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# Indium-catalyzed coupling reaction between silyl enolates and alkyl chlorides or alkyl ethers

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ABSTRACT

The coupling reactions of alkyl chlorides with silyl enolates catalyzed by $InBr_3$, and the coupling reactions of alkyl ethers with silyl enolates catalyzed by the combined Lewis acid of $InBr_3/Me_3SiBr$ are described. In both reaction systems, various types of silyl enolates were used to give corresponding α-alkylated esters, ketones, carboxylic acids, amides, thioesters, and aldehydes.



## 1. Introduction

Much effort has been spent on the development of methods for α-alkylation of carbonyl compounds, because various fine chemicals, pharmaceuticals, and agrochemicals contain carbonyl groups.[1] Many chemists have studied the coupling reactions between metal enolates and alkyl electrophiles like iodides and bromides, and have often afforded satisfactory results. In contrast, less-reactive alkyl chlorides have generally given poor results. Alkyl ethers are rarely employed as electrophiles due to their low reactivity. However, if alkyl chlorides and alkyl ethers could be employed, they would have the advantages of low cost and convenient processes because they are inexpensive and readily available (Fig. 1). Although Reetz reported coupling reactions with alkyl chlorides catalyzed by $ZnBr_2$ or $ZnCl_2$, some substrates such as primary benzylic chlorides were not applied in this system.[2,3] With respect to alkyl ethers, information appears to be limited to coupling reactions using tertiary and secondary allylic methyl ethers catalyzed by $TrClO_4$.[4] Herein we report two types of coupling reactions with silyl enolates: (1) the $InBr_3$-catalyzed reactions using alkyl chlorides[5] and (2) $InBr_3/Me_3SiBr$ combined Lewis acid catalyzed reactions using alkyl ethers. This system has some advantages in that various alkyl chlorides and ethers are successful and that low reactive aldehyde-derived enolates can also be employed to afford the corresponding α-alkylated aldehydes.

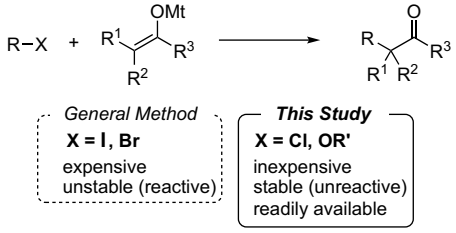


**Figure 1.** α-Alkylation of carbonyl compounds.

## 2. Coupling reaction of alkyl chlorides with silyl enolates

### 2.1. Results and discussion

Initially, the reaction of benzyl chloride **1a** with dimethylketene methyl trimethylsilyl acetal **2a** was investigated in the presence of various Lewis acid catalysts including indium compounds (Table 1). Indium catalysts like $InBr_3$ and $InI_3$ gave excellent results (entries 3 and 4), while $InF_3$, $InCl_3$, $In(OAc)_3$, $In(OH)_3$, and $In(OTf)_3$ were ineffective (entries 1, 2, and 5–7). $GaCl_3$ afforded the product **3aa** in a low yield (entry 8).[6] $ZnCl_2$ and $ZnBr_2$ had low catalytic ability as reported by Reetz (entries 9 and 10). Other group 13 Lewis acids such as $BF_3 \cdot OEt_2$, $B(C_6F_5)_3$,[7] and $AlCl_3$ yielded no product (entries 11–13). The acidity of these Lewis acids is enough to activate the alkyl chloride, but predominant interaction with enolates perhaps disturbs the desired coupling reaction due to their high oxophilicity. Other Lewis acids such as $BiBr_3$,[8] $FeBr_3$, $TiCl_4$, $Sc(OTf)_3$, or $Yb(OTf)_3$[9] gave no product as shown in entries 14–18. Consequently, the low oxophilicity and moderate Lewis acidity of $InBr_3$ and $InI_3$ are perhaps the reason why the coupling reaction with alkyl chlorides proceeded smoothly without deactivation by the oxygen atom of the ketene silyl acetal.[10]

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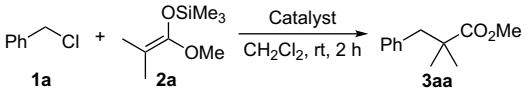
**Table 1**
Catalyst screening in the reaction of benzyl chloride **1a** with ketene silyl acetal **2a**[a]




**1a** **2a** **3aa**

| Entry | Catalyst | Yield[b] (%) |
|---|---|---|
| 1 | $InF_3$ | 0 |
| 2 | $InCl_3$ | 9 |
| 3 | $InBr_3$ | 99 |
| 4 | $InI_3$ | 99 |
| 5 | $In(OAc)_3$ | 0 |
| 6 | $In(OH)_3$ | 0 |
| 7 | $In(OTf)_3$ | 0 |
| 8 | $ZnCl_2$ | 6 |
| 9 | $ZnBr_2$ | 39 |
| 10 | $BF_3{\cdot}OEt_2$ | 0 |
| 11 | $B(C_6F_5)_3$ | 0 |
| 12 | $AlCl_3$ | 0 |
| 13 | $GaCl_3$ | 21 |
| 14 | $BiBr_3$ | 0 |
| 15 | $FeBr_3$ | 0 |
| 16 | $TiCl_4$ | 0 |
| 17 | $Sc(OTf)_3$ | 0 |
| 18 | $Yb(OTf)_3$ | 0 |

[a] Compound **1a** (1 mmol), **2a** (1.5 mmol), catalyst (5 mol %), and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.

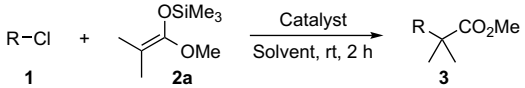
The correct choice of solvent is essential for this coupling (Table 2). The $InBr_3$-catalyzed reaction of benzyl chloride **1a** with ketene silyl acetal **2a** gave excellent results only in $CH_2Cl_2$ (entry 1). All aprotic and protic polar solvents having coordination ability completely disturbed the coupling reaction. A non-polar hydrocarbon solvent like hexane, however, produced the adduct **3aa** in moderate yields (entries 8–10). The achievement of the reaction under non-halogenated conditions is valuable from the point of view of green chemistry.[11] This coupling in hexane is characteristic for the indium catalyst to furnish the adduct **3ba** from secondary benzylic chloride **1b**, because no reaction took place in the case of $ZnBr_2$ catalyst (entries 12 and 13). These results strongly indicate that coordination by solvents readily disturbs the interaction between indium catalysts and substrates.

Considering these results noted in Tables 1 and 2, $InBr_3$ was chosen as a catalyst and $CH_2Cl_2$ as a solvent.

The reactivity of alkyl chlorides was examined using the coupling with ketene silyl acetal **2a** under optimized conditions (Table 3). Both benzylic chlorides **1c** and **1d** bearing electron-withdrawing and -donating groups gave satisfactory yields (entries 1 and 2). The coupling with cyclohexenyl chloride (**1e**) produced the corresponding ester **3ea** in 91% yield (entry 3). Inactivated tertiary alkyl chlorides **1f** and **1g** effectively gave the coupling products **3fa** and **3ga**, respectively, in high yields (entries 4 and 5). However, the couplings with inactivated primary or secondary alkyl chlorides were not successful (entries 6 and 7). When alkyl chlorides bearing ester or ether moieties **1j**–**1l** were used, the coupling reactions predominantly proceeded at the chloride moiety (entries 8–10). These higher yields of tertiary alkyl and benzylic chlorides than that of primary and secondary alkyl chlorides strongly indicate the involvement of a cationic intermediate.

The scope and limitations of ketene silyl acetals **2** were investigated (Table 4). In the case of dialkylketene silyl acetals **2b** and

**Table 2**
Effect of solvents on the reaction of alkyl chloride **1** with ketene silyl acetal **2a**[a]

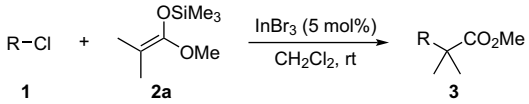



**1** **2a** **3**

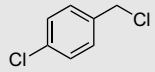
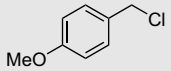
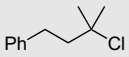
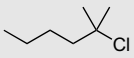
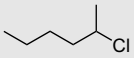
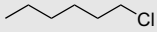
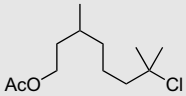
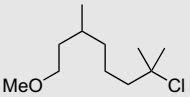
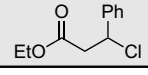
| Entry | R–Cl | Solvent | Catalyst | Yield[b] (%) |
|---|---|---|---|---|
| 1 | | $CH_2Cl_2$ | $InBr_3$ | **3aa** (99) |
| 2 | | $Et_2O$ | $InBr_3$ | **3aa** (0) |
| 3 | | THF | $InBr_3$ | **3aa** (0) |
| 4 | | $CH_3CN$ | $InBr_3$ | **3aa** (0) |
| 5 | Ph Cl **1a** | DMF | $InBr_3$ | **3aa** (0) |
| 6 | | MeOH | $InBr_3$ | **3aa** (0) |
| 7 | | $H_2O$ | $InBr_3$ | **3aa** (0) |
| 8 | | Hexane | $InBr_3$ | **3aa** (51) |
| 9 | | Benzene | $InBr_3$ | **3aa** (53) |
| 10 | | Toluene | $InBr_3$ | **3aa** (53) |
| 11 | Ph Cl **1b** | Hexane | $InBr_3$ | **3ba** (99) |
| 12 | Ph Cl **1a** | Hexane | $ZnBr_2$ | **3aa** (0) |
| 13 | Ph Cl **1b** | Hexane | $ZnBr_2$ | **3ba** (0) |

[a] Compound **1** (1 mmol), **2a** (1.5 mmol), catalyst (5 mol %), and solvent (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.

**Table 3**
Coupling reactions of various alkyl chlorides **1** with ketene silyl acetal **2a**[a]

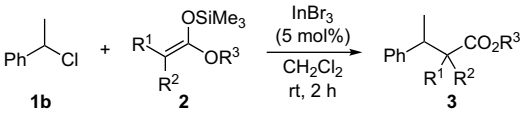


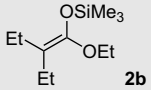
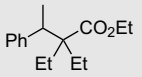
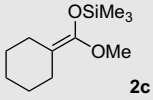
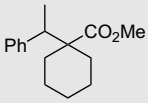
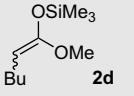
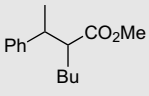
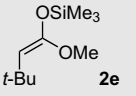
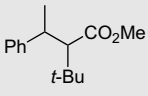
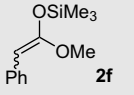
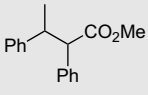
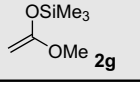
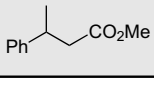

**1** **2a** **3**

| Entry | R–Cl | | Time (h) | Yield[b] (%) |
|---|---|---|---|---|
| 1 |  | **1c** | 12 | **3ca** (99) |
| 2 |  | **1d** | 2 | **3da** (86) |
| 3 |  | **1e** | 1 | **3ea** (91) |
| 4 |  | **1f** | 2 | **3fa** (83) |
| 5 |  | **1g** | 2 | **3ga** (82) |
| 6 |  | **1h** | 2 | **3ha** (0) |
| 7 |  | **1i** | 2 | **3ia** (0) |
| 8[c] |  | **1j** | 2 | **3ja** (53) |
| 9[c] |  | **1k** | 6 | **3ka** (75) |
| 10 |  | **1l** | 3 | **3la** (82) |

[a] Compound **1** (1 mmol), **2a** (1.5 mmol), $InBr_3$ (5 mol %), and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.
[c] Compound **2a** (3 mmol).

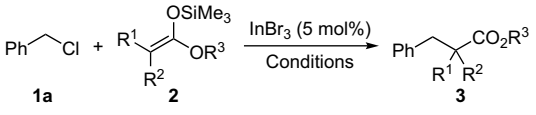
**Table 4**
Scope and limitation of ketene silyl acetals **2**[a]

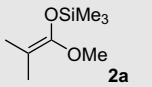
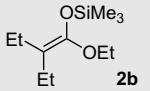
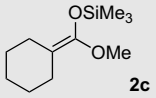
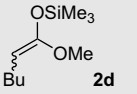
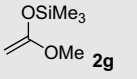



| Entry | Silyl enolate | Product | Yield[d] (%) |
|---|---|---|---|
| 1 |  **2b** |  | **3bb** (99) |
| 2 |  **2c** |  | **3bc** (99) |
| 3[b] |  **2d** |  | **3bd** (99) [52:48] |
| 4 |  **2e** |  | **3be** (99) [50:50] |
| 5[c] |  **2f** |  | **3bf** (62) [54:46] |
| 6 |  **2g** |  | **3bg** (46) |

[a] Compound **1b** (1 mmol), **2** (1.5 mmol), $InBr_3$ (5 mol %), and $CH_2Cl_2$ (1 mL).
[b] Compound **2d** (*E*/*Z*=89:11).
[c] Compound **2f** (*E*/*Z*=70:30).
[d] Yields were determined by $^1H$ NMR analysis. Diastereomeric ratio is shown in square brackets.

**Table 5**
Effect of the alkyl group at the reacting site in the ketene silyl acetal[a]




| Entry | Silyl enolate | Conditions | Yield[b] (%) |
|---|---|---|---|
| 1 |  **2a** | rt, 2 h | **3aa** (99) |
| 2 |  **2b** | rt, 2 h | **3ab** (83) |
| 3 |  **2c** | rt, 2 h | **3ac** (91) |
| 4[c] |  **2d** | rt, 2 h | **3ad** (0) |
| 5[c] | | 83 °C, 2 h | **3ad** (75) |
| 6 |  **2g** | rt, 2 h | **3ag** (0) |
| 7 | | 83 °C, 2 h | **3ag** (0) |

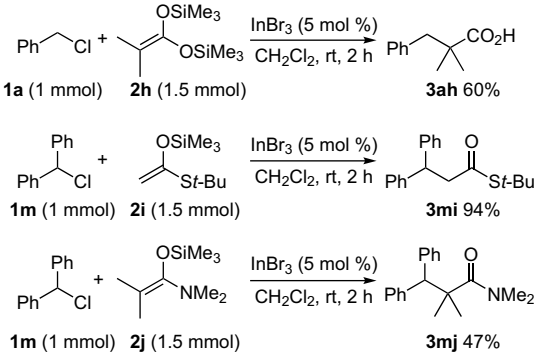
[a] Compound **1a** (1 mmol), **2** (1.5 mmol) $InBr_3$ (5 mol %), and $CH_2Cl_2$ (1 mL) or $ClCH_2CH_2Cl$ (2 mL).
[b] Yields were determined by $^1H$ NMR analysis.
[c] Compound **2d** (*E*/*Z*=89:11).

**2c**, coupling reactions smoothly proceeded to afford the desired esters **3bb** and **3bc**, respectively, in quantitative yields (entries 1 and 2). Monosubstituted ketene silyl acetal **2d** quantitatively gave the corresponding coupling product **3bd**, although diastereoselectivity was poor (entry 3). Other monosubstituted ketene silyl acetal bearing *tert*-butyl group **2e** and phenyl group **2f** afforded desired products in 99% and 62% yields, respectively (entries 4 and 5). Unfortunately, the use of unsubstituted ketene silyl acetal **2g** resulted in a moderate yield (entry 6).

In order to investigate more clearly the effect of alkyl groups ($R^1$ and $R^2$) at the reacting site of enolates, we examined reactions using benzyl chloride **1a**, which have lower reactivity than secondary benzylic chloride **1b** because a primary benzyl cation is less stable than a secondary one. The results are listed in Table 5. As expected, the reaction using dialkylketene silyl acetals **2a**–**2c** smoothly proceeded at room temperature (entries 1–3). In contrast, monosubstituted ketene silyl acetal **2d** gave no product under the same conditions (entry 4). In this case, the yield was improved up to 75% under heat conditions (entry 5). No coupling reaction of unsubstituted ketene silyl acetal **2g**, however, took place even under heat conditions (entries 6 and 7). Based on these results, electron-donation from alkyl groups is more important than the steric factor of the silyl ketene acetal.[12]

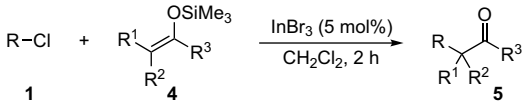
We examined to expand the scope of silyl enolates to other than ester-derived ones (Scheme 1). The α-alkylation of carboxylic acids, thioesters, and amides is also a promising protocol in organic chemistry. The silyl enolate **2h** derived from isopropionic acid gave the corresponding α-alkylated carboxylic acid **3ah** in 60% yield after conventional work-up. Reactions using thioester- and amide-derived enolates (**2i** and **2j**) proceeded smoothly without deactivation of $InBr_3$ by the coordination of nitrogen and sulfur atoms, affording the corresponding products in 94% and 47% yields, respectively. These are believed to be the first examples of the coupling of alkyl chlorides with silyl enolates derived from thioesters and amides.[13]

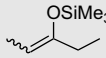
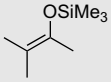
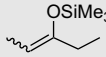
Ketone- and aldehyde-derived enolates were the next focus. Although a ketone-derived enolate generally has lower nucleophilicity than an ester-derived one,[12] our system exceeded expectations in allowing smooth coupling reactions with various enolates. Table 6 shows the results of the coupling reaction of 1-phenylethyl chloride **1b** or benzyl chloride **1a** with various ketone-derived enolates in the presence of 5 mol % of indium




**Scheme 1.** α-Alkylation of carboxylic acids and its derivatives.

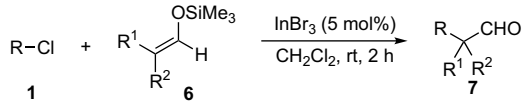
**Table 6**
Coupling reactions of alkyl chloride **1** with various ketone enolates **4**[a]

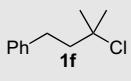
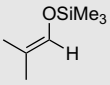



| Entry | R–Cl | Silyl enolate | | Yield[b] (%) |
|---|---|---|---|---|
| 1 |  **1b** |  | **4a** | **5ba** (99) |
| 2[c] | **1b** |  | **4b** | **5bb** (99) [50:50] |
| 3 | **1b** |  | **4c** | **5bc** (99) |
| 4 | **1b** |  | **4d** | **5bd** (83) [52:48] |
| 5 | **1b** |  | **4e** | **5be** (99) |
| 6 |  **1a** |  | **4a** | **5aa** (31) |
| 7[c] | **1a** |  | **4b** | **5ab** (58) |

[a] Compound **1** (1 mmol), **4** (1.5 mmol), $InBr_3$ (5 mol %), and $CH_2Cl_2$ (1 mL) or $ClCH_2CH_2Cl$ (2 mL).
[b] Yields were determined by $^1H$ NMR analysis.
[c] *E*/*Z*=18:82.

**Table 7**
Coupling reactions of alkyl chlorides **1** with aldehyde enolates **6**[a]



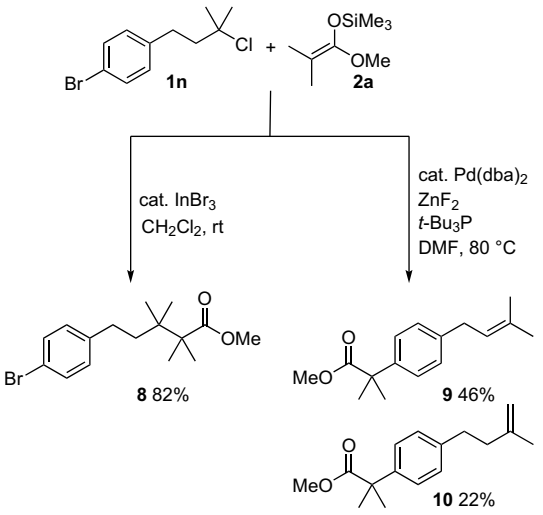

| Entry | R-Cl | Silyl enolate | | Yield[b] (%) |
|---|---|---|---|---|
| 1 |  **1f** |  | **6a** | **7fa** (54) |
| 2 | | | | **7fa** (72)[c] |
| 3 |  **1b** |  | **6a** | **7ba** (77) |
| 4[d] | **1b** |  | **6b** | **7bb** (83) [59:41] |
| 5[e] | **1b** |  | **6c** | **7bc** (83) [65:35] |
| 6 | **1b** |  | **6d** | **7bd** (0) |
| 7 |  **1a** |  | **6a** | **7aa** (68) |

[a] Compound **1** (1 mmol), **6** (2 mmol), $InBr_3$ (5 mol %) and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis. The diastereomeric ratio is shown in square brackets.
[c] Compound **6a** (3 mmol).
[d] **6b** (*E*/*Z*=44:56).
[e] **6c** (*E*/*Z*=64:36).

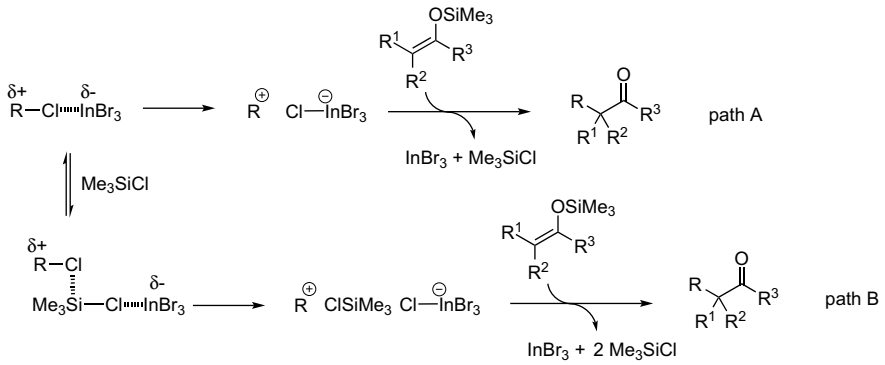
catalyst. In the case of 1-phenylethyl chloride **1b**, various ketone enolates **4a**–**4e** gave the corresponding products **5ba**–**5be** in good to quantitative yields (Table 6, entries 1–5). Even in the case of unsubstituted enolates **4a** and **4e** ($R^1$=$R^2$=H), quantitative yield was achieved. Moreover, the coupling between benzyl chloride **1a** and silyl enolates **4a** and **4b** at room temperature gave the corresponding ketones in 31% and 58% yields, respectively (entries 6 and 7), while the corresponding ester-derived enolates **2d** and **2g** gave no product under the same conditions (Table 5, entries 4 and 6).

Few examples using aldehyde-derived enolates have been reported due to lower nucleophilicity.[3,12,14] In addition, the expected aldehyde products could react with the starting enolates to give complicated mixtures. Gratifyingly, the reaction of silyl enolate **6a** (1.5 equiv) with inactivated tertiary alkyl chloride **1f** gave the corresponding aldehyde **7fa** in 54% yield (Table 7, entry 1). The yield was raised to 72% by increasing the amount of the silyl enolate (entry 2). Secondary benzylic chloride **1b** easily reacted with enolates **6a**, **6b**, and **6c** to produce the corresponding aldehydes **7ba**, **7bb**, and **7bc**, respectively, in high yields (entries 3–5). Unfortunately, silyl enolate **6d** derived from acetaldehyde was easily decomposed by $InBr_3$ to give a complicated mixture (entry 6). Primary benzylic chlorides **1a** also gave a satisfactory result (entry 7).

The fine control of chemoselectivity was demonstrated by changing the catalyst from $InBr_3$ into a Pd-system (Scheme 2). The alkyl chloride **1n**, bearing a bromide moiety selectively provided the chloro-coupling product **8** in 82% yield with $InBr_3$ catalyst. On the other hand, employment of Hiyama-coupling conditions promoted alternate coupling at the bromide moiety to furnish the dehydrochlorinated products **9** and **10**.[15] This result shows the complementary selectivity of the palladium- and indium-catalyzed reaction systems.




**Scheme 2.** Chemoselective reaction by the choice of catalyst.




**Scheme 3.** Plausible mechanism.

## 2.2. Mechanistic study

A plausible mechanism for the $InBr_3$-catalyzed coupling reaction of alkyl chlorides with silyl enolates is shown in Scheme 3. $InBr_3$ activates the alkyl chloride to produce a carbocation species. The resulting cation species then reacts with a silyl enolate to give the desired product and $Me_3SiCl$ along with the regeneration of $InBr_3$ (path A). The reaction may also be accelerated by the combination of $InBr_3$ and $Me_3SiCl$ generated in situ (path B), because the combination system showed strong Lewis acidity as already reported.[5] $InBr_3$ selectively activated an alkyl chloride irrespective of a silyl enolate because of its high halophilicity.[16] In contrast, high oxophilicity was the reason why the strong Lewis acids such as $AlCl_3$ and $BF_3{\cdot}OEt_2$ showed no activity.

Kinetic studies were performed in order to gain insights regarding the reaction mechanism (Fig. 2). The standard condition (◆) is the reaction of benzyl chloride **1a** (0.1 mmol, 0.18 M) with dimethylketene silyl acetal **2a** (0.2 mmol, 0.36 M) and $InBr_3$ (0.01 mmol, 0.018 M) in $CD_2Cl_2$. When the amount of either benzyl chloride **1a** (●) or $InBr_3$ (■) was doubled, the reaction rate increased. Thus, it is suggested that the rate-determining step may be the carbocation generation step by the interaction between **1a** and $InBr_3$. In contrast, an increase in the amount of the silyl enolate **2a** (▲) resulted in decreasing the reaction rate. This fact revealed that the coordination of the oxygen atom on the silyl enolate deactivates the catalytic activity of $InBr_3$.

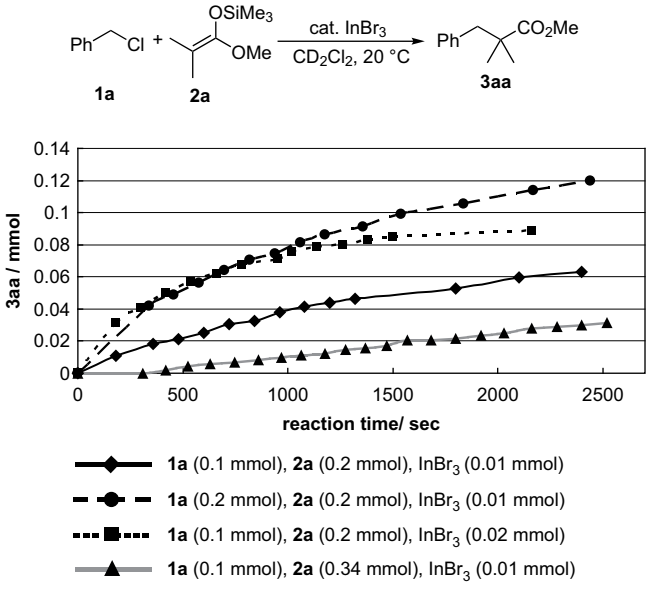



**Figure 2.** Effects of amounts of reactants and catalyst for the reaction rate.

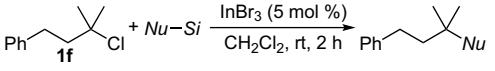
## 2.3. The coupling reaction of alkyl chloride with various silyl nucleophiles

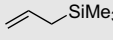
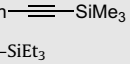
$InBr_3$ also accelerated the reaction of alkyl chlorides with silyl nucleophiles other than silyl enolates (Table 8). The reaction of tertiary alkyl chloride **1f** with allyltrimethylsilane **11** proceeded smoothly in the presence of 5 mol % $InBr_3$ to afford the desired product **12** in 91% yield.[17] The use of alkynylsilane **13** instead of the allylsilane gave a moderate yield.[18] Triethylsilane **15** was used as a reductant to afford the alkane **16** in 60% yield.

## 2.4. Three-component tandem reactions

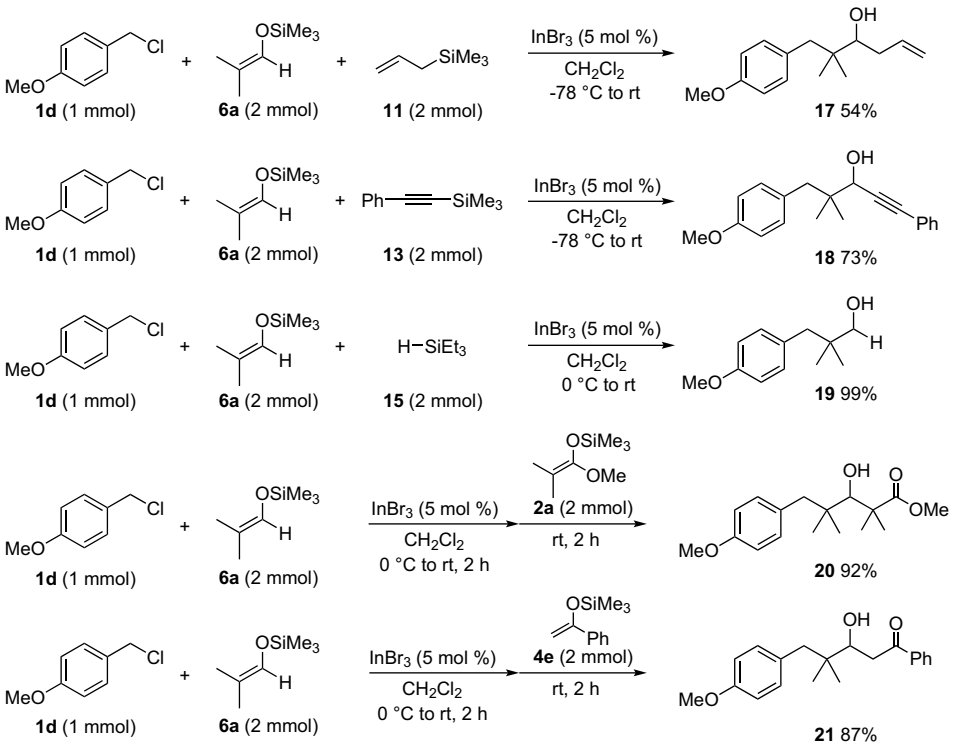
A three-component reaction was envisioned, in which the aldehyde generated from the reaction between aldehyde-derived enolate and alkyl chloride successively reacted with silyl nucleophiles (Scheme 4). If this addition to the generated aldehyde was also promoted by the $InBr_3$ catalyst, a convenient tandem reaction would be achieved without changing the catalyst and conditions. This idea was based on the previous report of a Hosomi–Sakurai reaction catalyzed by the combined Lewis acid of $InCl_3$ and $Me_3SiCl$.[19] In the present reaction system, the formation of In–Si combined Lewis acid was expected because $Me_3SiCl$ was generated as noted in Scheme 3. It was anticipated that this combined Lewis acid would accelerate the subsequent addition of the silyl nucleophile to the aldehyde. Initially, the three components, alkyl chloride **1d**, aldehyde enolate **6a**, and allylsilane **11** in the presence of 5 mol % of $InBr_3$ were mixed at one portion at −78 °C, and the resulting mixture was then warmed to room temperature. Gratifyingly, the desired tandem reaction selectively took place prior to the coupling of alkyl chloride and allylsilane, producing the adduct **17** in 54% yield. The addition of

**Table 8**
Coupling reactions of alkyl chloride **1f** with silyl nucleophiles[a]




| Entry | Nu–Si | | Yield[b] (%) |
|---|---|---|---|
| 1 |  | **11** | **12** (91) |
| 2 |  | **13** | **14** (25) |
| 3 | H–$SiEt_3$ | **15** | **16** (60) |

[a] Compound **1f** (1 mmol), Nu–Si (1.5 mmol), $InBr_3$ (5 mol %), and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.




**Scheme 4.** Three-component tandem reactions.

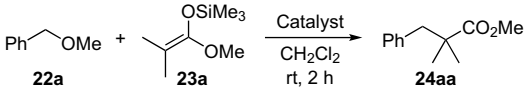
alkynylsilane **13**, instead of allylsilane, gave propargyl alcohol **18** in 73% yield. The sequential reduction of the generated aldehydes was also achieved by using triethylsilane **15** to afford the desired alcohol **19** in a quantitative yield. Unfortunately, when an ester-derived enolate was used as a subsequent nucleophile, the undesired coupling of this enolate with the alkyl chloride proceeded to give no desired product. This problem could be overcome by the addition of the ketene silyl acetal **2a** after completion of the coupling between alkyl chloride **1d** and aldehyde enolate **6a**. The sequential aldol reaction successfully proceeded to give the β-hydroxy ester **20** in 92% yield. In a similar manner, silyl enolate **4e** also gave the aldol product **21** in 87% yield. $InBr_3$ was found to be a good catalyst that promoted both coupling and successive addition reactions, and also controlled the reaction order.

## 3. The coupling reaction of alkyl ethers with silyl enolates

### 3.1. Results and discussion

There is no report regarding coupling reactions between silyl enolates and alkyl ethers, except reactions using tertiary or secondary allylic methyl ethers catalyzed by $TrClO_4$.[4] Initially, the reaction of benzyl methyl ether **22a** with ketene silyl acetal **23a** was attempted in the presence of 5 mol % $InBr_3$, but only 39% yield of adduct **24aa** was given (Table 9, entry 1). When the combination catalyst of $InBr_3$ and $Me_3SiBr$ was employed, the yield dramatically increased to 99% as noted in entry 2. The combination is essential for this reaction, because no reaction took place when only $Me_3SiBr$ was used (entry 3). Recently we have reported that a similar combination catalyst of indium trihalide and trimethylsilyl halide effectively activated such reactions as allylation of ketones or alcohols, and Friedel–Crafts reactions.[20]

**Table 9**
Effect of combined catalysts; $InBr_3/Me_3SiBr$[a]



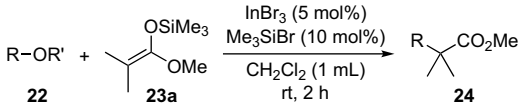

| Entry | Catalyst (mol %) | Yield[b] (%) |
|---|---|---|
| 1 | $InBr_3$ (5) | 39 |
| 2 | $InBr_3$ (5)+$Me_3SiBr$ (10) | 99 |
| 3 | $Me_3SiBr$ (10) | 0 |

[a] Compound **22a** (1 mmol), **23a** (1.5 mmol), $InBr_3$ (5 mol %), $Me_3SiBr$ (10 mol %), and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.

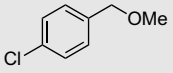
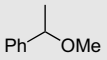
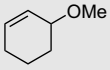
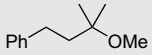
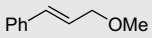
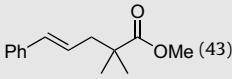
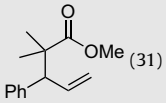
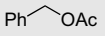
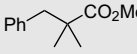
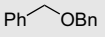
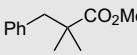
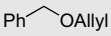
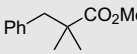
Reactions of various alkyl methyl ethers **22** with ketene silyl acetal **23a** in the presence of the combined catalyst are summarized in Table 10. Even the reaction using electron-deficient *p*-chlorobenzyl methyl ether **22b** proceeded quantitatively (entry 1). Predictably, secondary benzyl and allyl methyl ethers (**22c** and **22d**) gave excellent results (entries 2 and 3). The tertiary alkyl methyl ether **22e** afforded a lower yield than the corresponding chloride (entry 4). The reaction of primary allylic methyl ether **22f** also proceeded to give the mixture of isomers **25** and **26** in high yield (entry 5). This formation of the isomers suggests the incorporation of allylic cation species. Acetoxy **22g**[2,21,22] and benzyloxy **22h** groups were also smoothly substituted in high yields (entries 6 and 7). In the reaction using benzyl allyl ether **22i**, the allyloxy group was substituted prior to the benzyloxy group because of the higher stability of a benzylic cation compared with an allylic one (entry 8).

A series of silyl enolates were found to be applicable to this coupling reaction with ether **22c**, as shown in Table 11. Monoalkyl and monoarylketene silyl acetal (**23b** and **23c**) smoothly afforded the desired product in 92% and 58% yields, respectively. Methyl cyclohexylcarboxylate-derived enolate **23d** also furnished an excellent yield. Ketone- and aldehyde-derived enolates (**23e** and **23f**) also reacted with the methyl ether to give the desired ketone **24ce** and aldehyde **24cf**, respectively.

**Table 10**
Coupling reactions of various ethers **22** with silyl acetal **23a**[a]




22 23a 24

| Entry | R–OR′ | | Yield[b] (%) |
|---|---|---|---|
| 1 |  | **22b** | **24ba** (99) |
| 2 |  | **22c** | **24ca** (99) |
| 3 |  | **22d** | **24da** (91) |
| 4 |  | **22e** | **24ea** (28) |
| 5 |  | **22f** |  (43) **25** |
| | | |  (31) **26** |
| 6 |  | **22g** |  (62) **24aa** |
| 7 |  | **22h** |  (99) **24aa** |
| 8 |  | **22i** |  (89) **24aa** |

[a] Compound **22** (1 mmol), **23a** (1.5 mmol), $InBr_3$ (5 mol %), $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis.

### 3.2. Plausible mechanism

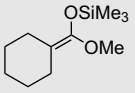
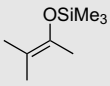
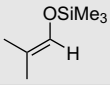
Scheme 5 shows a plausible mechanism. The combination of $InBr_3$ and $Me_3SiBr$ is essential, in which the coordination from the bromine atom on the silicon to $InBr_3$ increases the Lewis acidity of the silicon center. The combined catalyst effectively activates the ether due to the high oxophilicity of the silicone center, generating carbocation species. Perhaps this is the reason that the combination is required in the reaction of ether in contrast to that of alkyl chlorides. Indium has enough halophilicity to activate alkyl chloride by itself. The silyl enolate then attacks the carbocation to give the desired product and $Me_3SiOR'$ with a regeneration of $InBr_3$ and $Me_3SiBr$.

## 4. Conclusion

We have accomplished the coupling reactions of alkyl chlorides with silyl enolates catalyzed by $InBr_3$. This reaction system has a wide scope of alkyl chlorides and silyl enolates. Various types of silyl enolates such as ester, ketone, carboxylic acid, thioester, amide, and aldehyde enolates were successful. In particular, aldehyde enolates could be applied to a tandem reaction using the product aldehydes. $InBr_3$ succeeded in the three-component sequential carbon–carbon bond formations between alkyl chloride, aldehyde enolate, and other silyl nucleophiles. A coupling reaction of alkyl ether with silyl enolates was accomplished, catalyzed by the combined Lewis acid of $InBr_3$ and $Me_3SiBr$. Methyl, benzyl, and allyl ether were successfully applied to this reaction system, and various silyl enolates reacted with methyl ethers. The high halophilicity and low oxophilicity of indium catalysts play an important role in both reaction systems.

**Table 11**
Coupling reactions of ether **22c** with various silyl enolates[a]


22c 23 24

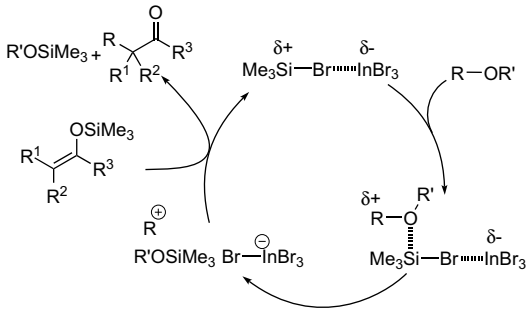
| Entry | Silyl enolate | | Yield[b] (%) |
|---|---|---|---|
| 1[c] |  | **23b** | **24cb** (92) [54:46] |
| 2[d] |  | **23c** | **24cc** (58) [50:50] |
| 3 |  | **23d** | **24cd** (96) |
| 4 |  | **23e** | **24ce** (93) |
| 5 |  | **23f** | **24cf** (88) |

[a] Compound **22c** (1 mmol), **23** (1.5 mmol), $InBr_3$ (5 mol %), $Me_3SiBr$ (10 mol %), and $CH_2Cl_2$ (1 mL).
[b] Yields were determined by $^1H$ NMR analysis. The diastereomeric ratio is shown in square brackets.
[c] *E*/*Z*=89:11.
[d] *E*/*Z*=70:30.

## 5. Experimental

### 5.1. General

New compounds were characterized by $^1H$, $^{13}C$, $^{13}C$ off-resonance techniques, $^1H$–$^1H$COSY, HMQC, HMBC, IR, MS, HRMS, and elemental analysis. $^1H$ (400 MHz) and $^{13}C$ NMR (100 MHz) spectra




**Scheme 5.** Plausible mechanism.

were obtained with TMS as internal standard. IR spectra were recorded as thin films or as solids in KBr pellets. Column chromatography was performed on silica gel (MERK C60 or Fuji Silysia FL100DX). Bulb-to-bulb distillation (Kugelrohr) was accomplished at the oven temperature and pressure indicated. Yields were determined by $^1$H NMR using internal standards.

### 5.2. Materials

Alkyl chlorides **1f**,[5] **1j**,[5] **1k**,[5] **1l**,[5] and **1n**[5] were synthesized by literature procedure. Silyl enolates **2b**,[23] **2c**,[24] **2d**,[25] **2e**,[26] **2f**,[24] **2g**,[27] **2h**,[28] **2i**,[5] **2j**,[5] **4a**,[29] **4b**,[30] **4c**,[31] **4d**,[5] **6b**,[5] and **6c**[5] were synthesized by literature procedure. Alkyl ether **22b**,[32] **22c**,[33] **22d**,[34] **22e**,[35] and **22f**[36] were synthesized by literature procedure. All other materials are commercially available.

### 5.3. Products

Products **3aa**–**3la**, **3mi**, **3mj**, **5bd**, **5be**, **7fa**, **7ba**, **7bb**, **7bc**, **7aa**, **7bd**, **8**, **9**, **10**, **17**, **18** were reported in Ref. 23. Products **3ad**,[37] **3ah**,[38] **5ba**,[39] **5ac**,[40] **5ab**,[41] **5aa**,[42] **12**,[43] **16**,[44] and **25**[45] were in an excellent agreement with the reported data. Compound **24aa** is the same product as **3aa**. Compound **24ba** is the same product as **3ca**. Compound **24ca** is the same product as **3ba**. Compound **24da** is the same product as **3ea**. Compound **24ea** is the same product as **3fa**. Compound **24cb** is the same product as **3bd**. Compound **24cc** is the same product as **3bf**. Compound **24cd** is the same product as **3bc**. Compound **24ce** is the same product as **5ac**. Compound **24cf** is the same product as **7ba**. The spectral data for the products **3ab**, **3ac**, **3bb**, **3bc**, **3bd**, **3be**, **3bf**, **5bb**, **5bc**, **14**, **19**, **20**, **21**, and **26** are shown below.

#### *5.3.1. Typical procedure of the coupling reaction of benzyl chloride **1a** with dimethylketene trimethylsilyl methyl acetal **2a** catalyzed by $InBr_3$*

To a solution of $InBr_3$ (0.05 mmol) and dimethylketene trimethylsilyl methyl acetal **2a** (1.5 mmol) in $CH_2Cl_2$ (1 mL) was added benzyl chloride **1a** (1 mmol), and the mixture was stirred for 2 h at room temperature. The resulting mixture was then poured into saturated $NaHCO_3$aq. The mixture was extracted with $Et_2O$ and the organic layer was dried over $MgSO_4$. The evaporation of the ether solution gave the crude product, which was analyzed by $^1$H NMR. The analytical data for this compound matched that previously reported (Ref. 5).

#### *5.3.2. Typical procedure of the coupling reaction of benzyl methyl ether **22a** with dimethylketene trimethylsilyl methyl acetal **23a** catalyzed by the combined Lewis acid of $InBr_3$ and $Me_3SiBr$*

To a solution of $InBr_3$ (0.05 mmol) and dimethylketene trimethylsilyl methyl acetal **23a** (1.5 mmol) in $CH_2Cl_2$ (1 mL) was added benzyl methyl ether **22a** (1 mmol). Then, to the mixture was added $Me_3SiBr$ and the mixture was stirred for 2 h at room temperature. The resulting mixture was then poured into saturated $NaHCO_3$aq. The mixture was extracted with $Et_2O$ and the organic layer was dried over $MgSO_4$. The evaporation of the ether solution gave the crude product, which was analyzed by $^1$H NMR. The analytical data for this compound matched that previously reported (Ref. 5).

#### *5.3.3. Ethyl 2,2-diethyl-3-phenylpropanoate **3ab***

According to the typical procedure, this compound was produced from $InBr_3$, **2b**, and **1a**. IR: (neat) 1728 (C=O) cm$^{-1}$; $^1$H NMR: (400 MHz, $CDCl_3$) 7.24 (t, *J*=7.2 Hz, 2H, *m*), 7.18 (t, *J*=7.2 Hz, 1H, *p*), 7.09 (d, *J*=7.2 Hz, 2H, *o*), 4.12 (q, *J*=7.2 Hz, 2H, $OCH_2CH_3$), 2.87 (s, 2H, 3-$H_2$), 1.62 (dq, *J*=15.2, 7.6 Hz, 2H, 2-($CH^AH^BCH_3$)$_2$), 1.52 (dq, *J*=15.2, 7.6 Hz, 2H, 2-($CH^AH^BCH_3$)$_2$), 1.23 (t, *J*=7.2 Hz, 3H, $OCH_2CH_3$), 0.88 (t, *J*=7.6 Hz, 6H, 2-($CH_2CH_3$)$_2$); $^{13}$C NMR: (100 MHz, $CDCl_3$) 176. 4 (s, C-1), 137.9 (s, *i*), 129.9 (d, *o*), 127.9 (d, *m*), 126.2 (d, *p*), 60.1 (t, $OCH_2CH_3$), 51.1 (s, C-2), 39.7 (t, C-3), 26.0 (t, 2-$CH_2CH_3$), 14.2 (q, $OCH_2CH_3$), 8.5 (q, 2-$CH_2CH_3$); MS: (EI, 70 eV) *m*/*z* 234 (M$^+$, 22), 164 (31), 160 (26), 115 (21), 91 ($PhCH_2$, 100); HRMS: (EI, 70 eV) calculated ($C_{15}H_{22}O_2$) 234.1620 (M$^+$), found: 234.1624. Analysis: $C_{15}H_{22}O_2$ (234.33) calcd: C, 76.88; H, 9.46. Found: C, 76.61; H, 9.19.

#### *5.3.4. Methyl 1-benzylcyclohexanecarboxylate **3ac***

According to the typical procedure, this compound was produced from $InBr_3$, **2c**, and **1a**. IR: (neat) 1728 (C=O) cm$^{-1}$; $^1$H NMR: (400 MHz, $CDCl_3$) 7.25 (t, *J*=6.8 Hz, 2H, *m*), 7.19 (t, *J*=6.8 Hz, 1H, *p*), 7.03 (d, *J*=6.8 Hz, 2H, *o*), 3.60 (s, 3H, OMe), 2.78 (s, 2H, 1-$CH_2$Ph), 2.13–2.00 (m, 2H), 1.68–1.50 (m, 3H), 1.36–1.09 (m, 5H); $^{13}$C NMR: (100 MHz, $CDCl_3$) 176.4 (s, *C*OOMe), 137.1 (s, *i*), 129.8 (d, *o*), 127.8 (d, *m*), 126.4 (d, *p*), 51.2 (q, OMe), 48.7 (s, C-1), 46.9 (t, 1-$CH_2$Ph), 34.0 (t, C-2), 25.7 (t, C-4), 23.3 (t, C-3); MS: (EI, 70 eV) *m*/*z* 232 (M$^+$, 15), 172 (25), 150 (33), 141 (22), 91 ($PhCH_2$, 100), 81 (59); HRMS: (EI, 70 eV) calculated ($C_{15}H_{20}O_2$) 232.1463 (M$^+$), found: 232.1466.

#### *5.3.5. Ethyl 2,2-diethyl-3-phenylbutanoate **3bb***

According to the typical procedure, this compound was produced from $InBr_3$, **2b**, and **1b**. Bp: 126 °C/0.2 mmHg. IR: (neat) 1720 (C=O) cm$^{-1}$; $^1$H NMR: (400 MHz, $CDCl_3$) 7.26–7.08 (m, 5H, Ar), 4.10 (dq, *J*=10.8, 7.2 Hz, 1H, $OCH^AHCH_3$), 4.02 (dq, *J*=10.8, 7.2 Hz, 1H, $OCH^BHCH_3$), 2.96 (q, *J*=7.4 Hz, 1H, 3-H), 1.88 (dq, *J*=14.8, 7.2 Hz, 1H, 2-($CH^AHMe$)$^A$), 1.69 (dq, *J*=14.8, 7.2 Hz, 1H, 2-($CH^BHMe$)$^A$), 1.59 (dq, *J*=15.2, 7.6 Hz, 1H, 2-($CH^AHMe$)$^B$), 1.43 (dq, *J*=15.2, 7.6 Hz, 1H, 2-($CH^BHMe$)$^B$), 1.34 (d, *J*=7.4 Hz, 3H, 4-$H_3$), 1.17 (t, *J*=7.2 Hz, 3H, $OCH_2CH_3$), 0.84 (t, *J*=7.2 Hz, 2-($CH_2CH_3$)$^A$), 0.84 (t, *J*=7.2 Hz, 2-($CH_2CH_3$)$^B$); $^{13}$C NMR: (100 MHz, $CDCl_3$) 175.7 (s, C-1), 143.5 (s, *i*), 128.7 (d), 127.6 (d), 126.3 (d, *p*), 59.8 (t, $OCH_2CH_3$), 52.9 (s, C-2), 44.5 (d, C-3), 24.5 (t, 2-$CH_2CH_3$), 24.1 (t, 2-$CH_2CH_3$), 16.5 (q, C-4), 14.0 (q, $OCH_2CH_3$), 8.7 (q, 2-$CH_2CH_3$), 8.5 (q, 2-$CH_2CH_3$); MS: (EI, 70 eV) *m*/*z* 248 (M$^+$, 0.45), 144 (M$^+$−$PhCHCH_3$, 32), 105 ($PhCHCH_3$, 100); HRMS: (EI, 70 eV) calculated ($C_{16}H_{24}O_2$) 248.1776 (M$^+$), found: 248.1796. Analysis: $C_{16}H_{24}O_2$ (248.36) calcd: C, 77.38; H, 9.74. Found: C, 77.45; H, 9.87.

#### *5.3.6. Methyl 1-(1-phenylethyl)cyclohexanecarboxylate **3bc***

According to the typical procedure, this compound was produced from $InBr_3$, **2c**, and 1-phenylethyl chloride **1b**. Bp: 124 °C/0.3 mmHg. IR: (neat) 1728 (C=O) cm$^{-1}$; $^1$H NMR: (400 MHz, $CDCl_3$) 7.25 (t, *J*=7.2 Hz, 2H, *m*), 7.19 (t, *J*=7.2 Hz, 1H, *p*), 7.09 (d, *J*=7.2 Hz, 2H, *o*), 3.60 (s, 3H, OMe), 2.88 (q, *J*=7.6 Hz, 1H, 1-$CH(CH_3)$Ph), 2.16–2.13 (m, 1H), 2.06–2.02 (m, 1H), 1.63–1.51 (m, 3H), 1.36–0.93 (m, 5H), 1.26 (d, *J*=7.6 Hz, 3H, 1-CH($CH_3$)Ph); $^{13}$C NMR: (100 MHz, $CDCl_3$) 176.1 (s, *C*OOMe), 142.6 (s, *i*), 128.9 (d, *o*), 127.5 (d, *m*), 126.4 (d, *p*), 51.6 (s, C-1), 51.1 (q, OMe), 48.3 (d, 1-$CH(CH_3)$Ph), 32.6 (t), 30.6 (t), 25.6 (t), 23.8 (t), 23.4 (t), 15.6 (q, 1-CH($CH_3$)Ph); MS: (EI, 70 eV) *m*/*z* 246 (M$^+$, 3), 142 (68), 105 ($C_6H_5CHCH_3$, 100); HRMS: (EI, 70 eV) calculated ($C_{16}H_{22}O_2$) 246.1620 (M$^+$), found: 246.1626. Analysis: $C_{16}H_{22}O_2$ (246.34) calcd: C, 78.01; H, 9.00. Found: C, 77.73; H, 8.96.

#### *5.3.7. Methyl 2-(1-phenylethyl)hexanoate **3bd** (diastereo mixture)*

According to the typical procedure, this compound was produced from $InBr_3$, **2d**, and 1-phenylethyl chloride **1b**. Bp: 165 °C/3 mmHg. IR: (neat) 1736 (C=O) cm$^{-1}$; $^1$H NMR: (400 MHz, $CDCl_3$) major isomer: 7.31–7.14 (m, 5H, Ar), 3.71 (s, 3H, OMe), 2.88 (dq, *J*=10.4, 7.2 Hz, 1H, 2-$CH(CH_3)$Ph), 2.57–2.50 (m, 1H, 2-H), 1.67–1.58 (m, 1H, 3-$H^A$), 1.49–1.06 (m, 5H, 4- and 5-$H_2$ and 3-$H^B$), 1.21 (d, *J*=7.2 Hz, 3H, 2-CH($CH_3$)Ph), 0.87 (t, *J*=6.8 Hz, 3H, 6-$H_3$); minor isomer: 7.31–7.14 (m, 5H, Ar), 3.38 (s, 3H, OMe), 2.96 (dq, *J*=9.2, 7.2 Hz, 1H, 2-$CH(CH_3)$Ph), 2.57–2.50 (m, 1H, 2-H), 1.67–1.58 (m, 1H, 3-$H^A$), 1.49–1.06 (m, 5H, 4- and 5-$H_2$ and 3-$H^B$), 1.28 (d, *J*=7.2 Hz, 3H, 2-CH($CH_3$)Ph), 0.76 (t, *J*=6.4 Hz, 3H, 6-$H_3$); $^{13}$C NMR: (100 MHz,

$CDCl_3$) 176.3 (s), 175.5 (s), 144.9 (s), 144.7 (s), 128.4 (d), 128.1 (d), 127.3 (d), 127.2 (d), 126.3 (d), 126.2 (d), 53.3 (d), 52.9 (d), 51.2 (q), 50.9 (q), 42.9 (d), 42.2 (d), 30.9 (t), 29.8 (t), 29.6 (t), 29.5 (t), 22.6 (t), 22.3 (t), 20.7 (q), 18.7 (q), 13.8 (q), 13.7 (q); MS: (EI, 70 eV) *m*/*z* major isomer: 234 ($M^+$, 3.6), 105 ($PhCHCH_3$, 100); minor isomer: 234 ($M^+$, 3.9), 105 ($PhCHCH_3$, 100); HRMS: (EI, 70 eV) major isomer: calculated ($C_{15}H_{22}O_2$) 234.1620, found: 234.1622; minor isomer: found: 234.1620.

### 5.3.8. Methyl 2-tert-butyl-3-phenylbutanoate **3be** (diastereo mixture)

According to the typical procedure, this compound was produced from $InBr_3$, **2e**, and 1-phenylethyl chloride **1b**. IR: (neat) 1736 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) major isomer 7.30–7.12 (m, 5H, Ar), 3.22 (s, 3H, OMe), 3.18–3.09 (m, 1H, 3-H), 2.51 (d, *J*=10.0 Hz, 1H, 2-H), 1.39 (d, *J*=7.2 Hz, 3H, 4-$H_3$), 1.10 (s, 9H, $CMe_3$); minor isomer 7.30–7.12 (m, 5H, Ar), 3.69 (s, 3H, OMe), 3.18–3.09 (m, 1H, 3-H), 2.61 (d, *J*=10.0 Hz, 1H, 2-H), 1.19 (d, *J*=7.2 Hz, 3H, 4-$H_3$), 0.79 (s, 9H, $CMe_3$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) major isomer 174.6 (s, C-1), 146.1 (s, *i*), 128.0 (d), 127.6 (d), 126.2 (d, *p*), 62.6 (d, C-2), 50.4 (q, OMe), 40.5 (d, C-3), 33.1 (s, *C*$Me_3$), 29.0 (q, C*Me*$_3$), 22.84 (q, C-4); minor isomer 175.3 (s, C-1), 146.6 (s, *i*), 128.4 (d), 127.5 (d), 126.2 (d, *p*), 61.7 (d, C-2), 50.8 (q, OMe), 39.3 (d, C-3), 33.5 (s, *C*$Me_3$), 28.6 (q, C*Me*$_3$), 22.76 (q, C-4); MS: (EI, 70 eV) *m*/*z* major isomer: 234 ($M^+$,1), 177 ($M^+-CMe_3$, 33), 105 ($PhCHCH_3$, 100); minor isomer: 234 ($M^+$,1), 177 ($M^+-CMe_3$, 26), 105 ($PhCHCH_3$, 100); HRMS: (EI, 70 eV) major isomer: calculated ($C_{15}H_{22}O_2$) 234.1620 ($M^+$), found: 234.1598; minor isomer: found: 234.1628.

### 5.3.9. Methyl 2,3-diphenylbutanoate **3bf** (diastereo mixture)

According to the typical procedure, this compound was produced from $InBr_3$, **2f**, and 1-phenylethyl chloride **1b**. IR: (neat) 1736 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.46–6.96 (m, 10H, Ar), 7.46–6.96 (m, 10H, Ar′), 3.73–3.68 (m, 1H, 2-H), 3.73–3.68 (m, 1H, 2′-H), 3.69 (s, 3H, OMe), 3.50–3.41 (m, 1H, 3-H), 3.50–3.41 (m, 1H, 3′-H), 3.35 (s, 3H, OMe), 1.39 (d, *J*=6.8 Hz, 3H, 4′-$H_3$), 1.02 (d, *J*=7.2 Hz, 3H, 4-$H_3$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 174.0 (s, C-1′), 173.4 (s, C-1), 144.8 (s, e), 143.5 (s, e′), 137.6 (s, a), 137.4 (s, a′), 128.6 (d), 128.5 (d), 128.4 (d), 128.3 (d), 128.1 (d), 128.0 (d), 127.5 (d), 127.3 (d), 126.9 (d), 126.5 (d), 126.1 (d), 59.4 (d, C-2), 59.1 (d, C-2′), 51.9 (q, OMe′), 51.6 (q, OMe), 43.8 (d, C-3′), 43.4 (d, C-3), 20.9 (d, C-4′), 19.9 (d, C-4); MS: (EI, 70 eV) *m*/*z* major 254 ($M^+$, 2), 150 (41), 105 ($C_6H_5CHCH_3$, 100); minor 254 ($M^+$, 2), 150 (41), 105 ($C_6H_5CHCH_3$, 100); HRMS: (EI, 70 eV) major calculated ($C_{17}H_{18}O_2$) 254.1307 ($M^+$), found: 254.1294; minor found: 254.1309. Analysis: $C_{17}H_{18}O_2$ (254.32) calcd: C, 80.28; H, 7.13. Found: C, 80.56; H, 7.13.

### 5.3.10. 4-Methyl-5-phenylhexan-3-one **5bb** (diastereo mixture)

According to the typical procedure, this compound was produced from $InBr_3$, **4b**, and 1-phenylethyl chloride **1b**. Bp: 150 °C/3 mmHg. IR: (neat) 1712 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) major isomer 7.32–7.11 (m, 5H, Ar), 2.93 (dq, *J*=10.4, 6.8 Hz, 1H, 5-H), 2.79–2.69 (m, 1H, 4-H), 2.58 (dq, *J*=17.6, 7.2 Hz, 1H, 2-$H^A$), 2.40 (dq, *J*=17.6, 7.2 Hz, 1H, 2-$H^B$), 1.17 (d, *J*=6.8 Hz, 3H, 6-$H_3$), 1.07 (t, *J*=7.2 Hz, 3H, 1-$H_3$), 0.83 (d, *J*=7.2 Hz, 3H, 4-Me); minor isomer 7.32–7.11 (m, 5H, Ar), 2.99 (dq, *J*=9.6, 7.2 Hz, 1H, 5-H), 2.79–2.69 (m, 1H, 4-H), 2.23 (dq, *J*=18.4, 8.0 Hz, 1H, 2-$H^A$), 1.94 (dq, *J*=18.4, 8.0 Hz, 1H, 2-$H^B$), 1.25 (d, *J*=7.2 Hz, 3H, 6-$H_3$), 1.10 (d, *J*=6.4 Hz, 3H, 4-Me), 0.78 (t, *J*=8.0 Hz, 3H, 1-$H_3$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 215.4 (s), 214.9 (s), 145.4 (s), 144.7 (s), 128.34 (d), 128.27 (d), 127.4 (d), 127.2 (d), 126.3 (d), 126.2 (d), 52.9 (d), 52.7 (d), 42.8 (d), 42.0 (d), 35.9 (t), 35.7 (t), 20.5 (q), 17.9 (q), 16.2 (q), 14.1 (q), 7.5 (q), 7.3 (q); MS: (EI, 70 eV) *m*/*z* major isomer 190 ($M^+$, 18), 105 ($PhCHCH_3$, 100), 91 ($PhCH_2$, 38); minor isomer 190 (M+, 17), 105 ($PhCHCH_3$, 100), 91 ($PhCH_2$, 37); HRMS: (EI, 70 eV) major isomer calculated ($C_{13}H_{18}O$) 190.1358 ($M^+$), found: 190.1350; minor isomer found: 190.1348. Analysis: $C_{13}H_{18}O$ (190.28) calcd: C, 82.06; H, 9.53. Found: C, 81.86; H, 9.66.

### 5.3.11. 3,3-Dimethyl-4-phenyl-2-pentanone **5bc**

According to the typical procedure, this compound was produced from $InBr_3$, **4c**, and 1-phenylethyl chloride **1b**. Bp: 70 °C/0.2 mmHg. IR: (neat) 1701 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.28 (t, *J*=7.2 Hz, 2H, *m*), 7.23 (d, *J*=7.2 Hz, 1H, *p*), 7.17 (d, *J*=7.2 Hz, 2H, *o*), 3.16 (q, *J*=7.2 Hz, 1H, 4-H), 2.09 (s, 3H, 1-$H_3$), 1.20 (d, *J*=7.2 Hz, 3H, 5-$H_3$), 1.06 (s, 3H, 3-$Me^A$), 0.99 (s, 3H, 3-$Me^B$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 214.2 (s, C-2), 142.2 (s, *i*), 129.1 (d, *o*), 127.8 (d, *m*), 126.5 (d, *p*), 51.3 (s, C-3), 45.6 (d, C-4), 26.1 (q, C-1), 23.7 (q, 3-$Me^B$), 19.5 (q, 3-$Me^A$), 15.8 (q, C-5); MS: (EI, 70 eV) *m*/*z* 190 ($M^+$, 1.3), 105 ($PhCHCH_3$, 100), 86 (37); HRMS: (EI, 70 eV) calculated ($C_{13}H_{18}O$) 190.1358 ($M^+$), found: 190.1363.

### 5.3.12. 3,3-Dimethyl-1,5-diphenyl-1-pentyne **14**

IR: (neat) 3062–3027 $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.44–7.39 (m, 2H, 1-Ph-*o*), 7.31–7.15 (m, 8H, Ar), 2.88–2.81 (m, 2H, 5-$H_2$), 1.83–1.75 (m, 2H, 4-$H_2$), 1.35 (s, 6H, 3-$Me_2$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 142.8 (s, 5-Ph-*i*), 131.6 (d), 128.4 (d), 128.3 (d), 128.1 (d), 127.5 (d), 125.7 (d), 123.9 (s, 1-Ph-*i*), 96.8 (s, C-2), 80.8 (s, C-1), 45.5 (t, C-4), 32.1 (t, C-5), 31.8 (s, C-3), 29.2 (q, 3-$Me_2$); MS: (EI, 70 eV) *m*/*z* 248 ($M^+$, 8), 233 ($M^+-CH_3$, 100), 143 ($M^+-CH_3-CH_3-C_6H_5$, 58), 128 (21), 91 ($PhCH_2$, 32); HRMS: (EI, 70 eV) calculated ($C_{19}H_{20}$) 248.1565 ($M^+$), found: 248.1571.

### 5.3.13. 3-(4-Methoxyphenyl)-2,2-dimethyl-1-propanol **19**

Mp 44–45 °C. IR: (KBr) 3352 (OH) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.09 (d, *J*=8.8 Hz, 2H, *o*), 6.83 (d, *J*=8.8 Hz, 2H, *m*), 3.80 (s, 3H, OMe), 3.31 (m, 2H, 1-$H_2$), 2.53 (s, 2H, 3-$H_2$), 1.59 (m, 1H, OH), 0.88 (s, 6H, 2-$Me_2$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 157.8 (s, *p*), 131.3 (d, *o*), 130.8 (s, *i*), 113.2 (d, *m*), 71.0 (t, C-1), 55.2 (q, OMe), 43.7 (t, C-3), 36.3 (s, C-2), 23.9 (q, 2-$Me_2$); MS: (EI, 70 eV) *m*/*z* 194 ($M^+$, 24), 121 ($MeOC_6H_4CH_2$, 100); HRMS: (EI, 70 eV) calculated ($C_{12}H_{18}O_2$) 194.1307 ($M^+$), found: 194.1303. Analysis: $C_{12}H_{18}O_2$ (194.27) calcd: C, 74.19; H, 9.34, found: C, 74.00; H, 9.32.

### 5.3.14. Methyl 3-hydroxy-5-(4-methoxyphenyl)-2,2,4,4-tetramethylpentanoate **20**

To a suspended solution of $InBr_3$ (0.05 mmol) and **6a** (2 mmol) in $CH_2Cl_2$ (1 mL) was added **1d** (2 mmol) at 0 °C. The mixture was stirred and warmed to room temperature for 2 h. Then, **2a** (2 mmol) was added to the reaction mixture and the mixture was stirred at room temperature for 2 h. The reaction was quenched by $H_2O$ aq (10 mL), and the mixture was extracted with diethyl ether. The collected organic layer was dried ($MgSO_4$). The solvent was evaporated and the residue was purified by column chromatography (hexane/ethyl acetate=85/15, column length 11 cm) to give the product. IR: (neat) 3545 (OH), 1724 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.08 (d, *J*=8.4 Hz, 2H, *o*), 6.81 (d, *J*=8.4 Hz, 2H, *m*), 3.78 (s, 3H, ArO*Me*), 3.65 (s, 3H, COOMe), 3.58 (d, *J*=8.0 Hz, 1H, 3-H), 2.73 (d, *J*=13.0 Hz, 1H, 5-*H*$^A$H), 2.65 (d, *J*=8.0 Hz, OH), 2.48 (d, *J*=13.0 Hz, 1H, 5-*H*$^B$H), 1.30 (s, 3H, 2-$Me^A$), 1.26 (s, 3H, 2-$Me^B$), 0.89 (s, 3H, 4-$Me^A$), 0.85 (s, 3H, 4-$Me^B$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 178.5 (s, C-1), 157.8 (s, *p*), 131.7 (d, *o*), 130.6 (s, *i*), 113.1 (d, *m*), 81.6 (d, C-3), 55.1 (q, ArO*Me*), 51.8 (q, COO*Me*), 46.9 (s, C-2), 46.2 (t, C-5), 40.7 (s, C-4), 26.0 (q, 2-$Me^B$), 24.3 (q, 4-$Me^B$), 22.9 (q, 2-$Me^A$), 22.7 (q, 4-$Me^A$); MS: (EI, 70 eV) *m*/*z* 294 ($M^+$, 4), 121 ($MeOC_6H_4CH_2$, 100); HRMS: (EI, 70 eV) calculated ($C_{17}H_{26}O_4$) 294.1831 ($M^+$), found: 294.1835.

### 5.3.15. 3-Hydroxy-5-(4-methoxyphenyl)-4,4-dimethyl-1-phenylpentan-1-one **21**

To a suspended solution of $InBr_3$ (0.05 mmol) and 2-methyl-1-trimethylsiloxy-1-propene (2 mmol) in dichloromethane (1 mL)

was added 4-methoxybenzyl chloride (1.0 mmol) at 0 °C. The mixture was stirred and warmed to room temperature for 2 h. Then, 1-phenyl-1-trimethylsiloxyethene (2 mmol) was added to the reaction mixture and the mixture was stirred at room temperature for 2 h. The reaction was quenched by $H_2O$aq, and the mixture was extracted with diethyl ether. The collected organic layer was dried ($MgSO_4$). The solvent was evaporated and the mixture of the crude product, 1 N HClaq (1.5 mL), and THF (10 mL) was stirred at 0 °C for 1 h. Then, the reaction was quenched by $NaHCO_3$aq. The mixture was extracted with diethyl ether. The collected organic layer was dried ($MgSO_4$). The solvent was evaporated and the residue was purified by column chromatography (hexane/ethyl acetate=70/30, column length 11 cm) to give the product. Mp 112–113 °C. IR: (KBr) 3518 (OH), 1670 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.94 (d, *J*=7.2 Hz, 2H, 1-Ph-*o*), 7.56 (t, *J*=7.2 Hz, 1H, 1-Ph-*p*), 7.45 (t, *J*=7.2 Hz, 2H, 1-Ph-*m*), 7.13 (d, *J*=8.8 Hz, 2H, 5-Ph-*o*), 6.82 (d, *J*=8.8 Hz, 2H, 5-Ph-*m*), 3.94 (ddd, *J*=10.0, 3.2, 1.6 Hz, 1H, 3-H), 3.77 (s, 3H, OMe), 3.38 (d, *J*=3.2 Hz, 1H, OH), 3.20 (dd, *J*=17.2, 1.6 Hz, 1H, 2-$H^A$), 3.03 (dd, *J*=17.2, 10.0 Hz, 1H, 2-$H^B$), 2.82 (d, *J*=13.2 Hz, 1H, 5-$H^A$), 2.51 (d, *J*=13.2 Hz, 1H, 5-$H^B$), 0.97 (s, 3H, 4-$Me^A$), 0.87 (s, 3H, 4-$Me^B$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 201.6 (s, C-1), 157.8 (s, 5-Ph-*p*), 136.4 (s, 1-Ph-*i*), 133.4 (d, 1-Ph-*p*), 131.6 (d, 5-Ph-*o*), 130.6 (s, 5-Ph-*i*), 128.6 (d, 1-Ph-*m*), 127.9 (d, 1-Ph-*o*), 113.1 (d, 5-Ph-*m*), 72.8 (d, C-3), 55.1 (q, OMe), 43.6 (t, C-5), 39.6 (t, C-2), 37.9 (s, C-4), 23.3 (q, 4-$Me^B$), 22.2 (q, 4-$Me^A$); MS: (EI, 70 eV) *m*/*z* 312 ($M^+$, 1.4), 121 ($MeOC_6H_4CH_2$, 100), 105 (24); HRMS: (EI, 70 eV) calculated ($C_{20}H_{24}O_3$) 312.1725 ($M^+$), found: 312.1727.

### 5.3.16. *Methyl 2,2-dimethyl-3-phenyl-4-pentenoate* **26**

IR: (deposit from $CDCl_3$) 1736 (C=O) $cm^{-1}$; $^1H$ NMR: (400 MHz, $CDCl_3$) 7.28 (t, *J*=7.0 Hz, 2H, *m*), 7.22 (t, *J*=7.0 Hz, 1H, *p*), 7.17 (d, *J*=7.0, 2H, *o*), 6.23 (ddd, *J*=16.0, 12.0, 8.0 Hz, 1H, 4-H), 5.14–5.12 (m, 1H, 5-*H*$^B$H), 5.12–5.08 (m, 1H, 5-*H*$^A$H), 3.61 (s, 3H, OMe), 3.61 (d, *J*=8.0 Hz, 1H, 3-H), 1.17 (s, 3H, 2-$Me^B$), 1.11 (s, 3H, 2-$Me^A$); $^{13}C$ NMR: (100 MHz, $CDCl_3$) 177.4 (s, C-1), 140.3 (s, *i*), 136.9 (d, C-4), 129.1 (d, *o*), 127.9 (d, *m*), 126.7 (d, *p*), 117.5 (t, C-5), 57.7 (d, C-3), 51.6 (q, OMe), 46.9 (s, C-2), 23.2 (q, 2-$Me^A$), 22.2 (q, 2-$Me^B$); MS: (EI, 70 eV) *m*/*z* 218 ($M^+$, 3), 117 ($M^+-C(CH_3)_2COOMe$, 100); HRMS: (EI, 70 eV) calculated ($C_{14}H_{18}O_2$) 218.1307 ($M^+$), found: 218.1301.

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## References and notes

1. Caine, D. In *Comprehensive Organic Synthesis*, Trost, B. M., Fleming, I., Eds.; Vol. 3, p 1.
2. For review of reactions of alkyl chlorides with silyl enolates, see: Reetz, M. T. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 96–108.
3. Reetz, M. T.; Maier, W. F. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 48–49; Reetz, M. T.; Schwellnus, K.; Hubner, F.; Massa, W.; Schmidt, R. E. *Chem. Ber.* **1983**, *116*, 3708–3724; Reetz, M. T.; Walz, P.; Hubner, F.; Huttenhain, S. H.; Heimbach, H.; Schwellnus, K. *Chem. Ber.* **1984**, *117*, 322–325.
4. Mukaiyama, T.; Nagaoka, H.; Ohshima, M.; Murakami, M. *Chem. Lett.* **1986**, 1009–1012; Mukaiyama, T.; Matsui, S.; Homma, K.; Kobayashi, S. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 2687–2690.
5. Nishimoto, Y.; Yasuda, M.; Baba, A. *Org. Lett.* **2007**, *9*, 4931–4934.
6. Coupling reaction of alcohol or its derivatives with allylsilane: Rubin, M.; Gevorgyan, V. *Org. Lett.* **2001**, *3*, 2705–2707; Schwier, T.; Rubin, M.; Gevorgyan, V. *Org. Lett.* **2004**, *6*, 1999–2001.
7. Chlorination of alcohol: Yasuda, M.; Shimizu, K.; Yamasaki, S.; Baba, A. *Org. Biomol. Chem.* **2008**, *6*, 2790–2795.
8. DFT analysis of Lewis acidity of $BiX_3$: Sanderson, J.; Bayse, C. A. *Tetrahedron* **2008**, *64*, 7685–7689; For selected reviews, see: Gaspard-Ilangovan, H. In *Acid Catalysis in Modern Organic Synthesis*; Yamamoto, H., Ishihara, K., Eds.; Wiley-VCH: Weinhein, 2008; Vol. 2, Chapter 11, pp 551–588; Komatsu, N. In *Organobismuth Chemistry*; Suzuki, H., Matano, Y., Eds.; Elsevier: Amsterdam, 2001; Chapter 5, pp 371–440; Recently C–C bond formation reaction using bismuth catalyst as a Lewis acid: Tanaka, S.; Tagashira, N.; Chiba, K.; Yasuda, M.; Baba, A. *Angew. Chem., Int. Ed.* **2008**, *47*, 6620–6623; De, S. K.; Gibbs, R. A. *Tetrahedron Lett.* **2005**, *46*, 8345–8350; Kobayashi, S.; Ogino, T.; Shimizu, H.; Ishikawa, S.; Hamada, T.; Manabe, K. *Org. Lett.* **2005**, *7*, 4729–4731; Evans, P. A.; Cui, J.; Gharpure, S. J.; Hinkle, R. J. *J. Am. Chem. Soc.* **2003**, *125*, 11456–11457.
9. For review of lanthanoid metal-Lewis acids, see: Kobayashi, S.; Sugiura, M.; Kitagawa, H.; Lam, W. W.-M. *Chem. Rev.* **2002**, *102*, 2227–2302.
10. Saito, T.; Nishimoto, Y.; Yasuda, M.; Baba, A. *J. Org. Chem.* **2006**, *71*, 8516–8522.
11. See Refs. 10 and 20.
12. Mayr, H.; Kempf, B.; Ofial, A. R. *Acc. Chem. Res.* **2003**, *36*, 66–77.
13. The coupling reaction of the phenylsulphenyl chloride with the imide enolate; Alexander, R. P.; Paterson, I. *Tetrahedron Lett.* **1985**, *26*, 5339–5340.
14. Sasaki, T.; Usuki, A.; Ohno, M. *J. Org. Chem.* **1980**, *45*, 3559–3564; Mayr, H.; Hellmann, W.; Lammers, R. *Tetrahedron* **1986**, *42*, 6663–6668; Bentley, T. W.; Irrgang, B.; Mayr, H.; Schleyer, P. v. R. *J. Org. Chem.* **1988**, *53*, 3492–3498.
15. Hama, T.; Liu, X.; Culkin, D. A.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 11176–11177.
16. Onishi, Y.; Ito, T.; Yasuda, M.; Baba, A. *Tetrahedron* **2002**, *58*, 8227–8235.
17. Alexander, R. P.; Paterson, I. *Tetrahedron Lett.* **1983**, *24*, 5911–5914; Mayr, H.; Pock, R. *Tetrahedron* **1986**, *42*, 4211–4214; Hagen, G.; Mayr, H. *J. Am. Chem. Soc.* **1991**, *113*, 4954–4961; Buckle, M. J. C.; Fleming, I.; Salvador, G. *Tetrahedron Lett.* **1992**, *33*, 4479–4482; Dau-Schmidt, J.; Mayr, H. *Chem. Ber.* **1994**, *127*, 205–212; Buckle, M. J. C.; Fleming, I.; Gill, S.; Pang, K. L. C. *Org. Biomol. Chem.* **2004**, *2*, 749–769.
18. Capozzi, G.; Romeo, G.; Marcuzzi, F. *J. Chem. Soc., Chem. Commun.* **1982**, 959–960.
19. Onishi, Y.; Ito, T.; Yasuda, M.; Baba, A. *Eur. J. Org. Chem.* **2002**, 1578–1581; Onishi, Y.; Ito, T.; Yasuda, M.; Baba, A. *Tetrahedron* **2002**, *58*, 8227–8235.
20. Saito, T.; Yasuda, M.; Baba, A. *Synlett* **2005**, 1737–1739; Saito, T.; Nishimoto, Y.; Yasuda, M.; Baba, A. *J. Org. Chem.* **2006**, *71*, 8516–8522; Saito, T.; Nishimoto, Y.; Yasuda, M.; Baba, A. *J. Org. Chem.* **2007**, *72*, 8588–8590.
21. Tsuji, J.; Minami, I.; Shimizu, I. *Chem. Lett.* **1983**, 1325–1326; Shimizu, I.; Minami, I.; Tsuji, J.; Takahashi, K.; Minami, I.; Shimizu, I. *Tetrahedron Lett.* **1984**, *25*, 4783–4786; Malkov, A. V.; Baxendale, I. R.; Dvořák, D.; Mansfield, D. J.; Kočovský, P. *J. Org. Chem.* **1999**, *64*, 2737–2750; Muraoka, T.; Matsuda, I.; Itoh, K. *Tetrahedron Lett.* **2000**, *41*, 8807–8811; Behenna, D. C.; Stoltz, B. M. *J. Am. Chem. Soc.* **2004**, *126*, 15044–15045; Bélanger, É.; Cantin, K.; Messe, O.; Tremblay, M.; Paquin, J. F. *J. Am. Chem. Soc.* **2007**, *129*, 1034–1035.
22. Grieco, P. A.; Handy, S. T. *Tetrahedron Lett.* **1997**, *38*, 2645–2648; Rubenbauer, P.; Bach, T. *Tetrahedron Lett.* **2008**, *49*, 1305–1309.
23. Reetz, M. T.; Schwellnus, K.; Hubner, F.; Massa, W.; Schmidt, R. E. *Chem. Ber.* **1983**, *116*, 3708–3724.
24. Stanković, S.; Espenson, J. H. *J. Org. Chem.* **2000**, *65*, 5528–5530.
25. Iida, A.; Nakazawa, S.; Okabayashi, T.; Horii, A.; Misaki, T.; Tanabe, Y. *Org. Lett.* **2006**, *8*, 5215–5218.
26. Adam, W.; Wang, X. *J. Org. Chem.* **1991**, *56*, 4737–4741.
27. Collins, D. J.; Choo, G. L. P.; Obrist, H. *Aust. J. Chem.* **1990**, *43*, 617–622.
28. Revis, A.; Hilty, T. K. *J. Org. Chem.* **1990**, *55*, 2972–2973.
29. Heathcock, C. H.; Davidsen, S. K.; Hug, K. T.; Flippin, L. A. *J. Org. Chem.* **1986**, *51*, 3027–3037.
30. Tirpak, R. E.; Rathke, M. W. *J. Org. Chem.* **1982**, *47*, 5099–5102.
31. Beutelman, H. P.; Xie, L.; Saunders, W. H., Jr. *J. Org. Chem.* **1989**, *54*, 1703–1709.
32. Imrie, C.; Modro, T. A.; Rohwer, E. R.; Wagener, C. C. P. *J. Org. Chem.* **1993**, *58*, 5643–5649.
33. Lambert, J. B.; Liu, X. *Tetrahedron* **1997**, *53*, 9989–9996.
34. Uemura, S.; Fukuzawa, S. *J. Am. Chem. Soc.* **1983**, *105*, 2748–2752.
35. Dinnocenzo, J. P.; Zuilhof, H.; Lieberman, D. R.; Simpson, T. R.; McKechney, M. W. *J. Am. Chem. Soc.* **1997**, 994–1004.
36. Huang, X.; Xu, X. H. *J. Chem. Soc., Perkin Trans. 1* **1998**, 3321–3322.
37. Chang, Y. H.; Ford, W. T. *J. Org. Chem.* **1981**, *46*, 5364–5371.
38. Arnold, R. T.; Kulenovic, S. T. *J. Org. Chem.* **1980**, *45*, 891–894.
39. House, H. O.; Weeks, P. D. *J. Am. Chem. Soc.* **1975**, *97*, 2770–2777.
40. Peter, M.; Gleiter, R.; Rominger, F.; Oeser, T. *Eur. J. Org. Chem.* **2004**, 3212–3220.
41. Gazzard, L. J.; Motherwell, W. B.; Sandham, D. A. *J. Chem. Soc., Perkin Trans. 1* **1999**, 979–993.
42. Kwon, M. S.; Kim, N.; Seo, S. H.; Park, I. S.; Cheedrala, R. K.; Park, J. *Angew. Chem., Int. Ed.* **2005**, *44*, 6913–6915.
43. Saito, T.; Nishimoto, Y.; Yasuda, M.; Baba, A. *J. Org. Chem.* **2007**, *72*, 8588–8590.
44. Martínez, A. G.; Barcina, J. O.; Díez, B. R.; Subramanian, L. R. *Tetrahedron* **1994**, *50*, 13231–13238.
45. Jarboe, S. G.; Beak, P. *Org. Lett.* **2000**, *2*, 357–360.