Activation of a water molecule under mild conditions by ruthenacyclopentatriene: mechanism of hydrative cyclization of diynes†

Yoshihiko Yamamoto,* Ken Yamashita and Hisao Nishiyama

Received 11th October 2010, Accepted 11th November 2010
DOI: 10.1039/c0cc04345a

A ruthenium cyclic biscarbene complex reacted with a H_2O molecule under mild conditions to produce η^5-oxapentadienyl complex, that proved to be the intermediate in the catalytic hydrative cyclization of a diyne.

Ruthenacyclopentatrienes, which are cyclic biscarbenes produced by the oxidative cyclization of two alkyne components in a low-valent ruthenium complex (Fig. 1),[1] have attracted considerable attention as key intermediates in transition-metal-catalyzed multi-component coupling processes. Kirchner, Saá, and our group have independently reported that the [2 + 2 + 2] cycloadditions of alkynes with other unsaturated molecules catalyzed by Cp*RuCl(cod) (**1**: Cp* = η^5-C_5Me_5, cod = 1,5-cyclooctadiene) proceed *via* a ruthenacyclopentatriene.[2,3] Recently, Dixneuf, Trost *et al.* have reported interesting coupling processes between alkynes with protic oxygen nucleophiles such as carboxylic acids, water, and alcohols.[4,5] Although the involvement of ruthenacyclopentatriene intermediates was proposed for these novel catalytic processes, no direct evidence on the reaction of ruthenacyclopentatrienes with non-acidic oxygen nucleophiles such as water has been provided thus far. We wish to report a concrete evidence in which a fused ruthenacyclopentatriene reacted with a water molecule *via* a novel activation mode, giving rise to an η^5-oxapentadienyl ruthenium complex and/or a bicyclic furan.

In an attempt to purify crude bicyclic ruthenacyclopentatriene **3** formed from **1** and 1,7-diphenyl-4-oxahepta-1,6-diyne (**2**) by neutral alumina column chromatography, new complex **4** was obtained (Fig. 1). The single-crystal X-ray analysis unambiguously showed that **4** is a half-open oxaruthenocene possessing a five-membered oxacycle-fused η^5-oxapentadienyl ligand. The Ru–O and Ru–C bond lengths (2.167–2.235 Å) are similar to those in previously characterized examples.[6] Although the relevant half-open oxaruthenocenes have already been reported by several groups, this is the first example of the formation of an η^5-oxapentadienyl ligand from a cyclic biscarbene complex involving a novel activation mode of a water molecule (*vide infra*).

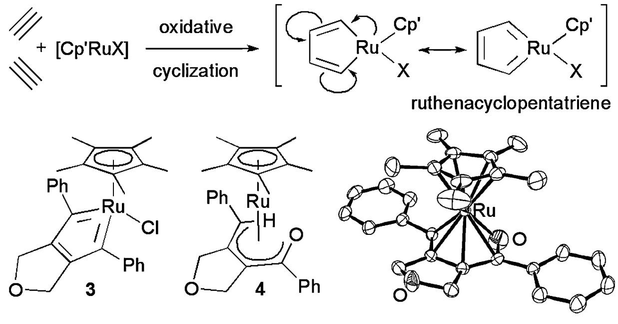
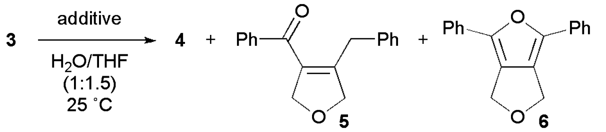


Fig. 1 Ruthenium complexes **3** and **4**. ORTEP drawing of **4** is shown with 50% probability ellipsoids. All hydrogen atoms are omitted for clarity.

In order to obtain further insights into the formation of **4**, we examined the reaction of **3** with water under various conditions (Table 1). It was observed that **3** slowly reacted with water in a tetrahydrofuran (THF) solution at 25 °C to afford **4** along with small amounts of dihydrofuryl ketone **5** and bicyclic furan **6** (entry 1). Obviously, **5** was produced by the protonolysis of **4**, whereas the formation of **6** cannot be clearly explained. To the best of our knowledge, this is the first example of the formation of a furan from a metallacycle by utilizing a water molecule as an oxygen source.[7] Because the chloride ligand was observed to be lost during the transformation of **3** into **4**, we examined the chlorine abstraction from **3** using various silver salts. The addition of a silver salt significantly accelerated the reaction: **3** was completely consumed within a few hours. When $AgBF_4$ was added, the yields of **4** reached 44% (entry 2). It should be noted that the reactions in the presence of the silver salt produced considerable amounts of **6**. Moreover, the reaction in the presence of $AgNO_3$ resulted in an almost exclusive formation of **6** (entry 3). It is assumed that the concomitant formations of Brønsted acids such as HBF_4 or HNO_3 play an important role in the formation of **6** when the corresponding silver salts are added. In fact, the reaction in the presence of Ag_2O selectively afforded **4** in 71% yield (entry 4). The selective formation of **4**

Table 1 Reaction of **3** with water in the presence of additives



Run	Additive	Time/h	Yields of **4**, **5**, and **6**[a] (%)
1	None	6[b]	54, 5, 3
2	$AgBF_4$[c]	1	44, —, 34
3	$AgNO_3$[c]	1	7, —, 52
4	Ag_2O[c]	2	71 (60)[d], —, 1
5	Al_2O_3[e]	4	79 (73)[d], —, —

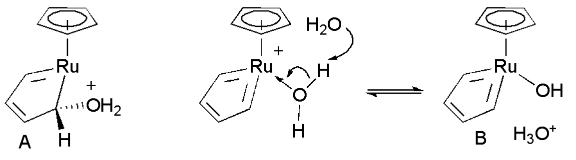
[a] Yields were determined by ^1H NMR analysis. [b] 84% conversion. [c] 1.1 equiv. of Ag^+ per **3**. [d] Yields of isolated product. [e] **3** : Al_2O_3 = 1 : 2.5 w/w.

Department of Applied Chemistry, Graduate School of Engineering, Nagoya University, Chikusa, Nagoya 464-8603, Japan.
E-mail: yamamoto@apchem.nagoya-u.ac.jp; Fax: +81 52 789 3209; Tel: +81 52 789 3337

† Electronic supplementary information (ESI) available: Experimental procedures, spectroscopic data, and CIF file. CCDC 766961. For ESI and crystallographic data in CIF or other electronic format see DOI:10.1039/c0cc04345a

presumably requires neutral reaction conditions; hence, we employed neutral alumina as an acid scavenger. As a result, **4** was exclusively produced in the highest yield of 79%, albeit with a reaction rate slower than those observed in the presence of silver additives (entry 5).

Dixneuf *et al.* proposed that 2 : 1 coupling of arylalkynes with carboxylic acids is initiated by protonation of ruthenacycles.[4] This assumption was supported by their DFT calculations for protonated ruthenacycle intermediates.[4b] However, the protonation of ruthenacycles by water seems to be unrealistic, because water is a much weaker proton donor (by 10^2–10^5 times) than carboxylic acids ($pK_a = 2–5$). Thus, we investigated on the protonation of a model ruthenacycle composed of the $[CpRu]^+$ fragment and two acetylene molecules using the density functional theory (DFT) calculations. The DFT calculations suggest that the protonation of the cationic model complex is highly unlikely because of the considerably large activation energy (27.6 kcal mol^{-1}) of this process (ESI† Fig. S1). Hence, alternative mechanisms should be operative during the reactions of cationic ruthenacycle with water. A reasonable option involves a hydroxylated ruthenacycle as proposed by Trost and coworkers.[5] Such an intermediate could be produced by the addition of a water molecule to one of the carbene carbons, followed by deprotonation. However, no stationary point could be located for the model water adduct **A** (Scheme 1). Thus, we investigated the hydroxo ligand migration with model **B**, because the deprotonation of an aquo precursor can afford such a hydroxo complex and a similar migration of PR_3 ligands has previously been reported by Kirchner and others.[2a] DFT calculations suggest that 1,2-migration of the hydroxo ligand takes place with an activation energy of 16.9 kcal mol^{-1} *via* **TS-BC** (Fig. 2). This activation barrier is much lower than that of the protonation of the cationic ruthenacycle shown in Fig. S1 (ESI†). The formation of the hydroxylated ruthenacycle **C** is estimated to be endothermic by 6.2 kcal mol^{-1}.



Scheme 1 Formation of hydroxo complex **B**.

Subsequently, the β-H abstraction took place through a late transition state, **TS-CD**, with an activation barrier of 18.8 kcal mol^{-1}. The Ru–H and O–H distances are 1.72 and 1.34 Å, respectively. The formation of hydride complex **D** is estimated as exothermic by 8.1 kcal mol^{-1}. The subsequent 1,2-H shift was found to be very facile. This process was estimated to proceed *via* an early transition state (**TS-DE**): the Ru–H bond was elongated by only 0.06 Å when compared with **D**. The activation energy was estimated to be very small (2.4 kcal mol^{-1}). The formation of σ-allyl complex **E** bearing a side-on bound formyl ligand from **D** was found to be exothermic by 6.6 kcal mol^{-1}.

The haptotropic rearrangement from the γ-formylallyl complex to an η^5-oxapentadienyl one was investigated using higher models including a 2,5-dihydrofuran moiety (Fig. 3). This modification helps us to simplify further investigations by avoiding the *s-cis*/*s-trans* conformational change of the diene moiety at the expense of computational efficiency. As a result, we could find that the γ-formylallyl complex **F** was transformed into the final η^5-oxapentadienyl complex **H** through an intermediate, σ-allyl complex **G** with an end-bound formyl group (the Ru–O and Ru–C bond distances are 2.06 and 3.04 Å, respectively). The initial side-on to end-on isomerization of **F** was estimated to occur with almost no barrier *via* an early transition state (**TS-FG**). The formation of **G** is thermodynamically favorable because of relatively large exothermicity

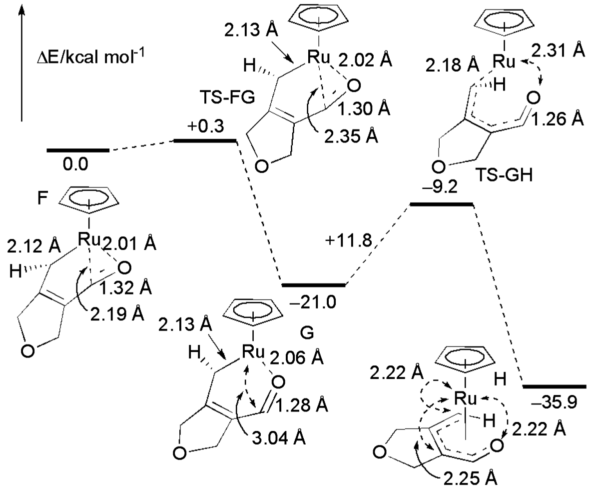


Fig. 3 Reaction profile for haptotropic rearrangement.

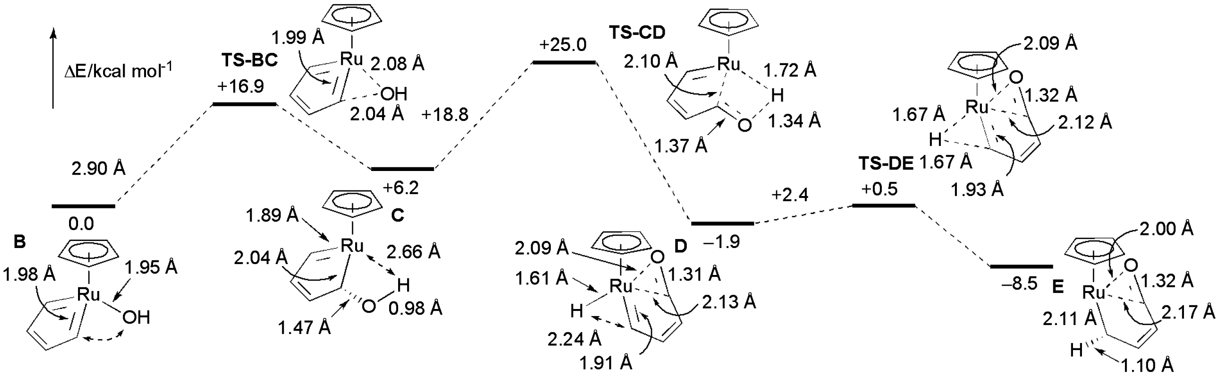
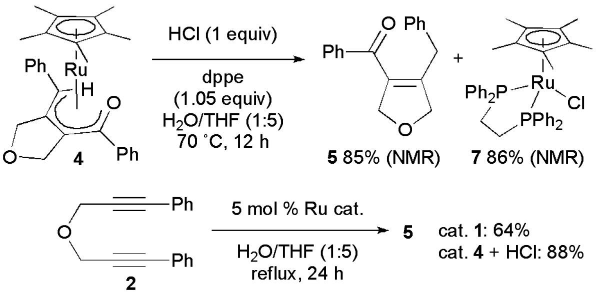


Fig. 2 Reaction profile for transformation of hydroxo complex **B** into σ-allyl complex **E**.

of −21.0 kcal mol^{-1}. Subsequent rearrangement to **H** took place with the dissociation of the formyl group. This process was estimated to require activation energy of 11.8 kcal mol^{-1}. The thermodynamically favorable formation of η^5-oxapentadienyl complex **H** (the Ru–O and Ru–C bond lengths are between 2.22 Å and 2.25 Å) is estimated to proceed with an exothermicity of 14.9 kcal mol^{-1}. The entire rearrangement pathway was found to be a downhill process with a considerable exothermicity of 35.9 kcal mol^{-1}.

We anticipated that η^5-oxapentadienyl complexes are possible intermediates in the hydrative cyclization that transforms diynes into cycloalkenyl ketones. In fact, ketone product **5** was obtained in the reaction of **3** with water, albeit in a low yield (Table 1, entry 1). To investigate the role of the oxapentadienyl complex in hydrative cyclization, the formation of **5** from **4** was examined. As is expected in the case of 18e complexes, **4** was inert to nucleophilic reaction and it remained intact after refluxing in an aqueous THF solution for 6 h. In contrast, ^{1}H NMR analysis indicated that **4** decomposed even under weakly acidic conditions (4.2 mM HCl, 1 equiv.). In the presence of diphenylphosphinoethane (dppe, 1.05 equiv.), 86% of **4** was consumed at 70 °C for 12 h to afford **5** and a dppe complex **7** in 85% and 86% NMR yields, respectively (Scheme 2). These results indicate that Brønsted acid plays an indispensable role in the formation of **5** from **4**. Because the Cp*RuCl fragment was restored effectively, a series of transformations were expected to proceed catalytically. In fact, an aqueous THF solution of diyne **2** was heated in the presence of 5 mol% **1** for 24 h to obtain **5** in 64% isolated yield (Scheme 2). Interestingly, the combination of 5 mol% each of **4** and HCl effectively catalyzed the hydrative cyclization to afford **5** in a higher isolated yield of 88%, although **4** itself exhibited no catalytic activity.

In conclusion, we observed novel transformation modes of a water molecule with a ruthenium cyclic biscarbene complex. Under a neutral condition, bicyclic ruthenacyclopentatriene **3** reacts with H_2O to afford new half-open oxaruthenocene complex **4** possessing an η^5-oxapentadienyl ligand. On the other hand, bicyclic furan **6** was predominantly formed in the presence of silver salts such as $AgNO_3$ *via* the incorporation of one oxygen atom from a water molecule. The DFT calculations suggested that the cationic ruthenacycle undergoes 1,2-migration of the hydroxo ligand to form the hydroxylated ruthenacycle. Subsequent β-H elimination followed by 1,2-hydride migration produces the γ-formylallyl complex, which finally evolves into the η^5-oxapentadienyl complex. The isolated complex **4** proved to be an intermediate in the catalytic hydrative cyclization of diynes.



Scheme 2 Catalytic formation of ketone **5** from diyne **2**.

This research was partially supported by the MEXT, Grant-in-Aid for Scientific Research (B) (20350045), and the Global COE program (Nagoya University).

Notes and references

1 (*a*) M. O. Albers, D. J. A. de Waal, D. C. Liles, D. J. Robinson, E. Singleton and M. B. Wiege, *J. Chem. Soc., Chem. Commun.*, 1986, 1680; (*b*) C. Gemel, A. LaPensée, K. Mauthner, K. Mereiter, R. Schmid and K. Kirchner, *Monatsh. Chem.*, 1997, **128**, 1189; (*c*) C. Ernst, O. Walter, E. Dinjus, S. Arzberger and H. Görls, *J. Prakt. Chem.*, 1999, **341**, 801.

2 For reviews, see: (*a*) R. Schmid and K. Kirchner, *Eur. J. Inorg. Chem.*, 2004, 2609; (*b*) J. A. Varela and C. Saá, *J. Organomet. Chem.*, 2009, **694**, 143.

3 (*a*) Y. Yamamoto, T. Arakawa, R. Ogawa and K. Itoh, *J. Am. Chem. Soc.*, 2003, **125**, 12143; (*b*) Y. Yamamoto, K. Kinpara, T. Saigoku, H. Takagishi, S. Okuda, H. Nishiyama and K. Itoh, *J. Am. Chem. Soc.*, 2005, **127**, 605; (*c*) Y. Yamamoto, J. Ishii, H. Nishiyama and K. Itoh, *J. Am. Chem. Soc.*, 2005, **127**, 9625; (*d*) Y. Yamamoto, K. Hattori and H. Nishiyama, *J. Am. Chem. Soc.*, 2006, **128**, 8336.

4 (*a*) J. Le Paih, S. Dérien and P. H. Dixneuf, *Chem. Commun.*, 1999, 1437; (*b*) J. Le Paih, F. Monnier, S. Dérien, P. H. Dixneuf, E. Clot and O. Eisenstein, *J. Am. Chem. Soc.*, 2003, **125**, 11964; (*c*) M. Zhang, H.-F. Jiang, H. Neumann, M. Beller and P. H. Dixneuf, *Angew. Chem., Int. Ed.*, 2009, **48**, 1681; (*d*) M. Zhang, H. Jiang and P. H. Dixneuf, *Adv. Synth. Catal.*, 2009, **351**, 1488.

5 (*a*) B. M. Trost and M. T. Rudd, *J. Am. Chem. Soc.*, 2003, **125**, 11516; (*b*) B. M. Trost and M. T. Rudd, *Org. Lett.*, 2003, **5**, 4599; (*c*) B. M. Trost and X. Huang, *Org. Lett.*, 2005, **7**, 2097; (*d*) B. M. Trost and X. Huang, *Chem.–Asian J.*, 2006, **1**, 469.

6 (*a*) M. Crocker, S. F. T. Froom, M. Green, K. R. Nagle, A. G. Orpen and D. M. Thomas, *J. Chem. Soc., Dalton Trans.*, 1987, 2803; (*b*) W. Trakarnpruk, A. M. Arif and R. D. Ernst, *Organometallics*, 1992, **11**, 1686; (*c*) W. Trakarnpruk, A. M. Arif and R. D. Ernst, *Organometallics*, 1994, **13**, 2423; (*d*) M. E. N. Clemente, P. J. Saavedra, M. C. Vásquez, M. A. Paz-Sandoval, A. M. Arif and R. D. Ernst, *Organometallics*, 2002, **21**, 592.

7 Fused furans were obtained by oxidation of metallacyclopentadiene, see: (*a*) E. Müller, *Synthesis*, 1974, 761; (*b*) K. Moseley and P. M. Maitlis, *J. Chem. Soc., Dalton Trans.*, 1974, 169.