Titanium(IV) Chloride-Mediated Ring Cleavage and Michael Addition of 3,3-Dialkylcyclobutanones and 3-[(Trimethylsilyl)methyl]-cyclobutanones

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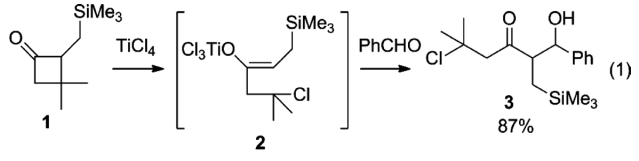
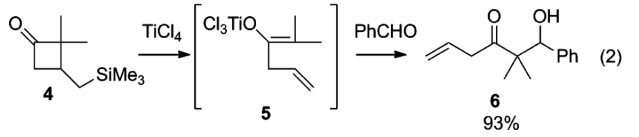
***β′*-Chloro and *β′,γ′*-unsaturated trichlorotitanium enolates, which were formed *in situ* by titanium(IV) chloride-mediated ring cleavage of 3,3-dialkylcyclobutanones and 3-[(trimethylsilyl)methyl]cyclobutanones, reacted with enones to give Michael adducts with keeping a labile *β′*-chloro or *β′,γ′*-unsaturated group.**

Key words cyclobutanone; Michael addition; enone; ring cleavage

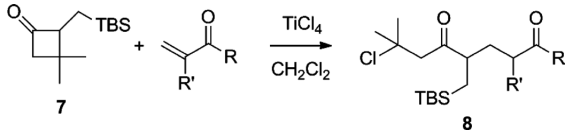
Facile ring expansion, ring contraction and ring cleavage of cyclobutanones have been utilized in the synthesis of target molecules.[1–4] We recently found a new synthetic utility of cyclobutanones: *β′*-chloro or *β′,γ′*-unsaturated enolates were readily prepared by titanium(IV) chloride-mediated ring cleavage of cyclobutanones. Thus, the four-membered ring of 3,3-dialkylcyclobutanone **1** was cleaved by treatment with titanium(IV) chloride to form trichlorotitanium enolate **2** having a *tert*-alkyl chloride group. The enolate **2** reacted with aldehyde to afford the corresponding aldol product **3**[5] (Eq. 1). Also, ring cleavage of 3-[(trimethylsilyl)(TMS)methyl]-cyclobutanone **4** with titanium(IV) chloride gave *β′,γ′*-unsaturated titanium enolate **5**, which reacted with aldehyde to give a *β′,γ′*-unsaturated aldol product **6**[6] (Eq. 2). The reactivity of an enolate bearing an easily eliminative chloride group at the *β′*-position (like **2**) and an easily isomerizable *β′,γ′*-unsaturated bond[7,8] (like **5**) has been unknown except for aldol reactions[5,6] because such enolates are difficult to prepare from the parent carbonyl compounds. To investigate the versatility of these functionalized titanium enolates, we studied their Michael addition[9–11] with enones, and we report here the results we obtained.





First, ring cleavage of 3,3-dialkylcyclobutanones followed by Michael addition to enones was investigated (Table 1). Addition of titanium(IV) chloride to a mixture of methyl vinyl ketone (MVK) and 3,3-dimethylcyclobutanone **7** bearing a (*tert*-butyldimethylsilyl)(TBS)methyl group at the 2-position gave an expected Michael adduct **8a** having a *tert*-alkyl chloride group in 69% yield (entry 1). Cyclobutanone **7** was preferentially activated with titanium(IV) chloride in the presence of MVK though it was reported that enones reacted with titanium(IV) chloride to form *β*-chloro enolate in the Michael-aldol and the Morita–Baylis–Hillman reaction.[12,13] The use of two equivalents of MVK was required to obtain **8a** efficiently because 1-*tert*-butyldimethylsilyl-5-chloro-5-methylhexan-3-one, which was formed by ring-cleavage of **7**, was obtained along with **8a** in the case of using less than two equivalents of enones. A similar reaction of **7** with pent-1-en-3-one (entry 2) and 5-phenylpent-1-en-3-one (entry 3) gave the corresponding adducts **8b** and **8c** in 68% and 39% yields, respectively. Though 3-methylpent-3-en-2-one also reacted with **7** to afford **8d** in 53% yield (entry 4), cyclic enones such as cyclopentenone and cyclohexenone did not give Michael adduct **8**. These

Table 1. Titanium(IV) Chloride-Mediated Reaction of **7** and Enones to **8**[a]



Entry	R	R′	Conditions	**8**	Yield/%[b]
1	Me	H	−78 to −40°C, 2 h	**8a**	69
2	Et	H	−40 to −18°C, 2 h	**8b**	68
3	$(CH_2)_2Ph$	H	−78 to −40°C, 1 h	**8c**	39
4	Me	Me	−78 to −40°C, 1 h	**8d**	53

a) Cyclobutanone **7** (1.0 eq), enone (2.0 eq), and $TiCl_4$ (1.5 eq) were used. *b*) Isolated yield.

The authors declare no conflict of interest.

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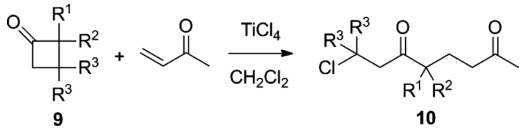
Table 2. Titanium(IV) Chloride-Mediated Reaction of Various 3,3-Dialkylcyclobutanone **9** and MVK[a)]



Entry	**9**		Conditions	Yield/%[b)]
1		R=Me **9a**	−78 to 0°C, 3 h	33
2		R=Et **9b**	−40 to 0°C, 2 h	45
3		R=*i*-Pr **9c**	−40 to rt, 4 h	30
4		**9d**	−78 to −18°C, 2.5 h	47
5		**9e**	−78 to −40°C, 1.5 h	55

a) For conditions, see Table 1. *b*) Isolated yield.

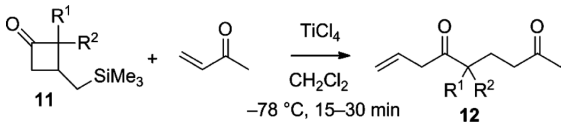
results suggested that β-alkyl substituents of enones retarded Michael addition of trichlorotitanium enolate.

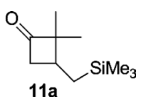
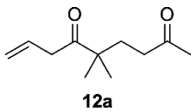
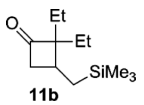
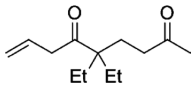
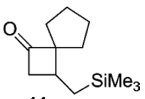
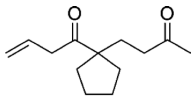
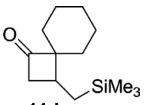
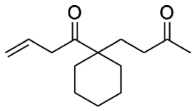
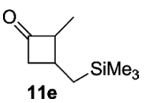
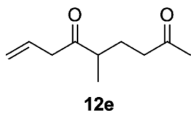
3,3-Dimethylcyclobutanones **9a**–**c** having a monoalkyl group such as a methyl, ethyl, or isopropyl group at the 2-position reacted with MVK to afford the corresponding β'-chloro adducts **10a**–**c** (Table 2, entries 1–3). The present ring cleavage and Michael addition of 3,3-dialkylcyclobutanones proceeded in the absence of the TBS group of **7**, but Michael adducts **10a**–**c** were obtained in lower yields. Ring cleavage of monoalkylcyclobutanones **9a**–**c** required higher reaction temperatures (0°C to rt) than in the case of 2-(TBSmethyl)-cyclobutanone **7**. The higher reaction temperatures might cause side reactions (*e.g.*, further Michael addition of **10** to MVK). The cyclobutanone ring was cleaved regioselectively at the more substituted C2–C3 bond,[5,6,14,15)] and the TBSmethyl group at the 2-position of cyclobutanone facilitated ring cleavage of the cyclobutanone ring[5)] by stabilizing a bicyclobutonium ion[16)] intermediate. In addition to 3,3-dimethylcyclobutanones, 3,3-diethylcyclobutanone **9d** also reacted with MVK to give **10d** with a hindered *tert*-alkyl chloride group (entry 4). Ring cleavage of 2,2,3,3-tetramethylcyclobutanone (**9e**) took place at a low temperature (−40°C) and the desired adduct **10e** was obtained in 55% yield (entry 5).

Next, titanium(IV) chloride-mediated Michael addition of 3-(TMSmethyl)cyclobutanone **11** with enones was investigated (Table 3). Treatment of a mixture of **11a** and MVK with titanium(IV) chloride at −78°C gave a Michael adduct **12a** having a β',γ'-unsaturated bond in 64% yield (entry 1). Thus, ring cleavage of **11a** took place at −78°C, and formed trichlorotitanium enolate (like **5**) smoothly reacted with MVK at the same temperature. Isomerization of the double bond of **12a** to the more stable α',β'-unsaturated one was not observed. 2,2-Diethylcyclobutanone **11b**, spirocyclobutanone **11c**, **d**, and 2-monomethylcyclobutanone **11e** also reacted with titanium(IV) chloride and MVK at −78°C to afford the corresponding Michael adducts **12b**–**e** in 42–58% yields (entries 2–5).

In conclusion, 3,3-dialkylcyclobutanones and 3-(TMSmethyl)cyclobutanones reacted with enones to give β'-chloro[17)] and β',γ'-unsaturated[18)] acyclic 1,5-diketones by using titanium(IV) chloride. It is expected that the β'-chloro and β',γ'-unsaturated trichlorotitanium enolates generated by the present method will react with other electrophilic components, and they offer a unique method for the synthesis of

Table 3. Titanium(IV) Chloride-Mediated Reaction of 3-[(Trimethylsilyl)-methyl]cyclobutanones **11** with MVK to **12**[a)]



Entry	**11**	**12**	Yield/%[b)]
1	 **11a**	 **12a**	64
2	 **11b**	 **12b**	58
3	 **11c**	 **12c**	44
4	 **11d**	 **12d**	50
5	 **11e**	 **12e**	42[c)]

a) Compound **11** (1.0 eq), MVK (2.0 eq), and $TiCl_4$ (2.0 eq) were used. *b*) Isolated yield unless otherwise mentioned. *c*) Determined by ^{1}H-NMR analysis.

functionalized carbonyl compounds.

Experimental

General All melting points were determined on Yanagimoto micro melting point apparatus and are uncorrected. Infrared spectra (IR) were recorded on Horiba IR-710. ^{1}H-NMR spectra were recorded on a JEOL JNM ECA600 (600 MHz) or a JEOL JNM ECS400 (400 MHz) spectrometer at room temperature; chemical shifts (δ) are reported in parts per million relative to tetramethylsilane. Splitting pattern are designated as s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; br, broad. ^{13}C-NMR spectra were recorded on a JOEL JNM ECA600 (150 MHz) spectrometer with complete proton decoupling. Chemical shifts are reported in parts per million relative to tetramethylsilane with the solvent resonance as the internal standard $CDCl_3$. Analytical TLC was performed on Merck precoated TLC plates (silica gel 60 GF254, 0.25 mm). Silica-gel column chromatography was carried out on silica gel 60 N (Kanto Kagaku Co., Ltd., spherical, neutral, 63–210 μm). Preparative thin-layer chromatography (PTLC) was carried out on silica gel Wakogel B-5F. All reactions were carried out under nitrogen in dried glassware with magnetic stirring. A solution of titanium(IV) chloride in dichloromethane (1 M) was purchased from Aldrich. 3,3-Dialkylcyclobutanones **7** and **9a**–**e** were synthesized by cycloaddition of dichloroketene with olefins, followed by reductive dechlorination of the dichlorocyclobutanone according to the literature procedures.[5,19] 3-[(Trimethylsilyl)methyl]cyclobutanones **11a**–**e** were prepared according to the literature procedures.[6]

2,3,3-Trimethylcyclobutanone (9a) To a suspension of 2-methyl-but-2-ene (492 mg, 7.01 mmol) and zinc–copper couple (1.37 g) in dry ether (25 mL) was added dropwise a solution of trichloroacetyl chloride (0.71 mL, 6.36 mmol) in dry ether (10 mL) for 1 h, and the reaction mixture was refluxed for 18 h. The mixture was filtered through Celite pad and the filtrate was concentrated. The residue was diluted with ether, and the ether solution was washed with brine, dried over anhydrous sodium sulfate, filtered, and concentrated. The crude product was purified by column chromatography on silica gel (silica gel (30 g), hexane) to afford 2,2-dichloro-3,3,4-trimethylcyclobutanone (610 mg, 48%).

To a stirred mixture of the above mentioned 2,2-dichlorocyclobutanone (587 mg, 3.24 mmol) and zinc–copper couple (1.06 g) in methanol (20 mL) was added ammonium chloride (1.21 g, 22.7 mmol) at room temperature. After stirred at 45°C for 4 h, the reaction mixture was filtered through Celite pad, and the filtrate was concentrated. The residue was diluted with ether, and the ether solution was washed with brine, dried over anhydrous sodium sulfate, filtered, and concentrated. The crude product was purified by column chromatography on silica gel (silica gel (15 g), pentane/ether=20 : 1) to afford **9a**[19] (134 mg, 37%) as a colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.01 (t, J=7.2 Hz, 3H), 1.10 (s, 3H), 1.39 (s, 3H), 2.57 (dd, J=16.5, 1.7 Hz, 1H), 2.88 (dd, J=16.5, 2.7 Hz, 1H), 2.98 (qdd, J=7.2, 2.7, 1.7 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 8.1, 22.6, 29.2, 29.3, 57.9, 69.4, 211.0; IR ($CHCl_3$, cm^{-1}) 1776.

2-Isopropyl-3,3-dimethylcyclobutanone (9c) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.87 (d, J=6.6 Hz, 3H), 1.10 (d, J=6.6 Hz, 3H), 1.18 (s, 3H), 1.44 (s, 3H), 1.87−1.95 (m, 1H), 2.43 (d, J=15.8 Hz, 1H), 2.54 (d, J=11.0 Hz, 1H), 2.78 (d, J=15.8 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 21.0, 21.2, 22.6, 26.2, 29.8, 30.5, 57.8, 74.4, 209.5; IR ($CHCl_3$, cm^{-1}) 1758; high resolution (HR)-MS (FAB+) Calcd for $C_9H_{17}O$ (m/z) 141.1279, Found 141.1269.

3,3-Diethyl-2-methylcylobutanone (9d) Pale yellow oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.88 (t, J=7.6 Hz, 3H), 0.91 (t, J=7.6 Hz, 3H), 1.05 (d, J=7.6 Hz, 3H), 1.27 (dq, J=14.3, 7.6 Hz, 1H), 1.54–1.66 (m, 2H), 1.82 (dq, J=14.3, 7.6 Hz, 1H), 2.58 (dd, J=16.4, 2.1 Hz, 1H), 2.67 (dd, J=16.4, 2.7 Hz, 1H), 2.99 (qdd, J=7.6, 2.7, 2.1 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 8.6, 8.7, 9.3, 23.6, 31.4, 36.3, 54.6, 61.3, 211.3; IR ($CHCl_3$, cm^{-1}) 1770; HR-MS (FAB+) Calcd for $C_9H_{17}O$ (m/z) 141.1279, Found 141.1291.

Typical Experimental Procedure for Titanium(IV) Chloride-Mediated Reaction of 3,3-Dialkylcyclobutanones and Enones: Preparation of 5-{[(*tert*-Butyldimethyl)silyl]-methyl}-8-chloro-8-methylnona-2,6-dione (8a) To a stirred solution of 3,3-dialkylcyclobutanone **7** (50.0 mg, 0.221 mmol, 1.0 eq) and methyl vinyl ketone (31.0 mg, 0.442 mmol, 2.0 eq) in dry dichloromethane (4 mL) was added at −78°C a 1.0 M solution of $TiCl_4$ in dichloromethane (0.33 mL, 1.5 eq). The resulting mixture was stirred at −78°C for 1.0 h and at −40°C for 1.0 h. The reaction was quenched by adding saturated sodium hydrogen carbonate solution at −40°C, and the mixture was extracted with dichloromethane. The combined organic extracts were dried over anhydrous sodium sulfate, filtered, and concentrated. The crude product was purified by column chromatography on silica gel (eluted with hexane/ether) to afford **8a** (50.7 mg, 0.152 mmol, 69%) as a colorless oil: ^{1}H-NMR (400 MHz, $CDCl_3$) δ −0.02 (s, 3H), −0.01 (s, 3H), 0.46 (dd, J=14.7, 7.3 Hz, 1H), 0.87 (s, 9H), 0.93 (dd, J=14.7, 6.0 Hz, 1H), 1.72 (s, 3H), 1.73 (s, 3H), 1.69–1.78 (m, 1H), 1.85 (dtd, J=16.0, 8.2, 6.0 Hz, 1H), 2.12 (s, 3H), 2.35 (ddd, J=17.9, 8.2, 6.9 Hz, 1H), 2.44 (ddd, J=17.9, 8.2, 6.0 Hz, 1H), 2.56–2.62 (m, 1H), 2.90 (d, J=16.5 Hz, 1H), 3.03 (d, J=16.5 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ −5.9, −5.3, 13.4, 16.6, 26.4, 27.0, 30.0, 32.2, 32.7, 40.6, 47.6, 54.7, 67.4, 207.9, 210.0; IR ($CHCl_3$, cm^{-1}) 1710; HR-MS (electron ionization (EI)+) Calcd for $C_{17}H_{33}ClO_2Si$ (m/z) 332.19384, Found 332.19328.

6-{[(*tert*-Butyldimethyl)silyl]methyl}-9-chloro-9-methyldeca-3,7-dione (8b) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ −0.02 (s, 3H), −0.01 (s, 3H), 0.46 (dd, J=14.8, 7.6 Hz, 1H), 0.87 (s, 9H), 0.93 (dd, J=14.8, 6.2 Hz, 1H), 1.04 (t, J=7.6 Hz, 3H), 1.72 (s, 3H), 1.73 (s, 3H), 1.72–1.78 (m, 1H), 1.86 (dtd, J=14.1, 8.2, 5.8 Hz, 1H), 2.33 (ddd, J=17.5, 8.2, 6.9 Hz, 1H), 2.40 (q, J=7.6 Hz, 2H), 2.38–2.44 (m, 1H), 2.57–2.61 (m, 1H), 2.90 (d, J=16.5 Hz, 1H), 3.04 (d, J=16.5 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ −5.9, −5.3, 7.7, 13.4, 16.5, 26.3, 27.0, 32.1, 32.6, 35.9, 39.2, 47.6, 54.6, 67.4, 210.0, 210.7; IR ($CHCl_3$, cm^{-1}) 2954, 2929, 1712; HR-MS direct analysis in real time (DART+) Calcd for $C_{18}H_{36}ClO_2Si$ (m/z) 347.21731, Found 347.21802.

6-{[(*tert*-Butyldimethyl)silyl]methyl}-9-chloro-9-methyl-1-phenyldeca-3,7-dione (8c) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ −0.03 (s, 3H), −0.02 (s, 3H), 0.43 (dd, J=14.8, 7.6 Hz, 1H), 0.86 (s, 9H), 0.91 (dd, J=14.8, 6.2 Hz, 1H), 1.71 (s, 3H), 1.71 (s, 3H), 1.71–1.76 (m, 1H), 1.83 (dtd, J=14.1, 8.2, 6.2 Hz, 1H), 2.30 (ddd, J=17.5, 8.2, 6.9 Hz, 1H), 2.39 (ddd, J=17.5, 8.2, 6.2 Hz, 1H), 2.54–2.59 (m, 1H), 2.70 (t, J=7.6 Hz, 2H), 2.88 (t, J=7.6 Hz, 2H), 2.88 (d, J=16.8 Hz, 1H), 3.00 (d, J=16.8 Hz, 1H), 7.16–7.20 (m, 3H), 7.26–7.29 (m, 2H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ −5.9, −5.3, 13.4, 16.6,

26.4, 26.9, 29.7, 32.1, 32.7, 39.9, 44.3, 47.6, 54.6, 67.4, 126.1, 128.3, 128.5, 140.9, 209.2, 210.0; IR ($CHCl_3$, cm^{-1}) 1712; HR-MS (DART+) Calcd for $C_{24}H_{40}ClO_2Si$ (*m/z*) 423.24861, Found 423.24921.

5-{[(*tert*-Butyldimethyl)silyl]methyl}-8-chloro-3,8-dimethylnona-2,6-dione (8d) Pale yellow oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ −0.04 (s, 3H), −0.03 (s, 3H), 0.47 (dd, *J*=14.8, 7.6 Hz, 1H), 0.87 (s, 9H), 0.91 (dd, *J*=14.8, 5.8 Hz, 1H), 1.09 (d, *J*=6.9 Hz, 3H), 1.20 (ddd, *J*=14.0, 7.9, 5.8 Hz, 1H), 1.74 (s, 6H), 2.10 (ddd, *J*=14.0, 7.9, 5.8 Hz, 1H), 2.17 (s, 3H), 2.49 (dq, *J*=14.0, 6.9 Hz, 1H), 2.52−2.57 (m, 1H), 2.92 (d, *J*=16.8 Hz, 1H), 3.08 (d, *J*=16.8 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ −5.8, −5.2, 13.9, 16.4, 16.6, 26.3, 28.2, 32.1, 32.7, 36.0, 45.1, 46.4, 54.6, 67.4, 209.6, 211.8; IR ($CHCl_3$, cm^{-1}) 1710; HR-MS (DART+) Calcd for $C_{18}H_{36}ClO_2Si$ (*m/z*) 347.21731, Found 347.21758.

8-Chloro-5,8-dimethylnona-2,6-dione (10a) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.08 (d, *J*=7.2 Hz, 3H), 1.62 (dtd, *J*=14.4, 8.2, 6.5 Hz, 1H), 1.71 (s, 3H), 1.72 (s, 3H), 1.92 (dtd, *J*=14.4, 8.2, 6.5 Hz, 1H), 2.13 (s, 3H), 2.41 (ddd, *J*=17.5, 8.2, 6.5 Hz, 1H), 2.46 (ddd, *J*=17.5, 8.2, 6.5 Hz, 1H), 2.62–2.68 (m, 1H), 2.94 (d, *J*=15.8 Hz, 1H), 2.98 (d, *J*=15.8 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 16.1, 25.9, 29.9, 32.3, 32.6, 40.7, 46.3, 54.7, 67.3, 208.2, 210.5; IR ($CHCl_3$, cm^{-1}) 1712; HR-MS (DART+) Calcd for $C_{11}H_{20}ClO_2$ (*m/z*) 219.11518, Found 219.11036.

8-Chloro-5-ethyl-8-methylnona-2,6-dione (10b) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.89 (t, *J*=7.2 Hz, 3H), 1.44 (dtd, *J*=13.7, 7.6, 6.2 Hz, 1H), 1.68 (dq, *J*=14.1, 7.2 Hz, 2H), 1.72 (s, 3H), 1.73 (s, 3H), 1.87 (dtd, *J*=14.1, 8.2, 6.2 Hz, 1H), 2.12 (s, 3H), 2.37 (ddd, *J*=17.5, 8.6, 6.5 Hz, 1H), 2.43 (ddd, *J*=17.5, 8.6, 6.2 Hz, 1H), 2.48–2.52 (m, 1H), 2.92 (d, *J*=16.5 Hz, 1H), 2.99 (d, *J*=16.5 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 11.5, 23.8, 24.2, 29.9, 32.2, 32.6, 40.8, 53.3, 55.7, 67.4, 208.2, 210.3; IR ($CHCl_3$, cm^{-1}) 1720, 1704; HR-MS (DART+) Calcd for $C_{12}H_{22}ClO_2$ (*m/z*) 233.13083, Found 233.12664.

8-Chloro-5-isopropyl-8-methylnona-2,6-dione (10c) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.86 (d, *J*=6.9 Hz, 3H), 0.97 (d, *J*=6.9 Hz, 3H), 1.72 (s, 3H), 1.73 (s, 3H), 1.73–1.77 (m, 1H), 1.83 (dtd, *J*=14.1, 8.9, 5.5 Hz, 1H), 1.97 (qd, *J*=13.4, 6.9 Hz, 1H), 2.11 (s, 3H), 2.29 (ddd, *J*=17.5, 8.9, 6.5 Hz, 1H), 2.36–2.39 (m, 1H), 2.42 (ddd, *J*=17.5, 8.9, 5.5 Hz, 1H), 2.89 (d, *J*=16.8 Hz, 1H), 3.00 (d, *J*=16.8 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 18.8, 20.6, 21.7, 29.3, 29.9, 32.0, 32.7, 41.1, 56.7, 58.2, 67.4, 208.3, 210.2; IR ($CHCl_3$, cm^{-1}) 1712; HR-MS (DART+) Calcd for $C_{13}H_{24}ClO_2$ (*m/z*) 247.14648, Found 247.14192.

8-Chloro-8-ethyl-5-methyldeca-2,6-dione (10d) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.98 (t, *J*=6.9 Hz, 3H), 0.98 (t, *J*=6.9 Hz, 3H), 1.09 (d, *J*=6.9 Hz, 3H), 1.61 (dtd, *J*=14.4, 8.2, 6.2 Hz, 1H), 1.88–2.05 (m, 5H), 2.13 (s, 3H), 2.39 (ddd, *J*=17.2, 8.2, 6.2 Hz, 1H), 2.44 (ddd, *J*=17.2, 8.2, 6.2 Hz, 1H), 2.64 (qt, *J*=6.9, 6.2 Hz, 1H), 2.67 (s, 2H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 8.8, 8.9, 16.4, 26.0, 29.9, 33.6, 33.8, 40.8, 46.3, 49.4, 76.5, 208.2, 210.7; IR ($CHCl_3$, cm^{-1}) 1720, 1704; HR-MS (DART+) Calcd for $C_{13}H_{24}ClO_2$ (*m/z*) 247.14648, Found 247.14258.

8-Chloro-5,5,8-trimethylnona-2,6-dione (10e) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.13 (s, 6H), 1.73 (s, 6H), 1.79 (t, *J*=7.9 Hz, 2H), 2.13 (s, 3H), 2.35 (t, *J*=7.9 Hz, 2H), 3.02 (s, 2H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 24.1, 29.9, 32.2, 32.7, 38.8, 47.2, 50.5, 67.8, 207.9, 211.3; IR ($CHCl_3$, cm^{-1}) 1720, 1702; HR-MS (EI+) Calcd for $C_{12}H_{21}ClO_2$ (*m/z*) 232.12301, Found 232.12322.

Typical Experimental Procedure for Titanium(IV) Chloride-Mediated Reaction of 3-[(Trimethylsilyl)methyl]-cyclobutanones and MVK: Preparation of 5,5-Dimethyl nona-8-ene-2,6-dione (12a) To a stirred solution of cyclobutanone **11** (81.3 mg, 0.441 mmol, 1.0 eq) and methyl vinyl ketone (61.8 mg, 0.882 mmol, 2.0 eq) in dry dichloromethane (4 mL) was added at −78°C a 1.0 M solution of $TiCl_4$ in dichloromethane (0.88 mL, 2.0 eq), and the reaction mixture was stirred at the same temperature for 15 min. The reaction was quenched with saturated aqueous sodium hydrogen carbonate solution at −78°C, and the mixture was extracted with dichloromethane. The combined organic extracts were dried over anhydrous sodium sulfate, filtered, and concentrated. The crude product was purified by column chromatography on silica gel (eluted with hexane/ether) to afford **12a** (51.7 mg, 0.284 mmol, 64%) as a colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.14 (s, 6H), 1.81 (t, *J*=7.6 Hz, 2H), 2.13 (s, 3H), 2.33 (t, *J*=7.6 Hz, 2H), 3.25 (dd, *J*=6.9, 1.4 Hz, 2H), 5.10 (dd, *J*=17.2, 1.4 Hz, 1H), 5.16 (dd, *J*=10.3, 1.4 Hz, 1H), 5.91 (ddt, *J*=17.2, 10.3, 6.9 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 24.2, 29.9, 32.8, 39.0, 41.6, 47.0, 118.1, 131.3, 208.1, 212.8; IR ($CHCl_3$, cm^{-1}) 1708; HR-MS (EI+) Calcd for $C_{11}H_{18}O_2$ (*m/z*) 182.13068, Found 182.13048.

5,5-Diethylnona-8-ene-2,6-dione (12b) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 0.74 (t, *J*=7.6 Hz, 6H), 1.54–1.65 (m, 4H), 1.82 (t, *J*=8.2 Hz, 2H), 2.13 (s, 3H), 2.23 (t, *J*=8.2 Hz, 2H), 3.21 (dt, *J*=6.9, 1.4 Hz, 2H), 5.08 (dd, *J*=17.2, 1.4 Hz, 1H), 5.14 (dd, *J*=10.3, 1.4 Hz, 1H), 5.93 (ddt, *J*=17.2, 10.3, 6.9 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 8.0, 25.4, 26.2, 26.3, 29.9, 38.2, 42.0, 54.0, 117.9, 131.5, 208.1, 212.9; IR ($CHCl_3$, cm^{-1}) 1710; HR-MS (DART+) Calcd for $C_{13}H_{23}O_2$ (*m/z*) 211.16980, Found 211.16488.

5-Cyclopentyl-8-ene-2,6-dione (12c) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.40–1.45 (m, 2H), 1.54–1.60 (m, 2H), 1.62–1.69 (m, 2H), 1.91 (t, *J*=8.2 Hz, 2H), 2.04–2.09 (m, 2H), 2.11 (s, 3H), 2.28 (t, *J*=8.2 Hz, 2H), 3.25 (dt, *J*=6.9, 1.4 Hz, 2H), 5.10 (dd, *J*=17.2, 1.4 Hz, 1H), 5.14 (dd, *J*=10.3, 1.4 Hz, 1H), 5.92 (ddt, *J*=17.2, 10.3, 6.9 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 24.9, 30.0, 31.2, 34.1, 39.7, 42.2, 59.5, 117.9, 131.6, 208.0, 211.8; IR ($CHCl_3$, cm^{-1}) 1708; HR-MS (DART+) Calcd for $C_{13}H_{21}O_2$ (*m/z*) 209.15415, Found 209.14967.

5-Cyclohexyl-8-ene-2,6-dione (12d) Colorless oil: ^{1}H-NMR (600 MHz, $CDCl_3$) δ 1.21–1.33 (m, 6H), 1.53–1.61 (m, 2H), 1.79 (t, *J*=7.9 Hz, 2H), 1.98–2.05 (m, 2H), 2.10 (s, 3H), 2.23 (t, *J*=7.9 Hz, 2H), 3.24 (dd, *J*=6.9, 1.4 Hz, 2H), 5.08 (dd, *J*=17.2, 1.4 Hz, 1H), 5.15 (dd, *J*=10.3, 1.4 Hz, 1H), 5.92 (ddt, *J*=17.2, 10.3, 6.9 Hz, 1H); ^{13}C-NMR (150 MHz, $CDCl_3$) δ 22.8, 25.8, 30.0, 31.5, 33.0, 37.8, 41.6, 51.3, 118.0, 131.5, 208.0, 212.8; IR ($CHCl_3$, cm^{-1}) 1710; HR-MS (DART+) Calcd for $C_{14}H_{23}O_2$ (*m/z*) 223.16980, Found 223.16527.

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