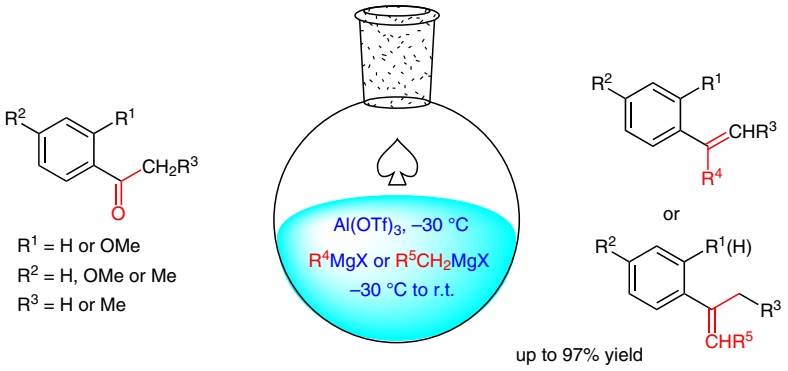
Synlett T. Pieterse et al. Letter

$Al(OTf)_3$: An Efficient Lewis Acid Additive for Domino Addition–Elimination of Grignard Reagents to Activated Ketones

Tanya Pieterse
Melanie Visser
Charlene Marais
Barend C. B. Bezuidenhoudt*

Department of Chemistry, University of the Free State, PO Box 339, Bloemfontein, 9300, South Africa
bezuidbc@ufs.ac.za



Received: 11.11.2015
Accepted after revision: 05.02.2016
Published online: 04.03.2016
DOI: 10.1055/s-0035-1561401; Art ID: st-2015-d0886-l

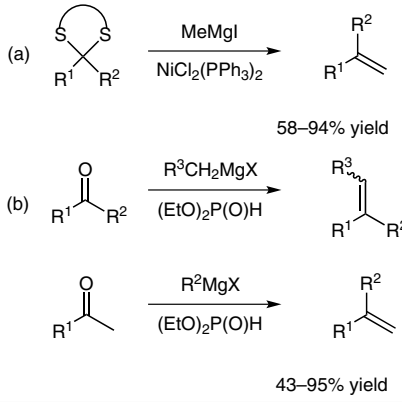
Abstract It has been demonstrated that aluminium triflate in either stoichiometric or catalytic quantities facilitates the addition–elimination of Grignard reagents to electron-rich ketones, such as methoxy substituted acetophenones, propiophenone and chromanone in a one-pot process, and that it has an enhancing effect on the addition of these reagents to the ketones. It has also been found that the reactions are highly stereoselective towards one regioisomer of the alkene in the case of oxygenated aryl-alkyl substituted substrates, but not when the elimination originates from a double benzylic alcohol intermediate.

Key words aluminium triflate, Grignard reagent, ketone, olefin, addition–dehydration, one-pot reaction

The olefination of carbonyl compounds represents an important transformation in the preparation of many organic molecules. The quest for alkenes of various substitution patterns have furthermore been intensified by the development of metathesis-based methodologies for the preparation of a variety of organic compounds. While classical methods for the transformation of carbonyl compounds into alkenes, such as the Wittig reaction and its variants,[1] Julia olefination,[2] and Peterson olefination,[3] do exist, many of these protocols are hampered by the inherent disadvantages of stoichiometric quantities of reagents and strong basic reaction conditions being required, as well as by the stepwise generation of the ylide or other intermediate. Although catalytic alternatives to the Wittig reaction based on several metals (Mo,[4] Re,[5] Fe,[6] Ru,[7] Co,[8] Rh,[9] Cu,[10] and Ir[11]) and ligands have been reported, these methods require the availability of diazocompounds, which, unlike ethyl diazoacetate (EDA), are not always commercially available and have to be prepared. Furthermore, many of these protocols are only high yielding when applied to aldehydes and electron-deficient ketones. When cyclohexanone, for example, was subjected to olefination with EDA over a methyltrioxorhenium (MTO) catalyst system, reasonable yields (ca. 70%) could only be obtained after 50 hours in the presence of benzoic acid as co-catalyst.[5g] Under the same conditions, 4-methoxyacetophenone gave a yield of only 30% after prolonged reaction time (132 h). In an effort to increase the electrophilicity of the carbonyl carbon in ketones, Lewis acids such as $SbCl_5$ and Et_3OBF_4 were also tested as co-catalysts, but unwanted side reactions meant that the olefin yield remained below 10%. These results showed that strong Lewis acids do not activate ketones towards olefination under these conditions.[5g]

Reports on the transformation of aldehydes and ketones into olefins utilizing Grignard reagents are limited to the papers by the groups of Luh[12] and Zhang.[13] Luh and coworkers utilized Grignard reagents and a nickel catalyst to convert dithioacetals, prepared from the corresponding carbonyl compounds, into alkenes, whereas Zhang and coworkers were successful in reacting the aldehyde or ketone directly with the Grignard reagent in the presence of diethyl phosphite for generating the corresponding olefin (Scheme 1). Although these methodologies are suitable to prepare the corresponding alkenes in good to excellent yields at room temperature from both aldehydes and ketones, two equivalents of the Grignard reagent and stoichiometric amounts of phosphite are needed.

Whereas strong Lewis acids did not lead to appreciable amounts of olefinic products being formed when ketones were subjected to MTO-catalysed reactions,[5g] it is well known that cuprate additions to carbonyl compounds are, in fact, enhanced by the addition of Lewis acids.[14] $CeCl_3$, for example, has been used to improve the reactivity of various carbonyl substrates toward Grignard addition reactions and increased yields of the alcohol products.[15]



Scheme 1 Methodologies of (a) Luh and co-workers[12] and (b) Zhang and co-workers[13] to convert aldehydes, ketones or the protected versions thereof into olefins

In a continuation of our work on determining the scope and limitations of aluminium triflate as Lewis acid reagent and catalyst in synthesis,[16] we decided to evaluate the effect, if any of aluminium triflate on Grignard reactions. Treatment of a solution of acetophenone (**1**) in anhydrous CH_2Cl_2 with one equivalent aluminium triflate and allowing the reaction mixture to warm to room temperature, did not lead to the formation of any addition product (Table 1, entry 1).

The use of $Al(OTf)_3$ at –30 °C for 30 minutes, followed by the addition of PhMgBr (2.0 equiv) in diethyl ether, and the same reaction without $Al(OTf)_3$, led to the expected tertiary alcohol, 1,1-diphenylethanol, in 44% yield.[17] When the substrate was changed to 4-methoxyacetophenone (**2**), we were delighted to observe that the desired product, α-(4-methoxyphenyl)styrene (**12**), was formed in 71% yield (Table 1, entry 2). To confirm that the product was indeed formed during the reaction and not the work-up process, and that $Al(OTf)_3$ played an essential role during the reaction leading to the product, the reaction with **2** was repeated at room temperature without the triflate. Under these conditions, however, no alcohol or olefinic products were observed (Table 1, entry 2). During the optimization of the reaction conditions, the reaction of **2** with $Al(OTf)_3$ (1 equiv) was also repeated with only one equivalent of PhMgBr, but although olefin **12** formation was still observed, the yield dropped to 40%. Two equivalents of Grignard reagent was therefore used throughout the rest of the investigation.

Table 1 Reaction of Ketones with Grignard Reagents in the Presence of $Al(OTf)_3$ in CH_2Cl_2 at –30 °C to Room Temperature[a]

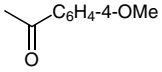
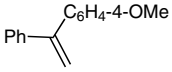
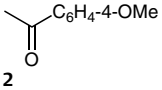
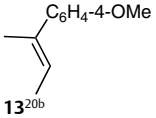
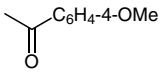
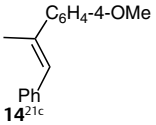
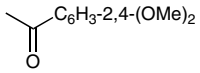
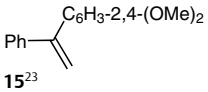
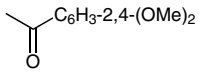
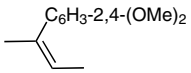
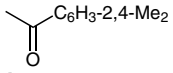
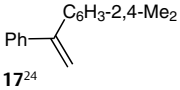
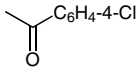
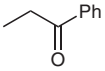
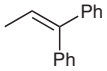
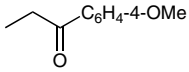
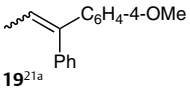
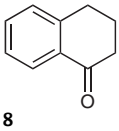
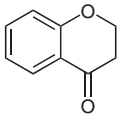
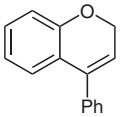
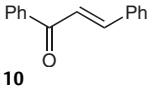
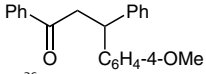
Entry	Substrate	Grignard reagent	Product	Yield (%)	
				$Al(OTf)_3$ (1 equiv)	No $Al(OTf)_3$[c]
1	 **1**	PhMgBr	 **11**[20a]	0	44[d,27]
2	 **2**	PhMgBr	 **12**[22]	71 (72)[b]	0
3	 **2**	EtMgBr	 **13**[20b]	53	0
4	 **2**	BnMgBr	 **14**[21c]	67	12
5	 **3**	PhMgBr	 **15**[23]	62 (45)[b]	0
6	 **4**	EtMgBr	 **16**	46	0

Table 1 (continued)

Entry	Substrate	Grignard reagent	Product	Yield (%) Al(OTf)$_3$ (1 equiv)	Yield (%) No Al(OTf)$_3$[c]
7	 **4**	PhMgBr	 **17**[24]	24	0
8	 **5**	PhMgBr	–	0	0[e,28]
9	 **6**	PhMgBr	 **18**	0	22[d,27]
10	 **7**	PhMgBr	 **19**[21a]	97 (67)[b]	85[d,29]
11	 **8**	PhMgBr	–	0	0
12	 **9**	PhMgBr	 **20**[25]	55 (39)[b]	0
13	 **10**	4-MeOC$_6$H$_4$MgBr	 **21**[26]	29	21

[a] Reaction conditions: A solution of ketone (200 mg) in anhydrous CH_2Cl_2 (2–5 mL) was cooled to –30 °C. Al(OTf)$_3$ (1.0 equiv) was added and the reaction mixture stirred for 30 min. Grignard reagent (2.0 equiv) in Et_2O was added and the reaction allowed to warm up to r.t. with stirring for 24 h.
[b] Reaction with catalytic Al(OTf)$_3$ (10 mol%).
[c] Ketone [200 mg in anhydrous CH_2Cl_2 (5–10 mL)], Grignard reagent in Et_2O (2.0 equiv), r.t.
[d] Tertiary alcohol was obtained as product.
[e] Repeating the reaction in THF led to the tertiary alcohol [1-(4-chlorophenyl)-1-phenylethan-1-ol] being obtained in 51% yield.

Subsequently, the success of this one-pot, two-step process for the formation of the olefin from acetophenone **2** prompted an evaluation of the applicability of this methodology to other acetophenones and carbonyl compounds with different Grignard reagents. Subjecting 4-methoxy-acetophenone (**2**) to ethyl and benzyl Grignard reagents under the reaction conditions described above led to the formation of the internal olefinic products **13** and **14** in 53 and 67% yields, respectively (Table 1, entries 3 and 4). While a mixture of the *cis*- and *trans*-products was expected from these reactions, only the *E*-isomers **13** and **14** were, in fact, obtained, as was confirmed by GC and NMR analysis.[18] Eliminating the Lewis acid from the reaction mixture in the case of the ethyl Grignard gave no addition product at all, whereas 12% of (*E*)-4-methoxy-α-methyl-β-phenylstyrene (**14**) was obtained with the benzyl Grignard reaction in this instance.[19] The reactions of PhMgBr with 2,4-dimethoxyacetophenone (**3**) and 2,4-dimethylacetophenone (**4**) led to the olefinic products **15** and **17** in 62 and 24% yield, respectively (Table 1, entries 5 and 7). These yields, taken in conjunction with the fact that acetophenone (**1**) and 4-chloroacetophenone (**5**) did not give any olefinic product at all (Table 1, entries 1, 5, 7 and 8), serves as an indication that an electron-rich aromatic ring is required for Grignard addition and subsequent alkene formation under these reaction conditions. Although the aluminium triflate is used in stoichiometric quantities, the fact that only the reactions of oxygenated ketones are accelerated points towards some complexation between the Lewis acid and the oxygen attached to the aromatic ring. The reaction of 2,4-dimethoxy-

acetophenone (**3**) with EtMgBr led to the formation of the alkene product in 46% yield, but only the *Z*-isomer was obtained in this case (Table 1, entry 6).

The formation of only the *E*-isomers during the reaction of 4-methoxyacetophenone (**2**) with the ethyl and benzyl Grignard reagents can be explained in terms of an aluminium triflate assisted E2-type elimination of the oxygen functionality wherein transition states **A** and **B** are possible during the elimination process (Figure 1). If it could be assumed that complexation of the bulky aluminium triflate to the Mg-alkoxide function would lead to it being in a perpendicular orientation towards the aromatic ring, steric interaction between the methyl/phenyl entity and the *ortho*-hydrogen atoms on the ring would lead to elimination from the gauche conformation **A** rather than the *anti*-conformer **B**. In the case of the 2,4-dimethoxy substrate **3**, complexation of the triflate to both the aromatic methoxy oxygen and the magnesium alkoxide **C** would keep the aromatic ring, benzylic carbon and alkoxide in the same plain, allowing free rotation for the ethyl group and subsequent preferred antiperiplanar elimination of the oxygen function from **C**. It may also be that the observed selectivity is a consequence of the reaction taking place under thermodynamic control.

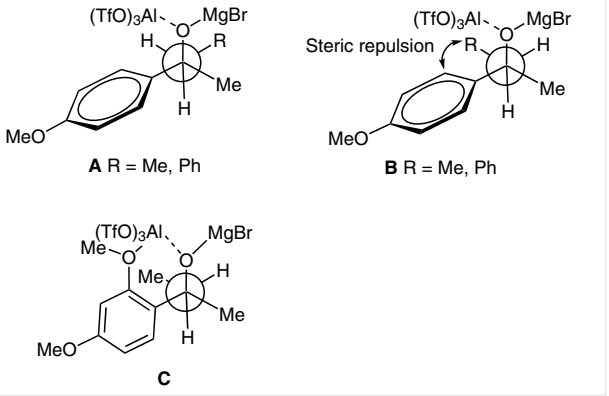


Figure 1 Possible TS conformations

The reaction of PhMgBr with propiophenone (**6**), 4-methoxypropiophenone (**7**), α-tetralone (**8**), and chromanone (**9**) confirmed activation of the aromatic ring to be a prerequisite for the olefination reaction, with the formation of only the 1,1-diphenyl-1-propene (**19**) and chromene **20** products in 97 and 55% yields, respectively (Table 1, entries 9, 10, 11, and 12). In this instance, an approximately 1:1 mixture of *E*- and *Z*-isomers was observed as product in the propiophenone reaction, which is probably explicable in terms of an E1-type elimination of the OH function from the double benzylic position in the tertiary alcohol intermediate.

Finally, it was also shown that the inclusion of aluminium triflate has a slight enhancing effect on the 1,4-addition of 4-$MeOC_6H_9MgBr$ to the α,β-unsaturated substrate **10** under the same reaction conditions (Table 1, entry 13). Interestingly, no 1,2-addition product was found in either of the reactions either with or without triflate.

Although $Al(OTf)_3$ was used in stoichiometric amounts in all of the reactions mentioned above, it was also determined that it could be used in catalytic quantities. In this regard, repeating the reactions of 4-methoxyacetophenone (**2**), 2,4-dimethoxy-acetophenone (**3**), 4-methoxypropiophenone (**7**) and chromanone (**9**) with PhMgBr in the presence of catalytic quantities (10 mol%) of $Al(OTf)_3$ led to the desired 1,1-disubstituted styrenes, **12**, **15**, **19**, and 4-phenylchromene (**20**) being formed in 72, 45, 67 and 39% yield, respectively (Table 1, entries 2, 5, 10 and 12).

In conclusion, it is evident from the results presented in this communication that aluminium triflate has an enhancing effect on the addition of Grignard reagents to electron-rich ketones and that this reagent also facilitates the formation of the olefinic product from the initially formed tertiary alkoxide in a one-pot process. It is also demonstrated that the reaction is highly stereoselective towards one regioisomer of the alkene in the case of oxygenated aryl-alkyl substituted substrates, but not when the elimination originates from a double benzylic alcohol intermediate. Finally, it has been found that aluminium triflate may be utilised in less than molar quantities, rendering this methodology the first Grignard based catalytic olefination process.

Acknowledgment

Funding from SASOL Technology limited is gratefully acknowledged.

Supporting Information

Supporting information for this article is available online at http://dx.doi.org/10.1055/s-0035-1561401.

References and Notes

(1) (a) Maercker, A. *Org. React.* **1978**, *14*, 270. (b) Still, W. C.; Gennari, C. *Tetrahedron Lett.* **1983**, *24*, 4405. (c) Blakemore, P. R. In *Comprehensive Organic Synthesis*; Knochel, P.; Molander, G. A., Eds.; Elsevier: Amsterdam, **2014**, 2nd ed. Vol. 1: 516–614. (d) Muller, C.; Cokoja, M.; Kuhn, F. E. In *Science of Synthesis, C-1 Building Blocks in Organic Synthesis*; Vol. 2; Van Leeuwen, P. W. N. M., Ed.; Thieme: Stuttgart, **2014**, 1–29. (e) Toy, P. H. *Pure Appl. Chem.* **2014**, *86*, 1651. (f) Boutagy, J.; Thomas, R. *Chem. Rev.* **1974**, *74*, 87. (g) Pascariu, A.; Ilia, G.; Bora, A.; Iliescu, S.; Popa, A.; Dehelean, G.; Pacureanu, L. *Cent. Eur. J. Chem.* **2003**, *1*, 491. (h) Odinets, I. L.; Matveeva, E. V. *Russ. Chem. Rev.* **2012**, *81*, 221. (i) Gu, Y.; Tian, S.-K. *Top. Curr. Chem.* **2012**, *327*, 197.

(2) (a) Blakemore, P. R. *J. Chem. Soc., Perkin Trans. 1* **2002**, 2563. (b) Dumeunier, R.; Marko, I. E. In *Modern Carbonyl Olefination*; Takeda, T., Ed.; Wiley-VCH: Weinheim, **2004**, 104–150. (c) Pospisil, J.; Pospisil, T.; Marko, I. E. *Org. Lett.* **2005**, *7*, 2373. (d) Christophe, A. *Eur. J. Org. Chem.* **2009**, 1831. (e) Wu, F.-L.; Hussein, W. M.; Ross, B. P.; McGeary, R. P. *Curr. Org. Chem.* **2012**, *16*, 1555. (f) Chatterjee, B.; Bera, S.; Mondal, D. *Tetrahedron: Asymmetry* **2014**, *25*, 1. (g) Pfund, E.; Lequeux, T.; Gueyrard, D. *Synthesis* **2015**, *47*, 1534.

(3) (a) Ager, D. J. *Org. React.* **1990**, *38*, 1. (b) Barrett, A. G. M.; Hill, J. M.; Wallace, E. M.; Flygare, J. A. *Synlett* **1991**, 764. (c) Van Staden, L. F.; Gravestock, D.; Ager, D. J. *Chem. Soc. Rev.* **2002**, *31*, 195. (d) Kano, N.; Kawashima, T. In *Modern Carbonyl Olefination*; Takeda, T., Ed.; Wiley-VCH: Weinheim, **2004**, 18–103. (e) Ager, D. J. *Science of Synthesis: Houben–Weyl Methods of Molecular Transformations*; Vol. 47a; de Meijere, A., Ed.; Georg Thieme: Stuttgart, **2010**, 85–104.

(4) Lu, X.; Fang, H.; Ni, Z. *J. Organomet. Chem.* **1989**, *373*, 77.

(5) (a) Herrmann, W. A.; Roesky, P. W.; Wang, M.; Scherer, W. *Organometallics* **1994**, *13*, 4531. (b) Ledford, B. E.; Carreira, E. M. *Tetrahedron Lett.* **1997**, *38*, 8125. (c) Santos, A. M.; Romao, C. C.; Kühn, F. E. *J. Am. Chem. Soc.* **2003**, *125*, 2414. (d) Zhang, X.; Chen, P. *Chem. Eur. J.* **2003**, *9*, 1852. (e) Harrison, R.; Mete, A.; Wilson, L. *Tetrahedron Lett.* **2003**, *44*, 6621. (f) Santos, A.; Pedro, F. M.; Yogalekar, A. A.; Lucas, I. S.; Romão, C. C.; Kühn, F. E. *Chem. Eur. J.* **2004**, *10*, 6313. (g) Pedro, F. M.; Hirner, S.; Kühn, F. E. *Tetrahedron Lett.* **2005**, *46*, 7777.

(6) (a) Mirfazal, G. A.; Cheng, G.; Woo, L. K. *J. Am. Chem. Soc.* **2002**, *124*, 176. (b) Aggarwal, V. K.; Fulton, J. R.; Sheldon, C. G.; De Vicente, J. *J. Am. Chem. Soc.* **2003**, *125*, 6034. (c) Chen, Y.; Huang, L.; Zhang, X. P. *J. Org. Chem.* **2003**, *68*, 5925. (d) Cheng, Y.; Huang, L.; Zhang, X. P. *Org. Lett.* **2003**, *5*, 2493. (e) Sharma, V. B.; Jain, S. L.; Sain, B. *Catal. Lett.* **2004**, *98*, 141.

(7) (a) Fujimura, O.; Honma, T. *Tetrahedron Lett.* **1998**, *39*, 625. (b) Graban, E.; Lemke, F. R. *Organometallics* **2002**, *21*, 3823. (c) Sun, W.; Yu, B.; Kühn, F. E. *Tetrahedron Lett.* **2006**, *47*, 1993. (d) Pedro, F. M.; Santos, A. M.; Baratta, W.; Kühn, F. E. *Organometallics* **2007**, *26*, 302.

(8) Lee, M.-Y.; Cheng, Y.; Zhang, X. P. *Organometallics* **2003**, *22*, 4905.

(9) (a) Lebel, H.; Paquet, V.; Proulx, C. *Angew. Chem. Int. Ed.* **2001**, *40*, 2887. (b) Grasa, G. A.; Moore, Z.; Martin, K. L.; Stevens, E. D.; Nolan, S. P.; Paquet, V.; Lebel, H. *J. Organomet. Chem.* **2002**, *658*, 126. (c) Lebel, H.; Paquet, V. *Org. Lett.* **2002**, *4*, 1671. (d) Lebel, H.; Paquet, V. *J. Am. Chem. Soc.* **2004**, *126*, 320.

(10) Lebel, H.; Davi, M.; Diez-Gonzalez, S.; Nolan, S. P. *J. Org. Chem.* **2007**, *72*, 144.

(11) Lebel, H.; Ladjel, C. *Organometallics* **2008**, *27*, 2676.

(12) (a) Ng, D. K. P.; Luh, T.-Y. *J. Am. Chem. Soc.* **1989**, *111*, 9119. (b) Ni, Z.-J.; Mei, N.-W.; Shi, X.; Tzeng, Y.-L.; Wang, M. C.; Luh, T.-Y. *J. Org. Chem.* **1991**, *56*, 4035. (c) Cheng, W.-L.; Luh, T.-Y. *J. Org. Chem.* **1992**, *57*, 3516.

(13) Wang, T.; Hu, Y.; Zhang, T. *Org. Biomol. Chem.* **2010**, *8*, 2312.

(14) (a) Perlmutter, P. *Conjugate Addition Reactions in Organic Synthesis*; Pergamon Press: Oxford, **1992**, 41. (b) Van Heerden, P. S.; Bezuidenhoudt, B. C. B.; Ferreira, D. *Tetrahedron Lett.* **1997**, *38*, 1821. (c) Nakamura, E.; Matsuzawa, S.; Horiguchi, Y.; Kuwajima, I. *Tetrahedron Lett.* **1986**, *27*, 4029. (d) Reetz, M. T.; Hullmann, M.; Massa, W.; Berger, S.; Rademacher, P.; Heymanns, P. *J. Am. Chem. Soc.* **1986**, *108*, 2405. (e) Lipshutz, B. H. *Synthesis* **1987**, 325. (f) Corey, E. J.; Boaz, N. W. *Tetrahedron Lett.* **1985**, *26*, 6015. (g) Corey, E. J.; Boaz, N. W. *Tetrahedron Lett.* **1985**, *26*, 6019.

(15) (a) Imamoto, T.; Takiyama, N.; Nakamura, K. *Tetrahedron Lett.* **1985**, *26*, 4763. (b) Imamoto, T.; Sugiuta, Y.; Takiyama, N. *Tetrahedron Lett.* **1984**, *25*, 4233. (c) Imamoto, T.; Takiyama, N.; Nakamura, K.; Hatajima, T.; Kamiya, Y. *J. Am. Chem. Soc.* **1989**, *111*, 4392. (d) Ashby, E. C.; Noding, S. A. *J. Org. Chem.* **1979**, *44*, 4371. (e) Richery, H. G. Jr.; DeStephano, J. P. *J. Org. Chem.* **1990**, *55*, 3281. (f) Krasovsiy, A.; Knochel, P. *Angew. Chem. Int. Ed.* **2004**, *43*, 3333. (g) Ipaktschi, J.; Eckert, T. *Chem. Ber.* **1995**, *128*, 1171. (h) Schneiper, B.; Bonnekessel, M.; Krause, H.; Fürstner, A. *J. Org. Chem.* **2004**, *69*, 3943. (i) Fürstner, A.; Krause, H.; Lehmann, C. W. *Angew. Chem. Int. Ed.* **2006**, *45*, 440. (j) Krasovskiy, A.; Kopp, F.; Knochel, P. *Angew. Chem. Int. Ed.* **2006**, *45*, 497. (k) Hatano, M.; Suzuki, S.; Ishihara, K. *J. Am. Chem. Soc.* **2006**, *128*, 9998.

(16) (a) Gohain, M.; Marais, C.; Bezuidenhoudt, B. C. B. *Tetrahedron Lett.* **2012**, *53*, 1048. (b) Gohain, M.; Marais, C.; Bezuidenhoudt, B. C. B. *Tetrahedron Lett.* **2012**, *53*, 4704. (c) Gohain, M.; Jacobs, J.; Marais, C.; Bezuidenhoudt, B. C. B. *Aust. J. Chem.* **2013**, *66*, 1594. (d) Gohain, M.; Lin, S.; Bezuidenhoudt, B. C. B. *Tetrahedron Lett.* **2015**, *56*, 2579.

(17) **General Procedure:** A solution of carbonyl compound in anhydrous CH_2Cl_2 (2–5 mL) was cooled to –30 °C. $Al(OTf)_3$ (1.0 equiv) was added and the reaction mixture was stirred at –30 °C for 30 min under Ar. Grignard reagent (3.0 M in Et_2O, 2.0 equiv) was subsequently added and the reaction mixture was allowed to warm to r.t. while being stirred. Once the reaction was deemed complete (TLC analysis), the reaction mixture was neutralised with aq NH_4Cl and the product was extracted into EtOAc (3 × 50 mL). The organic layer was dried over Na_2SO_4, filtered and evaporated under reduced pressure. Purification by prep. TLC gave the corresponding alkenes or alcohols (Table 1).
(*Z*)-2,4-Dimethoxy-α,β-dimethylstyrene (16): The general procedure with 2′,4′-dimethoxyacetophenone (**3**; 0.217 g, 1.22 mmol) and $Al(OTf)_3$ (0.531 g, 1.12 mmol, 0.9 equiv) in CH_2Cl_2 (5 mL) and ethylmagnesium bromide (3 M, 0.7 mL, 1.7 equiv) yielded **16** (0.107 g, 46%) as a colourless oil. R_f = 0.61 (hexane–acetone, 8:2). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.06 (d, *J* = 8.2 Hz, 1 H, H-6), 6.48 (d, *J* = 2.4 Hz, 1 H, H-3), 6.46 (dd, *J* = 8.2, 2.4 Hz, 1 H, H-5), 5.55 (qq, *J* = 6.7, 1.3 Hz, 1 H, H-β), 3.83 (s, 6 H, OMe), 2.00–1.98 (m, 3 H, α-CH_3), 1.80–1.78 (m, 3 H, β-CH_3). ^{13}C NMR (151 MHz, $CDCl_3$): δ = 159.8 (C-2/4), 157.6 (C-2/4), 135.3 (C-1/α), 130.0 (C-6), 128.1 (C-1/α), 123.5 (C-β), 103.9 (C-5), 98.7 (C-3), 55.4 (-OMe), 17.0 (α-CH_3), 14.0 (β-CH_3). MS (EI, 70 eV): *m*/*z* (%) = 192.1 (100) $[M]^+$. HRMS (AP^+): *m*/*z* = 193.1233 $[MH]^+$.

(18) Chemical shift of the residual β-proton in the *E*-isomer of aryl substituted 2-butenes of δ = 5.78 and 5.90 ppm vs. δ = 5.52–5.58 ppm for the *Z*-isomer.[20] Chemical shift of the residual β-proton in the *E*-isomer of methyl substituted stilbenes was δ = 6.78 and 6.81 vs. δ ≈ 6.32 ppm for the *Z*-isomer.[21]

(19) NMR analysis of the crude product mixture before work-up indicated that the olefin was the major product.

(20) (a) Yuan, D.-Y.; Tu, Y.-Q.; Fan, C.-A. *J. Org. Chem.* **2008**, *73*, 7797. (b) Yanagisawa, A.; Nezu, T.; Mohri, S. *Org. Lett.* **2009**, *11*, 5286. (c) Nave, S.; Sonawane, R. P.; Elford, T. G.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2010**, *132*, 17096.

(21) (a) Zhu, G.; Kong, W.; Feng, H.; Qian, Z. *J. Org. Chem.* **2014**, *79*, 1786. (b) Liu, G.; Kong, L.; Shen, J.; Zhu, G. *Org. Biomol. Chem.* **2014**, *12*, 2310. (c) McLaughlin, M. G.; McAdam, C. A.; Cook, M. J. *Org. Lett.* **2015**, *17*, 10.

(22) Nakao, Y.; Imanaka, H.; Chen, J.; Yada, A.; Hiyama, T. *J. Organomet. Chem.* **2007**, *692*, 585.

(23) Cole, J. G.; Wan, P. *Can. J. Chem.* **2002**, *80*, 46.

(24) Gollnick, K.; Schnatterer, A.; Utschick, G. *J. Org. Chem.* **1993**, *58*, 6049.
(25) Liu, G.; Lu, X. *Tetrahedron* **2008**, *64*, 7324.
(26) Terao, Y.; Nomoto, M.; Satoh, T.; Miura, M.; Nomura, M. *J. Org. Chem.* **2004**, *69*, 6942.
(27) Liao, Y.-X.; Xing, C.-H.; Hu, Q.-S. *Org. Lett.* **2012**, *14*, 1544.
(28) Clayden, J.; Farnaby, W.; Grainger, D. M.; Hennecke, U.; Mancinelli, M.; Tetlow, D. J.; Hillier, I. H.; Vincent, M. A. *J. Am. Chem. Soc.* **2009**, *131*, 3410.
(29) Maruyama, K.; Matano, Y.; Katagiri, T. *J. Phys. Org. Chem.* **1991**, *4*, 501.