Efficient Nickel Catalyst For Coupling Of Acetonitrile With Aldehydes

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Electronic Supplementary Information

Experimental

General considerations. Unless specified otherwise, all manipulations were performed under an argon atmosphere using standard Schlenk line or glovebox techniques. Ethyl ether, C_6D_6, THF, triethylamine and pentane were dried over NaK/Ph$_2$CO/18-crown-6, distilled or vacuum transferred and stored over molecular sieves in an Ar-filled glovebox. Fluorobenzene and acetonitrile were dried with and then distilled or vacuum transferred from CaH$_2$. Chlorodiisopropylphosphine (Aldrich) was vacuum transferred, leaving a small amount of yellow oil behind. (PNP)NiH (**2-Ni**),[1] (PNP)PtH (**2-Pt**),[1] and (PNP)PdOTf (**3-Pd**)[2] were prepared according to modified published procedures. All aldehydes and DBU were degassed and dried over 4A molecular sieves. All other chemicals were used as received from commercial vendors. NMR spectra were recorded on a Varian iNova 400 (^{1}H NMR, 399.755 MHz; ^{13}C NMR, 100.518 MHz; ^{31}P NMR, 161.822 MHz) spectrometer. Chemical shifts are reported in δ (ppm). For ^{1}H and ^{13}C NMR spectra, the residual solvent peak was used as an internal reference. ^{31}P NMR spectra were referenced externally using 85 % H$_3$PO$_4$ at δ 0 ppm. ^{19}F NMR spectra were referenced externally using CF$_3$CO$_2$H at δ -78.5 ppm. Elemental analyses were performed by CALI, Inc. (Parsippany, NJ).

(PNP)NiOTf (3-Ni). (PNP)NiH (**2-Ni**) (196 mg, 0.40 mmol) was dissolved in 10 mL C_6H_6, followed by the addition of MeOTf (113 μL, 1.0 mmol). The reaction mixture was stirred at ambient temperature for 12 h, and was changed to dark brown. All of the volatiles were removed in vacuo, and the resulting residue was washed with pentane (2 × 5 mL). All of the volatiles were evaporated, and orange solids were obtained. Yield: 228 mg (89%). ^{1}H NMR (C_6D_6): δ 7.26 (d, 2H, J = 8 Hz), 6.88 (s, 2H), 6.59 (d, 2H, J = 8 Hz), 2.37 (m, 4H), 2.04 (s, 6H), 1.54 (dvt, 12H), 1.18 (dvt, 12H). ^{13}C{^{1}H} NMR (C_6D_6): δ 161.6 (t, J_{C-P} = 11 Hz), 132.4, 131.2, 126.2, 118.8 (t), 118.1, 24.1 (t, J_{C-P} = 10 Hz), 20.2, 18.7, 17.7. ^{31}P{^{1}H} NMR (C_6D_6): δ 37.2. ^{19}F NMR (C_6D_6): δ -80.1. Anal. Calcd. For $C_{27}H_{40}P_2NNiSO_3F_3$: C, 50.96; H, 6.34. Found: C, 50.74; H, 6.31.

(PNP)PtOTf (3-Pt). (PNP)PtH (**2-Pt**) (25 mg, 0.04 mmol) was dissolved in 5 mL of C_6H_6, followed by the addition of MeOTf (23 μL, 0.20 mmol). The reaction mixture was stirred at ambient temperature for 2 h, and the color changed to orange. All of the volatiles were removed in vacuo, and the resulting residue was washed by pentane (2 × 3 mL). Pure red orange solid was obtained by recrystallization from a toluene/ pentane mixture. Yield: 27 mg (89 %). ^{1}H NMR (C_6D_6): δ 7.58 (d, 2H), 6.84 (s, 2H), 6.62 (d, 2H), 2.67 (m, 4H), 2.08 (s, 6H), 1.35 (dvt, 12H), 1.04 (dvt, 12H). ^{13}C{^{1}H} NMR (C_6D_6): δ 161.9 (t), 132.4, 118.8 (t), 116.6, 25.1 (t, J_{C-P} = 10 Hz), 20.6, 18.1, 17.6. ^{31}P{^{1}H} NMR (C_6D_6): δ 46.3 (s, J_{P-Pt} = 2708 Hz). ^{19}F NMR (C_6D_6): δ -79.5.

[(PNP)Ni(DBU)][+]OTf[-] (6). (PNP)NiOTf (**3-Ni**) (38 mg, 0.06 mmol) was dissolved in 5 mL of C_6H_6, followed by the addition of DBU (0.20 mL in 0.4M pentane solution) and the color changed to yellow green immediately. It was allowed to stir at ambient temperature for 10 min, and all of the volatiles were removed in vacuo. Yellow-green

solid was obtained after recrystallization from a fluorobenzene/pentane mixture. ^{1}H NMR (CD$_3$Cl$_3$): δ 6.97 (d, 2H, J = 8.8 Hz), 6.82 (s, 2H,), 6.77 (d, 2H, J = 8.8 Hz), 3.53 (m, 4H, DBU), 3.35 (m, 4H, DBU), 2.44 (m, 2H, CHMe$_2$), 2.33 (m, 2H, CHMe$_2$), 2.19 (s, 6H, Ar-CH_3), 1.87 (m, 2H, DBU), 1.77 (m, 4H, DBU), 1.62 (m, 2H, DBU), 1.41 (two broad apparent quartets overlapping, 12H, CHMe_2), 1.29 (two broad apparent quartets overlapping, 12H, CHMe_2). ^{31}P{^{1}H} NMR (CD$_2$Cl$_2$): δ 35.6. ^{19}F NMR (CD$_2$Cl$_2$): δ -79.9.

[(PNP)Ni(NCCH$_3$)]$^+$OTf (7). (PNP)NiOTf (**3-Ni**) (121 mg, 0.20 mmol) was dissolved in 5 mL of CH$_3$CN, and the color changed to green immediately. All of the volatiles were removed in vacuo and green solid was obtained, which was than washed with pentane (2 × 5 mL) and dried in vacuo. Yield: 119 mg (92%). ^{1}H NMR (C$_6$D$_6$): δ 7.27 (d, 2H, J = 7.8 Hz), 6.84 (s, 2H), 6.65 (d, 2H, J = 8 Hz), 2.69 (s, 3H), 2.36 (m, 4H), 2.06 (s, 6H), 1.39 (dvt, 12H), 1.17 (dvt, 12H). ^{13}C{^{1}H} NMR (C$_6$D$_6$): δ 161.9 (t, J = 12 Hz), 138.8, 133.3, 132.3, 127.3, 117.6 (t, J = 22 Hz), 117.2, 24.3 (t, J_{C-P} = 10 Hz), 20.4, 18.7, 17.9, 5.0. ^{31}P{^{1}H} NMR (C$_6$D$_6$): δ 51.3. ^{19}F NMR (C$_6$D$_6$): δ -79.9. Anal. Calcd. for C$_{29}$H$_{43}$P$_2$N$_2$NiSO$_3$F$_3$: C, 51.42; H, 6.40; N, 4.14. Found: C, 51.59; H, 6.43; N, 4.18.

(PNP)NiCH$_2$CN (10). Method 1. CH$_3$CN (17 μL, 0.31 mmol) was dissolved in 5 mL of THF, followed by the addition of *n*-butyllithium (96 μL of 2.5 M solution in hexanes, 0.24 mmol). The solution was stirred at ambient temperature for 15 min, and then (PNP)NiCl (**1-Ni**) (126 mg, 0.24 mmol) was added. The solution color changed to red immediately, and it was allowed to stir for 2 h. The volatiles were removed in vacuo, and the residue was redissolved in fluorobenzene. The mixture was filtered through Celite, and the filtrate was collected. Evaporation of solvents gave a red solid. Pure compound

was obtained via recrystallization from a toluene/pentane mixture at -35°C. Yield: 112

mg (88%). ^{1}H NMR (C_6D_6): δ 7.53 (d, 2H, J = 8 Hz), 6.84 (s, 2H), 6.75 (d, 2H, J = 8

Hz), 2.18 (m, 4H), 2.15 (s, 6H), 1.33 (dvt, 12H), 1.05 (dvt, 12H), 0.68 (t, J = 11Hz, 2H).

^{13}C{^{1}H} NMR (C_6D_6): δ 161.8 (t, J = 13 Hz), 132.5, 131.8, 126.5, 124.6, 117.8 (t, J = 20

Hz), 115.8, 23.6 (t, J_{C-P} = 10 Hz), 20.5, 18.7, 17.5. ^{31}P{^{1}H} NMR (C_6D_6): δ 36.6.

Method 2. (PNP)NiOTf (**3-Ni**, 25 mg, 0.04 mmol) was dissolved in 3 ml CH_3CN, and

the solution changed to green immediately. $KN(SiMe_3)_2$ (44 μL of 0.91 M THF solution,

0.04 mmol) was added in, and the color changed to red. It was allowed to stir at ambient

temperature for 30 min, and the solution was filtered through silica gel. All of the

volatiles were removed in vacuo, and dark red solid was obtained. NMR analysis

confirmed that the purity of compound (**10**) was > 95 %.

[DBUH]$^+$OTf⁻.   HOTf (777 mg, 6.93 mmol) was dissolved in 15 mL of CH_2Cl_2, and

DBU (1.07 mL, 6.95 mmol) was added to it. It was stirred at ambient temperature for 30

min, and all of volatiles were evaporated. The resulting oil was washed with pentane (2 ×

3 mL), and dried under vacuum. Colorless oil was obtained. Y ield: 1.65 g (90 %). ^{1}H

NMR (CD_3CN): δ 9.77 (s, 1H), 3.38 (m, 4H), 3.18 (t, 2H, J = 7.2 Hz), 2.49 (m, 2H), 1.87

(m, 2H), 1.65 (m, 6H).

General procedure for the catalytic reaction between acetonitrile and aldehydes.

(PNP)MOTf (**3-Ni**, 6.5 mg, 0.01 mmol; **3-Pd**, 7.0 mg, 0.01 mmol or **3-Pt**, 8.0 mg, 0.01

mmol), aldehyde (0.20 mmol) and DBU (31 μL, 0.20 mmol; 1.5 μL, 0.01 mmol; 3.1 μL,

0.02 mmol; 6.2 μL, 0.04 mmol; 15.5 μL, 0.10 mmol or 62 μL, 0.40 mmol) were mixed in

0.5 mL acetonitrile in a screw-cap NMR tube. 20 μL 1,4-dioxane was introduced as

internal ^{1}H NMR integration standard. The reactants were heated at 45 °C or stirred at

ambient temperature. After 24 h, the reaction mixture was analyzed by ^{1}H NMR. We take a conservative estimate that the uncertainty in the quantification of the yields via integration vs the dioxane standard is 5%.

General procedure for the catalytic reaction between acetonitrile and aldehydes in a smaller volume of CH₃CN (Table 3 in the main text). (PNP)NiOTf (**3-Ni**, 6.5 mg, 0.01 mmol or 13.0 mg, 0.02 mmol), aldehyde (0.20 mmol) and DBU (31 μL, 0.20 mmol) were mixed in 0.1 mL acetonitrile in a screw-cap reaction tube. 20 μL 1, 4- dioxane was introduced as internal ^{1}H NMR integration standard. The reactants were heated at 45 °C. After 24 h, the reaction mixture was analyzed by ^{1}H NMR.

The NMR data for compounds **5a**,[3] **5b**,[4] **5d**,[5] **5e**,[3] **5f**,[6] **5h**,[7] **5i**,[4] **5j**,[8] **5k**,[4] and **5n**[9] were in agreement with that reported in the literature.

3-hydroxy-3-(2,4-dichlorophenyl)propanenitrile (5c). ^{1}H NMR (CDCl$_3$): 7.70 (d, 1H), 7.26 (m, 2H), 5.20 (m, 1H), 2.68 (m, 2H). ^{13}C{^{1}H} NMR: 138.3, 133.5, 131.3, 128.6, 128.4, 127.2, 64.4, 28.7. GC-MS: 217 (M$^+$-1, ^{37}Cl/^{35}Cl), 215 (M$^+$-1, ^{35}Cl/^{35}Cl), 175, 147, 111, 75.

3-hydroxy-3-(4-trifluorophenyl)propanenitrile (5g). ^{1}H NMR (CDCl$_3$): 7.51 (m, 4H), 4.95 (m, 1H), 2.66 (d, 2H, J = 6.4 Hz). ^{13}C{^{1}H} NMR: 147.2, 129.5, 126.0, 125.1(q), 117.6, 67.9, 28.0. GC-MS: 215 (M$^+$), 196, 175, 145, 127.

3-hydroxy-3-(2,6-dichloro)propanenitrile (5l). ^{1}H NMR (CDCl$_3$): 7.32 (t, 1H, J = 6.4 Hz), 6.99 (t, 2H, J = 7.2 Hz), 4.91 (m, 1H), 2.66 (d, 2H, J = 5.6 Hz). ^{13}C {^{1}H} NMR: 137.7, 131.8, 127.0, 126.9, 117.3, 67.9, 28.8. GC-MS: 217 (M$^+$-1, ^{37}Cl/^{35}Cl), 215 (M$^+$-1, ^{35}Cl/^{35}Cl), 175, 139, 111, 75.

3-hydroxy-3-(2,6-dimethyl)propanenitrile (5m). ^{1}H NMR (CDCl$_3$): 6.97 (t, 1H, J = 6.8 Hz), 6.91 (t, 2H, J = 7.2 Hz), 5.40 (t, 1H, J = 7Hz), 2.66 (d, 2H, J = 5.6 Hz), 2.27 (s, 6H). ^{13}C {^{1}H} NMR: 135.8, 132.2, 129.2, 127.2, 117.6, 65.8, 29.5, 22.1. GC-MS: 175 (M$^+$), 157, 135, 107, 91, 77.

Side-products. The major side product in the reactions of RCHO is *trans*-R-CH=CH-CN, formally from the dehydration of **5**. It is generally distinguished by a doublet in the olefinic region of the ^{1}H NMR spectrum with a typical *trans*-$^3J_{HH}$ of ca. 16 Hz (the other doublet may be observed or obscured by the aromatic signals). For p-FC$_6$H$_4$CHO and p-MeC$_6$H$_4$CHO, these products were identified by comparison with the data from the literature.[10]

Initial rate Kinetic Studies.

General note. The kinetic studies presented here are intended to answer several questions about the rate law in a *qualitative* way.

Dependence on DBU. In four J. Young tubes, (PNP)NiOTf (**3-Ni**) (6.5 mg, 0.01 mmol), 4-fluorobenzaldehyde (21 µL, 0.20 mmol), fluorobenzene (10 µL) and different amounts of DBU (3.1 µL, 0.02 mmol; 6.2 µL, 0.04 mmol; 15.5 µL, 0.10 mmol; 31 µL, 0.20 mmol) were dissolved in 0.5 mL of CH_3CN. These solutions were stored frozen in Dry Ice/acetone until retrieved to perform VT NMR kinetic studies. Standard deviations for the determination of rate constants were obtained from the linear regression analysis by Microsoft Excel. Temperature was measured using the ethylene glycol chemical shift thermometer (T = 41.8 ± 0.5 ºC). At low conversion, it may be assumed that the rate law is pseudo-first order: $d[ArCHO]/dt = k_{app}$ or $d[ArCHO] = k_{app} \times dt$

Performing a series of low conversion experiments with different values of [DBU] permits the determination of the contribution of the [DBU] term to k_{app}. $k_{app} = k^*_{app} \times [DBU]^m$. Plotting $\ln(k_{app})$ vs $\ln[DBU]$ provides **m = 0.46(10)** as the slope.
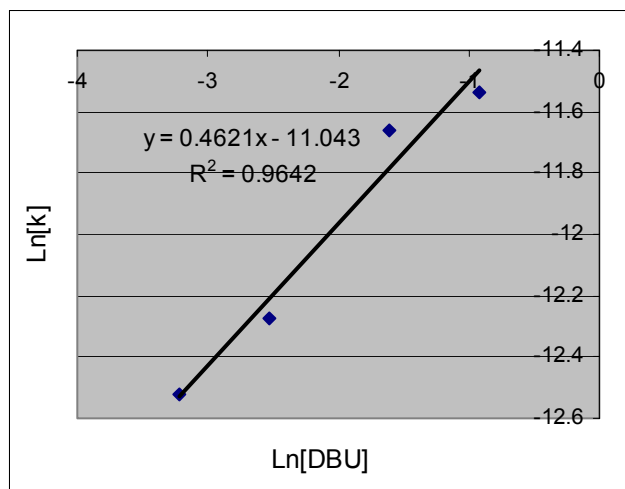
[DBU], mol %	k_{app} (s^{-1})	R^2
10%	3.64 (2)$\times 10^{-6}$	0.998
20%	4.67 (2) $\times 10^{-6}$	0.998
50%	8.61 (3) $\times 10^{-6}$	0.999
100%	9.8 (6) $\times 10^{-6}$	0.996

10% DBU
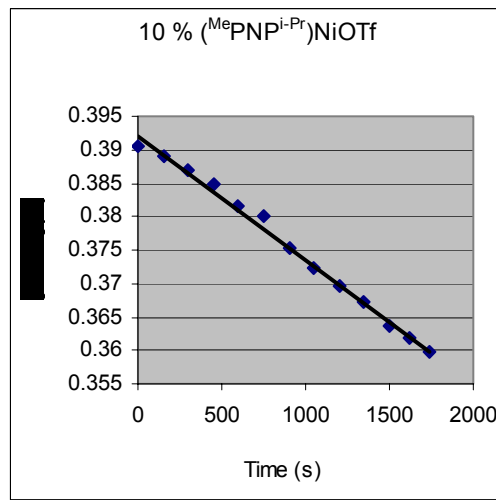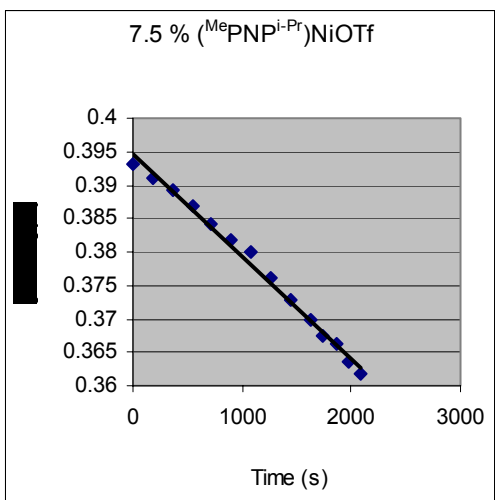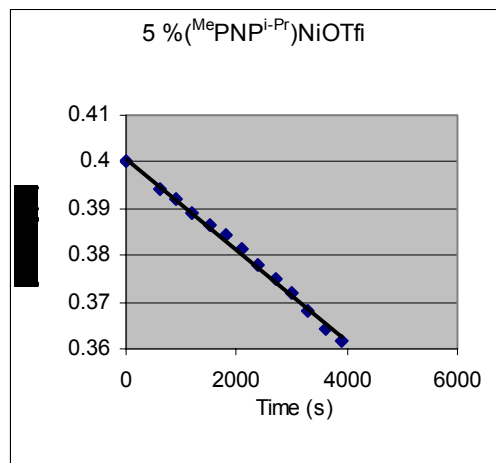
20% DBU
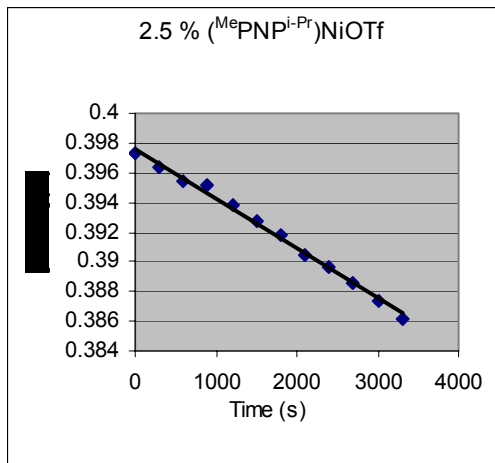
50% DBU

100% DBU
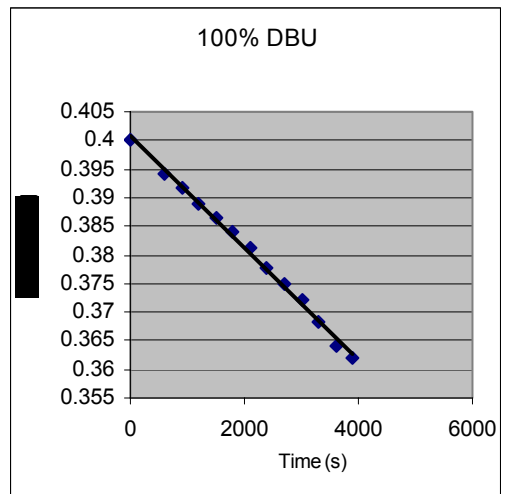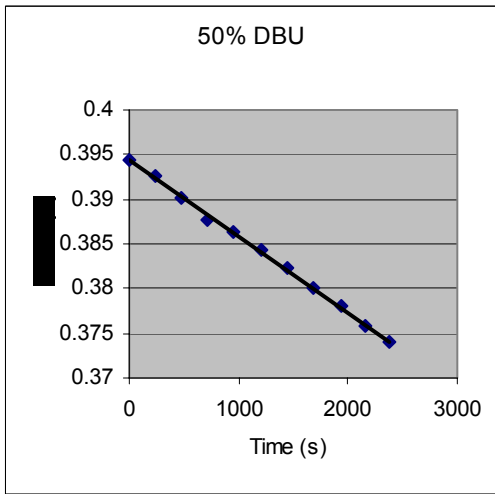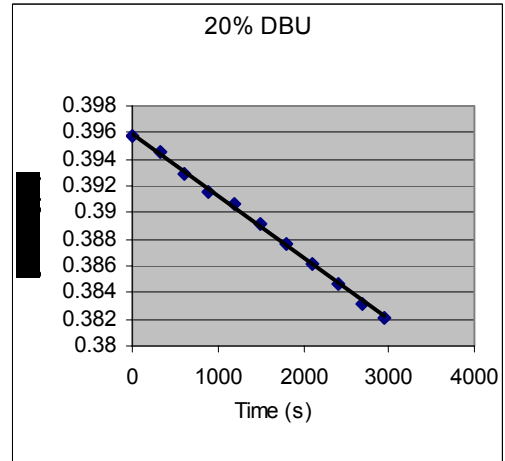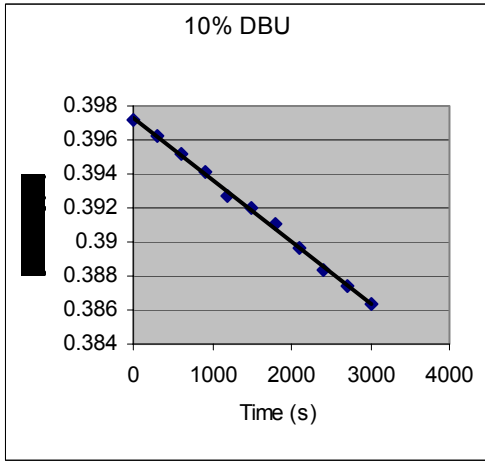
Dependence on (PNP)NiOTf (3-Ni).   In six different J. Young tubes, different amount of (PNP)NiOTf (**3-Ni**) (3.3 mg, 2.5%; 6.5 mg, 5%; 9.8 mg, 7.5%; 13 mg, 10%; 16.3 mg, 12.5%; 26 mg, 20%), 4-fluorobenzaldehyde (21 µL, 0.20 mmol), fluorobenzene (10 µL) and DBU (31 µL, 0.20 mmol) were dissolved in 0.5 mL of CH_3CN.   These solutions were stored frozen in Dry Ice/acetone until retrieved to perform VT NMR kinetic studies. Standard deviations for the determination of rate constants were obtained from the linear regression analysis by Microsoft Excel. Temperature was measured using the ethylene glycol chemical shift thermometer (T = 41.8 ± 0.5 ºC). At low conversion, it may be assumed that the rate law is pseudo-first order: $d[ArCHO]/dt = k_{app}$ or $d[ArCHO] = k_{app} \times dt$. Performing a series of low conversion experiments with different values of [**3-Ni**] permits the determination of the contribution of the [**3-Ni**] term to k_{app}. $k_{app} = k^*_{app} \times [\textbf{3-Ni}]^n$. Plotting $\ln(k_{app})$ vs $\ln[\textbf{3-Ni}]$ provides **n** = 1.07(10) as the slope, or effectively a first order dependence on [**3-Ni**].
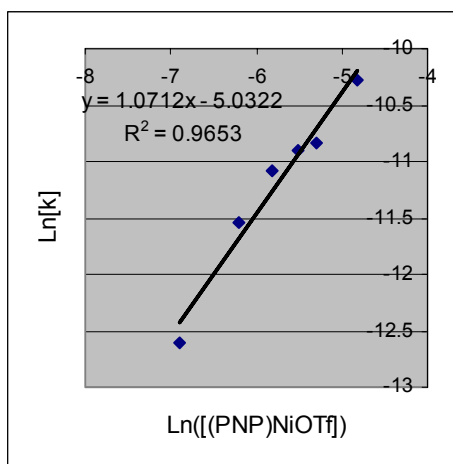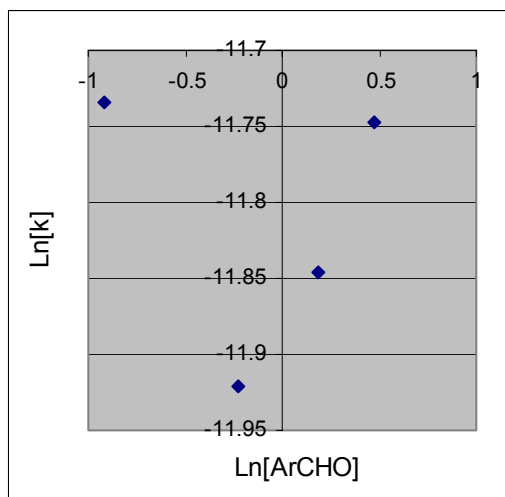

[3-Ni], (mol %)	k_{app} (s^{-1})	R^2
2.5 %	3.4 (2) × 10^{-6}	0.995
5 %	9.8 (6) × 10^{-6}	0.996
7.5 %	1.54 (10) × 10^{-5}	0.994
10 %	1.85 (12)× 10^{-5}	0.994
12.5 %	1.96 (8) × 10^{-5}	0.998

20 %	$3.43\,(15) \times 10^{-5}$	0.998

2.5 % (^{Me}PNP$^{i\text{-}Pr}$)NiOTf

5 %(^{Me}PNP$^{i\text{-}Pr}$)NiOTfi

7.5 % (^{Me}PNP$^{i\text{-}Pr}$)NiOTf

10 % (^{Me}PNP$^{i\text{-}Pr}$)NiOTf

### 12.5 % (^{Me}PNP$^{i\text{-}Pr}$)NiOTf

20 % (^{Me}PNP$^{i\text{-}Pr}$)NiOTf
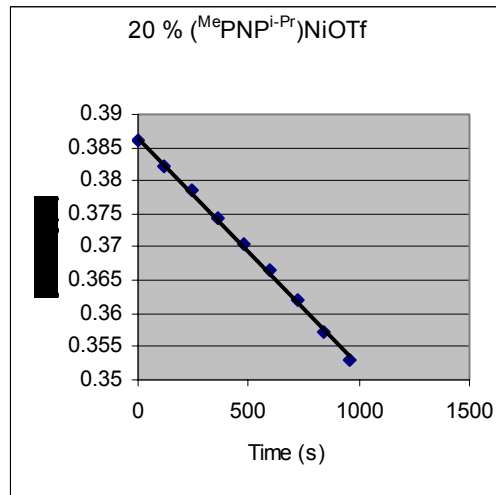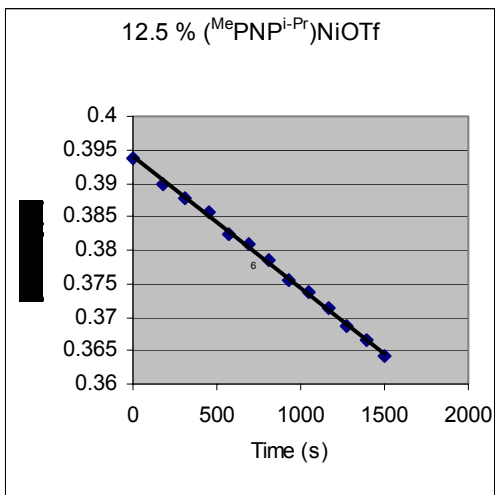
Dependence on [ArCHO]. In four different J. Young tubes, (PNP)NiOTf (**3-Ni**) (100 μL of 0.1 M CH_3CN solution, 0.010 mmol), different amounts of 4-fluorobenzaldehyde (21 μL, 0.20 mmol; 42 μL, 0.40 mmol; 63 μL, 0.60 mmol; 84 μL, 0.80 mmol), fluorobenzene (10 μL) and DBU (31 μL, 0.2 mmol) were dissolved in 0.5 mL of CH_3CN. These solutions were stored frozen in Dry Ice/acetone until retrieved to perform VT NMR kinetic studies. Standard deviations for the determination of rate constants were obtained from the linear regression analysis by Microsoft Excel. Temperature was measured using the ethylene glycol chemical shift thermometer and it was determined as $T = 41.8 \pm 0.5$ ºC. At low conversion, it may be assumed that the rate law is pseudo-first order: $d[\mathbf{ArCHO}]/d\mathbf{t} = \mathbf{k_{app}}$ or $d[\mathbf{ArCHO}] = \mathbf{k_{app}} \times d\mathbf{t}$. Performing a series of low conversion experiments with different values of [ArCHO] permits the determination of the contribution of the [ArCHO] term to k_{app}. $k_{app} = k*_{app} \times [ArCHO]^p$. Plotting $ln(k_{app})$ vs $ln[\mathbf{3\text{-}Ni}]$ results in effectively $p = 0$.

| [ArCHO], (mol %)	k_{app} (s^{-1})	R^2
100 %	8.0 (5) × 10^{-6}	0.996
200 %	6.7 (5) × 10^{-6}	0.995
300 %	7.2 (6) × 10^{-6}	0.997
400 %	7.9 (7) × 10^{-6}	0.996

1eq aldehyde

2eq aldehyde

3eq aldehyde
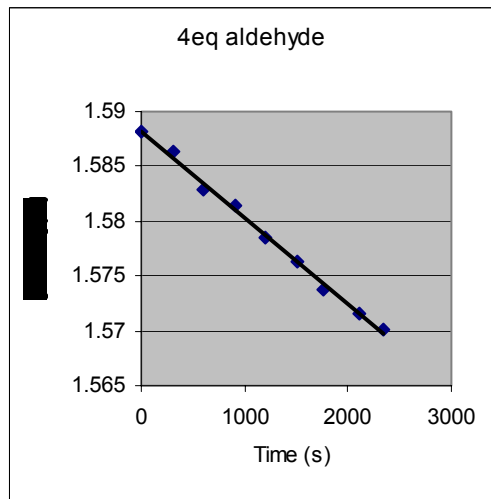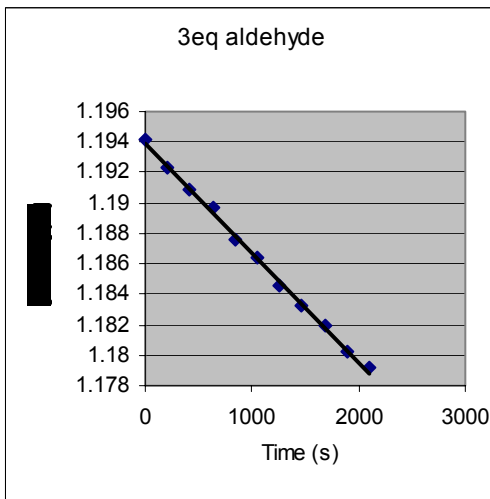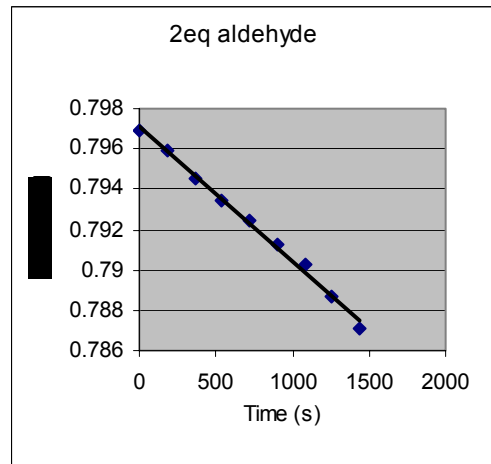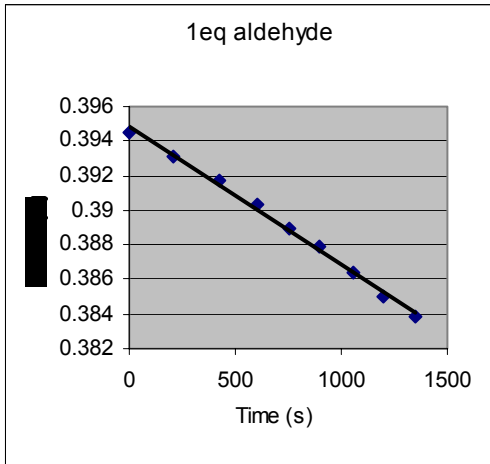
4eq aldehyde

Kinetic isotope effect study. In one J. Young tube, (PNP)NiOTf (**3-Ni**) (6.5 mg, 0.01 mmol), 4-fluorobenzaldehyde (21 μL, 0.20 mmol), fluorobenzene (10 μL) and DBU (31 μL, 0.20 mmol) were dissolved in 0.5 mL of CH_3CN. In another J. Young tube, the same amounts of **3-Ni**, 4-fluorobenzaldehyde, fluorobenzene and DBU were dissolved in 0.5 mL of CD_3CN. These solutions were stored frozen in Dry Ice/acetone until retrieved to perform VT NMR kinetic studies. Standard deviations for the determination of rate constants were obtained from the linear regression analysis by Microsoft Excel. Temperature was measured using the ethylene glycol chemical shift thermometer, and it was determined that T = 41.8 ± 0.5 ºC. At low conversion, it may be assumed that the rate law is pseudo-first order: $d[\text{ArCHO}]/dt = k_{app}$ or $d[\text{ArCHO}] = k_{app} \times dt$. Performing two low conversion experiments, one with CH_3CN, the other with CD_3CN, results in two apparent rate constants. The kinetic isotope effect (KIE) is then defined as k^H_{app}/k^D_{app}. In this case, $k^H_{app} = 9.9(4) \times 10^{-6}$; $k^D_{app} = 8.8(3) \times 10^{-6}$; KIE = 1.13(9).
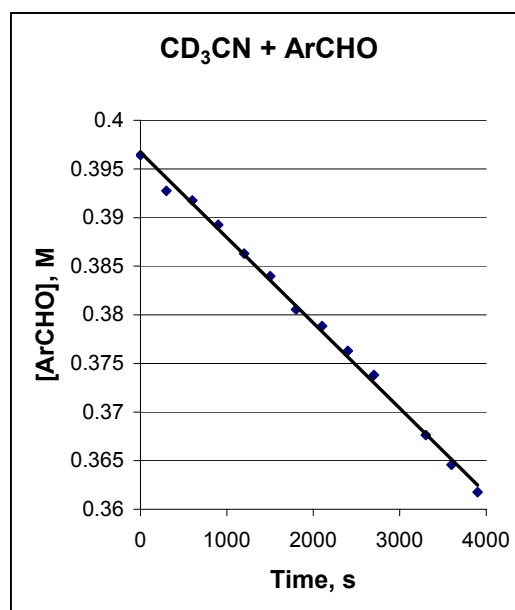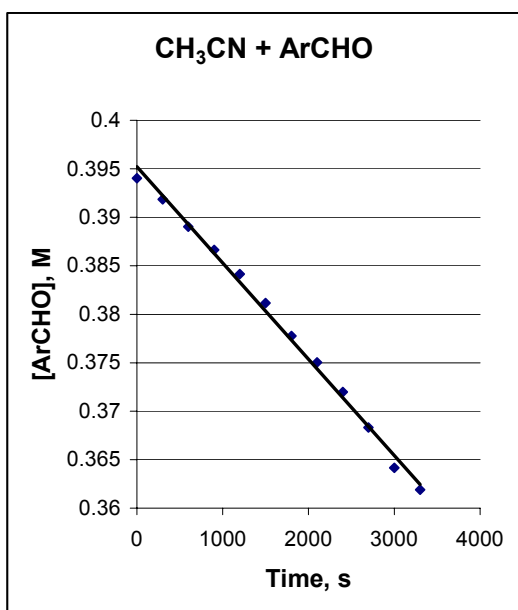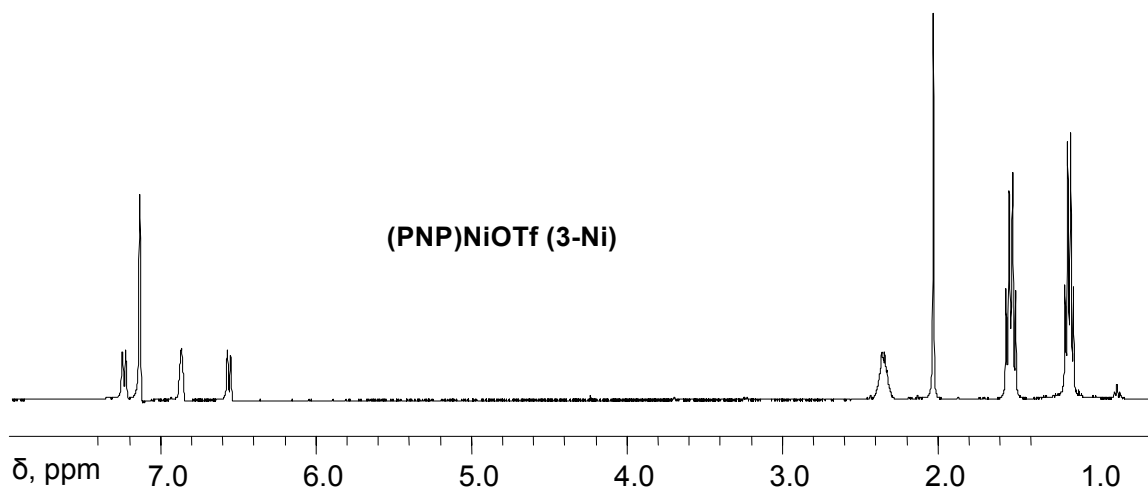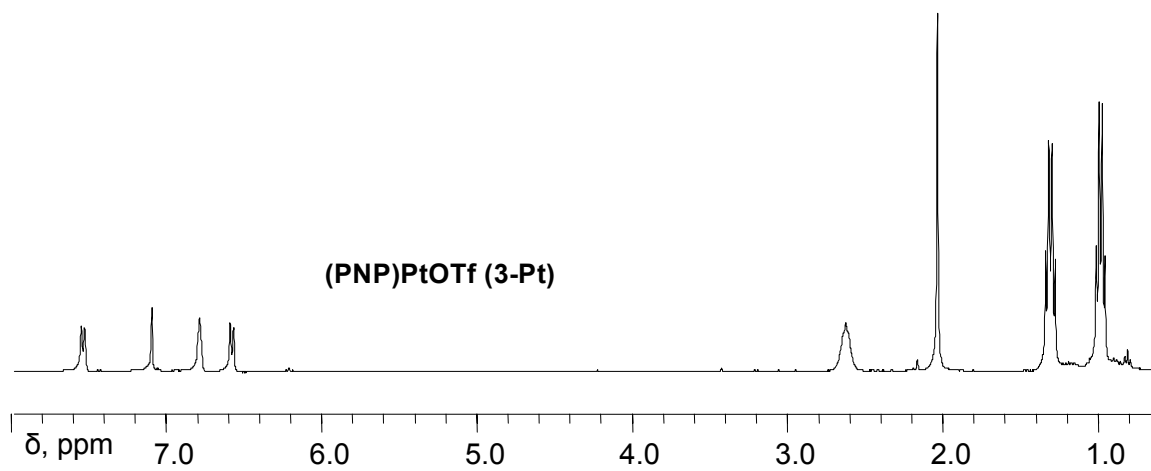
Figure S1. ^{1}H NMR spectrum of compound **3-Ni** in C_6D_6.
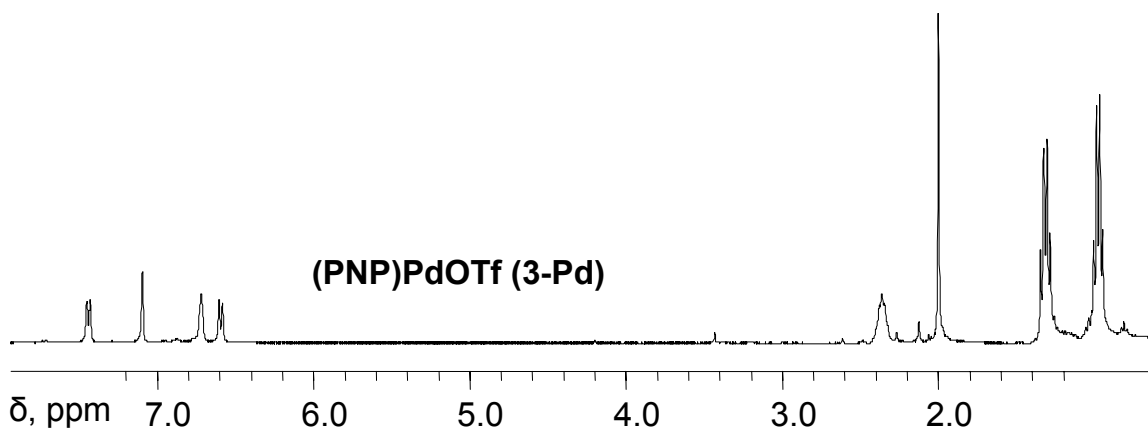
Figure S2. ^{1}H NMR spectrum of compound **3-Pd** in C_6D_6.

(PNP)PtOTf (3-Pt)
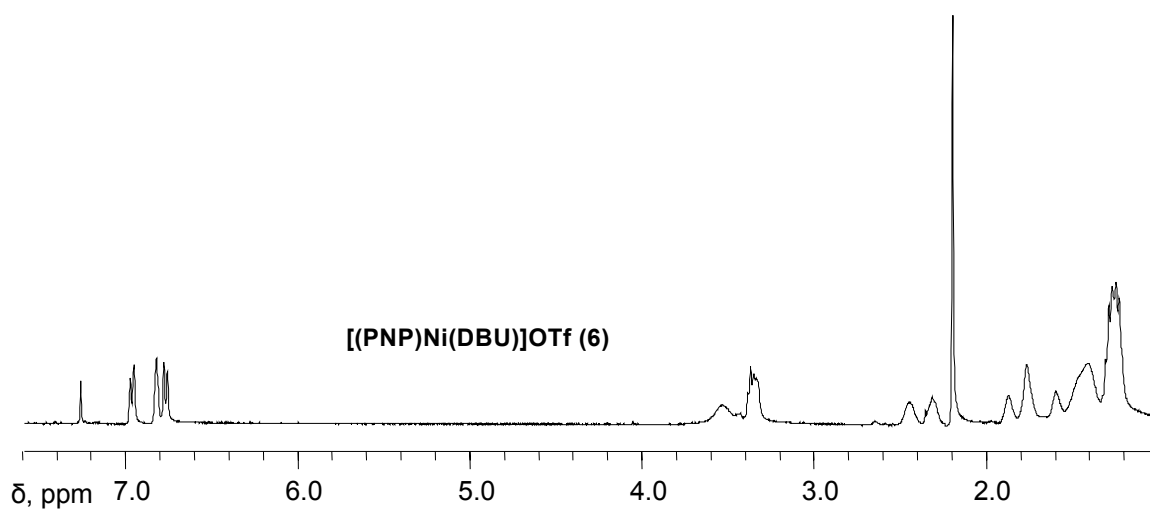
Figure S3. ^{1}H NMR spectrum of compound **3-Pt** in C$_6$D$_6$.
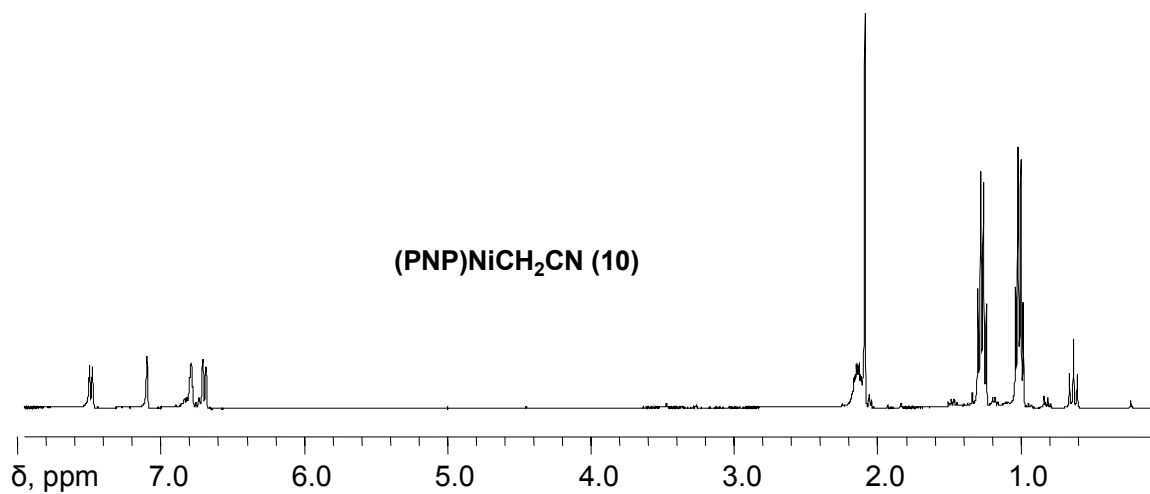
Figure S4. ^{1}H NMR spectrum of compound **10** in C_6D_6.

Figure S5. ^{1}H NMR spectrum of compound **6** in $CDCl_3$.

Supporting Information References

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