Palladium PEPPSI-IPr Complex Supported on a Calix[8]arene: a New Catalyst for Efficient Suzuki-Miyaura Coupling of Aryl Chlorides

Axel Labattut,[1] Ibrahim Abdellah, [1*] Julien Buendia,[2] Sandra Abi Fayssal,[1,2] Erika Adhel,[1] Diana Dragoe,[1] Cyril Martini,[2] Emmanuelle Schulz[1], Vincent Huc[1*]

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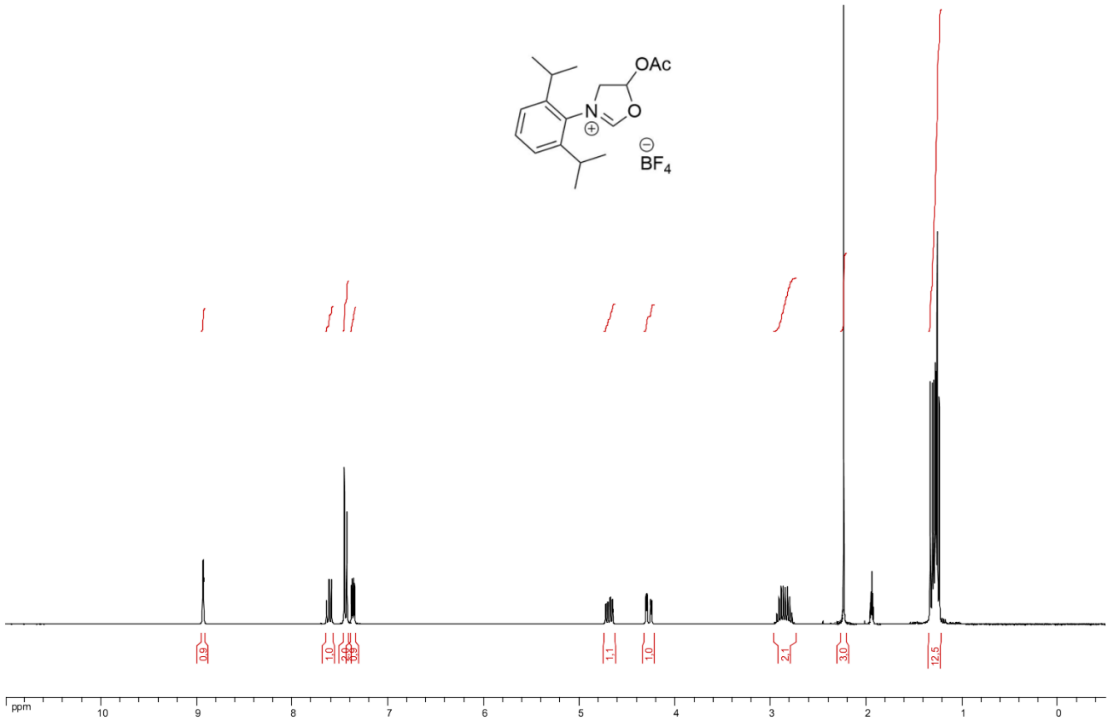
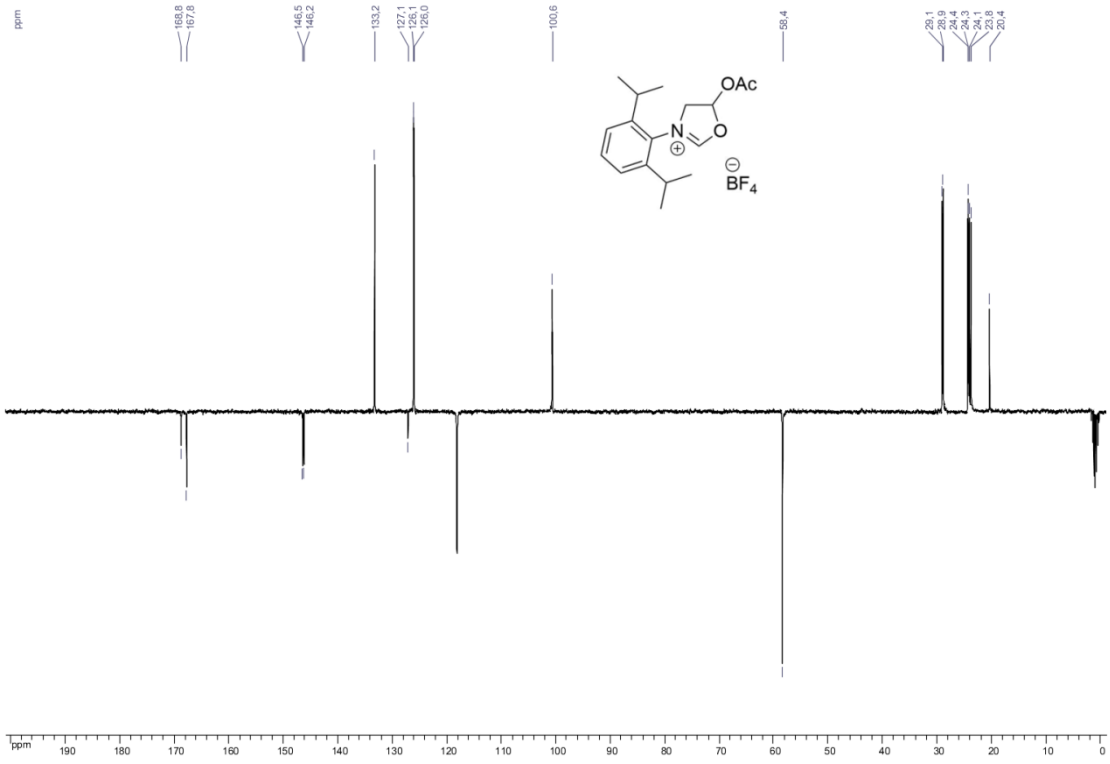
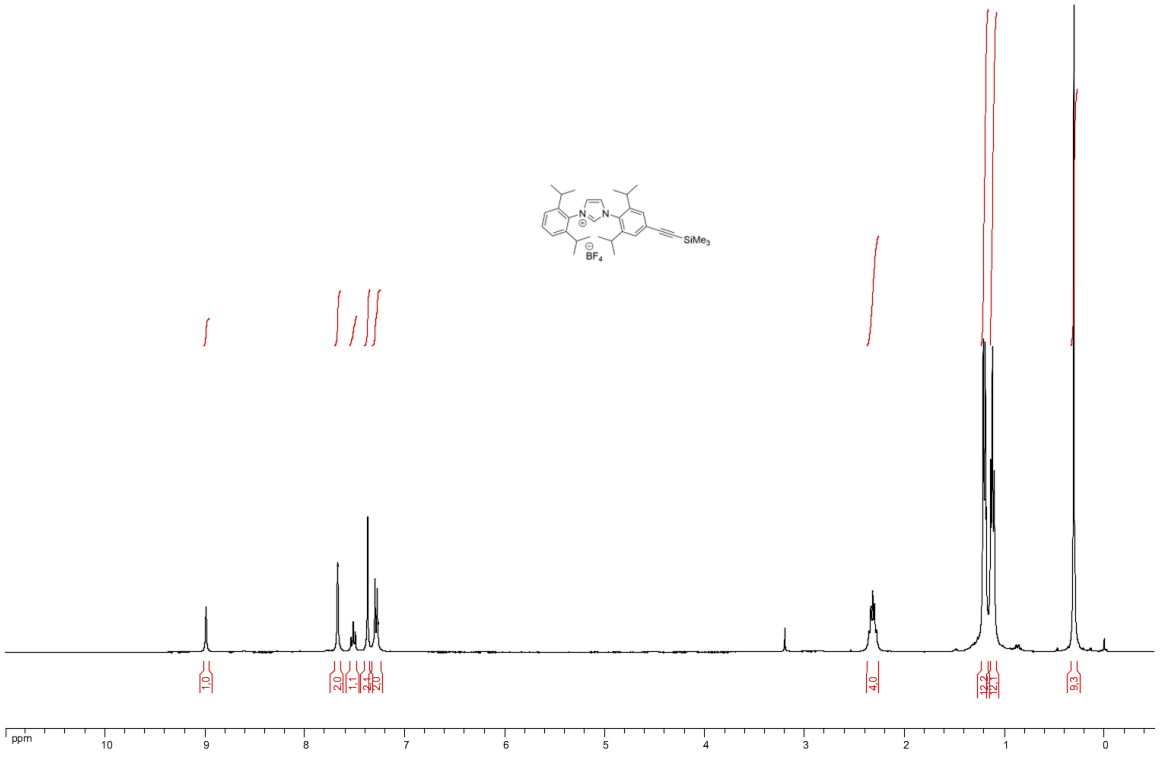
I. Copy of NMR spectra of compounds 1 to 5

Compound 1





Compound 3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7
6
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3
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1
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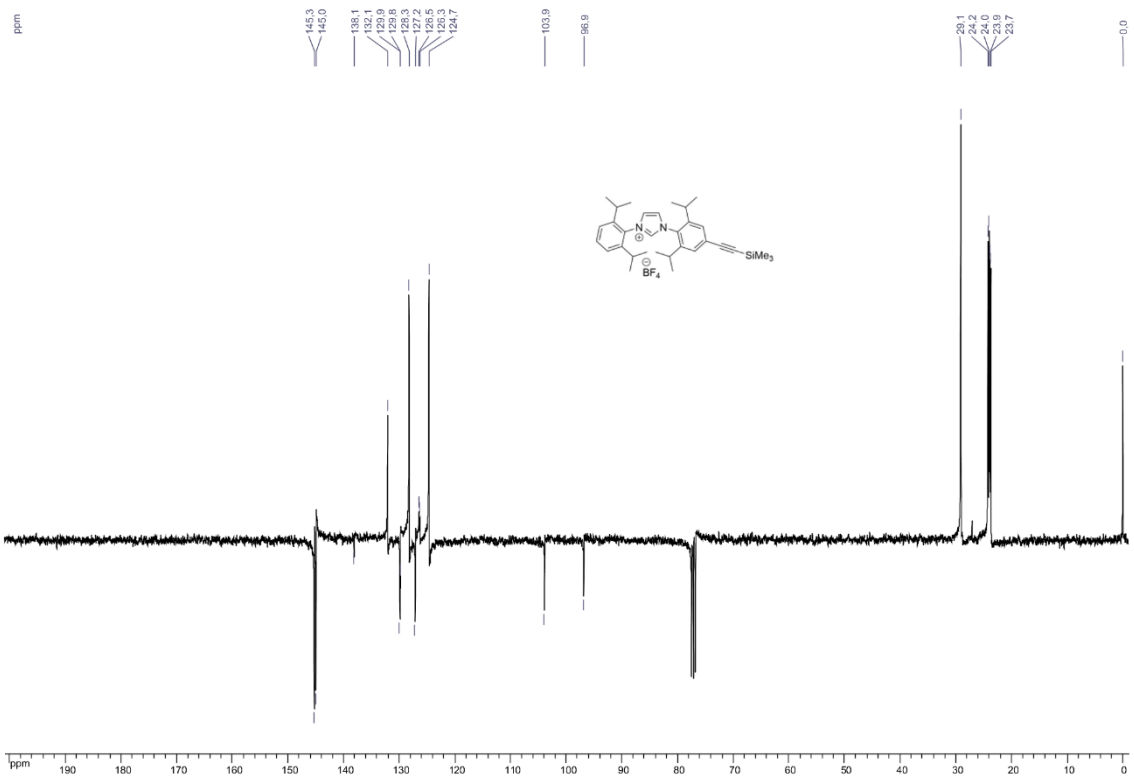
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29.1
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23.9
23.7
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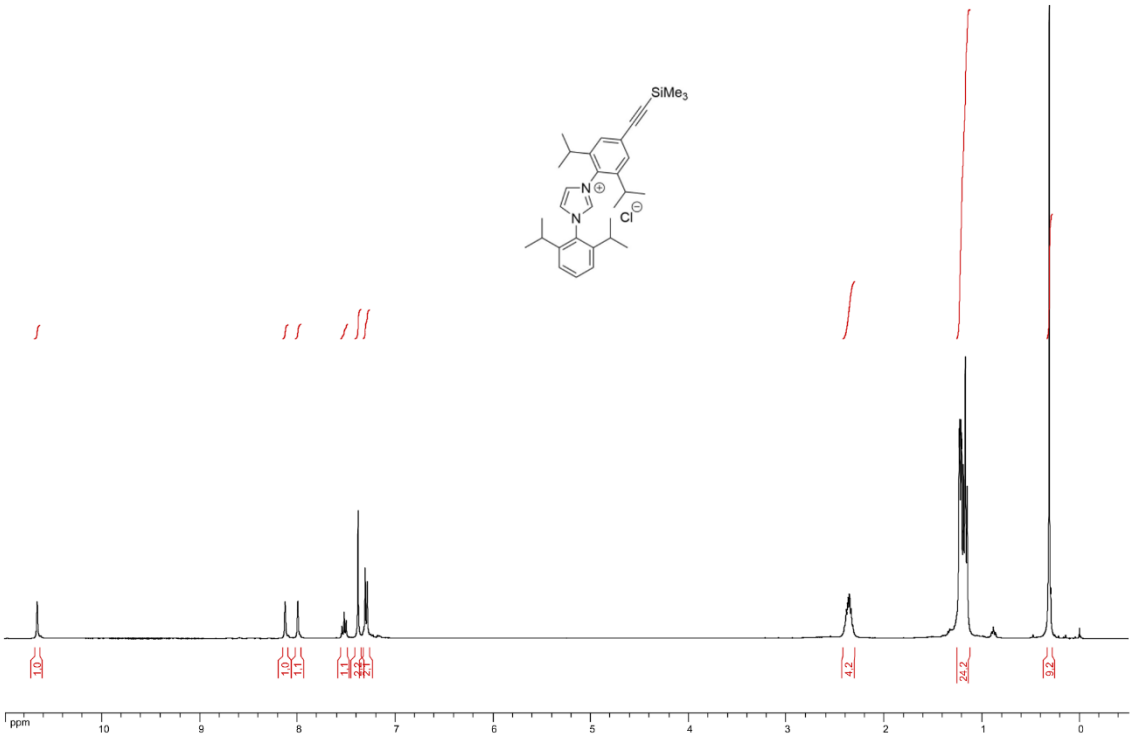
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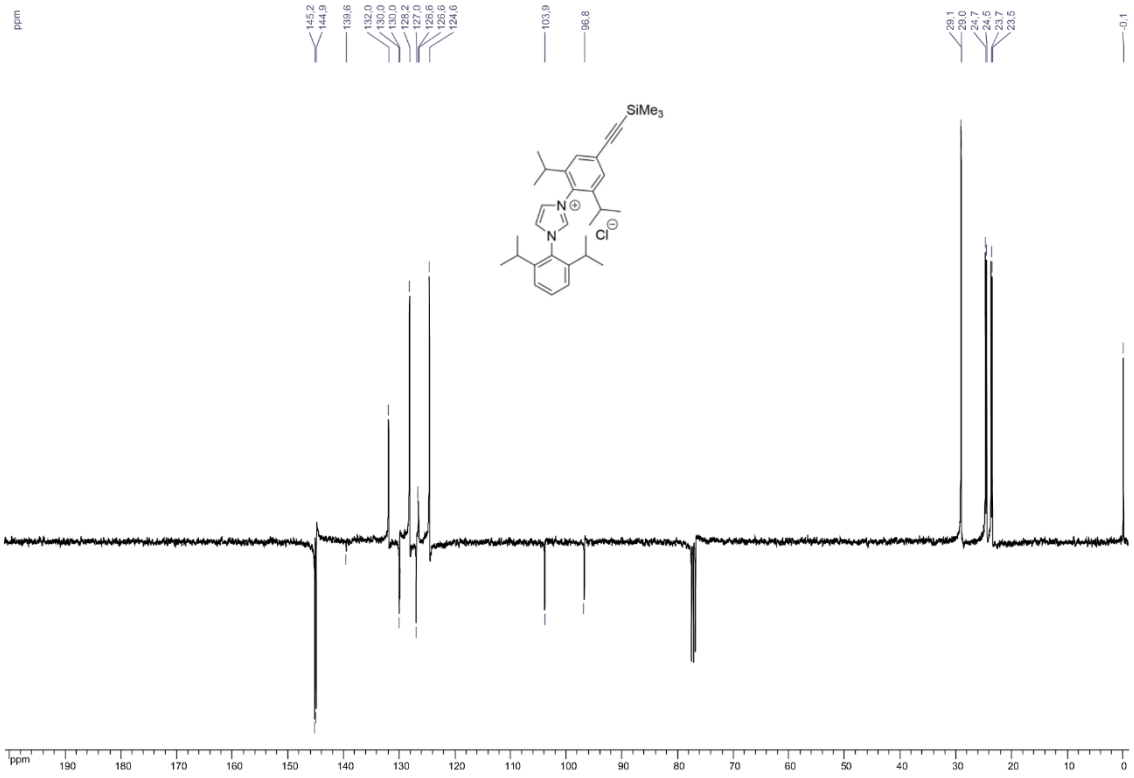
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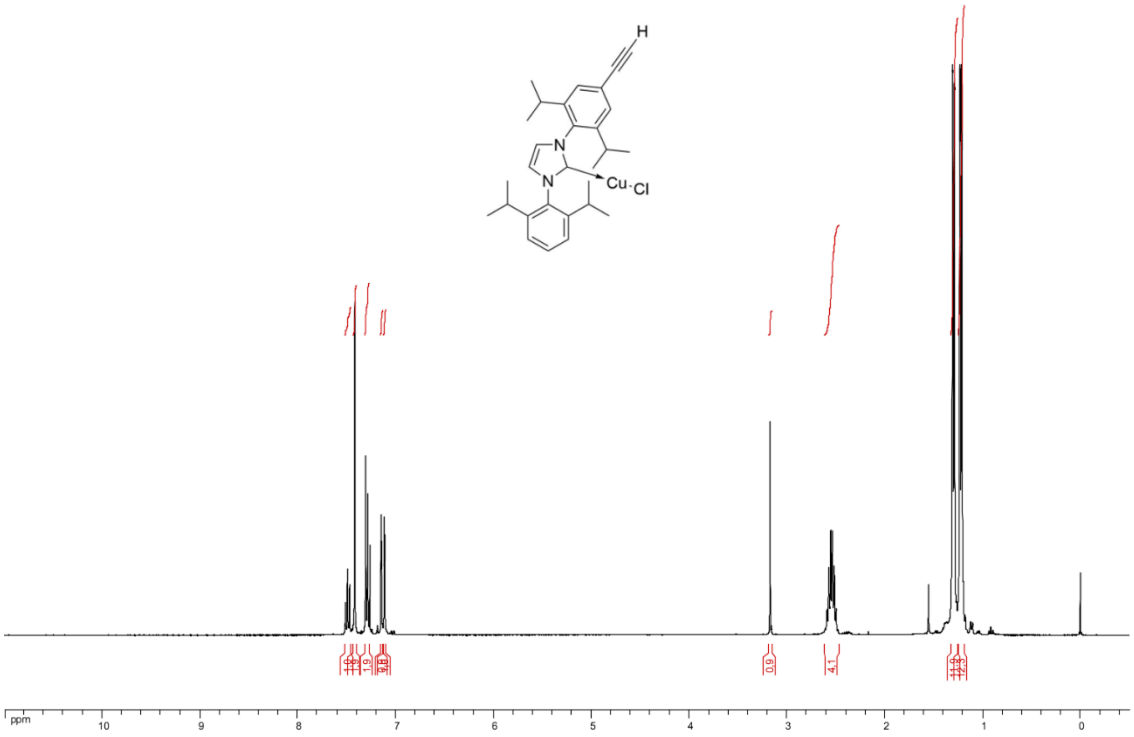
Compound 5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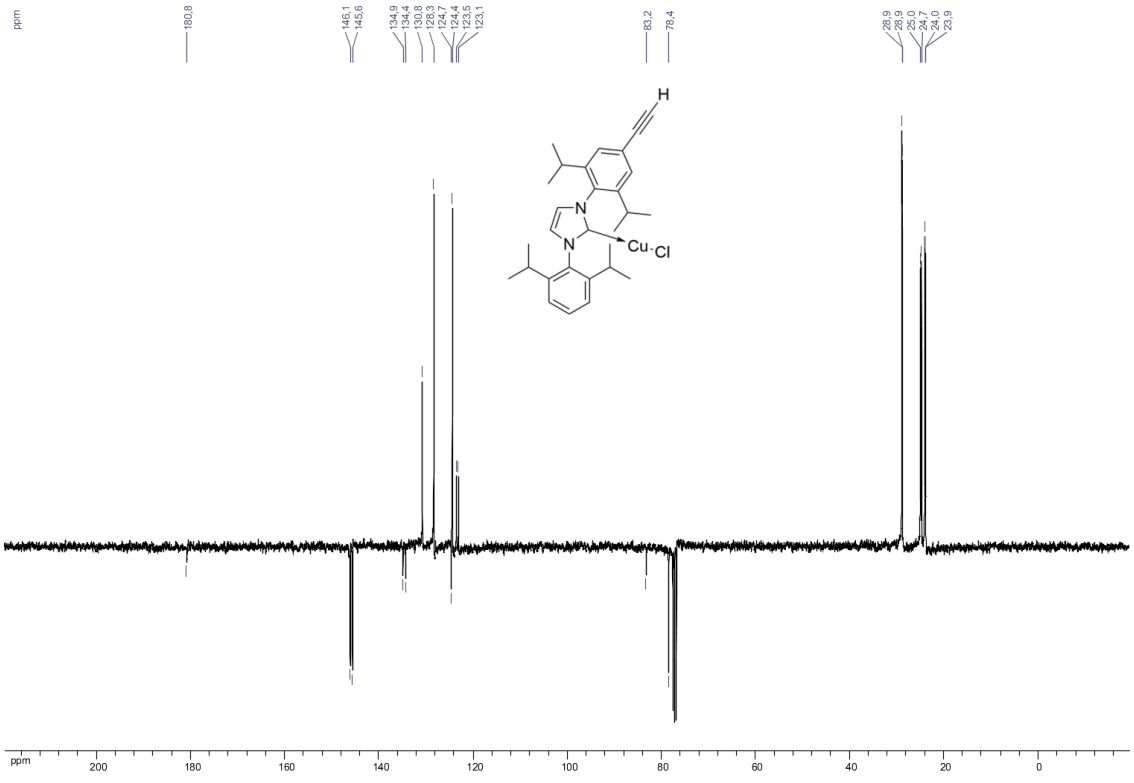
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H
N
N
Cu·Cl
ppm
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20
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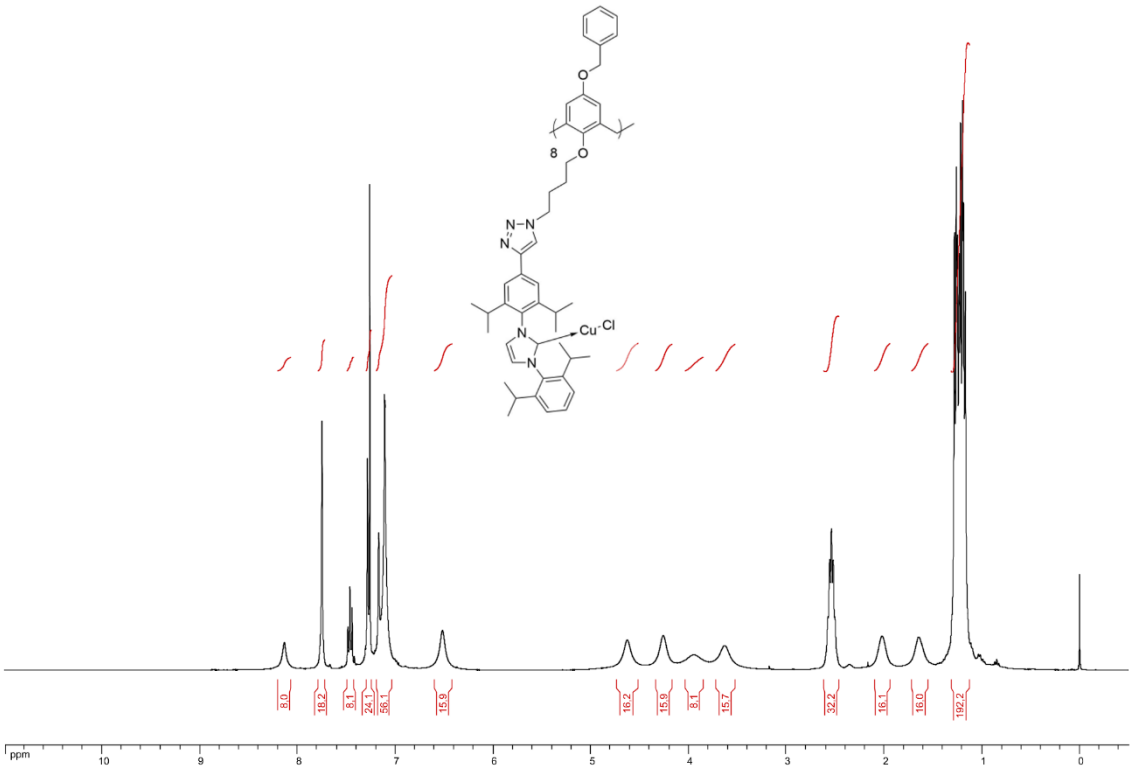
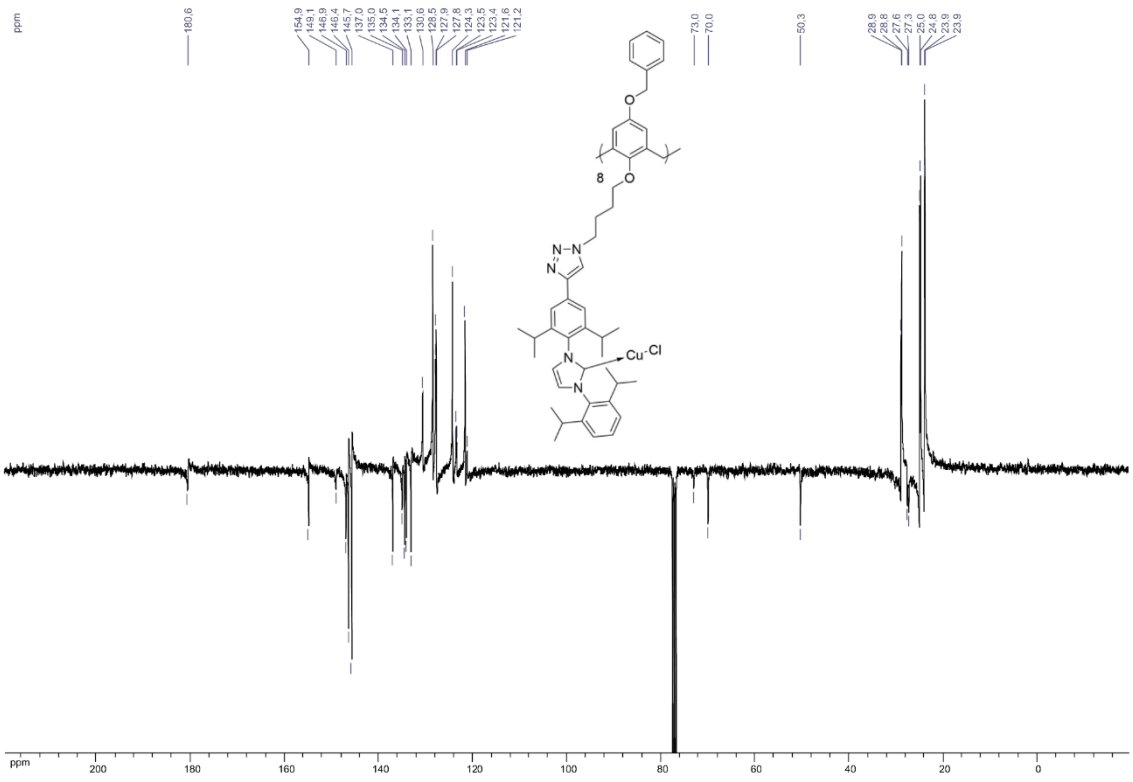
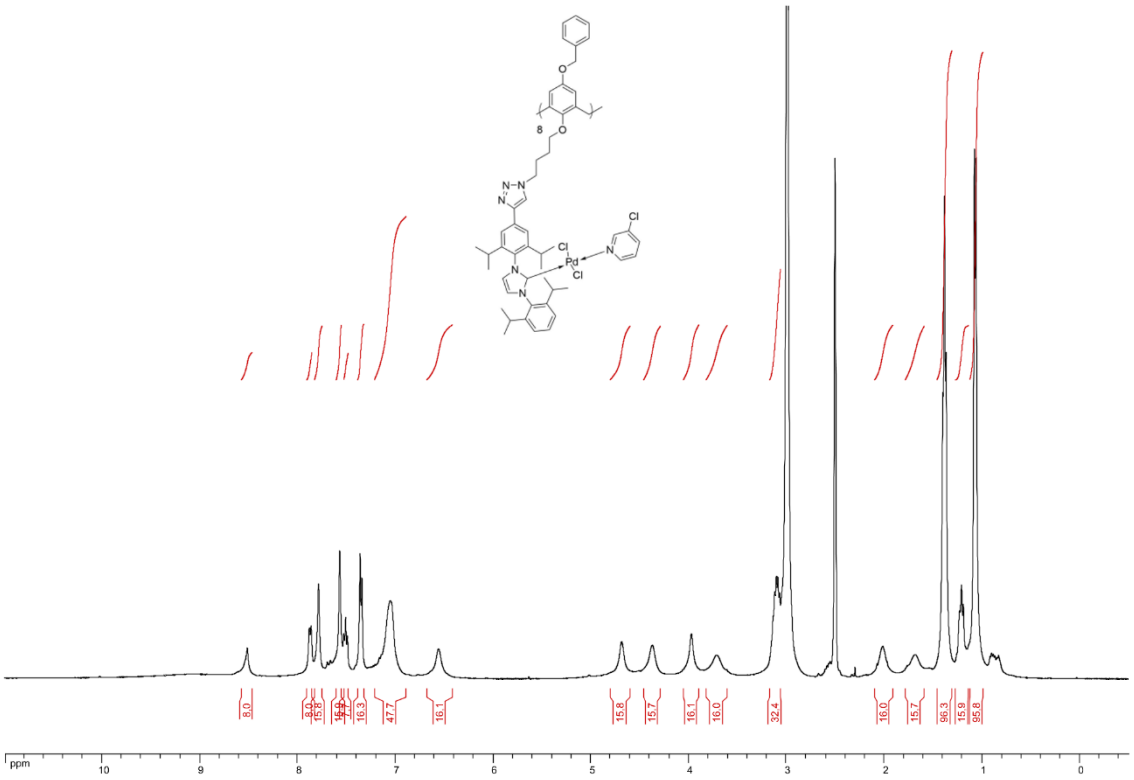
II. Copy of NMR spectra for complexes 6 and Calx-IPr

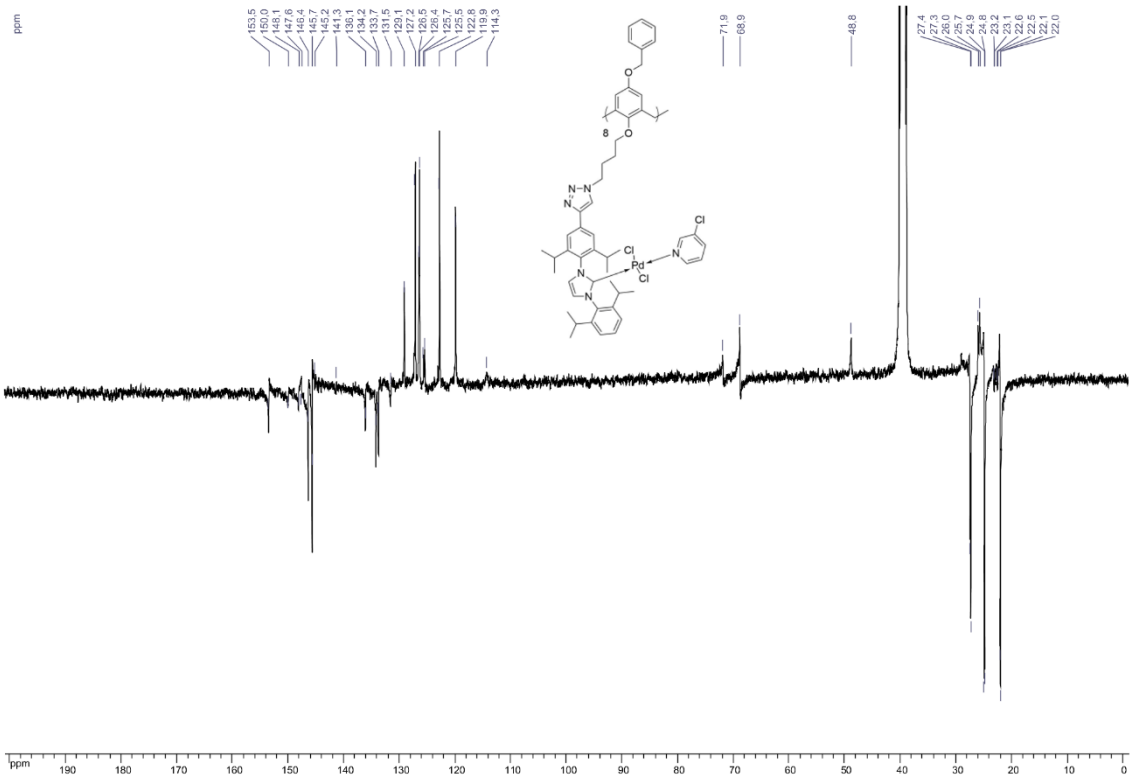
Complex 6



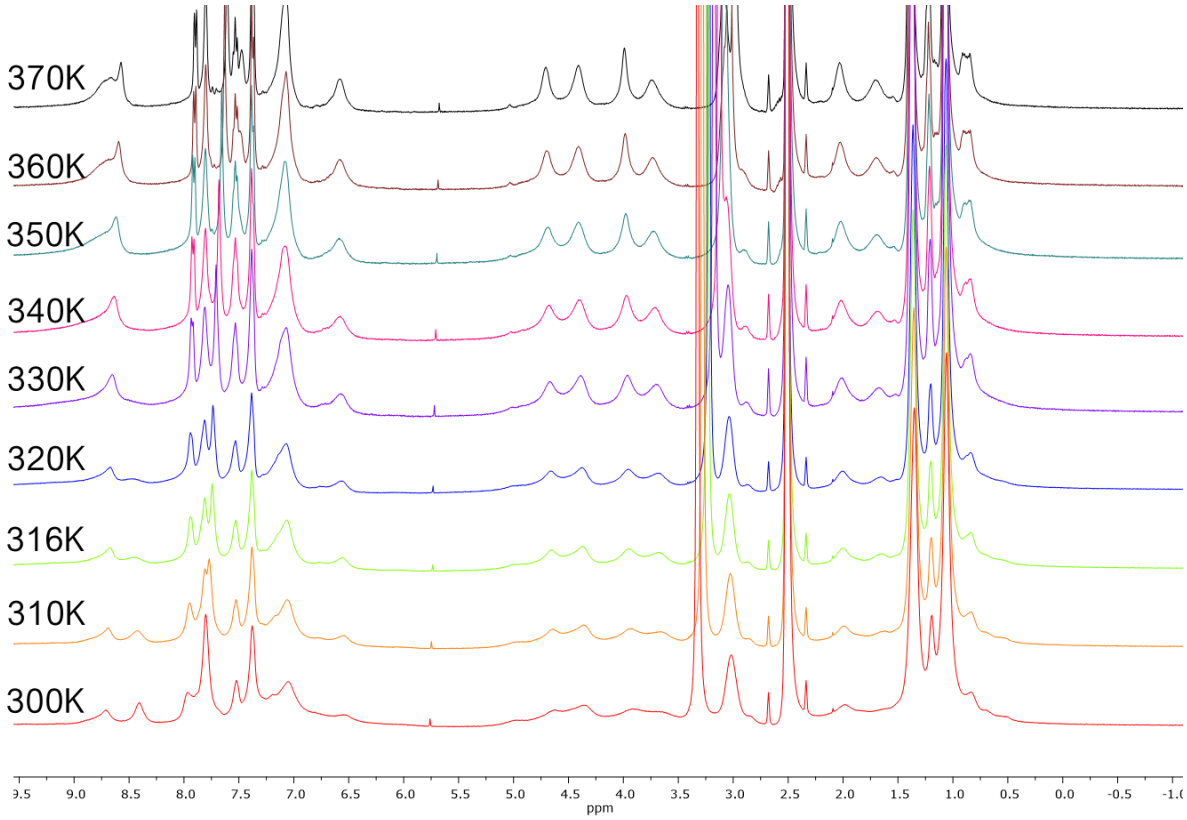


Complex Calx-IPr



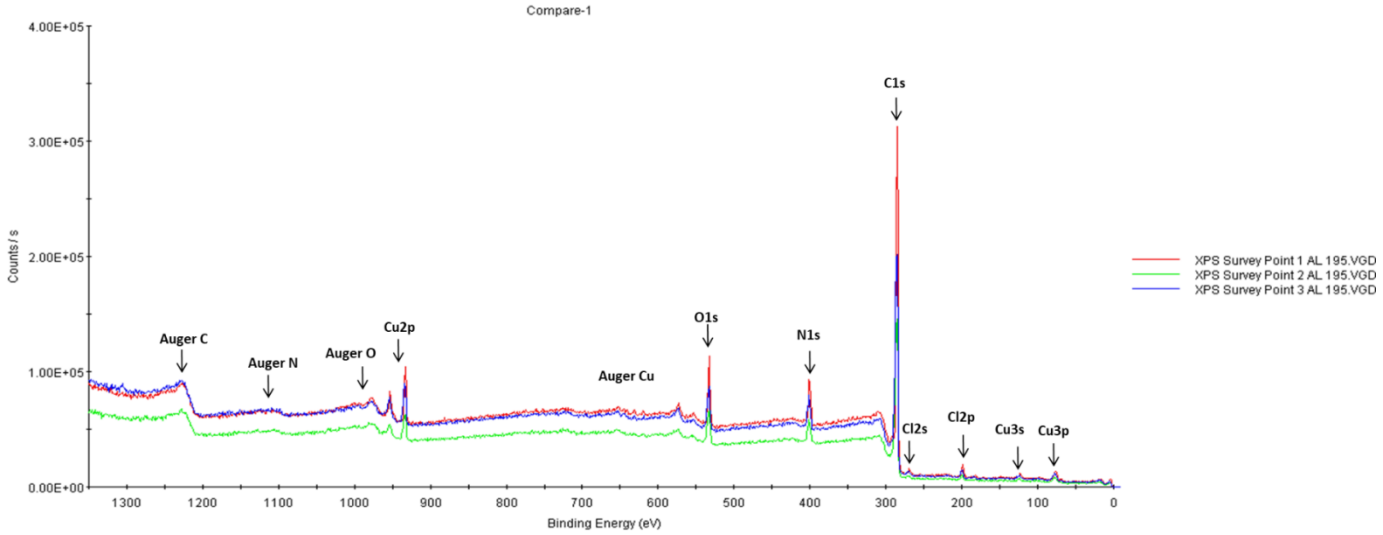


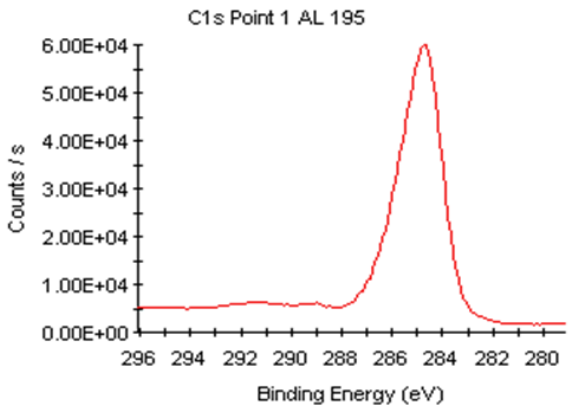
III. Stack plot of ^{1}H NMR spectra of Calx-IPr obtained at different temperatures

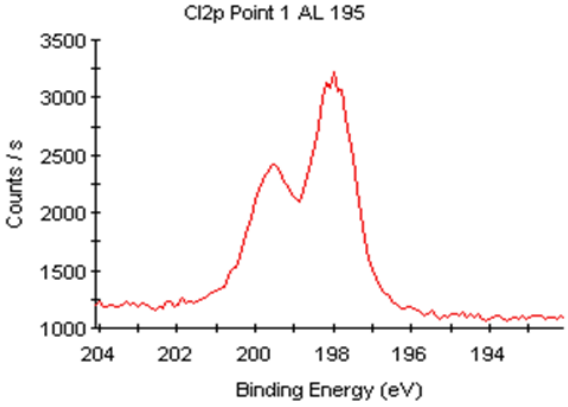


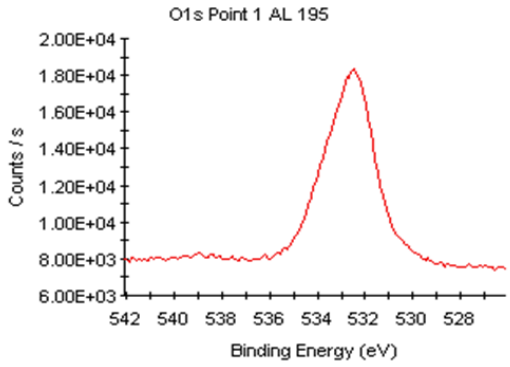
IV. XPS of Complexes 6 and Calix-IPr

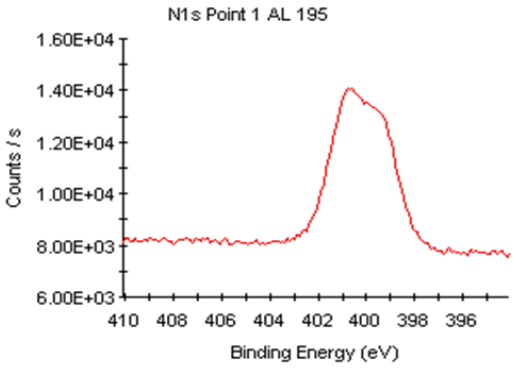
Complex 6

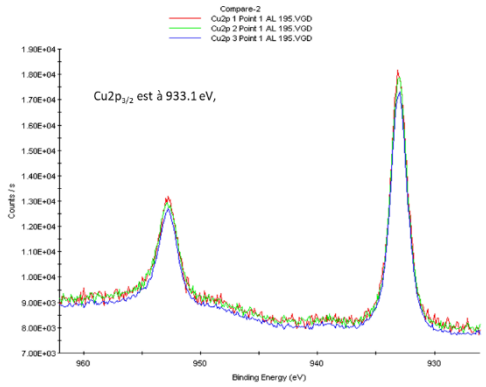




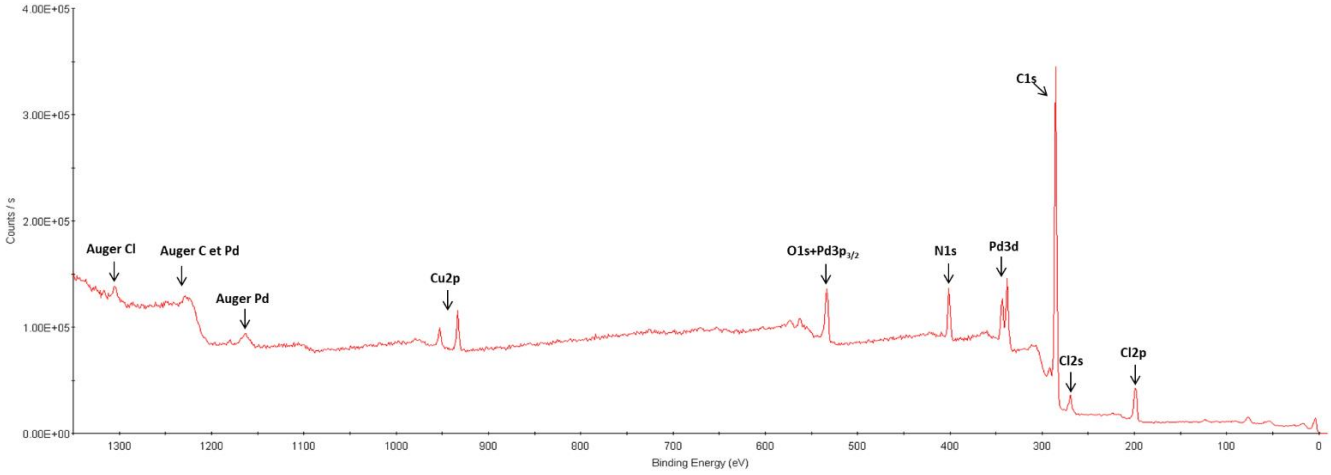




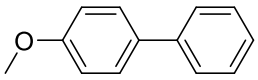




Complex Calix-IPr



V. Procedure and characterisations of cross-coupling compounds

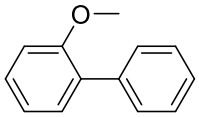


4-Methoxy-1,1'-biphenyl: white solid, 92 % (170 mg, 0.92 mmol) isolated yield, after purification by silica gel column chromatography (petroleum ether/EtOAc = 99:1), prepared from 4-chloroanisole (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (0.5 mol % Pd) in EtOH (0.5 M) at 80 °C.

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.43-7.36 (m, 4H), 7.29-7.24 (m, 2H), 7.18-7.13 (m, 1H), 6.83 (d, J = 8.9 Hz, 2H), 3.67 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$): δ 159.2, 140.9, 133.8, 128.8 (2C), 128.2 (2C), 126.8 (2C), 126.7, 114.3 (2C), 55.4.

The spectral data are in accordance with those reported in the literature.[1]



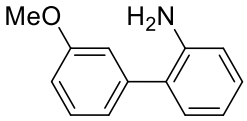
2-Methoxy-1,1'-biphenyl : colorless liquid, 93 % (171 mg, 0.93 mmol) isolated yield, after purification by silica gel column chromatography (pentane/EtOAc = 98:2), prepared from 2-chloroanisole (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (0.2 mol % Pd) in EtOH (0.5 M) at 80 °C.

^{1}H NMR (360 MHz, $CDCl_3$): *δ* 7.57 – 7.50 (m, 2H), 7.46 – 7.35 (m, 2H), 7.35 – 7.28 (m, 3H), 7.09 – 6.94 (m, 2H), 3.82 (s, 3H).

^{13}C NMR (90 MHz, $CDCl_3$): *δ* 156.5, 138.6, 131.0, 130.6, 129.6, 128.7, 128.1, 127.0, 120.9, 111.3, 55.6.

HRMS [APCI]: m/z [M+H]+ calculated for $[C_{13}H_{13}O]^+$: 185.0961, found: 185.0954.

The spectral data are in accordance with those reported in the literature.[2]



2-Amino-3'-methoxy-1,1'-biphenyl: orange oil, 90 % (180 mg, 0.90 mmol) isolated yield, after purification by silica gel column chromatography (petroleum ether/EtOAc/NEt_3 = 85:12:3 > 80:17:3), prepared from 1-chloro-3-methoxybenzene (1 equiv.), 2-aminophenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (1 mol % Pd) in EtOH (0.5 M) at 80 °C.

^{1}H NMR (300 MHz, $CDCl_3$): *δ* 7.35 (t, *J* = 8.0 Hz, 1H), 7.20-7.12 (m, 2H), 7.06-6.97 (m, 2H), 6.92-6.84 (m, 2H), 6.80 (d, *J* = 8.0 Hz, 1H), 3.96 (br.s, 2H), 3.82 (s, 3H).

^{13}C NMR (90 MHz, $CDCl_3$): *δ* 159.9, 143.5, 140.9, 130.3, 129.8, 128.5, 127.4, 121.4, 118.5, 115.6, 114.5, 112.9, 55.2.

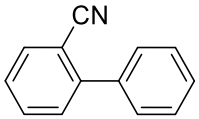
HRMS [ESI(+)]: *m*/z $[M+H]^+$ calculated for $[C_{13}H_{14}NO]^+$: 200.1070, found: 200.1066.

The spectral data are in accordance with those reported in the literature.[3]

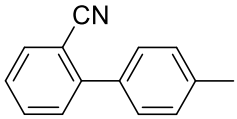
[1] E. Alacid and C. Nájera, *Org. Lett.*, *2008*, **10**, 5011-5014.

[2] L. Yadav, M. K. Tiwari, B. R. K. Shyamlal and S. Chaudhary, *J. Org. Chem.*, 2020, **85**, 8121–8141

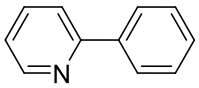
[3] B. J. Stokes, B. Jovanovic, H. Dong, K. J. Richert, R. D. Riell, T. G. Driver, *J. Org. Chem.* **2009**, *74*, 3225-3228.



2-Cyano-1,1'-biphenyl: white solid, 67 % (162 mg, 0.67 mmol) isolated yield after purification by silica gel column chromatography (petroleum ether/EtOAc = 95:5). This product was obtained as a mixture with 2-chloro-1-benzonitrile, and the molar ratio of the mixture was determined by NMR integration. Prepared from 2-chloro-1-benzonitrile (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (1 mol % Pd) in EtOH (0.5 M) at 80 °C. A pure sample of this product was obtained via purification by silica gel column chromatography (petroleum ether/$CHCl_3$ = 80:20).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.77 (dd, J = 7.7 Hz and 1.4 Hz, 1H), 7.65 (td, J = 7.7 Hz and 1.4 Hz, 1H), 7.60-7.41 (m, 7H).
^{13}C NMR (90 MHz, $CDCl_3$): δ 145.4, 138.1, 133.7, 132.8, 130.0, 128.72 (2C), 128.69 (3C), 127.6, 118.7, 111.2.
HRMS [ESI(+)]: m/z $[M+H]^+$ calculated for $[C_{13}H_{10}N]^+$: 180.0807, found: 180.0805.
The spectral data are in accordance with those reported in the literature.[4]



2-Cyano-4-methyl-1,1'-biphenyl: white solid, 56 % (162 mg, 0.56 mmol) isolated yield after purification by silica gel column chromatography (petroleum ether/EtOAc = 95:5). This product was obtained as a mixture with 2-chloro-1-benzonitrile, and the molar ratio of the mixture was determined by GC using hexadecane as internal standard. Prepared from 2-chloro-1-benzonitrile (1 equiv.), 4-tolylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (1 mol % Pd) in EtOH (0.5 M) at 80 °C.
A pure sample of this product was obtained via purification by silica gel column chromatography (petroleum ether/$CHCl_3$ = 80:20).
^{1}H NMR (300 MHz, $CDCl_3$): δ 7.75 (dd, J = 7.8 Hz and 1.2 Hz, 1H), 7.63 (td, J = 7.8 Hz and 1.2 Hz, 1H), 7.51 (dd, J = 7.8 Hz and 1.2 Hz, 1H), 7.47 (d, J = 8.0 Hz, 2H), 7.42 (td, J = 7.8 Hz and 1.2 Hz, 1H), 7.31 (d, J = 8.0 Hz, 2H), 2.43 (s, 3H).
^{13}C NMR (90 MHz, $CDCl_3$): δ 145.6, 138.8, 135.4, 133.8, 132.9, 130.1, 129.5 (2C), 128.7 (2C), 127.4, 119.0, 111.3, 21.3.
HRMS [ESI(+)]: m/z $[M+Na]^+$ calculated for $[C_{14}H_{11}NNa]^+$: 216.0784, found: 216.0780.
The spectral data are in accordance with those reported in the literature.[5]

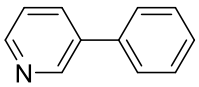


2-Phenylpyridine : slightly yellow oil, 98 % (152 mg, 0.98 mmol) isolated yield, after purification by silica gel column chromatography (petroleum ether/EtOAc = 95:5 > 90:10), prepared from 2-chloropyridine (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (0.5 mol% Pd) in EtOH (0.5 M) at 80 °C.
^{1}H NMR (300 MHz, $CDCl_3$): δ 8.70 (dt, J = 4.8 Hz and 1.2 Hz, 1H), 8.03-7.96 (m, 2H), 7.79-7.71 (m, 2H), 7.52-7.38 (m, 3H), 7.27-7.21 (m, 1H).
^{13}C NMR (75 MHz, $CDCl_3$): δ 157.4, 149.6, 139.3, 136.7, 128.9, 128.7 (2C), 126.9 (2C), 122.1, 120.5.
HRMS [ESI(+)]: m/z $[M+H]^+$ calculated for $[C_{11}H_{10}N]^+$: 156.0808, found: 156.0807.

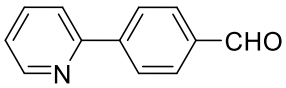
[4] Q. Yang, S. Ma, J. Li, F. Xiao, H. Xiong, *Chem. Commun.* **2006**, 2495-2497.

[5] A. S. Guram, A. O. King, J. G. Allen, X. Wang, L. B. Schenkel, J. Chan, E. E. Bunel, M. M. Faul, R. D. Larsen, M. J. Martinelli, P. J. Reider, *Org. Lett.* **2006**, *8*, 1787-1789.

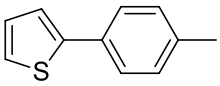
The spectral data are in accordance with those reported in the literature.[6]



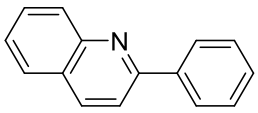
3-Phenylpyridine: colorless oil, 89 % (138 mg, 0.89 mmol) isolated yield, after purification by silica gel column chromatography (pentane/ diethyl ether = 50:50), prepared from 3-chloropyridine (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (0.5 mol % Pd) in EtOH (0.5 M) at 80 °C.
^{1}H NMR (360 MHz, $CDCl_3$): δ 8.85 (s, 1H), 8.58 (d, J = 4.6 Hz, 1H), 7.85 (ddd, J = 1.9 Hz, 1.9, 7.9 Hz, 1H), 7.58-7.55 (m, 2H), 7.48-7.44 (m, 2H), 7.41-7.32 (m, 2H).
^{13}C NMR (90 MHz, $CDCl_3$): δ 148.4, 148.3, 137.8, 136.7, 134.4, 129.1 (2C), 128.1, 127.2 (2C), 123.6.
HRMS [ESI(+)]: m/z [M+H]+ calculated for [C11H10N]+: 156.08077, found: 156.08069.
The spectral data are in accordance with those reported in the literature.[1]



2-(4-Formylphenyl)pyridine : slightly yellow solid, 68 % (124 mg, 0.68 mmol) isolated yield, after purification by silica gel column chromatography (petroleum ether/acetone = 80:20), prepared from 2-chloropyridine (1 equiv.), 4-formylphenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (1 mol % Pd) in EtOH (0.5 M) at 80 °C.
^{1}H NMR (300 MHz, $CDCl_3$): *δ* 10.08 (s, 1H), 8.75 (dt, *J* = 4.8 Hz and 1.2 Hz, 1H), 8.18 (dt, *J* = 8.2 Hz and 1.8 Hz, 2H), 7.99 (dt, *J* = 8.2 Hz and 1.8 Hz, 2H), 7.83-7.79 (m, 2H), 7.31 (q, *J* = 4.5 Hz, 1H).
^{13}C NMR (75 MHz, $CDCl_3$): *δ* 192.0, 155.8, 150.0, 144.9, 137.0, 136.4, 130.1 (2C), 127.5 (2C), 123.2, 121.2.
HRMS [ESI(+)]: *m*/*z* [M+H]$^+$ calculated for [$C_{12}H_{10}NO$]$^+$: 184.0757, found: 184.0757.
The spectral data are in accordance with those reported in the literature.[7]



2-(*p*-Tolyl)thiophene: slightly yellow solid, 87 % (152 mg, 0.87 mmol) isolated yield, after purification by silica gel column chromatography (pentane/ diethyl ether = 90:10), prepared from 2-chlorothiophene (1 equiv.), *p*-tolylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr** (0.5 mol % Pd) in EtOH (0.5 M) at 80 °C.
^{1}H NMR (360 MHz, $CDCl_3$): *δ* 7.38 (d, *J* = 8.2 Hz, 2H), 7.13 (dd, *J* = 1.2 and 3.6 Hz, 1H), 7.10 (dd, *J* = 1.2 and 5.1 Hz, 1H), 7.05 (d, 8.1 Hz, 2H), 6.93 (dd, *J* = 3.6 and 5 Hz, 1H), 2.23 (s, 3H).
^{13}C NMR (90 MHz, $CDCl_3$): *δ* 144.7, 137.4, 131.7, 129.6 (2C), 128.01, 125.9 (2C), 124.4, 122.6, 21.3.
HRMS [ESI(+)]: *m*/*z* [M+H]$^+$ calculated for [$C_{11}H_{11}S$]$^+$: 175.0576, found: 175.0572.
The spectral data are in accordance with those reported in the literature.[8]



[6] H. Hu, C. Ge, A. Zhang, L. Ding, *Molecules* **2009**, *14*, 3153-3160.

[7] C. M. Zinser, K. G. Warren, R. E. Meadows, F. Nahra, A. M. Al-Majid, A. Barakat, M. S. Islam, S. P. Nolan, C. S. J. Cazin, *Green Chem.* **2018**, *20*, 3246-3252.

[8] A. S. Guram, A. O. King, J. G. Allen, X. Wang, L. B. Schenkel, J. Chan, E. E. Bunel, M. M. Faul, R. D. Larsen, M. J. Martinelli and P. J. Reider, *Org. Lett.* 2006, **8,** 1787-1789.

2-Phenylquinoline : white solid, 93 % (190 mg, 0.93 mmol) isolated yield, after purification by silica gel column chromatography (pentane/Et2O = 95:5), prepared from 2-chloroquinoline (1 equiv.), phenylboronic acid (1.5 equiv.), K_3PO_4 (2 equiv.) and **Calx-IPr1** (0.5 mol % Pd) in EtOH (0.5 M) at 80 °C.

^{1}H NMR (360 MHz, $CDCl_3$): δ 8.26 – 8.14 (m, 4H), 7.88 (d, J = 8.6 Hz, 1H), 7.83 (d, J = 8.1, 1.5 Hz, 1H), 7.74 (ddd, J = 8.4, 6.8, 1.5 Hz, 1H), 7.61 – 7.51 (m, 3H), 7.51 – 7.45 (m, 1H).

^{13}C NMR (90 MHz, $CDCl_3$): δ 157.3, 148.3, 139.7, 136.7, 129.7, 129.6, 129.3, 128.8, 127.5, 127.4, 127.1, 126.2, 119.0.

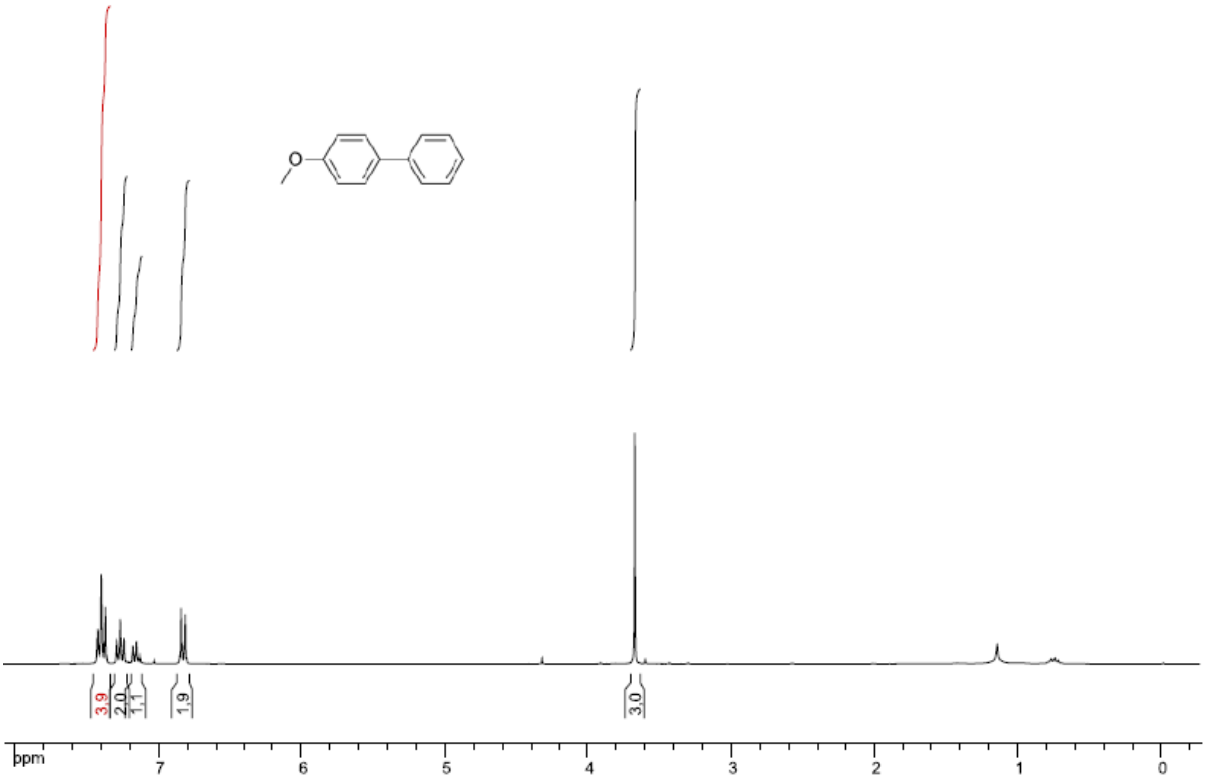
HRMS [ESI(+)]: m/z [M+H]+ calculated for $[C_{15}H_{12}N]^+$: 206.0964, found: 206.0960.

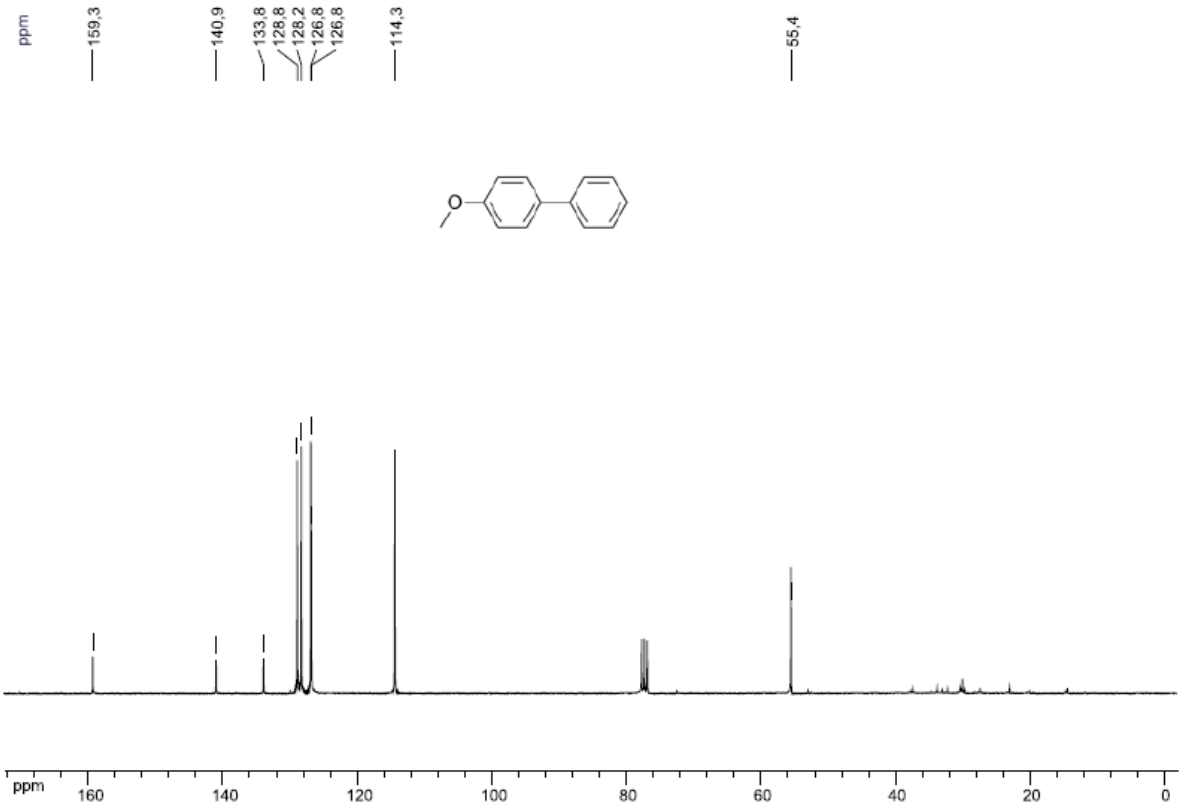
The spectral data are in accordance with those reported in the literature.[9]

[9] T. Xu, Y. Shao, L. Dai, S. Yu, T. Cheng and J. Chen, *J. Org. Chem.*, 2019, **84**, 13604–13614

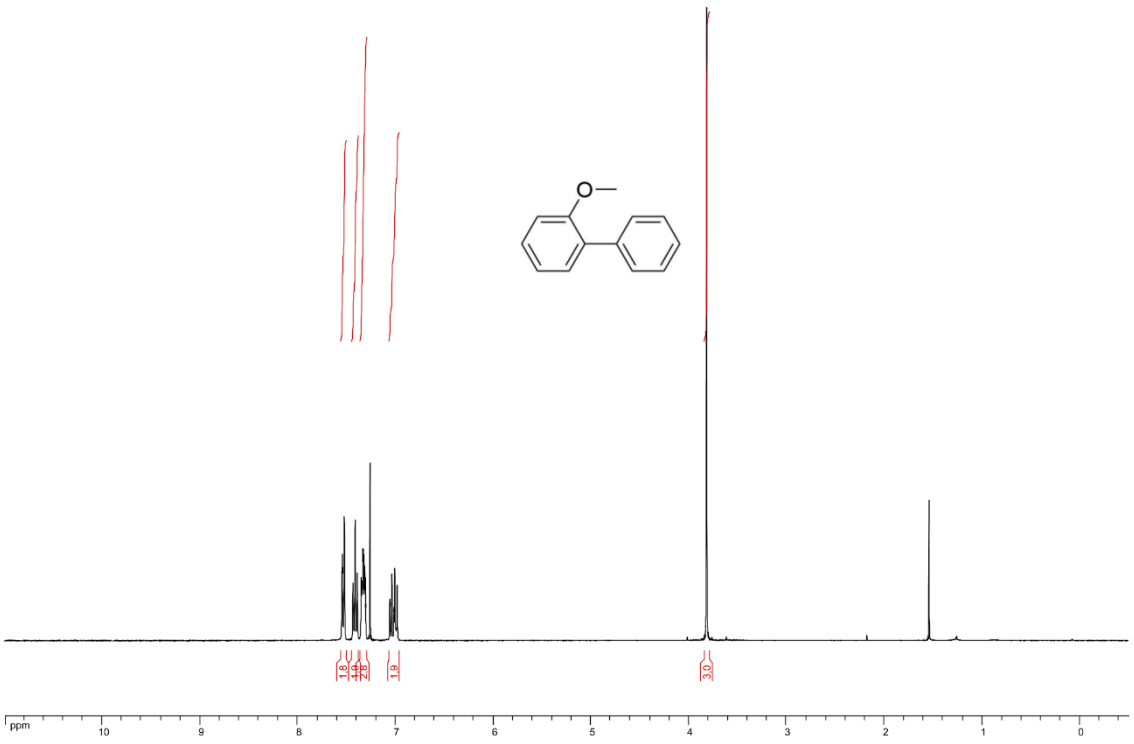
VI. Copy of NMR Spectra of the synthesized compounds

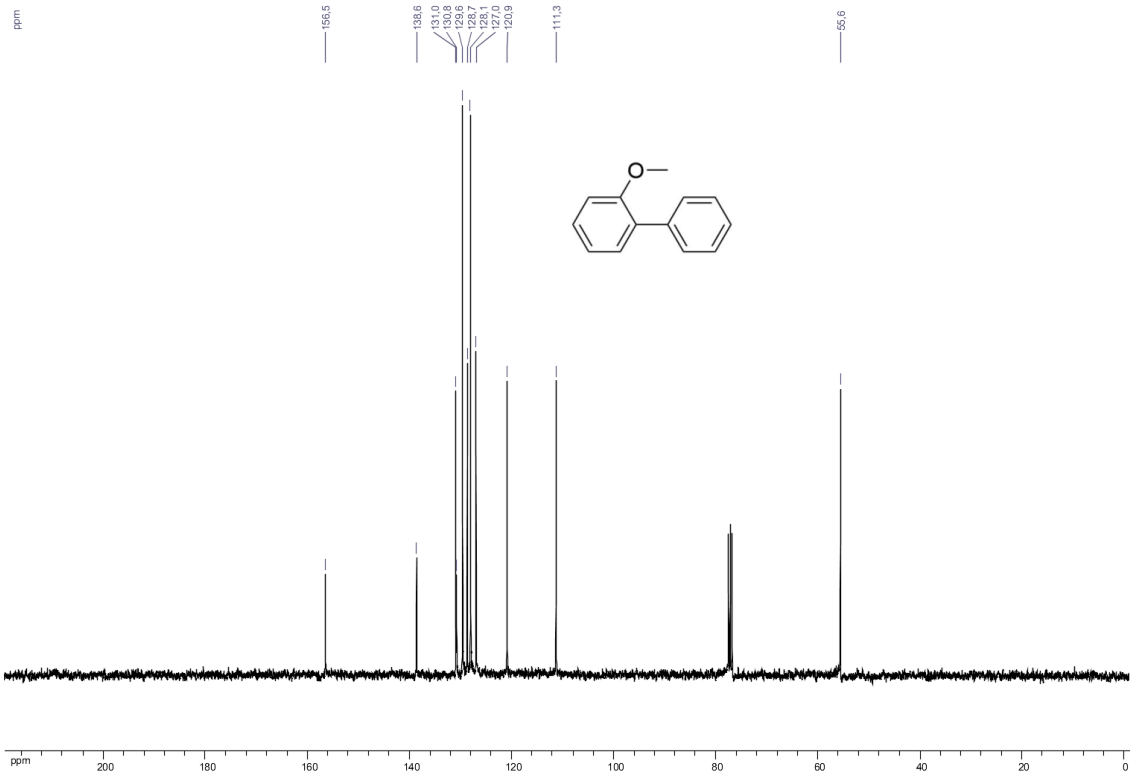
4-Methoxy-1,1'-biphenyl



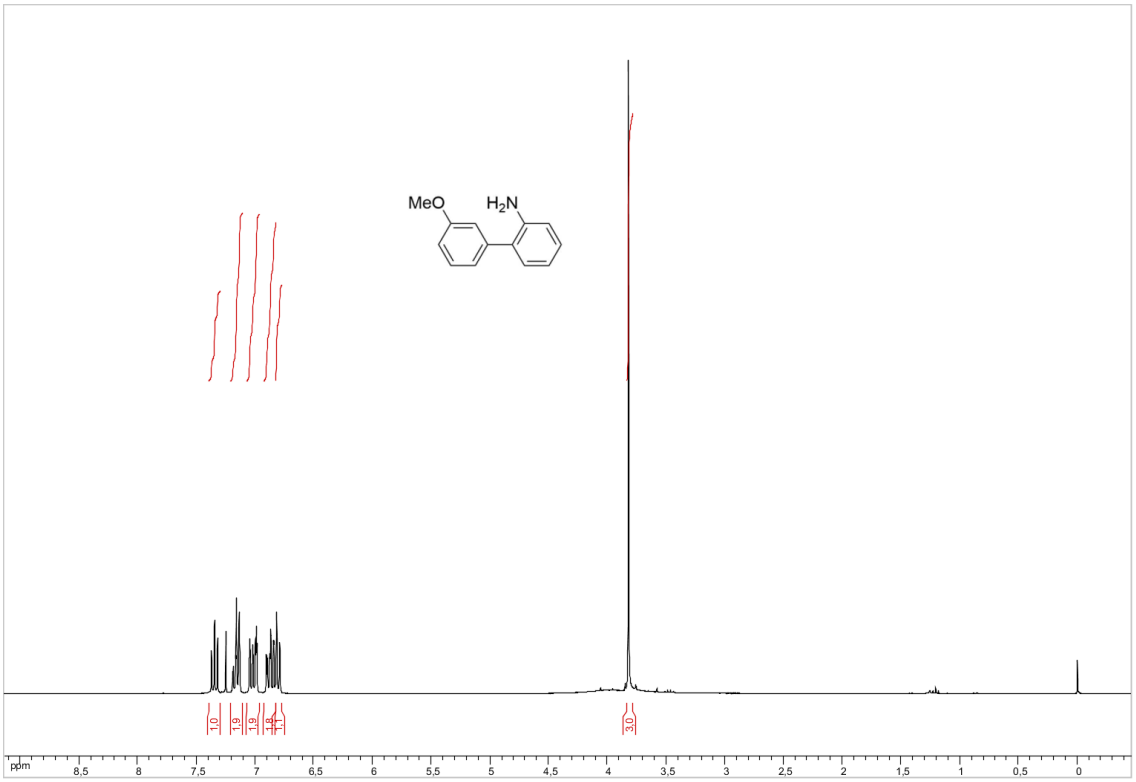


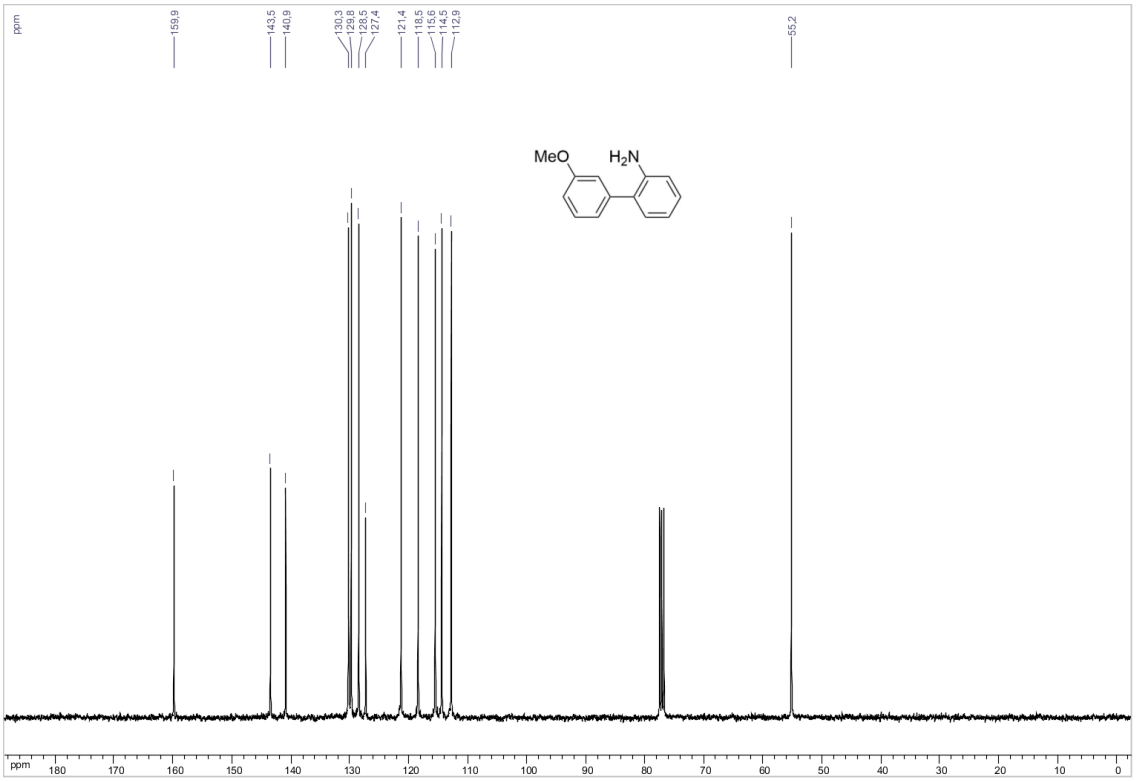
2-Methoxy-1,1'-biphenyl



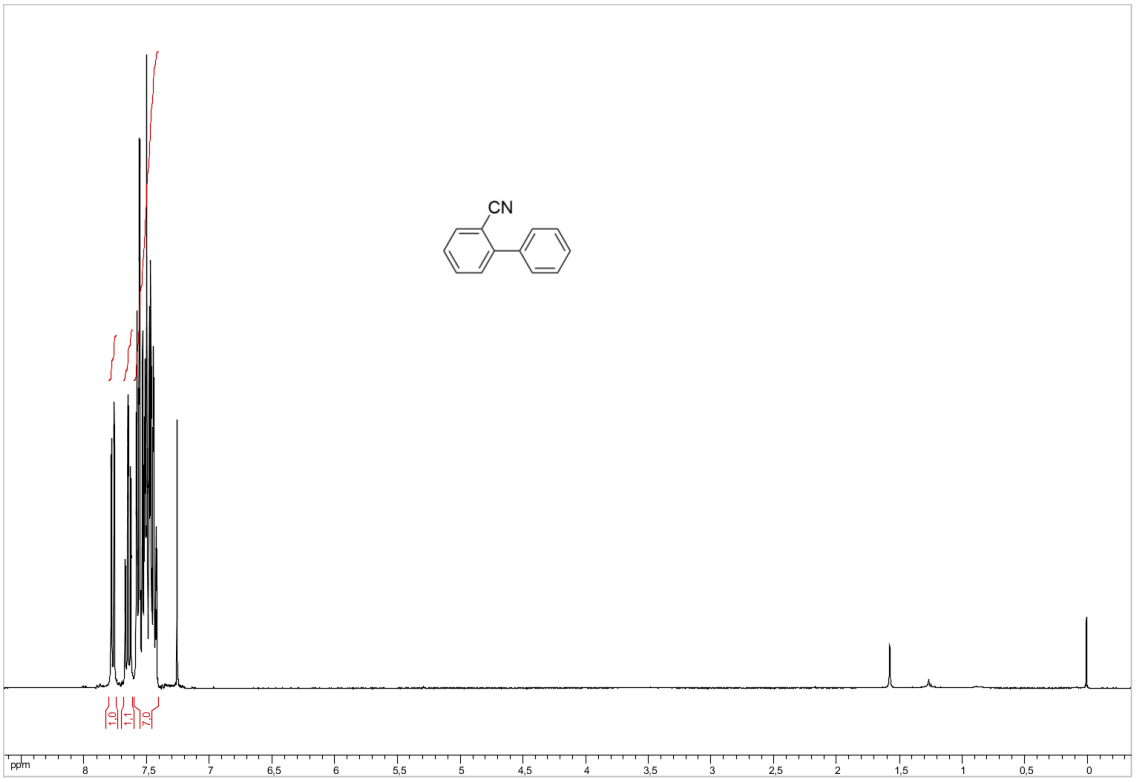


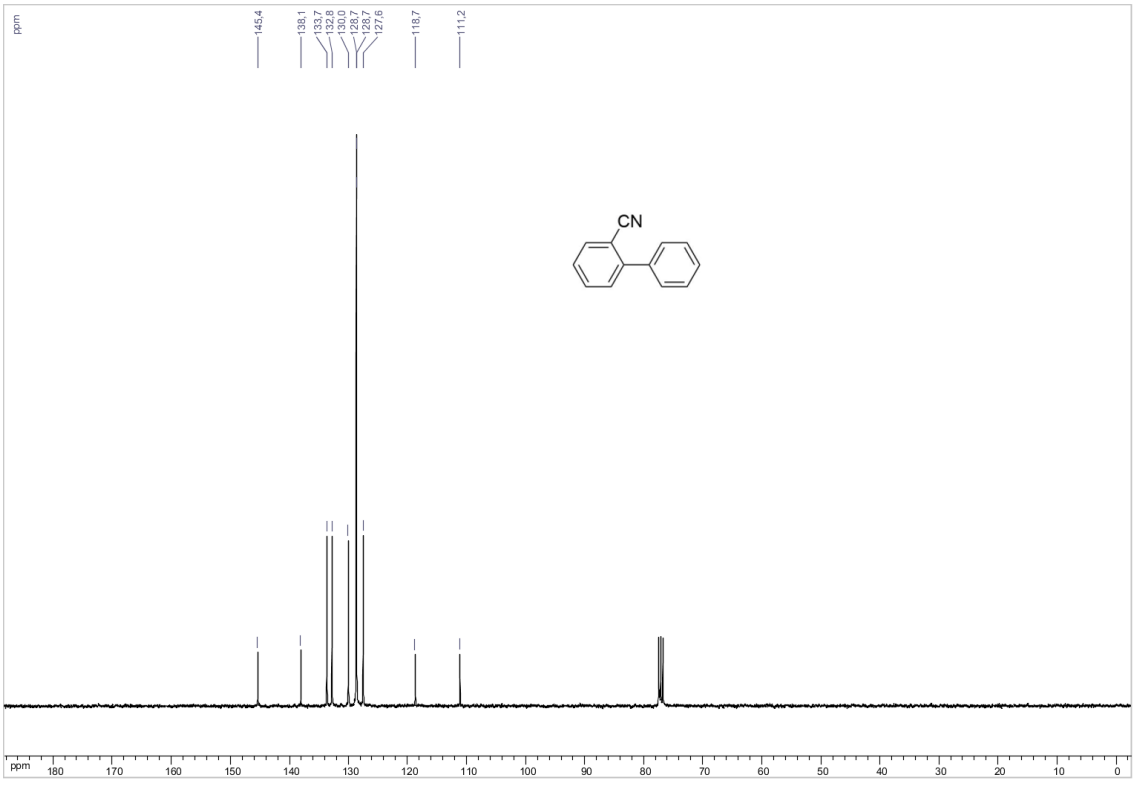
2-Amino-3'-methoxy-1,1'-biphenyl



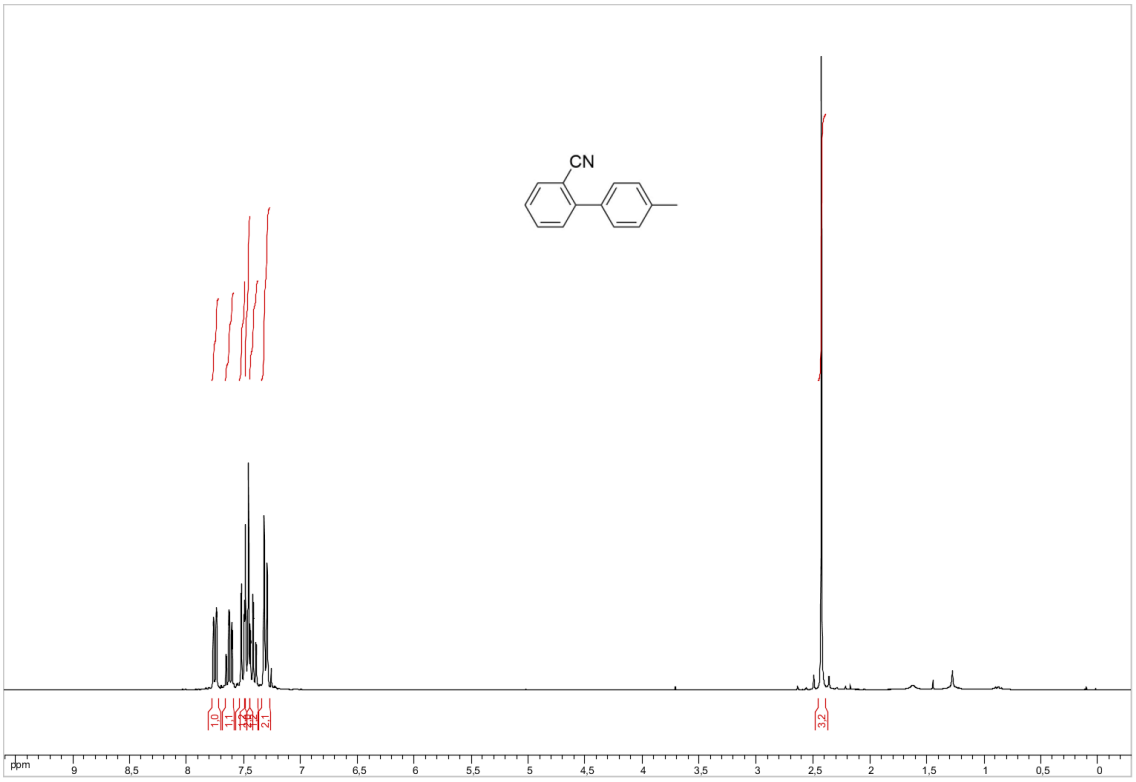


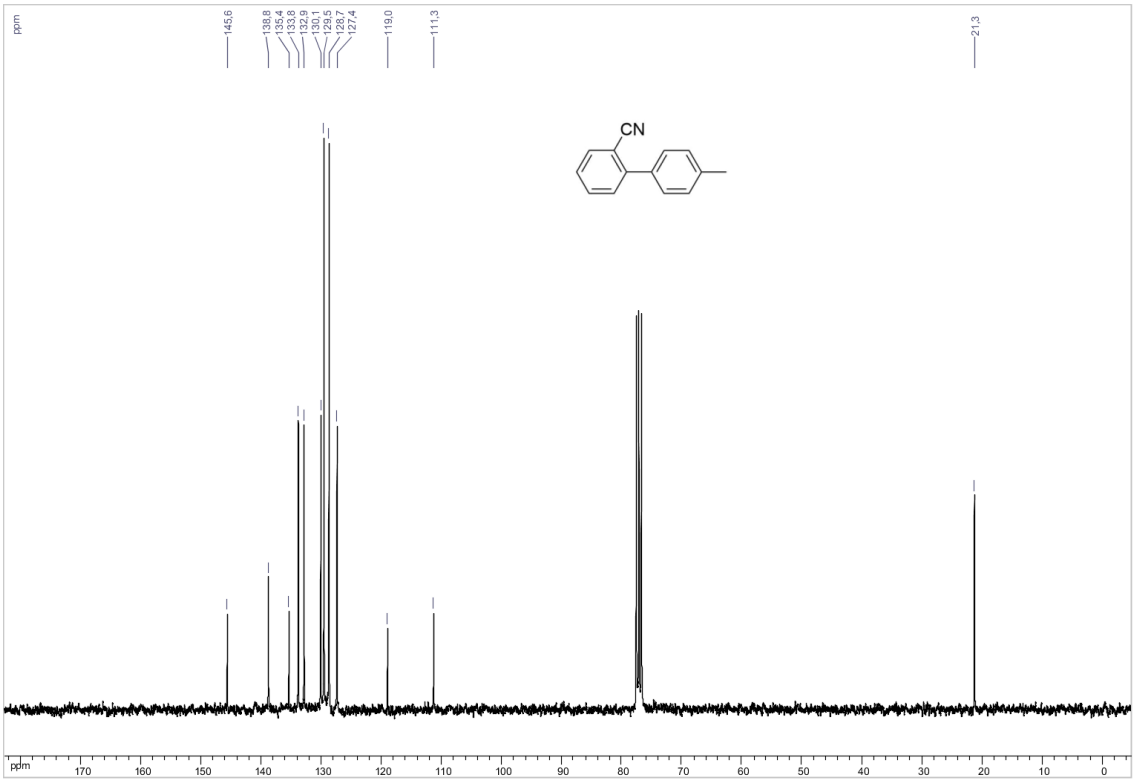
2-Cyano-1,1′-biphenyl



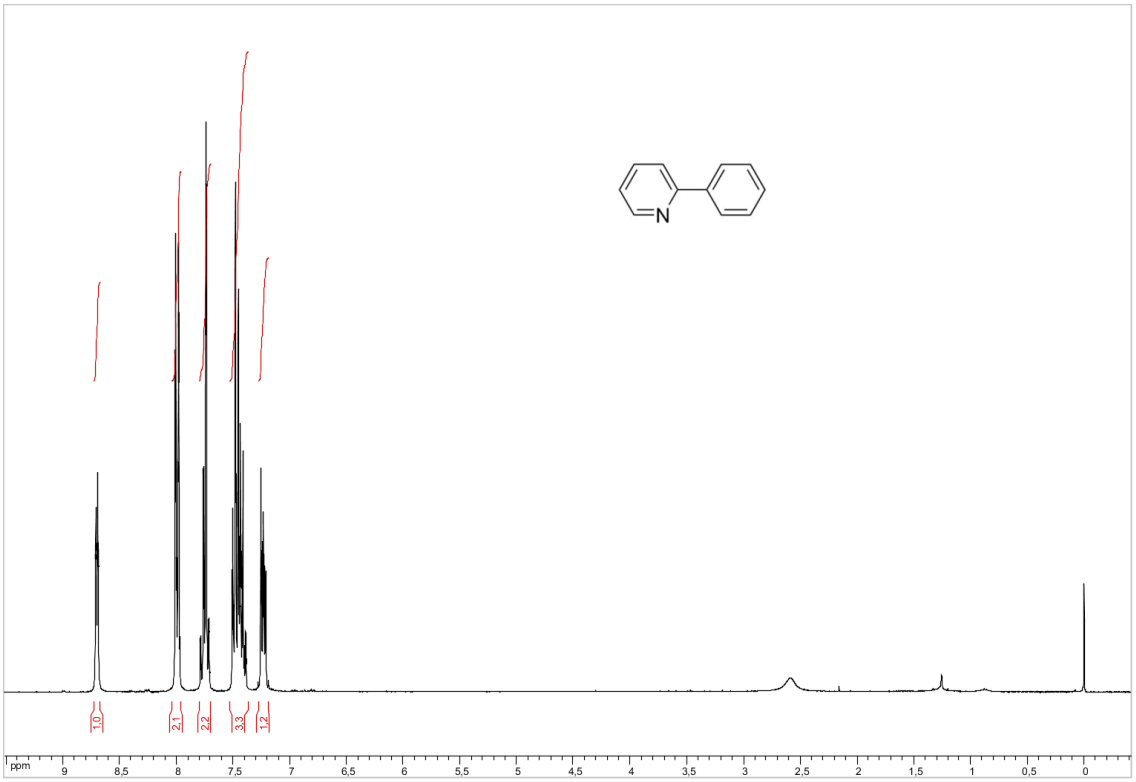


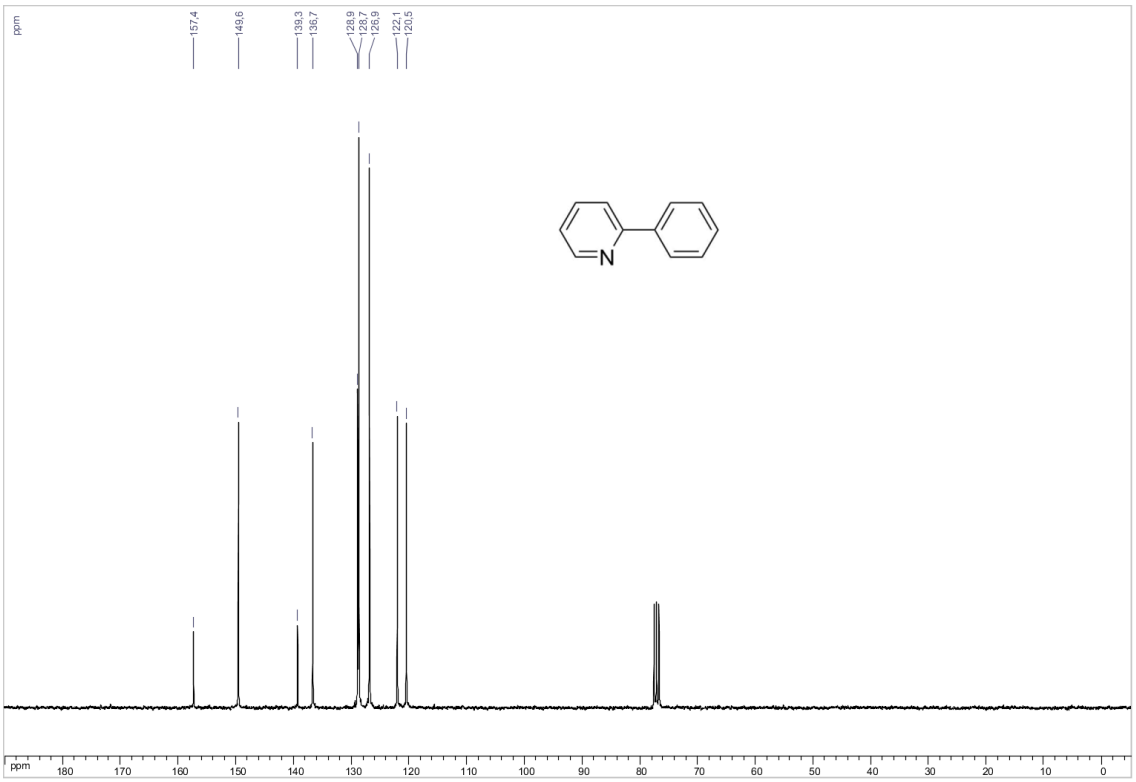
2-Cyano-4′-methyl-1,1′-biphenyl



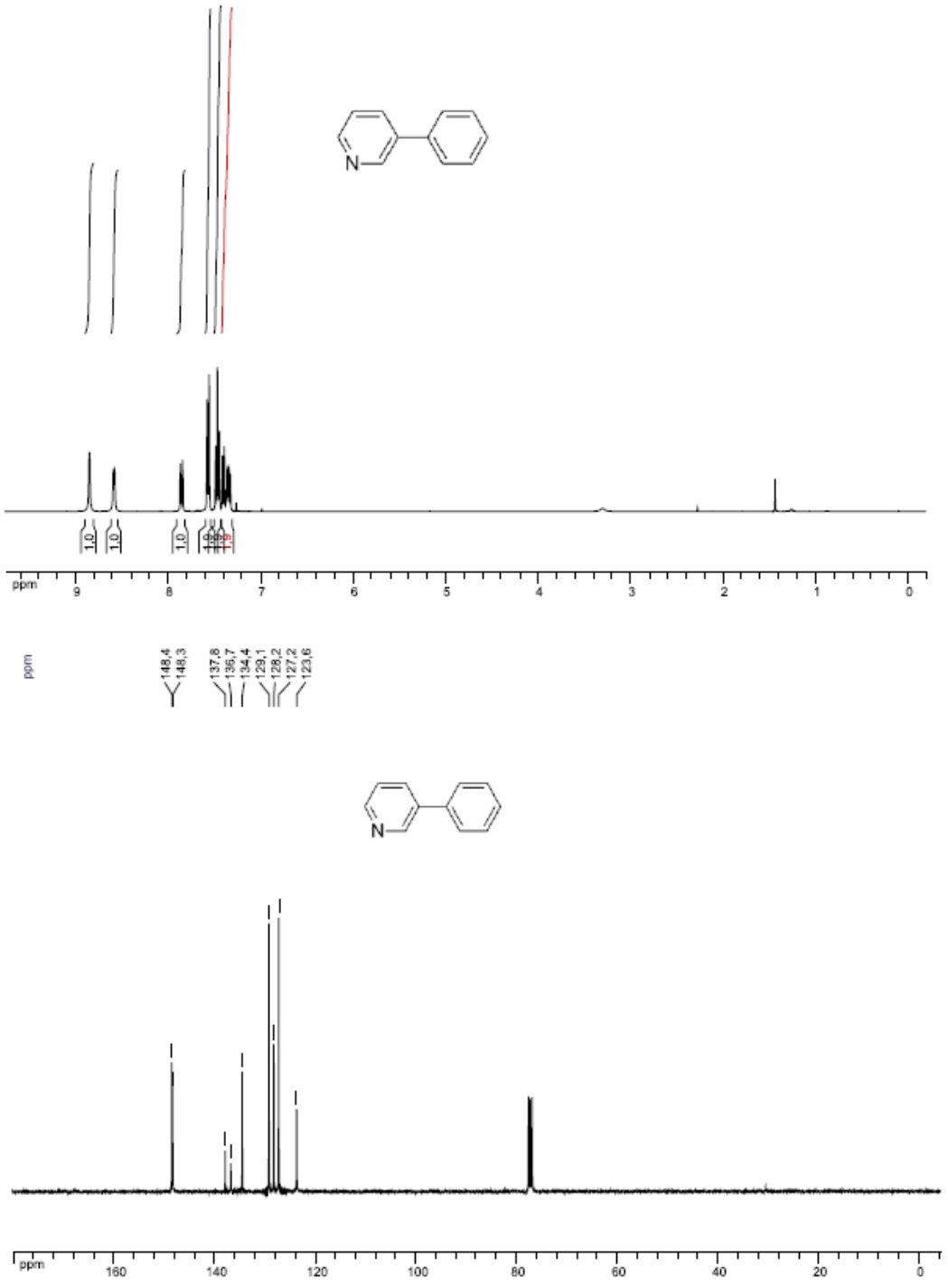


2-Phenylpyridine

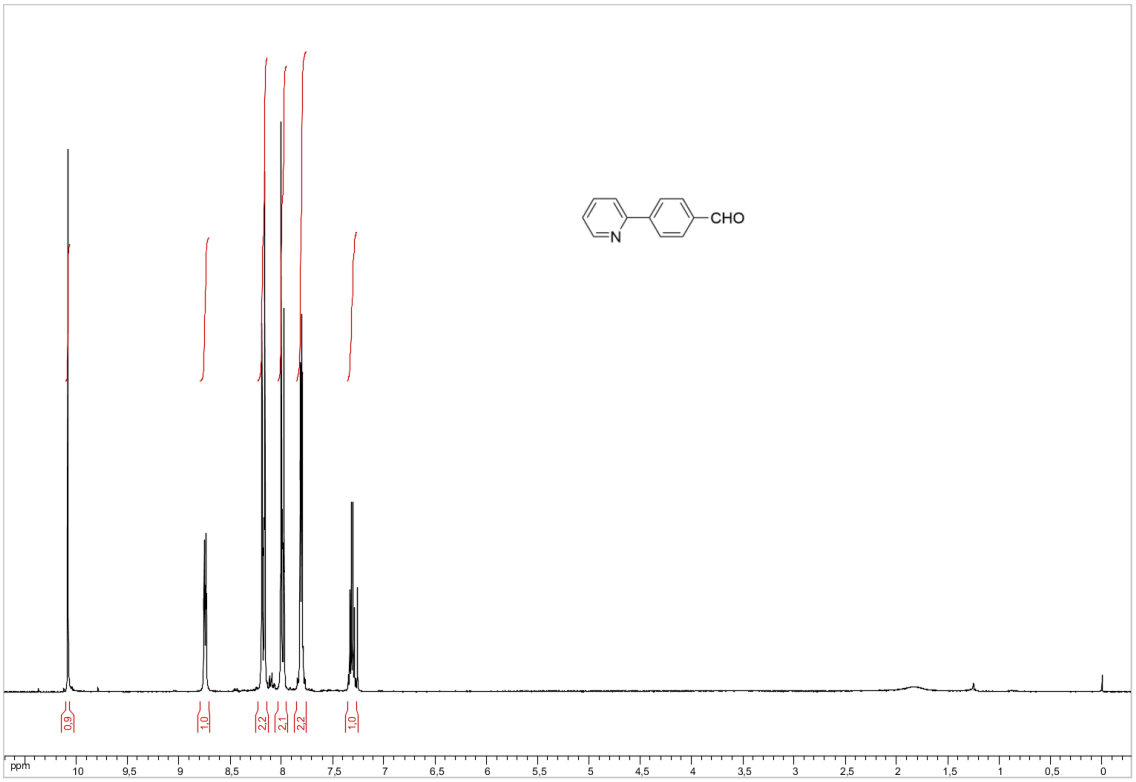


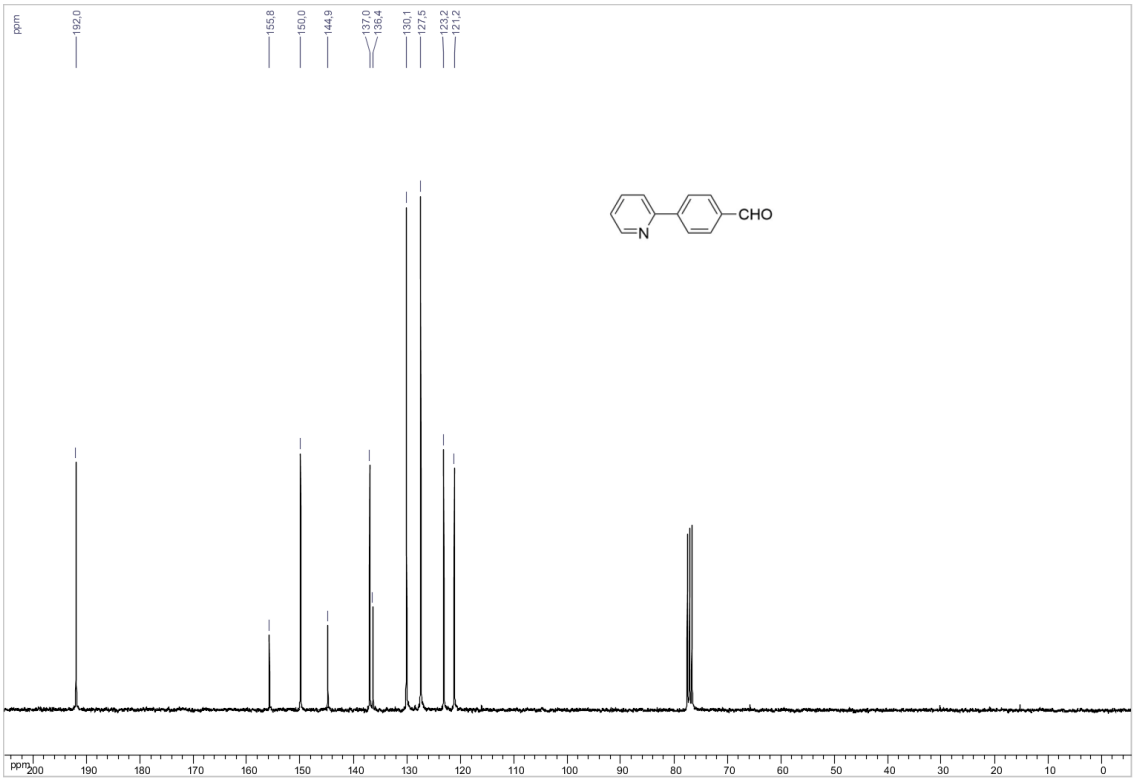


3-Phenylpyridine:

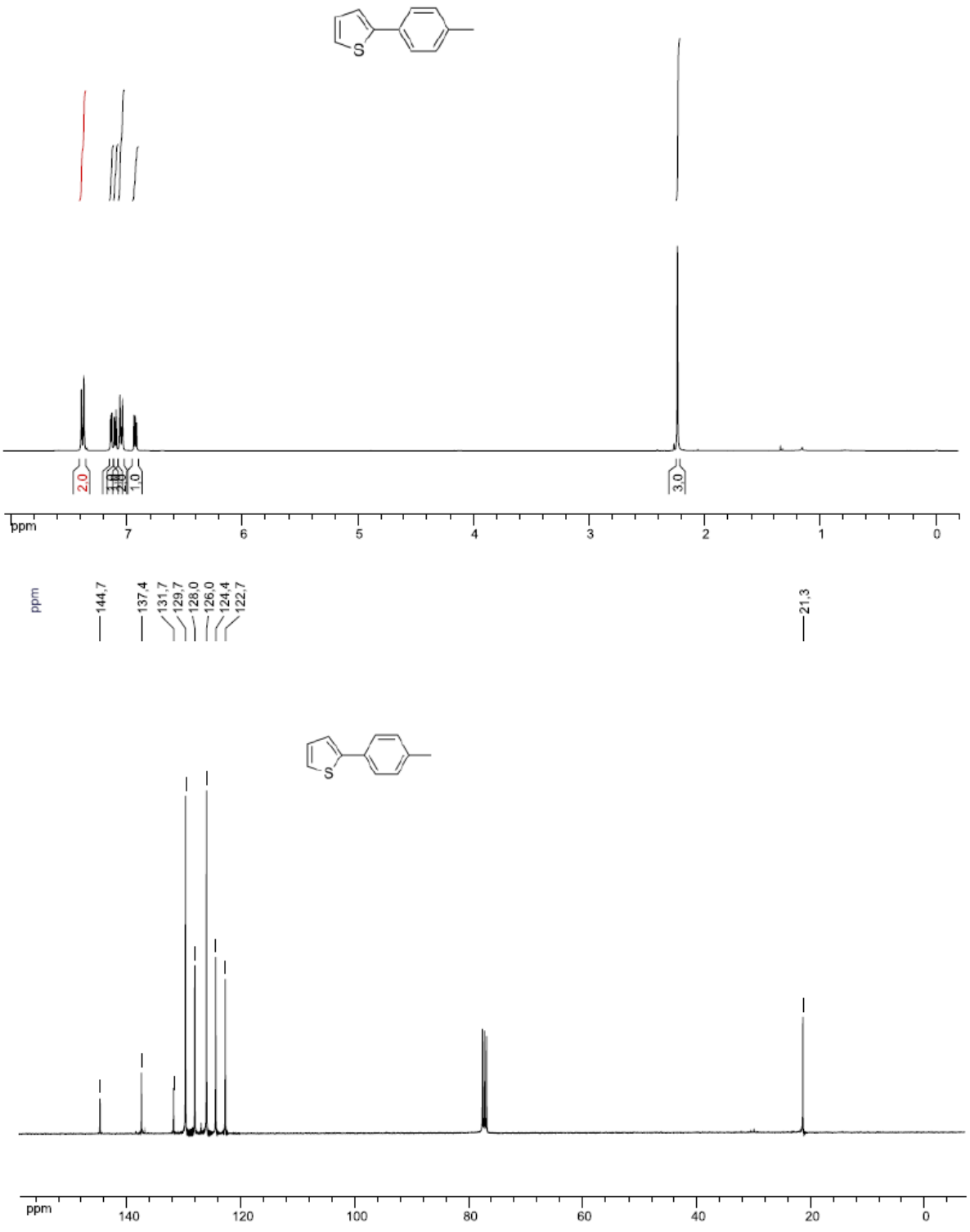


2-(4-Formylphenyl)pyridine

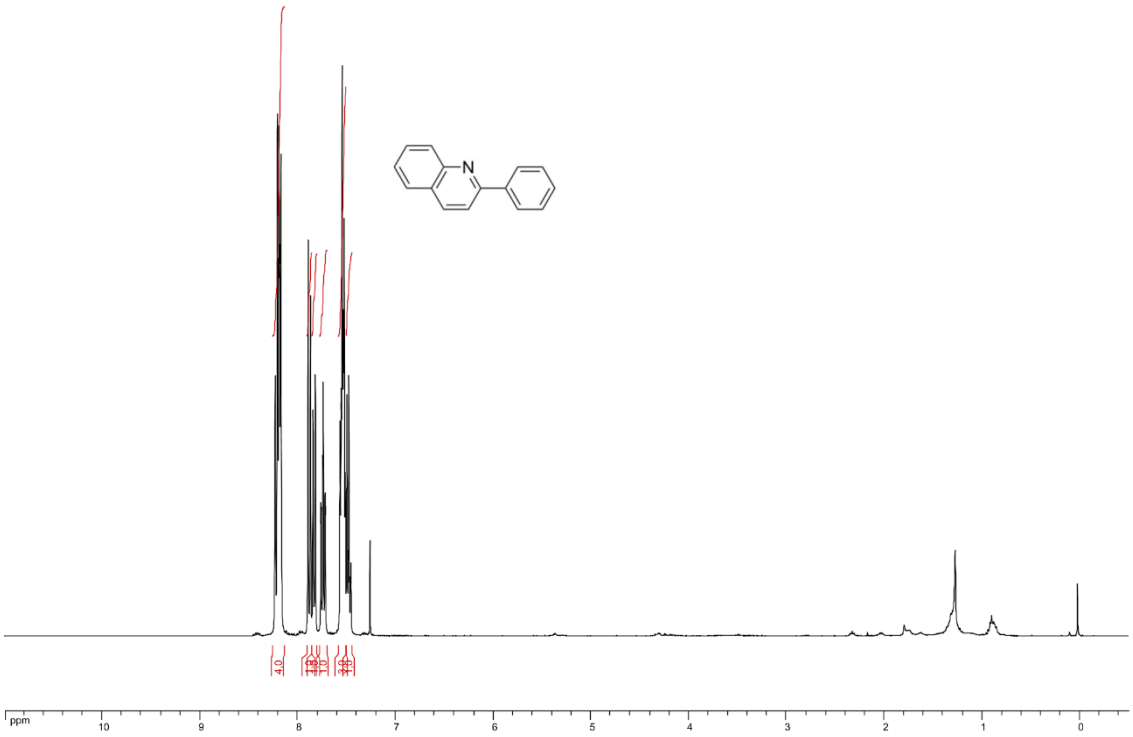


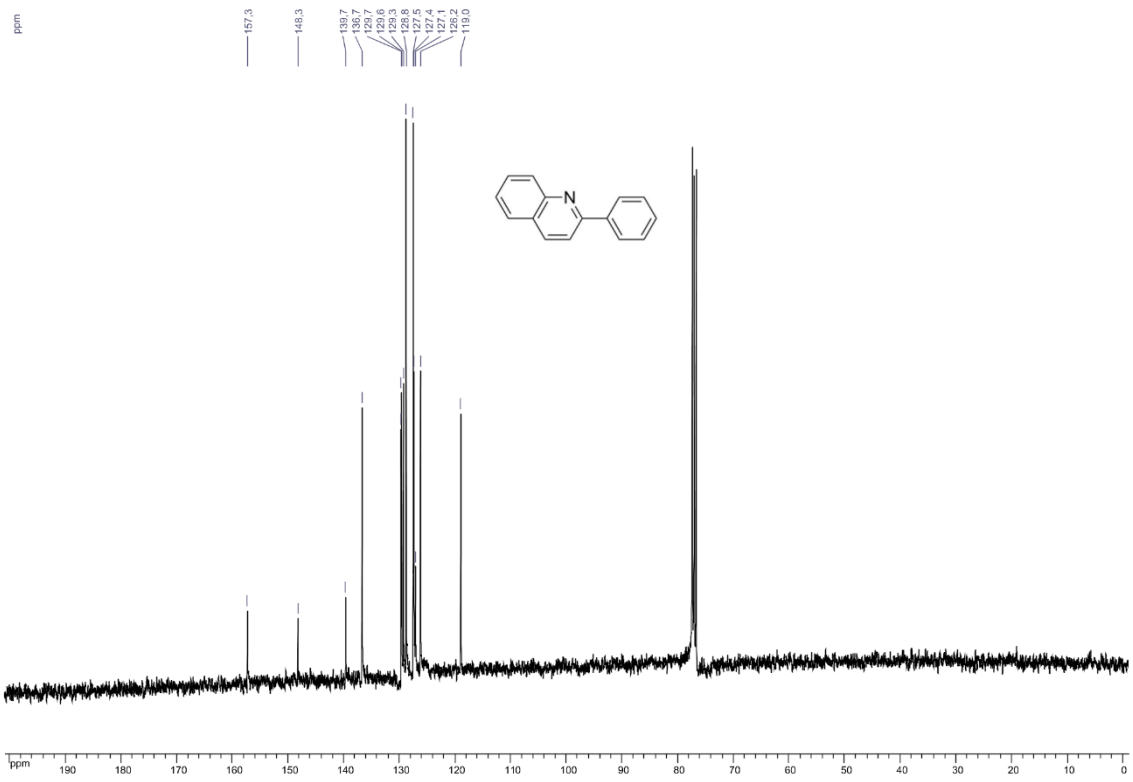


2-(*p*-Tolyl)thiophene



2-Phenylquinoline





VII. Illustration of bulkiness effect

A) Acceleration of the oxidative addition step by cooperative C-H π and π π interactions ;
B) Acceleration of the reductive elimination step due to the presence of bulky aromatic substituents.