

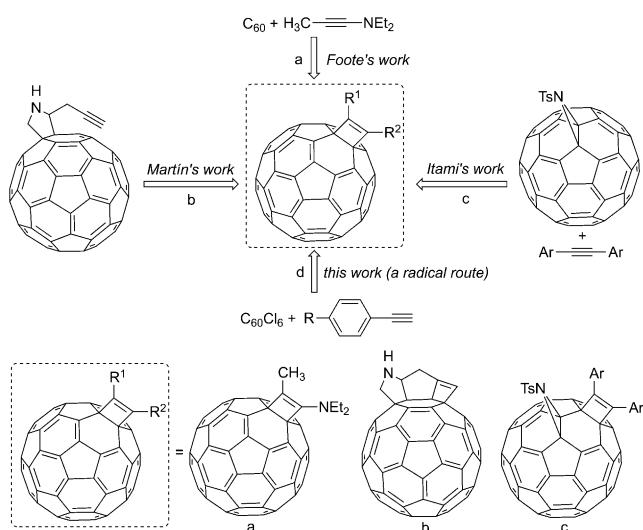
Construction of Fullerocyclobutene Derivatives through Copper(I)-Mediated Radical Annulation of C₆₀Cl₆ with Aryl Acetylenes

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Fullerenyl cyclobutene represents an interesting bridge to chemical modification of the C₆₀ cage.^[1] Synthesis of fullerocyclobutene derivatives, however, is challenging due to the strong tension of the four-membered ring.^[2] Via a [2+2] cycloaddition route, fullerocyclobutenes can be synthesized by the reaction of fullerene with alkynes. Foote and co-workers disclosed that ynamines reacted with C₆₀ to form C₆₀-fused cyclobutenamines (Scheme 1a), which were subject to further reaction in the presence of oxygen and light.^[1a-c] An interesting [2+2] intramolecular cycloaddition of fuller-1,6-enynes to produce fullereryl cyclobutene derivatives was re-

ported by Martín et al. (Scheme 1b).^[1d] Itami and co-workers reported a formal [2+2] cycloaddition with aziridinofullerene and diaryl acetylenes to produce C₆₀ cyclobutene derivatives (Scheme 1c).^[1e] To the best of our knowledge, however, synthesis of fullereryl cyclobutene derivatives through radical reaction has rarely been studied. Herein we report a novel copper(I)-mediated radical annulation involving C₆₀Cl₆ with aryl acetylenes to form fullerocyclobutene derivatives (Scheme 1d).

It was shown that C₆₀Cl₆ readily reacted with aryl acetylenes in the presence of cuprous iodide (Table 1). Purifica-



Scheme 1. Available methods for the synthesis of fullerocyclobutenes.

Table 1. Copper(I)-mediated radical annulation involving C₆₀Cl₆ with aryl acetylenes.^[a]

Entry	1	2	Yield of 2 [%] ^[b]
1	4-MeOC ₆ H ₄ C≡CH (1a)	2a	53
2	4- <i>n</i> -pent-C ₆ H ₄ C≡CH (1b)	2b	48
3	C ₆ H ₅ C≡CH (1c)	2c	44
4	4-BrC ₆ H ₄ C≡CH (1d)	2d	36
5	<i>n</i> -C ₄ H ₉ C≡CH (1e)	2e	0
6	C ₆ H ₅ C≡CC ₆ H ₅ (1f)	2f	0

[a] All reactions were carried out with a molar ratio of C₆₀Cl₆/I/CuI = 1:50:2 in toluene at 60°C. [b] Yield of isolated product.

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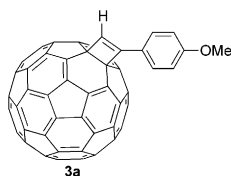
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tion by HPLC (eluted with toluene at 2 mL min⁻¹ flow rate) afforded **2a-d** (36–53%). Complete characterization of the structures of compounds **2a-d** was carried out by atmospheric pressure chemical ionization (APCI) mass spectrometry, ¹H and ¹³C NMR spectroscopy, and correlation NMR spectroscopy methods (DEPT, HSQC ¹H-¹³C, HMBC ¹H-¹³C, and NOESY; see the Supporting Information).

As listed in Table 1, the reaction of C₆₀Cl₆ with aryl acetylenes **1a-d** produced fullerocyclobutene derivatives **2a-d** in acceptable yields. Phenylacetylene gave the desired product in 44% yield (Table 1, entry 3). The fullerocyclobutenes **2a** and **2b** with electron-donating groups at the phenyl rings were obtained in higher yields (Table 1, entries 1 and 2),

whereas the fullerocyclobutene **2d** with electron-withdrawing group gave the product in a lower yield (Table 1, entry 4). However, both 1-hexyne (Table 1, entry 5) and 1,2-diphenylacetylene (Table 1, entry 6) remained intact in the otherwise identical reaction. The inertness of 1-hexyne and 1,2-diphenylacetylene in the reactions was presumed to result from the instability of the corresponding radical intermediate of 1-hexyne and the steric hindrance of 1,2-diphenylacetylene.

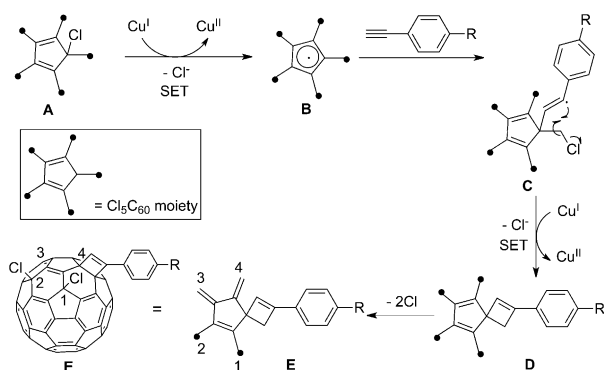


Scheme 2. Molecular structure of **3a**.

Interestingly, reaction of 4-MeOC₆H₄C≡CH (**1a**) with C₆₀Cl₆ in the presence of copper(I) iodide afforded a side product **3a** (Scheme 2), which was isolated by HPLC in 8% yield and structurally identified by a variety of correlation NMR methods (see the Supporting Information). Increasing the reaction temperature or the reaction time led to a higher yield of **3a**. This side product was very likely produced by dechlorination of **2a**. The thermal stability of **3a** over **2a** and the production of **3a** from **2a** had been confirmed by multi-stage mass spectrometry based on the principles previously proposed.^[3]

Chlorofullerene C₆₀Cl₆ is a valuable synthon for further preparation of novel fullerene derivatives. Selective substitution by replacing the chlorine atoms with appropriate functional groups predominates the reactions involving C₆₀Cl₆. Traditionally, these transformations can be achieved by electrophilic aromatic substitution^[4] or nucleophilic substitution reactions.^[5] However, selective substitution of C₆₀Cl₆ producing fullerene derivatives in a radical reaction has rarely been reported to date.

A possible reaction mechanism is proposed and shown in Scheme 3. On the basis of the observed reactivity profile and the reported studies,^[6] we consider a copper-mediated radical pathway starting with a single-electron transfer^[7] from an equivalent of Cu^I to C₆₀Cl₆ (**A**) to generate a cyclopentadienyl radical Cl₅C₆₀[•] (**B**).^[8] The reaction of aryl acety-



Scheme 3. Proposed mechanism responsible for the formation of fullerocyclobutenes **2a-d**. SET = single-electron transfer.

lene with **B** produces a phenylethylene radical intermediate **C**, which loses a neighbor chlorine group to form **D** in the presence of another equivalent of Cu^I. With two chlorine atoms reserved, the elimination of the other two chlorine atoms from **D** produces the final product **E**. There are two reasons to assume the two chlorine atoms in compound **E** are bonded to the 1- and 2-carbons (the mirror-image equivalent involves the attachment of the two chlorine atoms to the 4- and 3-carbons). First, attachment of chlorines to either of the 1/4- or 2/3-carbon pairs is irrational, because the resultant C_s symmetry of the products does not match the ¹³C NMR spectra. Second, the possibility of bonding chlorines to the 1- and 3-carbons (the mirror-image equivalent involves attachment to the 4- and 2-carbons) is ruled out, because this kind of structure is low-aromatic and theoretically predicted to be unstable.^[9]

In summary, we have developed a new copper(I)-mediated reaction of C₆₀Cl₆ with aryl acetylenes to produce fullerocyclobutenes with two remaining chlorine atoms. With two equivalents of copper(I) iodide, the reactions involving C₆₀Cl₆ with aryl acetylenes such as **1a-d** afford fullerocyclobutenes in 36–53% yields, depending on the electronic effect of the substituent at the phenyl ring. A possible radical mechanism responsible for the formation of fullerocyclobutenes is proposed. This novel reaction represents not only a new route to fullerocyclobutenes but also a valuable complement to the existing reactions of C₆₀Cl₆.

Experimental Section

Synthesis of Fullerocyclobutenes

The aryl acetylene (5.0 mmol, 50.0 equiv) and cuprous iodide (0.2 mmol, 2.0 equiv) were suspended in dry toluene (5 mL) and the mixture was stirred at room temperature for 15 min. C₆₀Cl₆ (0.1 mmol, 1.0 equiv) in dry toluene (40 mL) was added to the resulting solution. The reaction mixture was stirred for 10 h at 60°C and then cooled to room temperature. All insoluble products were filtered off, and the filtrate was concentrated in vacuum to give brown solids that were then washed with methanol and dried in vacuum.

Purification by HPLC

The products were purified using a LC-20AT Shimadzu instrument equipped with a 5PBB column (10×250 mm) using toluene as eluent at 2 mL min⁻¹ flow rate. The HPLC runs were conducted at room temperature. The HPLC chromatograms were monitored by an UV detector at 330 nm.

Structural characterization

Mass spectra were obtained on a Bruker Esquire HCT mass spectrometer with an atmospheric pressure chemical ionization (APCI) ion source in the negative-ion mode. The dry gas temperature was set at 250°C, and the APCI temperature was set at 300°C. UV/Vis spectra were determined on a Varian Cary5000 UV/Vis/NIR spectrometer, and IR spectra were measured on a Nicolet AVATER FTIR 330 spectrometer. ¹H and ¹³C NMR spectra were recorded on a Bruker AV-600 and an AV-400 spectrometer, respectively. ¹H NMR spectra were referenced to residual CHCl₃ (7.26 ppm) or C₆HD₅ (7.16 ppm), and ¹³C NMR spectra were referenced to CDCl₃ (77.0 ppm) or C₆D₆ (128.0 ppm). For complete identification of the structures in detail, DEPT, HSQC ¹H–¹³C, HMBC ¹H–¹³C, and NOESY spectra were measured. All the ¹³C NMR spectra were measured with complete proton decoupling.

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Keywords: cycloaddition • copper • fullerenes • homogeneous catalysis • radicals

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