Homogeneous Catalysis

Ru- and Rh-Catalyzed C–C Bond Cleavage of Cyclobutenones: Reconstructive and Selective Synthesis of 2-Pyranones, Cyclopentenes, and Cyclohexenones**

Teruyuki Kondo, Yoshinori Taguchi, Yushi Kaneko, Masatsugu Niimi, and Take-aki Mitsudo**

The reconstruction of new carbon skeletons after C–C bond cleavage, which leads to the rapid and selective synthesis of novel organic molecules that cannot be obtained by the simple combination of traditional synthetic methods,[1] is an important goal of many recent studies in atom-economical organic, organometallic, and industrial chemistry.[2] In our recent report on the unusual ruthenium-catalyzed coupling of cyclobutenediones with alkenes[3] and the ruthenium-catalyzed synthesis of pyranopyrandiones by ring-opening carbonylation of cyclopropenones,[4] we demonstrated the explicit cleavage of C–C bonds leading to the reconstruction of new carbon skeletons. Since ruthenacycles, which would be obtained by direct oxidative addition of strained cyclic substrates such as cyclobutenediones and cyclopropenones to low-valent ruthenium species, are postulated to be key intermediates, we next turned our attention to the reactivity of a similarly strained cyclic compound, cyclobutenone,

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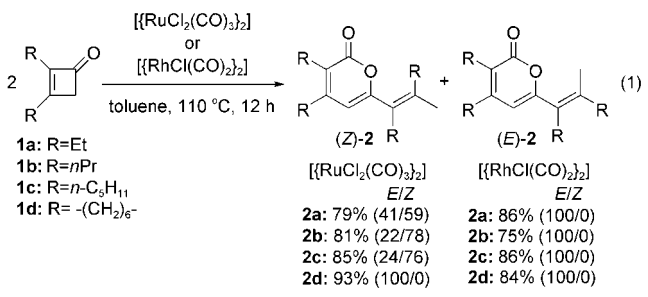
toward ruthenium and other transition-metal complexes. Particular attention has been focused on the thermal reactivity of cyclobutenones bearing alkynyl, alkenyl, aryl, and allenyl substituents at the 4-position because of their potential application to the synthesis of ring-expanded compounds.[5] On the other hand, 4-nonsubstituted cyclobutenones are relatively stable, and only the pioneering work by Liebeskind and co-workers on the transition-metal-complex-catalyzed synthesis of phenols from 4-nonsubstituted cyclobutenones and alkynes has been reported.[6,7] This methodology is quite attractive, since transition-metal vinylketene complexes have been postulated to be important intermediates in reactions leading to a variety of organic ring products, such as phenols, naphthols, cyclohexadienones, cyclopentenones, lactams, furans, α-pyrones, and 2-furanones.[8] After many trials, we developed a novel stereoselective synthesis of 2-pyranones by the ring-opening dimerization of cyclobutenones catalyzed by ruthenium and rhodium complexes. In addition, a rhodium complex, $[\{RhCl(CO)_2\}_2]$, showed high catalytic activity in the decarbonylative and/or direct coupling of cyclobutenones with alkenes by C–C bond cleavage. These results indicate that the present reactions likely involve both η^4-vinylketene and metallacyclopentenone intermediates.

Treatment of cyclobutenones **1** with 5-mol% $[\{RuCl_2(CO)_3\}_2]$ in toluene at 110°C for 12 h gave novel dimerization products, 6-alkenyl-2-pyranones **2**, in high yields with good *Z* selectivity (see Equation (1)) . In the present reaction, the starting cyclobutenones **1** were completely consumed, and the only products detected by GLC were the corresponding (*E*)- and (*Z*)-6-alkenyl-2-pyranones **2**.

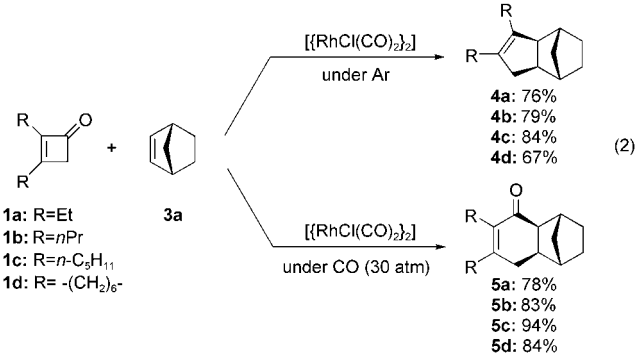
First, the catalytic activity of several ruthenium complexes was examined in the dimerization of **1b** to **2b**. Among the catalysts examined, $[\{RuCl_2(CO)_3\}_2]$ showed the highest catalytic activity (**2b**, 81%), and $RuCl_3\cdot 3H_2O$ showed moderate catalytic activity (**2b**, 31%). In both reactions, the *E*/*Z* ratio of the 6-alkenyl group in **2b** was 22/78. Other ruthenium complexes such as $[Ru_3(CO)_{12}]$, $[RuCl_2(PPh_3)_3]$, $[RuH_2(PPh_3)_4]$, and $[(\eta^5\text{-}C_5Me_5)RuCl(1,5\text{-cyclooctadiene})]$, were totally ineffective. No 2-pyranone **2b** was obtained with several other transition-metal complexes, such as $[RhCl(PPh_3)_3]$, $RhCl_3\cdot 3H_2O$, $[Pd(PPh_3)_4]$, and $[Ni(cod)_2]$. Surprisingly, only $[\{RhCl(CO)_2\}_2]$ showed high catalytic activity in the synthesis of **2b** from **1b**, and changing the $[\{RuCl_2(CO)_3\}_2]$ catalyst to the $[\{RhCl(CO)_2\}_2]$ catalyst led to a sharp reversal of stereoselectivity to give (*E*)-6-alkenyl-2-pyranone ((*E*)-**2b**) as the sole product in 75% yield [Eq. (1)].

The use of an appropriate solvent is critically important for the success of the present reaction. In the $[\{RuCl_2(CO)_3\}_2]$-catalyzed dimerization of **1b** to **2b**, toluene gave the best result. No **2b** was obtained in solvents, such as THF, 1,4-dioxane, *N*-methylpiperidine, DMF, and acetonitrile, partly due to their ability to coordinate with the active catalyst species. A similar critical solvent effect was also observed in the $[\{RhCl(CO)_2\}_2]$-catalyzed dimerization of **1b** to **2b**.



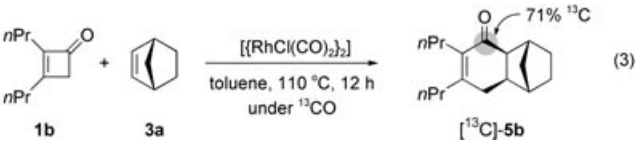
(1)

Furthermore, $[\{RhCl(CO)_2\}_2]$-catalyzed decarbonylative coupling and direct coupling of cyclobutenones with 2-norbornene **3a** have been developed [Eq. (2)].



(2)

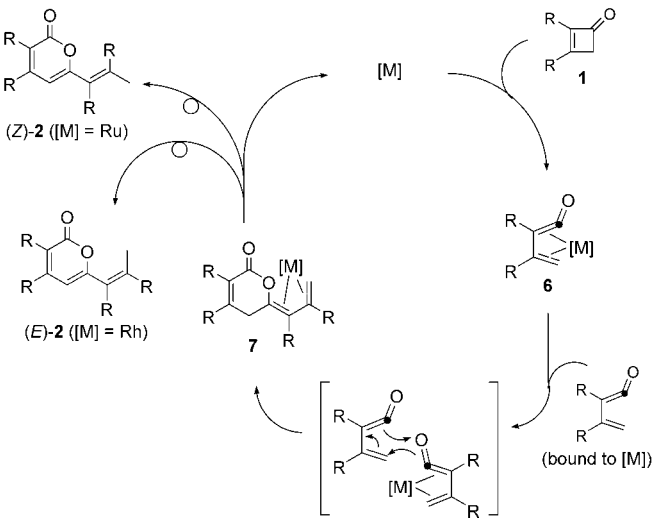
Under an argon atmosphere, decarbonylative coupling proceeded smoothly to give cyclopentenes **4** in high yields, while under 30 atm of carbon monoxide, direct coupling with **3a** gave cyclohexenones **5** in high yields. Use of ^{13}CO gave the corresponding ^{13}C-labeled cyclohexenone [^{13}C]-**5b** [Eq. (3)],[9] which strongly suggests that the decarbonylation of a rhodacyclopentenone and/or a rhodacycloheptenone is facile, but reversible. Under carbon monoxide pressure, subsequent reductive elimination from a stabilized rhodacycloheptenone predominantly occurs to give cyclohexenones **5** (see below).



(3)

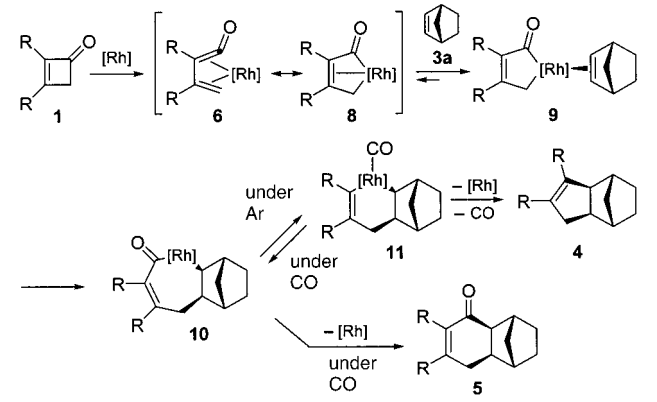
Considering all of our findings and evidence reported by Liebeskind and co-workers,[6] the most plausible mechanism for the ring-opening dimerization of cyclobutenones is illustrated in Scheme 1. The initial step might consist of regioselective ring-opening of cyclobutenone **1** by an active metal center to give an η^4-vinylketene intermediate **6**, which rapidly reacts with another molecule of metal-bound vinylketene according to a hetero-Diels–Alder reaction. Successive isomerization of **7** would give the corresponding 2-pyranone **2**.[10] No interconversion between (*Z*)-**2** and (*E*)-**2** was observed in the presence or absence of Ru and Rh catalysts.

On the other hand, in the presence of 2-norbornene (**3a**), the highly *exo*-selective coordination ability of **3a**[11] leads to the formation of a rhodacyclopentenone intermediate **9** from **6** via **8**,[6d] and subsequent stereoselective insertion of **3a** into a rhodium–carbon bond in **9** would give a rhodacycloheptenone intermediate **10**. Under an argon atmosphere, this



Scheme 1. Possible mechanism for the formation of 2-pyranones **2**.

rhodacycloheptenone **10** is easily decarbonylated to a rhodacyclohexene intermediate **11**, and subsequent reductive elimination gives the corresponding cyclopentene **4**. Even under carbon monoxide pressure, this decarbonylation process of **10** to **11** is facile, however, it is reversible (see above). Rapid reductive elimination from the stabilized **10** by carbon monoxide occurs to give the corresponding cyclohexenone **5** (Scheme 2).



Scheme 2. Possible mechanism for the formation of cyclopentenes **4** and cyclohexenones **5**.

An alternative pathway for the formation of cyclohexenone **5** by a direct stereoselective Diels–Alder reaction of η^4-vinylketene rhodium intermediate **6** with 2-norbornene (**3a**) is also possible, however, this mechanism cannot explain the decarbonylative coupling of cyclobutenone with **3a** under an argon atmosphere.

In conclusion, we have developed a novel ruthenium- and rhodium-catalyzed ring-opening dimerization of cyclobutenones to give 2-pyranones. The application of a rhodium catalyst to decarbonylative and direct coupling reactions of cyclobutenones with 2-norbornene is also successful and gives stereoselectively cyclopentenes and cyclohexenones, respectively.

Experimental Section

Cyclobutenones **1a–d** were prepared by a general two-step method based on the [2+2] cycloaddition of alkynes with dichloroketene, and the reductive dechlorination of the generated 4,4-dichlorocyclobutenones by zinc dust in the presence of tetramethylethylenediamine, ethanol, and acetic acid.[12]

Representative procedure for the synthesis of (*E*)-**2b** from **1b** catalyzed by $[\{RhCl(CO)_2\}_2]$: A mixture of 2,3-dipropylcyclobut-2-en-1-one (**1b**) (152 mg, 1.0 mmol), $[\{RhCl(CO)_2\}_2]$ (19.4 mg, 0.050 mmol), and toluene (2.0 mL) was placed in a 20-mL Pyrex flask equipped with a magnetic stirring bar under a flow of argon. The reaction was carried out at 110 °C for 12 h with stirring. After the reaction mixture was cooled, the product, 6-((1*E*)-2-methyl-1-propylpent-1-enyl)-3,4-dipropylpyran-2-one ((*E*)-**2b**), was isolated by Kugelrohr distillation as a pale yellow oil (228 mg, 0.75 mmol; 75% yield); b.p. 170–180 °C (1.0 mmHg, Kugelrohr); IR (neat): $\tilde{\nu}$ = 1562, 1635 (C=C), 1712 cm^{-1} (C=O); ^1H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 0.88 (t, J = 7.32 Hz, 3H), 0.94 (t, J = 7.32 Hz, 3H), 0.98 (t, J = 7.32 Hz, 3H), 0.99 (t, J = 7.32 Hz, 3H), 1.30–1.36 (m, 2H), 1.43–1.61 (m, 6H), 1.76 (s, 3H), 2.11(t, J = 7.81 Hz, 2H), 2.29 (t, J = 7.81 Hz, 2H), 2.41 (t, J = 7.81 Hz, 2H), 2.46 (t, J = 7.81 Hz, 2H), 5.83 ppm (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 25 °C): δ = 14.0, 14.0, 14.2, 14.3 20.5 21.3 22.1 22.1, 22.5 28.6, 32.4, 34.5 36.4, 108.3, 122.3, 128.6, 139.2 153.2, 159.3, 164.3 ppm; MS (EI, 70 eV): m/z: 304 [M^+]; elemental analysis (%) calcd for $C_{20}H_{32}O_2$: C 78.90, H 10.59; found: C 78.80, H 10.55.

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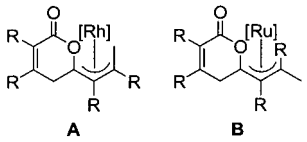
[10] Although it is not yet clear why the stereochemistry of **2** changed depending on the catalyst used, we now believe that the present isomerization reaction of diene **7** to 2-pyranone **2** may proceed through addition–elimination of a H-[M] species to 1,3-dienes **7**, generating π-allylmetal intermediates such as **A** and **B**.. A π-



allylrhodium intermediate has an energetically favorable *syn*-type configuration (**A**) leading to the selective formation of (*E*)-**2**, while a sterically congested *anti*-type π-allylruthenium species (**B**), which is also postulated as a key intermediate in our previously reported ruthenium-catalyzed codimerization of 1,3-dienes with acrylic compounds, could be generated to give (*Z*)-**2** in good selectivity. See: T. Mitsudo, S.-W. Zhang, T. Kondo, Y. Watanabe, *Tetrahedron Lett.* **1992**, *33*, 341 – 344.

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