Synthesis of Dimethyleneketene Acetals and Their [2 + 2] Cycloaddition to Olefins and [60]Fullerene as Cyclopropanecarboxylate Synthons

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Received 5 July 1996

The synthesis and synthetic utilization of the dimethyleneketene acetal **3** are described in this report. Thermal rearrangement of the methylenecyclopropanone acetal **1** at 150 °C gives the dimethyleneketene acetal **3**, which serves as a reactive surrogate of the enolate of alkyl cyclopropanecarboxylate, which has thus far been difficult to prepare. The ketene acetal **3** not only gives the corresponding alkyl cyclopropanecarboxylate **4** upon hydrolysis but also undergoes smooth [2 + 2] cycloaddition to electron-deficient olefins including C_{60}. The cycloadduct undergoes facile ring cleavage upon aqueous workup to give the Michael addition product **6** in high yield. While the cycloadduct **8** due to the reaction between **3** and C_{60} is thermally unstable to generate C_{60} upon thermolysis, it undergoes quantitative hydrolytic cleavage to give the ester **10** upon attempted hydrolysis of the acetal moiety under acidic conditions. The cycloaddition of **3** with dialkyl azodicarboxylate also proceeds smoothly to afford cyclopropyl amino acid derivative in excellent yield.

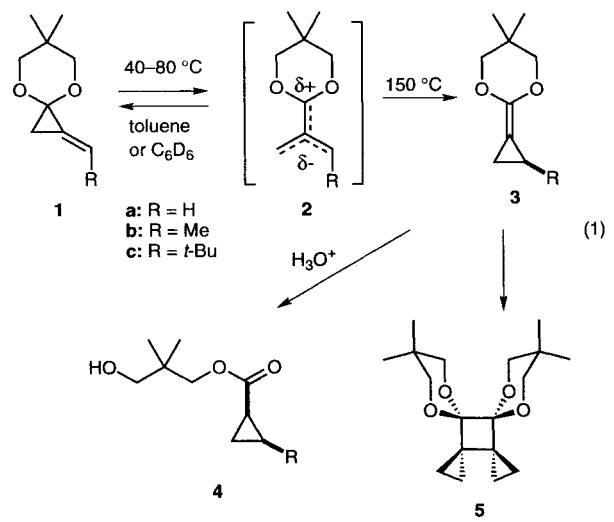
Introduction

Utilization of the internal energy of synthetically viable strained molecules has been the major target of our recent research activities. The strained molecules that we have studied include siloxycyclopropanes as homoenolate precursors,[1] dialkoxycyclopropenone acetals as vinylcarbene precursors[2] and as acceptors of organometallics[3] and radicals,[4] as well as methylenecyclopropanes.[5] As synthetic chemists, we were particularly interested in the synthetic viability of the starting materials, and all of the above strained molecules are stable, easy to handle, and readily available in multigram quantities. In our previous studies, the cyclopropane rings were cleaved in the reaction and served as an equivalent of three- to four-carbon open-chain nucleophilic synthons. In this article we describe synthetic transformations of a class of methylenecyclopropane derivatives as a synthon of a nucleophilic carbanion.

A cyclopropanecarboxylic acid structure constitutes a basic skeleton in various biologically active compounds[6] and may also serve as a useful building block for organic synthesis[7]. However, the use of the enolate of a cyclopropanecarboxylic acid derivative as a nucleophilic cyclopropyl synthon has not necessarily been a useful synthetic operation, since the angle strain inherent to such an enolate (i.e., methylenecyclopropane) makes it rather difficult to deprotonate the proton α to the carbonyl group from the parent cyclopropanecarboxylic acid derivative[8,9].

In the course of our studies on a dipolar trimethylenemethane (TMM) species,[2] we found that a 2,2-dialkoxymethylenecyclopropane **1** isomerizes to a dimethyleneketene acetal **3** upon prolonged heating at a temperature well over the one required to generate the TMM species (e.g., 40 °C vs. 120 °C). We immediately noted that **3** represents the *O*-alkylated enolates of cyclopropanecarboxylates and found that it shows high reactivities toward electron-deficient olefins.

The reaction of the dimethyleneketene acetal **3** with an olefin initially gave a [2 + 2] cycloaddition product, which, after hydrolytic workup, afforded the Michael addition products **7**, a type of reaction products previously unavailable (eq 2). Our interests in organo-functionalized fullerenes[10] led us to investigate the reactivities toward C_{60} and found that **3** reacts smoothly with C_{60} to give the [2 + 2] adduct **8**. We also noted intriguing C–C σ-bond cleavage reactions for some of the olefin cycloadducts. Furthermore, the hetero [2 + 2] cycloaddition of **3** to azodicarboxylic ester followed by hydrolysis afforded a cyclopropane amino acid derivative **12** in excellent yield. Details of the generation and the reactions of **3** are reported in the following paragraphs.[11]



Results and Discussion

Formation of Dimethyleneketene Acetal

We previously reported that dialkoxymethylenecyclopropane **1** exists in equilibrium with a dipolar TMM **2** at the temperature above 40 °C.[12] We now found that **1** isomerizes to an alternative methylenecyclopropane compound **3** upon heating above 120 °C. Studies on this iso-

merization reaction in various solvents revealed that the isomerization was extremely sensitive toward a trace amount of acid and oxygen. Reproducible results were obtained however by the use of a degassed solvent in a thoroughly silylated glass reaction vessel (see Experimental Section). With such a precaution, thermolysis of the methylenecyclopropane **1**[13] in degassed C_6D_6 in a sealed NMR tube for 4 hours produced the ketene acetal **3**, which can be characterized by its olefinic carbon signals at $\delta = 76.83$ and 148.40. Because of extreme hydrolytic sensitivity, **3** could not be isolated pure, and was characterized as the corresponding ester **4a** after aqueous work-up (Table 1, entry 1). The ketene acetal **3** was found also to be sensitive to excessive heating and a head-to-head dimer **5** became a major product after 64 hours (entry 2).[14] The NMR spectra revealed the C_s symmetry of the dimer and hence precluded the alternative head-to-tail dimer structure which is of C_2 symmetry. The isomerization reaction was insensitive to concentration (0.5 M vs. 1.0 M) and the reaction took place smoothly also in *o*-$Cl_2C_6H_4$ (entries 3 and 4).

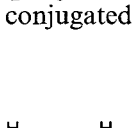
Table 1. Thermal Isomerization of the Methylenecyclopropane **1**[a]

Entry	Solvent	Conc. (M)	Additive	Time (h)	**4** (%)[b]	**5** (%)[b]
1	C_6D_6	0.5	–	4	61 (67)[c]	0
2	C_6H_6	0.5	–	64	26	55
3	C_6H_6	1.0	–	4	53 (60)[c]	2
4	*o*-$Cl_2C_6H_4$	0.5	–	4	58 (60)[c]	5
5	C_6D_6	0.5	DNB[d] (5 mol%)	4	60 (65)[c]	0
6	C_6D_6	0.5	TEMPO[e] (5 mol%)	4	62 (65)[c]	0
7	C_6H_6	0.5	Ph_3CH (2 equiv)	4	55 (57)[c]	1
8	Ph_3CH	ca. 0.5	–	4	52 (56)[c]	2
9	Ph_2CH_2	ca. 0.5	–	4	59 (63)[c]	5

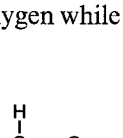
[a] Reaction was carried out in a sealed tube.
[b] Yield was determined by isolation (entry 3) and by estimation from ^1H NMR using an internal standard.
[c] Yield based on converted **1**.
[d] DNB = *p*-dinitrobenzene.
[e] TEMPO = 2,2,6,6-tetramethyl-1-piperidinooxy free radical.

Gel permeation chromatographic (GPC) analysis revealed the formation of sizable amounts of byproducts of the molecular weights corresponding to trimers and tetramers. The product distribution was not affected by the presence of radical inhibitors (entries 5 and 6), and triphenylmethane and diphenylmethane failed to trap any radical intermediates, suggesting that the isomerization and oligomerization do not involve radical species. The dimer **5** was thermally stable, and no sign of cycloreversion to **3** or conversion to higher oligomers was observed after heating at 150 °C for 83 h in C_6D_6 in the presence of excess MeOH as a trapping agent of **3** or **2** (>95% recovery).

The isomerization from **1** to **3** was found to be irreversible, and the calculated thermodynamics suggested that the driving force of the isomerization is the release of strain energy. The calculated potential energies (at the MP2/6-31G*//HF/6–31G* level optimized without symmetry assumption[15]) of the model compounds **i** and **ii** indicated that the latter is more stable by 6.7 kcal/mol. Kinetically speaking, the C_1–C_3 bond cleavage in the methylenecyclopropane **i** is expected to be more favorable than the C_2–C_3 bond cleavage in **ii** since the former bond is directly conjugated to the acetal oxygen while the latter is not.



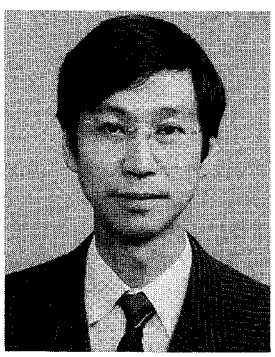
i
(-305.455931091 hartree)



ii
(-305.466588148 hartree)

The rearrangement of the methyl- and *tert*-butyl-substituted methylenecyclopropanes **1b** and **1c** (150 °C for 6–8 h) gave the corresponding ketene acetals **3b** and **3c**, which, upon hydrolysis, afforded **4b** and **4c** in 69% (66% *cis*) and 78% yield (87% *cis*), respectively, as a stereoisomeric mixture.[16] The improvement of the yield may be due to retardation of intermolecular reactions by the steric influence of the substitutent.

Biographical Sketch

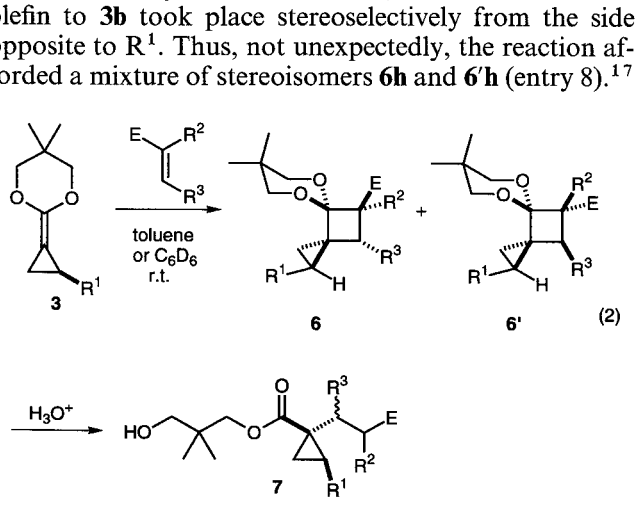


Eiichi Nakamura was born in 1951 in Tokyo. He is a graduate of the Tokyo Institute of Technology, where he also obtained his Ph. D. in organic chemistry. After two postdoctoral years at Columbia University, he took a position as assistant professor in 1980 at Tokyo Institute, where he was promoted to the rank of full professor. In 1995, he moved to his present position at the University of Tokyo. He is a recipient of several awards including the Chemical Society of Japan Award for Young Chemists, and Japan IBM Prize, and has been serving as an Associate Editor of *Chemistry Letters* since 1992. His research interest is focused on the development and synthetic utilization of new functional organic molecules ranging from short lived biradical intermediates to enzyme inhibitors and functional fullerenes. Since his association with the Institute for Molecular Science at Okazaki as adjunct professor, he has developed a group in his laboratories specializing in ab initio calculations, with which he explores the new possibilities of designing reactions and reagents.

[2 + 2] Cycloaddition with Electron-Deficient Olefins

While the dimethyleneketene acetal **3** is thermodynamically more stable than the dialkoxymethylenecyclopropane **1** (vide supra), we found that **3** is much more reactive toward electron-deficient olefins than **1**, which is totally unreactive by itself. Thus, the reaction of **3a** with methyl acrylate in C_6D_6 at room temperature for 12 h gave the [2 + 2] cycloadduct **6a**, which underwent surprisingly facile hydrolysis of the C–C bond to afford the cyclopropane carboxylic ester **7a** in 54% yield upon simple aqueous workup (Table 2, entry 1). The two-step transformation represents the Michael addition of an alkyl cyclopropanecarboxylate to an electron-deficient olefin, which has not been reported previously. The generality of the reaction is shown in Table 2. Cyclic enones participated in the cycloaddition with **3a** to give **7b** in good yield (entry 2). Olefins bearing two electron-withdrawing groups reacted smoothly with **3a**. For instance, the reaction of **3a** to malonate, malononitrile, maleate, and fumalate derivatives afforded **7** in excellent yield (entries 3–7).

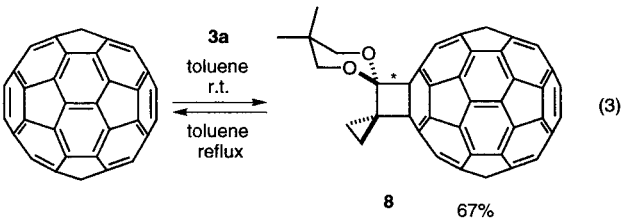
Whereas the cycloadducts **6** derived from olefins were hydrolytically unstable, the **3a**/acethylene adduct **6g** was stable and fully characterizable (entry 7). For the substituted dimethyleneketene acetals, the attack from the olefin to **3b** took place stereoselectively from the side opposite to R^1. Thus, not unexpectedly, the reaction afforded a mixture of stereoisomers **6h** and **6'h** (entry 8).[17]

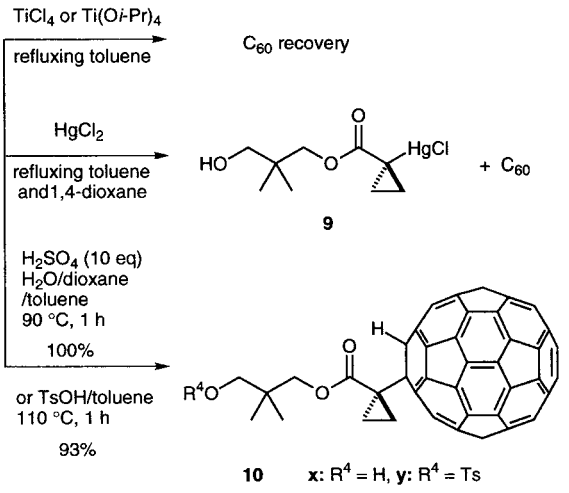


The reaction of **3a** with dimethyl fumarate took place stereospecifically (entry 5), yet that with dimethyl maleate gave a 63:37 *cis*/*trans* mixture of adduct (15 min, 40 °C, 19% yield). Upon further heating (entry 6), the isomeric ratio changed further (17:83 *cis*/*trans* mixture after heating 40 °C for 3 h, 81%, see Experimental Section for details). These results indicate not only that the [2 + 2] cycloaddition proceeds in a stepwise manner,[18] but also that the cycloadduct undergoes slow reversible thermal ring opening.

[2 + 2] Cycloaddition with C_{60}

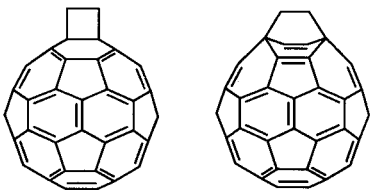
The ketene acetal **3** was also found to undergo thermal [2 + 2] cycloaddition to C_{60} with remarkable ease (eq 3). Thus, slow addition of a toluene solution of **3a** (2.2 equivalents) to a toluene solution of C_{60} afforded, after 20 h at room temperature, the cyclobutane product **8** in 67% isolated yield, together with 25% recovery of unreacted C_{60}.





The sp^3 carbon signals of the C_{60} core in **8** appeared at $\delta = 68.23$ and 80.50, and the ^1H and ^{13}C NMR spectra revealed the C_s symmetry of the molecule, indicating that the reaction took place on the 6,6-juncture.[19] 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_{60} even under a pressure of 9 kbar. The latter reaction takes place only under light irradiation.[20]

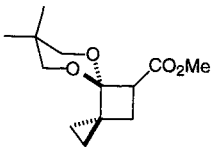
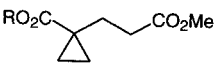
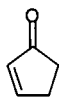
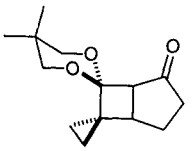
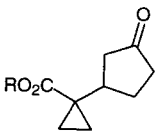
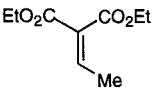
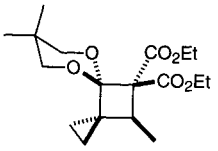
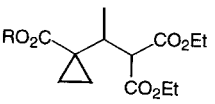
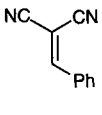
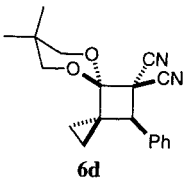
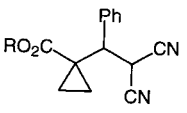
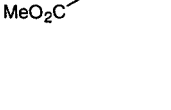
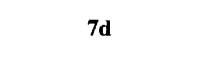
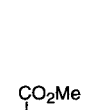
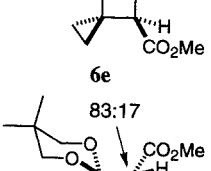
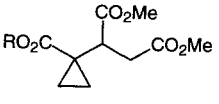
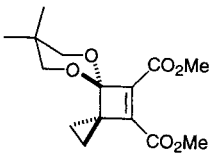
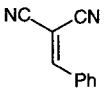
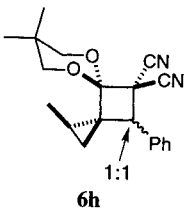
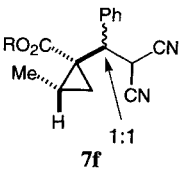
As olefins of C_{60} are electron deficient and **3a** is electron rich, one might expect that an inverse-electron Diels–Alder reaction takes place instead of the [2 + 2] cycloaddition reaction. In reality, no such a reaction took place. The AM1 calculations for model compounds, ethanofullerene **iii** (C_{2v}) and the Diels–Alder adduct **iv** (C_s), indicated that **iv** is far less stable than **iii** because of the strained bicyclo[2.2.2]octane structure in **iv**.



iii **iv**

While the cycloadduct **8** was stable at room temperature, it slowly underwent cycloreversion upon heating at 100 °C. Thus, heating a solution of **8** in refluxing toluene for 38 h resulted in regeneration of C_{60} (85% recovery; 100% recovery based on conversion). The instability of a C–C σ bond between the fullerene core and an acetal carbon was also found for a five-membered analog of **8d**.[21]

Table 2. [2 + 2] Cycloaddition of Dimethyleneketene Acetal with Olefins[a]

Entry	3[b]	Olefin	Time (h)	6	7[c]	Yield[d] (%)
1	**3a**		12	 **6a**	 **7a**	54
2	**3a**		23	 **6b**	 **7b**	56
3	**3a**		7	 **6c**	 **7c**	94
4	**3a**		2	 **6d**	 **7d**	91
5	**3a**		1	**6e**	 **7e**	98
6	**3a**		3	 **6f**	 **7f**	81
7	**3a**		4	 **6g**		54
8	**3b**		4	 1:1 **6h**	 1:1 **7f**	91

[a] The reaction was carried out at r.t. in toluene or C_6D_6 except for entries 2 and 5–7, where it was carried out at 40 °C. The cycloadducts **6** were fully characterized only for entry 7.

[b] The ketene acetal **3** was prepared from 2 equivalents of **1**, which generates approximately 1.2 equivalents of **3** for the acceptor.

[c] R = $CH_2C(CH_3)_2CH_2OH$.

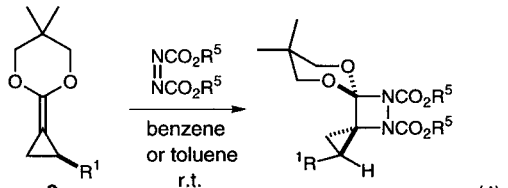
[d] Isolated yield of **7**, which is based on olefin.

Lewis acids were also found to effect cleavage of the C–C bond. When $TiCl_4$ (1.0 equivalent) was added to the reaction mixture, the cycloreversion took place faster than in the thermal reaction and was complete within 1.5 h at 110 °C to effect quantitative recovery of C_{60}.Ti(O*i*-Pr)$_4$ (1.0 equivalent) effected much slower bond cleavage to give C_{60} in 47 % yield after 64 h (100 % based on conversion). The cycloreversion in the presence of $HgCl_2$ (1.0 equivalent) in refluxing toluene was complete within 36 h, and gave C_{60} (100 %) and an α-mercurio ester **9** (43 %) after silica gel chromatography. The mechanism of the metal-assisted cycloreversion is yet unclear.

Upon attempting to hydrolyze the acetal group in **8**, we found that Brønsted acid effects hydrolysis of the asterisked C–C σ bond of the cyclobutane ring. Thus, heating of **8d** with 10 equivalents of H_2SO_4 and 100 equivalents of H_2O in a 1:1 1,4-dioxane/toluene mixture at 90 °C for 1 h afforded **10x** in quantitative yield (eq 3).[22] We also obtained the *p*-toluenesulfonate ester **10y** (93 %) upon heating **8d** with 10 equivalents 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 σ bond or by that of an adjacent C_{60} π bond. In view of chemical modifications of fullerene-containing molecules,[23] as well as their chemical and biochemical use,[24,25] the novel fullerene-substituted cyclopropanes **10** should prove to be interesting molecules for future studies.

Hetero [2 + 2] Cycloaddition with Diazo Compounds

Finally, we report that the reaction of **3** with a nitrogen electrophile proceeds smoothly.[26] Thus, stirring a solution of **3a** (2.0 equivalents) with diethyl azodicarboxylate in benzene at room temperature for 2 h followed by acid hydrolysis of the resulting cycloadduct afforded **12a** as a sole product in 100 % yield (eq 4). The [2 + 2] cycloaddition of **3b** (1.4 equivalents) with di-*tert*-butyl azodicarboxylate in toluene at room temperature for 1 h gave the norcoronamic acid derivative **12b** in 83 % yield.



All reactions dealing with air- and moisture-sensitive compounds were carried out in a dry reaction vessel under N_2 or, when appropriate, in a sealed tube. Routine chromatography was carried out as described by Still.[27] Purification by recycling preparative HPLC was performed on a Japan Analytical Industry LC-908 machine equipped with GPC column (JAIGEL 1 H and 2 H) using $CHCl_3$ as eluent. ^{1}H NMR (270, 400, and 500 MHz) and ^{13}C NMR (100 and 125 MHz) spectra were measured for a $CDCl_3$ or C_6D_6 solution of a sample on JEOL GSX-270, EX-400, and GSX-500 instruments. ^{1}H NMR spectra are reported in ppm (δ) from internal TMS, and ^{13}C NMR from $CDCl_3$ (77.0 ppm). IR spectra were recorded on a JASCO IR-800; absorptions are reported in cm^{-1}. Gas chromatographic (GC) analysis were performed on a Shimadzu 8A or 14A machine equipped with capillary columns (0.25 mm I.D. × 25 m) coated with OV-1 or OV-17. The reaction vessels and NMR tubes used for the thermal isomerization of **1** were treated with 35 % aq. NH_3 solution overnight followed by 10 % *N,O*-bistrimethylsilylamide (BSA) in hexane overnight before use.

Ethereal solvents were distilled from benzophenone ketyl under N_2 immediately before use. Toluene and *o*-dichlorobenzene were distilled from CaH_2 and stored over molecular sieves 4A. CH_2Cl_2 was dried over P_2O_5 overnight, distilled over CaH_2, and stored over molecular sieves 4A. Purification of crude fullerene extracted from carbon arc soot which contain 70–85 % C_{60} and 10–15 % C_{70} was carried out on a column of decolorizing carbon Norit-A/silica gel.[28] Commercially available reagents were distilled prior to use.

Isomerization of 1a:

A solution of **1a** (463 mg, 3.0 mmol) in benzene (5.5 mL) was heated at 150 °C for 4 h in a sealed glass tube. The solution was then treated with H_2O (100 μL) for 0.5 h, and the mixture was passed through a pad of silica gel. Removal of solvent followed by purification by silica gel chromatography afforded **4a** (259 mg, 53 % yield).

The hydrolytically unstable ketene acetal **3a** was characterized by ^{1}H and ^{13}C NMR in the reaction carried out in C_6D_6. Thus, a solution of **1a** (46.3 mg, 0.30 mmol) in C_6D_6 (0.55 mL) was heated at 150 °C for 4 h in a sealed NMR tube Hydrolysis of the crude product followed by purification by flash chromatography afforded **4a** (31.5 mg, 61 % yield).

2-Cyclopropylidene-5,5-dimethyl-1,3-dioxane (**3a**):

^{1}H NMR (270 MHz, C_6D_6): δ = 0.68 (s, 6 H, CH_3), 1.22 (s, 4 H, cyclopropyl), 3.45 (s, 4 H, OCH_2).

^{13}C NMR (67.5 MHz, C_6D_6): δ = 3.13 (CH_2, 2 C), 22.06 (CH_3, 2 C), 30.61 (C), 76,83 (C = C), 76,90 (OCH_2, 2 C), 148,40 (C = $C(O)_2$).

3-Hydroxypropyl-2,2-dimethyl Cyclopropanecarboxylate (**4a**):

IR(neat): ν = 3420 (br), 3100, 1730 cm^{-1}.

^{1}H NMR (270 MHz, $CDCl_3$): δ = 0.84–0.91 (m, 2 H, cyclopropyl), 0.92 (s, 6 H, CH_3), 0.97–1.05 (m, 2 H, cyclopropyl), 1.63 (tt, *J* = 7.8, 4.9 Hz, 1 H, cyclopropyl CHCO$_2$), 2.33 (br s, 1 H, OH), 3.28 (s, 2 H, CH_2OH), 3.94 (s 2 H, CO_2CH_2)

Anal. Calcd for $C_9H_{16}O_3$: C, 62.76; H, 9.36. Found: C, 62,46; H, 9.22.

10,10,16,16-Tetramethyl-8,12,14,18-tetraoxatetraspiro-[2.0.2.0.5.0.5.0]octadecane (**5**):

IR (neat): ν = 3080, 1120, 1080, 1060, 1025 cm^{-1}.

^{1}H NMR (270 MHz, $CDCl_3$): δ = 0.23 (dd, *J* = 6.9, 5.7 Hz, 4 H, cyclopropyl), 0.91 (s, 3 H), 0.94 (dd, *J* = 6.9, 5.7 Hz, 4 H, cyclopropyl), 0.98 (s, 3 H), 3.49 (d, *J* = 11.0 Hz, 4 H, OCH_2), 3.83 (d, *J* = 11.0 Hz, 4 H, OCH_2).

^{13}C NMR(67.5 MHz, $CDCl_3$): δ = 5.35 (CH_2 4 C, cyclopropyl), 22.15 (CH_3, 2 C), 22.49 (CH_3, 2 C), 30.04 (C, 2 C), 31.64 (C, 2 C), 73.18 (CH_2, 4 C), 102.48 (C, 2 C).

MS (EI): *m/z* = 308 (M^+, 5 %), 293 (7 %), 223 (77 %), 137 (70 %), 69 (100 %).

Anal. Calcd for $C_{18}H_{28}O_4$: C, 70.10; H, 9.15. Found: C, 69.80; H, 9.08.

Isomerization of 1b:

A solution of **1b** (50.5 mg, 0.30 mmol) in C_6D_6 (0.6 mL) was heated at 150 °C for 6 h in a sealed NMR tube, which was previously

treated with 10% BSA in hexane. The unstable ketene acetal **3b** was characterized by ^{1}H NMR. The solution was treated with a 5% 1M HCl in THF (0.6 mL) for 0.5 h, and the mixture was passed through a pad of silica gel. GLC analysis (110 °C) indicated the formation of a 66:34 mixture of *cis* and *trans* isomers. Removal of solvent followed by purification by silica gel chromatography afforded **4b** (38.6 mg, 69% yield).

5,5-Dimethyl-2-(2'-methylcyclopropylidene)-1,3-dioxane **(3b)**:

^{1}H NMR (200 MHz, C_6D_6): δ = 0.68 (s, 3 H, CH_3), 0.69–0.77 (m 1 H, cyclopropyl), 0.77 (s, 3 H CH_3), 0.98 (dd, J = 6.9, 3.8 Hz, 1 H cyclopropyl), 1.25 (d, J = 5.9 Hz, 3 H, CH_3), 1.47 (t, J = 6.9 Hz, 1 H, cyclopropyl), 3.50 (s, 4 H, OCH_2).

3-Hydroxypropyl-2,2-dimethyl 2-Methylcyclopropanecarboxylate **(4b)**:

IR and elementary analyses were carried out for 7:3 mixture of two diastereomers.

IR (neat): ν = 3425, 1725, 1710, 1400, 1175, 1160, 1052.

^{1}H NMR (500 MHz, $CDCl_3$): major product δ = 0.89–0.93 (m, 1 H, cyclopropyl), 0.92 (s, 3 H, CH_3), 0.93 (s, 3 H, CH_3), 1.05 (dt, J = 8.2, 4.3 Hz, 1 H, cyclopropyl), 1.20 (d, J = 6.0 Hz, 3 H, CH_3), 1.27–1.38 (m, 1 H, cyclopropyl C*H*CH_3), 1.70 (dt. J = 8.2, 5.5 Hz, 1 H, cyclopropyl), 2.47 (br s, 1 H, OH), 3.28 (br s, 2 H, C*H*$_2$OH), 3.88 (d, J = 11.2 Hz, 1 H, CO_2CH_2), 4.03 (d, J = 11.2 Hz, 1 H, CO_2CH_2); minor product δ = 0.71 (ddd, J = 7.8, 6.4, 4.1 Hz, 1 H, cyclopropyl), 0.91 (s, 6 H, CH_3), 1.12 (d, J = 6.0 Hz, 3 H, CH_3), 1.19 (distorted dt, J = 7.8, 4.1 Hz, 1 H, cyclopropyl), 1.36 (distorted dt, J = 7.8, 4.1 Hz, 1 H, cyclopropyl), 1.37–1.45 (m, 1 H, cyclopropyl C*H*CH_3), 2.34 (br s, 1 H, OH), 3.28 (br s, 2 H, C*H*$_2$OH), 3.90 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 3.99 (d, J = 11.2 Hz, 1 H, CO_2CH_2).

Anal. Calcd for $C_{10}H_{18}O_3$: C, 64.49; H, 9.74. Found: C, 64.23; H, 9.76.

Isomerization of 1c:

A solution of **1c** (21.3 mg, 0.10 mmol) in C_6D_6 (0.6 mL) was heated at 150 °C for 11 h in a sealed NMR tube, which was previously treated with 10% BSA in hexane. The solution was treated with 5% 1 M HCl in THF (0.6 mL) for 0.5 h, and the mixture was passed through a pad of silica gel. GLC analysis (110 °C) indicated the formation of a 87:13 mixture of *cis* and *trans* isomers. Removal of solvent followed by purification by silica gel chromatography afforded **4c** (17.8 mg, 78% yield).

2-(2'-tert-Butylcyclopropylidene)-5,5-dimethyl-1,3-dioxane **(3c)**:

^{1}H NMR (200 MHz, C_6D_6): δ = 0.69 (s, 3 H, CH_3), 0.73 (s, 3 H, CH_3), 1.07 [s, 9 H, $C(CH_3)_3$], 1.13 (dd, J = 7.6, 4.4 Hz, 1 H, cyclopropyl), 1.30 (t, J = 7.6 Hz, 1 H, cyclopropyl), 1.71 (dd, J = 7.6, 4.4 Hz, 1 H, cyclopropyl), 3.47 (s, 2 H, OCH_2), 3.49 (s, 2 H, OCH_2).

3-Hydroxypropyl-2,2-dimethyl 2-tert-Butylcyclopropanecarboxylate **(4c)**:

Spectra was taken for a 87:13 mixture of *cis* and *trans* isomers.

IR (neat): ν = 3425, (br), 3150 (br), 1730, 1710, 1400, 1165, 1050 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): major isomer δ = 0.92–0.97 (m, 1 H, cyclopropyl), 0.94 (s, 6 H, CH_3), 0.96 (s, 9 H, CH_3), 1.12–1.28 (m, 2 H, cyclopropyl), 1.63 (ddd, J = 9.6,7.8,7.4 Hz, 1 H, cyclopropyl), 2.25 (br d, J = 6.4 Hz, 1 H, OH), 3.34 (br d, J = 6.4 Hz, 2 H, C*H*$_2$OH), 3.92 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 3.93 (d, J = 11.0 Hz, 1 H, CO_2CH_2); minor product δ = 0.86 (s, 9 H, CH_3), 0.85–0.91 (m, 1 H, cyclopropyl), 1.07 (dt, J = 8.5, 4.1 Hz, 1 H, cyclopropyl), 1.36 (ddd, J = 8.5, 7.0, 4.1 Hz, 1 H, cyclopropyl), 1.51 (dt, J = 7.0, 4.1 Hz, 1 H cyclopropyl), 2.41 (br t, J = 6.4 Hz, 1 H, OH), 3.36 (br d, J = 6.4 Hz, 2 H, C*H*$_2$OH), 3.91 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 3.96 (d, J = 11.0 Hz, 1 H, CO_2CH_2).

^{13}C NMR (125 MHz, $CDCl_3$): major isomer δ = 9.14 (CH_2), 19.00 (CH), 21.54 (CH_3), 21.58 (CH_3), 29.48 (CH_3, 3 C), 30.54 (C), 33,92 (CH), 36.37 (C), 68.43 (OCH_2), 69.82 (OCH_2), 173.80 (C = O); minor isomer δ = 11.84 (CH_2), 16.35 (CH), 21.49 (CH_3, 2 C), 28.05 (CH_3, 3 C), 34.77 (CH), 36.69 (C), 68.04 (OCH_2), 69.07 (OCH_2), 175.97 (C = O). A signal corresponding to a quaternary carbon could not be observed probably due to overlap with another signal.

Anal. Calcd for $C_{13}H_{24}O_3$: C, 68.38; H, 10.51. Found C, 68.30; H, 10.41.

Reaction of 3a with Methyl Acrylate; Typical Procedure:

A solution of **1a** (61.7 mg, 0.40 mmol) in degassed C_6D_6 (0.74 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added methyl acrylate (17.2 mg, 0.20 mmol) at r.t. under N_2 and the solution was stirred at this temperature for 12 h. Removal of the solvent followed by purification by silica gel chromatography afforded **7a** (27.8 mg, 54% yield).

10-Methoxycarbonyl-7,7-dimethyl-5,9-dioxadispiro[2.0.5.2]undecane **(6a)**:

^{1}H NMR (200 MHz, C_6D_6): δ = 0.31 (s, 3 H, CH_3), 0.36 (dd, J = 5.7, 4.4 Hz, 2 H, cyclopropyl), 1.05 (s, 3 H, CH_3), 1.25 (dd, J = 5.7, 4.4 Hz, 2 H, cyclopropyl), 2.16 (d, J = 3.4 Hz, 2 H, C*H*$_2$CHCO$_2$Me), 3.17 (d, J = 11.0 Hz, 2 H, OCH_2), 3.31 (s, 3 H, OCH_3), 3.77 (t, J = 3.4 Hz, 1 H, CHCO$_2$Me), 4.03 (d, J = 11.0 Hz, 2 H, OCH_2).

Methyl 3-[1-(3-Hydroxypropoxycarbonyl-2,2-dimethyl-)cyclopropyl]propionate **(7a)**:

IR (neat): ν = 3450, 1740 (shoulder). 1725, 1380, 1190, 1175, 1145, 1060, 735 cm^{-1}.

^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.79 (dd, J = 6.7, 4.4 Hz, 2 H, cyclopropyl), 0.91 (s, 6 H, CH_3), 1.25 (dd, J = 6.7, 4.4 Hz, 2 H, cyclopropyl), 1.89 (distorted t, J = 8.0 Hz, 2 H, CH_2), 2.28 (br s, 1 H, OH), 2.55 (distorted t, J = 8.0 Hz, 2 H, C*H*$_2$CO$_2$CH$_3$), 3.29 (s, 2 H, C*H*$_2$OH), 3.69 (s, 3 H, CO_2CH_3), 3.94 (s, 2 H, CH_2CH_2).

Anal. Calcd for $C_{13}H_{22}O_5$: C, 60.44; H, 8.59, Found: C, 60.66; H, 8.54.

Reaction of 3a with 2-Cyclopentenone; 3-[1'-(3-Hydroxypropoxycarbonyl-2,2-dimethyl)cyclopropyl]cyclopentanone (7b):

A solution of **1a** (46.3 mg. 0.30 mmol) in degassed C_6D_6 (0.55 mL) was heated at 150 °C for 4 h in a sealed tube, and cooled to r.t. To this mixture was added cyclopentenone (14.8 mg, 0.18 mmol) at r.t. After 23 h at r.t., the mixture was added to a stirred solution of H_2O (0.1 mL) in THF (3 mL).The resulting mixture was stirred for 1 h at r.t. and $MgSO_4$ was added. Removal of solvent followed by purification by silica gel chromatography afforded **7b** (19.7 mg, 0.077 mmol, 43% yield).

IR (CCl_4): ν = 3460, 1743, 1720, 1471, 1400, 1378, 1311, 1170, 1150, 1056 cm^{-1}.

^{1}H NMR (270 MHz, $CDCl_3$): δ = 0.76–0.80 (m, 2 H, cyclopropyl), 0.92 (s, 6 H, CH_3), 1.23–1.27 (m, 2 H, cyclopropyl), 1.59 (m, 1 H, CH_2), 1.99 (dd, J = 9.6, 6.7 Hz, 1 H, CH_2), 2.06–2.12 (m, 1 H, CH_2), 2.12–2.22 (m, 1 H, CH_2), 2.23 (br s, 1 H, OH), 2.32–2.40 (m, 1 H, CH_2), 2.40 (dd, J = 9.6,6.7 Hz, 1 H, CH_2), 2.58–2.61 (m, 1 H, CH), 3.26 (br s, 2 H, CH_2OH), 3.92 (s, 2 H, CO_2CH_2).

^{13}C NMR (67.5 MHz, $CDCl_3$): δ = 13.44 (CH_2 2 C), 21.53 (CH_3, 2 C), 25.4 (C), 26.10 (CH_2), 36.52 (C), 38.14 (CH), 38.51 (CH_2), 42.38 (CH_2), 68.02 (CH_2), 69.45 (CH_2), 175.14 (C = O), 218.04 (C = O).

Reaction of 3a with Diethyl Ethylidenemalonate; Ethyl 3-[1'-(3-Hydroxypropoxycarbonyl-2,2-dimethyl)cyclopropyl]-2-ethoxycarbonylbutanoate (7c):

A solution of **1a** (61.7 mg, 0.40 mmol) in degassed C_6D_6 (0.74 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added diethyl ethylidenemalonate (37.6 mg, 0.20 mmol) at r.t. under N_2, and the solution was stirred at this temperature for 7 h. Removal of the solvent, followed by purification by silica gel chromatography afforded **7c** (67.7 mg, 94% yield).

IR (neat): ν = 3430, 1755, 1727, 1370, 1335, 1305, 1280, 1245, 1180, 1035, 735 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.73 (ddd, J = 9.6, 6.4, 3.7 Hz, 1 H, cyclopropyl), 0.87 (ddd, J = 13.1, 6.3, 3.0 Hz, 1 H, cyclopropyl), 0.93 (s, 3 H, CH_3), 0.94 (s, 3 H, CH_3), 1.19–1.32 (m involving peaks at 1.24, 1.247, 1.251, 1.252, 1.26, 1.265, 1.267, and 1.28, 11 H),

1.75 (dq, $J = 10.5$, 6.9 Hz, 1 H, C*H*CH_3), 2.56 (t, $J = 6.6$ Hz, 1 H, OH), 3.30 (dd, $J = 11.5$, 6.6 Hz, 1 H, CH_2OH), 3.32 (dd, $J = 11.5$, 6.6 Hz, 1 H, CH_2OH), 3.91 (d, $J = 11.0$ Hz, 1 H, CO_2CH_2), 3.97 (d, $J = 11.0$ Hz, 1 H, CO_2CH_2), 4.00 [d, $J = 10.5$ Hz, 1 H, C*H*$(CO_2Et)_2$], 4.10–4.26 (m, 4 H).

^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 13.94$ (CH_2CH_3), 14.01 (CH_2CH_3), 15.96 (CH_2), 17.04 ($CHCH_3$), 17.95 (CH_2), 21.65 (CH_3), 21.69 (CH_3) 26.13 (C), 36.48 (C), 39.55 (*C*HCH_3), 55.64 [*C*H$(CO_2Et)_2$], 61.27 (OCH_2CH_3), 61.34 (OCH_2CH_3), 67.97 (CH_2OH), 69.45 (CO_2CH_2), 168.66 (C = O), 168.95 (C = O), 174.49 (C = O).

Anal. Calcd for $C_{18}H_{30}O_7$: C, 60.31; H, 8.44. Found: C, 60.11; H, 8.31

Reaction of 3a with Benzylidenemalononitrile:

A solution of **1a** (46.3 mg, 0.30 mmol) in degassed C_6D_6 (0.55 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added dimethyl maleate (27.0 mg, 0.18 mmol) at r.t. under N_2, and the solution was stirred at this temperature for 2 h. Removal of the solvent followed by purification by silica gel chromatography afforded **7d** (52.4 mg, 91 % yield).

10,10-Dicyano-7,7-dimethyl-5,9-dioxa-11-phenyldispiro[2.0.5.2]undecane **(6d)**:

^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.22$ (s, 3 H, CH_3), 0.30 (ddd, $J = 10.1$, 6.9, 5.0 Hz, 1 H, cyclopropyl), 0.40 (ddd, $J = 10.1$, 6.3, 5.5 Hz, 1 H, cyclopropyl), 0.80 (s, 3 H, CH_3), 1.12 (ddd, $J = 10.5$, 6.3, 5.5 Hz, 1 H, cyclopropyl), 1.20 (ddd, $J = 10.5$, 6.9, 5.0 Hz, 1 H, cyclopropyl), 3.28 (d, $J = 11.5$ Hz, 2 H, OCH_2), 3.87 (s, 1 H, CHPh), 3.90 (d, $J = 11.5$ Hz, 2 H, OCH_2), 7.08–7.19 (m, 5 H, Ph).

^{13}C NMR (125 MHz, C_6D_6): $\delta = 8.31$ (CH_2), 10.22 (CH_2), 20.98 (CH_3), 21.17 (CH_3), 29.40 (C), 34.55 (C), 43.5 (C), 49.99 (CH), 72.71 (OCH_2), 72.78 (OCH_2), 102.35 (OCO), 112.79 (CN), 115.16 (CN), 128.80 (CH, 2 C), 129.05 (CH), 130.31 (CH, 2 C), 134.38 (C).

1-Cyano-3-[1'-(3-hydroxypropoxycarbonyl-2,2-dimethyl)cyclopropyl]-2-phenylpropionitrile **(7d)**:

IR ($CHCl_3$): $\nu = 3620$, 1705, 1150, 1375, 1320, 1035 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.877$ (s, 3 H, CH_3), 0.883 (s, 3 H, CH_3), 0.93–0.99 (m, 1 H, cyclopropyl), 1.16 (ddd, $J = 9.8$, 6.0, 3.7 Hz, 1 H, cyclopropyl), 1.46–1.56 (m, 2 H, cyclopropyl), 2.08 (br s, 1 H, OH), 2.91 (d, $J = 10.5$ Hz, 1 H, $CH(CN)_2$), 3.25 (d, $J = 10.5$ Hz, 1 H, CH_2OH), 3.28 (d, $J = 10.5$ Hz, 1 H, CH_2OH), 3.93 (d, $J = 11.0$ Hz, 1 H, CO_2CH_2), 3.98 (d, $J = 11.0$ Hz, 1 H, CO_2CH_2), 5.44 (d, $J = 10.5$ Hz, 1 H, CHPh), 7.37 (br s, 5 H, Ph).

^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 13.74$ (CH_2), 19.94 (CH_2), 21.33 (CH_3), 21.38 (CH_3), 25.80 (C), 26.51 (CHPh), 36.40 (C), 51.61 (*C*H$(CN)_2$), 68.08 (CH_2OH), 70.03 (CO_2CH_2), 112.32 (CN), 112.63 (CN), 128.34 (CH, 2 C), 129.00 (C), 129.20 (CH, 2 C), 135.81 (C), 173.80 (C = O).

Anal. Calcd for $C_{19}H_{22}O_3N_2$: C, 69.91; H, 6.80; N, 8.58, Found: C, 68.92; H, 6.89; N, 8.30.

Reaction of 3a with Dimethyl Maleate:

A solution of **1a** (46.3 mg, 0.30 mmol) in degassed C_6D_6 (0.55 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added dimethyl maleate (21.6 mg, 0.15 mmol) at r.t. under N_2, and the solution was stirred at this temperature for 10 min followed by 40 °C for 1 h. Removal of the solvent followed by purification by silica gel chromatography afforded **7e** (46.3 mg, 98 % yield).

10,11-Bis(methoxycarbonyl)-7,7-dimethyl-5,9-dioxadispiro[2.0.5.2]-undecane **(6e)**:

^{1}H NMR (500 MHz, C_6D_6): $\delta = 0.26$ (s, 3 H, CH_3), 0.62 (ddd, $J = 9.2$, 6.4, 4.1 Hz, 1 H, cyclopropyl), 0.99 (s, 3 H, CH_3), 1.05–1.12 (m, 1 H, cyclopropyl), 1.22–1.28 (m, 1 H, cyclopropyl), 1.32–1.37 (m, 1 H, cyclopropyl), 3.09–3.14 (m, 4 H, OCH_2), 3.13 (d, $J = 3.7$ Hz, 1 H, C*H*CO_2Me), 3.31 (s, 3 H, OCH_3), 3.41 (s, 3 H, OCH_3), 3.95 (d, $J = 8.7$ Hz, 1 H, OCH_2), 3.87 (d, $J = 8.7$ Hz, 1 H, OCH_2), 4.05 (d, $J = 3.7$ Hz, 1 H, $CHCO_2Me$).

^{13}C NMR (125 MHz, C_6D_6): $\delta = 7.49$ (CH_2), 8.77 (CH_2), 21.25 (CH_3), 22.55 (CH_3), 23.44 (C), 29.07 (C), 43.37 (*C*HCO_2), 51.15 (OCH_3), 54.51 (OCH_3), 69.50 (*C*HCO_2), 70.29 (OCH_2), 70.31 (OCH_2), 111.04 (OCO), 157.59 (C = O), 157.59 (C = O), 172.76 (C = O).

Methyl 3-[1'-(3-Hydroxypropoxycarbonyl-2,2-dimethyl)cyclopropyl]-2-methoxycarbonylpropionate **(7e)**:

IR (neat): $\nu = 3515$ (br), 3435 (br), 3125 (br), 1735, 1725, 1430, 1400, 1375, 1210, 1160 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.85$ (ddd, $J = 9.3$, 6.8, 3.9 Hz, 1 H, cyclopropyl), 0.89 (s, 6 H, CH_3), 1.12–1.22 (m, 1 H, cyclopropyl), 1.27–1.36 (m, 1 H, cyclopropyl), 1.42–1.52 (m, 1 H, cyclopropyl), 2.35 (br t, $J = 5.9$ Hz, 1 H, OH), 2.55 (dd, $J = 17.6$, 4.4 Hz, 1 H, CH_2CO_2Me), 2.56 (dd, $J = 10.3$, 4.4 Hz, 1 H, CH_2CO_2Me), 3.19 (dd, $J = 17.6$, 10.3 Hz, 1 H, CH), 3.26 (br d, $J = 5.9$ Hz, 2 H, CH_2OH), 3.70 (s, 3 H, CO_2CH_3), 3.71 (s, 3 H, CO_2CH_3), 3.91 (s, 2 H, CO_2CH_2).

^{13}C NMR (67.5 MHz, $CDCl_3$): $\delta = 15.13$ (CH_2), 18.40 (CH_2), 21.43 (CH_3), 21.46 (CH_3), 25.71 (C), 34.80 (CH_2), 36.37 (C), 45.36 (CH), 51.88 (OCH_3), 52.12 (OCH_3), 67.85 (OCH_2), 69.96 (OCH_2), 172.81 (C = O, 2 C), 174.12 (C = O).

Anal. Calcd for $C_{15}H_{24}O_7$: C, 56.95; H, 7.65. Found: C, 57.01; H, 7.69.

Reaction of 3a with Dimethyl Fumalate:

A solution of **3a**, which was prepared from **1a** (46.3 mg, 0.30 mmol) in degassed C_6D_6 (0.55 mL) as described above, and dimethyl fumalate (21.6 mg, 0.15 mmol) was stirred at r.t. for 10 min followed by 40 °C for 3 h under N_2, and the progress of the reaction was monitored by ^{1}H NMR. Results are summarized in the Figure. Following peaks could be characterized for the *cis* isomer **6f**.

^{1}H NMR (200 MHz, C_6D_6): $\delta = 0.26$ (s, 3 H, CH_3), 0.91 (s, 3 H, CH_3), 3.17 (s, 3 H, OCH_3), 3.57 (s, 3 H, OCH_3).

Reaction of 3a with Dimethyl Acetylenedicarboxylate; 7,7-dimethyl-10,11-Bis-(methoxycarbonyl)-5,9-dioxadispro[2.0.5.2]undeca-10-ene (6g):

A solution of **1a** (115,7 mg, 0.75 mmol) in degassed C_6H_6 (1.4 mL) was heated at 150 °C for 4 h in a sealed tube, and cooled to r.t. To this solution was added dimethyl acetylenedicarboxylate (64.0 mg, 0.45 mmol) at r.t. under N_2, and the solution was stirred at 40 °C for 4 h. Removal of the solvent followed by purification by silica gel chromatography afforded **6g** (75.8 mg, 0.79 mmol, 57 % yield).

IR (CCl_4): $\nu = 1740$, 1718, 1621, 1430, 1317, 1260, 1239, 1107, 1065 cm^{-1}.

^{1}H NMR (270 MHz, $CDCl_3$): $\delta = 0.81$ (s, 4 H, cyclopropyl), 1.14 (s, 6 H, CH_3), 3.50 (d, $J = 10.8$ Hz, 2 H, OCH_2), 3.77 (s, 3 H, CO_2CH_3), 3.85 (s, 3 H, CO_2CH_3), 4.20 (d, $J = 10.8$ Hz, 2 H, OCH_2).

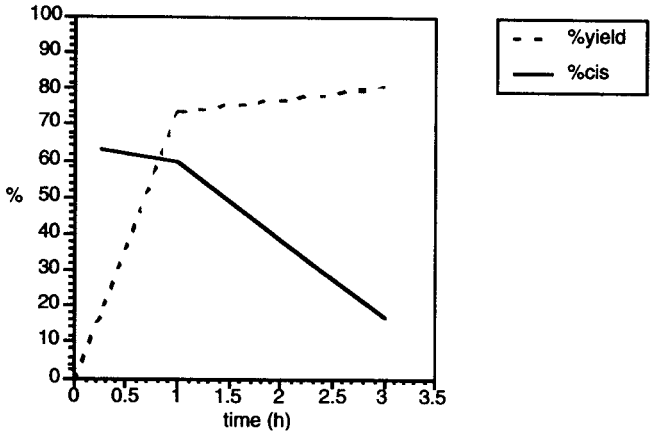


Figure. Time-Dependent Product Distribution

^{13}C NMR (67.5 MHz, $CDCl_3$): δ = 8.32 (CH_2, 2 C), 21.69 (CH_3), 22.63 (CH_3), 29.59 (C), 40.39 (C), 51.91 (OCH_3), 52.14 (OCH_3), 73.75 (OCH_2, 2 C), 101.16 (OCO), 142.72 (C = C), 150.32 (C = C), 161.30 (C = O), 161.53 (C = O).

Anal. Calcd for $C_{15}H_{20}O_6$: C, 60.80; H, 6.80. Found: C, 61.07; H, 6.95.

Reaction of 3b with Benzylidenemalononitrile; 1-Cyano-3-[1′-(3-hydroxypropoxycarbonyl-2,2-dimethyl)-2′-methylcyclopropyl]-2-phenylpropionitrile (7f):

A solution of **1b** (50.5 mg, 0.30 mmol) in degassed C_6D_6 (0.55 mL) was heated at 150 °C for 6 h in a sealed NMR tube, and cooled to r.t. To this solution was added benzylidenemalononitrile (27.8 mg, 0.18 mmol) at r.t. under N_2, and the solution was stirred at this temperature for 4 h. Removal of the solvent followed by purification by silica gel chromatography afforded **7f** (73.1 mg, 91 % yield) as a 88:12 mixture of two isomers.

Major isomer:

IR (CCl_4): ν = 3630, 1703, 1378, 1150, 1050 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.935 (s, 3 H, CH_3), 0.942 (s, 3 H, CH_3), 1.12 (dd, J = 7.8, 5.0 Hz, 1 H, cyclopropyl), 1.25 (d, J = 6.0 Hz, 3 H, CH_3), 1.38–1.47 (m, 2 H, cyclopropyl), 1.51 (dd, J = 9.2, 5.0 Hz, 1 H, cyclopropyl), 2.00 (br s, 1 H, OH), 3.14 [d, J = 9.2 Hz, 1 H, $CH(CN)_2$], 3.30 (d, J = 11.2 Hz, 1 H, CH_2OH), 3.36 (d, J = 11.2 Hz, 1 H, CH_2OH), 3.86 (d, J = 11.0 Hz. 1 H, CO_2CH_2), 4.22 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 5.23 (d, J = 9.2 Hz, 1 H, CHPh), 7.34–7.43 (m, 5 H, Ph).

Anal.Calcd for $C_{20}H_{24}O_3N_2$: C, 70.56; H, 7.11; N, 8.23. Found: C, 70.01; H, 6.73; N, 8.59.

Minor isomer:

IR (CCl_4: υ = 3625, 1708, 1380, 1153, 1052 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.89 (s, 3 H, CH_3), 0.92 (s, 3 H, CH_3), 0.98 (dd, J = 8.9, 5.7 Hz, 1 H, cyclopropyl), 1.26 (d, J = 6.4 Hz, 3 H, CH_3), 1.32 (dd, J = 7.1, 5.7 Hz, 1 H, cyclopropyl), 1.48–1.67 (m, 2 H, cyclopropyl), 1.94 (br s, 1 H, OH), 2.67 [d, J = 11.5 Hz, 1 H, $CH(CN)_2$], 3.27 (d, J = 11.5 Hz, 1 H, CH_2OH), 3.29 (d, J = 11.5 Hz, 1 H, CH_2OH), 3.78 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 4.25 (d, J = 11.0 Hz, 1 H, CO_2CH_2), 5.36 (d, J = 11.5 Hz, 1 H, CHPh), 7.35–7.40 (m, 2 H, Ph), 7.35–7.40 (m, 3 H, Ph),

Anal.Calcd for $C_{20}H_{24}O_3N_2$: C, 70.56; H, 7.11; N, 8.23. Found: C, 70.04; H, 7.35; N, 7.99.

Cycloadditon of 3a with C_{60}; Synthesis of Ethanofullerene 8:

A solution of **1a** (35.7 mg, 0.23 mmol) in degassed toluene (0.4 mL) was heated at 150 °C for 4 h in a sealed tube, and cooled to r.t. The mixture was added to a solution of C_{60} (50 mg, 0.069 mmol) in toluene (150 mL) by syringe pump over 30 min at r.t. under N_2, and the solution was stirred at this temperature for 20 h. Removal of solvent followed by purification by silica gel chromatography afforded **8** as a black powder (40.4 mg, 0.046 mmol, 67 % yield).

IR (CS_2): ν = 2948, 2919, 2825, 1460, 1180, 1140, 1080, 1060, 990, 908, 830, 521cm^{-1}.

^{1}H NMR (270 MHz, $CDCl_3$): δ = 1.25 (s, 3 H, CH_3), 1.36 (s, 3 H, CH_3) 1.58 (dd, J = 7.8, 5.8 Hz, 2 H, cyclopropyl CH_2CH_2), 1.80 (dd, J = 7.8, 5.8 Hz, 2 H, cyclopropyl CH_2CH_2), 3.85 (d, J = 10.4 Hz, 2 H, OCH_2), 4.39 (d, J = 10.4 Hz, 2 H, OCH_2).

^{13}C NMR (125 MHz, $CS_2/CDCl_3$): δ = 9.77 (CH_2 2 C), 21.93 (CH_3), 22.18 (CH_3), 29.62 [$C(CH_3)_2$], 39.78 (C), 68.23 (C_{60}), 73.79 (CH_2O, 2 C), 80.50 (C_{60}), 105.62 [$C(O)_2$], 138.01 (C_{60}, 2 C), 138.68 (C_{60}, 2 C), 140.33 (C_{60}, 2 C), 140.39 (C_{60}, 2 C), 141.80 (C_{60}, 2 C), 141.90 (C_{60}, 2 C), 142.05 (C_{60}, 2 C), 142.12 (C_{60}, 2 C), 142.16 (C_{60}, 2 C), 142.28 (C_{60}, 2 C), 142.50 (C_{60}, 2 C), 142.56 (C_{60}, 2 C), 142.74 (C_{60}, 2 C), 144.23 (C_{60}, 2 C), 144.31 (C_{60}, 2 C), 144.94 (C_{60}, 2 C), 144.97 (C_{60}, 2 C), 145.06 (C_{60}, 2 C), 145.17 (C_{60}, 2 C), 145.21 (C_{60}, 2 C), 145.60 (C_{60}, 2 C), 145.70 (C_{60}, 2 C), 145.75 (C_{60}, 2 C), 146.41 (C_{60}, 2 C), 146.55 (C_{60}, 1 C), 146.63 (C_{60}, 1 C), 150.08 (C_{60}, 2 C), 152.25 (C_{60}, 2 C).

Anal. Calcd for $C_{69}H_{14}O_2 \cdot (CHCl_3)_{0.5}$: C, 89.32; H, 1.56. Found: C, 89.11; H, 1.85.

Lewis Acid Promoted Cycloreversion of Ethanofullerene 8; Synthesis of α-Mercurio Ester 9:

A homogeneous solution of **8** (15.0 mg, 17.0 mmol) and $HgCl_2$ (46.2 mg, 0.17 mmol) in 1,4-dioxane and toluene (5 mL and 10 mL, respectively) were heated at 110 °C for 36 h. Removal of solvent followed by purification by silica gel chromatography afforded C_{60} (14.7 mg, quant.) and **9** (3.0 mg, 43 % yield).

^{1}H NMR (500 MHz, $CDCl_3$) 0.93 (s, 6 H, CH_3), 1.28 (dd, J = 8.0, 5.6 Hz cyclopropyl CH_2CH_2), 1.49 (dd, 2 H, J = 8.0, 5.6 Hz cyclopropyl CH_2CH_2), 2.01 (t, J = 5.9 Hz, 1 H, OH), 3.31 (d, J = 5.9 Hz, 2 H, CH_2OH), 3.95 (s, 2 H, CO_2CH_2).

Acid Hydrolysis of Ethanofullerene 8; Synthesis of 10x:

A homogeneous solution of **8** (5.0 mg, 5.7 μmol) and H_2SO_4 (55.6 mg, 57 μmol) in H_2O, 1,4-dioxane and toluene (0.5 mL, 5 mL and 4 mL, respectively) were heated at 90 °C for 1 h. Removal of solvent followed by purification by silica gel chromatography afforded **10x** (5.1 mg, 100 % yield).

IR (CCl_4): ν = 3400, 2954, 1733, 1258, 1092, 1012, 817, 521 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.11 (s, 6 H, CH_3), 2.09 (dd, J = 10.4, 7.8 Hz, 2 H, cyclopropyl CH_2CH_2), 2.18 (dd, J = 10.4, 7.8 Hz, 2 H, cyclopropyl CH_2CH_2), 2.29 (t, J = 11.9 Hz, 1 H, OH), 3.51 (d, J = 11.9 Hz, 2 H, CH_2OH), 4.34 (s, 2 H, OCH_2), 6.81 (s, 1 H, $C_{60}H$).

^{13}C NMR (125 MHz, $CS_2/CDCl_3$): δ = 14.96 (CH_2, 2 C), 21.65 (CH_3, 2 C), 36.07 (C), 36.70 (C), 61.82 ($C_{60}H$, $^1J_{CH}$ = 138.3 Hz), 65.41 ($C_{60}H$, $^2J_{CH}$ = 7.6 Hz), 68.11 (CH_2O), 70.24 (CH_2O), 136.57 (C_{60}, 2 C), 137.77 (C_{60}, 2 C), 139.45 (C_{60}, 2 C), 140.21 (C_{60}, 2 C), 141.21 (C_{60}, 2 C), 141.45 (C_{60}, 2 C), 141.56 (C_{60}, 2 C), 141.92 (C_{60}, 2 C), 142.03 (C_{60}, 2 C), 142.08 (C_{60}, 2 C), 142.49 (C_{60}, 2 C), 142.52 (C_{60}, 2 C), 143.09 (C_{60}, 2 C), 144.31 (C_{60}, 2 C), 144.75 (C_{60}, 2 C), 145.22 (C_{60}, 2 C), 145.29 (C_{60}, 2 C), 145.45 (C_{60}, 2 C), 145.65 (C_{60}, 2 C), 146.01 (C_{60}, 2 C), 146.06 (C_{60}, 2 C), 146.19 (C_{60}, 2 C), 146.31 (C_{60}, 2 C), 146.51 (C_{60}, 2 C), 146.77 (C_{60}, 2 C), 147.10 (C_{60}), 147.46 (C_{60}), 152.06 (C_{60}, 2 C), 153.80 (C_{60}, 2 C), 174.06 (C = O).

Anal. Calcd for $C_{69}H_{16}O_3 \cdot (CHCl_3)_{0.8}$: C, 84.82; H, 1.71. Found: C, 84.75; H, 1.74.

Acid Hydrolysis of Ethanofullerene 8; Synthesis of 10y:

A solution of **8** (18.9 mg, 0.022 mmol) and $TsOH \cdot H_2O$ (37.9 mg, 0.22 mmol) in toluene (10 mL) was refluxed for 1 h. Removal of solvent followed by purification by silica gel afforded **10y** (21.2 mg, 93 % yield).

IR ($CHCl_3$): ν = 1721, 1600, 1379, 1319, 522 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.13 (s, 6 H, CH_3), 1.98 (dd, J = 13.3, 7.4 Hz, 2 H, cyclopropyl), 2.11 (dd, J = 13.3, 7.4 Hz, 2 H, cyclopropyl), 2.48 (s, 3 H, CH_3), 3.96 (s, 2 H, CH_2OTs), 4.22 (s, 2 H, CO_2CH_2), 6.83 (s, 1 H, $C_{60}H$), 7.40 (d, J = 8.5 Hz, 2 H, C_6H_4), 7.88 (d, J = 8.5 Hz, 2 H, C_6H_4).

Reaction of 3a with Diethyl Azodicarboxylate; 3-Hydroxypropyl-2,2-dimethyl Cyclopropyl-1-(1′,2′-ethoxycarbonylhydrazino)carboxylate (12a):

A solution of **1a** (578.3 mg, 3.75 mmol) in degassed benzene (4.41 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added diethyl azodicarboxylate (295.3 μL, 1.86 mmol) at r.t. under N_2, and the resulting solution was stirred at r.t. for 2 h. The solution was then treated with H_2O (0.2 mL) and THF (7 mL) for 0.5 h, and the mixture was passed through a pad of silica gel. Removal of the solvent followed by purification by silica gel chromatography afforded **12a** (703.5 mg, 100 % yield).

IR (KBr): ν = 3470, 3310, 1735, 1380, 1335, 1310, 1245, 1180, 1100, 1060, 735 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.90 (s, 6 H, CH_3), 1.27 (t, J = 7.1 Hz, 6 H, CH_2CH_3), 1.61 (br s, 4 H, cyclopropyl), 2.50 (br s, 1 H, OH), 3.32 (s, 2 H, CH_2OH), 3.97 (s, 2 H, CH_2O), 4.15–4.21 (m, 2 H, CH_2CH_3), 7.27 (br s 1 H, NH).

^{13}C NMR (125 MHz, $CDCl_3$): δ = 14.34, 14.36, 21.38 (2 C), 36.25 (2 C), 44.06, 61.97, 62,97, 68.46, 70.79, 156.29, 156.80, 172.85. One

quaternary carbon signal due to the cyclopropyl group could not be located owing to overlapping with other signals or a long relaxation time.

Reaction of 3b with Di-*tert*-butyl Azodicarboxylate; 2,2-Dimethyl-3-hydroxypropyl 2-Methylcyclopropyl-1-(1′,2′-*tert*-butoxycarbonylhydrazino)carboxylate (12b):

A solution of **1b** (50.5 mg, 0.30 mmol) in degassed C_6D_6(0.6 mL) was heated at 150 °C for 4 h in a sealed NMR tube, and cooled to r.t. To this solution was added di-*tert*-butyl azodicarboxylate (48.4 mg, 0.21 mmol) dissolved in benzene (0.5 mL) at r.t. under N_2, and the solution was stirred at r.t. for 1 h. The solution was then treated with H_2O (100 μL) and THF (1 mL) for 0.5 h, and the mixture was passed through a pad of silica gel. Removal of the solvent followed by purification by silica gel chromatography afforded **12b** (72.4 mg, 83 %).

IR (KBr): ν = 3400, 2200, 1730, 1480, 1370, 1250, 1160 cm^{-1}.

^1H NMR (270 MHz, $CDCl_3$ at 60 °C): δ = 1.22 (s, 6 H, CH_3), 1.38 (d, J = 6.5 Hz, 3 H, CH_3), 1.59 (s, 18 H, CH_3), 1.68–1.80 (m, 1 H, cyclopropyl), 1.93–2.10 (m, 1 H, cyclopropyl), 2.20–2.28 (m, 2 H, cyclopropyl, OH), 3.34 (br d, J = 5.7 Hz, 2 H, CH_2OH), 4.00 (s, 2 H, CH_2O), 6.75 (br s, 1 H, NH).

^{13}C NMR (67.5 MHz, $CDCl_3$): δ = 11.98, 21.59 (2 C), 28.14 (8 C), 36.32, 68.53, 70.62, 80.99, 81.84, 156.00 (2 C), 172.10. One quaternary carbon signal due to the cyclopropyl group could not be located owing to overlapping with other signals or a long relaxation time.

We thank the Ministry of Education, Science and Culture for the financial support.

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