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Direct Orthoruthenation of Planar Prochiral Pyridine Derivatives by C–H Bond Activation with $[Ru(CO)_2Cl_2]_n$ and Its Unexpected Stereoselectivity

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The treatment of planar prochiral pyridine derivatives with d^6 $[Ru(CO)_2Cl_2]_n$ stereoselectively and efficiently produces new dimeric ortho-ruthenated complexes.

The most challenging applications of planar chiral chelating ligands lie in their use as metalloorganic catalysts whose topology is expected to enable a transfer of the chiral information to the reaction center via the chelated metal. Whereas the syntheses of planar chiral cyclometalated complexes derived from planar prochiral[1] racemic or nonracemic ferrocenes, [2,2]-cyclophanes, and cobaltocenes and from (η^6-arene)tricarbonylchromium complexes of square-planar d^8 metallacycles by direct C−H bond activation,[2] transmetalation,[3] and ligand exchange[4] are abundantly documented in the literature, to our knowledge, the direct cyclometalation by C−H bond activation of planar prochiral substrates with asymmetric octahedral d^6 metal complexes has not yet been reported. Such a transformation would be of utmost fundamental importance because it would lend access to chiral compounds with a dual *stereochemical feature*; they would be planar chiral at the chelate and centrochiral at the chelated metal. We recently undertook the search for new routes to planar chiral metallacycles using asymmetric octahedral d^6 complexes as metalation agents. Monosubstituted (η^6-arene)tricarbonylchromium complexes bearing an ancilliary ligand are inherently planar prochiral and can be readily ortho-manganated, rhenated, and even mercurated[5] by *direct aromatic C−H bond activation* despite the well-known electron-withdrawing effect of the $Cr(CO)_3$ moiety. This ability of (η^6-arene)tricarbonylchromium complexes to undergo direct metalations of either nucleophilic or electrophilic character questions the predominance of electronic effects in the C_{Ar}−H bond activation step.[5c] In this Communication, we report on the direct orthometalation[6] of planar prochiral pyridine derivatives such as 2-[tricarbonyl(η^6-phenyl)chromium]pyridine (**1**) with $[Ru(CO)_2Cl_2]_n$[7] and the stereoselective formation of the corresponding racemic dimeric ruthenacycles. The ready conversion of the obtained cycloruthenated product into a pair of resolved nonracemic (Cr, Ru) heteroleptic bischelates upon coordination of an anionic bidentate ligand preserves the relative stereochemistry at the ruthenium.

A mixture of $[Ru(CO)_2Cl_2]_n$,[7] Na_2CO_3, and compound **1** was dissolved in dry and degassed 1,2-dimethoxyethane, and the resulting suspension was brought to reflux for 15 h (Scheme 1). The color of the reaction mixture turned rapidly

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(1) The expression "planar prochiral" describes here an achiral molecule that may exhibit *planar chirality* upon *replacement* of an H atom by a different element, e.g. a metal, at a *stereogenic* position.

(2) (a) Sokolov, V. I.; Troitskaya, L. L.; Reutov, O. A. *J. Organomet. Chem.* **1977**, *133*, C28−C30. (b) Ryabov, A.; Panyashkina, I. M.; Polyakov, V. A.; Howard, J. A. K.; Kuz'mina, L. G.; Datt, M. S.; Sacht, C. *Organometallics* **1998**, *17*, 3615−3618. (c) Bolm, C.; Wenz, K.; Raabe, G. *J. Organomet. Chem.* **2002**, *662*, 23−33. (d) Overman, L. E.; Owen, C. E.; Pavan, M. M.; Richards, C. *Org. Lett.* **2003**, *5*, 1809−1812.

(3) (a) Cui, X. L.; Wu, Y. J.; Du, C. X.; Yang, L. R.; Zhu, Y. *Tetrahedron Asymm.* **1999**, *10*, 1255−1262. (b) Berger, A.; Djukic, J. P.; Pfeffer, M.; Lacour, J.; Vial, L.; de Cian, A.; Kyritsakas-Gruber, N. *Organometallics* **2003**, *22*, 5243−5260. (c) Wu, Y.; Yang, L.; Cui, X.; Du, C.; Zhu, Y. *Tetrahedron Asymm.* **2003**, *14*, 1073−1077. (d) Djukic, J. P.; Berger, A.; Duquenne, M.; Pfeffer, M.; de Cian, A.; Kyritsakas-Gruber, N. *Organometallics* **2004**, *23*, 5757−5767.

(4) Roca, F. X.; Motevalli, M.; Richards, C. *J. Am. Chem. Soc.* **2005**, *127*, 2388−2389.

(5) (a) Djukic, J. P.; Maisse, A.; Pfeffer, M.; de Cian, A.; Fischer, J. *Organometallics* **1997**, *16*, 657−667. (b) Djukic, J. P.; Maisse, A.; Pfeffer, M.; Doetz, K. H.; Nieger, M. *Organometallics* **1999**, *18*, 2786−2790. (c) Berger, A.; de Cian, A.; Djukic, J. P.; Fischer, J.; Pfeffer, M. *Organometallics* **2001**, *20*, 3230−3240.

(6) (a) Bruce, M. I.; Iqbal, M. Z.; Stone, F. G. A. *J. Chem. Soc., Chem. Commun.* **1970**, 1325−1327. (b) Bruce, M. I.; Iqbal, M. Z.; Stone, F. G. A. *J. Chem. Soc. A* **1971**, 2820−2820. (c) Pearson, P.; Kepert, C. M.; Deacon, G. B.; Spiccia, L.; Warden, A. C.; Skelton, B. W.; White, A. H. *Inorg. Chem.* **2004**, *43*, 683−691 and references cited therein.

(7) (a) Collman, J. P.; Roper, W. R. *J. Am. Chem. Soc.* **1965**, *87*, 4008−4009. (b) Colton, R.; Frathing, R. H. *Aust. J. Chem.* **1971**, *24*, 903−909. (c) Hiraki, K.; Obayashi, Y.; Oki, Y. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 1372−1376.

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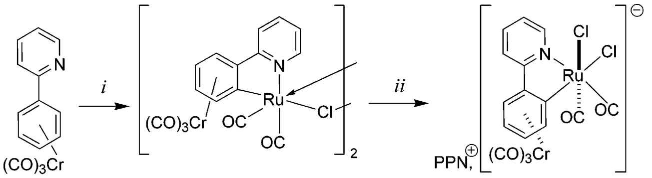
Scheme 1[a]



1 **2** [PPN][(p*S**-*OC*-6-42*A**)-**3**]

[a] *i*: $[Ru(CO)_2Cl_2]_n$, Na_2CO_3, 1,2-dimethoxyethane, reflux, 83%. *ii*: [PPN]Cl, acetone, or CH_2Cl_2, rt, 96%.

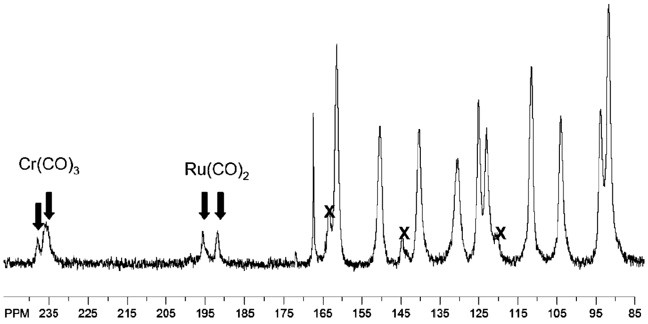


Figure 1. CP-MAS ^{13}C NMR spectrum of solid **2** at room temperature (Bruker DSX-500 spectrometer with a Bruker ^1H/X CP-MAS probe 3.2-mm-o.d. rotor): cross-polarization contact time, 3 ms; recycle delay, 4 s; 90° pulse, 2.6 μs; decoupling power, 100 kHz; spinning frequency, 20 kHz; 58 000 scans acquired, exponential multiplication with a 10 Hz line broadening.

to deep red, and a dense yellow precipitate of **2** started to form. The recovered yellow-orange solid displayed low solubility in coordinating solvents such as dimethyl sulfoxide, acetone, and 1,2-dimethoxyethane and almost no solubility in CH_2Cl_2, $CHCl_3$, Et_2O, and tetrahydrofuran. Compound **2**, which was expected to be a mixture of isomeric μ-chloro dimers, could not be analyzed by conventional solution NMR experiments. Indeed, solution ^1H and ^{13}C NMR analyses of **2** in dimethyl sulfoxide-d_6 afforded only one set of signals, suggesting that the chloro bridges underwent disruption by solvation of the ruthenium center (cf. Supporting Information). It is worth noting that a room-temperature cross-polarization magic angle spinning (CP-MAS) ^{13}C NMR experiment (Figure 1) carried out with solid **2** produced a spectrum similar to the one measured in dimethyl sulfoxide-d_6 in the 85−170 ppm region. Two relatively well-resolved and sharp ruthenium-bound carbonyl ligand resonances were detected at 191.8 and 195.6 ppm, which suggests that only one type of stereochemistry at the ruthenium exists. Because μ-chloro bridging is a source of stereoisomerism, at this early stage we cannot rule out the existence, in the solid state, of several isomeric dimers. Indeed, two broad signals of nonequivalent intensities were detected at 235.7 and 237.8 ppm. These signals may either result from a hindered rotation of the $Cr(CO)_3$ moiety[8] or indicate the existence of at least two isomers of dimer **2**.

Because the exact stereochemistry(ies) of **2** could not be firmly established, we resorted to its treatment with bis(triphenyl)phosphoranylideneammonium chloride (abbreviated as [PPN]Cl) at room temperature in order to generate a more soluble monomeric anionic chlororuthenate (Scheme 1).[6a,b] The experiment afforded a single stereoisomer [PPN]-**3**, which displayed a fair solubility in most dry polar solvents and some lipophilicity, allowing its purification by flash chromatography in acetone. Electrospray mass spectrometry (ES-MS) analyses of [PPN]**3** in the negative and positive modes complemented the analytical characterization of this salt. Figure 2 displays its molecular structure resolved by X-ray diffraction analysis.[9] It shows a cis relationship for the two ruthenium-bound carbonyl ligands and for the two chloro ligands. The carbonyl ligand of the principal axis of the ruthenium-centered octahedron lies in the vicinity of the $Cr(CO)_3$ fragment.

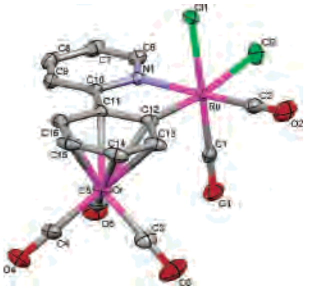
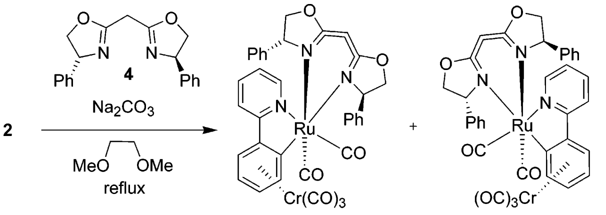


Figure 2. CCDC mercury "ellipsoid" view of the organometallic anionic residue of [PPN]**3** drawn at the 30% probability level. Atoms of hydrogen and the PPN^+ residue have been omitted for the sake of clarity. Selected interatomic distances (Å): Ru−Cl1, 2.4286(8); Ru−Cl2, 2.4895(10); Ru−N1, 2.129(2); Ru−C1, 1.861(3); Ru−C2, 1.860(3); Ru−C12, 2.046(3); Cr−C12, 2.290(3); Cr−C15, 2.199(4). Selected angles (deg): Cl1−Ru−Cl2, 90.12(3); Cl1−Ru−N1, 87.54(7); Cl1−Ru−C12, 86.07(8); Cl2−Ru−N1, 92.39(6).

In a subsequent experiment, the stability of the configuration at the ruthenium center was probed by treating **2** with a 4-fold excess/ruthenium of enantiopure (*R*,*R*)-**4**[10] (ee > 98%) in boiling 1,2-dimethoxyethane in the presence of Na_2CO_3 (eq 1). The reaction afforded two neutral diastereomers, **5a** and **5b**, in a 1:1.3 ratio with an overall yield of 66%. The latter two compounds, which differ only by the configurations of the planar chiral [C, N] chelate and the centrochiral ruthenium atom (Figure 3), were readily separated by chromatography (R_f of 1:2.2 acetone/pentane: **5a**, 0.73; **5b**, 0.65). Both **5a** and **5b** retained their configuration upon heating in refluxing 1,2-dimethoxyethane.



(1)

(*R*,*R*, p*S*, *OC*-6-42-*A*) **5a** (*R*,*R*, p*R*, *OC*-6-42-*C*) **5b**

$[\alpha]_D(CH_2Cl_2, 26\ °C,\ c\ 0.018) =$ −881 −168

The absolute structures[11] of both **5a**[9] (Figure 3) and **5b**[9] (cf. Supporting Information) indicate a position of the ruthenium-bound carbonyl ligands relative to the [C, N] chelate and the $Cr(CO)_3$ similar to that observed in **3**, which is best described by stereochemical descriptor *OC*-6-42.[12] The [N, N] chelate in both compounds occupies the principal axis of the octahedron and the equatorial position cis to the pyridyl group. In **5a**, a phenyl residue of the bis(oxazoli-

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(8) Wagner, G. W.; Hanson, B. E. *Inorg. Chem.* **1987**, *26*, 2019−2022.

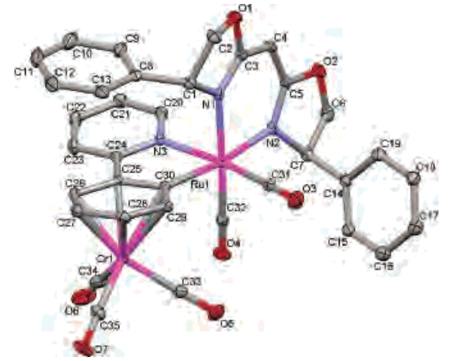


Figure 3. CCDC mercury "ellipsoid" view and absolute structure of **5a** drawn at the 30% probability level. Atoms of hydrogen have been omitted for the sake of clarity. Selected interatomic distances (Å): Ru−C31, 1.874(2); Ru−C32, 1.882(2); Ru−C30, 2.063(2); Ru−N1, 2.131(2); Ru−N3, 2.141(2); Ru−N2, 2.143(2); Cr−C30, 2.302(2); Cr−C27, 2,214(2). Selected angles (deg): C31−Ru−C32, 91.6(1); C32−Ru−C30, 90.6(1); C30−Ru−N3, 78.61(7); N1−Ru−N2, 86.80(7); C25−C30−C29, 116.4(2); C26−C27−C28, 119.8(2). Flack's *x* parameter: −0.012(14).

nylmethylidene) ligand stacks with the vicinal [C, N] chelate with an interplanar distance and an angle of ca. 3.3 Å and 10°.

It is worth noting that preliminary results on the ruthenation of 2-ferrocenylpyridine[13] (**6**) suggest a similar stereochemical trend. According to ^{1}H NMR analyses, the metalation reaction delivered a rough 2:1.5:1 mixture of at least three soluble stereoisomers of the corresponding cycloruthenated 2-ferrocenylpyridine μ-chloro-bridged dimer **7** in 41% yield (Scheme 2). The treatment of this mixture either with [*n*Bu$_4$N]Cl or with [PPN]Cl (cf. Supporting Information) afforded a single product putatively identified, according to ES-MS and NMR analyses, as anion **8** (Scheme 2). Unfortunately, the latter salt repeatedly failed to provide crystals suitable for X-ray diffraction analyses. Nonetheless, the molecular structure of **7a**,[9] a component of the above-mentioned mixture (Figure 4), reveals a quasi C_2 symmetry (the symmetry axis is defined by the Cl2−Cl1 segment) and, like in [PPN]**3**, a relative *OC*-6-42 configuration at the ruthenium center.

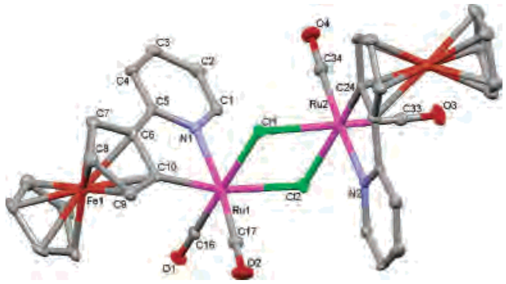
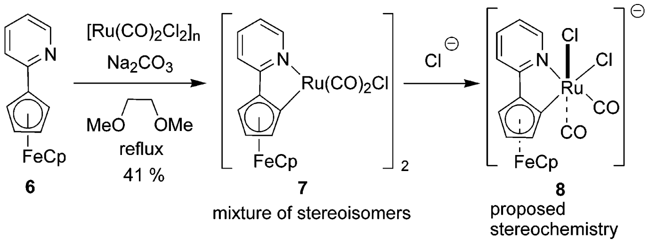


Figure 4. CCDC mercury "ellipsoid" view and structure of **7a** drawn at the 30% probability level. Atoms of hydrogen and molecules of CH$_2$Cl$_2$ have been omitted for the sake of clarity. Selected interatomic distances (Å): Ru1−Cl1, 2.475(2); Ru1−Cl2, 2.521(3); Ru2−Cl1, 2.486(3); Ru2−Cl2, 2.535(3); Ru1−N1, 2.180(9); Ru1−C17, 1.883(12); Ru1−C16, 1.845(10); Ru1−C10, 2.050(10); Ru2−C24, 2.033(10); Fe1−C10, 2.090(11). Selected angles (deg): C10−Ru1−N1, 79.6(4); Ru1−Cl1−Ru2, 98.31(8); Ru1−Cl2−Ru2, 95.86(8); C24−Ru2−N2, 79.4(4); Cl1−Ru1−Cl2, 83.16(8).

Scheme 2



In conclusion, the direct ortho ruthenation of both π-coordinated compounds **1** and **6** by [Ru(CO)$_2$Cl$_2$]$_n$ is somewhat efficient. It appears to be stereoselective as far as the relative configuration at the ruthenium center in the product is concerned: the base-promoted coordination of bidentate ligand **4**, which is seemingly thermodynamically controlled, preserves the relative configuration at the ruthenium center observed in [PPN]**3**. Further investigations on the origin of the stereoselectivity of the cycloruthenation reactions reported here as well as explorations of the activity of dimeric planar chiral ruthenacycles in atom transfer catalysis are underway.

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Supporting Information Available: Experimental procedures, circular dichrograms, ^{1}H and ^{13}C NMR spectra, ES-MS spectra, solid-state CP-MAS ^{13}C NMR spectra, and X-ray crystallographic files (CIF format). This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) Crystal data for [PPN]**3**: $C_{52}H_{38}Cl_2CrN_2O_5P_2Ru$, $M = 1056.75$, $a = 9.6520(2)$ Å, $b = 15.4920(3)$ Å, $c = 17.4660(3)$ Å, $\alpha = 68.6210(10)°$, $\beta = 84.5020(9)°$, $\gamma = 73.4510(8)°$, $V = 2331.13(8)$ Å^3, $T = 173$ K, space group $P\bar{1}$ (No. 2), $Z = 2$, μ(Mo Kα) = 0.791 mm^{-1}, 20 175 reflections collected, 13 604 unique reflections ($R_{int} = 0.031$), $R_1 = 0.0490$ [$I > 2\sigma(I)$], w$R_2 = 0.1167$ (all data). Crystal data for **5a**: $C_{35}H_{25}CrN_3O_7Ru$, $M = 752.65$, $a = 9.1010(10)$ Å, $b = 10.3070(10)$ Å, $c = 16.4280(10)$ Å, $\beta = 95.1000(10)°$, $V = 1534.9(2)$ Å^3, $T = 150.0(1)$ K, space group $P2_1$ (No. 4), $Z = 2$, μ(Mo Kα) = 0.902 mm^{-1}, 7411 reflections collected, 7411 unique reflections ($R_{int} = 0$), $R_1 = 0.0238$ [$I > 2\sigma(I)$], w$R_2 = 0.0657$ (all data). Crystal data for **5b**: $C_{35}H_{25}CrN_3O_7Ru{\cdot}CH_2Cl_2$, $M = 837.58$, $a = 10.7850(10)$ Å, $b = 11.9460(10)$ Å, $c = 26.1280(10)$ Å, $V = 3366.3(4)$ Å^3, $T = 150.0(1)$ K, space group $P2_12_12_1$ (No. 19), $Z = 4$, μ(Mo Kα) = 0.985 mm^{-1}, 17 743 reflections collected, 9653 unique reflections ($R_{int} = 0.0286$), $R_1 = 0.0351$ [$I > 2\sigma(I)$], w$R_2 = 0.0938$ (all data). Crystal data for **7a**: $C_{34}H_{24}Cl_2Fe_2N_2O_4Ru_2{\cdot}2CH_2Cl_2$, $M = 1079.14$, $a = 11.5130(8)$ Å, $b = 13.3500(9)$ Å, $c = 14.5880(12)$ Å, $\alpha = 116.896(5)°$, $\beta = 101.656(4)°$, $\gamma = 96.700(5)°$, $V = 1902.0(3)$ Å^3, $T = 173(2)$ K, space group $P\bar{1}$ (No. 2), $Z = 2$, μ(Mo Kα) = 1.990 mm^{-1}, 13 323 reflections collected, 9004 unique reflections ($R_{int} = 0.077$), 5712 observed reflections [$I > 2\sigma(I)$], $R_1 = 0.1099$, w$R_2 = 0.2031$ [$I > 2\sigma(I)$].

(10) Aggarval, V. K.; Bell, L.; Coogan, M. P.; Jubault, P. *J. Chem. Soc., Perkin Trans.* **1998**, 2037−2042.

(11) Flack, H. D.; Bernardinelli, G. *Acta Crystallogr.* **1999**, *A55*, 908−915.

(12) *IUPAC Nomenclature of Inorganic Chemistry, Recommendations 1990*; Leigh, G. J., Ed.; Blackwell Scientific: Oxford, U.K., 1990.

(13) Schloegl, K.; Fried, M. *Monatsh. Chem.* **1963**, *94*, 537−543.