Journal of Organometallic Chemistry, 382 (1990) 39–52
Elsevier Sequoia S.A., Lausanne – Printed in The Netherlands
JOM 20300

New role of tin(II) compounds in organic synthesis *

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(Received May 23rd, 1989)

Abstract

Three new carbon–carbon bond forming reactions by the use of new catalyst systems involving tin(II) compounds are described in this article. The aldol reaction of silyl enol ethers with acetals or aldehydes and the Michael reaction of silyl enol ethers with α,β-unsaturated ketones are catalyzed by the combination of a neutral molecule, trityl chloride, and a weak Lewis acid, tin(II) chloride, under extremely mild conditions. Similarly, an active species is generated by the combination of a Lewis acid and a tin(II) compound, for example, α,β-unsaturated thioesters smoothly react with silyl enol ethers to afford the corresponding Michael adducts stereoselectively in high yields by combined use of antimony(V) chloride and tin(II) triflate. Thirdly, a new chiral promoter has developed based on this concept of combination. Highly enantioselective aldol reaction between both achiral silyl enol ethers of thioesters and aldehydes is performed by combined use of chiral diamine coordinated tin(II) triflate and tributyltin fluoride.

Introduction

The element tin has been playing an increasingly important role in organic chemistry as well as organometallic chemistry, serving as a source of new reagents leading to selective transformations [1]. While the main activity in these fields has for a long time been focused on tin(IV) compounds, tin(II) compounds have only been known as reductants of aromatic nitro compounds to the corresponding aromatic amino compounds. Further possibilities of using tin(II) compounds in synthetic organic reactions, especially carbon–carbon bond forming reactions, have not been explored until tin(II) fluoride was employed in 1979 as a reductant of several α-halocarbonyl compounds or allylic halides to generate tin(IV) species, both of which further react with aldehydes to form a new carbon–carbon bond [2]. Through these investigations, we became interested in the following characteristic

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* Dedicated to Professor Günther Wilke on the occasion of his 65th birthday.

0022-328X/90/$03.50

properties of tin(II) compounds; (1) tin(II) species, having vacant *d* orbitals in low energy levels, can accept up to 4 ligands to work well as metal template, and (2) tin(II) species form tight complexes with amines, especially with diamines.

The chemistry of tin(IV) enolates has also been studied and several interesting features of these enolates have been reported [3], whereas tin(II) analogues are relatively unknown in synthetic organic chemistry probably due to lack of general methods of their generations. It was shown that tin(II) enolates could be successfully generated in situ by the oxidative addition of α-bromoketones to metallic tin and that tin(II) enolates thus generated react with aldehydes in a highly regioselective manner with high *syn* selectivity [4]. More conveniently, tin(II) enolates can be generated directly from ketones and tin(II) trifluoromethanesulfonate (tin(II) triflate) on treatment with a tertiary amine [5]. The enolates not only reacted with aldehydes to afford aldol products with high *syn*-selectivity but also gave cross aldols between ketones [6]. Furthermore, a highly enantioselective version of tin(II) promoted cross aldol reaction was developed employing chiral diamines derived from (*S*)-proline as ligands [7]. We have already demonstrated that such chiral diamines, which are postulated to form rigid *cis*-fused 5-membered bicyclic structures by chelation to the metal center, are effective ligands for highly enantioselective reactions [8]. Thus, based on such considerations, coordination of chiral diamine to metal center of the tin(II) enolate was presumed to lead to a highly enantioselective cross aldol reaction.

We have recently searched for further development of new catalysts which promote carbon–carbon bond forming reactions with effectiveness under mild conditions. Though Lewis acidities of tin(II) compounds are generally low compared to those of the corresponding tin(IV) compounds, combined use of a neutral molecule or a metal salt and a tin(II) compound was found to generate a novel active catalytic species. This may be an alternative characteristic feature of tin(II) compounds. In this article, we would like to describe three new carbon–carbon bond forming reactions by the use of new catalyst systems involving tin(II) compounds [9]. First, an efficient and extremely mild catalyst system, combined use of trityl chloride and tin(II) chloride, is described. The aldol reaction of silyl enol ethers with acetals or aldehydes and the Michael reaction of silyl enol ethers with α,β-unsaturated ketones are promoted by the combination of a neutral molecule, trityl chloride, and a week Lewis acid, tin(II) chloride, under extremely mild conditions. This concept was next applied to the combination of a Lewis acid and a tin(II) compound. By combined use of antimony(V) chloride and tin(II) triflate, α,β-unsaturated thioesters smoothly react with silyl enol ethers to afford the corresponding Michael adducts stereoselectively in high yields. Thirdly, a quite efficient asymmetric aldol reaction between both achiral silyl enol ethers and aldehydes by the use of a new and efficient chiral catalyst system involving chiral diamine coordinated tin(II) triflate is described.

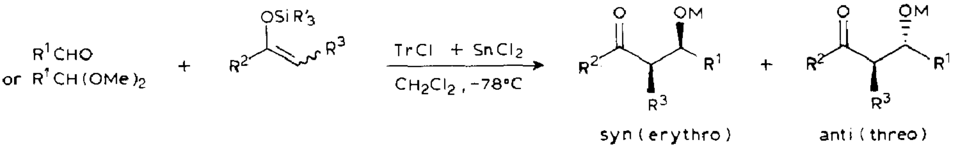
1. Combination of a neutral molecule and a tin(II) compound: An efficient and extremely mild catalyst system, combined use of trityl chloride and tin(II) chloride, in the aldol and Michael reactions.

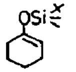
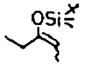
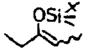
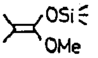
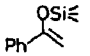
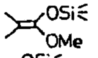
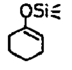
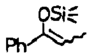
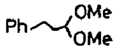
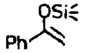
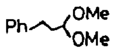
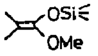
The reaction of rather stable carbon nucleophiles with activated carbonyl compounds is one of the most versatile synthetic tools for carbon–carbon bond formations [10]. Although Lewis acids such as $TiCl_4$, $SnCl_4$, and $BF_3 \cdot OEt_2$, etc. are frequently employed in the above reactions as useful promoters, it is still strongly desired to explore a new catalyst which accelerates the same reaction under essentially neutral conditions.

Recently, we have reported that trityl salts such as trityl perchlorate and trityl hexachloroantimonate are unique and excellent catalysts for several synthetic reactions [11]. For examples, trityl salts effectively catalyze the aldol reaction of silyl enol ethers with acetals [12] or aldehydes and *syn(erythro)* or *anti(threo)* aldol is obtained preferentially by the appropriate choice of the counter anions of trityl salts and the substituents on silicon of the enol ethers [13]. The Michael reaction of silyl enol ethers with α,β-unsaturated ketones is also catalyzed by trityl salts and 1,5-dicarbonyl compounds or intermediate silyl enol ethers can be isolated under appropriate quenching conditions [14]. One of the most characteristic features is that these reactions require only a catalytic amount of trityl salt, whereas the Lewis acid-promoted reactions generally require stoichiometric amounts of promoters [15]. In the course of our investigations on the exploration of new possibilities in the

Table 1

The aldol reaction catalyzed by the combined use of trityl chloride and tin(II) chloride

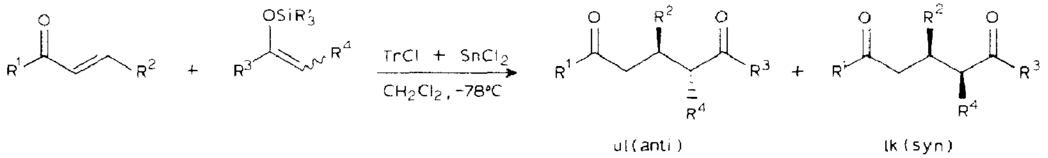


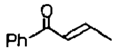
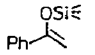
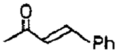
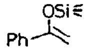
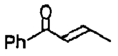
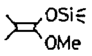
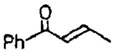
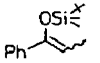
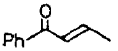
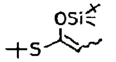
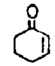
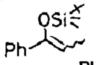
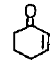
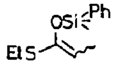
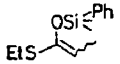
Entry	Aldehyde or acetal	Silyl enol ether	Amounts of catalyst (mol%)	Yield (%)	*syn : anti* [a] (*erythro : threo*)
1	PhCHO		5	99	20 : 80
2	PhCHO		5	95	18 : 82
3	PhCHO		5	92	31 : 69
4	PhCHO		5	96	———
5			10	79	———
6			10	83	———
7	$PhCH(OMe)_2$		10	99	90 : 10
8	$PhCH(OMe)_2$		5	95	85 : 15
9			5	85	———
10			10	88	———

[a] Determined by ^1H NMR.

Table 2

The Michael reaction catalyzed by the combined use of trityl chloride and tin(II) chloride



Entry	α,β-Unsaturated ketone	Silyl enol ether	Amounts of catalyst (mol%)	Yield (%)	*ul* : *lk* (*anti* : *syn*)
1			5	82	–
2			5	88	–
3			5	81	–
4			5	84	> 95 : 5 [a]
5			5	90	84 : 16 [b]
6			10	79	83 : 17 [c]
7			5	86	81 : 19 [c]
8			5	88	85 : 15 [c]

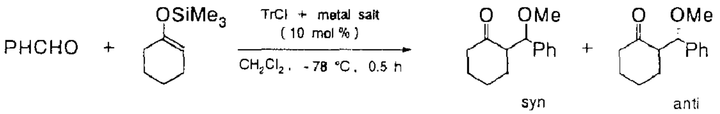
[a] Determined by ^{13}C NMR. [b] Determined by ^{1}H NMR. [c] Determined by GC.

trityl salt-promoted reactions, we have shown that combined use of trityl chloride and tin(II) chloride readily generates quite efficient catalytic species similar to that of trimethylsilyl chloride and tin(II) chloride [16]. The aldol and Michael reactions of silyl enol ethers with aldehydes, acetals, and α,β-unsaturated ketones are promoted by the above mentioned catalyst system under essentially neutral conditions.

Several examples of the aldol and Michael reactions are demonstrated in Table 1 and 2, respectively. In every case, the reactions smoothly proceeded at −78° C and

Table 3

Effect of metal salts



Metal salt	Yield (%)	*syn* : *anti*
$MgCl_2$	0	–
$PbCl_2$	0	–
$SbCl_3$	trace	–
$ZnCl_2$	43	86 : 14
$SnCl_2$	99	90 : 10

the adducts are obtained in high yields. The effectiveness of the combination of trityl chloride and tin(II) chloride is obvious from Table 3. The aldol adduct was scarcely obtained by combined use of trityl chloride and metal salts other than tin(II) chloride. Concerning the stereochemistry, *syn(erythro)* aldols were preferentially obtained by the reaction of acetals with trimethylsilyl enol ethers, whereas *anti(threo)* aldols were predominantly produced by treatment of aldehydes with t-butyldimethylsilyl enol ethers. In the Michael reaction, the *ul(anti)* adducts [17*] were obtained preferentially. These diastereoselectivities are almost consistent with those of trityl salts-promoted aldol and Michael reactions.

It is postulated that an active cationic species is generated readily from trityl chloride and tin(II) chloride based on the results that neither trityl chloride nor tin(II) chloride promotes the above mentioned reactions. Actually, a yellowish color appeared as soon as trityl chloride and tin(II) chloride were mixed in dichloromethane. After the mixture was stirred overnight at room temperature, solid tin(II) chloride still remained and the aldol and Michael reactions then proceed under this heterogeneous condition. The most characteristic and remarkable point is that this active promoter is generated by just mixing a neutral molecule and a weak Lewis acid and is enough to complete the reactions by using 5–10 mol% each of these reagents. These results show that, synthetically valuable carbon–carbon bond forming reactions can be completed under essentially neutral conditions by simple procedure.

2. Combination of a Lewis acid and a tin(II) compound: The stereoselective Michael reaction of α,β-unsaturated thioesters with silyl enol ethers promoted by combined use of antimony(V) chloride and tin(II) triflate.

The acid-catalyzed Michael reaction of α,β-unsaturated esters with enolate components is a useful method for the preparation of 5-oxocarboxylic acid esters or glutarate derivatives. However, there still remain several problems in the acid promoted reaction because of the low reactivities of α,β-unsaturated esters and the occurrence of competitive polymerization reaction [18].

We have already demonstrated that, in the presence of a catalytic amount of trityl salt, α,β-unsaturated orthoesters react with silyl enol ethers to afford the corresponding Michael adducts in good yields [19]. In the course of our investigations to search for effective catalysts and useful Michael acceptors as α,β-unsaturated ester equivalents, which are more reactive than α,β-unsaturated esters, it was found that α,β-unsaturated thioesters behave as excellent Michael acceptors in the presence of a new catalyst system, combined use of antimony(V) chloride and tin(II) triflate.

From the viewpoint of economy and mildness of reaction conditions, we searched for catalysts which promote the reaction by catalytic use. In the presence of a catalytic amount of trityl salt, which is an excellent catalyst in the glycosidation reaction [20], aldol reaction [12,13] and the Michael reaction with α,β-unsaturated ketones [14], however, the desired Michael adduct was obtained in rather low yields in case of the reaction of silyl enol ether of propiophenone with an α,β-unsaturated

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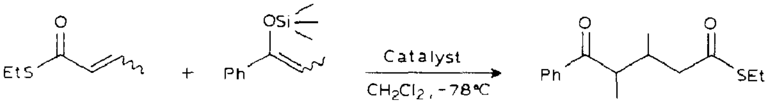
* Reference number with asterisk indicates a note in the list of references.

Table 4

Effect of catalysis



Entry	Catalyst	Yield (%)
1	$TiCl_4$	0
2	BF_3OEt_2	0
3	$SnCl_4$	32
4	$TiCl_4/SnCl_2$	8
5	$SnCl_4/SnCl_2$	41
6	$SbCl_5/SnCl_2$	49
7	$SbCl_5/Sn(OTf)_2$	70
8	$SbCl_5$	23
9	$Sn(OTf)_2$	0

thioester. Similarly, the use of catalytic amounts of several Lewis acids were not effective. On the other hand, as shown in Section 1, it was made clear that the combined use of trityl chloride and tin(II) chloride is an excellent catalyst system in the aldol and Michael reactions. Based on this result, we screened the combination of several Lewis acids and tin(II) chloride in this reaction (Table 4) and it was found that the desired Michael adduct was obtained in 70% yield by combined use of antimony(V) chloride and tin(II) triflate with high *ul(anti)* selectivities. It is noteworthy to point out that neither antimony(V) chloride nor tin(II) triflate is effective in this reaction indicating that a new active catalyst species is formed by combined use of the above two compounds.

Several examples are demonstrated in Table 5. In every case, the Michael adducts are obtained in good yields. Concerning the stereochemistry of the carbon–carbon bond forming process, the *ul(anti)* adducts are predominantly produced regardless of geometry of silyl enol ethers (Table 5, entries 2, 3). The reaction of silyl enol ethers derived from ketones, which is unprecedented in the conventional methods, can be easily carried out to afford the corresponding Michael adducts in good yields. In the reaction of *S*-ethyl 2-propenethiolate (acrylic acid ethyl thioester), the adduct was obtained in a rather low yield along with polymerization products. However, the yield was improved by employing t-butyl thioester instead of the above mentioned ethyl thioester (entries 6, 7). Furthermore, *S*-ethyl 3-methyl-2-butenethioate, an example of a β,β-disubstituted α,β-unsaturated thioester, can be successfully employed as an acceptor and the adduct with adjacent quarternary carbons is formed in a moderate yield (entry 13).

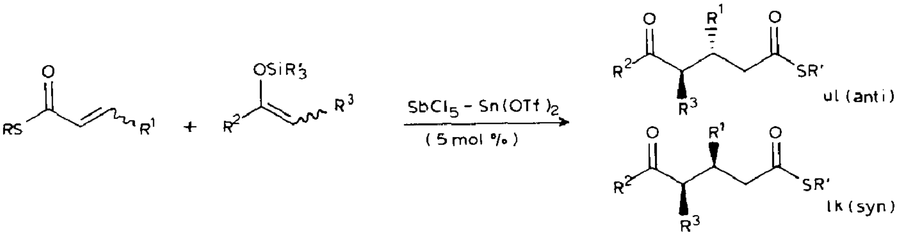
Thus, the reaction of α,β-unsaturated thioesters with silyl enol ethers is carried out in the presence of a catalytic amount of the new catalyst system, combined use of antimony(V) chloride and tin(II) triflate, to afford the corresponding Michael adducts, synthetically valuable 5-oxocarboxylic acid ester or gluterate derivatives, stereoselectively in good yields.

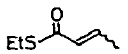
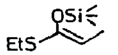
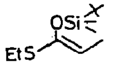
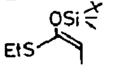
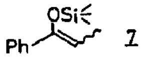
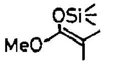
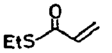
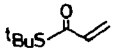
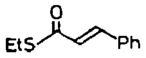
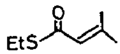
3. Combination of a neutral molecule and a chiral diamine coordinated tin(II) compound: Efficient asymmetric aldol reaction from both achiral silyl enol ethers and aldehydes promoted by combined use of chiral diamine coordinated tin(II) triflate and tributyltin fluoride

The aldol reaction of silyl enol ethers with aldehydes is one of the most useful methods for carbon–carbon bond formation [21]. The titanium tetrachloride promoted reaction reported from this laboratory is the first example successfully employed in the cross aldol reaction [15a] and, after that, several promoters containing trityl

Table 5

Reactions of α,β-unsaturated thioesters with silyl enol ethers



Entry	α,β-Unsaturated thioester	Silyl enol ether	Yield (%)	$(ul:lk)$ [a]
1	 1	 5	75	(87:13)
2	1	 6	78	(88:12)
3	1		84	(81:19)
4	1	 7	70	(94:6)
5	1	 8	81	
6		6	49	
7	 2	6	80	
8	2	7	48 [b]	
9	2	8	73	
10	 3	5	65	(85:15)
11	3	6	70	(84:16)
12	3	8	93	
13	 4	8	45 [b]	

[a] Determined by ^{13}C NMR and/or HPLC. [b] $SnCl_2$ was used instead of $Sn(OTf)_2$.

salts described in Section 1 have been developed. Recently, due to the added importance of asymmetric synthesis, some efforts have been made on the asymmetric version of this reaction by employing the combination of either chiral silyl enol ethers (ketene silyl acetals) and achiral aldehydes or achiral silyl enol ethers (ketene silyl acetals) and chiral aldehydes [22], however, asymmetric aldol reaction of achiral silyl enol ethers with achiral aldehydes by the use of a chiral promoter has never been developed to a practical level [23]. Recently we have found that the highly enantioselective aldol reaction of silyl enol ethers of thioesters with aldehydes is performed by the use of a new chiral promoter, a combination of chiral diamine coordinated tin(II) triflate and tributyltin fluoride.

As shown in Sections 1 and 2, we have found that new catalyst systems, such as ${}^{3}HCl/SnCl_2$ and $SbCl_5/Sn(OTf)_2$, are effective for carbon–carbon bond forming reactions between carbonyl compounds and silyl nucleophiles. These catalysts are characterized as active cationic species, which are generated by the combination of a neutral molecule and a tin(II) compound or a Lewis acid. In the course of our investigations based on this concept, we have investigated the suitable combination of these compounds in order to develop a new chiral system.

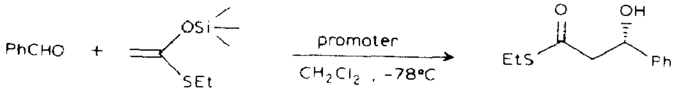
As one of chiral Lewis acids, we chose chiral diamine coordinated tin(II) triflate, successfully employed in the asymmetric allylation of aldehydes [24] and the catalytic asymmetric Michael reaction [25]. When silyl enol ether of *S*-ethyl ethanethiolate was treated with benzaldehyde in the presence of stoichiometric amounts of tin(II) triflate, (*S*)-1-methyl-2-[(piperidin-1-yl)methyl]pyrrolidine and tributyltin fluoride, the aldol reaction proceeded at −78 °C to afford the corresponding adduct in 78% yield with 82% ee. The importance of the combination of chiral diamine coordinated tin(II) triflate and tributyltin fluoride is obvious from the result that no enantiomeric selection was observed by just using chiral diamine coordinated tin(II) triflate or the combination of other metal salts, which similarly promotes the same reaction (Table 6). The appropriate choice of chiral diamines improved the optical yields (Table 7).

Several examples of this asymmetric aldol reaction are demonstrated in Table 8. In every case, aldols are obtained in high yields with high enantioselectivities.

We assume **9** to be the active species in this reaction, the formation of which is suggested by the observation that the mixture of tin(II) triflate, chiral diamine, and

Table 6

Reaction of silyl enol ether of *S*-ethyl ethanethiolate with benzaldehyde



Promoter [a]	Yield (%)	ee (%)
$Sn(OTf)_2$ + chiral diamine **A**	74	~ 0
$Sn(OTf)_2$ + chiral diamine **A** + AlF_3	76	~ 0
$Sn(OTf)_2$ + chiral diamine **A** + MgF_2	72	~ 0
$Sn(OTf)_2$ + chiral diamine **A** + ${}^{n}Bu_3SnF$	78	82

[a] Chiral diamine **A**

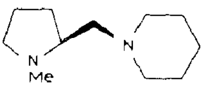
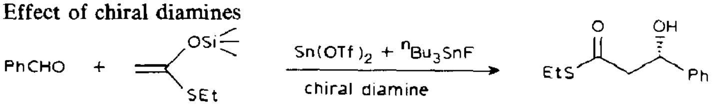


Table 7

Effect of chiral diamines



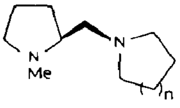
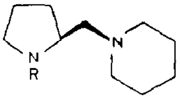
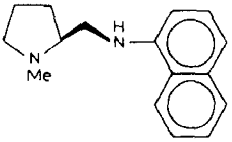
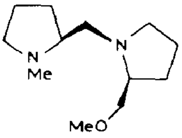
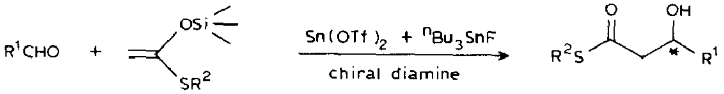
Chiral diamine		Yield (%)	ee (%)
	$n = 1$	58	62
	$n = 2$	78	82
	$n = 3$	65	69
	R = Me	78	82
	R = Et	67	83
	R = n-Pr	58	83
	R = n-Bu	61	81
	R = n-Pent	75	88
	R = n-Hex	68	78
		52	92
		74	78

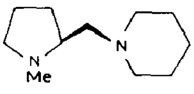
Table 8

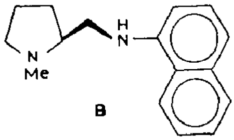
Asymmetric aldol reaction of silyl enol ethers with aldehydes

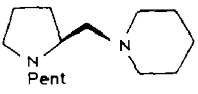


Entry	R^1	R^2	Chiral diamine [a]	Yield (%)	ee (%) (config.)
1	Ph	Et	A	78	82 (*S*)
2	Ph	Et	B	52	92 (*S*)
3	Ph	Et	C	75	88 (*S*)
4	Ph	^{t}Bu	A	73	86 (*S*)
5	$Ph(CH_2)_2$	Et	A	70	78
6	$Ph(CH_2)_2$	Et	B	50	81
7	$Ph(CH_2)_2$	^{t}Bu	A	71	85
8	^{i}Pr	Et	A	77	95
9	^{t}Bu	Et	A	90	> 95

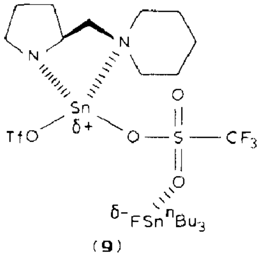
[a] Chiral diamine


A


B


C

tributyltin fluoride is completely soluble in dichloromethane, while either tin(II) triflate or tributyltin fluoride is sparingly soluble under the conditions.



(9)

The reaction would be promoted by double activations; namely, the cationic center of tin(II) triflate activates an aldehyde and, at the same time, a fluorine atom of tributyltin fluoride is able to interact with a silicon atom of a silyl enol ether to make the enol ether more reactive along with the formation of the entropically advantageous intermediate.

Thus, combined use of chiral diamine coordinated tin(II) triflate and tributyltin fluoride realizes the highly enantioselective aldol reaction from both achiral silyl enol ethers of thioesters and aldehydes. The product of the present reaction, optically active β-hydroxy ester derivatives are the important chiral building blocks, thus this reaction could provide an alternative method for the preparation of these useful chiral synthetic intermediates [26].

Experimental

IR spectra were recorded on a Hitachi 260-30 or JASCO IRA-2 infrared spectrophotometer. ^{1}H NMR spectra were recorded on a Hitachi R-24B, R-1100, or Bruker AM250 spectrometer, and ^{13}C NMR spectra on a JEOL FX-90Q FT or Bruker AM250 spectrometer. Optical rotations were measured with a JASCO DIP-360 digital polarimeter. Column chromatography was performed on Silica gel 60 (Merck) or Wakogel C-200 and preparative thin layer chromatography on Wakogel B5F. All reactions were carried out under argon in dried glassware.

Tin(II) chloride and tributyltin fluoride [27*] were dried in vacuo at 100 °C for 2 and 6 h, respectively. Tin(II) triflate and chiral diamines were prepared by a literature method [7b]. α,β-Unsaturated thioesters were prepared according to a known method [28].

The reaction of silyl enol ethers with aldehydes, acetals, or α,β-unsaturated ketones in the presence of catalytic amounts of trityl chloride and tin(II) chloride.

A typical procedure is described for the reaction of t-butyldimethylsilyl enol ether of 3-pentanone with benzaldehyde. Trityl chloride (0.05 mmol) and tin(II) chloride (0.05 mmol) were stirred in dichloromethane (1 ml) at room temperature for 30 min, then the mixture was cooled to -78 °C. t-Butyldimethylsilyl enol ether of 3-pentanone (1.1 mmol, E/Z 76/24) and benzaldehyde (1 mmol) in dichloromethane (4 ml) were added and the mixture was stirred for 100 min. Then the aqueous sodium hydrogen carbonate was added and the aqueous layer was extracted with dichloromethane. The organic layer was dried and the solvent removed under reduced pressure. The residue was chromatographed on Silica gel to yield 1-tbutyldimethylsiloxy-1-phenyl-2-methyl-3-pentanone (95%, *syn(erythro)/anti(threo)* 18/82, Table 1, entry 2). IR(neat) 1720, 1255, 1070 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ −0.3 (*anti*, s, 3H), −0.2(s, 3H, *syn*), −0.1(s, 3H, *anti*), 0(s, 3H, *syn*), 0.5–1.3(m, 6H), 0.7(s, 9H), 2.5(q, 2H, *J* 7 Hz), 2.8 (m, 1H), 4.5(d, 1H, *J* 10 Hz, *anti*), 4.6(d, 1H, *J* 7 Hz, *syn*), 7.1(m, 5H); ^{13}C NMR(CDCl$_3$) δ −4.7, 7.1(*syn*), 7.3(*anti*), 13.8(*anti*), 17.9, 18.1(*syn*), 25.7, 25.8, 36.5(*syn*), 37.9(*anti*), 54.0, 78.0, 142.9(*anti*), 143.5(*anti*), 214.5.

All other aldol and Michael adducts gave identical spectral data to those reported in the literature.

The reaction of silyl enol ethers with α,β-unsaturated thioesters in the presence of catalytic amounts of antimony(V) chloride and tin(II) triflate.

A typical procedure is described for the reaction of *S*-ethyl 2-butenethioate with silyl enol ether of propiophenone. Antimony(V) chloride (0.025 mmol) and tin(II) triflate (0.025 mmol) was stirred in dichloromethane (1 ml) at room temperature for 30 min, and the mixture was cooled to −78 ° C. *S*-Ethyl 2-butenethioate (0.4 mmol) and silyl enol ether of propiophenone (0.44 mmol) in dichloromethane (2 ml) was added and the mixture was allowed to stand for 4 h, then pH 7 phosphate buffer was added. After separation of the organic layer, the aqueous layer was extracted with dichloromethane. The organic layer was dried and the solvent was removed under reduced pressure. The residue was chromatographed on silica gel to yield *S*-ethyl 3,4-dimethyl-5-oxo-5-phenyl-pentanethioate (70%, *ul(anti)/lk(syn)* 94/6, Table 5, entry 4). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.02(d, 3H, *J* 6.51 Hz), 1.16(d, 3H, *J* 6.93 Hz), 1.22(t, 3H, *J* 7.31 Hz), 2.42(dd, 1H, *J* 14.1, 9.03 Hz), 2.46–2.66(m, 14H), 2.69(dd, 1H, *J* 14.1, 3.4 Hz), 2.84(q, 2H, *J* 7.3 Hz), 3.50(dq, 1H, *J* 6.5 Hz), 7.43–7.55(m, 3H), 7.92–7.97(m, 2H); ^{13}C NMR (CDCl$_3$) δ 13.6, 14.5, 18.0, 23.1, 24.1(*lk*), 32.5(*lk*), 33.1, 44.6, 46.9, 48.6(*lk*), 198.4, 203.3.

Other spectral data:

S-Ethyl 3,4-dimethyl-5-ethylthio-5-oxo-pentanethioate (Table 5, entry 1). IR (neat) 1730 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 0.946 (d, 1H, *J* 6.43 Hz, *lk*), 0.991(d, 1H, *J* 6.30 Hz, *ul*), 1.138(d, 1H, *J* 6.95 Hz, *lk*), 1.249(t, 3H, *J* 7.44 Hz), 2.30–2.45(m, 2H), 2.55–2.75(m, 2H), 2.871(q, 2H, 7.44 Hz), 2.881(q, 2H, *J* 7.44 Hz); ^{13}C NMR (CDCl$_3$) δ 13.5(*lk*), 14.5, 14.8, 16.1(*lk*), 17.4, 23.3, 29.8, 34.0(*lk*), 34.2, 47.8, 48.5(*lk*), 52.7(*lk*), 53.1, 198.2, 203.1.

S-Ethyl 3,4,4-trimethyl-5-methoxy-5-oxo-pentanethioate (Table 5, entry 5). IR (neat) 1720, 1680 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 0.80–1.00(m, 3H), 1.20(s, 6H), 1.30(t, 3H, *J* 7.0 Hz), 2.10–2.60(m, 3H), 2.70–3.10(q, 2H, *J* 7.0 Hz), 3.70(s, 3H).

S-Ethyl 4-methyl-5-ethylthio-5-oxo-pentanethioate (Table 5, entry 6). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.15 (d, 2H, *J* 7.0 Hz), 1.20(t, 3H, *J* 7.0 Hz), 1.70–2.05(m, 2H), 2.35–2.70(m, 3H), 2.65–3.05(q, 4H, *J* 7.0 Hz).

S-t-Butyl 4-methyl-5-ethylthio-5-oxo-pentanethioate (Table 5, entry 7). IR (neat) 1685 cm^{-1}; ^{1}H NMR(CDCl$_3$) δ 1.05–1.40(m, 6H), 1.40(s, 9H), 1.60–2.00(m, 2H), 2.20–2.65(m, 3H), 2.80(q, 2H, *J* 7.0 Hz).

S-t-Butyl 4-methyl-5-oxo-5-phenyl-pentanethioate (Table 5, entry 8). IR (neat) 1685 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 1.15(d, 2H, *J* 7.0 Hz), 1.40(s, 3H), 1.55–2.25(m, 1H), 2.25–2.55(m, 1H), 3.50(q, 1H, *J* 7.0 Hz), 7.30–7.50(m, 3H), 7.75–8.00(m, 2H).

S-t-Butyl 4,4-dimethyl-5-methoxy-5-oxo-pentanethioate (Table 5, entry 9). IR (neat) 1730, 1690 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.15(s, 6H), 1.40(s, 9H), 1.65–2.00(m, 2H), 2.15–2.50(m, 2H), 3.60(s, 3H).

S-Ethyl 3-phenyl-4-methyl-5-ethylthio-5-oxo-pentanethioate (Table 5, entry 10). IR (neat) 1690 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.85–1.40(m, 9H), 2.40–3.05(m, 7H), 3.10–3.75(m, 1H), 7.05–7.15(m, 5H); ^{13}C NMR ($CDCl_3$) δ 14.5, 14.6(*lk*), 14.9, 16.6(*lk*), 23.0, 23.2, 45.0, 45.6(*lk*), 46.1, 48.1(*lk*), 53.4, 53.5, 197.4, 201.7.

S-Ethyl 3-phenyl-4,4-dimethyl-5-methoxy-5-oxo-pentanethioate (Table 5, entry 12). IR (neat) 1725, 1695 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.05(t, 3H, *J* 7.0 Hz), 1.10(s, 3H), 1.15(s, 3H), 2.70(q, 2H, *J* 7.0 Hz), 2.75–3.10(m, 2H), 3.25–3.80(m, 1H), 3.70(s, 3H), 7.15(m, 5H).

S-Ethyl 3,3-dimethyl-4,4-dimethyl-5-methoxy-5-oxo-pentanethioate (Table 5, entry 13). IR (neat) 1725, 1690 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.10(s, 6H), 1.15(s, 6H), 1.20(t, 3H, *J* 7.0 Hz), 2.60(s, 2H), 2.85(q, 2H, *J* 7.0 Hz), 3.70(s, 3H).

The reaction of silyl enol ethers of thioesters with aldehydes in the presence of tin(II) triflate, chiral diamine and tributyltin fluoride

A typical procedure is described for the reaction of silyl enol ether of *S*-ethyl ethanethioate with benzaldehyde; to a solution of tin(II) triflate (0.4 mmol) and (*S*)-1-pentyl-2-[(piperidin-1-yl)methyl]-pyrrolidine (0.48 mmol) in dichloromethane (1 ml) was added tributyltin fluoride (0.44 mmol) at room temperature. The mixture was stirred for 30 min and then cooled to −78°C. After silyl enol ether of *S*-ethyl ethanethioate (0.4 mmol) in dichloromethane (0.5 ml) was added, the mixture was further stirred for 30 min. Then, benzaldehyde (0.36 mmol) in dichloromethane (1 ml) was added, and the reaction mixture was stirred for 12 h, then quenched with aqueous sodium hydrogen carbonate. After the aqueous layer was extracted with dichloromethane, the organic layer was dried, and the solvent was removed under reduced pressure. The crude product was purified by thin layer chromatography (silica gel) to yield *S*-ethyl 3-hydroxy-3-phenyl-propanethioate (75%, Table 9, entry 3). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.15(t, 3H, *J* 7.0 Hz), 2.70 (q, 2H, *J* 7.0 Hz), 2.70(d, 2H, *J* 6.0 Hz), 3.10(brs, 1H), 4.85(t, 1H, *J* 6.0 Hz), 7.00(m, 5H).

Other spectral data:

S-t-Butyl 3-hydroxy-3-phenyl-propanethioate (Table 8, entry 4). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.45(s, 9H), 2.65(d, 2H, *J* 6.0 Hz), 3.05(brs, 1H), 4.85(t, 1H, *J* 6.0 Hz), 7.00(m, 5H).

S-Ethyl 3-hydroxy-5-phenyl-pentanethioate (Table 8, entry 5). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.25(t, 3H, *J* 7.0 Hz), 1.50–1.90(m, 2H), 2.60–3.05(m, 7H), 3.75–4.10(m, 1H), 7.10(m, 5H).

S-t-Butyl 3-hydroxy-5-phenyl-pentanethioate (Table 8, entry 7). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 1.45(s, 9H), 1.55–1.95(m, 2H), 2.45–2.95(m, 7H), 3.95(m, 1H), 7.15(m, 5H).

S-Ethyl 3-hydroxy-4-methyl-pentanethioate (Table 8, entry 8). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.90(d, 6H, *J* 7.0 Hz), 1.25(t, 3H, *J* 7.0 Hz), 1.40–1.80(m, 1H), 2.50–2.75(m, 3H), 2.85(q, 2H, *J* 7.0 Hz), 3.70(m, 1H).

S-Ethyl 3-hydroxy-4,4-dimethyl-pentanethioate (Table 8, entry 10). IR (neat) 1680 cm^{-1}; ^{1}H NMR (CCl_4) δ 0.90(s, 3H), 1.25(t, 3H, *J* 7.0 Hz), 2.45–2.75(m, 3H), 2.85(q, 2H, *J* 7.0 Hz), 3.65(m, 1H).

Acknowledgement

We are grateful to Mr. Masanori Tamura and Mr. Yukihiro Sagawa for their contribution to some of this research. We also wish to express our thanks to Ms. Yuko Fujishita for her help in some of the experiments.

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