# Rhodium(I)-Catalyzed Successive Double Cleavage of Carbon−Carbon Bonds of Strained Spiro Cyclobutanones

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Transition metals have been successfully exploited in organic synthesis, in particular, for the formation of C−C bonds.[1] One of the most important elementary steps constituting C−C bond formation is the reductive elimination of a di(organyl)metal complex, which leads to the extrusion of the coupled product from the metal (eq 1). On the contrary, the reverse process,

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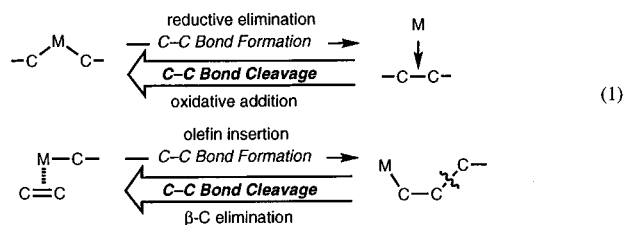
oxidative addition of a C−C bond onto a transition metal, provides a direct approach to C−C bond cleavage. Although stoichiometric reactions involving this elementary step have been the subject of a number of investigations,[2−5] catalytic reactions are still few in number[6,7] due to the inertness of C−C σ-bonds toward transition metals. An alternative method of breaking C−C bonds is accessible by using σ alkyl−metal complexes. The bond between the β- and γ-carbon atoms can be cleaved via β-carbon elimination, the reverse of olefin insertion.

Although found rarely in either stoichiometric or catalytic reactions,[8] this process has recently received growing attention especially in the field of polymer chemistry.[9] In terms of organic synthesis, however, both elementary steps of C−C bond cleavage have received much less attention than those of C−C bond formation, despite their great synthetic potential.

The oxidative addition of a C−C bond onto a transition metal results in the formation of a σ alkyl−metal complex. Hence, the two elementary steps of C−C bond cleavage, *i.e.*, oxidative addition and β-carbon elimination, possibly operate in sequence, making an interesting synthetic reaction (eq 2). A leading

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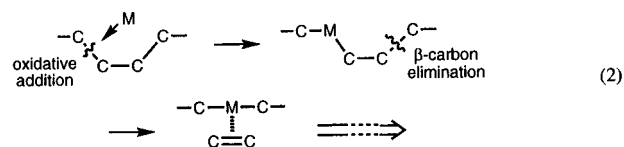
example of this sort has been identified by Liebeskind *et al.*[10] We have recently found that the α C−C bond of a cyclobutanone is catalytically cleaved by a rhodium(I) complex, wherein the carbonyl group directs insertion of the metal.[7] As a continuation of our approach to the problem of C−C bond activation from the viewpoint of synthetic chemistry, we report herein a new example of organic transformations in which two C−C bonds are successively cleaved by a transition metal in a way shown in eq 2.

A preliminary experiment was carried out by using spiro cyclobutanone equipped with another four-membered ring (**1**),[11] which was expected to favor β-carbon elimination by relief of the ring strain.[8b,f,g,9d] Heating a xylene solution of **1** at reflux in the presence of [Rh(cod)(dppe)]BF$_4$ (5 mol %)[12] for 18 h gave rise to 2-cyclohexenone (**5**) in 28% isolated yield along with decarbonylated products. The formation of **5** can be explained by assuming the pathway pictured in eq 3. Initially, rhodium(I) undergoes an insertion into the bond between the carbonyl carbon and the α-carbon of **1**. The resultant five-membered cyclic acylrhodium (**2**) undergoes β-carbon elimination to open the appended cyclobutane ring, forming seven-membered cyclic acylrhodium (**3**). Subsequent reductive elimination gives rise to the methylenecyclohexanone (**4**), which finally isomerizes to the conjugated cyclohexenone (**5**). In the net transformation of **1** to **5**, rhodium(I) successively cleaved

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(10) Huffman, M. A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1993**, *115*, 4895. The authors reported a rhodium-catalyzed useful ring fusion reaction of cyclobutenone derivatives, which are more labile thermally[13] as well as catalytically[14] than cyclobutanone. Although the exact mechanism was not mentioned, the reaction seemed to involve a sequence similar to that of the present work.

(11) Spiro cyclobutanone (**1**) was readily prepared by [2 + 2] cycloaddition of methylenecyclobutane with dichloroketene and the subsequent dechlorination with zinc.

(12) The complex (cod = cycloocta-1,5-diene, dppe = Ph$_2$PCH$_2$CH$_2$-PPh$_2$) was prepared *in situ* according to a literature procedure: Green, A.; Kuc, T. A.; Taylor, S. H. *J. Chem. Soc. A* **1971**, 2334.

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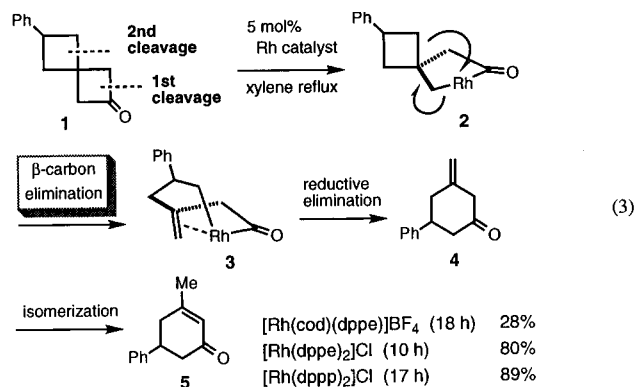
the two C−C bonds of **1**, the first by oxidative addition and the second by β-carbon elimination. Further examination of the rhodium catalyst in detail revealed that complexes having two bidentate diphosphines per rhodium were excellent catalysts for the selective formation of **5**. In particular, [Rh(dppp)₂]Cl produced **5** in 89% isolated yield.

Other examples of successive double cleavage of C−C bonds of spiro cyclobutanones are shown below. Alkyl-substituted spiro cyclobutanone (**6**) yielded the corresponding 3,5-disubstituted 2-cyclohexenone (**7**). Trisubstituted cyclohexenone (**9**) was obtained in 59% yield from disubstituted spiro cyclobutanone (**8**). Spiro cyclobutanone (**10**) possesses two C−C bonds (**A** and **B**) possibly susceptible to cleavage by β-carbon elimination. Different products are predicted, depending on which bond is cleaved; cleavage of the C−C bond **A**, connected to a primary alkyl carbon atom, would lead to the formation of cyclohexenone (**11**), whereas cleavage of bond **B**, connected to a tertiary carbon atom, would lead to cyclohexenone (**12**). The fact that the tetrasubstituted 2-cyclohexenone (**11**) was obtained selectively from **10** suggests that in the process of β-carbon elimination, cleavage of bond **A** is much favored over that of bond **B**. A probable explanation might be that a sterically less-hindered carbon atom is likely to be in closer proximity to the rhodium.


(4)
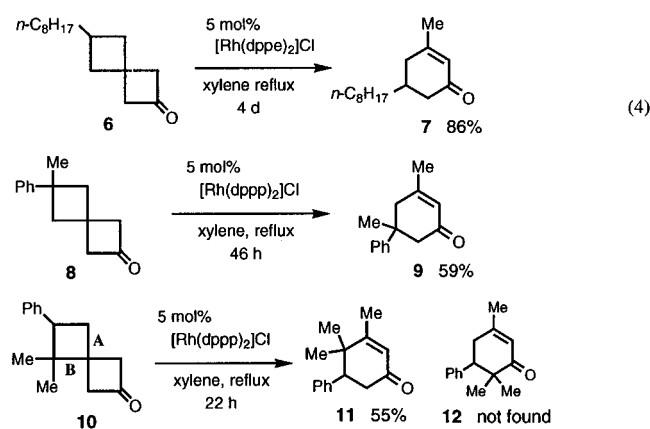
Next, the reaction of cyclobutanone equipped with double spiro structures (**13**) was examined in the hope that a third C−C

bond cleavage by β-carbon elimination would follow the second C−C bond cleavage. However, the rhodium-catalyzed C−C bond cleavage occurred only twice to afford spiro cyclohexenone (**14**) (eq 5). In this particular case, [Rh(dppe)BPh₄] gave the best isolated yield (84%) of **14**.


(5)
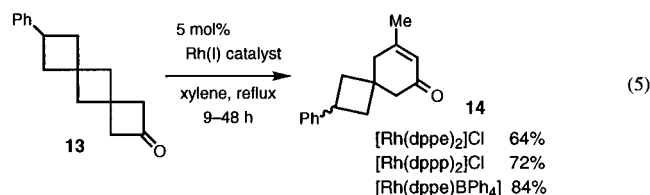
Successive double cleavage of C−C bonds also took place with spiro cyclobutanone (**15**) appended with a cyclopropane ring (eq 6). The reaction proceeded in an analogous way to

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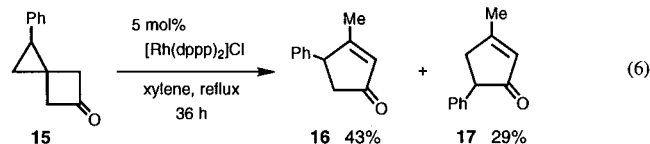
afford cyclopentenone derivatives (**16** and **17**). The spiro cyclobutanone (**15**) also has two C−C bonds possibly cleaved by β-carbon elimination, and the two regioisomers were formed as a result of the cleavage of each of them. Formed predominantly was isomer **16**, which resulted from the second cleavage of the less-substituted C−C bond.

With the other cyclobutanones, for example a spiro substrate joined by a seven-membered ring (**18**) or a non-spiro compound (**19**), analogous successive double cleavage of C−C bonds failed to occur. Instead, attempted reactions with various rhodium(I) complexes led to the predominant formation of a decarbonylated product, *i.e.*, cyclopropane. Relief of the structural strain of the two small rings, therefore, may make a large contribution to the driving force of the catalytic reactions mentioned above.
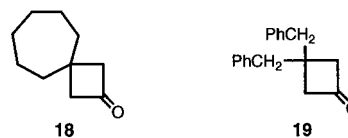
In conclusion, a new tandem sequence was developed in which two C−C bonds are cleaved, the first through the insertion of rhodium and the second by subsequent β-carbon elimination. The present example clearly demonstrates the versatility of transition metal-mediated C−C bond cleavage and its promising application in synthetic organic chemistry.

Supporting Information Available: Experimental details and characterization for **5**, **7**, **9**, **11**, **14**, **16**, and **17** (2 pages). See any current masthead page for ordering and Internet access instructions.

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