Metallacycles

DOI: 10.1002/ange.201000356

Concerted [2+2] Cycloaddition of Alkenes to a Ruthenium–Phosphorus Double Bond**

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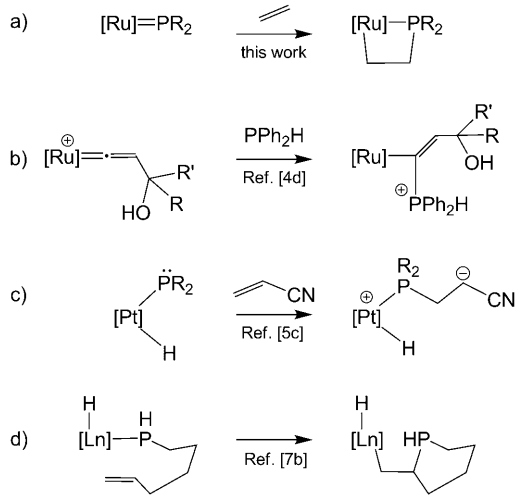
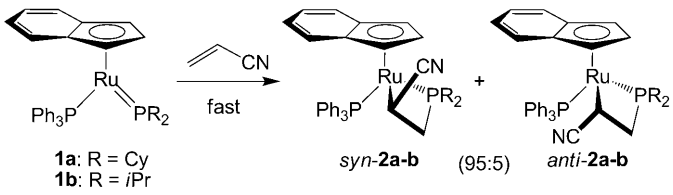
We recently described a terminal phosphido complex of ruthenium containing a Ru=PR_2 π bond, and demonstrated its high activity in 1,2-addition reactions of polar and nonpolar substrates.[1] Herein we report the [2+2] cycloaddition reactions of this planar phosphido complex with both activated and simple alkenes to yield metallaphosphacyclobutanes, and we provide evidence for a concerted cycloaddition pathway in these P–C bond-forming reactions (Scheme 1a). Metal-mediated P–C bond-forming reactions



Scheme 1. Types of metal-mediated P–C bond formation involving primary or secondary phosphine reagents.

represent a direct and potentially stereoselective route to useful ligands or reagents,[2] but the development and understanding of metal-catalyzed phosphination and hydrophosphination by primary or secondary phosphines lags behind that of the corresponding amination chemistry.[3] Among late-metal examples of such catalysis, the critical P–C bond-forming step has been attributed either to nucleophilic attack of free phosphine onto an unsaturated substrate that has been activated through binding with the metal (e.g. Scheme 1b),[4] or to attack of the strongly nucleophilic P of a phosphido intermediate (M–PR_2) onto a substrate containing an electrophilic carbon atom (e.g. Scheme 1c).[5] Lanthanide- or calcium-catalyzed hydrophosphination of alkynes and alkenes,[6–8] which involve the insertion of an unsaturated substrate into the metal–phosphorus bond of a phosphido intermediate (Scheme 1d), include the only examples of metal-mediated hydrophosphination of simple alkenes.[7b,8] Our results point to an alternative mechanism for hydrophosphination catalyzed by late-metals that will allow the incorporation of a much wider range of alkene substrates (electron rich and electron deficient) than are currently viable in this transition metal mediated process.[9]

The five-coordinate half-sandwich complex [Ru(η^5-indenyl)(PR_2)(PPh_3)] (**1a**,**b**) reacts rapidly with acrylonitrile to give two isomers of the metallacyclic product **2a**,**b**, in which the nitrile group on the ruthenium-bound α-carbon atom is oriented either *syn* or *anti* with respect to the Ru–indenyl bond (Scheme 2). In solution, these complexes show diag-



Scheme 2.

nostic upfield $^{31}P\{^1H\}$ NMR signals due to the phosphorus atom in the metallacycle (e.g., *syn*-**2a**: $\delta = -13.3$ ppm), and upfield $^{13}C\{^1H\}$ NMR signals for the α-carbon atom attached to Ru (e.g., *syn*-**2a**: $\delta = -28.3$ ppm). $^{13}C\{^1H\}$DEPT-135 NMR analysis of a mixture of *syn*- and *anti*-**2a** confirmed their identical regiochemistry, showing that the α-carbon atom in both isomers ($\delta = -29.1$ ppm in ^{13}C NMR spectrum for *anti*-**2a**) contains one proton and not two. Unequivocal assignment of the stereochemistry of *syn*-**2b** was obtained from solution NMR studies of a purified sample, which allowed identification of the signal resulting from the lone proton on the α-carbon atom, and showed its proximity to the PPh_3 aryl protons.[10] X-ray crystallography confirmed the analogous *syn* structure of the major isomer of **2a** in the solid state (Figure 1).[11] We detected no trace of the other regioisomers

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[**] We are grateful to the NSERC of Canada for financial support.
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201000356.

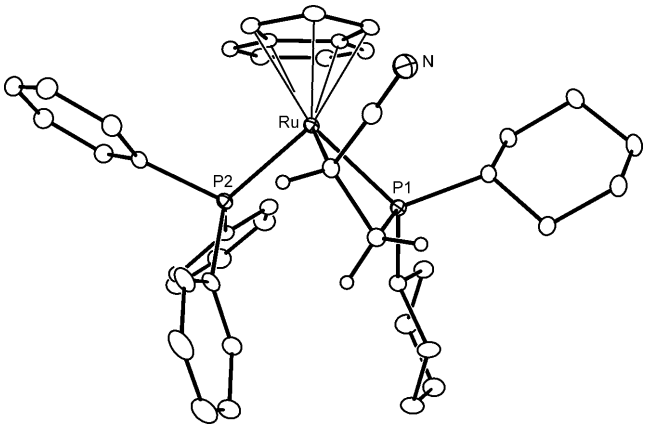


Figure 1. Molecular structure of *syn*-**2a**.[11] The thermal ellipsoids are drawn at the 20% probability level.

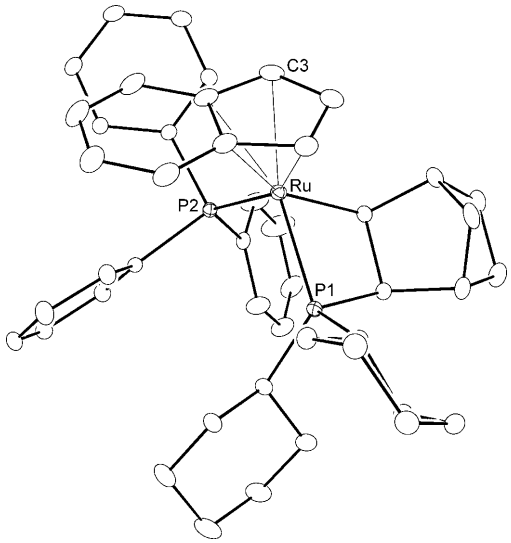
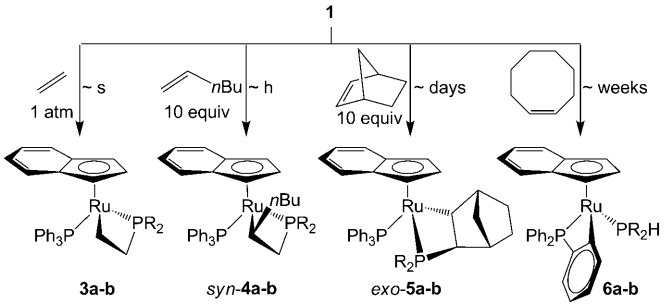


Figure 2. Molecular structure of *exo*-**5a**.[19] The thermal ellipsoids are drawn at the 20% probability level

of complexes **2a**,**b**, in which the nitrile is bound to the carbon atom β to Ru in the metallacycle. Despite the high basicity of P in **1a**,**b**,[1a] we did not observe base-catalyzed acrylonitrile polymerization in these reactions,[12] nor did we see telomerization resulting from additional insertions into the Ru–C bond.[5c] Finally, we previously showed that **1a**,**b** in solution exists in equilibrium with a small amount of phospha-alkene/hydride isomer (e.g., for **1b**, [Ru(P{=C(CH_3)$_2$}*i*Pr)(H)(η^5-indenyl)(PPh_3)]).[1] Apparently conversion of this structural isomer into **1** occurs more rapidly than its reaction with alkenes, since we neither see it in any of the product mixtures described in this paper, nor do we see any products attributable to its cycloaddition or insertion reactions.

Simple alkenes also undergo [2+2] cycloaddition reactions at the Ru–P π bond in **1a**,**b** (Scheme 3). Solutions of **1** placed under 1 atm of ethylene rapidly and quantitatively



Scheme 3.

transform into [Ru(η^5-indenyl)(κ^2-*C*H_2CH_2*P*R_2)(PPh_3)] (**3a**,**b**) at room temperature, as determined by $^{31}P\{^1H\}$ NMR analysis. Similar products were obtained from the addition of 1-hexene (**4a**,**b**) and the strained internal alkene norbornene (**5a**,**b**); the latter gave exclusive addition at the *exo* face (see the Supporting Information and Figure 2). For 1:1 reactions of these more sterically demanding substrates long reaction times were required, which resulted in competing decomposition to the orthometalated complexes **6a**,**b**.[1b] The use of excess alkene gave much less decomposition and shorter reaction times (although still longer than that for ethylene; Scheme 3), a qualitative indication of the rate dependence of cycloaddition upon the concentration of alkene. The sensitivity of this reaction to the steric bulk of the incoming alkene is also highlighted by the complete absence of cycloaddition when one equivalent of cyclooctene was added to **1a**,**b**, even after four weeks, by which time the samples had mostly decomposed into **6a**,**b**.

The participation of simple alkenes in these reactions, and the sensitivity of rates to the size of the alkene, point to a possible concerted [2+2] cycloaddition mechanism, as opposed to the stepwise Michael-addition mechanism responsible for other late-metal phosphido-mediated P–C bond-forming reactions.[13] Furthermore, we observe no change in the rate of the cycloaddition of 1-hexene to **1a**,**b** when this reaction is carried out in a 1:1 mixture of [D_8]toluene/THF, relative to that in pure [D_8]toluene.[14] If a stepwise reaction were occurring, we would expect the rate to increase in the more polar solvent mixture because of the stabilization of a zwitterionic intermediate.[15] More compelling evidence for the concerted nature of these [2+2] cycloadditions comes from the reactions of *cis*- and *trans*-[D_2]ethylene with **1a**,**b**. The barrier to rotation around the terminal CHD^- group in a putative zwitterionic intermediate would be sufficiently low to give significant isotopic scrambling (i.e., four isomers: two *cis* and two *trans*) if a stepwise mechanism were important.[16,17] The reactions proceed rapidly at room temperature, giving quantitative conversion into yellow solutions of [D_2]-**3a**,**b** that each contain just two major isotopomers in a 1:1 ratio, as determined by $^{31}P\{^1H\}$ NMR analysis (Figure 3).[18] These results indicate that stereochemistry at the alkene is conserved, and provide strong evidence for the importance of a concerted cycloaddition mechanism in this P–C bond-forming reaction.

Inspection of the molecular structure of *syn*-**2a** (Figure 1) suggests that the diastereoselectivity observed for products **2** and **4** results from crowding at Ru in these metallacycles: the

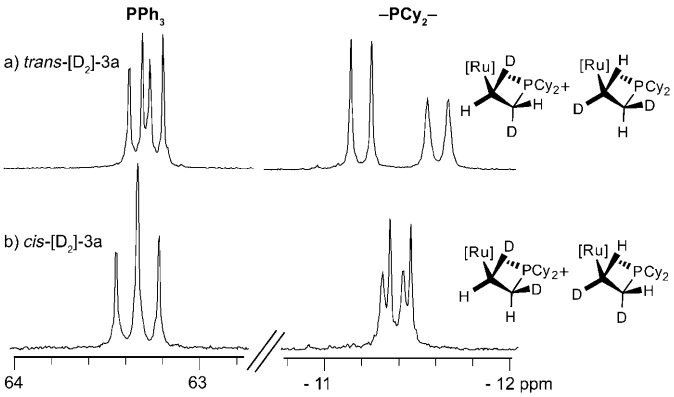


Figure 3. 202.46 MHz $^{31}P\{^1H\}$ NMR spectra showing a total of four distinct products from the addition of a) *trans*-[D_2]ethylene and b) *cis*-[D_2]ethylene to **1a** in [D_8]toluene. [Ru] = Ru(η^5-indenyl)(PPh3). Downfield signals represent PPh_3, and upfield signals represent PCy_2.

proton on the metallacycle α-carbon atom points down, toward the bulky PPh_3 ligand in the *syn*-isomer, whereas for *anti*-**2** or *anti*-**4** the more sterically demanding nitrile or butyl group would point down. However, DFT calculations indicate that the optimized structures of *syn*- and *anti*-**2a** are isoenergetic at zero Kelvin, although thermodynamic corrections lead to a $\Delta G°$ value that is 5.3 kcal mol^{-1} lower for *syn*-**2a** than that for *anti*-**2a**. Interestingly, when PPh_3 is replaced with PH_3 in these calculations, which should eliminate the anticipated steric preference for the *syn* isomer, the optimized structure of the resulting *syn* isomer is 1.5 kcal mol^{-1} lower in energy than the *anti* isomer, and thermodynamic corrections give a $\Delta G°$ value for the *syn* isomer that is 4.6 kcal mol^{-1} lower than that for the *anti* isomer. Therefore, differences in steric crowding in the two diastereomers are small, and their ground-state stabilities are comparable. This suggests that transition-state effects, possibly electronic in origin,[20] dictate the observed stereoselectivity (i.e., these are kinetic product distributions).[21] We continue to search computationally for the relevant transition states in these concerted cycloaddition reactions to explain both the diastereo- and regioselectivity observed.

There are surprisingly few examples of discrete complexes containing metal–heteroatom bonds that undergo the insertion of simple alkenes, despite the wide range of metal-catalyzed reactions of alkenes for which the proposed mechanisms invoke such chemistry.[22] The cycloaddition reactions reported herein include the first examples of intermolecular insertion of simple alkenes into a metal–phosphorus bond, and are distinct from the lanthanide- and calcium-catalyzed hydrophosphination described above in that the additions are occurring at a M–P double bond.[23] Currently we are investigating the conditions required to protonolyze the Ru–C bond in these and related metallacyclic ruthenium complexes to achieve a complete hydrophosphination cycle via this metathesis-like chemistry.

Experimental Section

Full synthetic, spectroscopic, and computational details, as well as X-ray crystallographic experimental details for the structures of **2a** and **5a**, are available in the Supporting Information. CCDC 761575 (**2a**) and 761576 (**5a**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.[11,19]

Received: January 20, 2010
Published online: March 31, 2010

Keywords: alkenes · cycloadditions · metallacycles · P ligands · ruthenium

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[10] See the Supporting Information for details. Similar data obtained for **2a** was complicated by overlap of the peaks of interest with those from the Cy groups.
[11] Crystallographic data for **2a**: $C_{42}H_{47}NP_2Ru$, $M_r = 728.82$; crystal dimensions (mm) $0.57 \times 0.28 \times 0.28$; monocclinic space group $P2_1/n$ (an alternate setting of $P2_1/c$ [No. 14]); $a = 13.1935(8)$, $b = 16.9872(11)$, $c = 15.6856(10)$ Å; $\beta = 91.1278(9)°$; $V = 3514.8(4)$ Å^3; $Z = 4$; $\rho_{calcd} = 1.377$ g cm^{-3}; $\mu = 0.568$ mm^{-1}; $\lambda = 0.71073$ Å; $T = -80°C$; $2\theta_{max} = 52.80°$; total data collected = 27646; $R_1 = 0.0229$ (6571 observed reflections with $F_o^2 \geq 2\sigma(F_o^2)$); $wR_2 = 0.0632$ for 415 variables and all 7203 unique reflections; residual electron density = 0.532 and −0.247 e Å^{-3}.
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[15] Solvent effects on rate are particularly pronounced for zwitterionic intermediates in [2+2] additions, which are generally less successful in achieving conformations that minimize the coulombic separation than are those in, for example, [2+4] cycloadditions; a) R. Huisgen, *Acc. Chem. Res.* **1977**, *10*, 117; b) R. Huisgen, *Pure Appl. Chem.* **1980**, *52*, 2283.
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[17] We also examined the addition of *cis*- and *trans*-2-butene to **1a**,**b**, but these internal alkenes reacted very slowly, allowing competing orthometalation of **1a**,**b** (see Ref. [1b]). The somewhat ambiguous results of these experiments (see the Supporting Information) point to a stereochemical preference, in this sterically congested system, for the formation of *cisoid* metallacycles, which is avoided through the use of *cis*- and *trans*-[D_2]ethylene.
[18] In the ^{1}H NMR spectra of *cis*- and *trans*-[D_2]-**3a**,**b**, peaks resulting from the metallacycle protons show reduced multiplicities and intensities relative to those in the spectra of [D_0]-**3a**,**b**. ^{2}H NMR spectra confirmed the equal distribution of deuterium throughout all four positions on the metallacycle.
[19] Crystal data for **5a**: $C_{46}H_{54}P_2Ru$, $M_r = 769.90$; crystal dimensions (mm) $0.54 \times 0.40 \times 0.22$; monocclinic space group $P2_1/n$ (an alternate setting of $P2_1/c$ [No. 14]); $a = 11.6081(7)$, $b = 17.4813(11)$, $c = 19.5737(12)$ Å; $\beta = 105.6999(8)°$; $V = 3823.8(4)$ Å^3; $Z = 4$; $\rho_{calcd} = 1.337$ g cm^{-3}; $\mu = 0.525$ mm^{-1}; $\lambda = 0.71073$ Å; $T = -80$ °C; $2\theta_{max} = 54.98°$; total data collected = 33061; $R_1 = 0.0272$ (7822 observed reflections with $F_o^2 \geq 2\sigma(F_o^2)$); $wR_2 = 0.0728$ for 442 variables and all 8721 unique reflections; residual electron density = 0.622 and -0.264 e Å^{-3}.
[20] Addition of excess ethylvinylether, an electron-rich terminal alkene of intermediate bulk, to **1a**,**b** gave quantitative [2+2] cycloaddition within 30 min at RT (a rate intermediate between acrylonitrile and 1-hexene), but gave the *syn* and *anti* isomers (**7a**,**b**) in a 1:1 ratio. It is not yet clear whether this selectivity arises from transition state effects in the original cycloaddition (i.e. a purely kinetic phenomenon) or whether the electron-rich nature of the resulting metallacycle hastens equilibration of these isomers (DFT calculations again indicate that these *syn* and *anti* isomers are isoenergetic).
[21] We have seen no evidence for the reversibility of these [2+2] cycloaddition reactions (i.e., no free alkene appears in solution samples of the purified metallacyclic products). ^{31}P{^{1}H} NMR analysis of sealed samples of **2a**,**b** showed a slight increase in the relative amount of the *anti* isomers (from $< 5\%$ to ca. 10%) over a year at RT, consistent with extremely slow equilibration, presumably via reversible dissociation of the phosphine end of the metallacycle, which would allow the requisite bond rotation(s) and inversion at Ru to give epimerization at the α-carbon atom.
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