

# Synthesis and [2 + 2] Cycloaddition of Dimethyleneketene Acetals. Reaction with C<sub>60</sub> and Facile Hydrolysis of the C-C Bond Connected to C<sub>60</sub>

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The enolate of cyclopropanecarboxylic acid and its derivatives is an important building block for organic synthesis.<sup>1</sup> However, the strained methylenecyclopropane structure of the enolate renders this species not only difficult to prepare<sup>2</sup> but also unstable, making it rather exist in its  $\alpha$ -metallo carbonyl tautomeric form.<sup>3</sup> Hence, information on this enolate remains scarce and its utility unexplored. We report here that the *O*-alkylated enolates of cyclopropanecarboxylates (dimethyleneketene acetals **3**) can be prepared from readily available precursors **1**, and that they are extremely reactive, serving as useful surrogates of the elusive parent enolates (Scheme 1). Their utility is illustrated by the [2 + 2] cycloaddition to electron-deficient olefins, which, after hydrolytic workup, gives rise to the Michael addition products **8**: a type of reaction product previously unavailable. We also found that **3** reacts smoothly with C<sub>60</sub> to give the [2 + 2] adduct **5** and, most remarkably, that the asterisked C-C  $\sigma$  bond in **5** directly connected to the fullerene core is hydrolytically unstable and can be quantitatively cleaved with aqueous acid.

Thermolysis of the readily available methylenecyclopropane **1**<sup>4</sup> at 150 °C for 4 h in toluene (or 1,2-dichlorobenzene) produces the ketene acetal **3** in 60–80% yield. Since mild thermolysis of **1** (40–80 °C) reversibly generates a dipolar trimethylenemethane **2**,<sup>5</sup> the formation of **3** at higher temperature must be due to an alternative ring closure of **2**.<sup>6</sup> While **3** is hydrolytically unstable, it can be characterized by its olefinic carbon signals at  $\delta$  76.83 and 148.40 ppm in the reaction carried out in C<sub>6</sub>D<sub>6</sub> and by isolation of the corresponding ester **4a** (63% yield) after aqueous workup. The rearrangement of the substituted methylenecyclopropanes **1b** and **1c** (150 °C for 6–8 h) gave the corresponding ketene acetals **3b** and **3c**, which were hydrolyzed to **4b** and **4c** in 69% (66% cis) and 78% yields (87% cis), respectively.<sup>7</sup>

Next, we describe the thermal [2 + 2] cycloaddition of **3** with C<sub>60</sub>, which proceeded with remarkable ease. Thus, upon mixing 0.4 mL of a toluene solution of **3a** (2.2 equiv) with 150 mL of a toluene solution of C<sub>60</sub> (50 mg, 0.069 mmol) at room temperature for 20 h, the cyclobutane product **5** formed in 67% isolated yield and 25% of C<sub>60</sub> was recovered. The sp<sup>3</sup> carbon signals of the C<sub>60</sub> core in **5** appeared at  $\delta$  68.23 and 80.50 ppm, and the <sup>1</sup>H and <sup>13</sup>C NMR spectra revealed the C<sub>s</sub> symmetry of the molecule, indicating

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(6) While the extremely high reactivity of **2** so far precluded detailed investigations, the formation of **3** appears to be irreversible (see supplementary material).

(7) Difference NOE experiments for **4c** indicated the cis stereochemistry between the <sup>t</sup>Bu and the ester groups. The stereochemistry of **4b** was determined by analogy.

## Scheme 1

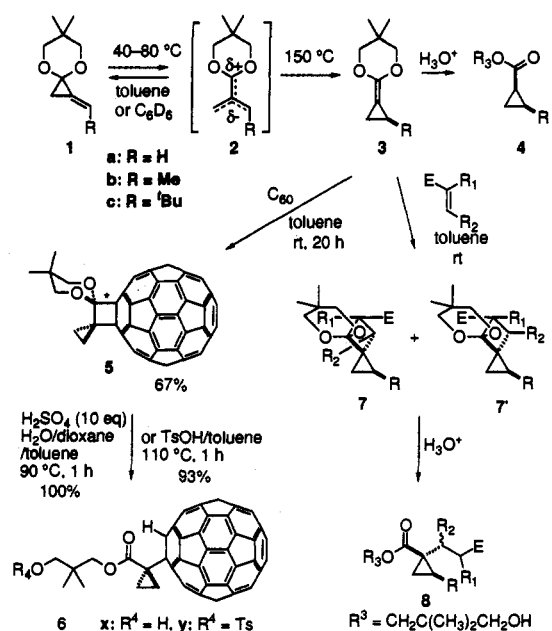


Table 1. [2 + 2] Cycloaddition of Dimethyleneketene Acetal with Olefins<sup>a</sup>

| entry | <b>3</b> <sup>b</sup> | olefin | time (h) | <b>7</b> | <b>8</b> | %yield <sup>c</sup> |
|-------|-----------------------|--------|----------|----------|----------|---------------------|
| 1     | <b>3a</b>             |        | 12       |          |          | 54                  |
| 2     | <b>3a</b>             |        | 23       |          |          | 56                  |
| 3     | <b>3a</b>             |        | 7        |          |          | 94                  |
| 4     | <b>3a</b>             |        | 2        |          |          | 91                  |
| 5     | <b>3a</b>             |        | 1        |          |          | 98                  |
| 6     | <b>3a</b>             |        | 3        |          |          | 81                  |
| 7     | <b>3a</b>             |        | 4        |          |          | 54                  |
| 8     | <b>3b</b>             |        | 4        |          |          | 91                  |

<sup>a</sup> The reaction was carried out at room temperature in toluene or C<sub>6</sub>D<sub>6</sub> except for entries 2 and 5–7, where it was carried out at 40 °C. The cycloadducts **7** were fully characterized only for entry 7. <sup>b</sup> The ketene acetal **3** was prepared from 2 equiv of **1**, which generates approximately 1.2 equiv of **3** for the acceptor. <sup>c</sup> Isolated yield of **8**, which is based on olefin.

that the reaction took place on the 6,6-juncture.<sup>8,9</sup> The success of the cycloaddition crucially depends on the strain in **3**, since a

nonstrained equivalent of **3**, the *O*-trimethylsilyl ketene acetal of methyl isobutyrate, did not react at all with C<sub>60</sub> even under a pressure of 9 kbar.

The cycloadduct was thermally stable and showed no sign of cycloreversion upon heating at 100 °C in the presence of dimethyl fumarate as a trapping agent of **3** (vide infra). In contrast, under acidic conditions, hydrolysis of the asterisked C–C  $\sigma$  bond of the cyclobutane ring took place instead of the expected acetal hydrolysis. Thus, heating of **5d** with 10 equiv of H<sub>2</sub>SO<sub>4</sub> and 100 equiv of H<sub>2</sub>O in a 1:1 1,4-dioxane/toluene mixture at 90 °C for 1 h afforded **6x** in quantitative yield.<sup>10</sup> We also obtained the *p*-toluenesulfonate ester **6y** (93%) upon heating **5d** with 10 equiv of *p*-toluenesulfonic acid in refluxing toluene for 1 h. While the mechanism of this intriguing reaction awaits further studies, it can be envisaged that the cleavage is caused either by direct protonation of the C–C  $\sigma$  bond or by that of an adjacent C<sub>60</sub>  $\pi$  bond. In view of chemical modifications of fullerene-containing molecules<sup>11</sup> as well as their chemical and biochemical use,<sup>12,13</sup> the novel fullerene-substituted cyclopropanes **6** would prove to be interesting molecules for future studies.

The ketene acetal **3** also reacts smoothly with electron-deficient olefins to give the Michael adducts **8**. Thus, a mixture of **3a** and

methyl acrylate in C<sub>6</sub>D<sub>6</sub> at room temperature for 12 h gave initially the cyclobutane **7a**, which then afforded the cyclopropanecarboxylic ester **8a** in 54% yield upon aqueous workup (Table 1, entry 1). The cycloadducts **7a** were hydrolytically unstable and could only be characterized by NMR, except in the case of the **3a**/acetylene adduct in entry 7, which was stable and fully characterizable. The Michael addition reaction was found to be quite general for various electron-deficient olefins as shown in Table 1. Unlike the protonation (vide supra), the cycloaddition of **3b** took place stereoselectively from the less hindered face to give **7b** and **7'b** (entry 8).<sup>14</sup>

The reaction of **3a** and dimethyl fumarate and maleate indicated that the [2 + 2] cycloaddition proceeds in a stepwise manner.<sup>15</sup> Thus, while the former reaction took place stereospecifically (entry 5), the latter gave a 63:37 *cis/trans* mixture of adduct (15 min, 40 °C, 19% yield). Upon further heating (entry 6), the isomeric ratio changed further (17:83 *cis/trans* mixture after heating at 40 °C for 3 h, 81%), suggesting that there is also a reversible opening of the cyclobutane ring upon thermolysis.

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**Supplementary Material Available:** Experimental data for the reactions in Scheme 1 and in Table 1 (19 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(9) The cycloaddition could have proceeded in a [4 + 2] manner which would, however, give a highly strained adduct (see supplementary material).

(10) The <sup>13</sup>C NMR resonances of protonated and alkylated C<sub>60</sub> carbons appeared at  $\delta$  61.26 (<sup>1</sup>J<sub>CH</sub> = 138.3) and 65.41 (<sup>2</sup>J<sub>CH</sub> = 7.6 Hz) ppm, respectively.

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(14) NOE experiments for **8** indicated the *cis* stereochemistry between the methyl and the ester groups.

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