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Nickel Complexes of a Pincer NN_2 Ligand: Multiple Carbon−Chloride Activation of CH_2Cl_2 and $CHCl_3$ Leads to Selective Carbon−Carbon Bond Formation

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Significant advance has been made for transition-metal-catalyzed carbon−carbon coupling reactions employing aryl and alkenyl halides and pseudohalides as the electrophiles.[1] However, catalytic coupling of unactivated alkyl halides remains a challenge.[2] This is often attributed to the reluctance of alkyl halides to undergo oxidative addition and the tendency of metal alkyl intermediates to undergo β-H elimination, producing undesired products. These limitations are severe for unactivated alkyl chlorides. There are only a few reported examples of efficient C−C coupling catalysis employing these cheap and readily available starting materials.[3] Coupling of a di- or polychloroalkane to an organometallic reagent to form new C−C bonds is even more scarce. The only example we are aware of is the Ag-catalyzed insertion of carbene into one C−Cl bond of CH_2Cl_2, $CHCl_3$, and CCl_4.[4] Only one new C−C bond was formed, and all chlorines remained in the products. Herein we report a new class of isolated and well-characterized nickel(II) alkyl complexes that are able to cleave all the C−Cl bonds in CH_2Cl_2 and $CHCl_3$ under mild conditions. Most significantly, these reactions yield exclusively the C−C coupled products in which each chlorine atom has been replaced by an organic group originating from the nickel alkyl species. To the best of our knowledge, this is the first time that such transformation has been observed, which leads to the first efficient double alkyl−alkyl coupling of CH_2Cl_2.

We recently set out to develop the coordination chemistry of a new pincer-type amido bis(amine) ligand $^{Me}NN_2$. This is inspired by the fascinating chemistry that has been unfolded lately on metal complexes of analogous amido or pyridyl bis(phosphine) ligands (NP_2). The NP_2 ligands combine structural rigidity and electronic flexibility and stabilize nucleophilic and electron-rich late metal centers. This leads to a broad range of applications in N_2,[5] C−H,[6] and N−H[7] activation, hydrogenation, and C−C bond forming reactions.[8,9] Replacing two phosphine donors with amine donors in NN_2 significantly increases the “hardness” of the ligand and should stabilize metals in higher oxidation states. A few related cyclometalated bis(amine) and amido bis(quinoline) ligands are known and show interesting reactivities.[10,11] However, the chemistry of late metal complexes of pincer amide/amine ligands remains to be explored.

The protonated form of ligand $^{Me}NN_2$ is accessible through a Pd-catalyzed C−N coupling[12] of *N*,*N*-dimethylaminoaniline with *o*-*N*,*N*-dimethylaminobromobenzene (Figure 1).[13] Lithiation of $H^{Me}NN_2$ produced $[(^{Me}NN_2)Li]_2$ (**1**). The dimeric structure of **1** was first inferred by the presence of two methyl singlets corresponding to the diastereotopic methyl groups of $^{Me}NN_2$ in its ^1H NMR spectrum. The structure was confirmed by an X-ray crystallographic analysis.[13] Similar structure was found previously for the bis(quinolinyl)amide complex $[(BQA)Li]_2$.[10]

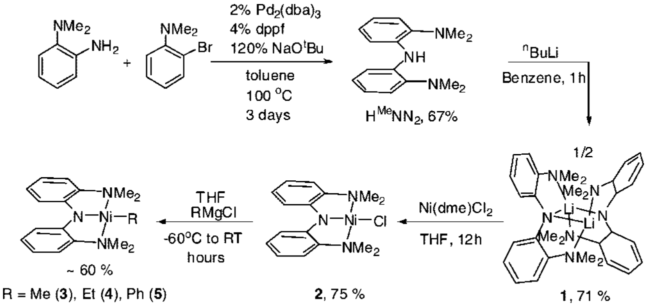

Figure 1. Synthesis of the new NN_2 ligand and its Li and Ni complexes.

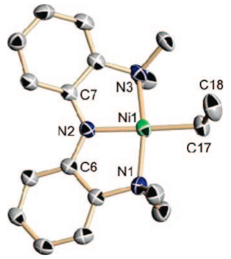

Figure 2. Crystal structure of complex **4**. Selected bond lengths (Å): Ni1−N2, 1.8907(17); Ni1−N1, 1.970(2); Ni1−N3, 1.982(2); Ni1−C17, 1.959(2).

1 reacts smoothly with $Ni(dme)Cl_2$ to produce the Ni(II) complex $[(^{Me}NN_2)NiCl]$ (**2**). The monomeric structure of **2** was indicated by the presence of only one singlet ^1H NMR signal for the methyl groups of $^{Me}NN_2$ and was confirmed by an X-ray single-crystal diffraction study.[13] Reactions of **2** with alkyl and aryl Grignards yield the corresponding Ni(II)−R species (R = Me (**3**), Et (**4**), and Ph (**5**)). These organometallic Ni(II) species are stable under an inert atmosphere, even for **4** which contains β-hydrogens. This suggests that dissociation of one amine donor to give an open coordination site is either slow or does not occur in complexes **3**−**5**. The crystal structure of **4** is shown in Figure 2.

3 reacts cleanly with alkyl halides to give the C−C coupled products (eq 1).[13] In general, the reaction rates follow the order of RI > RBr > RCl and benzyl > octyl > cyclohexyl.[13] Although Ni-based catalysts have been used for C−C coupling reactions,[2,14,15] well-defined Ni alkyl compounds that react with alkyl halides,[9,15] especially alkyl chlorides, to give the alkyl−alkyl coupled products[15] as shown in eq 1 are rare. These reactions suggest that similar Ni(II) alkyl compounds *can* be the active species in Kumada coupling of alkyl halides with Grignards. Interestingly, reactions of **3** with aryl halides are slower than those with alkyl halides. **3** reacts with 10 equiv of PhI at room temperature for 3 h to give

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50% conversion. The metal-containing products are **5** (25%) and $^{Me}NN_2Ni$-I (15%). No toluene was formed.

$$[(^{Me}NN_2)\text{Ni-Me}] + R'X \rightarrow [(^{Me}NN_2\text{Ni-X}] + \text{Me-R}' \qquad (1)$$

Most surprisingly, **3** reacts rapidly with CH_2Cl_2 and $CHCl_3$ (eqs 2 and 3) at room temperature, giving **2** as the main metal-containing product in more than 95% yield. The only detectable organic products are the fully C−C coupled products. Thus, in reactions with CH_2Cl_2 and $CHCl_3$, propane and isobutane are formed exclusively and respectively. While it was difficult to quantify the yields for gases, the observed yields for the products that remained in the solution mixture were ca. 50% for propane and 55% for isobutane, underscoring the high selectivity for the multiple C−C bond forming reactions. Formation of partially methylated products such as CH_3CH_2Cl, CH_3CHCl_2, or $(CH_3)_2CHCl$ were not observed, even when an excess of CH_2Cl_2 or $CHCl_3$ was used. Monitoring by ^{1}H NMR,[13] the reactions of **3** with CH_2Cl_2 and $CHCl_3$ were found to be approximately first and second order in the concentration of **3**, respectively. Similar reactivity patterns were found for ethyl complex **4**. The phenyl complex **5** is however inert under the same conditions.

$$2[(^{Me}NN_2)\text{Ni-R}] + CH_2Cl_2 \rightarrow 2[(^{Me}NN_2)\text{Ni-Cl}] + R_2CH_2 \qquad (2)$$

$$3[(^{Me}NN_2)\underset{R=Me,\ Et}{\text{Ni-R}}] + CHCl_3 \rightarrow 3[(^{Me}NN_2)\text{Ni-Cl}] + R_3CH \qquad (3)$$

These reactions are unusual in several ways. They take place under very mild conditions and are the first examples of late metal alkyl compounds that react with CH_2Cl_2 and $CHCl_3$ to give fully alkylated organic products in high yields.[9,16] The selectivity is impressive as the overall process involves *the cleavage of up to three C−Cl bonds to form three new C−C bonds at the same carbon center*. Concerning the mechanism, a radical pathway is proposed based on the following observations: (1) CH_2Cl_2 and $CHCl_3$ react faster than octyl-Cl; (2) reaction of **3** with CH_2Cl_2 was retarded in the presence of radical trap TEMPO and TEMPO-CH_3 was formed during the reaction; (3) 1-pentene was formed in the reaction of **3** with bromomethylcyclopropane.

The multiple C−C coupling reactions described here are applicable in organic synthesis if they can be rendered catalytic. Indeed, our preliminary study demonstrates that CH_2Cl_2 can be doubly coupled to an alkyl Grignard (^{n}BuMgCl) using **2** as the precatalyst (Table 1). Higher yields were obtained when CH_2Cl_2 was in excess and the optimal CH_2Cl_2:^{n}BuMgCl ratio is 25:1 (entries 1−3). The optimal temperature is −20 °C, and the catalysis is complete within 30 min (entries 4−10). Higher loadings of catalyst increase both the reaction rates and yields but decrease the turnover numbers (entries 8−10). A conversion of 82% was achieved in 5 min at −20 °C using 12 mol % of catalyst (entry 9), and a TON of 47 was obtained in 30 min at −20 °C using 1 mol % of catalyst (entry 10). Control experiment shows that, without the precatalyst, the product yield is negligible (entry 11). CD_2Cl_2 can be used and gives $BuCD_2Bu$ in 84% yield (entry 12). Coupling of 1,1-dichloro-3,3-dimethylbutane (RCl_2) with ^{n}BuMgCl is possible, with 42% yield of BuRRBu rather than BuRBu though (entry 13).

In summary, using nickel alkyl complexes of a new pincer NN_2 ligand, we have discovered a new type of multiple C−Cl activation reactions on CH_2Cl_2 and $CHCl_3$. The reactions lead to selective C−C bond formations which enable the first catalytic couplings of CH_2Cl_2 with Grignard reagents. We are currently investigating the mechanistic details of these intriguing transformations and exploring the scope and utility of their catalytic applications.

Table 1. Catalytic Alkyl−Alkyl Coupling of Dichloroalkanes[a]

$$2^n\text{BuMgCl} + RCl_2 \xrightarrow[\text{solvent}]{\text{cat } \mathbf{2}} \text{Bu-}\mathbf{R}\text{-Bu}$$

entry	equiv of halide	R	mol % of catalyst	temp (°C)	time (h)	yield (%)[b]
1	0.5[c]	CH_2	3	20	24	5
2	25[d]	CH_2	3	20	24	15
3	100[d]	CH_2	3	20	24	11
4	25[d]	CH_2	3	20	0.5	17
5	25[d]	CH_2	3	0	0.5	25
6	25[d]	CH_2	3	−20	0.1	44
7	25[d]	CH_2	3	−40	0.5	16
8	25[d]	CH_2	6	−20	0.1	59
9	25[d]	CH_2	12	−20	0.1	82
10	25[d]	CH_2	1	−20	0.5	47
11	25[d]	CH_2	0	−20	0.5	0.4
12	25[d]	CD_2	12	−20	0.1	84
13	1[c,e]	neo-hexyl	12	0	0.1	42

[a] With 0.95 mmol of ^{n}BuMgCl (2.0 M solution in THF) as the limiting reagent. [b] GC yields relative to ^{n}BuMgCl. [c] THF as the solvent. [d] BuMgCl was added dropwise to 1.5 mL of CH_2Cl_2 (CD_2Cl_2) solution of catalyst. [e] BuRRBu formed.

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Supporting Information Available: Experimental and crystallographic details. This material is available free of charge via the Internet at http://pubs.acs.org.

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