Cross-Coupling Hot Paper

Deutsche Ausgabe: DOI: 10.1002/ange.201504524
Internationale Ausgabe: DOI: 10.1002/anie.201504524

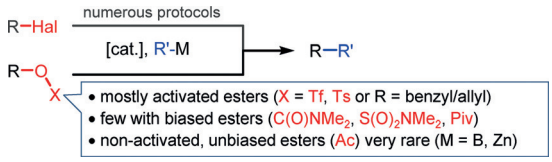
Iron-Catalyzed Cross-Coupling of Alkenyl Acetates

*Dominik Gärtner, André Luiz Stein, Sabine Grupe, Johannes Arp, and Axel Jacobi von Wangelin**

Dedicated to Professor Manfred Scheer on the occasion of his 60th birthday.

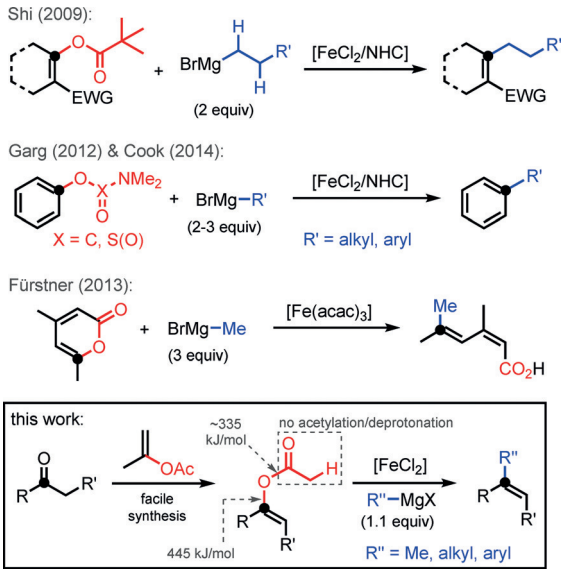
Abstract: *Stable C–O linkages are generally unreactive in cross-coupling reactions which mostly employ more electrophilic halides or activated esters (triflates, tosylates). Acetates are cheap and easily accessible electrophiles but have not been used in cross-couplings because the strong C–O bond and high propensity to engage in unwanted acetylation and deprotonation. Reported herein is a selective iron-catalyzed cross-coupling of diverse alkenyl acetates, and it operates under mild reaction conditions (0 °C, 2 h) with a ligand-free catalyst (1–2 mol %).*

The recent developments of selective iron-catalyzed cross-coupling reactions rival their conventional palladium- and nickel-catalyzed counterparts in terms of reactivity and scope while displaying higher sustainability and operational simplicity.[1] However, the use of non-activated halide-free electrophiles remains a true challenge for all cross-coupling methods (Scheme 1).[2] Oxygen-based electrophiles are especially attractive starting materials because of their ubiquitous occurrence in biomass-derived chemicals and facile preparation from alcohols or carbonyl compounds. However, the general stability of C–O bonds has limited the scope of most cross-coupling methods to activated esters (triflate, tosylate or in benzyl/allyl position). There are very few nickel- or rhodium-catalyzed protocols which employ non-activated ester derivatives at elevated temperatures.[3]



Scheme 1. Electrophiles in metal-catalyzed cross-coupling reactions. Tf = trifluoromethanesulfonyl, Ts = 4-toluenesulfonyl.

Iron-catalyzed cross-coupling was reported with alkenyl pivalates and aryl carbamates/sulfamates (Scheme 2) where the undesired carbonyl/sulfonyl attack is suppressed by steric shielding (*tert*-butyl) or electronic deactivation (OR, NR_2).[4] To the best of our knowledge, there are no reports of iron-catalyzed cross-coupling reactions of simple unbiased esters. Among them, organic acetates are an especially attractive class of cheap, halide-free C–O electrophiles bearing a small, nonhazardous leaving group, and is easily accessible by various acetylation protocols.[5] However, the considerable electrophilicity and acidity (pK_a 24), and low bond dissociation energy of the acetyl–O bond appear to prohibit, on thermodynamic grounds, the use of acetates in coupling reactions with highly basic/nucleophilic organometallic reagents. Consistently, all known cross-coupling protocols involve mild organoboron/zinc species.[3] Thus, iron-catalyzed cross-couplings between organic acetates and Grignard reagents requires an especially active catalyst which operates under kinetic control where the competing deprotonation and acetylation pathways are suppressed. We envisioned capitalizing on the combination of a) a ligand-free, low-valent iron catalyst which favors rapid oxidative addition of the non-activated electrophile, b) Grignard reagents as good nucleophiles which exhibit rapid transmetalation, and c) low temperatures/short reaction times to achieve selective cross-coupling of alkenyl acetates. Similar reaction conditions have been reported for the mechanistically different ring-opening of 2-pyrones (Scheme 2).[6]



Scheme 2. Iron-catalyzed cross-coupling of non-activated C–O electrophiles. EWG = electron-withdrawing group.

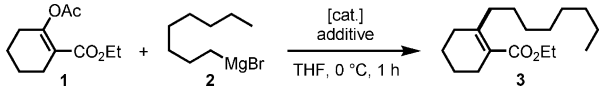
[*] M.Sc. D. Gärtner, Dr. A. L. Stein, Dr. S. Grupe, Dr. J. Arp, Prof. Dr. A. Jacobi von Wangelin
Institute of Organic Chemistry, University of Regensburg
Universitaetsstr. 31, 93040 Regensburg (Germany)
E-mail: axel.jacobi@ur.de

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201504524.

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

To provide reaction conditions which would strictly favor kinetic control, we set out to study ligand-free iron catalysts (prepared in situ by reduction of ferrous salts with strongly nucleophilic alkyl Grignard reagents) in cross-coupling reactions at 0 °C. We initially probed the feasibility of chemoselective cross-coupling of *n*-octyl magnesium bromide with the alkenyl acetate **1**, bearing a vicinal ester group, to give the tetrasubstituted olefin **3** (Table 1).[7] To our delight, iron

Table 1: Selected optimization experiments.[a]



Entry	Catalyst (mol%)	Additive (equiv)	Yield [%][b]
1	$FeCl_2$ (10)	–	31[c]
2	$FeCl_2$ (10)	LiCl (1)	62
3	$FeCl_2$ (10)	SIMes·HCl (0.2)	57
4	$FeCl_2$ (10)	IPr HCl (0.2)	62
5	$FeCl_2$ (10)	TMEDA (0.2)	82
6	$FeCl_2$ (10)	BDMAEE (0.2)	91
7	$FeCl_2$ (2)	NMP (2)	98
8	–	NMP (2)	2
9	–	–	0 (0)[d,e]
10	$FeCl_2$ (2)	NMP (2)	99[d] (97)[f]

[a] Reaction onditions: 0.25 mmol 1, 0.5 mmol **2** in 1 mL THF, 1 h, 0 °C. [b] Quantitative GC versus internal *n*-$C_{15}H_{32}$. [c] 25 °C. [d] Addition of 1.25 equiv **2** over 5 min. [e] 6 h, 60 °C, **1** was recovered. [f] 1.1 equiv **2**, −30 °C. BDMAEE = bis(2-(*N*,*N*-dimethyl-amino)ethyl)ether, NMP = *N*-methyl-2-pyrrolidinone, SIMes = 1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidene, THF = tetrahydrofuran, TMEDA = *N*,*N*,*N*′,*N*′-tetramethylethylendiamine.

precatalysts showed far superior activity to $PdCl_2$, $NiCl_2$, and CuI (< 8% yield). Donor ligands (chloride, amine, phosphine, N-heterocyclic carbene) enhanced the selectivity (entries 2–7). As expected from thermodynamic control, catalyst-free reaction conditions effected rapid acetyl deprotonation (determined by D_2O quench) and only minimal conversion of **1** (< 10%, entry 9). The optimized reaction conditions involved reaction of **1** with a slight excess of **2** (1.1–1.25 equiv, slow addition) in the presence of 2 mol% $FeCl_2$ in THF/NMP (20:1) at 0 °C for 1 hour (entry 10). The reactivity of the starting materials with different O-based leaving groups followed the order OTf > OAc > OPiv > $OCONMe_2$ (Figure 1).[4] The substrate scope of this protocol was further explored by variation of the Grignard reagents (Table 2).[7] Primary and secondary alkylMgX were effective, and *t*BuMgCl gave low conversion and some deacetylation.[8] The reaction conditions also allowed clean methyl transfer from MeMgCl (entry 4). Vinyl and phenyl magnesium bromides gave very low conversion of **1**. Halides (F, Cl), amines, alcoholates, arylmethylethers, aryl sulfides, esters, ketones, and nitriles were tolerated, with the latter two proceeding at lower temperature (< −10 °C). A wide chemical space was explored by use of various alkenyl acetates, vinylogous carbonates and anhydrides, 1-styryl acetates, and 2-pyrones (Table 3). Thermodynamic migration to the higher-substituted olefin products was not observed (entries 8–15, 18, and 19).[9]

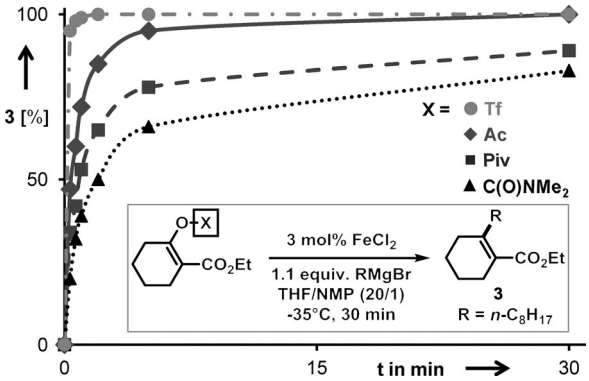
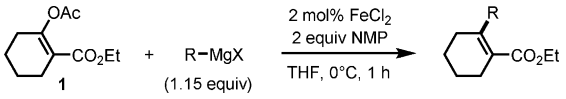
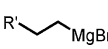
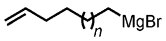
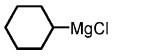
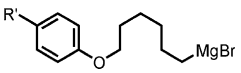
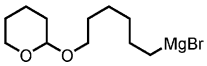


Figure 1. Comparison of O-based leaving groups (X = Tf, Ac, Piv, $CONMe_2$). Piv = pivaloyl.

Table 2: Cross-coupling of **1** with organomagnesium halides.[a]



Entry	Grignard reagent		Yield [%][b]
1		R′ = H	86[c]
2		R′ = *n*-$C_{10}H_{21}$	94[c]
3		R′ = Ph	87[c]
4	MeMgBr		85[c]
5		*n* = 1	79[c]
6		*n* = 2	83[c]
7			74
8		R′ = Cl	89[c]
9		R′ = F	68[c]
10		R′ = OMe	76
11		R′ = SMe	75
12			71
13	$TMSCH_2MgCl$		–[c]
14	$H_2C{=}CHMgBr$		< 5[c]
15	PhMgBr		16

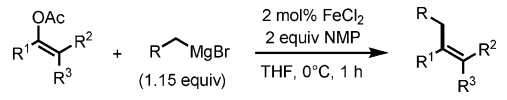
[a] Reaction conditions: 0.5 mmol **1**, 0.58 mmol (1.15 equiv) Grignard reagent, 2 mol% $FeCl_2$, 1 mmol NMP in 1.9 mL THF, 0 °C, 1 h. [b] Yield of isolated product. [c] 0.76 mmol (1.5 equiv) Grignard reagent. TMS = trimethylsilyl.

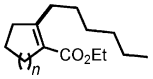
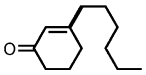
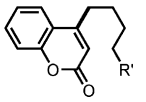
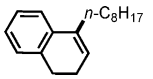
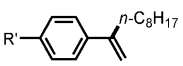
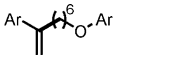
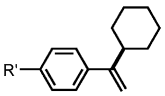
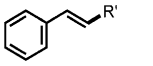
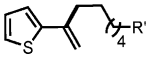
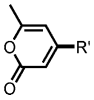
Homogeneous and heterogeneous catalysis mechanisms can be distinguished by kinetic experiments.[10] Quantitative analyses of the model reaction between **1** and **2** documented an extremely rapid onset of catalyst activity even between −35 and 0 °C without induction periods or sigmoidal curves, which could indicate nanocluster nucleations en route to particle formation.[10,11] The reaction is complete (> 97% yield) after 3 minutes at 0 °C (20 min at −35 °C) with turnover frequencies (TOF) of 3000 h^{-1}.

Kinetic poisoning studies were also in agreement with a homogeneous catalysis. The addition of mercury (100 equiv per Fe, at 45% conversion) resulted in no alteration of catalyst activity (Scheme 3).[12] A similar experiment with the π-acceptor ligand dibenzo[*a*,*e*]cyclo-octatetraene (dct; 2 equiv per Fe, at 35% conversion)[10,13] resulted in immediate and complete inhibition.[7] We thus postulate the operation of

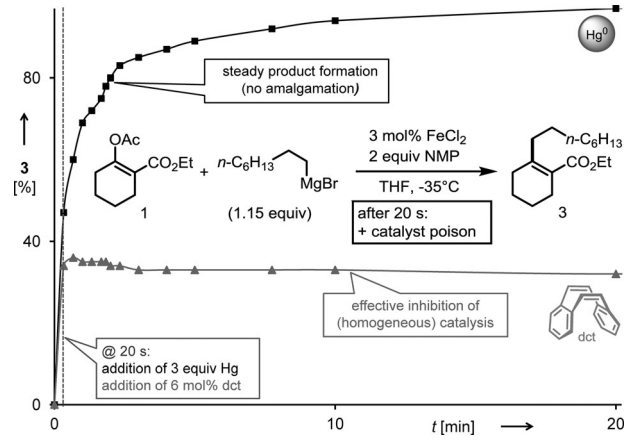
© 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Table 3: Cross-coupling of alkenyl acetates with alkylmagnesium halides.[a]



Entry	Product		Yield [%][b]
1		$n=1$	83[c]
2		$n=2$	99
3			68[d]
4		R′ = Et	86[c]
5		R′ = CH=CH$_2$	76[c]
6		R′ = (CH$_2$)$_4$O-(4-ClC$_6$H$_4$)	81[c]
7[c]			84
8		R′ = H	66[d]
9		R′ = Cl	65
10		R′ = OMe	91
11		Ar = 4-anisyl	76
12		R′ = OMe	92[e]
13		R′ = F	69[e]
14		R′ = CO$_2$Me	48[e]
15		R′ = CN	28[e]
16		R′ = n-C$_6$H$_{13}$	66[c,e,f]
17		R′ = c-C$_6$H$_{11}$	69[f]
18		R′ = Et	82
19		R′ = OC$_6$H$_4$-OMe	75
20		R′ = Me	78[d]
21		R′ = n-C$_8$H$_{17}$	49

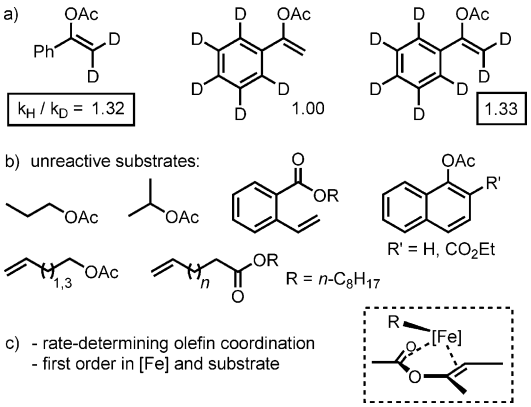
[a] Reaction conditions (see Table 2). [b] Yield of isolated product. [c] 1.5 equiv Grignard reagent; [d] 1.05 equiv *n*-hexylMgBr. [e] Cyclohexylmagnesium chloride. [f] *E*/*Z* (starting material) 3.2:1; *E*/*Z* (product) 5:1.



Scheme 3. Poisoning studies with Hg (100 equiv/Fe) and dct (2 equiv/Fe).

a homogeneous mechanism by soluble low-valent iron catalysts. In the absence of strong ligands, such iron species were reported to coordinate π-hydrocarbons.[14] In recent studies, we discovered an assisting role of olefin substituents in cross-couplings at strong C–X bonds within the electrophile.[15]

The significant secondary kinetic isotope effects (secondary KIE)[14] observed with D-labelled alkenyl acetates are consistent with a rate-determining olefin coordination, whereas catalyst–arene interactions are negligible (Scheme 4a). Accordingly, saturated and aromatic acetates and

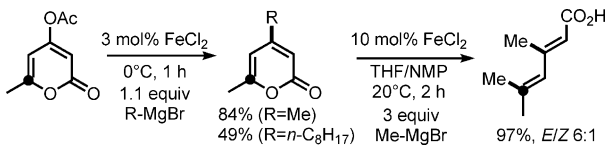


Scheme 4. The assisting role of conjugated olefin substituents.

substrates with distal olefin units did not undergo cross-coupling (< 10%), possibly because of the lack of competent coordination sites (Scheme 4b).[15,16] Alkylations of allyl acetates were reported earlier.[17a] The reaction order **1**→**3**, with respect to [$FeCl_2$], is about 1 at low concentrations (< 10 mM, < 5 mol%), and about 0.9 with respect to [**1**] under standard conditions.[7,18] Therefore, we postulate a mechanism involving rate-determining olefin coordination to the catalyst.[19] The formation of iron(I) catalysts under similar reaction conditions was recently shown by various studies.[20]

The coordination of pentadienoates to iron catalysts under similar reaction conditions was proposed, by Sun and Fürstner, to operate in the ring-opening methylation of 2-pyrones to (2*Z*)-hexadienoates.[6] Accordingly, we performed sequential cross-couplings with 4-acetoxy-6-methyl-2-pyrone. Clean acetate substitution occurred with subsequent methylative ring-opening with a vinylogous acetate acting as formal leaving group to give the (2*E*,4*E*)-hexadienoate at room temperature in excellent yield (Scheme 5).

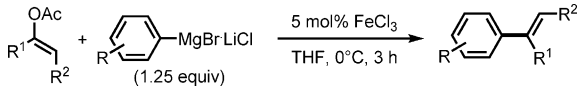
Arylations of alkenyl acetates were very sensitive to steric bulk (entry 15, Table 2).[7] Good conversions were only obtained with vinyl acetate and monosubstituted alkenyl acetates (Table 4).[21] The addition of LiCl and NMP afforded similar results.[22] The formation of arylmagnesium halides

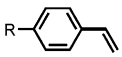
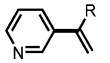
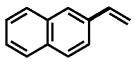
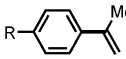
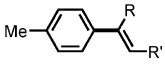
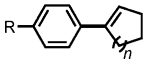


Scheme 5. Cross-coupling of 2-pyrones according to Fürstner and Sun.[6]

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Table 4: Cross-coupling of alkenyl acetates with arylmagnesium bromides.[a]



Entry	Product	R	Yield [%][b]
1		R = H	97
2		R = Me	99
3		R = OMe	82
4		R = F	53
5		R = Cl	60
6		R = CN	50
7		R = H	95
8		R = Me	96
9			96
10		R = Me	100
11		R = OMe	81
12		R = F	83
15		R = Ph, R′ = H	75
16		R = H, R′ = *n*-C_8H_{17}	69
17		R = H, *n* = 1	40
18		R = OMe, *n* = 2	15

[a] Reaction conditions: Mg (1.5 equiv), LiCl (1.5 equiv), THF (2 mL), 0 °C, ArBr (1.25 equiv), 0→20 °C over 2 h; then addition of $FeCl_3$ (5 mol %) in THF (0.5 mL) at 0 °C, alkenyl acetate (1 mmol), 3 h. [b] Yield of isolated product.

was effected by LiCl-assisted magnesium insertion to give ArMgBr·LiCl reagents which were directly employed in the subsequent cross-coupling.

In summary, we have developed a practical iron-catalyzed cross-coupling of alkenyl acetates with Grignard reagents which effectively suppresses the thermodynamically favored acylation and deprotonation as well as post-synthesis olefin migration. Kinetic studies support a homogeneous mechanism. The observed secondary KIEs suggest rate-determining coordination of the conjugated alkenyl acetate. This protocol constitutes a significant extension of the scope of metal-catalyzed cross-coupling methods which, thus far, mostly employed organohalides or activated esters as electrophiles.

Experimental Section

General procedure: An oven-dried flask was charged with the alkenyl acetate (0.50 mmol) under argon. Then, 2.0 mL of a solution of $FeCl_2$ (19.0 mg, 0.15 mmol) in NMP (0.96 mL, 10 mmol) and THF (19 mL) were added. The mixture was cooled (0 °C, ice bath) and the alkyl magnesium bromide (1 M in THF, 0.53 mmol) was added by syringe pump over 10 min. After 1 h at 0 °C, the reaction was quenched (1 mL sat. aqu. NH_4Cl) and extracted (3 × 1.5 mL ethyl acetate). The organic phases were dried (Na_2SO_4), the solvents evaporated and the residues purified by flash column chromatography (SiO_2, *n*-pentane).

Acknowledgements

This work was generously supported by the Deutsche Forschungsgemeinschaft (DFG).

Keywords: alkenes · cross-coupling · enols · Grignard reaction · iron catalysis

How to cite: *Angew. Chem. Int. Ed.* **2015**, *54*, 10545–10549
Angew. Chem. **2015**, *127*, 10691–10695

[1] a) *Catalysis without Precious Metals* (Ed.: R. M. Bullock), Wiley-VCH, Weinheim, **2010**; b) W. M. Czaplik, M. Mayer, J. Cvengros, A. Jacobi von Wangelin, *ChemSusChem* **2009**, *2*, 396; c) B. D. Sherry, A. Fürstner, *Acc. Chem. Res.* **2008**, *41*, 1500; d) C. Bolm, J. Legros, J. Le Paih, L. Zani, *Chem. Rev.* **2004**, *104*, 6217.

[2] a) B.-J. Li, D.-G. Yu, C.-L. Sun, Z.-J. Shi, *Chem. Eur. J.* **2011**, *17*, 1728; b) J. Cornella, C. Zarate, R. Martin, *Chem. Soc. Rev.* **2014**, *43*, 8081; c) B. Su, Z.-C. Cao, Z.-J. Shi, *Acc. Chem. Res.* **2015**, *48*, 886.

[3] Nickel catalysis: a) K. W. Quasdorf, X. Tian, N. K. Garg, *J. Am. Chem. Soc.* **2008**, *130*, 14422; b) B.-T. Guan, Y. Wang, B.-J. Li, D.-G. Yu, Z.-J. Shi, *J. Am. Chem. Soc.* **2008**, *130*, 14468; c) B.-J. Li, Y.-Z. Li, X.-Y. Lu, J. Liu, B.-T. Guan, Z.-J. Shi, *Angew. Chem. Int. Ed.* **2008**, *47*, 10124; *Angew. Chem.* **2008**, *120*, 10278; d) C.-L. Sun, Y. Wang, X. Zhou, Z.-H. Wu, B.-J. Li, B.-T. Guan, Z.-J. Shi, *Chem. Eur. J.* **2010**, *16*, 5844; e) G. A. Molander, F. Beaumard, *Org. Lett.* **2010**, *12*, 4022; f) J. Cornella, E. P. Jackson, R. Martin, *Angew. Chem. Int. Ed.* **2015**, *54*, 4075; *Angew. Chem.* **2015**, *127*, 4147; Rhodium catalysis: g) J.-Y. Yu, R. Kuwano, *Angew. Chem. Int. Ed.* **2009**, *48*, 7217; *Angew. Chem.* **2009**, *121*, 7353; h) H. W. Lee, F. Y. Kwong, *Synlett* **2009**, 3151; i) H. Kinuta, J. Hasegawa, M. Tobisu, N. Chatani, *Chem. Lett.* **2015**, *44*, 366.

[4] a) B.-J. Li, L. Xu, Z.-H. Wu, B.-T. Guan, C.-L. Sun, B.-Q. Wang, Z.-J. Shi, *J. Am. Chem. Soc.* **2009**, *131*, 14656; b) A. L. Silberstein, S. D. Ramgren, N. K. Garg, *Org. Lett.* **2012**, *14*, 3796; c) T. Mesganaw, N. K. Garg, *Org. Process Res. Dev.* **2013**, *17*, 29; d) T. Agrawal, S. P. Cook, *Org. Lett.* **2014**, *16*, 5080.

[5] *Science of Synthesis: Houben-Weyl Methods of Molecular Transformations*, *Vol. 20b* (Ed.: J. S. Panek), Thieme, New York, **2006**, p. 643.

[6] C.-L. Sun, A. Fürstner, *Angew. Chem. Int. Ed.* **2013**, *52*, 13071; *Angew. Chem.* **2013**, *125*, 13309.

[7] Further experimental details are given in the Supporting Information.

[8] W. M. Czaplik, S. Grupe, M. Mayer, A. Jacobi von Wangelin, *Chem. Commun.* **2010**, *46*, 6350.

[9] M. Mayer, A. Welther, A. Jacobi von Wangelin, *ChemCatChem* **2011**, *3*, 1567.

[10] a) J. A. Widegren, R. G. Finke, *J. Mol. Catal. A* **2003**, *198*, 317; b) D. Astruc, F. Lu, J. Ruiz Aranzaes, *Angew. Chem. Int. Ed.* **2005**, *44*, 7852; *Angew. Chem.* **2005**, *117*, 8062; c) R. H. Crabtree, *Chem. Rev.* **2012**, *112*, 1536.

[11] a) P. H. Phua, L. Lefort, J. A. F. Boogers, M. Tristany, J. G. de Vries, *Chem. Commun.* **2009**, 3747; b) C. Rangheard, C. de Julian Fernandez, P.-H. Phua, J. Hoorn, L. Lefort, J. G. de Vries, *Dalton Trans.* **2010**, *39*, 8464; c) A. Welther, A. Jacobi von Wangelin, *Curr. Org. Chem.* **2013**, *17*, 326; d) A. Welther, M. Bauer, M. Mayer, A. Jacobi von Wangelin, *ChemCatChem* **2012**, *4*, 1088.

[12] Iron forms metastable amalgams with max. 2–3 wt.% Fe@Hg: a) S. Mørup, S. Linderoth, J. Jacobsen, M. Holmblad, *Hyperfine Interact.* **1992**, *69*, 489; b) S. Linderoth, S. Mørup, *J. Phys. Condens. Matter* **1992**, *4*, 8627.

[13] a) D. R. Anton, R. H. Crabtree, *Organometallics* **1983**, *2*, 855; b) G. Franck, M. Brill, G. Helmchen, *J. Org. Chem.* **2012**, *89*, 55.

[14] a) F. H. Westheimer, *Chem. Rev.* **1961**, *61*, 265; b) F. A. Carey, R. J. Sundberg, *Advanced Organic Chemistry*, *Part A*, 3rd ed., Plenum Press, New York, **1990**.

[15] a) E. O. Fischer, H. Werner, *Angew. Chem. Int. Ed. Engl.* **1963**, *2*, 80; *Angew. Chem.* **1963**, *75*, 94; b) A. Fürstner, R. Martin, H.

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Krause, G. Seidel, R. Goddard, C. W. Lehmann, *J. Am. Chem. Soc.* **2008**, *130*, 8773; c) K. Weber, E.-M. Schnöckelborg, R. Wolf, *ChemCatChem* **2011**, *3*, 1572; d) M. Stein, J. Wieland, P. Steurer, F. Tölle, R. Mülhaupt, B. Breit, *Adv. Synth. Catal.* **2011**, *353*, 523.

[16] a) S. Gülak, A. Jacobi von Wangelin, *Angew. Chem. Int. Ed.* **2012**, *51*, 1357; *Angew. Chem.* **2012**, *124*, 1386; b) S. Gülak, T. N. Gieshoff, A. Jacobi von Wangelin, *Adv. Synth. Catal.* **2013**, *355*, 2197.

[17] a) M. Mayer, W. M. Czaplik, A. Jacobi von Wangelin, *Adv. Synth. Catal.* **2010**, *352*, 2147; b) D. Gärtner, H. Konnerth, A. Jacobi von Wangelin, *Catal. Sci. Technol.* **2013**, *3*, 2541.

[18] The reaction is of higher order ($\approx$2–3) in Grignard reagent **2** and approaches 0 at higher concentrations (>0.2 M, >1.2 equiv). The reaction order in substrate **1** is about 0 at concentrations of greater than 0.5 M.

[19] We cannot exclude the operation of a radical mechanism. The observation of inhibition by TEMPO does not imply the presence of radical intermediates as TEMPO also reacts with the Grignard reagent itself. For the discussion of radical mechanisms, see: a) U. Jahn in *Radicals in Synthesis III*, *Vol. 320* (Ed. M. Heinrich, A. Gansäuer), Springer, Berlin, Heidelberg, **2012**, p. 191; b) B. Hölzer, R. W. Hoffmann, *Chem. Commun.* **2003**, 732.

[20] With aryl/benzylmagnesium halides: a) R. B. Bedford, *Acc. Chem. Res.* **2015**, *48*, 1485; b) A. Hedström, Z. Izakian, I. Vreto, C.-J. Wallentin, P.-O. Norrby, *Chem. Eur. J.* **2015**, *21*, 5946; c) G. Lefèvre, A. Jutand, *Chem. Eur. J.* **2014**, *20*, 4796. With β-hydrogen-containing alkylmagnesium halides: d) M. Guisán-Ceinos, F. Tato, E. Bunuel, P. Calle, D. J. Cardenas, *Chem. Sci.* **2013**, *4*, 1098; e) J. Kleimark, A. Hedstrøm, P.-F. Larsson, C. Johansson, P.-O. Norrby, *ChemCatChem* **2009**, *1*, 152.

[21] Arylations of alkenyl halides under similar reaction conditions: W. M. Czaplik, M. Mayer, A. Jacobi von Wangelin, *ChemCatChem* **2011**, *3*, 135.

[22] NMP in iron-catalyzed cross-couplings: a) G. Cahiez, H. Avedissian, *Synthesis* **1998**, 1199; b) G. Cahiez, S. Marquais, *Pure Appl. Chem.* **1996**, *68*, 53; c) W. Dohle, F. Kopp, G. Cahiez, P. Knochel, *Synlett* **2001**, 1901. LiCl-mediated Grignard formation: d) F. M. Piller, A. Metzger, M. A. Schade, B. A. Haag, A. Gavryushin, P. Knochel, *Chem. Eur. J.* **2009**, *15*, 7192.

Received: May 19, 2015
Published online: July 14, 2015

 © 2015 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim