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MgI_2-catalyzed halo aldol reaction: a practical approach to (*E*)-β-iodovinyl-β′-hydroxyketones

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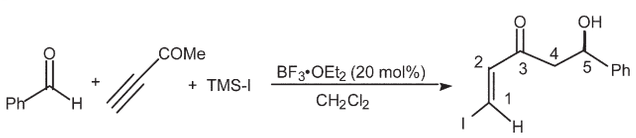
A novel generation of 1-iodo-3-siloxy-1,3-butadienes has been developed by reacting trimethylsilyl iodide (TMS-I) with α,β-unsaturated ketones in dichloromethane at 0 °C without the use of any catalyst. The halo aldol reaction of these butadiene intermediates with aldehydes was efficiently carried out by using magnesium iodide as the catalyst. Twelve β-iodo-α,β-unsaturated-β′-hydroxyketones (halo aldols) have been synthesized under the new condition with excellent geometric selectivity and good chemical yields (>80% chemical yields for 11 examples).

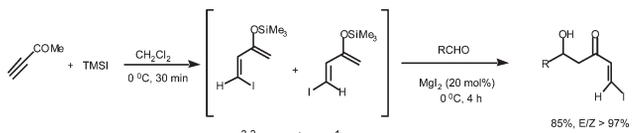
Introduction

The study of multiple-component reactions that occur in regio-, stereo- and enantioselective fashion has been an important topic in modern organic chemistry.[1–2] Among these reactions is the halo aldol reaction, which has been developed for tandem C–X/C–C bond formation.[3–5] This reaction can greatly extend the scope of classical aldol reactions because the resulting halo aldol products can be converted into extended aldols and many other important building blocks for organic synthesis.

Recently, we have reported a novel halo aldol reaction *via* a tandem functionalization of the 1,4-positions of α,β-acetylenic ketones.[6] The reaction consists of the α,β-conjugate addition of TMS-I to ethynyl ketones, $BF_3{\cdot}OEt_2$ catalyzed-isomerization and aldol coupling steps, which were conducted in a one-pot process.



The resulting β-halo-α,β-unsaturated-β′-hydroxyketones are very useful for the total synthesis of many biologically important targets.[7–10] Unfortunately, we later found that this protocol is quite sensitive to temperature variations. For example, when the reaction temperature was increased by 5 °C (from −15 °C), the desired product was isolated in <40% yield. Furthermore, when the reaction was carried out at 0 °C, the yield was even worse. Herein, we would like to report a more convenient method for the generation of 1-iodo-3-siloxy-1,3-butadienes and the efficient aldol reactions of these intermediates with aldehydes catalyzed by magnesium(II) iodide. The reaction is represented in Scheme 1 with results listed in Table 1.

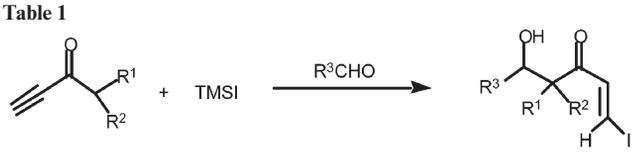


Scheme 1

Results and discussion

The initial reaction optimization was carried out by adding TMS-I dropwise into a CH_2Cl_2 solution of 3-butyn-2-one at −78 °C. Benzaldehyde was added after 30 minutes and the resulting mixture was stirred overnight at −78 °C. This resulted in 80% consumption of benzaldehyde, while the β-iodo Baylis–Hillman-type adduct was obtained in approximately 50% yield with an *E*/*Z* selectivity ratio of 1 : 1.5, as observed by crude

Table 1



Entry	R^1	R^2	R^3	Product	% Yield[b]
1	H	H	Ph	**1**	85
2	H	H	4-Me–C_6H_4	**2**	83
3	H	H	4-F–C_6H_4	**3**	87
4	H	H	4-Cl–C_6H_4	**4**	85
5	H	H	4-Br–C_6H_4	**5**	83
6	H	H	1-naphthyl	**6**	81
7	H	H	4-BnO–C_6H_4	**7**	86[d]
8	H	H	4-MeO–C_6H_4	**8**	82[d]
9	Et	H	Ph	**9**	82[c]
10	Me	Me	Ph	**10**	86
11	Me	Me	4-Me–C_6H_4	**11**	87
12	H	H	*trans*-cinnamyl	**12**	40[e]

[a] For the typical procedure and analytical data, see Experimental section. All products were isolated as colorless oils except for entries 7 and 8, which had mp of 95–97 °C and 70–72 °C, respectively. [b] Yields after purification by column chromatography. [c] The two isomers (*anti* : *syn* = 3 : 1) were not separable *via* column chromatography. [d] Reaction time = 5 h. [e] Reaction was conducted at room temperature for 5 h.

^{1}H NMR analysis. Increasing the reaction temperature to 0 °C resulted in 90% consumption of benzaldehyde and the formation of the β-iodo-α,β-unsaturated-β′-hydroxyketone product in 70% yield with an *E*/*Z* selectivity of 1.25 : 1 (Scheme 2). There were no β-iodo Baylis–Hillman-type adducts detected after the reaction temperature was changed to 0 °C, suggesting that 1-iodo-3-siloxy-1,3-butadiene intermediates were formed completely. For the model addition reaction of TMS-I with the 3-butyn-2-one substrate, the reaction was performed in CD_2Cl_2 in a sealed NMR tube, and the formation of the intermediates was monitored by NMR analysis. It was observed that when the reaction was run at −78 °C and analyzed 30 minutes after the addition of TMS-I, only TMS-allenolate was observed, with the terminal proton signal appearing at δ 6.13 ppm as a group of multiplets. However, when the reaction was carried out at 0 °C, a Danishefsky-type diene intermediate was formed with characteristic signals for the terminal proton of the *cis*-olefin appearing at δ 6.57 ppm (ddd, J = 14.1, 1.6 and 0.5 Hz) and at 7.14 ppm (ddd, J = 15.1, 1.8 and 0.6 Hz) for *trans*-olefin (Scheme 2), with a *cis* : *trans* ratio of 3.3 : 1. Interestingly, the β-iodo TMS-allenolate intermediate formed at −78 °C could be easily converted into the Danishefsky-type diene intermediate in as little as 5 minutes if the reaction was warmed from −78 °C to 0 °C. However, under the reverse conditions, the Danishefsky-type diene intermediate formed at 0 °C could

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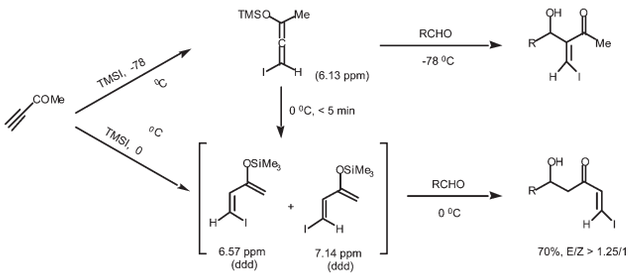


Scheme 2

not be converted back to the β-iodo-TMS-allenolate intermediate when the reaction mixture was cooled to −78 °C. This irreversibility observed for the Danishefsky-type diene intermediate suggests that it is the more thermodynamically stable of the two intermediates.

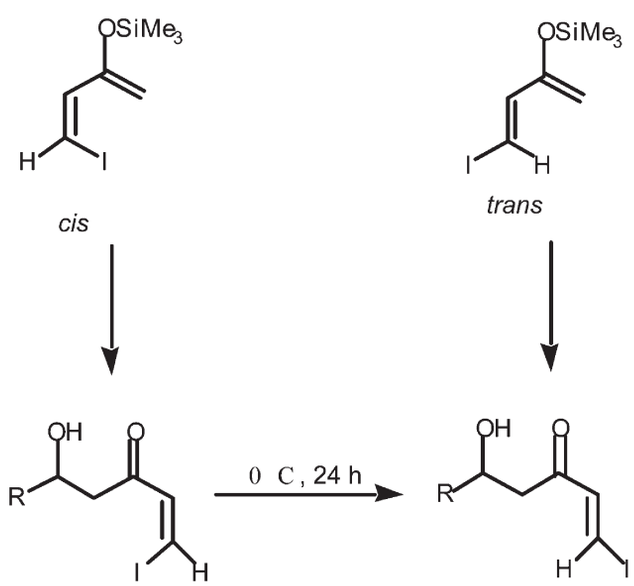
After identifying the nature of the Danishefsky-type diene intermediate directly formed at 0 °C and noting that this intermediate can react with benzaldehyde in the absence of a catalyst to afford the β-iodo-α,β-unsaturated-β′-hydroxyketone in 70% yield with an *E*/*Z* selectivity ratio of 1.25 : 1 when the reaction was run overnight, we sought to improve the synthetic utility of this sequence. Unfortunately, it was found that the reaction did not go to completion even when the reaction time was prolonged to 24 hours. Thus, a number of catalysts were screened for this reaction at 0 °C with the hope of improving both the yield and the *E*/*Z* selectivity. As mentioned earlier, attempts to utilize the Lewis acid, $BF_3{\cdot}OEt_2$, for the reaction at 0 °C resulted in a low yield. After screening a variety of catalysts, such as $TiCl_4$, $SnCl_4$, MgI_2, $Sn(OTf)_2$, $MgBr_2$, $ZnCl_2$ and $Cu(OTf)_2$, it was found that the first three candidates ($TiCl_4$, $SnCl_4$ and MgI_2) could catalyze the reaction to produce the desired products at this temperature. However, $TiCl_4$ and $SnCl_4$ resulted in dark red solutions and produced complex product mixtures in low yields as estimated based on crude ^{1}H NMR analysis. We were pleased to find that MgI_2 is an ideal catalyst for this system. In fact, MgI_2 was also proven to be an excellent Lewis acid promoter for our previous halo aldol couplings.[11] For the present system, where 20 mol% of MgI_2 was used as catalyst, the reaction proceeded smoothly at 0 °C to afford β-iodo-α,β-unsaturated-β′-hydroxyketone in good yield and exclusive *E* selectivity. MgI_2 was found to be crucial for controlling the *E*/*Z* selectivity, since the selectivity was almost nonexistent (*E* : *Z* = 1.25 : 1) when the reaction was run in the absence of any catalyst. In an effort to ascertain the role of MgI_2 in influencing the observed stereochemistry, the diene was prepared in deuterated solvent in the presence of 20 mol% MgI_2. It was found that MgI_2 plays no role in influencing the *cis*/*trans* selectivity of the diene, where an identical mixture of *cis* and *trans* isomers was obtained when either MgI_2 was present or absent. Furthermore, when the halo aldol reaction between the diene and benzaldehyde was performed in deuterated solvent, followed by subsequent addition of MgI_2 after two hours, it was found that the product mixture was converted completely to the *E* isomer within one hour. These results indicate that the role of MgI_2 in controlling the stereochemical outcome lies in the *Z* to *E* isomerization of the halo aldol product rather than in enhancing the stereoselectivity of the diene-formation step. The *E* geometry of products was determined by an NOE experiment in which 5% enhancement was observed between the signals of the vinyl proton and methylene protons. In the present system, the preparation of β-iodo-α,β-unsaturated-β′-hydroxyketones is very convenient, and was conducted by simply adding TMS-I dropwise into the solution of 3-butyn-2-one in CH_2Cl_2 at 0 °C under argon protection. The reaction mixture was stirred at 0 °C for 30 minutes before aldehyde (1.0 mmol) and MgI_2 (56.0 mg, 0.20 mmol) were added. In most cases the reaction went to completion within 4 h as indicated by TLC or ^{1}H NMR analysis, and good to high yields were realized for all aromatic aldehydes that were examined (Table 1).

Among the various solvents (CH_2Cl_2, Et_2O, MeCN and EtCN) which were examined, dichloromethane resulted in the highest efficiency in terms of both chemical yield and *E*/*Z* selectivity when benzaldehyde was employed as the electrophilic acceptor. Diethyl ether gave a lower yield of 68% within 4 h. Acetonitrile and propionitrile both gave more complex product mixtures based on TLC analysis.

Unlike the previous $BF_3{\cdot}OEt_2$ system,[6] in which both aromatic and aliphatic aldehydes were suitable electrophilic acceptors, in the present system only aromatic aldehydes provided satisfactory yields. When propionaldehyde was utilized as the substrate, no halo aldol product was observed, presumably due to enolization of aldehydes bearing an α-hydrogen. When *trans*-cinnamaldehyde was employed as the electrophilic acceptor only 40% of the product was produced, even when the reaction was performed at room temperature for 5 hours (entry 12, Table 1). Substitution of an electron-withdrawing group on the aromatic ring resulted in no obvious effect on the reaction efficiency (entries 3, 4 and 5, Table 1). However, an electron-donating group attached to the aromatic aldehyde decreased the reaction rate. For example, when 4-benzyloxybenzaldehyde and *p*-anisaldehyde (entries 7 and 8, Table 1) were employed as electrophilic acceptors, the reactions needed at least 5 hours to go to completion and to give more than 82% yield, with only 95% conversion of 4-benzyloxybenzaldehyde and *p*-anisaldehyde within 4 h.

Exclusive *E* selectivity for all products was found by ^{1}H NMR spectroscopic analyses of the crude product mixtures. In all cases, the terminal proton signal of the *E* isomeric products appeared as a doublet at around 7.17 ppm with a coupling constant of 15.1 Hz, which is clearly distinguishable from the *Z* isomer with the terminal proton signal appearing at around 7.12 ppm as a doublet with a coupling constant of 14.2 Hz.

As for the high *E*/*Z* stereoselectivity of this halo aldol reaction, we believe that thermodynamic effects played a key role in determining the geometric selectivity of the products (Scheme 3). The *E* isomer is more stable due to the dipole–dipole interaction of the carbonyl substituent and C–I bond. Indeed, we have observed that *Z* isomers can be completely converted into *E* isomers when their mixture was set at 0 °C for 24 hours, as observed by ^{1}H NMR analysis.



Scheme 3

Conclusions

In summary, 1-iodo-3-siloxy-1,3-butadienes have been generated by reacting trimethylsilyl iodide (TMS-I) with α,β-unsaturated ketones in dichloromethane at 0 °C without the use of any catalyst. The halo aldol reaction of these intermediates

with aldehydes catalyzed by MgI_2 can provide a more efficient and simple route to β-iodo-α,β-unsaturated-β′-hydroxyketones than our previous $BF_3{\cdot}OEt_2$-based halo aldol reaction.

Experimental

General procedure

All reactions were conducted at 0 °C in a 10 mL flask with magnetic stirring. CH_2Cl_2 was dried and freshly distilled from calcium hydride under a nitrogen atmosphere. Other commercial chemicals were used without further purification and their stoichiometries were calculated based on the reported purities from the manufacturers. Flash chromatography was performed on Merck silica gel 60 (230–400 mesh). ^{1}H NMR spectra were recorded on a Varian 500 MHz NMR spectrometer. ^{13}C NMR spectra were recorded at 125 MHz or 75 MHz using $CDCl_3$ as the solvent and the internal reference. Chemical shifts are given in ppm from tetramethylsilane internal standard. Infrared spectra (IR) were recorded on a HYPER IR (SHIMADZU) FTIR-8400 spectrophotometer. Peaks are reported in cm^{-1} with indicated relative intensities: s (strong, 67–100%); m (medium, 34–66%); w (weak, 0–33%). Mass spectra were recorded with a JEOL JMS-D300 mass spectrometer using direct inlet electron impact ionization (70 eV). Products **3**, **6**, and **9**–**12** were identified based on comparison to known compounds.[6] Product **8** was found to be unstable and elemental analysis was not possible.

Typical procedure

(Table 1, entry 1). A dry standard glass test tube (150 × 22 mm) with a magnetic stirring bar was flushed with nitrogen at 0 °C. Into the tube was added 3-butyn-2-one (0.10 mL, 1.3 mmol), freshly distilled dichloromethane (5.0 mL) and TMSI (0.18 mL, 1.2 mmol). The mixture was stirred at 0 °C for 30 minutes before benzaldehyde (0.10 mL, 1.0 mmol) and magnesium iodide (56.0 mg, 0.2 mmol) were added. The reaction mixture was stirred at 0 °C for 4 hours and then quenched by drop-wise addition of 2 N aqueous hydrochloric acid. The two phases were separated, and the aqueous phase was extracted with ethyl acetate (3 × 15 mL). The combined organic layers were then washed with brine, dried over anhydrous magnesium sulfate and concentrated. The residue was purified by flash column chromatography (hexane : EtOAc, 5 : 1, v/v) to provide products (257 mg, 85% yield) as a colorless oil.

1. ^{1}H NMR (300 MHz, $CDCl_3$): 7.92 (d, J = 15.0 Hz, 1H), 7.26–7.37 (m, 5H), 7.18 (d, J = 15.0 Hz, 1H), 5.19 (m, 1H), 3.15 (d, J = 3.0 Hz, OH), 2.84–3.02 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): 202.0, 140.1, 139.7, 127.8 × 3, 127.7 × 2, 99.9, 76.3, 50.9; IR: ($CHCl_3$) 3018 (w), 1215 (s), 742.5 (s), 667.3 (s). HRMS calcd for 302.1116; found: 302.1111.

2. ^{1}H NMR (300 MHz, $CDCl_3$): 7.91 (d, J = 15.0 Hz, 1H), 7.14–7.30 (m, 4H), 7.16 (d, J = 15.0 Hz, 1H), 5.16 (m, 1H), 3.06 (d, J = 3.0 Hz, OH), 2.82–3.02 (m, 2H), 2.34 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): 196.8, 144.5, 139.6, 137.5, 129.2 × 2, 125.5 × 2, 100.6, 76.5, 69.6, 48.8; IR: ($CHCl_3$) 3020 (w), 1213 (s), 742.5 (s), 667.8 (s). HRMS calcd for 316.1385; found: 316.1380.

3. ^{1}H NMR (300 MHz, $CDCl_3$): 7.86 (d, J = 15.1 Hz, 1H), 7.26–7.31 (m, 2H), 7.11 (d, J = 15.1 Hz, 1H), 6.94–7.02 (m, 2H), 5.12 (m, 1H), 3.13 (d, J = 3.0 Hz, OH), 2.77–2.93 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): 196.7, 164.7, 144.5, 138.3, 127.4, 127.2, 115.6, 115.2, 100.9, 69.1, 48.8; IR: ($CHCl_3$) 3018 (w), 1217 (s), 742.8 (s), 667.3 (s).

4. ^{1}H NMR (500 MHz, $CDCl_3$): 7.92 (d, J = 15.1 Hz, 1H), 7.26–7.32 (m, 4H), 7.17 (d, J = 15.1 Hz, 1H), 5.17 (m, 1H), 3.25 (d, J = 3.0 Hz, OH), 2.84–2.92 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$): 196.6, 144.4, 141.0, 133.4, 128.7 × 2, 127.0 × 2, 101.0, 69.0, 48.6; IR: ($CHCl_3$) 3018 (w), 1216 (s), 743.0 (s), 667.0 (s). HRMS calcd MNa^+ 358.9306; found: 358.9309.

5. ^{1}H NMR (500 MHz, $CDCl_3$): 7.91 (d, J = 15.1 Hz, 1H), 7.46 (m, 2H), 7.22 (m, 2H), 7.15 (d, J = 15.1 Hz, 1H), 5.14 (m, 1H), 3.356 (d, J = 3.0 Hz, OH), 2.81–2.94 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$): 196.8, 144.6, 141.8, 131.9 × 2, 127.6 × 2, 121.8, 101.4, 69.3, 48.8; IR: ($CHCl_3$) 3019 (w), 1216 (s), 742.3 (s), 667.5 (s). HRMS calcd MNa^+ 402.8801; found: 402.8801.

6. ^{1}H NMR (300 MHz, $CDCl_3$): 7.99 (m, 1H), 7.95 (d, J = 15.0 Hz, 1H), 7.87 (m, 1H), 7.80 (m, 1H), 7.72 (m, 1H), 7.49–7.56 (m, 3H), 7.19 (d, J = 15.0 Hz, 1H), 6.00 (m, 1H), 3.26 (d, J = 3.0 Hz, OH), 3.07 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): 197.0, 144.6, 138.0, 133.7, 129.7, 129.0, 128.2, 126.3, 125.6, 125.5, 123.0, 122.6, 100.8, 66.6, 48.1; IR: ($CHCl_3$) 3018 (w), 1213 (S), 744.2 (s), 666.8 (s).

7. ^{1}H NMR (500 MHz, $CDCl_3$): 7.89 (d, J = 15.5 Hz, 1H), 7.26–7.41 (m, 7H), 7.15 (d, J = 15.5 Hz, 1H), 6.95 (m, 2H), 5.13 (m, 1H), 5.05 (s, 2H), 3.08 (brs, OH), 2.82–2.98 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$): 196.8, 158.4, 144.6, 136.8, 135.0, 128.5 × 2, 127.9, 127.4 × 2, 126.9 × 2, 114.9 × 2, 100.7, 69.9, 69.4, 48.7; IR: ($CHCl_3$) 3018 (w), 1212 (s), 746.5 (s), 668.3 (s). HRMS calcd MNa^+ 431.0115; found: 431.0118.

8. ^{1}H NMR (500 MHz, $CDCl_3$): 7.90 (d, J = 15.4 Hz, 1H), 7.26–7.30 (m, 2H), 7.17 (d, J = 15.4 Hz, 1H), 6.88–6.90 (m, 2H), 5.15 (m, 1H), 3.81 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$): 196.8, 159.2, 144.6, 134.7, 126.9 × 2, 113.9 × 2, 100.6, 69.4, 55.3, 48.7; IR: ($CHCl_3$) 3019 (w), 1213 (S), 744.5 (s), 667.3 (s).

10. ^{1}H NMR (300 MHz, $CDCl_3$): 7.91 (d, J = 15.0 Hz, 1H), 7.54 (d, J = 15.0 Hz, 1H), 7.25–7.33 (m, 5H), 4.92 (d, J = 3.3 Hz, 1H), 2.75 (d, J = 3.3 Hz, OH), 1.12 (s, 3H), 1.04 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): 202.0, 140.1, 139.7, 127.8 × 3, 127.7 × 2, 99.9, 76.3, 50.9, 22.1, 17.7; IR: ($CHCl_3$) 3018 (w), 1217 (S), 744.5 (s), 666.3 (s).

11. ^{1}H NMR (300 MHz, $CDCl_3$): 7.92 (d, J = 15.0 Hz, 1H), 7.52 (d, J = 15.0 Hz, 1H), 7.15–7.31 (m, 4H), 4.93 (d, J = 3.2 Hz, 1H), 2.78 (d, J = 3.2 Hz, OH), 2.36 (s, 3H), 1.12 (s, 3H), 1.06 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): 202.0, 140.2, 137.5, 136.8, 128.5 × 2, 127.6 × 2, 99.6, 78.1, 50.9, 22.2, 21.0, 17.7; IR: ($CHCl_3$) 3020 (w), 1213 (s), 744.5 (s), 665.8 (s).

12. ^{1}H NMR (300 MHz, $CDCl_3$): 7.95 (d, J = 15.0 Hz, 1H), 7.22 (d, J = 15.0 Hz, 1H), 7.27–7.40 (m, 5H), 6.66 (d, J = 15.0 Hz, 1H), 6.21 (dd, J = 15.0, 6.0 Hz, 1H), 4.80 (m, 1H), 2.96 (brs, OH), 2.84 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): 196.8, 144.6, 136.3, 130.7, 129.8, 128.5 × 2, 127.8, 126.5 × 2, 100.7, 68.4, 46.8; IR: ($CHCl_3$) 3016 (w), 1215 (s), 744.5 (s), 665.0 (s).

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References

1 (*a*) A. Domling and I. Ugi, *Angew. Chem., Int. Ed.*, 2000, **39**, 3169; (*b*) S. Kobayashi, *Chem. Soc. Rev.*, 1999, **28**, 1.
2 (*a*) B. M. Trost and A. B. Pinkerton, *J. Am. Chem. Soc.*, 2000, **122**, 3534; (*b*) B. M. Trost and A. B. Pinkerton, *Angew. Chem., Int. Ed.*, 2000, **39**, 360.
3 (*a*) For several reviews on the aldol reaction see: D. A. Evans, J. V. Nelson and T. R. Taber, *Top. Stereochem.*, 1982, **13**, 1–115;

(*b*) E. M. Carreira, in *Comprehensive Asymmetric Catalysis*, eds. E. J. Jacobsen, A. Pfaltz and H. Yamamoto, Springer, Berlin, 1999, vol. III, pp 997–1065; (*c*) B. M. Kim, S. F. Williams and S. Masumune, in *Comprehensive Organic Synthesis*, eds. B. M. Trost, I. Fleming and C. H. Heathcock, Pergamon, Oxford, 1991, vol. 2, ch. 1.7, pp 239–275; (*d*) R. Mahrwald, *Chem. Rev.*, 1999, **99**, 1095–1120; (*e*) P. Arya and H. Qin, *Tetrahedron*, 2000, **56**, 917–948; (*f*) S. G. Nelson, *Tetrahedron: Asymmetry*, 1998, **9**, 357–389.

4 (*a*) For the asymmetric halo aldol reaction see: G. Li, H.-X. Wei, B. S. Phelps, D. W. Purkiss and S. H. Kim, *Org. Lett.*, 2001, **3**, 823–826; (*b*) G. Li, X. Xu, D. Chen, C. Timmons, M. D. Carducci and A. D. Headley, *Org. Lett.*, 2003, **5**, 329–331; (*c*) C. Timmons, J. F. Cannon, A. D. Headley and G. Li, *Org. Lett.*, 2004, **6**, 2075–2078.

5 (*a*) For the recent racemic halo aldol reaction see: T. Kataoka, H. Kinoshita, S. Kinoshita, T. Iwamura and S. Watanable, *Angew. Chem., Int. Ed.*, 2000, **39**, 2358–2360; (*b*) H.-X. Wei, T. D. Caputo, D. W. Purkiss and G. Li, *Tetrahedron*, 2000, **56**, 2397–2401; (*c*) S. Uehira, Z. Han, H. Shinokubo and K. Oshima, *J. Org. Chem.*, 2001, **66**, 7854–7857; (*d*) G. Li, H.-X. Wei and T. D. Caputo, *Tetrahedron Lett.*, 2000, **41**, 1–4; (*e*) M. Shi, J.-K. Jiang and Y.-S. Feng, *Org. Lett.*, 2000, **2**, 2397–2400; (*f*) D. Basavaiah, B. Sreenivasulu and A. J. Rao, *J. Org. Chem.*, 2003, **68**, 5983–5991.

6 H.-X. Wei, S. H. Kim and G. Li, *Org. Lett.*, 2002, **4**, 3691–3694.

7 (*a*) A. B. Smith, III, P. R. Verhoest, K. P. Minbiole and M. Schelhaas, *J. Am. Chem. Soc.*, 2001, **123**, 4834–4936; (*b*) M. M. Gleason and F. E. McDonald, *J. Org. Chem.*, 1997, **62**, 6432–6435.

8 (*a*) T. Esumi, N. Okamoto and S. Hatakeyama, *Chem. Commun.*, 2002, **24**, 3042–3043; (*b*) I. S. Mitchell, G. Pattenden and J. P. Stonehouse, *Tetrahedron Lett.*, 2002, **43**, 493–497.

9 (*a*) J. S. Panek and P. Liu, *J. Am. Chem. Soc.*, 2000, **122**, 11090–11097; (*b*) A. Arefolov, N. F. Langille and J. S. Panek, *Org. Lett.*, 2001, **3**, 3281–3284.

10 (*a*) I. Paterson and J. D. Smith, *J. Org. Chem.*, 1992, **33**, 3261–3264; (*b*) I. Paterson and J. D. Smith, *Tetrahedron Lett.*, 1993, **34**, 5351–5354; (*c*) I. Paterson and S. Osborne, *Tetrahedron Lett.*, 1990, **31**, 2213–2216; (*d*) I. Paterson, J. D. Smith and R. A. Ward, *Tetrahedron*, 1995, **34**, 9413–9436.

11 (*a*) H.-X. Wei, D.-J. Chen, X. Xu, G. Li and P. W. Paré, *Tetrahedron: Asymmetry*, 2003, **14**, 971–974; (*b*) H.-X. Wei, J.-L. Hu, D. W. Purkiss and P. W. Paré, *Tetrahedron Lett.*, 2003, **44**, 949–952; (*c*) G. H. Deng, H. Hu, H.-X. Wei and P. W. Paré, *Helv. Chim. Acta*, 2003, **86**, 3510–3515.