

Reaction of Zirconacyclopentadienes with CO in the Presence of *n*-BuLi. Selective Formation of Cyclopentenone Derivatives from Two Alkynes and CO

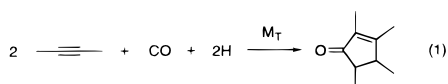
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Received July 20, 1998

Cyclopentenones are very useful intermediates for organic synthesis. It is well-known that three components, namely an alkyne, an alkene, and CO, provide cyclopentenone derivatives with transition metal compounds.¹ However, use of two alkynes and CO for preparation of cyclopentenones is very rare. (eq 1).

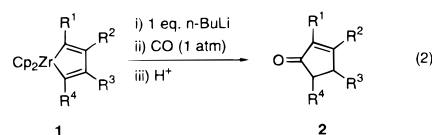


Only several examples have been reported with Co,^{2,3} Rh,² Ir,² and Ni.⁴ Moreover, there is no report for the selective preparation of cyclopentenones from two different alkynes and CO.

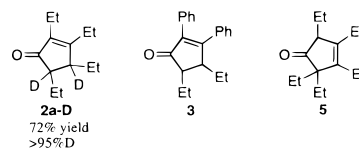
Recently we have reported several reactions of zirconacyclopentadienes,⁵ which can be selectively prepared from two alkynes.⁶ However, it is known that zirconacyclopentadienes are inert toward the CO insertion reactions. Under usual conditions as used for zirconacyclopentanes and zirconacyclopentenes, the CO insertion reaction of zirconacyclopentadienes does not proceed. Therefore, to develop a coupling reaction of two alkynes and CO, some different approach is required. It was reported that the reaction of Cp₂Zr(CO)₂ with an excess of diphenylacetylene in a sealed vessel at high temperature gave a cyclopentadienone as a minor product, but not a cyclopentenone.⁷ Recently, Jordan reported a coupling reaction of two alkynes and CO using zirconocene cation complexes under mild conditions.⁸ This reaction gave divinyl ketones.⁸ During the course of our study, we found that a mixture of zirconacyclopentadienes and 1 equiv

of *n*-BuLi showed an interesting reactivity toward CO. In this paper we would like to report the cyclopentenone formation by the reaction of zirconacyclopentadienes with CO in the presence of *n*-BuLi. This is the first example of a CO insertion reaction of zirconacyclopentadienes which gives the cyclopentenones.

The reaction was carried out as follows. Typically, to a solution of zirconacyclopentadiene **1a** (1 mmol) in THF was added *n*-BuLi (1 mmol) at -78°C . After the mixture was stirred for 1 h, CO (1 atm) was introduced to the mixture at -78°C . The mixture

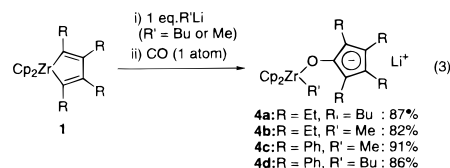


was stirred at -78°C under a slightly positive pressure of CO for 1 h and quenched with 3 N HCl at -78°C . Cyclopentenone **2a** was obtained in 88% yield (75% isolated yield) as a mixture of trans and cis isomers in a ratio of 5.5 to 1. No formation of cyclopentadienone was detected. The results are shown in Table 1 and the following points are noteworthy. Without *n*-BuLi **1a** did not give any CO insertion products under CO (1 atm) atmosphere, and the starting compound **1a** remained unreacted. The use of *n*-BuMgCl instead of *n*-BuLi did not give the product. Deuteriolysis of the resulting mixture instead of hydrolysis afforded dideuterated **2a-D** in 72% isolated yield with >95% of



deuterium incorporation. This indicates that one of two double bonds of the diene moiety was reduced to a single bond during the hydrolysis. Zirconacyclopentadienes **1b–d** afforded similar results. The products **2b–d** were obtained in good to high yields as a mixture of trans and cis isomers. The structure of the trans isomer of **2d** was determined by X-ray crystallography. It is noteworthy that when two different alkynes, diphenylacetylene and 3-hexyne, were used for this reaction—in other words, when unsymmetrical zirconacyclopentadiene **1e** was used—cyclopentenone **2e** was selectively formed. No formation of a positional isomer of the double bond **3** was detected. The double bond originated from 3-hexyne was reduced to a single bond selectively. Similar site selectivity was expected for indanone formation. As expected, zirconaindene **1f–g** gave **2f–g** selectively by this reaction. For terminal alkynes, unfortunately, the reaction was not selective.

To understand the reaction, the reaction mixture of **1a**, *n*-BuLi, and CO was investigated by NMR study. The NMR study of the resulting mixture after CO insertion indicated the formation of **4a** in 87% NMR yield. ¹³C NMR of **4a** showed a methine carbon



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















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Table 1. Formation of Cyclopentenones from Zirconacyclopentadienes and CO in the Presence of *n*-BuLi^a

Zirconacyclopentadienes	Product	Isolated Yield/% ^b
		75(88)
		72(82)
		49(66)
		89
		82
		70
		61
		70(85)

^a The reactions were carried out in THF. *n*-BuLi (1 equiv) was added at -78°C . The mixture was treated with CO at -78°C under slight positive pressure. Cyclopentenones were obtained after hydrolysis.^b GC yields are in parentheses.

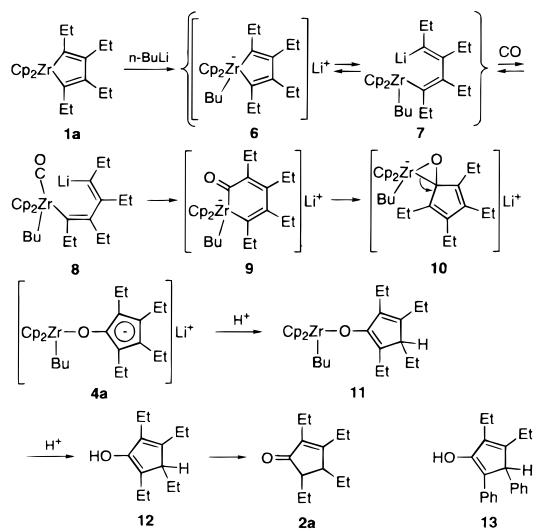
at 111.01 ppm assigned to Cp and four signals at 40.38, 36.92, 30.80, and 14.21 ppm assignable to a Bu group attached to zirconium. These four carbon signals are consistent with the Bu group of $\text{Cp}_2\text{Zr}(\text{Bu})(\text{OMe})$, which shows four carbons at 40.34, 36.01, 29.87, and 14.27 in its ^{13}C NMR spectrum.¹⁰ The ^{13}C NMR spectrum of **4a** also showed three signals at 100.92, 106.83, and 146.62 ppm assignable to five ring carbons of a symmetrical cyclopentadienyl anion. The reaction of **4a** with EtBr for 1 h at 0°C gave an ethylated cyclopentenone **5** in 59% GC yield (44% isolated yield) along with the formation of its isomers. In the case of use of MeLi instead of BuLi the formation of a similar type of complexes **4b–d** was observed.

The following is a plausible mechanism of this reaction (Scheme 1). *n*-BuLi coordinates to zirconium of zirconacyclopentadiene **1a** to produce zirconium-ate complex **6**.¹¹ This compound is in equilibrium with **7**. In fact, the reaction of a mixture of **1a** and *n*-BuLi with CBrCl_3 afforded 3-bromo-4,5-diethylocta-3,5-diene in 72% yield after hydrolysis. Since zirconacyclopentadiene **1a** is inert toward CBrCl_3 , it suggests that an alkenyllithium moiety is formed in **7**. The real structure of **7** is not clear yet. It might contain multicenter bonds between zirconium, carbon, and lithium. However, we tentatively use this conventional structure here for intermediate **7**.

The reaction of **7** with CO gives **8**, and the alkenyllithium moiety in **8** attacks the CO on zirconium to produce **9**. Subsequent

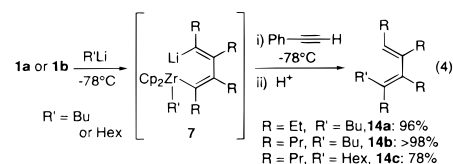
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Scheme 1

cyclization of **9** affords **10** as observed for the CO insertion reactions of zirconacyclopentanes⁵ or zirconacyclopentenes.⁶ Since the cyclopentadienyl anion is more stable, transformation of **10** proceeds to produce **4a** which was observed by NMR. Hydrolysis of **4a** affords **2a** via **11** and **12** as shown in Scheme 1. The ratio of trans and cis isomers was dependent on the conditions of protonation reactions. Selective reduction of double bonds originated from 2-butyne and 3-hexyne in **1f–g** was attributed to an aromatic ring system. The reason for the site selectivity for **2e** is not clear yet, but it can be explained by predominant protonation at the benzyl carbon to afford **13**, which finally produces **2e**.

Further investigation of the reactivity of **7** led us to an interesting reaction. When phenylacetylene was added instead of CO to the mixture of **1a** (or **1b**) and *n*-BuLi at -78°C , unexpected butylated diene **14a** (or **14b**) was obtained in 96% yield (or 98% yield). A similar reaction proceeded when hexyl-



lithium was used instead of *n*-BuLi, and the hexylated product **14c** was formed in 78% yield. With use of deuterated phenylacetylene, monodeuterated diene **14a–D** was formed in high yield with >99% deuterium incorporation. This result suggests that the alkenyllithium moiety in **7** was protonated with phenylacetylene and reductive coupling of a Bu (or hexyl) group and a dienyl group occurred. The coupling reaction on zirconocene of an alkyl group such as a butyl group and a hexyl group with an alkenyl group is unprecedented.

Although we must await further investigation to elucidate the reaction mechanism, it is clear that the ate complexes prepared from zirconacyclopentadienes and alkenyllithium show novel interesting reactivities and provide a useful preparative method of cyclopentenones from two alkynes and CO. Further investigation of the reactions of the zirconacyclopentadienes and alkenyllithium system is now in progress.

Supporting Information Available: All experimental details and crystallographic data, positional and thermal parameters, and lists of bond lengths and angles for **2d** (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.