

# Concise Route to Highly Reactive Ruthenium Metathesis Catalysts Containing a Labile Donor and an N-Heterocyclic Carbene (NHC) Ligand

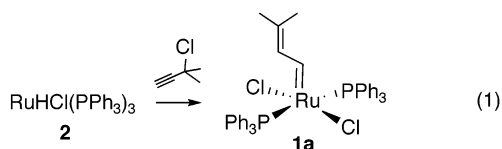
Jay C. Conrad, Glenn P. A. Yap, and Deryn E. Fogg\*

Center for Catalysis Research and Innovation, Department of Chemistry, University of Ottawa, 10 Marie Curie, Ottawa, Ontario, Canada K1N 6N5

Received March 19, 2003

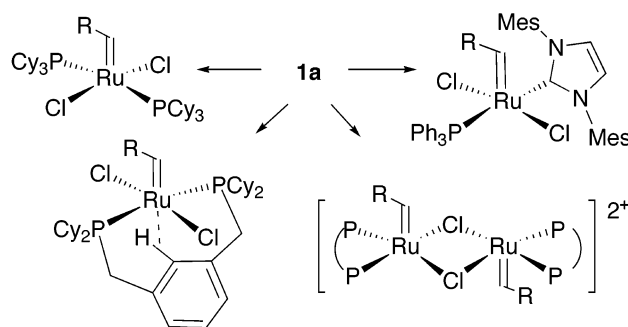
**Summary:** Complex **1a**, containing two labile phosphine ligands, is a versatile precursor to the important class of olefin metathesis catalysts containing an activating NHC ligand and a labile phosphine donor. The lability of the remaining PPh<sub>3</sub> ligand can also permit disubstitution by IMes; this side reaction is easily prevented by precise stoichiometric control.

Catalytic formation of new C–C bonds by olefin metathesis has enabled major advances in both organic synthesis and materials chemistry.<sup>1</sup> The scope of the reaction has increased dramatically with the advent of robust functional-group-tolerant catalysts based on ruthenium.<sup>1,2</sup> Considerable current effort has focused on designing new Ru–alkylidene catalysts with enhanced activity, selectivity, and lifetime. A versatile entry point into phosphine derivatives is RuCl<sub>2</sub>L<sub>2</sub>(=CHR) (**1a**; L = PPh<sub>3</sub>, R = CH=CMe<sub>2</sub>), accessible in one step from commercially available **2** (eq 1).<sup>3</sup> A key feature



in **1a** is the presence of two arylphosphine ligands, which are more weakly bound to the metal center than the ubiquitous alkylphosphine donors. This amplified phosphine lability renders **1a** much more reactive than Grubbs' catalyst **1b** (L = PCy<sub>3</sub>, R = Ph), the most widely

used precursor to new Ru alkylidenes.<sup>4,5</sup> Indeed, the synergy between an activating N-heterocyclic carbene (NHC) ligand and a labile PPh<sub>3</sub> donor is responsible for the exceptionally high metathesis activity of "mixed ligand" catalysts RuCl<sub>2</sub>(NHC)(PPh<sub>3</sub>)(=CHR) (**4**).<sup>5–7</sup> Of keen interest, therefore, is expansion of the synthetic chemistry based on **1a** to include routes to the NHC class of complexes (Figure 1).



**Figure 1.** Metathesis catalysts accessible from **1a**.

In our original synthesis of **1a**, we remarked that small amounts (5–10%) of a carbyne byproduct were formed, which could not be removed by reprecipitation.<sup>3b</sup> While this did not impede isolation of phosphine derivatives in high yields, attempts to install NHC ligands such as *N,N*-bis(mesityl)imidazol-2-ylidene (IMes)<sup>8</sup> give unidentified side products that cannot be separated. Here we describe a modified synthesis of **1a** to give a carbyne-free product, which provides convenient access to "mixed ligand" derivatives such as **4a** (eq 2).<sup>9</sup> The lability of bound PPh<sub>3</sub>, which underlies the catalytic activity of this class of catalysts, can also result in formation of unreactive bis(NHC) derivatives such as **5a**,

\* To whom correspondence should be addressed. E-mail: dfogg@science.uottawa.ca. Fax: (613) 562-5170.

(1) Recent reviews: (a) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18. (b) Fürstner, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3012. (c) Buchmeiser, M. R. *Chem. Rev.* **2000**, *100*, 1565.

(2) Grubbs, R. H.; Miller, S. J.; Fu, G. C. *Acc. Chem. Res.* **1995**, *28*, 446.

(3) Precursor **1a** gives access to Ru–alkylidenes containing mono-, bi-, or tridentate phosphine ligands: (a) Volland, M. A. O.; Rominger, F.; Eisenträger, F.; Hofmann, P. *J. Organomet. Chem.* **2002**, *641*, 220. (b) Amoroso, D.; Snelgrove, J. L.; Conrad, J. C.; Drouin, S. D.; Yap, G. P. A.; Fogg, D. E. *Adv. Synth. Catal.* **2002**, *344*, 757. We find that synthesis of **1a** at –15 °C followed by warming to room temperature over 1.5 h, as in ref 3a, has no effect on formation of the carbyne byproduct but significantly increases bimolecular decomposition.

(4) Advantages of **1a** vs the reactive precursor RuCl<sub>2</sub>(IMesH<sub>2</sub>)(py)<sub>2</sub>(CHPh) (**3**)<sup>5</sup> are the accessibility of a more diverse ligand set and synthetic efficiency (**3** requiring a multistep synthesis from RuCl<sub>2</sub>(PPh<sub>3</sub>)<sub>3</sub>).

(5) Sanford, M. S.; Love, J. A.; Grubbs, R. H. *Organometallics* **2001**, *20*, 5314.

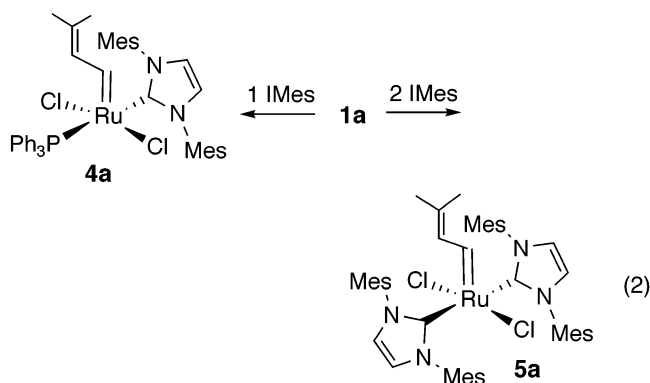
(6) (a) Huang, J.; Stevens, E. D.; Nolan, S. P.; Peterson, J. L. *J. Am. Chem. Soc.* **1999**, *121*, 2674. (b) Huang, J.; Schanz, H.-J.; Stevens, E. D.; Nolan, S. P. *Organometallics* **1999**, *18*, 5375.

(7) Weskamp, T.; Kohl, F. J.; Hieringer, W.; Gleich, D.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **1999**, *38*, 2416.

(8) Arduengo, A. J.; Dias, H. V. R.; Harlow, R. L.; Kline, M. *J. Am. Chem. Soc.* **1992**, *114*, 5530.

(9) Prior routes to related complexes: **4b** (R = Ph) was obtained by reaction of IMes with **1c** (L = PPh<sub>3</sub>, R = Ph).<sup>6a</sup> Its IMesH<sub>2</sub> analogue was obtained by reaction of PPh<sub>3</sub> with **3**.<sup>5</sup>

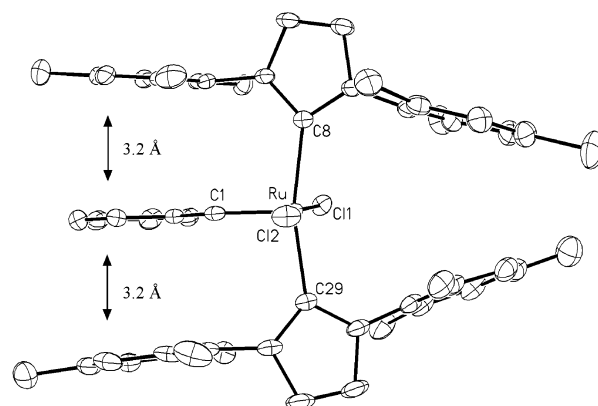
containing two bulky IMes ligands.<sup>10</sup>



We noted previously that the proportion of carbyne increased on use of undistilled or excess 3-chloro-3-methyl-1-butyne and speculated that an acidic contaminant was responsible.<sup>3b</sup> Indeed, this side reaction can be completely suppressed by carrying out the synthesis in the presence of base. Reaction of 1 equiv of IMes with a homogeneous solution of carbyne-free **1a** yields solely **4a**.

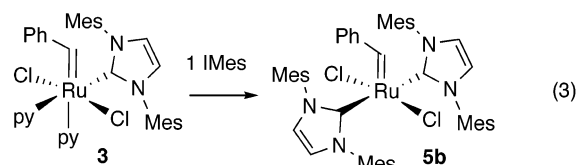
Treatment of suspensions of **1a** with 1 equiv of IMes gives mixtures of **4a**, unreacted **1a**, and a new product, which we formulate as the bis(IMes) derivative **5a**. Use of excess IMes effects quantitative transformation to **5a**. While isolation and structural characterization were hampered by its high solubility, the identity of **5a** is strongly supported by NMR and mass spectrometric data. <sup>31</sup>P NMR analysis shows only free PPh<sub>3</sub>, and the IMes carbene carbon and the alkylidene carbon C<sub>α</sub> appear as singlets. The latter signal correlates (HMQC) with a doublet for H<sub>α</sub> (19.55 ppm, <sup>3</sup>J<sub>HH</sub> = 11.2 Hz). A key piece of evidence indicating the presence of two IMes ligands is the 1:8 integration ratio of H<sub>α</sub> vs the singlet for the mesitylene protons (6.65 ppm) or 1:4 vs the IMes olefinic protons (5.98 ppm). The electrospray mass spectrum shows the molecular ion minus one chloride, with the appropriate isotope pattern.

Facile formation of **5a** via phosphine displacement from **1a** contrasts with the inaccessibility of bis(IMes) derivatives from **1b**, even on treatment with a 10-fold excess of IMes.<sup>6</sup> The resistance of **1b** to disubstitution was originally attributed to steric constraints present in the IMes systems,<sup>6</sup> vs the N-alkyl analogues of **5a**.<sup>10</sup> Further suggestions of steric pressure may be read into the participation of a Ru–bis(IMes) species in reactions involving IMes activation and displacement.<sup>11</sup> However, this is difficult to reconcile with rotation about the Ru–C(NHC) bond implied by the equivalence of the IMes signals in **5a**.<sup>12</sup> In the hope of accessing a crystalline product, we undertook the synthesis of benzylidene analogue **5b** via **3**,<sup>5</sup> in which one IMes ligand is



**Figure 2.** ORTEP structure of **5b** (hydrogen atoms and solvate omitted), with thermal ellipsoids at the 30% probability level. Selected bond distances (Å) and angles (deg) with estimated standard deviations: Ru–C1 = 1.829(3), Ru–C8 = 2.117(3), Ru–C29 = 2.108(3), Ru–Cl1 = 2.3872(9), Ru–Cl2 = 2.3999(8); C1–Ru–C29 = 96.80(13), C1–Ru–C8 = 98.00(12), C29–Ru–C8 = 164.41(12), C1–Ru–Cl1 = 104.88(10), C29–Ru–Cl1 = 91.91(9), C8–Ru–Cl1 = 89.03(8), C1–Ru–Cl2 = 88.96(10), C29–Ru–Cl2 = 86.87(9), C8–Ru–Cl2 = 88.51, Cl1–Ru–Cl2 = 166.16(3).

preinstalled (eq 3). Reaction of **3** is 40% complete after



1 h and quantitative within 8 h at 22 °C. Complex **5b** is isolated as a crystalline, air-stable solid. X-ray analysis (Figure 2)<sup>13,14</sup> reveals a distorted square pyramid, in which the Ru–C(IMes) distances are statistically identical with those for the *N,N*-diisopropylimidazol-2-ylidene analogue<sup>10</sup> and minimally longer than the value of 2.069(11) Å for RuCl<sub>2</sub>(PCy<sub>3</sub>)(IMes)(=CHPh).<sup>6a</sup> The Ru–C(alkylidene) distance is ca. 1.8 Å in all three cases. Noteworthy in the structure of **5b** is the minimization of unfavorable steric interactions by  $\pi$ -stacking of the benzylidene and mesitylene aromatic rings, ca. 3.2 Å apart, and within 8° of coplanarity.

(13) Data for X-ray analysis of **5b**: crystals from toluene, C<sub>52.5</sub>H<sub>58</sub>Cl<sub>2</sub>N<sub>4</sub>Ru (*M* = 917.00); crystal size 0.20 × 0.10 × 0.10 mm; monoclinic, *C2/c*, *Z* = 8, *a* = 35.144(2) Å, *b* = 15.4590(11) Å, *c* = 20.9336(15) Å;  $\alpha$ ,  $\gamma$  = 90°,  $\beta$  = 123.191 10(10)°; *V* = 9517.4(12) Å<sup>3</sup>;  $\rho_{\text{calcd}}$  = 1.280 mg/m<sup>3</sup>;  $2\theta$  = 1.38–29.00°; absorption coefficient 0.480 mm<sup>-1</sup>; *T* = 203(2) K;  $\lambda$  = 0.7107 Å; 34 541/11 386 measured/unique reflections; semiempirical from equivalents (SADABS, Bruker AXS, Madison, WI, 2000); maximum and minimum transmission 0.9535 and 0.9101; full-matrix least squares on *F*<sup>2</sup>, goodness of fit on *F*<sup>2</sup> 1.026; direct methods completed with difference Fourier syntheses and refined with full-matrix least-squares procedures based on *F*<sup>2</sup>. A molecule of toluene solvent was located disordered at a 2-fold axis. All hydrogen atoms were treated as idealized contributions. All scattering factors are contained in the SHELXTL 6.12 program library (G. M. Sheldrick, Bruker AXS, Madison, WI, 2001). Crystallographic data (excluding structure factors) have been deposited with the Cambridge Crystallographic Data Centre as CCDC publication #203512. These data can be obtained free of charge on application to the CCDC at 12 Union Road, Cambridge CB2 1EZ, U.K.; fax (+44) 1223-336-033; email deposit@ccdc.cam.ac.uk.

(14) Following the original submission of this MS, a report appeared describing synthesis of a bis(IMesH<sub>2</sub>) complex analogous to **5b**. Crystallographic data for a “mixed” IMes/IMesH<sub>2</sub> complex were also reported, though bond lengths and angles are compromised by disorder between the two NHC ligands: Trnka, T. M.; Morgan, J. P.; Sanford, M. S.; Wilhelm, T. E.; Scholl, M.; Choi, T.-L.; Ding, S.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2003**, *125*, 2546.

(10) Alkyl-NHC analogues have been described: (a) Weskamp, T.; Schattenmann, W. C.; Spiegler, M.; Herrmann, W. A. *Angew. Chem., Int. Ed.* **1998**, *37*, 2490. (b) Herrmann, W. A. *Angew. Chem., Int. Ed.* **1999**, *38*, 262.

(11) Jazzar, R. F. R.; Macgregor, S. A.; Mahon, M. F.; Richards, S. P.; Whittlesey, M. K. *J. Am. Chem. Soc.* **2002**, *124*, 4944.

(12) This implies a smaller rotational barrier for **5a** vs **4a**: two trans-orthogonal “banana-shaped” IMes ligands are presumably permitted greater motion than an IMes ligand trans to the 3-D bulk of a phosphine ligand.

The foregoing expands the range of Ru(II) alkylidenes accessible from **1a** to include the important class of metathesis catalysts containing an N-heterocyclic carbene and a labile phosphine donor. This versatile precursor can thus be used to generate, in one step, a library of metathesis catalysts, including PCP-pincer, mono- or bidentate phosphines, and NHC ligands. The presence of labile phosphine donors in **1a** facilitates ligand exchange, and retention of one such ligand is desired for high metathesis activity in the products. In the presence of excess IMes ligand, however, double displacement affords bis(IMes) products. The ease of the latter reaction under mild conditions should be recog-

nized in designing efficient routes to *mono*(NHC) complexes; it is also potentially relevant to their catalytic deactivation.

**Acknowledgment.** This work was supported by the NSERC of Canada, the Canada Foundation for Innovation, and the Ontario Innovation Trust.

**Supporting Information Available:** Text giving synthetic and spectroscopic details for **1a**, **4a**, and **5a,b** and tables giving crystallographic data for **5b**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

OM0302084