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COMMUNICATIONS

Published on Web 02/05/2003

Formation of a Cyclobutylidene Ring: Intramolecular [2 + 2] Cycloaddition of Allyl and Vinylidene C═C Bonds under Mild Conditions

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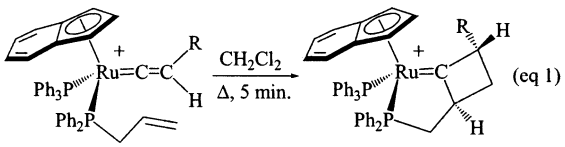
The [2 + 2] cycloaddition process is the most versatile and efficient method for synthesizing four-membered rings containing both heterocyclic and isocyclic skeletons.[1] Nevertheless, and despite the rich and versatile reactivity of the vinylidene group in metal complexes [M]═C═CR^{1}R^2, [2 + 2] cycloadditions of the vinylidene C_α═C_β bond are limited to a few examples involving coupling with the triple bond of alkynes and metal alkynyls or the C═N bond of azabutadienes and imines.[2] Metal vinylidene complexes are well-known active substrates in a series of stoichiometric and catalytic C−C and C−heteroatom coupling reactions[3] which proceed with high selectivity and atom economy. In particular, ruthenium(II) vinylidenes have proven to be efficient catalysts in RCM of olefins, with the key step in the catalytic process being the [2 + 2] coupling of the olefin with the Ru═C bond of the vinylidene moiety.[4] However, [2 + 2] cycloaddition of the vinylidene C_α═C_β bond with an olefin has not previously been described. We report here an unprecedented diastereoselective [2 + 2] intramolecular cycloaddition of two C═C bond systems which proceeds readily under mild conditions to give a cyclobutylidene ring. We also present rate studies of the coupling reaction.

The process takes place by heating the vinylidene complexes [Ru(η^5-C_9H_7){═C═C(R)H}{κ^1-(*P*)-$PPh_2(C_3H_5)$}(PPh_3)][BF_4] (R = Ph (**1**), *p*-MeC_6H_4 (**2**)),[5] yielding the bicyclic alkylidenes [Ru(η^5-C_9H_7){κ^2-(*P*,*C*)-(═CC(R)HCH$_2$CHCH$_2$PPh$_2$)}(PPh_3)][BF_4] (R = Ph (**3**), *p*-MeC_6H_4 (**4**))[6] each as the only product of its respective reaction. Thus, complexes **3** and **4** have been prepared (70%) by refluxing a dichloromethane solution of **1** or **2** for 5 min (eq 1).



R= Ph (**1**), *p*-MeC_6H_4 (**2**) R= Ph (**3**), *p*-MeC_6H_4 (**4**)

These complexes can also be obtained by the one-pot reaction of [Ru(η^5-C_9H_7){κ^3-(*P*,*C*,*C*)-$PPh_2(C_3H_5)$}(PPh_3)][PF_6] (**5**)[7] with an excess of the corresponding terminal alkyne (eq 2). Similarly, complex **5** reacts with $Me_3SiC{\equiv}CH$ in the presence of NH_4PF_6 to afford [Ru(η^5-C_9H_7){κ^2-(*P*,*C*)-(═CCH$_2$CH$_2$CHCH$_2$PPh$_2$)}(PPh_3)]-[PF_6] (**6**)[8] (85%) (eq 2). Complexes **3** , **4**, and **6** have been isolated

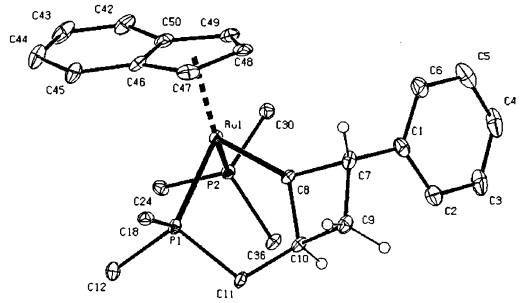
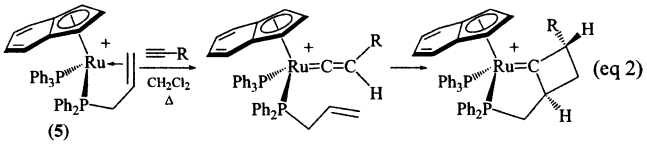


Figure 1. One unit of complex **3**, showing the atom naming scheme. Some hydrogen atoms and phenyl carbon atoms have been excluded for clarity. Non-hydrogen atoms are represented by their 50% probability ellipsoids.

as air-stable yellow solids and fully characterized by elemental analysis and spectroscopic means.



The formation of the transient vinylidene species is assessed by the $^{31}P\{^1H\}$ NMR spectrum (CH_2Cl_2) of the reaction mixture (R = Ph), which shows, after a few minutes in refluxing CH_2Cl_2, two doublet resonances (δ 43.4/32.4) of the corresponding vinylidene complex **1**. After ca. 30 min at room temperature, only the resonances of the cycloaddition product **3** are observed.

The $^{31}P\{^1H\}$ NMR spectra of **3**, **4**, and **6** reveal that the reaction proceeds stereoselectively because only one diastereoisomer is formed. The ^1H and $^{13}C\{^1H\}$ NMR spectra are also consistent with the formation of the bicycle.[6,8] In particular, the $^{13}C\{^1H\}$ NMR spectra show the low field carbene resonances as a broad singlet at δ 366.0 (**3**) and δ 371.0 (**4**) or doublets at δ 360.6 (J_{CP} = 19.6 Hz) (**6**) along with the expected resonances for the rest of the carbocycle.

The crystal structure of complex **3** has been determined by X-ray diffraction (Figure 1).[9] The most remarkable feature is the presence of a metallaphosphabicycle resulting from the [2 + 2] cycloaddition. The bicycle contains a cyclobutylidene ring attached to the ruthenium atom (the bond length Ru−C(8) of 1.864(5) Å is typical of a ruthenium−carbon double bond) and a five-membered ruthenaphospha ring. Figure 1 also shows the absolute configuration of *S* at C(7) and *S* at C(10).

The molecule shown in the figure is present in the crystal in equal numbers with its enantiomer, as the crystal belongs to the

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10.1021/ja027209s CCC: $25.00

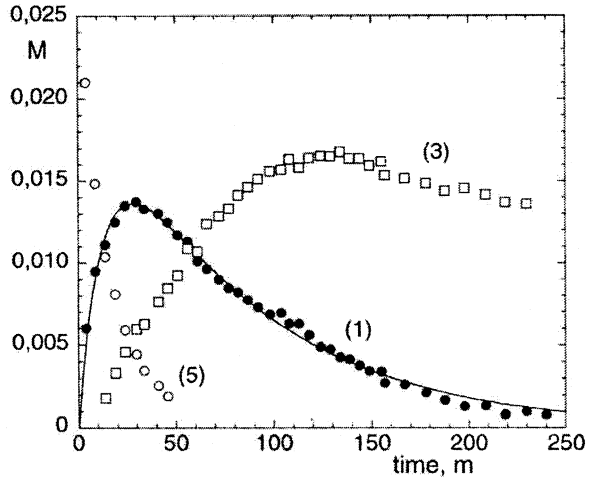

Figure 2. Graphical representation of the reaction of complex **5** (12 mg, 0.0147 mmol, 0.027 M) with PhC≡CH (0.040 mL, 0.36 mmol, 0.674 M) at 45.6 °C in $CDCl_3$, showing the evolution of complexes **5**, **1**, and **3**. The solid line applied to complex **1** represents the fitting with eq 3.

centric space group $P2_1/n$. The other two possible diastereoisomers and their enantiomers are absent.

To gain kinetic information on the reaction pathway, the reaction of complex **5** with an excess of PhC≡CH in $CDCl_3$ was monitored in situ by $^{31}P\{^1H\}$ NMR spectroscopy. A reaction profile obtained from the experiment at 45.6 °C is shown in Figure 2.

The concentration of complex **5** decreases as the reaction proceeds and is fitted conveniently with a first-order rate equation to obtain the observed rate constant for its disappearance, $k_{obs} = 1.20 \times 10^{-3}$ s^{-1} (45.6 °C). With the assumption that the back reactions from the vinylidene intermediate **1** to complex **5** and from the bicyclic product **3** to the vinylidene are negligible, the overall process can be simplified to a sequence of two consecutive first-order reactions, from **5** to **1** (k_1), via a fast π-alkyne/vinylidene tautomerization, and from **1** to **3** (k_2).[10] Fitting the concentration values of complex **1** with eq 3 yields the values of k_1 (1.28×10^{-3} s^{-1}) (comparable to the value given by the first-order rate equation) and of k_2 (2.12×10^{-4} s^{-1}), the rate constant of the [2 + 2] coupling reaction.

$$[\mathbf{1}] = [\mathbf{5}]_0 \frac{k_1}{k_2 - k_1} (\exp(-k_1 t) - \exp(-k_2 t)) \qquad (3)$$

Experiments at different temperatures in the range 38−59 °C allow us to obtain the activation parameters for the coupling step, which are $\Delta H^{\ddagger} = 19$ (±2) kcal mol^{-1} and $\Delta S^{\ddagger} = -16$ (±4) cal mol^{-1} K^{-1}.[11] The value of the activation entropy is consistent with an ordered structure of the transition state, essentially due to the loss of conformational freedom of the three single bonds of complex **1**.[12]

In summary, in this work, an unprecedented stereospecific [2 + 2] cycloaddition of two C=C bonds under mild thermal conditions is reported. It is worth emphasizing that only allenes or activated alkenes (bearing electron-donating or -withdrawing substituents)[13] are able to undergo [2 + 2] cycloadditions under mild conditions. Otherwise, reaction at high temperature (>100 °C) is required. Theoretical calculations aimed at shedding light on the stereospecific cycloaddition mechanism are in progress.

Acknowledgment. This work was supported by the Ministerio de Educación y Ciencia (PB98-1593, MCT-00-BQU-0227) and by the COST Chemistry Project "Ruthenium catalysts for Fine Chemistry" (D12/0025/99).

Supporting Information Available: Crystallographic data of **3**, kinetic data, and experimental details for **1**−**6** (PDF and TXT). This material is available free of charge via the Internet at http://pubs.acs.org.

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(5) Complexes **1** and **2** have been obtained by protonation of the corresponding alkynyl derivatives $[Ru(\eta^5\text{-}C_9H_7)(C{\equiv}CR)\{\kappa^1\text{-}(P)\text{-}PPh_2(C_3H_5)\}(PPh_3)]$. The latter complexes were prepared (85−90%) by reaction of $[Ru(\eta^5\text{-}C_9H_7)\text{-}Cl\{\kappa^1\text{-}(P)\text{-}PPh_2(C_3H_5)\}(PPh_3)]$ with the correspondent alkyne and KO^{t}Bu in CH_2Cl_2 (see Supporting Information). Selected spectroscopic data for vinylidene complexes **1** and **2**. (**1**): $^{31}P\{^1H\}$ NMR ($CDCl_3$) δ 43.4 (d, J_{PP} = 23.6 Hz), 32.4 (d, J_{PP} = 23.6 Hz); ^1H NMR ($CDCl_3$) δ 2.81 (m, 2H, PCH_2), 4.82 (m, 1H, =CH), 4.32 (m, 1H, =CH_2), 4.58 (m, 1H, =CH_2), 5.34 (s br, 1H, =C=C(Ph)H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 360.1 (s br, =*C*=C(Ph)H). (**2**): $^{31}P\{^1H\}$ NMR ($CDCl_3$) δ 43.6 (d, J_{PP} = 25.4 Hz), 32.2 (d, J_{PP} = 25.4 Hz); ^1H NMR ($CDCl_3$) 2.31 (s, Me), 2.82 (m, 2H, CH_2), 4.29 (m, 1H, =CH_2), 4.57 (m, 1H, =CH_2), 5.12 (m, 1H, =CH), 5.31 (s a, =C=CH); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 369.2 (s a, =*C*=C(*p*-MeC_6H_4)H) (see Supporting Information).

(6) Selected spectroscopic data. (**3**): $^{31}P\{^1H\}$ NMR ($CDCl_3$) δ 81.5 (d, J_{PP} = 32.6 Hz), 42.3 (d, J_{PP} = 32.6 Hz); ^1H NMR ($CDCl_3$) δ 1.31 (m, 2H, PCH_2), 3.01 (m, 1H, =CCHPh); $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 366.0 (s br, =C). (**4**): $^{31}P\{^1H\}$ NMR ($CDCl_3$) δ 78.5 (d, J_{PP} = 31.2 Hz), 45.7 (d, J_{PP} = 31.2 Hz); ^1H NMR ($CDCl_3$) 1.23 (m, 2H, P−CH_2), 3.21 (m, 1H, =C−CHPh); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 371.0 (s br, =C) (see Supporting Information).

(7) Complex **5** was prepared (90%) by reaction of $[Ru(\eta^5\text{-}C_9H_7)Cl\{\kappa^1\text{-}(P)\text{-}PPh_2(C_3H_5)\}(PPh_3)]$ with $NaPF_6$ in refluxing methanol (see Supporting Information).

(8) Selected spectroscopic data. (**6**): $^{31}P\{^1H\}$ NMR ($CDCl_3$) δ 88.4 (d, J_{PP} = 31.6 Hz), 42.3 (d, J_{PP} = 31.6 Hz); ^1H NMR ($CDCl_3$): δ 1.71 (v t, J_{HH} = 13.0 Hz, 1H, PCH_2), 1.91 (m, 1H, PCH_2), 2.57 (m, 1H, CH); $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 360.6 (d, J_{CP} = 19.6 Hz, =C) (see Supporting Information).

(9) $[RuC_{50}H_{43}P_2](PF_6)\cdot CH_2Cl_2$, monoclinic, $P2_1/n$, yellow-orange crystal, a = 11.073(3), b = 25.216(6), c = 16.324(4) Å, β = 99.21(2)°, V = 4499(2) Å^3, T = −123 ± 1 °C, Z = 4, R1 = 0.0556, wR2 = 0.1517, GOF = 1.044.

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JA027209S