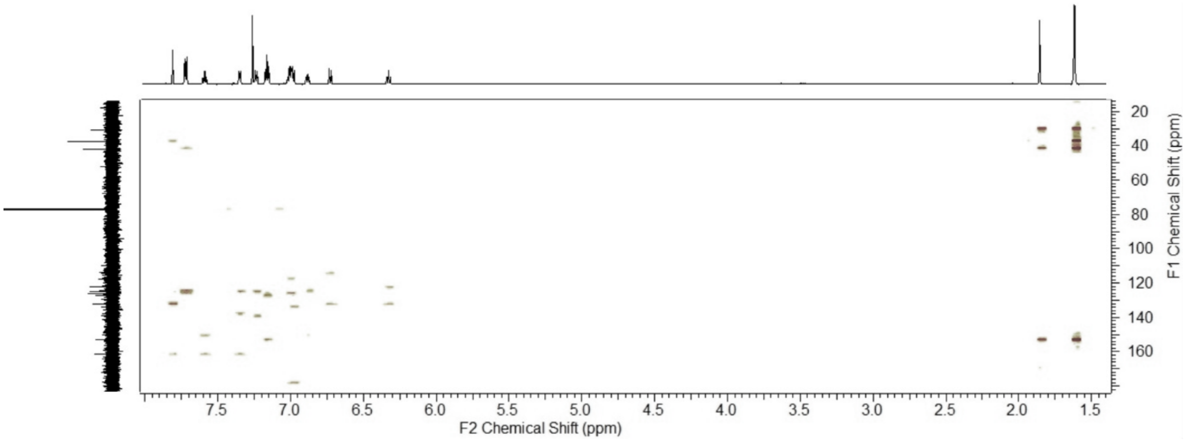


Figure S5- ^1H–^{13}C HMBC spectrum ($CDCl_3$) of **1**, at 25°C.

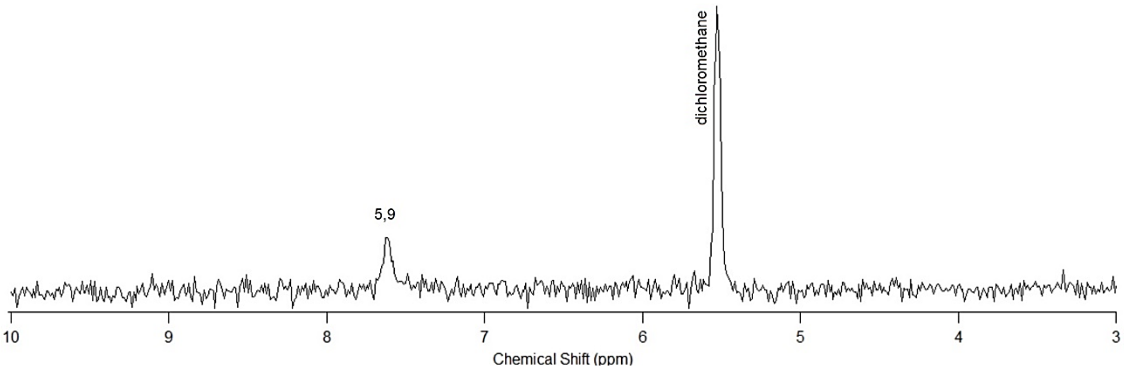


Figure S6- ^{2}H NMR Spectrum of **1-*d*$_1$** in CH_2Cl_2

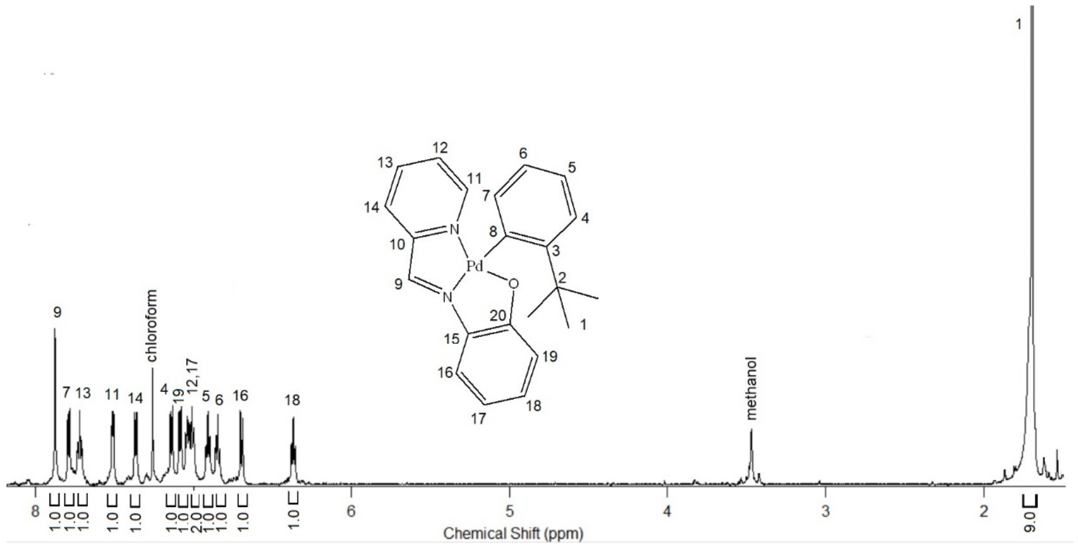


Figure S7- ^{1}H NMR spectrum ($CDCl_3$) of **2**, at 25°C.

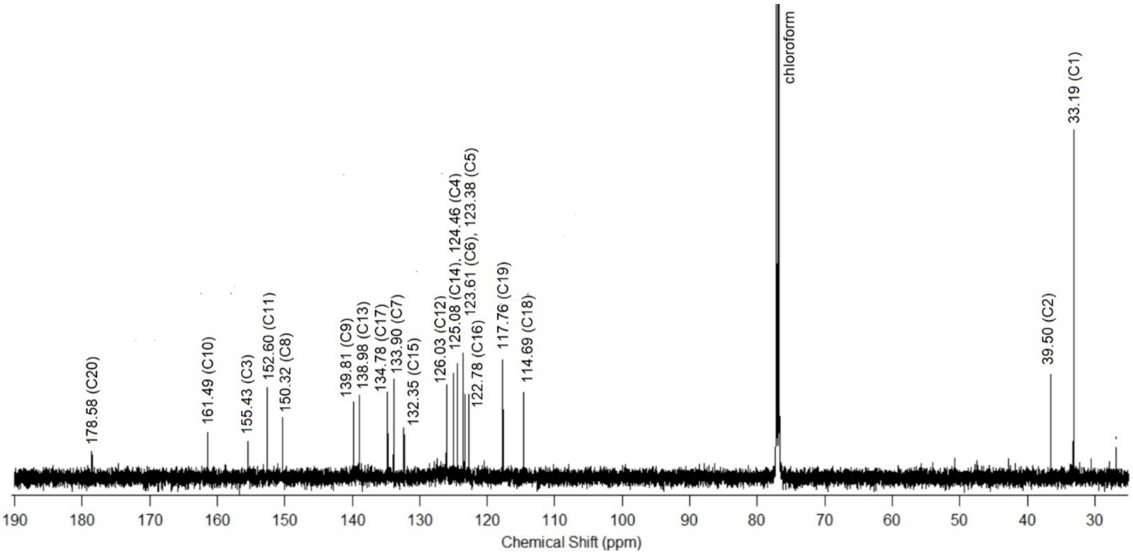


Figure S8- $^{13}C\{^{1}H\}$ NMR spectrum ($CDCl_3$) of **2**, at 25°C.

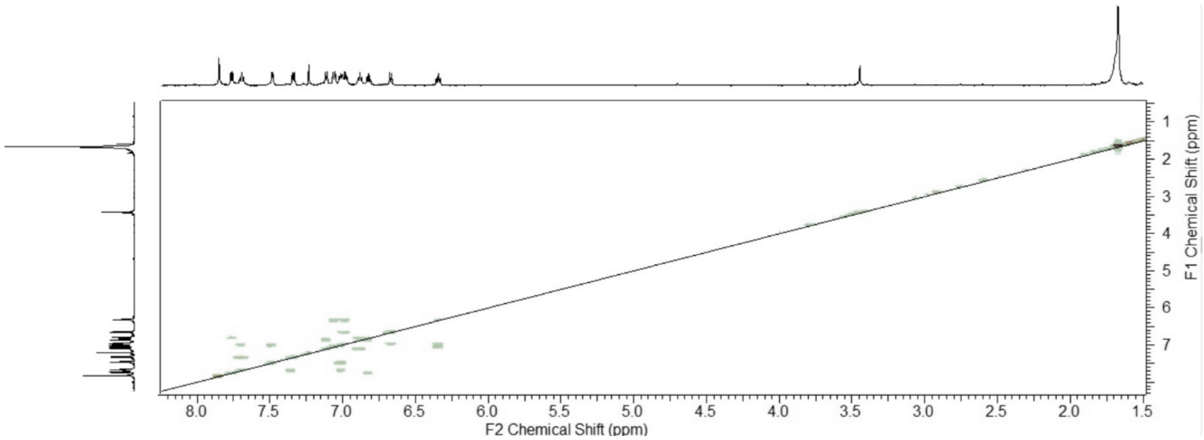


Figure S9- ^{1}H–^{1}H gCOSY spectrum ($CDCl_3$) of **2**, at 25°C.

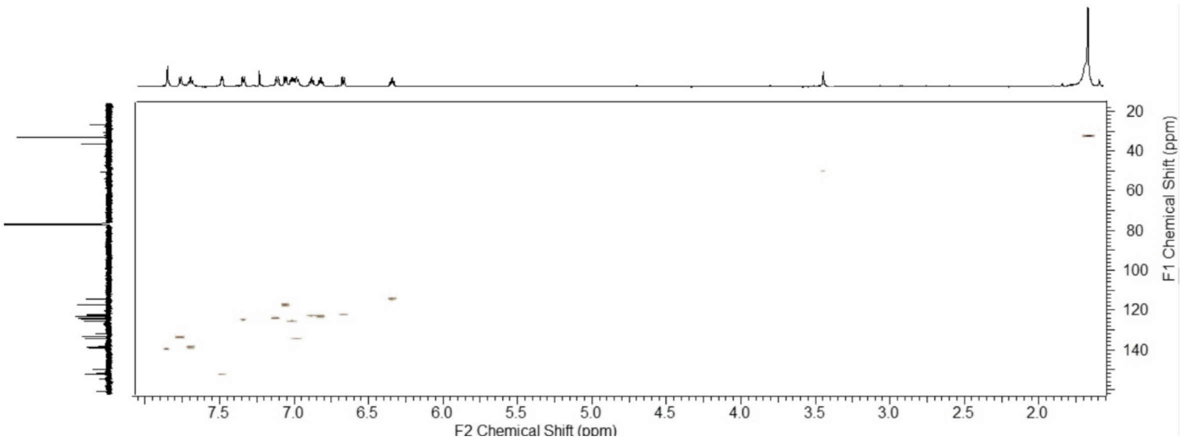


Figure S10- ^{1}H–^{13}C HSQC spectrum ($CDCl_3$) of **2**, at 25°C.

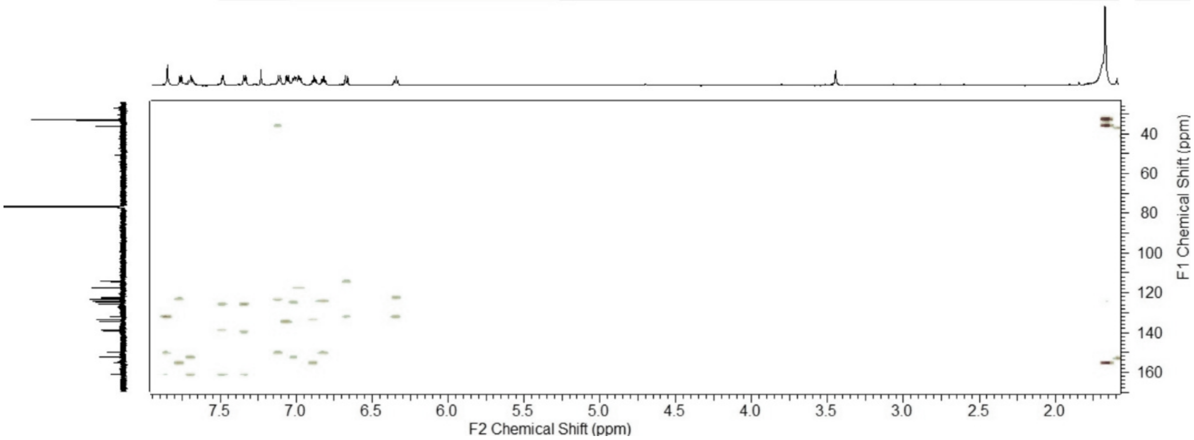


Figure S11- ^{1}H–^{13}C HMBC spectrum ($CDCl_3$) of **2**, at 25°C.

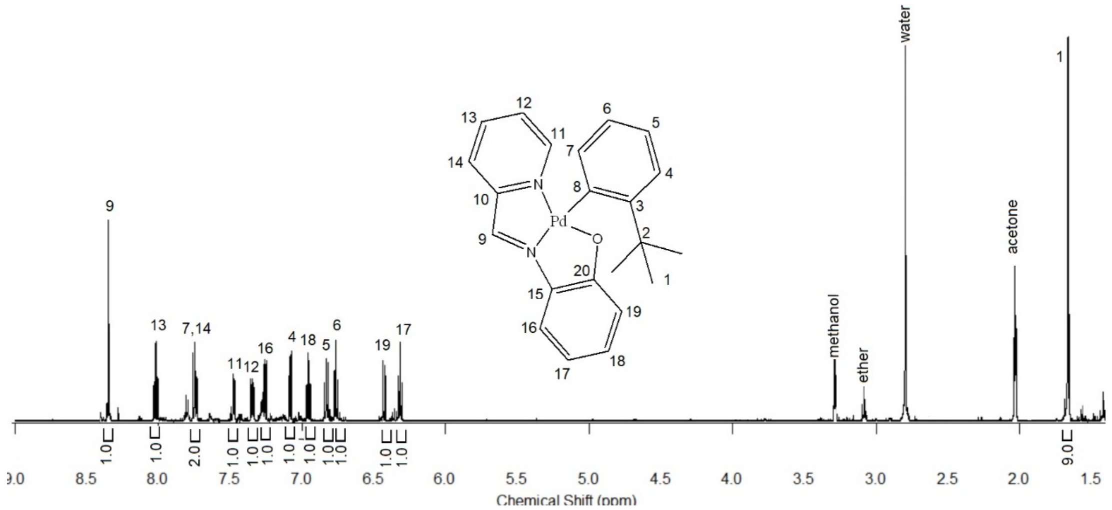


Figure S12- ^{1}H NMR spectrum ($(CD_3)_2CO$) of **2**, at 25°C.

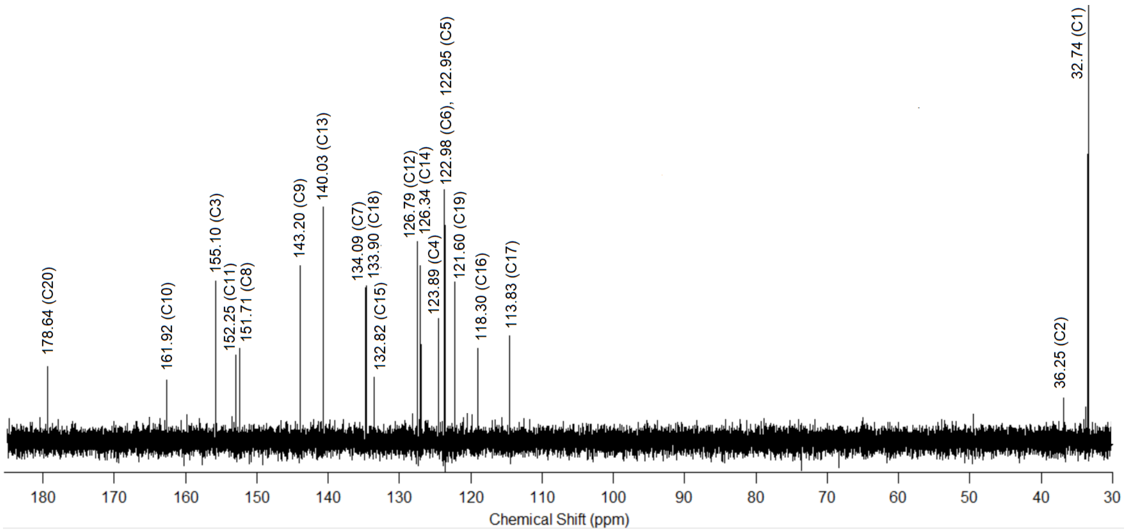


Figure S13- $^{13}C\{^{1}H\}$ NMR spectrum ($(CD_3)_2CO$) of **2**, at 25°C.

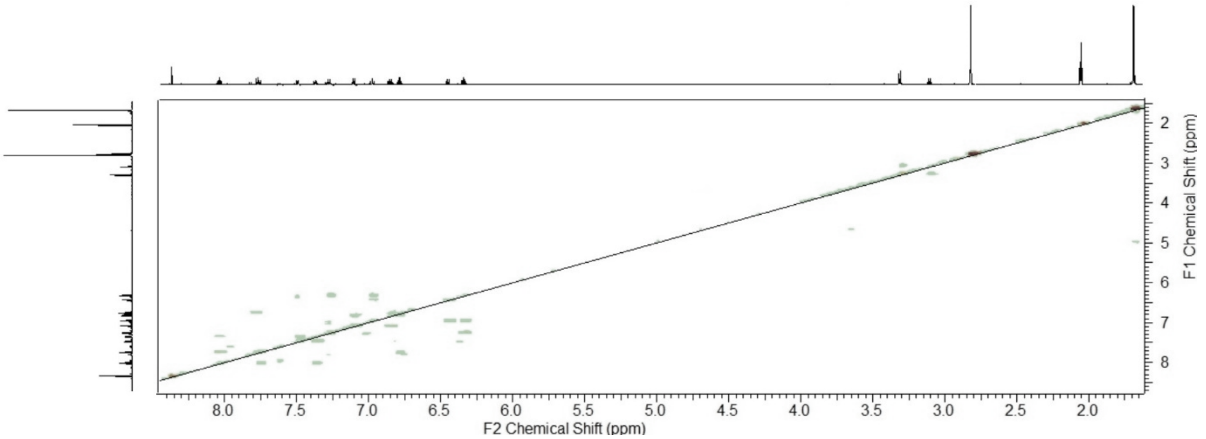


Figure S14- $^{1}H{-}^{1}H$ gCOSY spectrum ($(CD_3)_2CO$) of **2**, at 25°C.

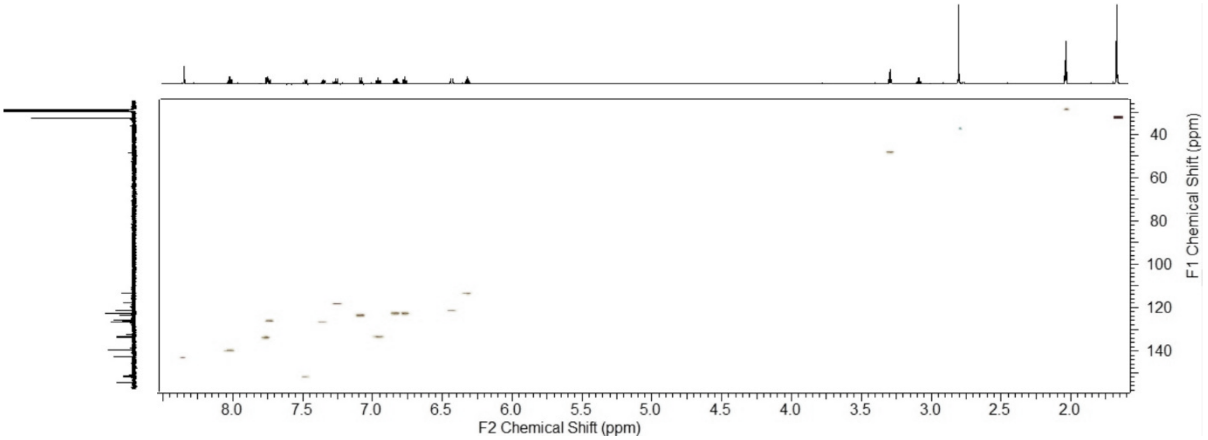


Figure S15- ^{1}H$-$^{13}C HSQC spectrum ($(CD_3)_2CO$) of **2**, at 25°C.

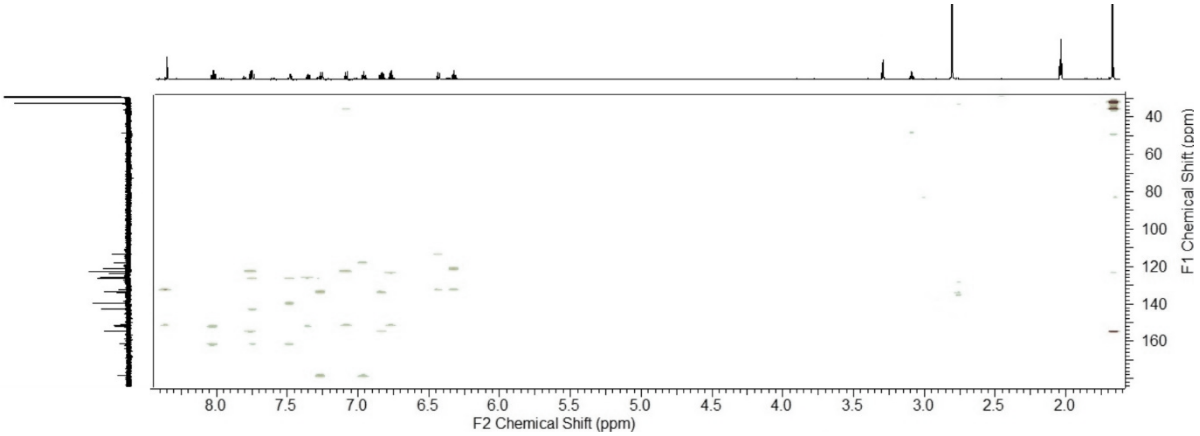


Figure S16- ^{1}H$-$^{13}C HMBC spectrum ($(CD_3)_2CO$) of **2**, at 25°C.

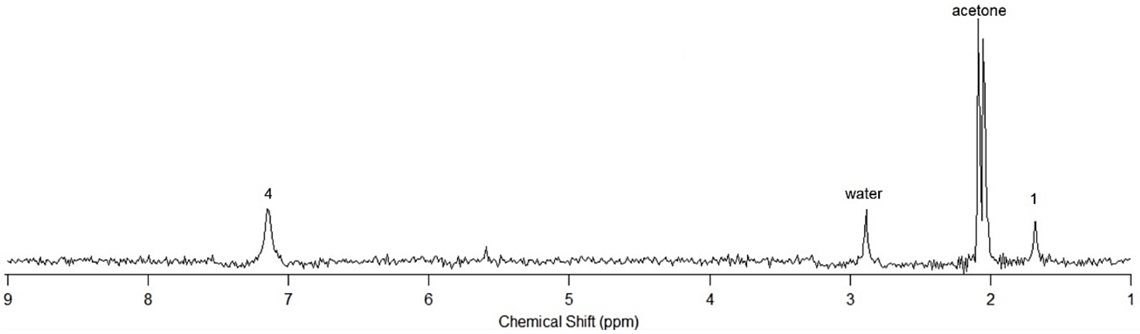


Figure S17- ^{2}H NMR spectrum ($(CH_3)_2CO$) of **2-*d*$_2$**, at 25°C.

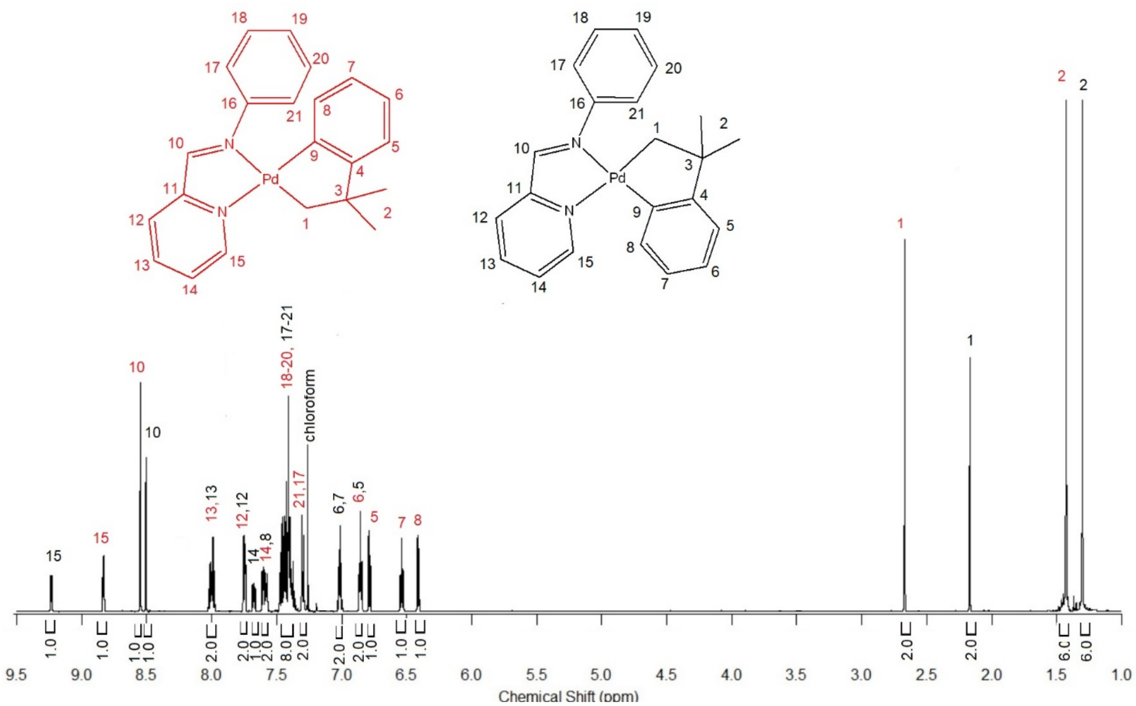


Figure S18- ^{1}H NMR spectrum (CDCl$_3$) of **3a/3b**, at 25°C.

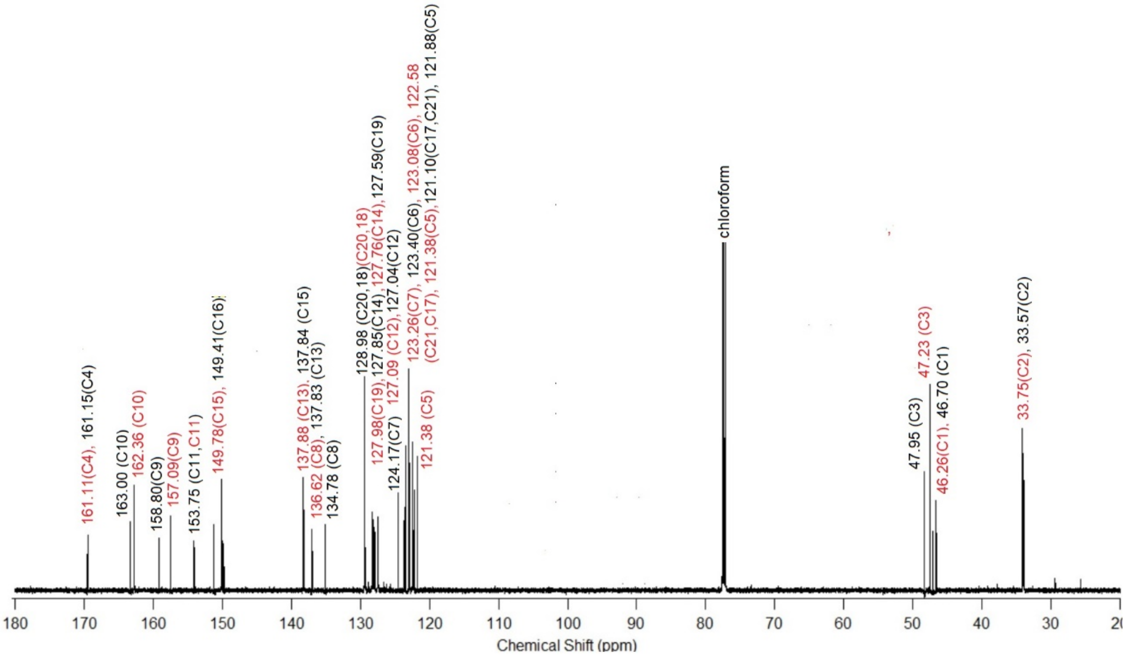


Figure S19-^{13}C{^{1}H} NMR spectrum (CDCl$_3$) of **3a/3b**, at 25°C.

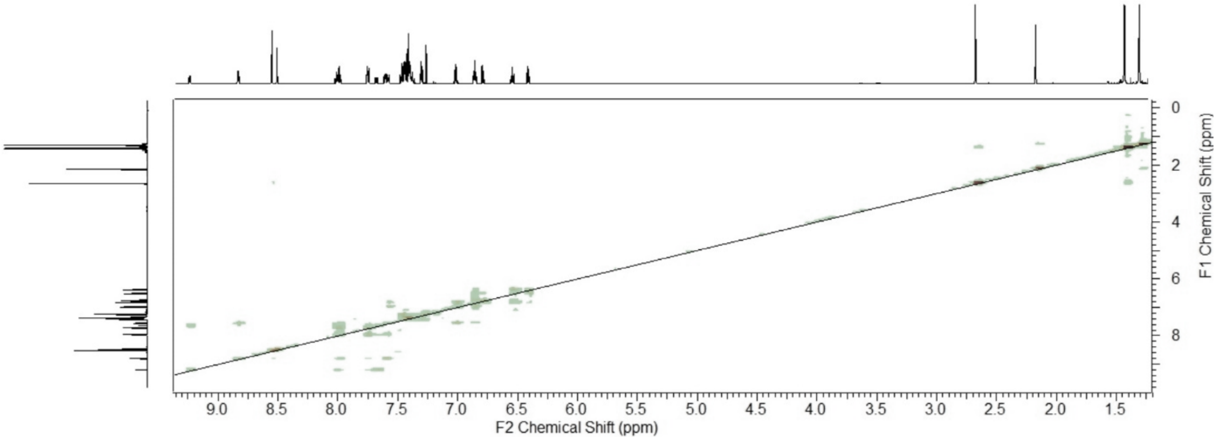


Figure S20- ^1H–^1H gCOSY spectrum ($CDCl_3$) of **3a/3b**, at 25°C.

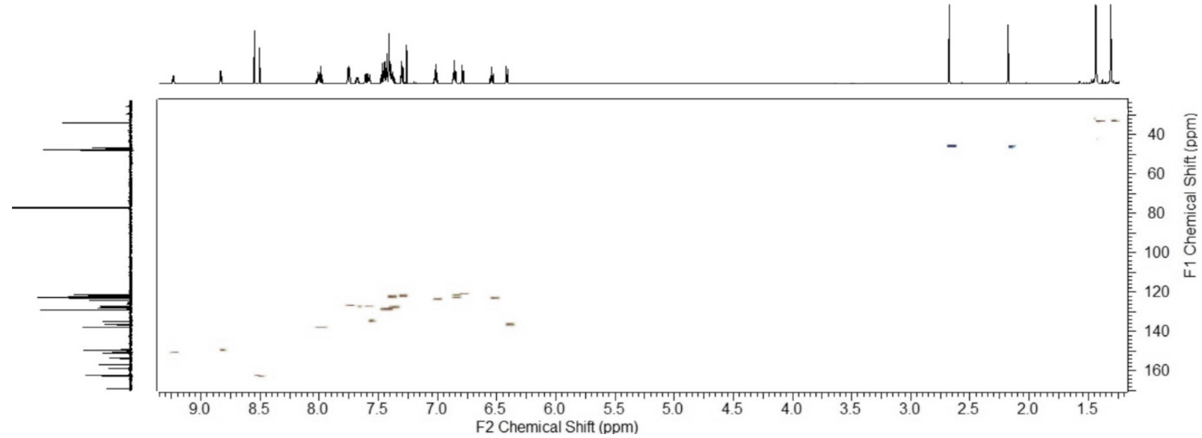


Figure S21- ^1H–^{13}C HSQC spectrum ($CDCl_3$) of **3a/3b**, at 25°C.

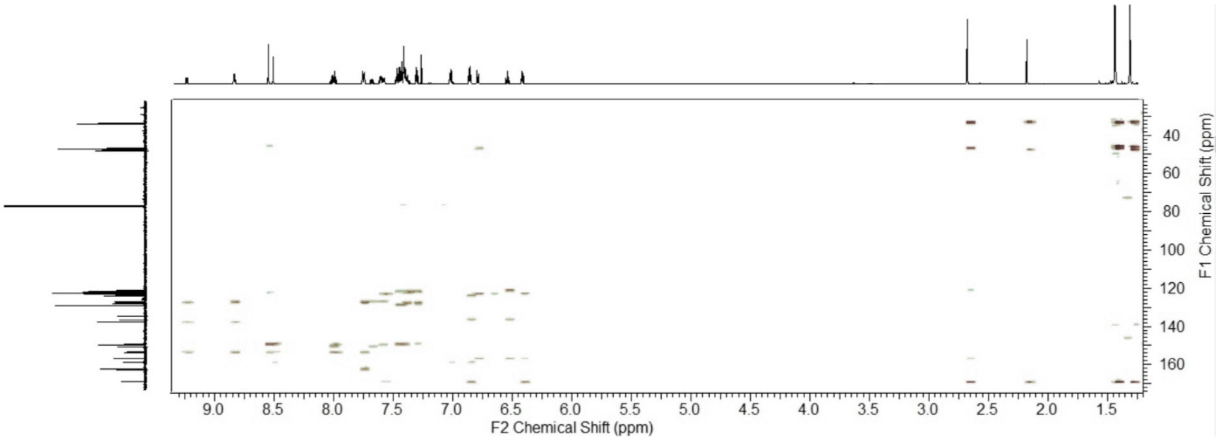


Figure S22- ^1H–^{13}C HMBC spectrum ($CDCl_3$) of **3a/3b**, at 25°C.

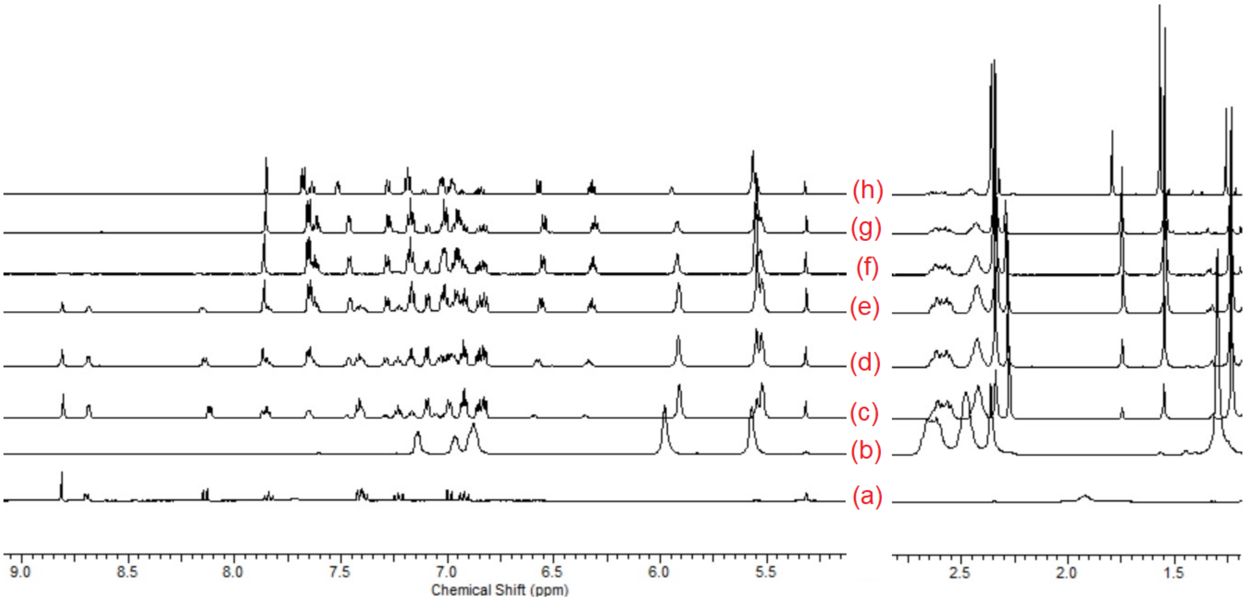


Figure S23- ^{1}H NMR spectra (CD_2Cl_2) of a) **H(L1)** at 25°C; b) **[Pd($CH_2CMe_2C_6H_4$)(COD)]** at –20°C; and a 1:1 mixture of pre-cooled **H(L1)** (–35 ˚C) and **[Pd($CH_2CMe_2C_6H_4$)(COD)]** (–20˚C) at c) –20°C; d) –10°C; e) –5°C; f) 0°C; g) 5°C; and h) 25°C.

Mass Spectroscopy of Pd(II) Complexes

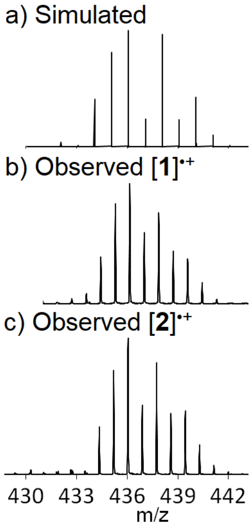


Figure S24- The MALDI MS isotope patterns for $[\mathbf{1}]^{\bullet+}$ and $[\mathbf{2}]^{\bullet+}$ obtained using anthracene matrix: (a) simulated, (b) observed $[\mathbf{1}]^{\bullet+}$ and (c) observed $[\mathbf{2}]^{\bullet+}$.

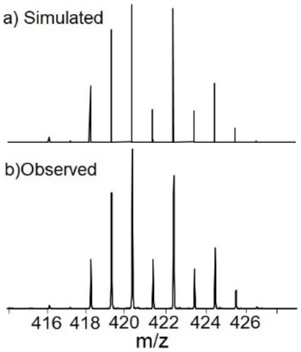


Figure S25- The MALDI MS isotope patterns for [**3a/3b**]$^{\bullet+}$ obtained using anthracene matrix: (a) simulated and (b) observed.

UV-VIS Study

Experimental Procedure

A solution of complex **1** (8.58×10^{-5} M, 3.0 mL) was prepared in different solvents (methanol, acetonitrile, dichloromethane, chloroform and benzene) and placed into a 4 mL cuvette (optical path length 1 cm) at room temperature.

Table S1. UV-Vis absorption spectroscopy data for **1** in different solvents.

Solvent	ε [a]	E_T^N [b]	λ_{max} (nm)	$1/\lambda_{max}$ (10^3 cm^{-1})	ε [c]
MeOH	33.6	55.5	525	19.04	1375
CH_3CN	37.5	46	555	18.02	940
CH_2Cl_2	8.9	41.1	570	17.54	1904
$CHCl_3$	4.8	39.1	580	17.24	1652
C_6H_6	2.2	34.5	585	17.09	1525

[a] Dielectric constant. [b] Normalized Reichardt solvent polarity factor (kcal mol^{-1} at 25°C).[1-3] [c] Molar absorptivity (cm^{-1} mol^{-1} L).

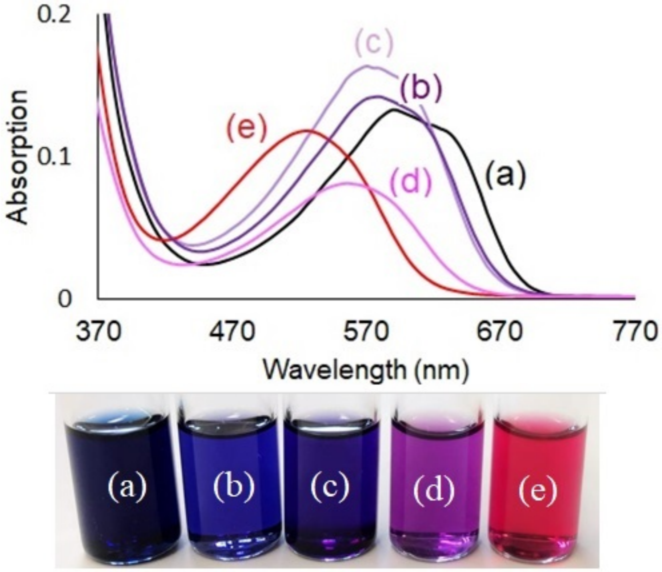


Figure S26. Top: UV-Visible absorption spectra of **1** (8.58×10^{-5} M) in (a) C_6H_6, (c) CH_2Cl_2 and (e) CH_3OH. Bottom: photograph of solutions of **1** (8.58×10^{-5} M) in (a) C_6H_6; (b) $CHCl_3$; (c) CH_2Cl_2; (d) CH_3CN; (e) CH_3OH.

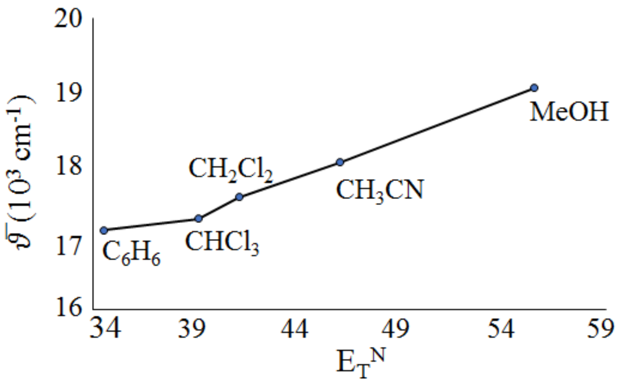


Figure S27. Correlation of wavenumber ($\bar{\upsilon}$) with the solvent Normalized Reichardt polarity factor (E_T) value.

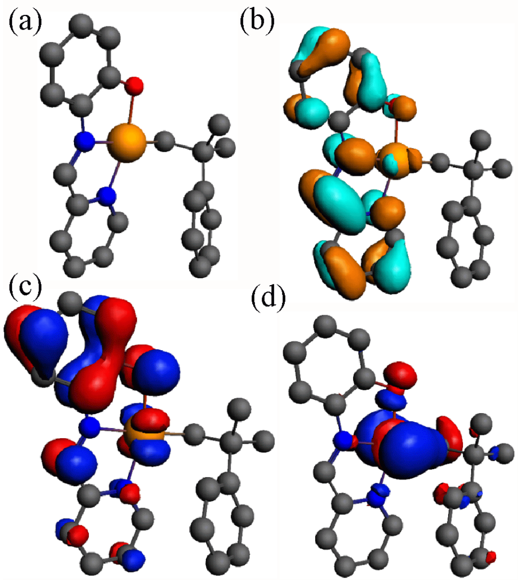


Figure S28. Calculated structure and frontier orbitals for complex **1**; (a) structure, (b) LUMO, (c) HOMO, (d) HOMO–1.

Efforts toward Mechanism Characterization

General Procedure for the Isomerization of 1 to 2

All reactions were carried out under air and on an NMR scale. Internal standard, (1,3,5-trimethoxybenzene) (0.002 g, 0.012 mmol) was added to a solution of **1** (0.016 g, 0.036 mmol) in an appropriate solvent (1.5 mL) and the reaction was stirred in a 4 mL vial. At specific time points, reactions were monitored by ^{1}H NMR spectroscopy. More details are included in the tables (Table S2-S8).

Table S2. Solvent effect study for the isomerization reaction.

Entry	Solvent	$\mathcal{E}^b$	**1** (%)	**2** (%)	By-product (%)
1	CD_3CN	37.5	67	33	0
2	DMF	36.7	48	35	17
3	CH_3OH	33.6	42	58	0
4	Isopropanol	17.9	95	5	0
5	CD_2Cl_2	8.9	70	30	0
6	2,2,2-	8.55	0	0	100

	trifluoroethanol				
7	THF	7.58	92	8	0
8	$CDCl_3$	4.8	68	32	0
9	CS_2	2.6	0	0	100
10	1,4-Dioxane	2.25	100	0	0
11	CCl_4	2.24	100	0	0
12	C_6D_6	2.2	98	2	0

Conditions: [**1**] = 0.72 mM. Time = 22h. [b] Dielectric constant.

Table S3. Concentration study for the isomerization reaction.

Entry	Solvent	ε[b]	[**1**] (mM)	**1** (%)	**2** (%)	BP (%)
1	$CDCl_3$	4.8	0.72	68	32	0
2	$CDCl_3$	4.8	3.33	70	30	0
3	$CDCl_3$	4.8	5	74	26	0
4	$CDCl_3$	4.8	10	70	30	0

Condition: Time = 22h. [b] Dielectric constant

Table S4. Time study for the isomerization reaction.

Entry	Solvent	ε[b]	Time (h)	**1** (%)	**2** (%)	BP (%)
1	$CDCl_3$	4.8	22	68	32	0
2	$CDCl_3$	4.8	44	55	45	0
3	$CDCl_3$	4.8	66	43	57	0
4	$CDCl_3$	4.8	154	27	58	15
5	CH_3OH	33.6	22	42	58	0
6	CH_3OH	33.6	154	10	90	0

Condition: [1] = 0.72 mM. [b] Dielectric constant.

Table S5**.** Light effect study for the isomerization reaction.

Entry	Solvent	ε[b]	Condition	Time (h)	**1** (%)	**2** (%)	BP (%)
1	$CDCl_3$	4.8	Light	22	68	32	0
2	$CDCl_3$	4.8	Light	44	55	45	0

3	$CDCl_3$	4.8	Light	66	43	57	0
4	$CDCl_3$	4.8	Dark[c]	22	65	35	0
5	$CDCl_3$	4.8	Dark	44	60	50	0
6	$CDCl_3$	4.8	Dark	66	40	60	0

Condition: [**1**] = 0.72 Mm, Time = 22 h. [b] Dielectric constant. [c] The vial was wrapped in an aluminum foil.

Table S6**.** Heating effect study for isomerierization reaction.

entry	Solvent	ε^b	Time (h)	Temperature[c]	**1** (%)	**2** (%)	BP (%)
1	CH_3OH	33.6	22	43°C	25	75	0
2	CH_3OH	33.6	44	43°C	8	80	12
3	CH_3OH	33.6	66	43°C	4	30	66

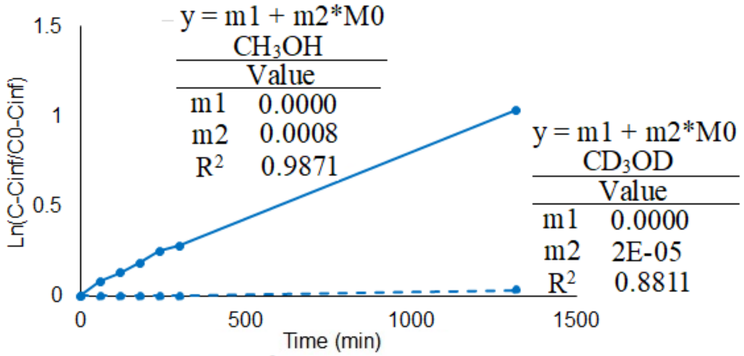
Condition: [**1**] = 0.72 mM. [b] Dielectric constant. [c] The vial was heated in an oil bath.

Table S7. Deuterium effect study for the isomerization reaction.

Entry	Solvent	ε^b	Time (min)	**1** (%)	**2** (%)	BP (%)
1	CH_3OH	33.6	60	93	7	0
2	CH_3OH	33.6	120	89	11	0
3	CH_3OH	33.6	180	85	15	0
4	CH_3OH	33.6	240	80	20	0
5	CH_3OH	33.6	300	78	22	0
6	CH_3OH	33.6	1320	42	58	0
7	CH_3OH	33.6	2640	34	66	0
8	CH_3OH	33.6	6600	10	90	0
9	CD_3OD	33.6	60	100	0	0
10	CD_3OD	33.6	120	100	0	0
11	CD_3OD	33.6	180	100	0	0
12	CD_3OD	33.6	240	100	0	0

13	CD_3OD	33.6	300	100	0	0
14	CD_3OD	33.6	1320	97	3	0
15	CD_3OD	33.6	2640	95	5	0
16	CD_3OD	33.6	6600	0	0	100
17	$CHCl_3$	4.8	1320	70	30	0
18	$CDCl_3$	4.8	1320	68	32	0
19	CH_2Cl_2	8.9	1320	72	28	0
20	CD_2Cl_2	8.9	1320	70	30	0

Condition: [**1**] = 0.72 mM. [b] Dielectric constant.



$$\text{KIE} = \frac{k_H}{k_D} = \frac{2E\text{-}05}{0.0008} = 40$$

Figure S29. Isomerization reaction of **1** to **2** in protonated- and deuterated-methanol. *Plot of* $Ln\frac{([\mathbf{2}]-[\mathbf{2}]\infty)}{([\mathbf{2}]0-[\mathbf{2}]\infty)}$ *versus time (min). solid line:* CH_3OH*. Dash line:* CD_3OD*, both fit to y=(m1)+(m2)*(M0) where y=*$Ln\frac{([\mathbf{2}]-[\mathbf{2}]\infty)}{([\mathbf{2}]0-[\mathbf{2}]\infty)}$ *and M0=time.*

Table S8. Water effect study for the isomerization study.

Entry	Solvent	ε^b	Condition	Time (h)	**1** (%)	**2** (%)	BP (%)
1	CH_3OH	33.6	----	22	42	58	0
2	CH_3OH	33.6	H_2O (10 μL)	22	46	54	0
3	CH_3OH	33.6	H_2O (50 μL)	22	44	56	0
4	CH_3OH	33.6	H_2O (100 μL)	22	46	54	0
5	$CDCl_3$	4.8	Dry[c]	22	66	34	0
6	$CDCl_3$	4.8	Dry[c]	44	48	52	0
7	$CDCl_3$	4.8	H_2O (100 μL)	22	67	33	0

8	$CDCl_3$	4.8	H_2O (100 μL)	44	46	54	0
9	$CDCl_3$	4.8	D_2O (100 μL)	22	93	7	0
10	$CDCl_3$	4.8	D_2O (100 μL)	44	86	14	0
11	$CDCl_3$	4.8	CH_3OH (0.5 mL)	22	37	63	0
12	$CDCl_3$	4.8	CH_3OH (0.5 mL)	44	32	68	0
13	$CDCl_3$	4.8	CD_3OD (0.5 mL)	22	91	9	0
14	$CDCl_3$	4.8	CD_3OD (0.5 mL)	44	83	17	0
15	CD_2Cl_2	8.9	Dry[c]	22	74	26	0
16	CD_2Cl_2	8.9	H_2O (100 μL)	22	82	18	0
17	CD_2Cl_2	8.9	D_2O (100 μL)	22	100	0	0
18	CH_3CN	37.5	Dry[c]	22	66	34	0
19	CH_3CN	37.5	H_2O (100 μL)	22	70	30	0
20	CH_3CN	37.5	D_2O (100 μL)	22	100	0	0

Condition: [**1**] = 0.72 mM. [b] Dielectric constant. [c] Dry solvents (1 mL ampules) were purchased from Sigma-Aldrich and stored on 4 A sieves in the dry-box for three days before usage.

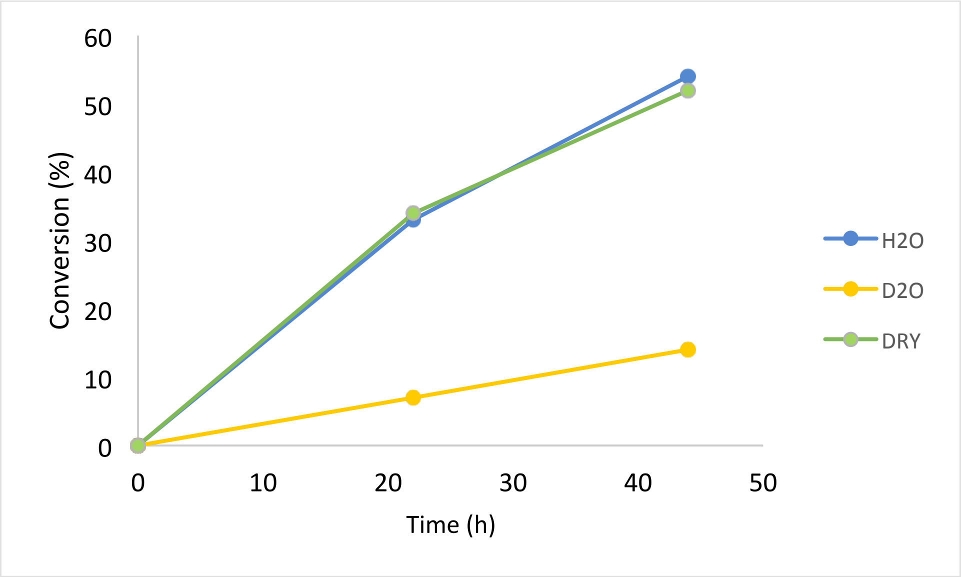


Figure S30. Isomerization of **1** to **2** in dry $CHCl_3$ (green), dry $CHCl_3$ with 10 equiv. H_2O (blue) and dry $CHCl_3$ with 10 equiv. D_2O (orange) Reactions were carried out in the presence of an internal standard (1,3,5-trimethoxybenzene).

X-ray Structure Determinations.[4-7]

Data Collection and Processing. A crystal was mounted on a Mitegen polyimide micromount with a small amount of Paratone N oil. All X-ray measurements were made using a Bruker Kappa Axis Apex2 diffractometer at a temperature of 110 K. The frame integration was performed using SAINT, and the resulting raw data were scaled and absorption corrected using a multiscan averaging of symmetry equivalent data using SADABS.

Structure Solution and Refinement. The structures were solved by using the SHELXT program. All non-hydrogen atoms were obtained from the initial solution. The hydrogen atoms were introduced at idealized positions and were allowed to ride on the parent atom. The structural model was fit to the data using full-matrix least squares based on F^2. The calculated structure factors included corrections for anomalous dispersion from the usual tabulation. The structure was refined using the SHELXL-2014 program from the SHELX suite of crystallographic software.[4-7] Details are given in Table S9 and in CCDC 1811772-1811773.

Table S9. Crystallographic data and parameters for compounds **1**, **2** and **3b**

	1	**2**	**3b**
CCDC	1811772	1811771	1811773
Formula	$C_{22}H_{22}N_2OPd.C_6H_6$	$C_{22}H_{22}N_2OPd.C_6H_6$	$C_{22}H_{22}N_2Pd$
Formula weight	514.92	514.92	420.81
Crystal system	monoclinic	monoclinic	monoclinic
Space group	$P\ 2_1/c$	$P\ 2_1$	P 21/c
a [Å]	6.515(2)	8.509(4)	11.322(4)
b [Å]	18.388(7)	9.397(4)	17.535(5)
c [Å]	18.995(7)	14.443(7)	9.999(2)
α [°]	90	90	90
β [°]	91.858(10)	91.146(17)	112.549(9)
γ [°]	90	90	90
V [Å^3]	2274.4(14)	1154.6(9)	1833.3(9)
Z	4	2	4
ρ_{cal} [g cm^{-3}]	1.504	1.481	1.525
l, Å, (MoKa)	0.71073	0.71073	0.71073
F(000)	1056	528	856
Temperature [K]	110	110	110
θ_{min}, θ_{max} [°]	6.16, 57.24	5.18, 65.18	3.03, 38.30
Total reflns	60652	24450	10890
Unique reflns	5850	3724	9155
R_1	0.0493	0.0372	0.0236
wR_2 [$I \geq 2\sigma(I)$]	0.1046	0.0910	0.0628
R_1 (all data)	0.0952	0.0431	0.0337
wR_2 (all data)	0.1252	0.0948	0.0726
GOF	1.003	1.011	1.095

References

1) A. Marini, A. Muñoz-Losa, A. Biancardi and B. Mennucci, *J. Phys. Chem. B*, 2010, **114**, 17128-17135.
2) N. Chaudhury and R. J. Puddephatt, *J. Organomet. Chem.*, 1975, **84**, 105-115.
3) T. Yamamoto, A. Yamamoto and S. Ikeda, *J. Am. Chem. Soc.*, 1971, **93**, 3350-3359.
4) SAINT version 2013.8; Bruker-AXS, Madison, WI 53711, USA, **2013**.

5) SADABS version 2012.1; Bruker-AXS, Madison, WI53711, USA, 2012.
6) G. M. Sheldrick. *Acta Crystallogr., Sect. A: Found. Adv*. **2015**, 71, 3.
7) G. M. Sheldrick. *Acta Crystallogr., Sect. C: Struct. Chem.* **2015**, 71, 3.