Manganese-Catalyzed Cross-Coupling Processes

Xiaoping Liu, Florian Jaroschik, Marc Taillefer

► To cite this version:

Xiaoping Liu, Florian Jaroschik, Marc Taillefer. Manganese-Catalyzed Cross-Coupling Processes. Manganese Catalysis in Organic Synthesis, Wiley, 2021, 10.1002/9783527826131.ch8 . hal-03455760

HAL Id: hal-03455760

<https://hal.science/hal-03455760>

Submitted on 29 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Manganese-Catalyzed Cross-Coupling Processes

By Xiaoping Liu, Florian Jaroschik* and Marc Taillefer*

Affiliation

Mr. X. Liu, Dr. F. Jaroschik, Dr. M. Taillefer

ICGM – Univ Montpellier - ENSCM

Montpellier, 34080 (France)

Keywords: manganese, cross-coupling, homogeneous catalysis, mechanism, trace metal contamination, C-C bond formation, Kumada coupling, Stille coupling, biaryls, C-heteroatom bond formation, arylation

Abstract: This chapter describes recent developments in the manganese-catalyzed cross-coupling reactions for the formation of C-C or C-heteroatom bonds, including C-N, C-O, C-S and C-B bonds. The nature of the organic halide and the organometallic coupling partner (organolithium, Grignard or organostannyl reagents) are important parameters in these reactions. Mechanistic studies are discussed as well as the recently arisen question about the influence of trace-metal contamination in certain reactions.

1. Introduction

The use of highly abundant, cheap and non-toxic Mn salts in cross-coupling reactions has emerged over the last 25 years. In contrast to Pd- or Ni-catalyzed processes, the Mn-catalyzed reactions are less well understood from a mechanistic point of view, the scope is not fully exploited and most of the reactions are based on simple Mn halide salts without any specific ligand. We herein describe recent applications of MnCl₂ in the catalytic C-C coupling of aryl, vinyl or alkyl halides with various organometallic reagents. This first part includes Kumada and Stille-type cross-couplings as well as the homo and heterocoupling of different types of organometallic species (Li, Mg, Sn) under oxidative conditions. In a second part, the recently emerging field of Mn-catalyzed arylation or alkylation of nitrogen-, sulphur-, oxygen- and boron-based nucleophiles is presented. In both parts, selected mechanistic pathways as well as

the possible influence of contamination or presence of other metals in small quantities are discussed. Coupling reactions involving hydrogen formation via C-H activation or HAT processes are not considered in this chapter. Several reviews have covered this research area [1-4], including a nice comprehensive review by Valyaev and Lugan and a review on the use of Grignard reagents in Mn-catalyzed cross-coupling reactions by Cahiez, both describing the literature until 2015 [3,4]. This chapter aims to provide a non-exhaustive overview on the development of different Mn-catalyzed cross-coupling processes over the last 20 years with the literature leading up to the end of 2019.

2. C-C bond formation via Mn-catalyzed cross-coupling reactions

2.1 Mn-catalyzed Kumada cross-coupling reactions

2.1.1 Arylhalides with Grignard reagents

In 1999, Cahiez reported that activated aryl halides, especially cheap and widely available aryl chlorides, could undergo a cross-coupling with different Grignard reagents with a simple manganese catalyst to form the corresponding biaryls (Scheme 1) [5]. The list of efficient activating groups involved nitriles, imines or oxazolidines in the *ortho* position, whereas a stilbene moiety used as *ortho* substituent provided lower yields. A substrate bearing an imine group in the *para* position was also a suitable reagent, whereas for its isomer with the imine in the *meta* position no reaction took place. In this initial study, aryl halides containing ester or amide groups could not be employed, mainly due to side reactions on the carbonyl functionality. In general, good to moderate results were obtained with several aryl, 1° and 2° alkyl or alkenyl Grignard reagents and the reaction was successful with chloride, bromide, fluoride and methoxide as leaving group. Interestingly, with the aryl fluoride reagent the reaction was slower than with the other halides, providing first evidence that a mechanism other than nucleophilic aromatic substitution might be at play. It is important to note that blank experiments in the absence of metal catalyst with different substrates showed no or very slow reactions, leading to the assumption that the metal-catalyzed reaction was the largely favoured process compared to an S_NAr pathway.

Scheme 1. First example of Mn-catalyzed Kumada cross-coupling between activated arylchlorides and various Grignard reagents reported by Cahiez [5].

In an attempt to extend this chemistry to *ortho*-chloroaryl ketones, as for example *o*-chlorovalerophenone or *o*-chlorobenzophenone, the limitation to aryl Grignard reagents became evident (Scheme 2) [6]. With PhMgCl high yields of the cross-coupled biaryls were obtained, however, with a more reactive alkyl Grignard reagent, such as *n*-BuMgCl, only a low yield of 45% was observed, due to competitive reaction with the carbonyl group. This problem was overcome by replacing the Grignard reagent by stoichiometric or excess amounts of less reactive organomanganese reagents RMnCl in the coupling reaction. This way a large range of *ortho*-chloroaryl ketones could be coupled with different alkyl and arylmanganese compounds.

Scheme 2. Extension of Mn-catalyzed cross-coupling to *ortho*-chloroaryl ketones [6].

A further study indicated that *o*-halobenzoyl chlorides could be efficiently reacted with diorganyl magnesium complexes R₂Mg•LiCl under MnCl₂ catalysis to provide tandem cross-coupling products (Scheme 3) [7]. This reaction worked in general best with *o*-chlorobenzoyl chlorides in the case of dialkylmagnesium compounds, whereas with diarylmagnesium

compounds higher yields were observed for the bromo and iodobenzoyl chloride derivatives. No coupling reaction occurred in the case of *meta*- or *para*-halobenzoyl chlorides. The limitation of this process resides in the introduction of the same group on the ring and on the carbonyl group.

Scheme 3. Mn-catalyzed tandem cross-coupling of diorganomagnesium complexes with *o*-halobenzoyl chlorides [7].

Nearly twenty years after the initial report by Cahiez, two contributions by Madsen in 2017 provided some synthetic extensions and new mechanistic insights into the field of MnCl_2 -catalyzed Kumada cross-coupling reactions [8,9]. The coupling of *para*-halo benzonitrile reagents with the cyclohexyl Grignard complex was first investigated (Scheme 4) [8]. In this case, the chloride compound provided the highest yield with 94%, whereas with the bromide analogue only a moderate 45% yield was obtained and no reaction was observed with iodide or fluoride substrates. Furthermore, Madsen showed that an ester group in the *para* position was a suitable activating group, providing 65% yield of coupling product, but an amide group was not tolerated similarly as observed by Cahiez (Scheme 1) [5]. Also, *p*- CF_3 or *p*- NO_2 groups did not provide the desired cross-coupled product. The *p*-chlorobenzonitrile substrate was then used for testing the influence of solvent and temperature on the reaction outcome, showing that THF provided the best results and that the reaction was fast above 6 °C, whereas below 0 °C nearly no reaction took place. This reaction could be conveniently carried out at room temperature

providing the cross-coupling of various aryl and alkyl Grignard reagents with *ortho*- or *para*-chlorobenzonitriles, while allyl Grignards gave no reliable results (Scheme 4).

Scheme 4. Extending the scope of activated aryl halide substrates in MnCl₂-catalyzed cross-coupling reactions [8].

A competition experiment using PhMgCl and cyclohexylMgCl in combination with *p*-chlorobenzonitrile provided by far the *p*-cyclohexylbenzonitrile as major product, in agreement with the higher reactivity of alkyl vs aryl Grignard reagents. No remarkable difference was observed in the reactivity of *p*-CN or *p*-CO₂Me arylhalide substrates with cyclohexylMgCl, as shown in another competition experiment, affording the coupling products in equal yields. The influence of an additional methyl group in the aromatic ring was then investigated. No remarkable difference was obtained in the case of the *p*-CN substrate having a methyl group in the *meta* position with respect to the substrate without methyl group (Scheme 5). However, an interesting result was the reaction of 1-chloro-3-cyano-4-methylbenzene with cyclohexylMgCl providing the coupled product in 62% yield, whereas the similar substrate without the methyl group gave no conversion due to the cyano group in the *meta* position (Scheme 5).

Scheme 5. Influence of methyl substituent in the cross-coupling reaction of chlorobenzonitriles [8].

Further variation of the reaction conditions, i.e. change of the solvent from THF to diethyl ether and using microwave heating in sealed vials with an increase in Grignard concentration (3 M), provided some new substrates in the MnCl₂-catalyzed Kumada cross-coupling reaction [9]. Non-activated substrates, such as different iodotoluenes could now be coupled with moderate to good yields with phenylmagnesium bromide, however, other electron-donating substituents (OMe, NMe₂) on the aryl iodides provided lower yields (Scheme 6). Other halides (Br, Cl) were less efficient and triflates did not work at all. The reaction could also be conducted in 2-methyl-THF and conventional heating was also possible, albeit with longer reaction times (18h at 120 °C).

Scheme 6. MnCl₂-catalyzed cross-coupling with non-activated aryl halides [9].

Mechanistic studies on these MnCl₂ catalyzed Kumada cross-coupling reactions are scarce. Madsen has provided some important contributions to the understanding of these processes. Several radical clock experiments were conducted to obtain insights on the involvement of

radical species in the reaction course [8,9]. Substrates containing allyl ether or but-3-enyl moieties were reacted with Grignard reagents under different reaction conditions (solvent, temperature) to provide mixture of compounds from which the cyclised products were isolated as major compounds, indicative of radical intermediates (Scheme 7a,b). Only small amounts of cross-coupled products were observed. Furthermore, under microwave conditions, the reaction in the presence of 1,4-cyclohexadiene provided mainly the dehalogenation product, thus being another indication of radical formation (Scheme 7c).

Scheme 7. Mechanistic investigations: Radical clock experiments (a,b) and radical trapping with 1,4-cyclohexadiene (c) [8,9].

From these experiments, Madsen deduced that aryl radical species might form in the reaction course, leading to the proposed reaction mechanism of an $S_{RN}1$ reaction, shown in Scheme 8. The first step would involve the reduction of the arylhalide by an *in situ* formed triorganomanganate complex **A**, to yield radical anion **B**, which would lose a halide anion to form the intermediate free aryl radical **C**. Radical processes triggered by triorganomanganate complexes have been studied since the 1990s by Oshima [10]. Radical **C** would be attacked by either the nucleophilic Grignard reagent or by **A**. This rapid reaction would be followed by a single-electron-transfer (SET) from the resulting radical anion **D** to another starting arylhalide. The limited scope of this transformation under the room temperature conditions in THF can be attributed to the necessity of having an EWG in the *ortho* or *para* position, responsible for

stabilising the radical anion and facilitating the dehalogenation process (see Scheme 4). On the other hand, in diethyl ether higher temperatures are presumably necessary as the EDG destabilises the radical anion and also makes the aryl radical less electrophilic for the reaction with another Grignard or triorganomanganate complex (see Scheme 6).

Scheme 8. Mechanistic proposal of an S_{RN1} reaction involving free aryl radicals for Mn-catalyzed Kumada cross-coupling [8,9].

In this context, it should be mentioned that some $MnCl_2$ -catalyzed coupling reactions occur with C-O cleavage, for which radical mechanisms based on triorganomanganate complexes have been proposed: (i) In the $MnCl_2$ -catalyzed coupling of 2-iodobenzofurane with Grignard reagents the ring opening of the benzofuran moiety was proposed, based on the literature, to proceed via mixed manganate complex **E** obtained from iodo/manganese exchange between starting compound and an *in situ* formed triorganomanganate complex (Scheme 9a)[11]; (ii) For the $MnCl_2$ -catalyzed three component coupling of benzonitriles, Grignard reagent and THF, there is experimental and theoretical evidence, that the mechanism for the formation of the final product involves alpha-manganated THF **F**. Reductive coupling of two phenyl groups on the manganese(IV) center is followed by transfer of the remaining phenyl group onto the THF moiety with concomitant ether cleavage to afford manganate(II) complex **G**, which is stabilised by another $PhMgCl$ moiety. Complex **G** can then react with different nitriles to afford the three-component coupling product (Scheme 9b)[12].

Scheme 9. C-O bond cleavage involving triorganomanganate-triggered radical processes in MnCl₂-catalyzed coupling reactions [11,12].

2.1.2 Heteroarylhalides with Grignard reagents

In 2007, Rueping reported on the efficient Mn-catalyzed cross-coupling of several nitrogen-containing heterocyclic chlorides with phenyl and alkylmagnesium chlorides under mild conditions [13]. Various 2- or 4-chloroquinoline derivatives were successfully reacted with primary or secondary alkyl Grignard reagents as well as phenylmagnesium chloride in the presence of 1-5 mol% of MnCl₂ as catalyst between 0 °C and room temperature with short reaction times (often between 1.5 and 4 h) (Scheme 10). MnCl₂ sources of different quality, ranging from 99.999% to 98% purity, provided the same yields. Depending on the substrate, a 2-4 fold excess of Grignard reagent was required to obtain good yields. Various other heterocyclic substrates such as quinazoline, benzothiazole, purine, pyrimidine, quinoxaline and pyridine could also be successfully employed, but the yields were generally lower with less conjugated heterocycles.

Scheme 10. Mn-catalyzed cross-coupling of N-heterocyclic chlorides with Grignard reagents [13].

This initial study was extended to the coupling of various pyridine and pyrazine derivatives with alkyl Grignard reagents by Matson in 2018 [14]. Preliminary results concerning the coupling of 2-chloropyridine with *n*-butylmagnesium chloride (2.6 equivalents) at room temperature revealed that among numerous first row transition metal halides (3 mol%) tested as catalysts, only MnCl_2 gave efficient cross-coupling in 88% yield. Furthermore, it was shown that with lithium or zinc reagents, for example *n*-BuLi, PhLi or PhZnBr, lower yields or no cross-coupling product were obtained. In the absence of Mn catalyst no reaction occurred. The coupling reaction was successful with several aliphatic Grignard reagents (Scheme 11), however the reaction furnished low yields with methylmagnesium chloride and no product with trimethylsilylmethylmagnesium chloride or tertiary Grignard reagents. An improved yield of 90% was obtained for the reaction of PhMgCl with 2-chloropyridine at higher temperature and longer reaction time (c.f. 58% yield in Scheme 10). The fact that attempts with 3- or 4-halopyridines provided the cross-coupling products only in low yields led the authors to the assumption that the nitrogen atom in the pyridine ring might act as a directing group in these transformations. It was further observed that the influence of the halide in the 2-halopyridine on the reaction rate follows the often observed order $\text{Cl} > \text{Br} \gg \text{F}$ (see 2.1.1). The substrate scope was further extended to substituted pyridines, showing that electron-withdrawing groups, such as 5-F or 5- CF_3 groups were well tolerated and electron-donating methyl groups to a lesser extent. In the case of the CF_3 group, the reaction provided high yields with shorter reaction times and the amount of Grignard reagent could be reduced to 1.2 equivalents. With the even more activated 2-chloropyrazine heterocycle, highly efficient cross-coupling was observed with

primary and secondary alkyl Grignard reagents and even PhMgBr reacted at r.t. in only 3 h to provide a 89% product yield.

Scheme 11. Extension of Mn-catalyzed cross-coupling of pyridine and pyrazine derivatives with Grignard reagents [14].

2.1.3 Vinyl(pseudo)halides with Grignard reagents

Following a preliminary report on the MnCl_2 -catalyzed cross-coupling reaction of a vinyl iodide with phenylmagnesium chloride (Scheme 12a) by Cahiez and Normant in 1976 [15], Oshima showed in 1987 that vinyl triflates could undergo cross-coupling with an excess of Grignard reagent in the presence of Li_2MnCl_4 salt at 0 °C (Scheme 12b) [16]. Depending on the nature of the Grignard reagent, moderate to high yields were obtained, often accompanied by some reduction or homocoupling products. The best results were observed with phenyl, benzyl and allyl magnesium halides. A postulated mechanism was based on the existing literature, involving a Mn/triflate exchange by reaction of a triphenylmanganate complex with the iodoalkene to afford intermediate **H**, followed by reductive elimination.

Scheme 12. Early work by Cahiez/Normant (a) and Oshima (b) on the Mn-catalyzed cross-coupling of vinylhalides or triflates with Grignard reagents [15,16].

In 1998, Cahiez reported on the efficient and highly stereoselective coupling of chloroenynes with an excess of primary, secondary or tertiary aliphatic Grignard reagents (Scheme 13) [17]. Use of an excess of tetrasubstituted urea derivatives, such as *N,N*-dimethylpropylene urea (DMPU), turned out to be crucial for high product yields. Under these conditions, phenylmagnesium chloride gave only a low 25 % yield and non-conjugated vinyl chlorides did not react. The reaction showed good chemoselectivity, e.g. aliphatic chloride or nitrile groups and free alcohols were tolerated. The procedure could also be extended to a chlorodiene substrate to afford the coupled product in high 80% yield. Interestingly, PdCl₂ or NiCl₂ based catalysts provided much lower yields in the coupling of chloroenyne with *n*-butylmagnesium chloride than the MnCl₂/DMPU system.

Scheme 13. Mn-catalyzed cross-coupling of chloroenynes or chlorodiene with Grignard reagents [17].

An extension towards the stereoselective coupling of simple, non-activated alkenyl halides with various aryl Grignard reagents was reported in 2008 by Cahiez (Scheme 14) [18]. Higher catalyst loadings (10 mol% of MnCl_2) and sometimes temperatures up to 50 °C were required, especially with β,β -disubstituted alkenyl iodides. Aryl Grignard reagents bearing an electron-withdrawing group (*p*-fluoro) or sterically more hindered aryl groups (*o*-tolyl) provided lower yields, whereas electron-donating groups (*p*-methoxy, *p*-NMe₂) did not significantly influence the outcome. In these reactions, alkenyl bromides and iodides provided good results, whereas chlorides were much less reactive. The vast majority of substrates provided a highly stereospecific reaction outcome, however, the (*Z*)-pyridinyl-alkenyl iodide led to complete inversion of the stereochemistry, providing the cross-coupled (*E*)-alkene in 71% yield. It should further be noted, that in contrast to many MnCl_2 -catalyzed reactions, which frequently employ more soluble lithium manganate Li_2MnCl_4 (see Scheme 12), in this case, addition of LiCl slowed down the reaction significantly from 3 h to 18 h.

Scheme 14. Mn-catalyzed stereospecific cross-coupling of non-activated alkenyl halides with aryl Grignard reagents [18].

Some alkyl Grignard reagents, such as methyl or cyclohexyl magnesium halides, could also be successfully coupled with styryl bromide (Scheme 15). However, with propylmagnesium bromide only reduction and homocoupling of the alkenyl derivatives was observed due to the ready β -hydrogen elimination. A solution to this problem was found by the addition of 8 equivalents of DME or TMEDA to the reaction mixture. Under these conditions, the reaction of 1-iodo-1-octene with PrMgBr the cross-coupled product was obtained in 55-59% yield after heating for 18 h (Scheme 15) [18].

Scheme 15. Mn-catalyzed cross-coupling of non-activated alkenyl halides with alkyl Grignard reagents [18].

In addition to alkenyl halides and triflates, the groups of Comasseto and Gariani have shown that alkenyl tellurides could also be employed in the cross-coupling reaction with aryl Grignard reagents under a combined Mn/Cu catalysis [19]. The optimization of reaction conditions has shown that a 1:1 mixture of MnCl₂ with CuI (5 mol% each) provided good to moderate yields in the coupling of various alkenyl tellurides with phenylmagnesium chloride under mild conditions (Scheme 16). In contrast, using only MnCl₂ or only CuI provided very low yields. The majority of substrates concerned conjugated alkenyl tellurides based on styrene, enyne or α,β -unsaturated carbonyl compounds. Even tetrasubstituted alkenyl telluride substrates could be employed, as well as *p*-substituted aryl Grignard reagents with electron-withdrawing or donating substituents. Apart from the disubstituted ester substrate, which undergoes full inversion of the double bond configuration, all the other substrates reacted with a retention of the double bond configuration. The mechanism of this transformation still needs to be inquired.

Scheme 16. Mn/Cu-catalyzed cross-coupling of alkenyl tellurides with aryl Grignard reagents [19].

2.1.4 Conclusion on Mn-catalyzed Kumada cross-coupling reactions

Mn-catalyzed Kumada cross-coupling reactions of aryl, heteroaryl and vinyl halides or pseudohalides with a variety of Grignard reagents has made considerable progress over the last twenty years, even though only a limited amount of heterocyclic halide compounds (only nitrogen heterocycles) has been investigated. Recent contributions on the mechanism in the case of aryl halides have opened up the way for further progress. The generality of the

implication of radical species in these transformations still has to be explored. Further mechanistic studies, especially supported by theoretical studies, are required to elucidate the role of coordinating solvents (such as DMPU or TMEDA) in some of the transformations and to improve the potential of these easy to perform cross-coupling reactions.

2.2 Mn-catalyzed Stille cross-coupling reactions

In 1997, the first report on a Mn-catalyzed Stille coupling involving various organostannanes (vinyl, styryl, aryl, acetylenic) and styryl or aryl iodides showed the importance of the presence of one equivalent of NaCl or KCl to avoid homocoupling of stannanes (Scheme 17) [20]. Whereas MnBr₂ gave the best yields, MnCl₂ provided lower yields and MnI₂ did not yield any coupled product. High temperatures (90-120 °C), slow addition of organostannanes and polar solvents such as NMP or DMF were necessary to obtain the cross-coupled products in high yields. Aryl bromides or triflates did not lead to the coupling product. In the same study it was shown that the results are analogous to a procedure involving catalytic CuI instead of MnBr₂.

Scheme 17. First reported Mn-catalyzed Stille cross-coupling reaction by Kang [20].

In an attempt to repeat the cross-coupling reaction between *p*-tolyl iodide and phenylstannane under exactly the same Mn-catalyzed conditions with extremely pure reagents and solvents, Madsen in 2017 did not observe any product formation, despite several attempts. (Scheme 18).[9] In addition, experiments with CuI or NiCl₂ as catalysts were also unsuccessful. However, in the presence of very small amounts of Pd(OAc)₂ (down to 0.003 mol%), the cross-coupling product was obtained in moderate to good yields. This report casts therefore some doubt on the

involvement of Mn catalysis in the original report and some Pd contamination may be the actual catalyst source.

Scheme 18. Mn- or Pd-catalyzed cross-coupling reaction? Kang vs Madsen [9,20].

One year after the initial report, Kang reported in 1998 on the Mn-catalyzed cross-coupling and on the carbonylative cross-coupling of various organostannanes with phenyl or styryl iodonium salts (Scheme 19) [21]. Moderate to high yields were obtained with MnCl_2 (5 mol%) after refluxing the organostannane with iodonium salt under a CO atmosphere in an NMP/THF mixture. In this reaction MnBr_2 was not active and the yields were significantly lower when only NMP or THF was employed.

Scheme 19. Mn-catalyzed carbonylative cross-coupling with iodonium salts [21].

Twenty years later, Falck disclosed a report on the Mn-catalyzed stereospecific Stille cross-coupling in the reaction of protected α -alkoxy(tri-*n*-butyl)stannanes with organic electrophiles (Scheme 20) [22]. The $\text{MnCl}_2/(S)\text{-BnCH}_2\text{PyBOX}$ system, employed in 50 mol%, mediated the coupling of various aryl iodides bearing electron-rich or electron-withdrawing groups and even heteroaryl iodides with the organostannanes (Scheme 20a). The reaction was rather slow (2-4 days), even when performed at 70 °C. Interestingly, no Newman-Kwart rearrangement of the thiocarbamate occurred, which is often observed in copper(I) thiophene-2-carboxylate (CuTC) mediated cross-couplings. Importantly, with enantiomerically enriched substrates the reaction proceeded with a variety of electrophiles with >98% retention of the configuration (Scheme 20b). Furthermore, an adjacent asymmetric center as in the acetonide substrate had no influence

on the stereofidelity of the reaction (Scheme 20c). A large variety of electrophiles (allylic, aryl, heteroaryl and olefinic) could be employed and the reaction conditions were compatible with many functionalities, such as nitro, cyano, acetyl, methoxy, CF₃, Br or I groups. The stereochemistry of olefinic iodides was also maintained in the product.

Scheme 20. Scope of stereospecific Mn-mediated cross-coupling with alkylstannanes [22].

In order to improve the reaction kinetics, it was found that a mixture of MnCl₂ (15 mol%) with Cu(OTf)₂ (20 mol%) and Jackphos (15 mol%) as ligand was superior to the Mn/Pybox-only system. Addition of KF and K₃PO₄ provided cleaner products under overall significantly faster and milder conditions (6-24 h, room temperature) (Scheme 21) [22].

Scheme 22: Proposed mechanism for Mn/Cu-catalyzed Stille coupling [22].

To date only very few examples of Mn-catalyzed Stille coupling reactions have been reported, which have led, in one case, to some controversy about the catalytic metal species involved in the reaction process. More in-depth mechanistic studies would be required to understand the role of the Mn catalyst in these reactions and to reduce the catalytic charge.

2.3. Mn-catalyzed coupling reactions of organometallic reagents under oxidative conditions

The Mn-catalyzed oxidative homo or heterocoupling of two organometallic species is an intriguing transformation with high synthetic potential. The general reaction scheme is the mixing of two equivalents of the same or of different organometallic complexes (R-Li, R-MgX, R-SnR'₃) in the presence of a catalytic amount of MnCl₂ or MnCl₂·2Li (often between 10-20 mol%) at low temperature followed by addition of an oxidizing reagent, such as iodine, dichloroethane or dry air, to afford the corresponding homo or heterocoupled products (Scheme 23). This reaction has been best explored for the synthesis of biaryls, but other coupling processes have also been successfully conducted, involving for example alkynyl, alkenyl or benzyl organometallics.

Scheme 23. General scheme for Mn-catalyzed oxidative homo or heterocoupling of organometallics.

2.3.1 Homocoupling reactions

The first oxidative homocoupling of *in situ* generated vinyl lithium reagents, catalyzed by small amounts of MnCl₂, was reported in 1975 by Cahiez and Normant (Scheme 24) [24]. In this case, the iodobutane, produced during the halogen-lithium exchange between vinyl iodide and *n*-BuLi, has been proposed to act as the oxidizing agent. Interestingly, in THF only the heterocoupling product was obtained whereas from the reaction in diethylether the dienes were isolated in high yields.

Scheme 24. Mn-catalyzed homocoupling of *in situ* generated vinyl lithium reagents [24].

A more classical oxidizing agent, i.e. elemental iodine, was used by Kang and coworkers in 1999, for the homocoupling of various organotin reagents under manganese catalysis. Elevated temperatures were necessary (NMP, 100 °C) to obtain the coupled products in good yields (Scheme 25) [25].

Scheme 25. Mn-catalyzed homocoupling of organostannanes under oxidative conditions [25].

Ten years later, in 2008, Cahiez showed in a seminal contribution that atmospheric oxygen could be employed in combination with Grignard reagents to access a wide range of homocoupled products in very high yields (Scheme 26) [26]. Among the limitations were sterically hindered arenes, e.g. mesityl groups, or very electron-poor arenes, e.g. C_6F_5 , which did not provide the homocoupling products.

Scheme 26. Scope of Mn-catalyzed homocoupling of Grignard reagents using air as oxidant [26].

In the following year, the group of Zhou showed that dichloroethane (DCE) was also a suitable oxidizing reagent for the homocoupling of various aryl magnesium chlorides, even though the yields were generally lower than with dry air [27].

The combination of Mg/Zn superbases with several arenes or heteroarenes to generate *in situ* Grignard reagents, provided the homocoupling products in the presence of MnCl_2 and oxygen

as shown by Daugulis in 2010 (Scheme 27) [28]. Even an ester group was well tolerated under these conditions. It should be noted that these superbases could also be employed in combination with NiCl_2 or CoCl_2 and oxygen to furnish efficient homocoupling reactions.

Scheme 27. Mn-catalyzed homocoupling of *in situ* generated Grignard reagents from arenes using air as oxidant [28].

In the following years, the use of organic quinone-type oxidizing agents was reported in homocoupling reactions. In 2014, Peng showed the homocoupling of *in situ* generated organomanganese halides with 3,3,5,5-tetra-*tert*-butyl-[1,1-bi(cyclohexylidene)]-2,2,5,5-tetraene-4,4-dione [29]. In 2015, Knochel reported the stoichiometric *in situ* preparation of diaryl and di(heteroaryl)manganese complexes which could oxidatively couple to the diaryl compounds in the presence of chloranil (Scheme 28) [30]. A good functional group tolerance was observed under these conditions. Interestingly, air or DCE as oxidizing agents did not provide the homocoupling products under these conditions.

Scheme 28. Homocoupling of *in situ* generated diarylmanganese complexes with chloranil as oxidizing agent [30].

In 2019, the combination of dry air and *in situ* generated organolithiums (via Li/halide exchange) was reported for the successful Mn-catalyzed homocoupling reaction of aryl, heteroaryl or benzyl halides (Scheme 29) [31]. The best yields were obtained with aryl iodides or bromides, however, in certain cases chlorides also furnished satisfactory yields. *tert*-butyllithium provided better results than *sec*- or *n*-butyl lithium.

Scheme 29. Mn-catalyzed homocoupling of *in situ* generated lithium reagents by Li/halide exchange using air as oxidant.[31]

In addition, substrates, such as alkynes, certain arenes (anisole, trifluorotoluene) or ferrocene, could be employed after deprotonation with the organolithium base (Scheme 30) [31].

Scheme 30. Mn-catalyzed homocoupling of *in situ* generated lithium reagents by deprotonation using air as oxidant [31].

2.3.2 Heterocoupling reactions

With respect to heterocoupling reactions, Cahiez demonstrated for the first time that two Grignard reagents with different electronic or steric properties could be coupled using MnCl_2 (20 mol% with respect to the excess reagent) and dry air at low temperature (0°C) (Scheme

31) [32]. The combination of alkynyl/aryl or alkynyl/alkenyl Grignards, but also two different alkynyl or alkenyl Grignards in a 2.5:1 ratio gave good results. In the case of two different aryl Grignard reagents one of the coupling partners needed to be an electron-rich arene.

Scheme 31. Mn-mediated oxidative heterocoupling of Grignard reagents with air [32].

In 2017, Madsen further examined this heterocoupling reaction of aryl Grignard reagents by lowering the catalyst loading (20 mol% with respect to the default reagent), using a 2:1 ratio between the coupling partners and decreasing the temperature to -10°C [33]. Under these conditions, Grignard reagents having *p*-OMe, *p*-NMe₂, *p*-F or *p*-Cl substituted aryl groups afforded no or only very small amounts of homocoupling byproduct. Hence, these reagents turned out to be excellent coupling partners with various other aryl Grignard reagents. In this case, even two Grignard reagents with electron-withdrawing substituents provided good yields whereas heterocyclic reagents gave only moderate outcomes (Scheme 32).

Scheme 32. Extension of Mn-catalyzed oxidative heterocoupling of Grignard reagents with air [33].

2.3. Mechanistic insights

From a mechanistic point of view, some recent theoretical and mass-spectrometric studies have been conducted concerning the homocoupling reaction of organolithium and organomagnesium compounds to provide support for the generally proposed mechanism shown in Scheme 33 [31, 34]. Initially, a diarylmanganese complex **M** is formed via the transmetalation from the organometallic reagent onto MnCl₂. The addition of oxygen affords a monomeric diarylmanganese(IV) peroxo complex **N** which rapidly undergoes reductive elimination to yield the coupled biaryl product and the concomitant formation of a Mn(II)-peroxo species **O**. The latter reacts with two equivalents of the organometallic reagent to provide again a diarylmanganese species **M**. Experimentally it has been observed that after addition of air, the coupling reaction proceeds very quickly, in often less than 10 minutes, so that side reactions between the oxidizing agent and the organometallic reagents are very limited and rarely observed.

Scheme 33. Generally proposed mechanism for Mn-catalyzed coupling of organometallics under air [31,34].

From a theoretical point of view, the formation of species **M**, **N** and **O** could be confirmed for Grignard and organolithium reagents with the transmetalation and oxygen coordination steps being two strongly exothermic processes [31,34]. An attempt to calculate the formation of the homocoupling product **P** directly from diarylmanganese complex **M** without oxygen revealed a very high energy barrier for the transition state (ca. 35 kcal/mol) [31]. On the other hand, the reductive elimination from the diarylmanganese(IV) peroxo complex **N** has a reasonable energy barrier (ca. 10 kcal/mol) and the process is exergonic by -13 kcal/mol. In an attempt to observe an intermediate Mn-oxo complex, such as **N**, experimentally, the solution of a diarylmanganese complex after addition of air was studied by electrospray mass spectrometry (ESMS) [31]. The proposed peroxo species **N** could not be detected, however, a bimetallic oxygen-containing complex **Q** was clearly identified by isotope distribution and HRMS. According to DFT calculations, this complex cannot provide the homocoupled product [31]. Further theoretical

studies confirmed that for mesityl or C_6F_5 groups the energy barrier for the homocoupling product was too high (over 20 kcal/mol) to provide such products under the given reaction conditions [34].

For the heterocoupling reaction of an alkynyl Grignard with a bulky aryl group (mesityl or 1-naphthyl), it has been proposed that a rapid equilibrium between three organometallic manganese complexes **R**, **S**, **T** operates which will preferentially lead to the heterocoupling product when the steric or electronic properties disfavor the homocoupling reaction Scheme 34 [32].

Scheme 34. Proposed mechanism for Mn-catalyzed heterocoupling reaction of two different Grignard reagents [32].

2.3. Conclusion on Mn-catalyzed coupling reactions of organometallic reagents under oxidative conditions

The results presented above clearly show the potential of Mn-catalyzed oxidative homo and heterocoupling reactions: a) the products can be obtained from readily available organic halide precursors, (mainly Br, I) or arenes/heteroarenes/alkynes via *in situ* deprotonation; b) the reaction conditions are mild (-10 °C to room temperature); c) atmospheric oxygen can be used as widely available, green oxidizing agent; d) a wide scope of C-C bond formation reactions is possible. Despite the recent progress in understanding the reaction mechanism further studies on the reaction intermediates are still necessary to get the full picture of these transformations.

3 Mn-catalyzed carbon-heteroatom bond formation

The formation of carbon-heteroatom bonds C-Y (Y = N, O, S, B) starting from readily available organic halide precursors under metal-catalyzed (Pd, Ni, Cu) or metal-free conditions has been widely studied. However, until about ten years ago, no Mn-catalyzed reaction was reported in this flourishing field. The following sections will describe some recent advances in the formation of C-Y bonds employing catalytic Mn or Mn/Cu systems with a critical analysis on the role of the manganese catalyst and possible trace-metal contaminations.

3.1 C-N bond formation

Several Mn-catalyzed C-N bond formation reactions using aryl or heteroaryliodides have been described. In 2009, Teo and coworkers reported a high-temperature protocol for the C-N cross-coupling reaction of nitrogen nucleophiles and aryl iodides, which employed $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ as catalyst, trans-1,2-diaminocyclohexane as ligand, K_3PO_4 as base and water as solvent (Scheme 1) [35].

Scheme 35. Mn-catalyzed C-N cross-coupling of aromatic nitrogen nucleophiles and aryl halides in water [35].

A wide range of N-arylation products were successfully synthesized according to this procedure. Limitations concerned *ortho*-substituted aryl iodides which afforded products in poor yields. On the other hand, the electronic character of the aryl iodides did not significantly influence the reactivity, for example *p*-CF₃ or *p*-OMe substituents provided the coupling products with pyrazole in equally good yields. Concerning the nitrogen nucleophiles, pyrazole, 7-azaindole, indazole, 3-methylpyrazole and indole derivatives all gave good results, whereas the reaction did not proceed with pyrrole, imidazole, triazole, benzylamine, pyrrolidin-2-one, benzamide or aniline. It is worth noting that control experiments using pyrazole and iodobenzene as parent reagent under optimized reaction conditions were carried out to test the catalytic activity of high purity MnCl₂·4H₂O (99.99%, Sigma Aldrich), providing the final product in 64% yield [35]. Nevertheless, in an attempt to gain more insights into the reaction mechanism, especially the intermediacy of a radical species, in 2017, Madsen *et al.* repeated the reaction of *m*-iodotoluene and pyrazole with freshly distilled starting materials and deionized water, obtaining the corresponding 1-(*m*-tolyl)-1H-pyrazole in an only very low yield of 6-8% (instead of the 75% yield reported by Teo) (Scheme 36) [9]. In addition, under the same conditions, but in the absence of Mn source, the yield was quite similar (around 2-3%). However, when deionized water was replaced with undistilled tap water, the yield of the product increased to 45%. As no indication on the water purity was given in the original paper by Teo, Madsen suggested that a possible metal-contamination was responsible for the observed catalytic reaction. Moreover, the fact that the reaction only works well in water and not in organic solvents such as toluene,

THF, DMF, DMSO or acetonitrile might be a further indication towards the interplay of another metal in water. It should be noted that Madsen further showed that the above C-N coupling reaction works already with very small amounts of Cu-catalyst (0.01 mol% of $\text{CuCl}_2 \cdot \text{H}_2\text{O}$) under the exact same conditions, to provide the coupled product in 78% yield [9], in agreement with the literature [36].

Scheme 36. Mn- or Cu-catalyzed arylation of pyrazole? Madsen vs. Teo [9,35].

Teo's initial work was extended in 2012 to the coupling of indole, 7-azaindole and indazole derivatives with pyridine and thiophene iodides in water under quite similar conditions (Scheme 37) [37]. The use of MnF_2 and Cs_2CO_3 provided the best results for several C-N coupling products. It should be noted that a blank test without Mn gave only 6% of the expected product but the purity of the MnF_2 was only 98%.

Scheme 37. Mn-mediated N-heteroarylation of indoles and indazoles in water [37].

In order to extend the scope of N-nucleophiles, a catalytic system based on $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ associated with L-proline as a ligand was presented, for the N-arylation of aliphatic amines using aryl halides (Scheme 38) [38].

Scheme 38. Mn-mediated N-arylation of aliphatic amines with aryl halides [38].

This protocol provided good to moderate yields for a range of aliphatic amines, such as morpholine and several primary and secondary amines. For some *meta*- or *para*-substituted aryl iodides, two regioisomers were observed in the product mixture pointing towards possible aryne-intermediates. The best yield was obtained in the case of pyrrolidine (80%), whereas benzylamine (22%) gave the lowest result. It should further be noted, that an intriguing blank test with morpholine and iodobenzene under Mn-free condition revealed that the ligand L-proline with NaOtBu and DMSO provided 50% of the corresponding N-arylation product, whereas in the presence of Mn the yield was 72%. The influence of the Mn salt as catalyst seems therefore rather limited in this process, which is further corroborated by a report on a transition metal free process using the KOtBu/DMSO system, which appeared some years earlier [39].

In order to lower the reaction temperatures in the above presented reactions and to further broaden the substrate scope a bimetallic system MnF_2/CuI was subsequently developed (Scheme 39) [40]. Under these conditions many C-N coupling reactions proceeded at 60 °C. Furthermore, this catalytic system also enabled the coupling of benzamide and sulfonamide derivatives with various aryl halides. In all cases, electron-withdrawing groups and *ortho*-substituents on the aryl iodide led to lower yields. Experiments with different concentrations of Cu and Mn catalysts and different bases showed that a bimetallic cooperation may occur. Decreasing the amount of Mn salt to 5% led to significant drop in yield, however, no blank experiment without Mn catalyst was reported.

Scheme 39. Mn/Cu co-catalyzed N-arylation of benzamides and sulfonamides with various substituted aryl iodides in water [40].

3.2 C-O bond formation

To date, there is only one report on the synthesis of biaryl ethers from phenols and aryl halides employing Mn catalysis. In 2019, Anilkumar *et al.* provided a protocol which employed $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ as catalyst at elevated temperatures in a Cs_2CO_3 - CH_3CN system under ligand-free conditions (Scheme 39) [41]. The coupling was limited to electron deficient aryl iodides derivatives, i.e. 4-iodonitrobenzene, 4-iodobenzonitrile and 4-iodoacetophenone, but was successful with a variety of phenols.

Scheme 40. Manganese-catalyzed C-O coupling for the O-arylation of phenols [41].

Blank experiments without Mn catalyst revealed a strong decrease in yield from 99 to 29%, whereas an experiment with Mn but without base gave only trace amounts of product. No detailed information of the purity of Mn-catalysts was provided. As an experiment with TEMPO did not influence the reaction outcome a radical mechanism was ruled out by the authors. A postulated mechanism for this catalytic system is depicted in Scheme 41. The Mn(II) complex **U** obtained from salt metathesis reaction between MnCl_2 with phenoxide ions, activates the aryl iodide leading to intermediate **V**, which evolves to intermediate **W** via C-O bond formation. The latter releases the biaryl ether product and the catalytically active species. As indicated above the reaction proceeds also partially in the absence of a Mn source. As a quite similar reaction has already been described without the presence of any transition metal precatalyst [42], the exact role of the metal or even the necessity of a metal needs to be clarified. Nucleophilic aromatic substitution ($\text{S}_{\text{N}}\text{Ar}$), typically involving electron poor substituents, could also explain the reaction.

Scheme 41. Proposed mechanism for Mn-catalyzed O-arylation of phenols [41].

3.3 C-S bond formation

A report in 2010 on the cross-coupling of thiophenols with aryl or vinyl halides using a high-temperature $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ /DMSO/KOH system provided first hints into the potential of Mn catalysis in C-S bond formation reactions (Scheme 42) [43].

Scheme 42. Synthesis of aryl and vinyl sulfides in $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ /DMSO/KOH system [43].

However, some years later it was shown by Lee that using this system with high-purity MnCl_2 and KOH (99.99%) led to a significant drop in yield, for example from 82 to 19% in the coupling of thiophenol with iodobenzene, indicating that other metal impurities might be involved in the catalytic process [44]. Consequently, a new Mn-catalytic system was devised by Lee using 1,10-phenanthroline derivatives as ligands in toluene or dioxane with Cs_2CO_3 as a base with high purity reagents (Scheme 43) [44]. These conditions enabled the coupling of a wide array of mainly electron-rich aryl halides, even sterically encumbered *ortho*-substituted substrates, with a range of thiophenols and thioalkanes in good yields. A mechanistic proposal has not been provided.

Scheme 43. Mn-catalyzed S-arylation of aryl iodides with aryl thiols [44].

3.4 C-B bond formation

The Mn-catalyzed cross-coupling of alkyl halides with bis(pinacolato)-diboron provided an efficient access to a wide range of primary, secondary and tertiary boronic esters [45]. Linear, branched and cyclic alkyl chlorides were employed successfully in such reactions, which proceeded in the presence of small amounts of $\text{MnBr}_2/\text{TMEDA}$ as catalyst system (0.1-5 mol%) in DME at room temperature (Scheme 44).

Scheme 44. Mn-catalyzed C-B bond formation cross-coupling reaction [45].

Even though no detailed mechanism was provided, first insights were obtained from radical clock experiments and reactions with different halide precursors. The involvement of a radical process was suggested from the isolation of a racemic product from an enantiomerically enriched secondary alkyl halide as well as from the faster reaction of tertiary over secondary over primary alkyl halides. Furthermore, the reaction of 6-bromo-1-hexene under standard conditions provided a 3:1 mixture of products derived from direct borylation *vs.* a ring-closing process. By varying the temperature, it was shown that at 0 °C only the borylation product was obtained with 79% yield, whereas at 65 °C the ring-closing product was dominant (Scheme 45a). This unique temperature-controlled switch in selectivity was further exploited in the first

synthesis of cyclopropylmethylboronate from the corresponding alkyl bromide, in a 1:2.5 mixture with the ring-opened product (Scheme 45b).

Scheme 45. Radical clock experiments: Temperature-controlled linear vs. cyclized reaction [45].

From these results, the reaction was proposed to proceed *via* a stepwise, radical oxidative addition process during which the metal has a close association to the intermediate radical, as the radical recombination with Mn occurred faster than the 5-exo-dig cyclisation or could at least compete with the ring-opening of the cyclopropyl ring. Finally, the higher reactivity of primary alkyl bromides over alkyl chlorides was demonstrated in the selective borylation of 1-bromo-6-chlorohexane.

3.5 Conclusion on Mn-catalyzed C-Y bond formation

This part has provided an overview on the currently known C-Y bond formation processes (Y = N; O, S, B) in the presence of Mn compounds. Most reactions involve high-temperatures and strong bases rendering the determination of the catalytic species complicated. This still young research area also lacks mechanistic studies to determine the exact role of the Mn salt in certain processes. It further shows the difficulty to determine whether the catalytic activity is due to the Mn species or to the presence of other transition metals in small quantities. A rigorous series of blank experiments involving the metal, but also the ligand, the base and the solvents or additives should be conducted to avoid any misinterpretations of results.

4. Summary and conclusions

The recent progress made in the field of Mn-catalyzed cross-coupling reactions has revealed the high potential of this transition metal for the development of more sustainable processes to access various classes of organic compounds, such as substituted alkenes, biaryls, heteroaryls and other heteroatom containing compounds (Scheme 46).

Scheme 46. Overview on Mn-catalyzed C-C and C-heteroatom bond formation processes described in this chapter.

As shown all along the chapter, most reactions work well with simple manganese salts, especially $MnCl_2$, providing cost-efficient processes due to its high availability and reduced waste production. In addition, the absence of sophisticated organic ligands requires less synthetic efforts and makes these coupling reactions readily available to the wider chemistry community. Some reactions have also been shown to be compatible with green solvents such as 2-methyl-THF or water.

Compared to other transition metals, cross-coupling reactions with Mn are still much less developed and future directions may go towards the development of specific ligands to reduce the amount of catalyst required or explore photocatalytic processes. The area is still dominated by the use of Grignard reagents as coupling partners, so many other types of organometallic species and organic substrates need to be investigated. In addition, in-depth mechanistic studies, combining experimental, analytical and theoretical approaches are required to gain further knowledge on these non-trivial processes to further explore their potential for organic synthesis. The difficulty related to Mn-chemistry lies in the paramagnetism of many Mn-complexes making the identification of reaction intermediates by conventional means, especially NMR spectroscopy, difficult. The combination of other analytical methods such as EPR or ESI-MS, monitoring the reactions by UV/vis or *in situ* IR techniques and the isolation and characterisation of reaction intermediates by X-ray diffraction studies may help to advance this area in combination with theoretical studies.

Finally, special care has to be taken on the identification of the true catalytic species and rigorous methodologies are required to exclude any metal-contaminations, which may induce erroneous conclusions.

5. References

- [1] Cahiez, G., Duplais, C., Buendia, J., *Chem. Rev.* **2009**, *109*, 1434-1476.
- [2] Carney, J. R., Dillon, B. R., Thomas, S. P., *Eur. J. Org. Chem.* **2016**, 3912-3929.
- [3] Valyaev, D. A., Lavigne, G., Lugan, N., *Coord. Chem. Rev.* **2016**, *308*, 191-235.
- [4] Cahiez, G., Moyeux, A., in *Grignard Reagents and Transition metal catalysts* (ed. J. Cossy), de Gruyter, Berlin, Germany, **2016**, pp. 210-243.
- [5] Cahiez, G., Lepifre, F., Ramiandrasoa, P., *Synthesis* **1999**, 2138-2144.
- [6] Cahiez, G., Luart, D., Lecomte, F., *Org. Lett.* **2004**, *6*, 4395-4398.
- [7] Zhang, F., Shi, Z., Chen, F., Yuan, Y., *Appl. Organometal. Chem.* **2010**, *24*, 57-63.
- [8] Antonacci, G., Ahlburg, A., Fristrup, P., Norrby, P. -O., Madsen, R., *Eur. J. Org. Chem.* **2017**, 4758-4764.
- [9] Santilli, C., Beigbaghlou, S. S., Ahlburg, A., Antonacci, G., Fristrup, P., Norrby, P. -O., Madsen, R., *Eur. J. Org. Chem.* **2017**, 5269-5274.
- [10] Inoue, R., Shinokubo, H., Oshima, K., *J. Org. Chem.* **1998**, *63*, 910-911.
- [11] Kakiya, H., Inoue, R., Shinokubo, H., Oshima, K., *Tetrahedron*, **2000**, *56*, 2131-2137.
- [12] He, R., Jin, X., Chen, H., Huang, Z. -T., Zheng, Q. -Y., Wang, C., *J. Am. Chem. Soc.* **2014**, *136*, 6558-6561.
- [13] Rueping, M., and Ieawsuwan, W., *Synlett* **2007**, 247-250.
- [14] Petel, B. E., Purak, M., Matson, E. M., *Synlett* **2018**, *29*, 1700-1706.
- [15] Cahiez, G., Bernard, D., Normant, J. F., *J. Organomet. Chem.* **1976**, *113*, 107-113.
- [16] Fugami, K., Oshima, K., Utimoto, K., *Chem. Lett.* **1987**, *16*, 2203-2206.
- [17] Alami, V., Ramiandrasoa, P., Cahiez, G., *Synlett*, **1998**, 325-327.
- [18] Cahiez, G., Gager, O., Lecomte, F., *Org. Lett.* **2008**, *10*, 5255-5256.
- [19] Silva, M. S., Ferrarini, R. S., Sousa, B. A., Toledo, F. T., Comasseto, J. V., Gariani, R. A., *Tetrahedron Lett.* **2012**, *53*, 3556-3559.
- [20] Kang, S. -K., Kim, J. -S., Choi, S. -C., *J. Org. Chem.* **1997**, *62*, 4208-4209.
- [21] Kang, S. -K., Kim, W.-Y., Lee, Y. -T., Ahn, S. -K., Kim, J. -C., *Tetrahedron Lett.* **1998**, *39*, 2131-2132.
- [22] Dakarapu, R., and Falck, J. R., *J. Org. Chem.* **2018**, *83*, 1241-1251.
- [23] Sarbajna, A., He, Y.-T., Dinh, M. H., Gladkovskaya, O., Rahaman, S. M. W., Karimata, A., Khaskin, E., Lapointe, S., Fayzullin, R., Khusnutdinova, J. R., *Organometallics* **2019**, *38*, 4409-4419.
- [24] Cahiez, G., Bernard, D., Normant, J. F., *J. Organomet. Chem.* **1976**, *113*, 99-106.

- [25] Kang, S. -K., Baik, T. -G., Jiao, X. H., Lee, Y. -T., *Tetrahedron Lett.* **1999**, *40*, 2383–2384.
- [26] Cahiez, G., Moyeux, A., Buendia, J., Duplais, C., *J. Am. Chem. Soc.* **2007**, *129*, 13788–13789.
- [27] Zhou, Z., and Xue, W., *J. Organomet. Chem.* **2009**, *694*, 599–603.
- [28] Truong, T., Alvarado, J., Tran, L. D., Daugulis, O., *Org. Lett.* **2010**, *12*, 1200–1203.
- [29] Peng, Z., Li, N., Sun, X., Wang, F., Xu, L., Jiang, C., Song, L., Yan, Z.-F., *Org. Biomol. Chem.* **2014**, *12*, 7800–7809.
- [30] Haas, D., Hammann, J. M., Moyeux, A., Cahiez, G., Knochel, P., *Synlett* **2015**, *26*, 1515–1519.
- [31] Liu, Y., Bergès, J., Zaid, Y., Ouazzani Chahdi, F., Van der Lee, A., Harakat, D., Clot, E., Jaroschik, F., Taillefer, M., *J. Org. Chem.* **2019**, *84*, 4413–4420.
- [32] Cahiez, G., Duplais, C., Buendia, J., *Angew. Chem. Int. Ed.* **2009**, *48*, 6731–6734.
- [33] Ghaleshahi, H. G., Antonacci, G., Madsen, R., *Eur. J. Org. Chem.* **2017**, 1331–1336.
- [34] Bottoni, A., Cahiez, G., Calvaresi, M., Moyeux, A., Giacinto, P., Miscione, G. P., *J. Organomet. Chem.* **2016**, *814*, 25–34.
- [35] Teo, Y. -C., Yong, F. -F., Poh, C. -Y., Yana, Y. -K., Chua, G. -L., *Chem. Commun.* **2009**, 6258–6260.
- [36] Monnier, F., and Taillefer, M., *Angew. Chem. Int. Ed.* **2009**, *48*, 6954–6971.
- [37] Yong, F. -F., and Teo, Y. -C., *Synlett* **2012**, *23*, 2106–2110.
- [38] Yong, F. -F., and Teo, Y. -C., *Tetrahedron Lett.* **2010**, *51*, 3910–3912.
- [39] Shi, L., Wang, M., Fan, C.-A., Zhang, F.-M., Tu Y.-Q., *Org. Lett.* **2003**, *5*, 3515–3517.
- [40] Teo, Y. -C., Yong, F. -F., Ithnin, I. K., Yio, S. -H. T., Lin, Z., *Eur. J. Org. Chem.* **2013**, 515–524.
- [41] Rohit, K. R., Saranya, S., Harry, N. A., Anilkumar, G., *ChemistrySelect* **2019**, *4*, 5150–5154.
- [42] Pichette Drapeau, M., Ollevier, T., Taillefer, M., *Chem. Eur. J.* **2014**, *20*, 5231–5236.
- [43] Bandaru, M., Sabbavarpu, N. M., Katla, R., Yadavalli, V. D. N., *Chem. Lett.* **2010**, *39*, 1149–1151.
- [44] Liu, T. -J., Yi, C. -L., Chan, C. -C., Lee, C. -F., *Chem. Asian J.* **2013**, *8*, 1029–1034.
- [45] Atack, T. C., and Cook, S. P., *J. Am. Chem. Soc.* **2016**, *138*, 6139–6142.