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journal or publication title	Tetrahedron Letters
volume	53
number	17
page range	2257-2259
year	2012-04-25
URL	http://hdl.handle.net/2297/30315

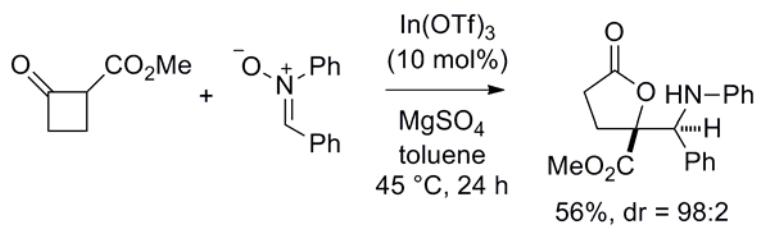
doi: 10.1016/j.tetlet.2012.02.092

Graphical Abstract

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ABSTRACT

2-Carbomethoxycyclobutanone reacted with N-phenyl-C-arylnitrones to afford methyl 5-oxo-2-[aryl(phenylamino)methyl]tetrahydrofuran-2-carboxylates by the catalysis of indium(III) triflate in the presence of magnesium sulfate.

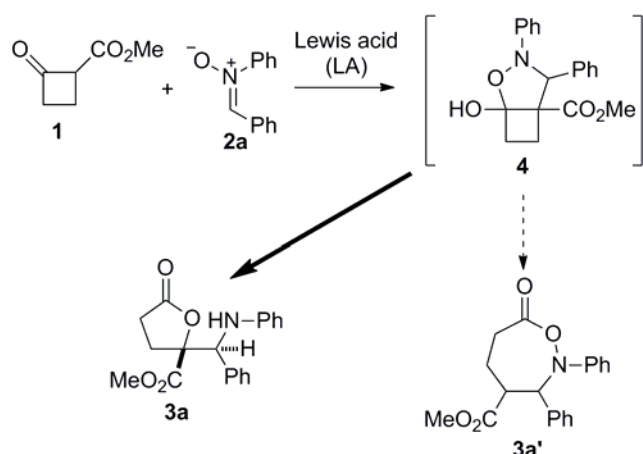
Keywords

Nitronone ; γ -Lactone ; Indium(III) triflate ; Cyclobutanone ; Rearrangement

Nitrones are useful synthetic intermediates in organic synthesis and have been used mainly in the 1,3-dipolar cycloaddition with olefins to give isoxazolidines.¹ In addition to olefins, nitrones reacted with donor-acceptor cyclopropanes and cyclobutanes for [3+3]^{2,3} and [4+3]⁴ cycloadditions, respectively. Moreover, nucleophilic additions to nitrones have been studied for carbon nucleophiles such as Grignard reagents,⁵ cyanide ion,⁶ and sodium salts of diethyl malonate.⁷ We were interested in a reaction of 2-carbomethoxycyclobutanone (**1**)⁸ with nitrones because four-membered ketoester **1** can work as a carbon nucleophile and it has a characteristic feature of facile ring cleavage.⁹ Thus, we tried to synthesize a seven-membered ring compound **3a'** by nucleophilic addition of **1** to nitronone **2a** followed by ring cleavage of four-membered ring of **4** (Scheme 1). However, we found unexpected formation of a γ -butyrolactone derivative **3a** by Lewis acid-catalyzed reaction of nitronone **2a** with **1**, and we report here the results.

Scheme 1

Formation of γ -butyrolactone **3a** by Lewis acid-catalyzed reaction between **1** and **2a**



First, various Lewis acids were screened in a model reaction between **1** and nitronone **2a** to afford γ -butyrolactone **3a** (Table 1). In the absence of a Lewis acid, cyclobutanone **1** was not react with **2a** at refluxing temperature of toluene, and even ring cleavage of **1** did not observed by TLC analysis (Entry 1). The

use of catalytic amounts (10 mol%) of the typical Lewis acids TiCl_4 , $\text{BF}_3\text{-Et}_2\text{O}$ and Me_3SiOTf gave the desired product **3a** in 16%, 34% and 27% yields, respectively (Entries 2–4), while the use of more than stoichiometric amounts (1.3 equiv) of these Lewis acids did not afford **3a** at all. Catalytic amounts (10 mol%) of several metal triflates were then tested in this reaction, and it was found that $\text{In}(\text{OTf})_3$ promoted the reaction most efficiently (Entries 5–11). The Brønsted acid TsOH also catalyzed the reaction, but the reaction proceeded sluggishly (Entry 12). It should be noted that high diastereoselectivity was observed in the Lewis acid-catalyzed reaction of **1** and **2a** as shown in Table 1. We employed $\text{In}(\text{OTf})_3$ in the following experiments since the reaction time was shorter than that for $\text{BF}_3\text{-OEt}_2$ (Entries 3 and 11).¹⁰

Table 1

Effects of Lewis acids in a reaction of **1** and **2a** to give γ -butyrolactone **3a** (eq 1)^a

Entry	Lewis acid	Time (h)	Isolated yield (%)	dr ^b
1 ^c	none	48	0	
2	TiCl_4	48	16	99:1
3	$\text{BF}_3\text{-Et}_2\text{O}$	48	34	96:4
4	Me_3SiOTf	18	27	98:2
5	AgOTf	24	29	96:4
6	$\text{Zn}(\text{OTf})_2$	23	18	97:3
7	$\text{Cu}(\text{OTf})_2$	53	1	98:2
8	$\text{Yb}(\text{OTf})_3$	19	12	96:4
9	$\text{La}(\text{OTf})_3$	29	17	98:2
10	$\text{Sc}(\text{OTf})_3$	19	19	96:4
11	$\text{In}(\text{OTf})_3$	20	32	96:4
12	$\text{TsOH-H}_2\text{O}$	48	20	96:4

^a Unless otherwise mentioned, the following reaction conditions were used: cyclobutanone **1** (1.0 equiv), nitronone **2a** (1.3 equiv), and Lewis acid (10 mol%) were reacted in toluene at 45 °C.

^b Determined by ¹H NMR.

^c Reaction conditions: 45 °C (24 h) and reflux (24 h).

Next, effects of additives in the $\text{In}(\text{OTf})_3$ -catalyzed reaction of **1** and **2a** were investigated (Table 2). Some drying agents were employed as additives because benzaldehyde was detected by TLC analysis in the above-mentioned Lewis acid screening. The use of molecular sieves 4A and 5A was not effective and led to

considerably lower yields of the desired product **3a** (Entries 2 and 3). The addition of Na₂SO₄ did not cause any change compared with the case of no additives, whereas the use of MgSO₄ greatly improved the yield of **3a** to 56% (Entries 4 and 5). TLC analysis of the reaction mixture showed smooth consumption of cyclobutanone **1** in the presence of MgSO₄, but benzaldehyde was still detected even in the presence of MgSO₄. MgSO₄ did not work as a Lewis acid in this reaction because the product **3a** was detected only in a trace amount by using MgSO₄ in the absence of In(OTf)₃ (Entry 6). Therefore, at present, the role of MgSO₄ is not clear. The use of Mg(ClO₄)₂ gave the desired product **3a** in 6% yield (Entry 7), and it was found that MgSO₄ was an appropriate additive in the present In(OTf)₃-catalyzed reaction.¹¹

Table 2

Effects of additives in an In(OTf)₃-catalyzed reaction of **1** and **2a** to afford **3a** (eq 1)^a

Entry	Additive	Time (h)	Isolated yield (%)	dr ^b
1	none	24	36	96:4
2	MS4A	48	0	
3	MSSA	72	5	99:1
4	Na ₂ SO ₄	14	39	97:3
5	MgSO ₄	24	56	98:2
6 ^c	MgSO ₄	48	trace	
7	Mg(ClO ₄) ₂	24	6	87:13

^a Reaction conditions: cyclobutanone **1** (1.0 equiv), nitron **2a** (2.0 equiv), In(OTf)₃ (10 mol%), and additive (300 mg/mmol of **2**) were reacted in toluene at 45 °C.

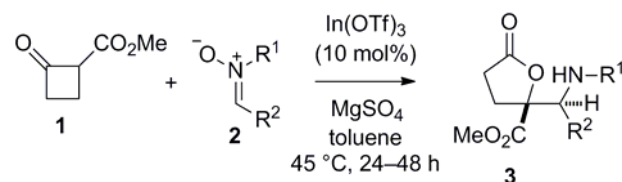
^b Determined by ¹H NMR.

^c In the absence of In(OTf)₃.

The scope and limitations of the reaction of cyclobutanone **1** and nitrones were investigated by employing various nitrones **2b–g** (Table 3). *N*-Phenyl-*C*-arylnitrones **2b–d** with electron-withdrawing groups such as fluoro, chloro, and bromo groups at the *p*-position of the phenyl ring gave results comparable to those with the parent unsubstituted nitron **2a** (Entries 1–3). Substitution with a methyl group resulted in a slightly decreased yield of **3e** (Entry 4). The use of a nitron **2f** bearing a *C*-2-naphthyl group instead of the *C*-phenyl group lowered the yield of the corresponding γ -butyrolactone **3f** (entry 5). *C*-Alkyl nitron **2g**, which was prepared in situ from 3-phenylpropanal and *N*-phenylhydroxylamine, reacted with **1** to afford **3g** in 24% yield (Entry 6) whereas *N*-methyl nitron **2h** did not react with **1** (Entry 7). Stereochemistry of **3** was determined by X-ray crystallography of **3d**.

Table 3

Scope and limitations of In(OTf)₃-catalyzed reaction of cyclobutanone **1** and nitron **2b–g** to give γ -butyrolactone **3b–g**^a



Entry	2	R ¹	R ²	X	3	Yield (%)	dr ^b
1	2b	Ph		X = F	3b	51	96:4
2	2c	Ph		X = Cl	3c	46	97:3
3	2d	Ph		X = Br	3d	51	97:3
4	2e	Ph		X = Me	3e	41	98:2
5	2f	Ph	2-Naphthyl		3f	40	95:5
6	2g	Ph	(CH ₂) ₂ Ph		3g	24	93:7
7	2h	Me	Ph		3h	0	

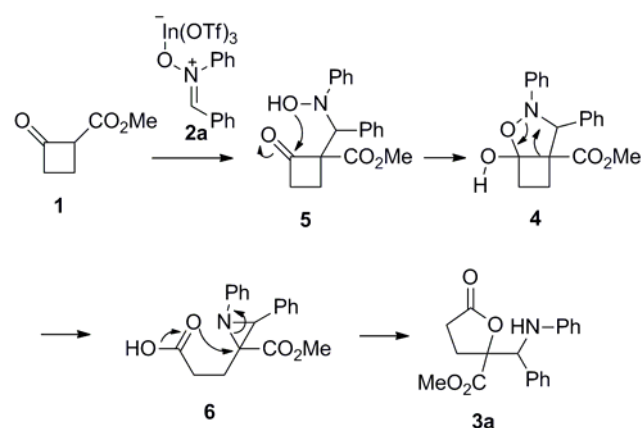
^a Reaction conditions: cyclobutanone **1** (1.0 equiv), nitron **2** (2.0 equiv), In(OTf)₃ (10 mol%), and MgSO₄ (300 mg/mmol of **2**) were reacted in toluene at 45 °C.

^b Determined by ¹H NMR.

A proposed mechanism for the In(OTf)₃-catalyzed reaction between cyclobutanone **1** and nitron **2a** is shown in Scheme 2. Nucleophilic attack of cyclobutanone **1** to nitron **2a** which is activated with In(OTf)₃ gives hydroxylamine **5**, in which intramolecular attack of the hydroxyl group to the carbonyl group of cyclobutanone gives isoxazolidine derivative **4**.¹² Valence rearrangement¹³ of the isoxazolidine ring of **4** gives aziridin-2-yl carboxylic acid **6**. Intramolecular attack of the carboxylic acid group to the aziridine ring gives γ -butyrolactone **3a**. Each step shown in Scheme 1 can be catalyzed with In(OTf)₃.

Scheme 2

A proposed mechanism for In(OTf)₃-catalyzed reaction of **1** and nitron **2a** to γ -butyrolactone **3a**



In conclusion, we found a new method for synthesis of functionalized γ -butyrolactone by a reaction of 2-carbomethoxycyclobutanone¹⁴ with *N*-phenyl-*C*-arylnitrones. This reaction was effectively promoted by using a catalytic amount of In(OTf)₃ in the presence of MgSO₄. Valence rearrangement of an isoxazolidine intermediate followed by intramolecular attack of a carboxylate group to an aziridine ring was proposed for the formation of γ -butyrolactone.

Acknowledgments

The authors thank Prof. Shuhei Fujinami (Kanazawa University) for X-ray crystallographic analysis. This study was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

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10. Use of other solvents such as dichloromethane, THF, and acetonitrile gave **3a** in low yields.
11. Under the reaction conditions of entry 5 (Table 1), the starting material **1** was completely consumed, and some very polar co-products were detected by TLC analysis.
12. A concerted mechanism for [3+2] cycloaddition between an enol form of **1** and nitrone **2a** is also possible for generation of **4**. [3+2] Cycloaddition of nitrones and silyl enol ethers: (a) Hosomi, A.; Shoji, H.; Sakurai, H. *Chem. Lett.* **1985**, 1049; (b) Dhavale, D. D.; Trombini, C. *J. Chem. Soc., Chem. Commun.* **1992**, 1268; (c) Camiletti, C.; Dhavale, D. D.; Gentilucci, L.; Trombini, C. *J. Chem. Soc. Perkin Trans. 1* **1993**, 3157.
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14. Indium(III) triflate-catalyzed reaction of nitrone **2a** with ethyl 2-oxocyclopentanecarboxylate or ethyl 2-oxocyclohexanecarboxylate did not afford the corresponding lactones

Supplementary Material

Supplementary data associated with this article can be found in the online version.