

Iridium-Catalyzed [5 + 1] Cycloaddition: Allenylcyclopropane as a Five-Carbon Assembling Unit

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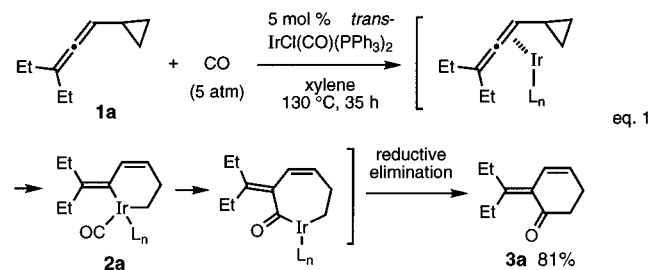
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Cycloaddition reactions have provided many prominent methods for the construction of cyclic compounds of structural and functional complexity.¹ Among the typical promoters of these reactions are heat, light, and Lewis acids. Transition metals provide another powerful catalyst for cycloaddition, particularly for unactivated substrates.² Assembly modes that are otherwise difficult or impossible have been made feasible by the use of transition metals as a template to bring unsaturated substrates together. For instance, Wender et al. disclosed a striking example of a metal-catalyzed intramolecular [5 + 2] cycloaddition, which opened a new route to seven-membered carbocycles.³ Thus, an increase in the variety of the assembly modes and the substrate structures would expand the range of the synthetic application of cycloaddition reactions. Whereas the [4 + 2] mode is most widely used for the construction of six-membered carbon rings,^{1,4} examples of the [5 + 1] cycloaddition are rare in either stoichiometric or catalytic reactions. Sarel et al.⁵ and Aumann⁶ reported a stoichiometric reaction of vinylcyclopropane with Fe(CO)₅ forming cyclohexenone. Relevant [5 + 1] cycloaddition with cyclopropene derivatives, which are much more catalytically labile than cyclopropane analogues, can be found in the work of Hughes,⁷ Liebeskind,⁸ and Semmelhack.⁹ The cobalt-mediated transformation of allenylcyclopropanol to 1,4-hydroquinone was recently reported by Iwasawa et al.¹⁰ A drive to aromaticity has often been exploited.^{8–10}

The use of vinylallene in transition metal-catalyzed cycloaddition reactions has been studied by us and others. Vinylallene readily binds to a metal to form a complex.¹¹ The rhodium complex is viewed as bearing a significant degree of metallacyclic character on the basis of its reactivity as well as its structural features.^{11d,e} When applied to catalytic cycloaddition reactions, vinylallene offers a four-carbon unit to the resulting cyclic skeleton.¹² We designed

its homologue by appending a cyclopropane ring¹³ to an allenyl group, albeit the coordination ability being substantially diminished. In this paper, we report a catalytic sequence of a [5 + 1] assembly mode, wherein iridium(I) opens allenylcyclopropane to incorporate a five-carbon unit into the resulting six-membered ring.

In our initial attempts to effect carbonylative [5 + 1] cycloaddition of allenylcyclopropane,¹⁴ we used rhodium(I) complexes including neutral ones such as RhCl(CO)(PPh₃)₂ and cationic ones, which are potent catalysts for the [4 + 1] cycloaddition of vinylallenes with carbon monoxide.^{11d} However, allenylcyclopropane underwent no carbonylation but rapidly isomerized to methylenecyclopentene instead.^{15–17} Interestingly, careful examination of related transition metal complexes revealed that a neutral iridium(I) complex is an excellent catalyst for [5 + 1] cycloaddition. For example, when a mixture of substituted allenylcyclopropane (**1a**) and 5 mol % of IrCl(CO)(PPh₃)₂ in xylene was heated at 130 °C under pressure of carbon monoxide (5 atm) for 35 h, cyclohexenone (**3a**) was obtained in 81% isolated yield (eq 1). The production of **3a** can be explained by assuming the



following mechanism. Initial coordination of the allenyl group brings the metal into the proximity of the cyclopropane ring, which is then opened by the metal to form a six-membered metallacycle (**2a**). Release of the cyclopropane ring strain assists overall oxidative addition of **1a** to iridium, whether by a concerted mechanism or by way of a metallacyclobutane. Migratory insertion of carbon monoxide into

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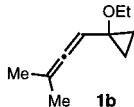
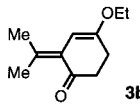
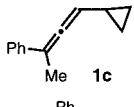
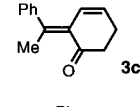
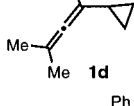
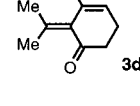
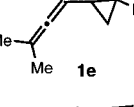
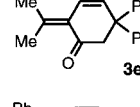
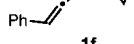
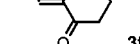
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Table 1. Iridium-Catalyzed [5 + 1] Cycloaddition of Allenylcyclopropanes (1) with Carbon Monoxide^a

1	product (3)	isolated yield, %
		74
		83 ^b
		81
		63
		28 ^b

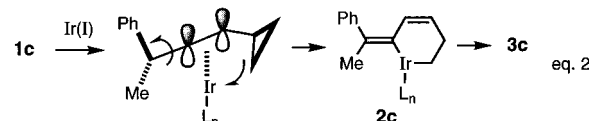
^a The reaction was carried out using 5 mol % of IrCl(CO)(PPh₃)₂ in xylene at 130–140 °C. ^b The stereochemistry was determined by ¹H NMR NOE studies. The other geometric isomer was not detected by ¹H and ¹³C NMR (300 and 75 MHz, respectively).

the Ir–C_{sp2} (or Ir–C_{sp3}) bond¹⁸ and the subsequent reductive elimination accomplish [5 + 1] cycloaddition to give **3a**. It is likely that, in the case of rhodium catalysis, methylenecyclopentene eliminates directly from a six-membered metallacycle prior to insertion of carbon monoxide.

Listed in Table 1 are other examples of the iridium-catalyzed [5 + 1] cycloaddition reactions. The substituents of the terminal allenic carbon atom significantly influenced the reaction. Allenylcyclopropanes with the allenic terminus being disubstituted (**1a–e**) afforded cyclohexenones (**3a–e**) in good yield. From **1f** with the allenic terminus being monosubstituted, cyclohexenone (**3f**) was produced in 28% yield. In contrast, allenylcyclopropane lacking substituents at the allenic terminus such as **1g** afforded no [5 + 1] cycloadduct under analogous conditions. These contrasting results can be understood in terms of the site preference of the allenyl group in coordination. With **1g**, η²-coordination at the allenic π-bond distal to the cyclopropyl group would

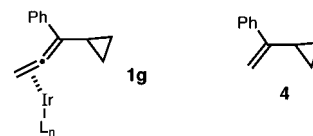
be favored, as observed with a vinylallene-rhodium complex.^{11d} The metal is too distant to open the cyclopropyl ring. The presence of one, or preferably, two substituents at the allenic terminus seems to be a steric requisite to forcing the metal to complex adjacent to the cyclopropyl moiety.

The stereochemical outcome of the reactions of **1c** and **1f** merits comment. From **1c**, one stereoisomer with regard to the exocyclic double bond (**3c**) was obtained. Face-selective approach of the metal from the less hindered side, i.e., the methyl side of the allenic π-orbital proximal to the cyclopropyl group and subsequent rotatory motion forming a metallacycle (**2c**) account for this stereoselectivity (eq 2).¹⁹ An analogous geometrical selectivity was observed with **1f**, although the chemical yield was unsatisfactory because of single substitution at the allenic terminus.



The cyclopropyl ring of **1e** has two C–C bonds potentially susceptible to cleavage. The less-substituted one was selectively opened, presumably due to steric reasons, to afford **3e** as the exclusive product.

For comparison, a reaction of vinylcyclopropane **4** was examined. Although lack of a cumulated double bond with **4** would necessitate coordination adjacent to the cyclopropyl group, neither formation of a [5 + 1] cycloadduct nor isomerization to cyclopentene was observed under analogous conditions. This result demonstrated the importance of the substituted allene functionality for an initial grasp of the metal at an appropriate site.



In summary, a new carbonylative [5 + 1] cycloaddition reaction is developed in which iridium activates allenylcyclopropane lacking polarized functional groups to contribute a five-carbon unit into the cycloadduct. It is noteworthy that an iridium catalyst mediates a C–C bond formation²⁰ that is hardly possible by the use of a rhodium counterpart. This study augments the existing repertoire of synthetic tools for the construction of six-membered rings, especially carbon frameworks related to cyclic terpenoids such as pulegone.

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Supporting Information Available: Experimental details and characterization for **1a** and **3a–3f** (2 pages).

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(18) The result of [4 + 1] cycloaddition reported by Dixneuf *et al.*^{12d} may favor migration of the sp² carbon atom.

(19) Similar facial selectivities of unsymmetrical allenyl groups have been reported.^{11d,12a–d,h}

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