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| Journal: | *Organometallics* |
| Manuscript ID | om-2021-00316d.R2 |
| Manuscript Type: | Article |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | DeGroot, Henry; Vanderbilt University, Chemistry<br>Hanusa, Timothy; Vanderbilt University, Chemistry |
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# Solvate-assisted grinding: metal solvates as solvent sources in mechanochemically driven organometallic reactions

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## ABSTRACT

Solvent effects in synthetic chemistry can be analyzed in various ways, but a perhaps counterintuitive approach is to remove the solvent entirely from the reaction environment. Mechanochemical initiation (grinding or milling of solid reagents) can then be used to replace the mixing and energy that would be supplied by a solvent. The effect of complete solvent elimination can be unpredictable, however, and even partial removal, as found in the realm of liquid-assisted grinding (LAG), can alter reaction outcomes profoundly. Reduced quantities of solvents can also be present in the form of solvates, and although their use has been classified under the category of "neat" or "dry" grinding, "solvate-assisted grinding" (SAG) might be a more descriptive term, as the outcome of such reactions can differ from both LAG and neat grinding, with the latter term more properly restricted to the use of anhydrous or unsolvated reagents only. This study examines the mechanochemically driven synthesis of the bis(allyl)metal complexes [MA´$_2$] (M = Cr, Fe, Co, Ni; A´ = 1,3-$(SiMe_3)_2C_3H_3$) via halide metathesis. Particular emphasis is given to the nickel-based system, whose synthesis from nickel halide solvates is compared with the same reaction using the anhydrous metal halide and either large or LAG quantities of solvent (a few µL of solvent per mg of reagents). The reactions employing solvate-assisted grinding, either alone (e.g., with [Ni(py)$_4$Cl$_2$]) or with LAG amounts of a different solvent (e.g., with [Ni(dme)Br$_2$] and THF as the LAG solvent) yield the nickel allyl complex the most efficiently, suggesting that the intimate interaction of coordinated solvents with the metal centers is an important variable in determining the outcome of the metathesis reactions. Although developed in the context of mechanochemically driven reactions, these results have implications for solution-based synthesis as well, where the use of solvated reagents can strongly affect outcomes.

## INTRODUCTION

How does one disentangle the myriad roles of solvents in synthetic chemistry, given that everything from dispersing the heat of exothermic processes to affecting reaction rates and yields can be in play?[1-3] An established approach to addressing this complex question involves exchanging one solvent for another with different chemical or physical properties (e.g., basicity or hydrogen bonding capability), and then analyzing changes in the yields or identities of products. Although perhaps counterintuitive, completely *omitting* the solvent from a reaction and then observing the outcome can also provide insights into solvent-reagent interactions. The mixing and energy input that accompanies solvent use can be replaced with mechanochemical activation, by the grinding or milling of the dry reagents.[4-9] Not surprisingly, such omission frequently—although not always—changes the products or their yields, and in possibly dramatic ways. In particular, the high concentration of reagents and the often far-from-equilibrium conditions that exist during solid-state reactions can lead to the preferential formation of kinetic products that do not reflect the stoichiometric ratios of the starting reagents.[10-12] Given the potential insights that could be gained from the mechanochemical approach, however, there remains a critical need to accurately understand, predict, and control the effects of solvent removal or restriction during synthetic reactions.

Halide metathesis is one of the most versatile synthetic methods for the production of transition metal organometallic complexes, with proven utility for a broad range of metals and ligands.[13] These reactions are most commonly done using binary metal halide salts, $MX_n$, but in cases where these are not sufficiently reactive, a solvated metal halide, $M(L)_mX_n$, can be substituted as a more reactive precursor. The increased reactivity of solvated precursors has been attributed to their increased solubility, but this has not been a well-studied conclusion.[14]

A bridge between traditional solution-based chemistry and the solid-state alternative is the use of liquid-assisted grinding (LAG; also known as 'solvent-drop grinding'[15] or 'kneading'[16]). In a reaction conducted under LAG conditions, a small amount of liquid is introduced into the mechanochemical environment, which can have substantial effects on the outcome.[17-19] The field has developed enough that there are multiple variations on the technique, such as ILAG (the use of room temperature ionic liquids as the additive)[20] and POLAG (polymer additives),[21] and the method has been included in several reviews.[22-25]

Under conventionally defined LAG conditions, the solubility of reagents in the added solvent is no longer an important consideration—as such, the solvent has been described as functioning essentially as a catalyst.[26,27] Thus a commonly used descriptor of the LAG environment is the '$\eta$' scale, defined as a simple volume/mass ratio (specifically, $\eta$ is the µL solvent added per mg of total reagents, or equivalently, mL/g).[26] A completely solvent-free reaction has $\eta = 0$, and empirical study has suggested that distinct LAG reactivity occurs in the range $\eta \approx 0$–1 (Figure 1).[28] Given its definition, the $\eta$ scale is independent of a solvent's identity (and hence core properties such as polarity, basicity, or hydrogen bonding ability) and the relative molar masses of the solvent and reagents.

The operation of LAG in organometallic systems is particularly complex, as direct solvent involvement in the coordination sphere of a metal can produce a variety of reaction outcomes, whether by generating weak interactions that are easily replaced with other substrates (so-called 'virtual' or 'latent' sites)[29, 30] or by more direct changes, such as oxidative addition.[31-33] Despite such issues, the η parameter has found repeated use as a descriptor in organometallic reactions.[34-40]

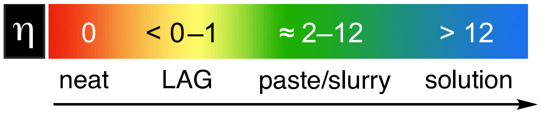

**Figure 1.** The conventional η scale for mechanochemical reactions (μL liquid added/mg of total reagents). Distinctive liquid-assisted grinding (LAG) is proposed to occur in the region immediately above solvent-free conditions ($\eta = 0$) and before the formation of paste-like mixtures ($\eta \approx 2$).

Even as LAG conditions lie between dry reactions and those conducted in solution, the line between dry and LAG environments is blurred with the use of solvated reagents. Because such compounds introduce molecules of solvent into reactions in a solid form,[41, 42] their use has been considered a type of dry grinding,[42] and so outside the realm of LAG (and η). Nevertheless, hydrates and their organic equivalents, solvates, can display complicated behavior when it comes to providing solvent molecules, and the outcome of reactions may not be the same as when free liquid is added to the anhydrous species.[42]

The use of metal solvates as the sole source of solvent molecules has not been a systematically explored option in organometallic mechanochemistry, and even when solvates are employed as the metal source in solution-based reactions, it is rare to find much methodical study of their effects.[43, 44] The topic is one of potentially enormous scope, and could not be given even superficially adequate coverage within the confines of a single manuscript. To narrow the focus to a tractable level, we elected to study the formation of the known polymerization initiators[45] [MA´$_2$] ([A´] = [1,3-(SiMe$_3$)$_2$C$_3$H$_3$]$^-$; M = Cr, Fe, Co, Ni)[46, 47] (Figure 2), primarily under reduced-solvent mechanochemical conditions, either using LAG or solvated metal salts, with some solution-based reactions added for context. Such results could help address the question of whether the use of solvates as reagents deserves its own category of mechanochemical reaction type, and could make a contribution to our understanding of the function of solvated reagents in solution-based reactions.

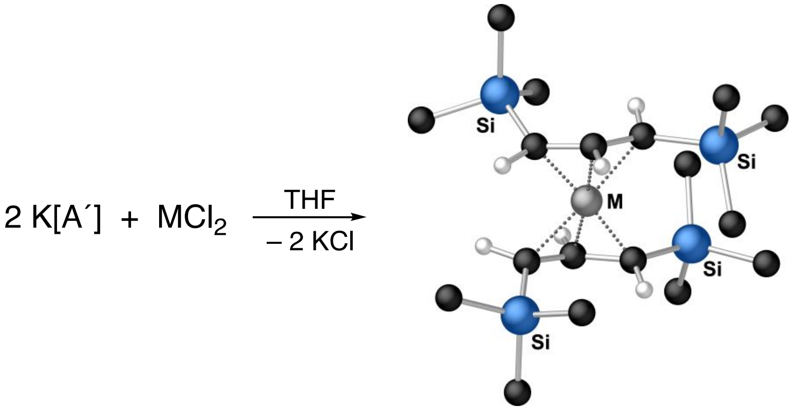

**Figure 2**. Formation of [MA´$_2$] complexes via halide metathesis; in solution the solvent is commonly THF. The geometric conformation with staggered allyl ligands (as shown, with hydrogens removed on TMS groups) is crystallographically confirmed for Cr, Fe, Co, and Ni. A structure with eclipsed allyl ligands is also known for M = Ni.

## Results

### (a) Initial solution phase investigation

Previous work has shown that the metathetical reaction of Cr, Fe, and Co dichlorides with K[A´] in THF produces the corresponding bis(allyl) complexes in very good to excellent yields (all ≥ 75%).[45, 48, 49] As such, there would be little incentive to investigate other compounds of these metals for the sole purpose of improving yields of the complexes in solution. In sharp contrast, however, K[A′] reacts with the anhydrous, and virtually insoluble, nickel halides ($NiCl_2$, $NiBr_2$, or $NiI_2$) in THF via a redox reaction pathway. Evidently oxidation of the $[A′]^-$ anion to the corresponding radical $[A′]^•$ occurs, followed by its homocoupling to produce the coupled ligand product 1,3,4,6-tetrakis(trimethylsilyl)hexa-1,5-diene ($\{A′\}_2$);[50] the desired [$NiA′_2$] appears in no more than trace yields, if that.[51] Switching to the chelated halide [$Ni(dme)Br_2$] in THF instead leads to the metathesis pathway proceeding efficiently, allowing for the isolation of [$NiA′_2$] in 72% yield. The intriguing change in reaction outcome induced by the use of a metal halide solvate suggested that the nickel system could provide a useful testing ground for evaluating the effects of solvates.

In an initial study, the slightly soluble THF solvate [$Ni(thf)_{1.5}Cl_2$][52] was allowed to react in THF with K[A′], and the outcome compared to that with unsolvated $NiCl_2$ (See SI, Table S1, entries 1,2). The yield of [$NiA′_2$] detectably increases with [$Ni(thf)_{1.5}Cl_2$] (from 2 to 10%), and the complex:hexadiene ratio falls somewhat (from 1:15 to 1:7), suggesting slightly greater activity for the solvate. The same reaction with [$Ni(thf)_{1.5}Cl_2$] in diethyl ether, in which the adduct has only trace solubility, results in the same yield as with unsolvated $NiCl_2$, but with even more production of $\{A′\}_2$ (Table S1, entry 3). Remarkably, however, if the solvate precursor is changed to the highly THF-insoluble pyridine solvate [$Ni(pyr)_4Cl_2$],[53] [$NiA′_2$] is produced in 91% yield without any trace of $\{A′\}_2$ (Table S1, entry 4). Clearly solubility alone does not correlate with the reactivity of the solvates. In order to study these effects decoupled from the influence of bulk solubility, further studies were focused on reactions performed under mechanochemical conditions.

### (b) Dry grinding and use of THF (LAG conditions) with $MCl_2$

Considering the uncertain importance that metal halide solubility has on the synthesis of [$MA′_2$], the dry grinding of K[A′] with $MCl_2$ (M = Cr, Fe, Co, Ni) was examined. The bis(allyl)metal complexes are in fact obtained, but always in a mixture with $\{A'\}_2$, and the yield of $[MA'_2]$ is never greater than 12% (Figure 3; exact quantities are given in Table 1, entries 1, 5, 9, 13).

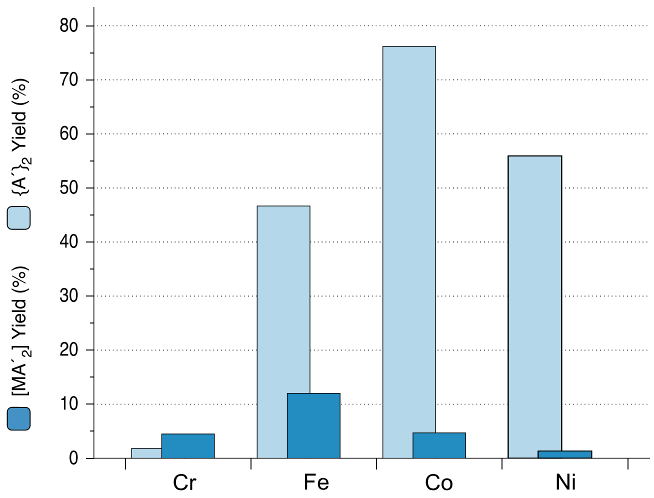

**Figure 3.** Outcomes of 10 min. dry grinds between 2 equiv. of $K[A']$ and $MCl_2$. The dimerized ligand $\{A'\}_2$ is always the major product except in the case of Cr, for which the yield of $[CrA'_2]$ does not exceed 5%.

The proportion of the complex to the hexadiene decreases on moving from chromium to nickel, with the hexadiene as the predominant product for all but the chromium system. This behavior tracks with the increasing reduction potential along the series,[54] becoming progressively easier to reduce the metal and oxidize the allyl anion.

The reactions were then repeated under LAG conditions ($\eta \approx 0.7$–$1.5$)[55] by introducing a small amount of THF into the grinding jars before 10-minute grinds at 600 RPM. In all cases, addition of THF increased the proportion of complex to the hexadiene formed (Figure 4; Table 1, entries 1/2, 5/6, 9/10, 13/14). Doubling the molar equivalents of THF from 5 to 10 generally improved the yield of the $[MA'_2]$ complexes, and in the case of chromium, by as much as 70%. This effect becomes less pronounced moving across the row, such that no increase is observed in the case of nickel (Table 1, entries 2/3, 6/7, 10/11, 14/15). For comparison, the reactions were also performed in solution for all the metals under uniform conditions, which confirmed the good yields for the three earlier metals, and again highlighted the poor outcome with nickel. (It should be noted that the reactions referred to as taking place in "solution" might be more accurately termed as "in a slurry", owing to the limited solubility of the metal halide salts in the solvents. In any case, large excesses (>> 10 equiv.) of the solvent were always present, and the reactions were well outside the LAG regime ($\eta > 100$).)

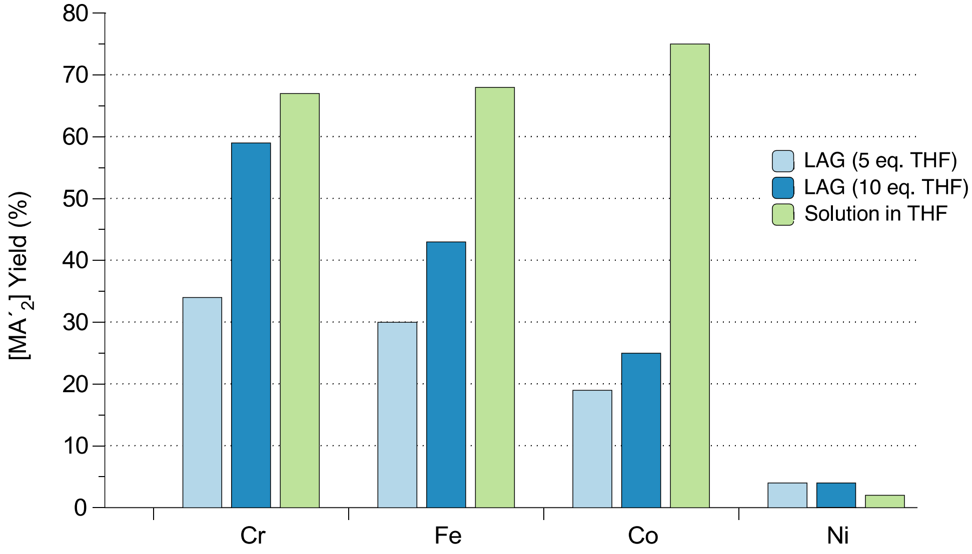

**Figure 4.** Yields of [MA´$_2$] from the reaction between K[A´], MCl$_2$, and THF.

As yields from the nickel halide systems varied from no better than near-trace (NiCl$_2$ in THF, or dry grind with NiCl$_2$) to 90% ([Ni(pyr)$_4$Cl$_2$] in THF), there was a large reaction space in which to examine the details of LAG/solvate effects. Consequently, continued study focused on nickel precursors, specifically the metal halides and their solvates.

**Table 1**. Reaction outcomes from mixing K[A´], $MCl_2$, and THF

| No. | Condition | Metal halide | Time | Equiv. THF[a] | η | [$MA'_2$] yield[c] (%) | {$A'_2$} yield[c] (%) |
|---|---|---|---|---|---|---|---|
| 1 | Dry grind | $CrCl_2$ | 10 min | 0 | 0 | 5 | 2 |
| 2 | LAG | | 10 min | 5 | 0.75 | 34 | 9 |
| 3 | | | 10 min | 10 | 1.47 | 59 | 9 |
| 4 | Solution | | 1 day | >>10 | >100 | 67 | 1 |
| 5 | Dry grind | $FeCl_2$ | 10 min | 0 | 0 | 12 | 47 |
| 6 | LAG | | 10 min | 5 | 0.78 | 30 | 25 |
| 7 | | | 10 min | 10 | 1.48 | 43 | 16 |
| 8 | Solution | | 1 day | >>10 | >100 | 68 | 10 |
| 9 | Dry grind | $CoCl_2$ | 10 min | 0 | 0 | 5 | 76 |
| 10 | LAG | | 10 min | 5 | 0.75 | 19 | 41 |
| 11 | | | 10 min | 10 | 1.49 | 25 | 45 |
| 12 | Solution | | 1 day | >>10 | >100 | 75 | 7 |
| 13 | Dry grind | $NiCl_2$ | 10 min | 0 | 0 | 1 | 56 |
| 14 | LAG | | 10 min | 5 | 0.73 | 4 | 55 |
| 15 | | | 10 min | 10 | 1.44 | 4 | 68 |
| 16 | Solution | | 1 day | >>10 | >100 | 2 | 37 |

[a] Molar equivalents relative to $MCl_2$; [b] determined by protonolysis of the product mixture followed by $^1H$ NMR (M = Cr, Fe, Co) or $^1H$ NMR of the product mixture (M = Ni); [c] determined by assigning the isolated mass between the two products according to their $^1H$ NMR ratios.

### (b) Use of other nickel halides and THF solvates

The effect of the identity of halide counterion in the nickel chemistry was investigated. $NiBr_2$ and $NiI_2$ were already known to be ineffective in generating [NiA′$_2$] in solution reactions,[51] and the same was also found to be true under mechanochemical conditions (Table S2). Used either as a dry grind with K[A′] or under LAG conditions, the other halides produced only trace or near-trace quantities (≲ 5%) of the allyl complex, and the hexadiene was consistently generated in high yield. The nickel chloride THF adduct [Ni(thf)$_{1.5}$Cl$_2$][52] was also examined as a halide source (Table S2, entry 7). Although [NiA′$_2$] was identified in a very low but easily detectable yield of 5%, {A′}$_2$ was still the overwhelmingly favored product by a ratio of 14:1. The behavior of the [Ni(thf)$_{1.5}$Cl$_2$] adduct was paralleled, and slightly bettered, with the [Ni$_3$(thf)$_5$Br$_6$] adduct,[56] giving a yield of 9% and with far less production of the hexadiene compared with the unsolvated $NiBr_2$ ({A′}$_2$ : [NiA′$_2$] ratios of 4:1 and 44:1, respectively) (Table S2, entries 5,8).

### (c) Use of metal dimethoxyethane solvates as the solvent source

Even though the [Ni(thf)$_{1.5}$Cl$_2$] or [Ni$_3$(thf)$_5$Br$_6$] solvates were not synthetically promising nickel sources, the dimethoxyethane solvate [Ni(dme)Br$_2$] had been effective in the synthesis of [NiA′$_2$] in THF solution, and so its reactivity and that of its chloride analogue were examined under several conditions. The “solution-based” interaction of $NiBr_2$ with K[A′] in DME (as noted above, more of a slurry, owing to the near insolubility of anhydrous $NiBr_2$ in DME) generated a complex mixture in which [NiA′$_2$] could be identified, but in only negligible yield (1%, Table S3, entry 4). Introduction of liquid DME under LAG conditions (5 equiv.) produced the same trace yield with $NiBr_2$ (Table S3, entry 1). Grinding the solvates [Ni(dme)Br$_2$] and [Ni(dme)Cl$_2$] with

K[A′] produced essentially the same results, with near-trace production of [NiA′$_2$] (3–4%; Table S2, entries 2, 3).

Before abandoning further study of the dme adducts, an additional experiment was performed in which [Ni(dme)Br$_2$] was the nickel source and THF was the LAG solvent. Even before grinding, exposure of [Ni(dme)Br$_2$] to THF caused a color shift from a salmon pink to lavender, indicating the onset of a reaction. Upon grinding for 10 minutes at 600 RPM, the allyl complex was found in a dramatically improved 52% yield, with a 2:1 ratio of [NiA′$_2$] to {A′}$_2$ (eq 1).

$$2\ \mathrm{K[A']} + [\mathrm{Ni(dme)Br_2}] \xrightarrow[\substack{\text{LAG with THF} \\ (\eta = 0.6)}]{} \underset{(52\%)}{[\mathrm{NiA'_2}]} + 2\ \mathrm{KBr} + \{\mathrm{A'}\}_2 \qquad (1)$$

The increase in reactivity prompted a separate investigation of the interaction of THF with bulk [Ni(dme)Br$_2$]. Adding excess THF to solid [Ni(dme)Br$_2$] generates a lavender solution from which red crystals can be obtained; these crystals were identified with X-ray crystallography as the known solvate [Ni$_3$(thf)$_5$Br$_6$].[56,57] However, the behavior of [Ni(dme)Br$_2$] in a large excess of THF could be distinct from its reactivity in the small amount of THF present under LAG conditions, and in fact the behavior of the lavender solid produced from the addition of LAG quantities of THF does not match that of the red [Ni$_3$(thf)$_5$Br$_6$]. As noted above (Section (b)), dry grinding of isolated [Ni$_3$(thf)$_5$Br$_6$] with K[A′] yields {A′}$_2$ as the major product and the allyl complex in only 9% yield (Table S2, entry 8), so it appears that the presence of DME has an important auxiliary effect in the synthesis.

### (d) The dihydrate [Ni(H$_2$O)$_2$Cl$_2$] as the nickel source

As part of the survey of the nickel solvates, nickel chloride dihydrate [Ni(H$_2$O)$_2$Cl$_2$] was also included. The dihydrate is the usual endpoint of heating the hexahydrate.[58] Although the hexahydrate has been used to prepare a variety of nickel coordination complexes[59-64] and even some organometallic complexes as water-sensitive as Ni(COD)$_2$,[65] use of the dihydrate in synthesizing coordination complexes species is rarer,[66-69] and to the best of our knowledge, has not previously been reported for organometallic species. In fact, the dihydrate was found to display reactivity similar to that of the anhydrous salt. As with anhydrous $NiCl_2$, $[Ni(H_2O)_2Cl_2]$ appeared as an unpromising precursor to [NiA′$_2$], and grinding either by itself, or with THF, DME, $Et_2O$, or benzene under LAG conditions ($\eta \approx 0.7–0.9$) never produced more than trace amounts of [NiA′$_2$], but always large yields of the hexadiene (Table S4, entries 1–5).

### (e) Impact of pyridine on reactivity

The pronounced effect on [NiA′$_2$] yield from the use of the pyridine solvate $[Ni(py)_4Cl_2]$ in diethyl ether solution (Section (a)) prompted further investigation of the general nickel chloride/pyridine system. As a start, a 10 min grind at 600 RPM between K[A′] and $[Ni(py)_4Cl_2]$ was found to produce [NiA′$_2$] cleanly in 69% yield, with no evidence of {A′}$_2$ formation (Table 2, entry 5). The consistently effective reactivity of $[Ni(pyr)_4Cl_2]$ under both solution and solvent-free conditions raised the broader question of just how the form and quantity in which pyridine is introduced into the $NiCl_2$ + K[A′] reaction affects the outcome.

The reaction of unsolvated nickel chloride and K[A′] was then studied in pyridine solution, where obviously a large excess of pyridine was present. Unlike the reactions previously studied, this yielded a dark brown viscous oil. $^1$H NMR analysis of a hexane extract of the dried oil showed the presence of [NiA′$_2$] and the absence of {A′}$_2$. However, the complex was only a minor component of a highly complex mixture of species, not all of which could be identified, and the amount of [NiA′$_2$] itself could not be quantified (Figure S1). A related outcome was found when $[Ni(H_2O)_2Cl_2]$ was used as the nickel source, and bulk pyridine was the solvent. After 48 hours, the mixture was evaporated, leaving a dark brown residue. The $^1$H NMR spectrum was somewhat cleaner than that from anhydrous $NiCl_2$, and now both $[NiA'_2]$ and $\{A'\}_2$ in a ratio of 15:1 could be identified, with a net yield of $[NiA'_2]$ of 14% (Table 2, entry 2). Clearly, pyridine as a bulk solvent was less promising for $[NiA'_2]$ yield than when it was introduced in the form of the solvate.

Under LAG conditions, unsolvated $NiCl_2$ and 5 equiv. of pyridine ($\eta = 0.70$) generated both $[NiA'_2]$ and $\{A')_2$ in about 30% yield (Table 2, entry 3). In contrast, $[Ni(H_2O)_2Cl_2]$ under the same LAG conditions produced $[NiA'_2]$ in 46% yield, without any trace of the hexadiene (Table 2, entry 1). It is possible that the water released from the $[Ni(H_2O)_2Cl_2]$ hydrate degrades other sensitive products, resulting in a cleaner spectrum, or that it shuts down a redox pathway. Taking the $NiCl_2/[Ni(H_2O)_2Cl_2]$ LAG data together, the dihydrate exhibits somewhat greater reactivity and selectivity as a nickel source with pyridine compared to the behavior of the anhydrous chloride.

The curious difference in reactivity between $NiCl_2/[Ni(H_2O)_2Cl_2]$ under LAG conditions led us to directly examine the interactions between pyridine and the two nickel halide sources (without $K[A']$). A 10-minute grind of $NiCl_2$ with 5 equiv. of pyridine generated a grey powder, which PXRD analysis indicates is a mixture of compounds, primarily $[Ni(pyr)_4Cl_2]$ and $[Ni(pyr)_2Cl_2]$[70] (Figure S2). On the other hand, applying the same conditions (5 equiv. pyridine, 10 min grinding) converted the yellow $[Ni(H_2O)_2Cl_2]$ into a bright blue power, revealed from PXRD data as essentially pure $[Ni(pyr)_4Cl_2]$ (Figure S3). Grinding of the isolated $[Ni(pyr)_4Cl_2]$ for 20 min did not yield any evidence for decomposition. The high metathesis reactivity and ease of formation of the tetrakis(pyridine) complex further underscores its importance in the formation of $[NiA'_2]$.

**Table 2.** Reaction outcomes of grinding K[A′], $[Ni(H_2O)_2Cl_2]/NiCl_2$, and pyridine (or adduct)

| No. | Condition | Nickel source | Time | Equiv. pyridine | η (or equiv.) | [NiA′$_2$] yield (%) | [NiA′$_2$] : {A′}$_2$ |
|---|---|---|---|---|---|---|---|
| 1 | LAG | $[Ni(H_2O)_2Cl_2]$ | 10 min | 6.4 | 0.70 | 46 | no {A′}$_2$ |
| 2 | Solution | $[Ni(H_2O)_2Cl_2]$ | 48 h | >>10 | >100 | 14 | 15:1 |
| 3 | LAG | $NiCl_2$ | 10 min | 5 | 0.70 | 29 | 0.9:1 |
| 4 | Solution | $NiCl_2$ | 48 h | >>10 | >100 | *a* | no {A′}$_2$ |
| 5 | Adduct grind | $[Ni(py)_4Cl_2]$ | 10 min | 4 | 0.55 | 69 | no {A′}$_2$ |

[a] Complex mixture of products prevented quantification of [NiA′$_2$].

The results with the nickel halides suggested that reaction of the isolated pyridine adduct of a metal chloride might be effective with other metals. As a preliminary test of this, a 10 min grind of K[A′] with the monomeric $[Fe(py)_4Cl_2]$ complex[71] was conducted. This precursor generated [FeA′$_2$] in 61% yield and in a 22:1 ratio with the hexadiene. These represent nearly the same yield of complex as the THF solution reaction with $FeCl_2$ (Table 1, entry 8) but with much greater selectivity for the complex (i.e., the complex:hexadiene molar ratio is 8:1 from solution).

## Discussion

Extrapolation of the requirements for the effective synthesis of [MA′$_2$] complexes to other compounds cannot be made casually. Yet as the use of halide metathesis is widespread in organometallic synthesis,[13] there are certain features of the reactions that may be relevant to related systems. It is clear that dry grinding of K[A′] and $MCl_2$ is not an effective route to the formation of [MA′$_2$] species, certainly not when compared to solution outcomes for M = Cr, Fe, and Co

(Figures 2, 3). Using THF in LAG quantities notably increases the yield of the bis(allyl) complexes, although this is strongly metal dependent, ranging from 59% with M = Cr to ≤ 4% with M = Ni. The exact reasons for this difference are unclear, although the relative oxophilicities of the metals may be involved, with chromium the most likely to interact with an ethereal solvent and nickel the least.[72]

Compared to grinding the respective nickel halide dry or in the presence of the free solvent, solvated salts are slightly to greatly superior precursors for reaction with K[A′] under mechanochemical conditions. Although they differ marginally in efficacy, $[Ni(dme)Br_2]$, $[Ni(thf)_{1.5}Cl_2]$, and $[Ni_3(thf)_5Br_6]$ all produced low yields of only 3–9%. However, the use of $[Ni(pyr)_4Cl_2]$ as a dry precursor and $[Ni(dme)Br_2]$ in the presence of THF as a LAG solvent both produced the nickel allyl complex as the major product in greater than 50% yield.

There are distinctive differences between the latter two solvate-supported reactions that deserve individual comment. In the case of the reaction of $[NiBr_2(dme)]$ with THF, it should be noted that $[Ni_3(thf)_5Br_6]$ was originally reported as a by-product of the reaction of $NiBr_2$ with 4 equiv. of $[PhP(CH_2NHEt_2)_2]Br_2$ in refluxing THF.[56] The authors of the study were unable to confirm that the THF adduct was obtainable from the reaction of $NiBr_2$ alone in hot THF. The fact that we have found that crystals of $[Ni_3(thf)_5Br_6]$ can be had by simply extracting $[Ni(dme)Br_2]$ with THF at room temperature, and the solution evaporated, illustrates the effect that coordinated DME has on the reactivity of $NiBr_2$. In the $[Ni(dme)Br_2]$/THF LAG system, it is possible that the $[Ni(dme)Br_2]$ is converted to a $[NiBr_2(thf)_x]$ species and that the released DME then provides some synergic effect as an additional LAG solvent. However, given the minimal effects seen with the use of either THF or DME alone as LAG solvents or with their solvates, it is also possible that with only a limited amount of THF the DME is not entirely displaced, and instead a mixed-solvent adduct of the form [Ni(dme)$_x$(thf)$_y$Br$_2$] is present. We have yet to isolate such a species, although work on this is continuing.

The use of pyridine in the synthesis of [NiA′$_2$] merits special mention. The [Ni(py)$_4$Cl$_2$] adduct appears to be an especially useful precursor to [NiA′$_2$], but it should be noted that nickel and pyridine actually form an extensive series of adducts with the formula [Ni(py)$_n$Cl$_2$] ($n = {}^2/_3$, 1, 2, 4), and all of them have been structurally authenticated (Figure 5).[70, 73, 74] [Ni(py)$_4$Cl$_2$] comprises monomeric molecules (Figure 5a), but the rest are coordination polymers that display an inverse relationship between the number of Ni–Cl interactions and the number of bound pyridines. In this way, these adducts represent a spectrum from fully monomeric [Ni(py)$_4$Cl$_2$] to the complete 3-dimensional lattice of [NiCl$_2$]$_n$ with its edge-sharing NiCl$_6$ octahedra and $\mu_3$-Cl atoms (Figure 5e).

The series provides an illustration of how adduct formation may be associated with increased reactivity. An extended review of organometallic synthesis, reactivity, and catalysis in the solid state[30] noted that general reactivity, including access to metal coordination sites, is assisted by increases in the porosity of the extended solid structures (such a structural difference aids in the formation of reaction cavities, and ultimately increases the ease with which a new ligand could incorporate itself into the coordination sphere of a metal ion). Not surprisingly, as $n$ increases in the [Ni(py)$_n$Cl$_2$] adducts, the bulk density decreases (from 3.55 g cm$^{-3}$ for NiCl$_2$ to 1.40 g cm$^{-3}$ for [Ni(py)$_4$Cl$_2$]), with a corresponding increase in calculated porosity (see Figure S7 for plots of the data).

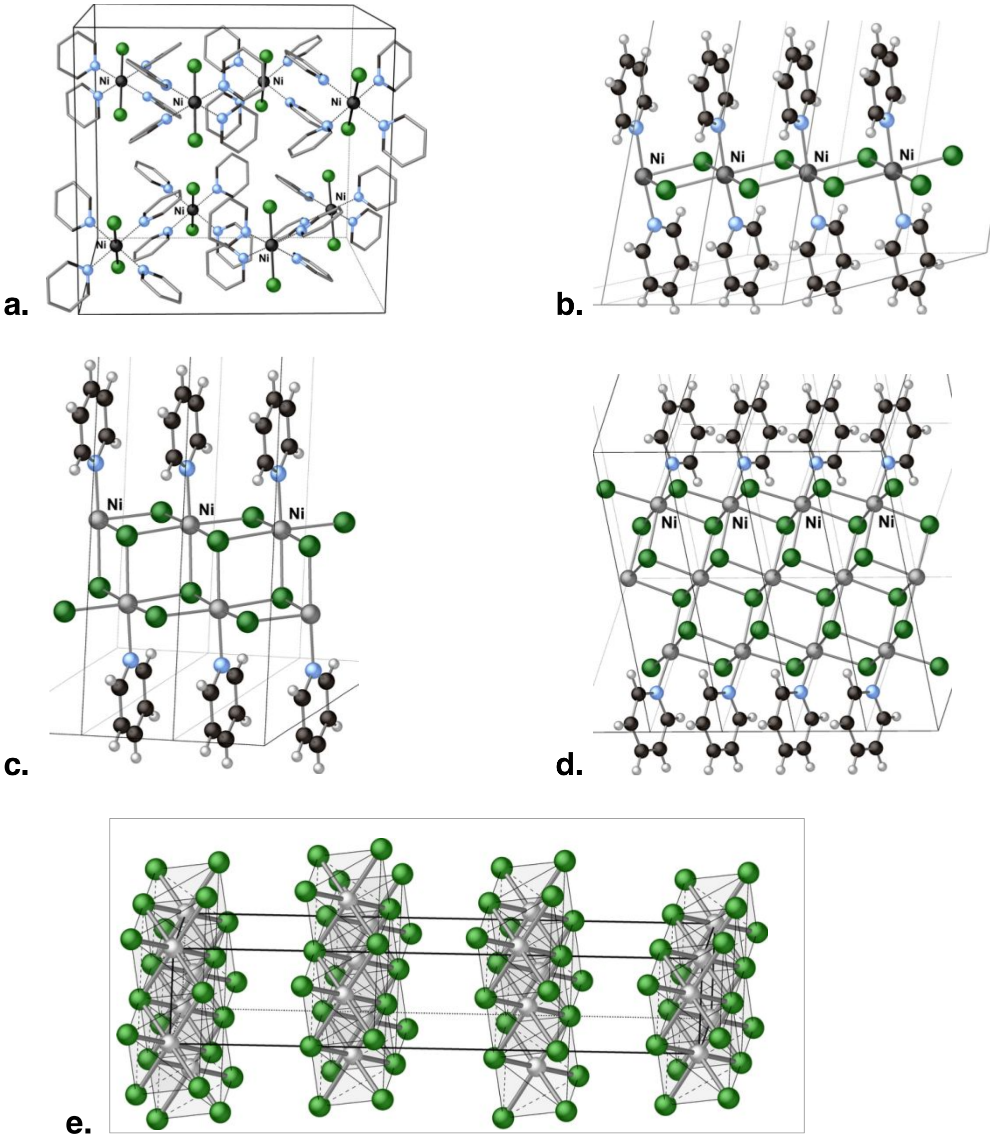

**Figure 5. a.** The unit cell of [Ni(py)$_4$Cl$_2$], with hydrogens removed for clarity ($I4_1/acd$);[74] **b.** Portions of several unit cells of [Ni(py)$_2$(μ-Cl)$_2$]$_n$ ($P2/c$);[70] **c.** Portions of several unit cells of [Ni(py)(μ-Cl)$_2$]$_n$ ($P\bar{1}$);[73] **d.** Portions of several unit cells of [Ni(py)$_{2/3}$Cl$_2$]$_n$ ($P\bar{1}$);[73] **e.** the unit cell and environment of NiCl$_2$ ($R\bar{3}m$), illustrating the CdCl$_2$-layered structure (4.4 Å interlayer spacing); the same structure is shared with FeCl$_2$ and CoCl$_2$.[75]

Apart from such structural changes, the relative lability of metal–ligand bonds (in particular, metal-halide bonds) needs to be considered. Even qualitatively, electroneutrality considerations[76] would lead to the expectation that the strong donation ability of pyridine would contribute to weakening of the nickel–chloride interactions, and thus assist in the halide metathesis reaction pathway. However, quantitative, or even seni-quantitative comparisons of the metal-ligand bond strength in a discrete molecule (e.g., [Ni(py)$_4$Cl$_2$]) and coordination polymers/3D lattices in the other pyridine adducts and NiCl$_2$) are not as easily made. For a simple comparison, however, one could evaluate the energy change involved in the loss of a chloride ion from the monomeric molecular species NiCl$_2$[77] and from [Ni(py)$_4$Cl$_2$] (i.e., the reactions represented by the processes $NiCl_2 \rightarrow [NiCl]^+ + Cl^-$ and $[Ni(py)_4Cl_2] \rightarrow [Ni(py)_4Cl]^+ + Cl^-$). At the B3PW91-D3BJ/def2TZVPD level, $\Delta G°$ for the two reactions are +202 kcal mol$^{-1}$ and +99 kcal mol$^{-1}$, respectively. Of course, the Ni environment around monomeric NiCl$_2$ and the bulk NiCl$_2$ are substantially different, but even allowing for difficulties in the comparisons, replacement of the chloride appears to be more facile in [Ni(py)$_4$Cl$_2$]. It suggests that the activating effect that solvates offer in halide metathetical reactions in general is to weaken the metal–halide bond, and thus assist in the halide/ligand exchange pathway.

## Conclusions

It is clear that the presence of solvent has a profound effect on the reactivity of transition metal halide salts undergoing metathesis reactions to form allyl complexes. However, with the substituted bis(allyl) [MA′$_2$] complexes, there is no exact relationship between the volume of solvent and its effect on reactivity. This is especially true when the molar equivalents of solvents present under LAG, solvate, or solution conditions are considered. The maximum number of THF ligands that have been documented to bind to Fe or Co is 6, for example, so that the LAG reactions run with 10 molar equivalents of THF ($\eta \approx 1.5$, Figure 3) have more than enough solvent molecules to coordinately saturate the metal center, yet the solution reactions generate a higher yield of product.

A dominant role of solvent in these systems appears to be direct chemical interaction with the metal center. The mechanism(s) by which this interaction alters the reactivity profile of the nickel precursor is still to be determined, but it could certainly be true that a chief function of solvents, and more specifically, metal solvates, is that they serve to activate metal-containing precursors, labilizing M–X bonds and making them more active. It seems that metal solvates hold a great deal of potential as ‘solvent reservoirs’; but it appears that, distinct from LAG, the concept of “solvate assisted grinding” (SAG) would be appropriate to introduce. These results support the concept that solvated metal salts can provide access to more active solid-state transition metal precursors than does just the addition of solvent alone.

## Experimental Procedures

**General Considerations.** All manipulations were performed with the rigorous exclusion of air and moisture using Schlenk or glovebox techniques in a glovebox free of coordinating solvents. Proton ($^1$H) NMR spectra of the organometallic compounds were obtained on a Bruker-400 spectrometer at 400 MHz and were referenced to the residual proton resonances of $C_6D_6$.

**Materials.** Anhydrous metal halides, [Ni(dme)$Br_2$], and [$NiCl_2$•$6H_2O$] were purchased from Aldrich; the hydrate was heated to 80 °C for 24 h under vacuum to remove water and form the dihydrate [$NiCl_2$•$2H_2O$].[58] [Ni(thf)$_{1.5}$$Cl_2$],[52] [$NiCl_2(py)_4$],[53] [$Fe(py)_4Cl_2$],[71] and both 1,3-$(SiMe_3)_2C_3H_4$ and Li[A′][38] were synthesized according to literature procedures. K[A′] was prepared by transmetallation of Li[A′] with potassium *tert*-butoxide in hexanes solution. THF and hexanes were refluxed over Na/K/benzophenone and distilled prior to use. Anhydrous pyridine, benzene, and dimethoxyethane were received from Sigma and used as received. Diethyl ether was purified over a solvent purification column. All solvents were stored in the glovebox over 4A molecular sieves. Benzene-$d_6$ was obtained from Cambridge Isotopes and stored over 4A molecular sieves.

**Mechanochemical protocol.** Ball milling reactions used stainless steel (440 grade) ball bearings ($^3/_{16}$ in (5 mm), 0.44 g) that were thoroughly cleaned with detergent and water, then washed with acetone, and dried in a 125 °C oven prior to use. Planetary milling was performed with a Retsch PM100 mill, 50 mL stainless steel grinding jar type C, and a safety clamp for air-sensitive grinding. A typical mechanochemical reaction was performed as follows. In a nitrogen-filled glovebox, a stainless steel grinding jar was charged with 25 g ball bearings, $NiCl_2$ (56.0 mg, 0.43 mmol), K[A′] (200 mg, 0.89 mmol), then THF (0.19 mL). The jar was then tightly sealed, removed from the glovebox, and placed in the planetary mill. The mixture was ground for 10 min at 600 rpm, at which point the jar was returned to the glovebox. The jar was opened, and products were taken up in hexane and filtered through a glass frit. Evaporation of solvent yielded the isolated product, which was weighed and then analyzed with $^1$H NMR.

For syntheses of the paramagnetic complexes (M = Cr, Fe, Co), an additional protonolysis procedure was performed. The isolated product mixture was taken up in benzene-$d_6$ in a glass vial. To this was added pyridinium chloride[78] (0.125 g, 1.1 mmol) and the contents well mixed. After standing overnight, the solution was filtered and analyzed by $^1$H NMR. This spectrum was then compared to the original spectrum of the isolated product; the proportion of the complex in the isolated product was taken to be one-half the difference in the relative abundance of the protonated ligand.

**Solution protocol.** A typical solution phase reaction was performed as follows. In a nitrogen-filled glovebox, a 125 mL Schlenk flask was charged with $NiCl_2$ (56.0 mg, 0.43 mmol), approximately 20 mL of THF, and a magnetic stir bar. A pressure-equalizing addition funnel was attached to the neck of the flask and charged with K[A′] (200 mg, 0.89 mmol) and approx. 15 mL THF. The homogenous K[A′] solution was added dropwise over 20 minutes, during which time the stirred reaction mixture adopted a dark orange-brown color. After stirring overnight, THF was removed via vacuum, the residue was extracted with hexanes and filtered, and the hexane was then removed. A sample of the isolated product was analyzed with $^1$H NMR. For the syntheses of paramagnetic complexes, an identical protonolysis procedure to that described above was performed.

**General Procedures for Calculations.** All calculations were performed with the Gaussian 16W.[79] The B3PW91 functional, which incorporates Becke's three-parameter exchange functional with the 1991 gradient-corrected correlation functional of Perdew and Wang, was used.[80] To add dispersion corrections, Grimme's D3 correction[81] with additional Becke-Johnson damping[82] was used (Gaussian keyword: empiricaldispersion=GD3BJ). Either the def2TZVP or def2TZVPD (with diffuse functions) basis sets were used on all atoms.[83] Porosity calculations were made with CrystalMaker® software (CrystalMaker Software Ltd, Oxford, England).

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website. Optimized coordinates of structures (.xyz format), exact yields of reactions, and crystal data and summary of X–ray data collection for *meso*-{A′}$_2$ are included (PDF format). Crystallographic data for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as CCDC 2085292. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. Grateful acknowledgement is made to Prof. Nathan D. Schley for collecting and solving the single crystal X-ray data, and to Christopher G. Sharp for collection and analysis of the powder X-ray crystallographic data.

### Funding Sources

Financial support by the National Science Foundation (CHE-1665327) is gratefully acknowledged.

### Notes

The authors declare no competing financial interest.

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Izmaylov, A. F.; Sonnenberg, J. L.; Williams; Ding, F.; Lipparini, F.; Egidi, F.; Goings, J.; Peng, B.; Petrone, A.; Henderson, T.; Ranasinghe, D.; Zakrzewski, V. G.; Gao, J.; Rega, N.; Zheng, G.; Liang, W.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Throssell, K.; Montgomery Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M. J.; Heyd, J. J.; Brothers, E. N.; Kudin, K. N.; Staroverov, V. N.; Keith, T. A.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A. P.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Millam, J. M.; Klene, M.; Adamo, C.; Cammi, R.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Farkas, O.; Foresman, J. B.; Fox, D. J. *Gaussian 16 Rev. C.01*, Wallingford, CT, 2016.

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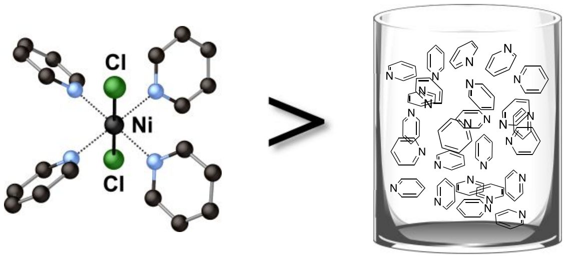
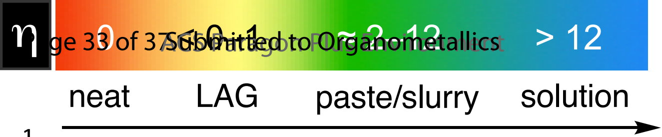


Metal solvates such as [Ni(py)$_4$Cl$_2$] serve as a type of 'solvent reservoir' in mechanochemical organometallic reactions, and can be more effective than using a bulk solvent or limited amounts of solvent under liquid-assisted grinding (LAG) conditions.


η
0
< 0–1
≈ 2–12
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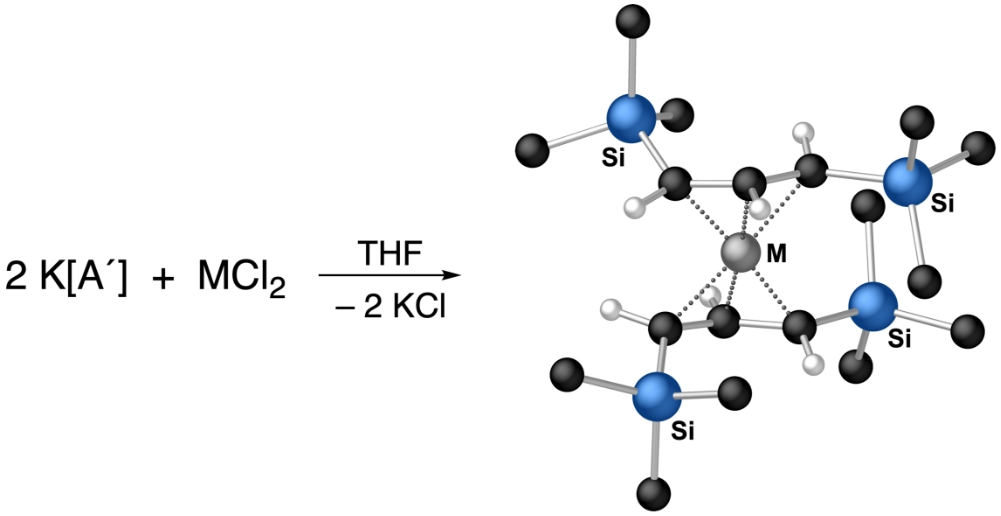
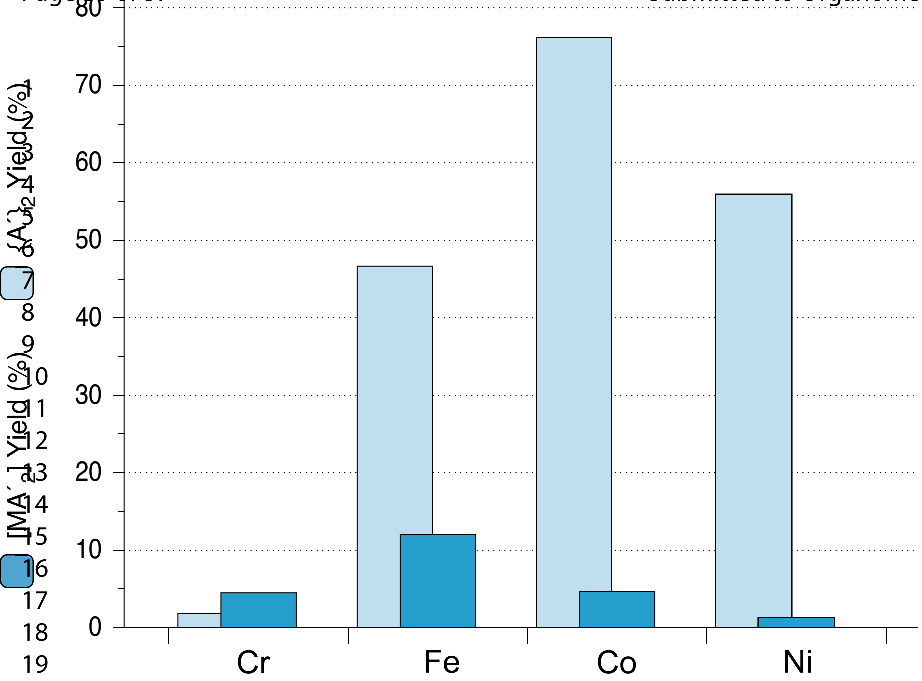
neat
LAG
paste/slurry
solution

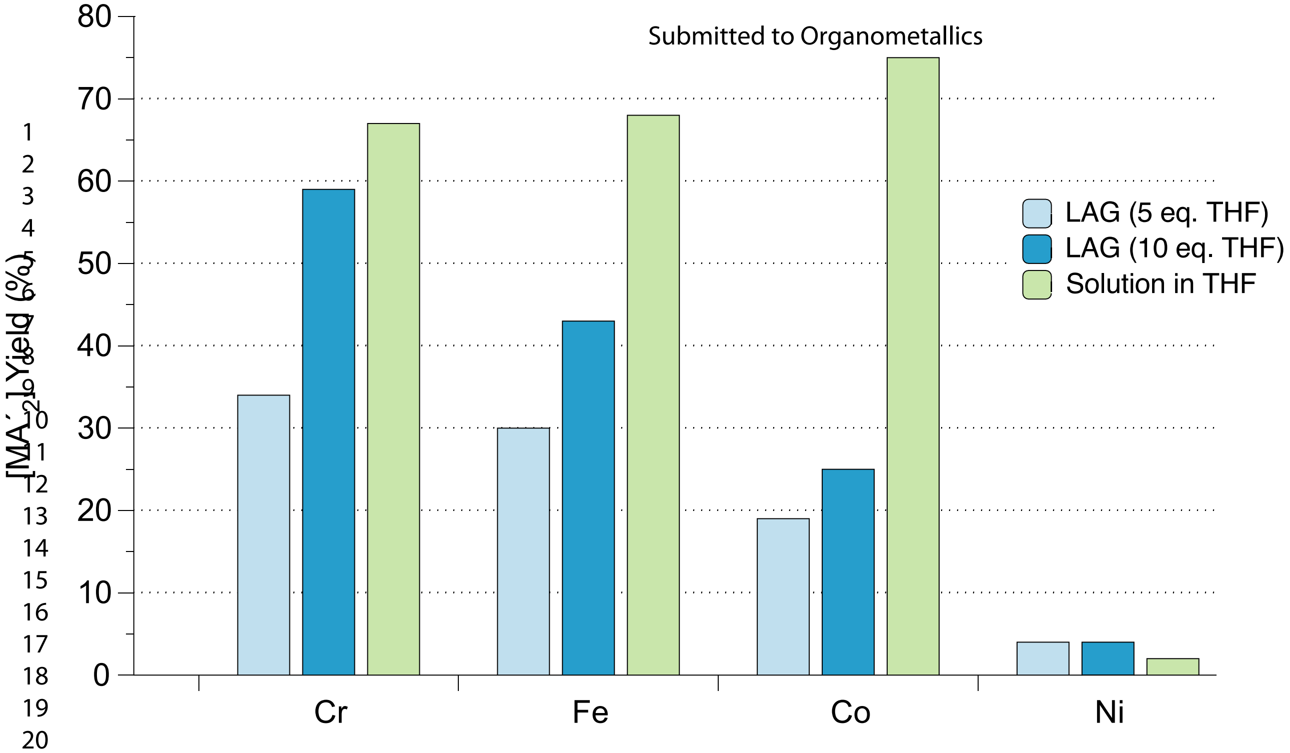


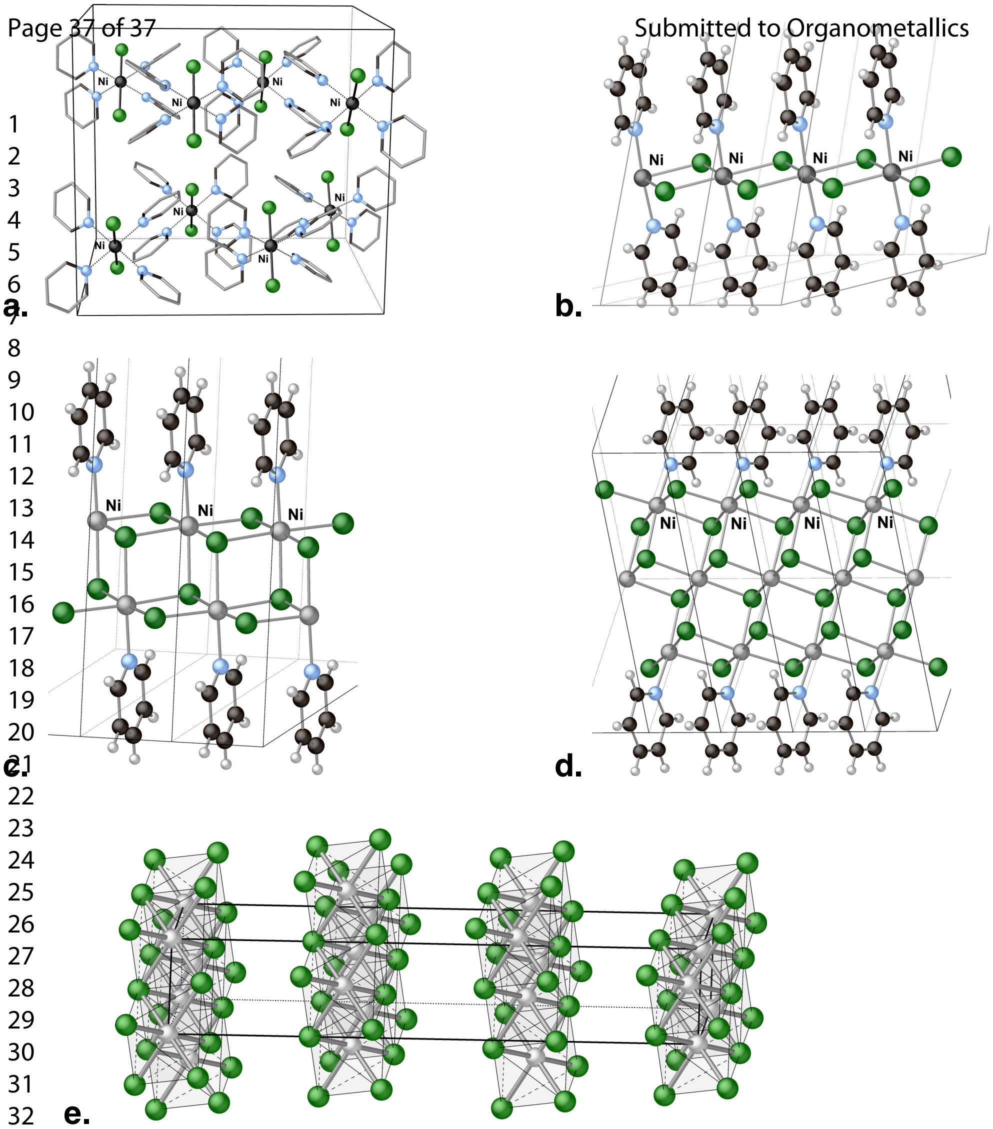
Formation of [MA´$_2$] complexes via halide metathesis; in solution the solvent is commonly THF. The geometric conformation with staggered allyl ligands (as shown) is crystallographically confirmed for Cr, Fe, Co, and Ni. A structure with eclipsed allyl ligands is also known for M = Ni.

130x67mm (576 x 576 DPI)



{A´}2 Yield (%)
[MA´]2 Yield (%)
0
10
20
30
40
50
60
70
80
Cr
Fe
Co
Ni


$[MA'_2]$ Yield (%)
0
10
20
30
40
50
60
70
80
Cr
Fe
Co
Ni
LAG (5 eq. THF)
LAG (10 eq. THF)
Solution in THF


a.
Ni
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b.
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c.
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d.
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