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NEW SYNTHESIS OF *t*-BUTYL 1,2-DIHYDRO-1-OXAAZULENE-3-CARBOXYLATES USING LITHIUM TRIMETHYLSILYLDIAZOMETHANE

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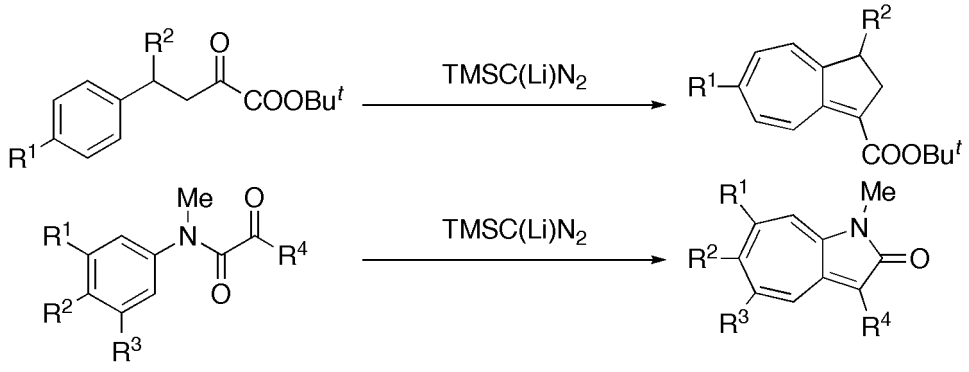
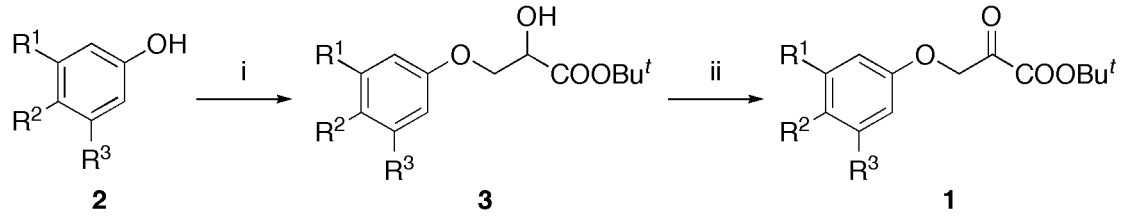
Abstract – Lithium trimethylsilyldiazomethane reacts with *t*-butyl aryloxypyruvates to give *t*-butyl 1,2-dihydro-1-oxaazulene-3-carboxylates *via* alkylidenecarbene intermediates.

Alkylidenecarbenes are attractive intermediates in organic synthesis.[1] We have already demonstrated that the lithium salt of trimethylsilyldiazomethane (TMSC(Li)N_2) smoothly reacts with carbonyl compounds to generate alkylidenecarbenes which undergo various types of reactions to give homologous alkynes, aldehydes, and heterocycles.[2] Furthermore, we have found that TMSC(Li)N_2 chemoselectively reacts with 4-aryl-2-oxobutanoates[3] and *N*-methylanilides of α-keto acids[4] at the carbonyl moiety giving 2,3-dihydroazulenes and 1-aza-1,2-dihydroazulen-2-ones *via* intramolecular cycloaddition of the generated alkylidenecarbenes to a benzene ring, followed by ring expansion, respectively (Scheme 1). Our continuous interest in this area has led us to investigate the reaction of aryloxypyruvates with TMSC(Li)N_2 giving 1,2-dihydro-1-oxaazulene derivatives. In this paper, the details are described.

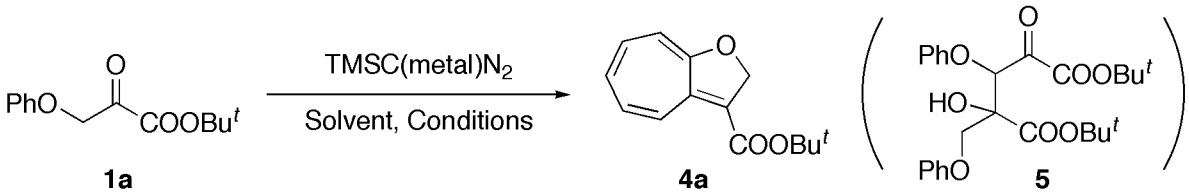


Scheme 1.



Scheme 2. *Reagents and conditions*. i, *t*-butyl glycidate (1.1-2.2 eq.), NaH (0.3–1.0 eq.), *t*-BuOMe, rt–reflux, 43–65 h, 34–67 %; ii, Dess-Martin periodinane (3.0 eq.), CH_2Cl_2, rt, 3 h, 59–87 %. R^1, R^2, R^3 = H, H, H (**a**); H, Me, H (**b**); H, MeO, H (**c**); H, Br, H (**d**); H, CF_3, H (**e**); Me, H, Me (**f**).

Table 1. Examination of reaction conditions.



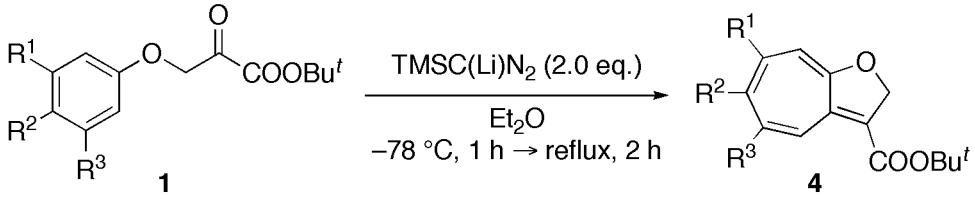
Entry	TMSC(metal)N_2	Solvent	Conditions	Yield
1	TMSC(Li)N_2 (1.2 eq.) [a]	Et_2O	–78 °C, 1 h → reflux, 2 h	19 %
2	TMSC(Li)N_2 (1.2 eq.) [a]	THF	–78 °C, 1 h → 40 °C, 2 h	– [f]
3	TMSC(Li)N_2 (1.2 eq.) [a]	*i*-Pr_2O	–78 °C, 1 h → 40 °C, 2 h	8 %
4	TMSC(Li)N_2 (1.2 eq.) [a]	*t*-BuOMe	–78 °C, 1 h → 40 °C, 2 h	6 %
5	TMSC(Li)N_2 (1.2 eq.) [a]	Et_2O-TMEDA (1.2 eq.)	–78 °C, 1 h → reflux, 2 h	– [f] (85 %) [g]
6	TMSC(Na)N_2 (1.2 eq.) [b]	Et_2O	–78 °C, 1 h → reflux, 2 h	4 %
7	TMSC(K)N_2 (1.2 eq.) [c]	Et_2O	–78 °C, 1 h → reflux, 2 h	– [f]
8	TMSC(MgBr)N_2 (1.2 eq.) [d]	Et_2O	–78 °C, 1 h → reflux, 2 h	– [f] (42 %) [g]
9	TMSC(Li)N_2 (2.0 eq.) [a]	Et_2O	–78 °C, 1 h → reflux, 2 h	28 %
10	TMSC(Li)N_2 (2.0 eq.) [e]	Et_2O	–78 °C, 1 h → reflux, 2 h	27 %

[a] Prepared from $TMSCHN_2$ and LDA. [b] Prepared from $TMSCHN_2$ and NaHMDS. [c] Prepared from $TMSCHN_2$ and KHMDS. [d] Prepared from $TMSCHN_2$, LDA and $MgBr_2$. [e] Prepared from $TMSCHN_2$ and *n*-BuLi. [f] Not obtained. [g] Obtained the aldol product (**5**).

The synthesis of *t*-butyl aryloxypyruvates (**1**) as substrates is shown in Scheme 2. The epoxy-opening reaction of *t*-butyl glycidate[5] by phenols (**2**) yielded α-hydroxy esters (**3**), which were oxidized by Dess-Martin periodinane giving the desired **1**.

The reaction conditions were optimized on the basis of reaction using *t*-butyl phenoxypyruvate (**1a**) (Table 1). Treatment of **1a** with TMSC(Li)N_2 (1.2 eq.), prepared from $TMSCHN_2$ and LDA, in Et_2O gave the desired *t*-butyl 1,2-dihydro-1-oxaazulene-3-carboxylate (**4a**) in 19 % yield (Entry 1). Et_2O was found to be the solvent of choice though THF, *i*-Pr_2O and *t*-BuOMe were also tried (Entries 1-4). Interestingly, reaction in Et_2O containing TMEDA as an additive afforded the aldol product (**5**), and **4a** was not obtained at all (Entry 5). This result was probably due to an increase in basicity of TMSC(Li)N_2 by the addition of TMEDA. As shown in Entries 6–8, in this reaction, other metal salts of $TMSCHN_2$ such as TMSC(Na)N_2, TMSC(K)N_2 and TMSC(MgBr)N_2 were quite ineffective. When two equivalents of TMSC(Li)N_2 were used, the best result was obtained and the yield of **4a** increased to 28 % (Entry 9).[6] The use of *n*-BuLi, instead of LDA, for the preparation of TMSC(Li)N_2 was also applicable in this reaction (Entry 10).

Table 2. The synthesis of *t*-butyl 1,2-dihydro-1-oxaazulene-3-carboxylates.



1 **4**

Entry	R^1	R^2	R^3	Substrate	Yield
1 [a]	H	H	H	**1a**	28 %
2	H	Me	H	**1b**	31 %
3	H	MeO	H	**1c**	23 %
4	H	Br	H	**1d**	28 %
5	H	CF_3	H	**1e**	22 %
6	Me	H	Me	**1f**	20 % [b]

[a] Shown in Entry 9 of Table 1. [b] Obtained a mixture of **4f** and its isomer (1.7:1).

Next, reactions using other *t*-butyl aryloxypyruvates were carried out under the optimized reaction conditions described above (Table 2). Various aryloxypyruvates bearing methyl (**1b**), methoxy (**1c**), bromo (**1d**) and trifluoromethyl groups (**1e**) at the 4-position of the benzene ring reacted with $TMSC(Li)N_2$ to give the desired **4b-e** in 22-31 % yields (Entries 2-5). In these cases, substituents on the benzene ring of **1** had no effect on the yields of **4**. Reaction with (3,5-dimethylphenoxy)pyruvate (**1f**) also proceeded but the product was a mixture of **4f** and its isomer (concerning the position of double bonds) in 20 % yield (Entry 6). Unfortunately, reaction with *N,N*-diisopropyl-phenoxypyruvamide[7] or phenoxypropan-2-one gave a complex mixture and the desired 1,2-dihydro-1-oxaazulene derivative was not obtained.

In conclusion, we have found that the reaction of *t*-butyl aryloxypyruvates with lithium trimethylsilyldiazomethane gave *t*-butyl 1,2-dihydro-1-oxaazulene-3-carboxylates bearing substituents on the 7-membered ring. Although the yield was still unsatisfactory, this synthetic method allows us to easily synthesize *t*-butyl 1,2-dihydro-1-oxaazulene-3-carboxylates from *t*-butyl acrylate.

EXPERIMENTAL

All melting points were measured on a Yanagimoto micro melting points apparatus and are uncorrected. IR spectra were recorded on a SHIMADZU FTIR-8400S spectrophotometer. ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-EX-270 spectrometer (^1H, 270 MHz; ^{13}C, 67.8 MHz). MS spectra were recorded on a JEOL JMS-SX-102A spectrometer.

***t*-Butyl 2-hydroxy-3-phenoxypropioate (3a).** To a stirred solution of phenol (1.88 g, 20 mmol) in *t*-butyl methyl ether (4 mL) were added NaH (400 mg, 60 % dispersion in oil, 10 mmol) and *t*-butyl glycidate (3.17 g, 22 mmol) under argon atmosphere. After being stirred at 45 °C for 43 h, the mixture was quenched with H_2O and extracted with EtOAc (2 times). The organic extracts were washed with water and saturated brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by Kugelrohr

distillation (1.0 mmHg, 150 °C) to give **3a** (3.17 g, 67 %). Colorless needles, mp 67-68 °C (Et_2O-hexane). IR (nujol): 3018, 1734 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.48 (s, 9H), 3.21 (d, 1H, *J* = 6.5 Hz), 4.18-4.28 (m, 2H), 4.36-4.40 (m, 1H), 6.89-6.91 (m, 3H), 7.25-7.31 (m, 1H). ^{13}C NMR ($CDCl_3$) δ: 28.0, 69.8, 70.3, 83.0, 114.6, 121.1, 129.0, 158.4, 171.2. MS (EI): *m/z* 238 (M^+), 94 (bp). HRMS calcd for $C_{13}H_{18}O_4$: 238.1205, found: 238.1216.

***t*-Butyl 2-hydroxy-3-(4-methylphenoxy)propioate (3b).** Prepared from 4-methylphenol (541 mg, 5.0 mmol) and *t*-butyl glycidate (865 mg, 6.0 mmol). The residue was purified by Kugelrohr distillation (1.2 mmHg, 140 °C) to give **3b** (516 mg, 41 %). Colorless crystals, mp 98-100 °C (hexane). IR (nujol): 3439, 1734 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.47 (s, 9H), 2.28 (s, 3H), 3.21(br s, 1H), 4.14-4.24 (m, 2H), 4.35-4.37 (m, 1H), 6.80 (d, 2H, *J* = 8.4 Hz), 7.07 (d, 2H, *J* = 8.4 Hz). ^{13}C NMR ($CDCl_3$) δ: 20.6, 28.1, 70.0, 70.3, 83.1, 114.5, 129.8, 130.4, 156.3, 171.3. MS (EI): *m/z* 252 (M^+), 108 (bp). HRMS calcd for $C_{14}H_{20}O_4$: 252.1362, found: 252.1368.

***t*-Butyl 2-hydroxy-3-(4-methoxyphenoxy)propioate (3c).** Prepared from 4-methoxyphenol (621 mg, 5.0 mmol) and *t*-butyl glycidate (865 mg, 6.0 mmol). The residue was purified by Kugelrohr distillation (1.0 mmHg, 150 °C) to give **3c** (644 mg, 48 %). Colorless needles, mp 74-75 °C (Et_2O-hexane). IR (nujol): 3439, 1740 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.48 (s, 9H), 3.21 (d, 1H, *J* = 6.1 Hz), 3.77 (s, 3H), 4.16-4.19 (m, 2H), 4.30-4.35 (m, 1H), 6.79 (d, 2H, *J* = 8.4 Hz), 7.07 (d, 2H, *J* = 8.7 Hz). ^{13}C NMR ($CDCl_3$) δ: 28.1, 55.7, 70.4, 70.7, 83.1, 114.5, 115.7, 152.6, 154.0, 171.3. MS (EI): *m/z* 268 (M^+), 212 (bp). HRMS calcd for $C_{14}H_{20}O_5$: 268.1311, found: 268.1309.

***t*-Butyl 3-(4-bromophenoxy)-2-hydroxypropioate (3d).** Prepared from 4-bromophenol (346 mg, 5.0 mmol) and *t*-butyl glycidate (634 g, 4.4 mmol). The residue was purified by Kugelrohr distillation (1.4 mmHg, 168 °C) to give **3d** (263 mg, 42 %). White powder, mp 96-97 °C. IR (nujol): 3434, 1732 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.47 (s, 9H), 3.21 (d, 1H, *J* = 6.5 Hz), 4.14-4.24 (m, 2H), 4.36 (br s, 1H), 6.78 (d, 2H, *J* = 8.3 Hz), 7.37 (d, 2H, *J* = 8.3 Hz). ^{13}C NMR ($CDCl_3$) δ: 28.1, 70.1, 70.2, 83.3, 113.4, 116.4, 132.2, 157.6, 171.0. MS (EI): *m/z* 318 (M^+), 316 (M^+), 57 (bp). HRMS calcd for $C_{13}H_{17}O_4{}^{79}Br$: 317.0310, found: 317.0337.

***t*-Butyl 2-hydroxy-3-(4-trifluoromethylphenoxy)propioate (3e).** Prepared from 4-trifluoromethylphenol (811 mg, 5.0 mmol) and *t*-butyl glycidate (865 mg, 6.0 mmol). The residue was purified by Kugelrohr distillation (1.4 mmHg, 168 °C) to give **3e** (513 mg, 34 %). Colorless crystals, mp 121-122 °C (Et_2O). IR (nujol): 3437, 1730 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.57 (s, 9H), 3.27 (br s, 1H), 4.22-4.32 (m, 2H), 4.38-4.42 (m, 1H), 6.96 (d, 2H, *J* = 8.7 Hz), 7.54 (d, 2H, *J* = 8.7 Hz). ^{13}C NMR ($CDCl_3$) δ: 28.0, 70.0, 70.1, 83.5, 114.5, 115.4, 126.8, 126.9, 160.8, 170.9. MS (EI): *m/z* 306 (M^+), 162 (bp). HRMS calcd for $C_{14}H_{17}O_4F_3$: 306.1079, found: 306.1087.

***t*-Butyl 3-(3,5-dimethylphenoxy)-2-hydroxypropioate (3f).** Prepared from 3,5-dimethylphenol (611 mg, 5.0 mmol) and *t*-butyl glycidate (793 g, 5.5 mmol). The residue was purified by Kugelrohr distillation (1.1 mmHg, 155 °C) to give **3f** (559 mg, 42 %). Colorless oil. IR (neat): 3434, 1736 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.48 (s, 9H), 2.28 (s, 6H), 3.19 (d, 1H, *J* = 6.6 Hz) 4.13-4.23 (m, 2H), 4.35 (t, 1H, *J* = 3.0 Hz), 6.53 (s, 2H), 6.61 (s, 2H). ^{13}C NMR ($CDCl_3$) δ: 21.4, 28.0, 69.7, 70.3, 112.3, 122.9, 139.0, 158.4, 171.3. MS (EI): *m/z* 266 (M^+), 122 (bp). HRMS calcd for $C_{15}H_{22}O_4$: 266.1518, found: 266.1526.

***t*-Butyl phenoxypyruvate (1a).** To a solution of *t*-butyl 2-hydroxy-3-phenoxypropioate (**2a**) (218 mg, 0.91 mmol) in CH_2Cl_2 (4 mL) was added Dess-Martin periodinane (1.16 g, 2.74 mmol) and the mixture was stirred at rt for 3 h. After the mixture was diluted by Et_2O, a 1:1 mixture of saturated $NaHCO_3$ aq. and saturated $Na_2S_2O_3$ aq. was added and the mixture was further stirred overnight. The mixture was extracted with Et_2O (3 times). The organic extracts were washed with water and saturated brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1a** (183 mg, 85 %). Pale yellow oil. IR (neat): 1746, 1734 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.56 (s, 9H), 5.09 (s, 2H), 6.91 (d, 2H, *J* = 8.1 Hz), 7.01 (t, 1H, *J* = 7.6 Hz), 7.27-7.33 (m, 2H). ^{13}C NMR ($CDCl_3$) δ: 27.9, 70.9, 85.1, 114.8, 121.9, 129.5, 157.4, 159.3, 189.7. MS (EI): *m/z* 236 (M^+), 107 (bp). HRMS calcd for $C_{13}H_{16}O_4$: 236.1049, found: 236.1056.

***t*-Butyl (4-methylphenoxy)pyruvate (1b).** Prepared from **2b** (510 mg, 2.0 mmol) and Dess-Martin periodinane (2.57 g, 6.1 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1b** (437 mg, 86 %). Pale yellow oil. IR (neat): 1755, 1720 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.56 (s, 9H), 2.29 (s, 3H), 5.04 (s, 2H), 6.81 (d, 2H, *J* = 8.4 Hz), 7.08 (d, 2H, *J* = 8.4 Hz). ^{13}C NMR ($CDCl_3$) δ: 20.6, 27.8, 71.3, 85.0, 114.7, 129.9, 131.2, 155.4, 159.4, 189.9. MS (EI): *m/z* 250 (M^+), 121 (bp). HRMS calcd for $C_{14}H_{18}O_4$: 250.1205, found: 250.1200.

***t*-Butyl (4-methoxyphenoxy)pyruvate (1c).** Prepared from **2c** (553 mg, 2.1 mmol) and Dess-Martin periodinane (2.62 g, 6.2 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1c** (430 mg, 78 %). Yellow oil. IR (neat): 1749, 1734 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.56 (s, 9H), 3.77 (s, 3H), 5.09 (s, 2H), 6.80-6.87 (m, 4H). ^{13}C NMR ($CDCl_3$) δ: 27.9, 55.7, 72.0, 85.0, 114.6, 116.1, 151.7, 154.6, 159.3, 190.1. MS (EI): *m/z* 266 (M^+), 210 (M^+- ^{t}Bu), 57 (bp). HRMS calcd for $C_{14}H_{18}O_5$: 266.1154, found: 266.1154.

***t*-Butyl (4-bromophenoxy)pyruvate (1d).** Prepared from **2d** (266 mg, 0.84 mmol) and Dess-Martin periodinane (1.07 g, 2.5 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1d** (227 mg, 86 %). Pale yellow oil. IR (neat): 1747, 1732 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.56 (s, 9H), 5.07 (s, 2H), 6.79 (d, 2H, *J* = 9.1 Hz), 7.39 (d, 2H, *J* = 9.1 Hz). ^{13}C NMR ($CDCl_3$) δ: 27.9, 71.1, 85.3, 114.2, 116.5, 132.3, 156.6, 159.1, 189.1. MS (EI): *m/z* 316 (M^+), 314 (M^+), 57 (bp). HRMS calcd for $C_{13}H_{15}O_4{}^{79}Br$: 314.0154, found: 314.0152.

***t*-Butyl (4-trifluoromethylphenoxy)pyruvate (1e).** Prepared from **2e** (500 mg, 1.6 mmol) and Dess-Martin periodinane (2.08 g, 4.9 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1e** (295 mg, 59 %). Colorless crystals, mp 78-79 °C (hexane). IR (nujol): 1751 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.57 (s, 9H), 5.15 (s, 2H), 6.97 (d, 2H, J = 8.6 Hz), 7.56 (d, 2H, J = 8.6 Hz). ^{13}C NMR ($CDCl_3$) δ: 27.9, 70.7, 85.4, 114.7, 122.1, 123.8, 124.3, 126.1, 159.0, 159.8, 188.7. MS (EI): *m/z* 304 (M^+), 248 (M^+- ^{t}Bu), 175 (bp). HRMS calcd for $C_{14}H_{17}O_4F_3$: 304.0922, found: 304.0929.

***t*-Butyl (3,5-dimethylphenoxy)pyruvate (1f).** Prepared from **2f** (175 mg, 0.66 mmol) and Dess-Martin periodinane (936 mg, 2.0 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 7:1) to give **1f** (121 mg, 70 %). Yellow needles, mp 84-85 °C (Et_2O-hexane). IR (nujol): 1751, 1726 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.56 (s, 9H), 2.28 (s, 6H), 5.04 (s, 2H), 6.53 (s, 2H), 6.65 (s, 1H). ^{13}C NMR ($CDCl_3$) δ: 21.5, 27.9, 70.9, 85.0, 112.5, 123.7, 139.3, 157.5, 159.4, 190.0. MS (EI): *m/z* 264 (M^+), 135 (M^+-$COCO_2{}^t$Bu), 57 (bp). HRMS calcd for $C_{15}H_{20}O_4$: 264.1362, found: 264.1368.

***t*-Butyl 1,2-dihydro-1-oxaazulene-3-carboxylate (4a).** To a stirred solution of diisopropylamine (95 mg, 0.94 mmol) in Et_2O (4 mL) was added dropwise *n*-butyllithium (1.60 M in hexane solution, 0.59 mL, 0.94 mmol) at -78 °C under argon atmosphere, and the mixture was stirred for 20 min. $TMSCHN_2$ (1.55 M in hexane solution, 0.60 mL, 0.94 mmol) was added dropwise at –78 °C, and the mixture was stirred for 10 min. A solution of *t*-butyl phenoxypyruvate (**3a**) (111 mg, 0.47 mmol) in Et_2O (0.6 mL) was added dropwise. This mixture was stirred at -78 °C for 1 h, then refluxed for 2 h. After being quenched with H_2O, the mixture was extracted with EtOAc (3 times). The organic extracts were washed with water and saturated brine, dried over Na_2SO_4, and concentrated in vacuo. The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **4a** (29 mg, 27 %). Red oil. IR (neat): 1686 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.46 (s, 9H), 5.36 (s, 2H), 5.63 (d, 1H, J = 9.3 Hz), 5.79 (dd, 1H, J = 8.2 and 11.0 Hz), 6.12 (dd, 1H, J = 9.3 and 11.0 Hz), 6.23 (dd, 1H, J = 8.2 and 11.9 Hz), 7.22 (d, 1H, J = 11.9 Hz). ^{13}C NMR ($CDCl_3$) δ: 27.8, 78.1, 79.7, 104.9, 112.7, 123.3, 123.8, 133.5, 134.4, 144.6, 162.1, 172.1. MS (EI): *m/z* 232 (M^+), 176 (M^+-^{t}Bu), 131(bp). HRMS calcd for $C_{14}H_{16}O_3$: 232.1100, found: 232.1100.

***t*-Butyl 4-(*t*-butoxycarbonyl)-3,5-diphenoxy-4-hydroxy-2-oxopentanoate (5).** Prepared from **3a** (61 mg, 0.26 mmol), $TMSC(Li)N_2$ (0.31 mmol) and TMEDA (36 mg, 0.31 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **5** (52 mg, 85 %). Colorless needles, mp 127-128 °C (Et_2O). IR (nujol): 3522, 1747, 1728 cm^{-1}. ^1H NMR (CD_2Cl_2) δ: 1.36 (s, 9H), 1.42 (s, 9H), 3.99 (br s, 1H), 4.30 (d, 1H, J = 9.6 Hz), 4.34 (d, 1H, J = 9.6 Hz), 5.71 (s, 1H), 6.87-7.02 (m, 6H), 7.29 (m, 4H). ^{13}C NMR (CD_2Cl_2) δ: 27.8, 27.8, 69.8, 79.2, 79.5, 84.3,

85.0, 114.8, 115.1, 121.5, 122.2, 129.3, 129.5, 156.9, 158.0, 161.0, 168.9, 191.3. MS (FAB): *m/z* 473 (MH^+). Anal. Calcd for $C_{26}H_{32}O_8$: C, 66.09; H, 6.83. Found: C, 65.79; H, 6.85.

***t*-Butyl 1,2-dihydro-6-methyl-1-oxaazulene-3-carboxylate (4b).** Prepared from **3b** (132 mg, 0.53 mmol) and TMSC(Li)N_2 (1.1 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **4b** (41 mg, 31 %). Red solid, mp 46-48 °C. IR (nujol): 1682 cm^{-1}. ^1H NMR (CD_2Cl_2) δ: 1.46 (s, 9H), 1.90 (s, 3H), 5.32 (s, 2H), 5.56 (d, 1H, *J* = 9.3 Hz), 6.03 (d, 1H, *J* = 9.3 Hz), 6.20 (d, 1H, *J* = 12.2 Hz), 7.23 (d, 1H, *J* = 12.2 Hz). ^{13}C NMR (CD_2Cl_2) δ: 25.3, 27.8, 77.5, 79.6, 104.3, 112.2, 123.4, 130.7, 132.4, 137.8, 143.9, 162.3, 169.8. MS (EI): *m/z* 246 (M^+), 190 (bp). HRMS calcd for $C_{15}H_{18}O_3$: 246.1256, found: 246.1257.

***t*-Butyl 1,2-dihydro-6-methoxy-1-oxaazulene-3-carboxylate (4c).** Prepared from **3c** (99 mg, 0.37 mmol) and TMSC(Li)N_2 (0.75 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **4c** (23 mg, 23 %). Red solid, mp; 73-74 °C. IR (nujol): 1678 cm^{-1}. ^1H NMR (CD_2Cl_2) δ: 1.47 (s, 9H), 3.56 (s, 3H), 5.28 (s, 2H), 5.51 (d, 1H, *J* = 9.4 Hz), 5.63 (d, 1H, *J* = 9.4 Hz), 6.19 (d, 1H, *J* = 12.8 Hz), 7.36 (d, 1H, *J* = 12.8 Hz). ^{13}C NMR (CD_2Cl_2) δ: 27.8, 54.7, 76.9, 79.7, 101.8, 106.5, 113.0, 124.1, 132.0, 142.5, 154.8, 162.3, 165.4. MS (EI): *m/z* 262 (M^+), 205 (bp). HRMS calcd for $C_{15}H_{18}O_4$: 262.1205, found: 262.1205.

***t*-Butyl 6-bromo-1,2-dihydro-1-oxaazulene-3-carboxylate (4d).** Prepared from **3d** (172 mg, 0.55 mmol) and TMSC(Li)N_2 (1.1 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **4d** (48 mg, 28 %). Red solid, mp 121-123 °C. IR (nujol): 1688 cm^{-1}. ^1H NMR (CD_2Cl_2) δ: 1.47 (s, 9H), 5.33 (s, 2H), 5.40 (d, 1H, *J* = 9.7 Hz), 6.40 (d, 1H, *J* = 11.7 Hz), 6.51 (d, 1H, *J* = 9.7 Hz), 7.08 (d, 1H, *J* = 11.7 Hz). ^{13}C NMR (CD_2Cl_2) δ: 27.7, 78.0, 80.4, 102.9, 115.7, 116.5, 123.6, 134.9, 137.8, 142.4, 161.7, 171.4. MS (EI): *m/z* 312 (M^+), 310 (M^+), 254 (bp). HRMS calcd for $C_{14}H_{15}O_3{}^{79}Br$: 310.0205, found: 310.0202.

***t*-Butyl 1,2-dihydro-1-oxa-6-trifluoromethylazulene-3-carboxylate (4e).** Prepared from **3e** (273 mg, 0.90 mmol) and TMSC(Li)N_2 (1.8 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give **4e** (60 mg, 22 %). Red solid, mp <30 °C. IR (nujol): 1659 cm^{-1}. ^1H NMR (CD_2Cl_2) δ: 1.47 (s, 9H), 5.39 (s, 2H), 5.58 (d, 1H, *J* = 9.6 Hz), 6.24 (d, 1H, *J* = 12.5 Hz), 6.55 (d, 1H, *J* = 9.6 Hz), 7.27 (d, 1H, *J* = 12.5 Hz). ^{13}C NMR (CD_2Cl_2) δ: 27.7, 78.6, 80.8, 101.8, 124.3, 128.6, 128.7, 132.8, 142.4, 161.5, 174.7. MS (EI): *m/z* 300 (M^+), 244 (M^+- ^{t}Bu), 199 (bp). HRMS calcd for $C_{15}H_{15}O_3F_3$: 300.0973; found: 300.0979.

***t*-Butyl 1,2-dihydro-3,5-dimethyl-1-oxaazulene-3-carboxylate (4f).** Prepared from **3f** (86 mg, 0.33 mmol) and TMSC(Li)N_2 (0.65 mmol). The residue was purified by column chromatography on silica gel (Fuji Sylisia BW-200MH, hexane:EtOAc = 30:1) to give a mixture of **4f** and its isomer (17 mg, 20 %, **4f** : its isomer = 1.7 : 1). Red oil. IR (nujol): 1688 cm^{-1}. **4f**, ^1H NMR (CD_2Cl_2) δ: 1.70 (s, 9H), 2.27 (s, 3H),

2.30 (s, 3H), 5.30 (s, 2H), 5.62 (s, 1H), 5.72 (s, 1H), 7.17 (s, 1H); its isomer, ^{1}H NMR (CD_2Cl_2) δ: 1.54 (s, 9H), 1.95 (s, 3H), 2.00 (s, 3H), 4.86 (s, 2H), 6.54 (s, 1H), 6.63 (s, 1H), 7.55 (s, 1H). MS (EI): *m/z* 260 (M^+), 203 (M^+- ^{t}Bu), 159 (bp). HRMS calcd for $C_{16}H_{20}O_3$: 260.1412; found: 260.1414.

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REFERENCES AND NOTES

1. R. Knorr, *Chem. Rev*., 2004, **104**, 3795 and references cited therein.
2. T. Shioiri and T. Aoyama, *J. Synth. Chem., Jpn.*, 1996, **54**, 918 and references cited therein; T. Yagi, T. Aoyama, and T. Shioiri, *Synlett*, 1997, 1063; Y. Ito, T. Aoyama, and T. Shioiri, *Synlett*, 1997, 1163; A. Sakai, T. Aoyama, and T. Shioiri, *Tetrahedron*, 1999, **55**, 3687; R. Miyabe, T. Shioiri, and T. Aoyama, *Heterocycles*, 2002, **57**, 1313; T. Miyagi, Y. Hari, and T. Aoyama, *Tetrahedron Lett*., 2004, **45**, 6303.
3. Y. Hari, S. Tanaka, Y. Takuma, and T. Aoyama, *Synlett*, 2003, 2151.
4. H. Ogawa, T. Aoyama, and T. Shioiri, *Synlett*, 1994, 757.
5. Conversion of *t*-butyl acrylate into *t*-butyl glycidate was performed by epoxidation with sodium hypochlorite (or *t*-butyl hydroperoxide).
6. The use of methyl phenoxypyruvate instead of the *t*-butyl ester (**4a**) as a substrate resulted in a remarkable decrease in the yield (12 %).
7. E. R. Koft, P. Dorff, and R. Kullnig, *J. Org. Chem*., 1989, **54**, 2936.