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Why Are (NN$_2$)Ni Pincer Complexes Active for Alkyl−Alkyl Coupling: *β*-H Elimination Is Kinetically Accessible but Thermodynamically Uphill

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Summary: Isomerization and olefin exchange experiments show that β-H elimination is kinetically viable but thermodynamically unfavorable in [(^{Me}NN$_2$)Ni-alkyl] complexes. The intermediacy of Ni-hydride species was corroborated by a trapping experiment. The alkyl complex [(^{Me}NN$_2$)Ni-propyl] catalyzes olefin isomerization.

Metal-catalyzed C−C cross-coupling has become one of the most powerful tools in organic synthesis.[1] However, the coupling of nonactivated and *β*-hydrogen-containing alkyl halides has been challenging because the corresponding metal alkyl intermediates often undergo unproductive *β*-H elimination.[2−4] In the past few years, advances in metal catalysis,[2−4] especially Ni catalysis,[5−12] have started to improve the scope and utility of cross-coupling reactions of alkyl halides. The mechanism of many Ni-catalyzed reactions, however, remains speculative. Furthermore, very few studies on isolated catalytic intermediates have been reported.[11,13] We recently developed a well-defined Ni pincer[14−22] complex, [(^{Me}NN$_2$)NiCl] (**1**),[23] as an efficient catalyst for C−C cross-coupling of alkyl halides.[24−30] For alkyl−alkyl Kumada−Corriu−Tamao type coupling, our mechanistic study suggested a catalytic cycle shown in Figure 1.[26,27]

The intermediacy of [(^{Me}NN$_2$)Ni-alkyl] species was confirmed in both stoichiometric and catalytic reactions.[26] Because coupling reactions proceeded in high yields, *β*-H elimination must be slow or nonoccurring. This is consistent with the stability of the isolated complex [(^{Me}NN$_2$)Ni-Et] (**2**), with which no *β*-H elimination was observed at 80 °C.[26] Whereas the stability against *β*-H elimination is a crucial factor for the efficiency of the catalyst in alkyl−alkyl coupling, the origin of this stability was not clear. Classic organometallic chemistry suggests two possibilities:[31,32] (1) The square-planar Ni^{II} center in the pincer complex is coordinatively saturated and has no open site for *β*-agostic interaction prior to H-elimination. (2) *β*-H elimination is thermodynamically unfavorable. The second scenario is common for early transition metals, but less encountered for late transition metals.[19,20,33,34] Liang et al. recently showed several such examples in the (PNP)Ni pincer system.[19,20] Here we report a study of the isomerization and olefin exchange reactions of the Ni alkyl complexes. The reactions occur through a transient Ni−H

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(1) *Metal-Catalyzed Cross-Coupling Reactions*, 2nd ed.; de Meijere, A.; Diederich, F., Eds.; Wiley-VCH: Weinheim, 2004.

(2) Netherton, M. R.; Fu, G. C. *Adv. Synth. Catal.* **2004**, *346*, 1525–1532.

(3) Frisch, A. C.; Beller, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 674–688.

(4) Rudolph, A.; Lautens, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 2656–2670.

(5) Devasagayaraj, A.; Studemann, T.; Knochel, P. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2723–2725.

(6) Zhou, J. R.; Fu, G. C. *J. Am. Chem. Soc.* **2003**, *125*, 14726–14727.

(7) Powell, D. A.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 7788–7789.

(8) Zhou, J.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 1340–1341.

(9) Terao, J.; Watanabe, H.; Ikumi, A.; Kuniyasu, H.; Kambe, N. *J. Am. Chem. Soc.* **2002**, *124*, 4222–4223.

(10) Terao, J.; Kambe, N. *Acc. Chem. Res.* **2008**, *41*, 1545–1554.

(11) Jones, G. D.; Martin, J. L.; McFarland, C.; Allen, O. R.; Hall, R. E.; Haley, A. D.; Brandon, R. J.; Konovalova, T.; Desrochers, P. J.; Pulay, P.; Vicic, D. A. *J. Am. Chem. Soc.* **2006**, *128*, 13175–13183.

(12) Phapale, V. B.; Bunuel, E.; Garcia-Iglesias, M.; Cardenas, D. J. *Angew. Chem., Int. Ed.* **2007**, *46*, 8790–8795.

(13) Jones, G. D.; McFarland, C.; Anderson, T. J.; Vicic, D. A. *Chem. Commun.* **2005**, 4211–4213.

(14) See refs 15−22 for selected examples of Ni pincer complexes.

(15) *The Chemistry of Pincer Compounds*; Morales-Morales, D.; Jensen, C. M., Eds.; Elsevier: Amsterdam, 2007.

(16) Albrecht, M.; van Koten, G. *Angew. Chem., Int. Ed.* **2001**, *40*, 3750–3781.

(17) Fan, L.; Ozerov, O. V. *Chem. Commun.* **2005**, 4450–4452.

(18) Pandarus, V.; Zargarian, D. *Organometallics* **2007**, *26*, 4321–4334.

(19) Liang, L. C.; Chien, P. S.; Lin, J. M.; Huang, M. H.; Huang, Y. L.; Liao, J. H. *Organometallics* **2006**, *25*, 1399–1411.

(20) Liang, L. C.; Chien, P. S.; Lee, P. Y. *Organometallics* **2008**, *27*, 3082–3093.

(21) Tran, B. L.; Pink, M.; Mindiola, D. J. *Organometallics* **2009**, *28*, 2234–2243.

(22) Chakraborty, S.; Krause, J. A.; Guan, H. *Organometallics* **2009**, *28*, 582–586.

(23) Complex **1** is now commercially available from Sigma-Aldrich bearing the synonym “Nickamine”. The name reflects the combination of nickel and amine ligands.

(24) Csok, Z.; Vechorkin, O.; Harkins, S. B.; Scopelliti, R.; Hu, X. L. *J. Am. Chem. Soc.* **2008**, *130*, 8156–8157.

(25) Vechorkin, O.; Barmaz, D.; Proust, V.; Hu, X. L. *J. Am. Chem. Soc.* **2009**, *131*, 12078–12079.

(26) Vechorkin, O.; Csok, Z.; Scopelliti, R.; Hu, X. L. *Chem.—Eur. J.* **2009**, *15*, 3889–3899.

(27) Vechorkin, O.; Hu, X. L. *Angew. Chem., Int. Ed.* **2009**, *48*, 2937–2940.

(28) Vechorkin, O.; Proust, V.; Hu, X. L. *J. Am. Chem. Soc.* **2009**, *131*, 9756–9766.

(29) Vechorkin, O.; Proust, V.; Hu, X. L. *Angew. Chem., Int. Ed.* **2010**, *49*, 3061–3064.

(30) Hu, X. L. *Chimia* **2010**, *64*, 231–234.

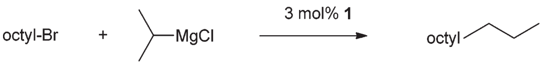
(31) Crabtree, R. H. *The Organometallic Chemistry of Transition Metals*, 4th ed.; John Wiley & Sons, Inc.: Hoboken, 2005.

(32) Hartwig, J. F. *Organotransition Metal Chemistry−From Bonding to Catalysis*; University Science Books: Sausalito, CA, 2010.

(33) Vela, J.; Smith, J. M.; Lachicotte, R. J.; Holland, P. L. *Chem. Commun.* **2002**, 2886–2887.

(34) Vela, J.; Vaddadi, S.; Cundari, T. R.; Smith, J. M.; Gregory, E. A.; Lachicotte, R. J.; Flaschenriem, C. J.; Holland, P. L. *Organometallics* **2004**, *23*, 5226–5239.

intermediate. The work shows that β-H elimination also occurs in the $[(^{\mathrm{Me}}\mathrm{NN}_2)\mathrm{Ni}^{\mathrm{II}}]$ system, but it is energetically uphill and, thus, does not affect the efficiency of alkyl–alkyl coupling.



(1)

While exploring the scope of alkyl–alkyl coupling, we found that coupling of octyl-Br with isopropylMgCl in the presence of 3 mol % of **1** led to *n*-undecane in 91% yield (eq 1).[35] The *n*-propyl group in the product originated from the isopropyl group of the Grignard reagent. Presumably, the isomerization occurred at the Ni center and before reaction of octyl bromide with the Ni alkyl intermediate (Figure 1). To confirm this hypothesis, we sought to study the isomerization in a stoichiometric manner. Reaction of **1** with isopropylMgCl gave the isomerized Ni alkyl complex $[(^{\mathrm{Me}}\mathrm{NN}_2)\mathrm{Ni}\text{-}\mathrm{Pr}^n]$ (**3**) in 75% yield (eq 2, Figure 2). The direct transmetalation product, $[(^{\mathrm{Me}}\mathrm{NN}_2)\mathrm{Ni}\text{-}\mathrm{Pr}^i]$ (**4**), could not be observed. Likewise, reaction of **1** with *tert*-butylMgCl gave the isomerized complex $[(^{\mathrm{Me}}\mathrm{NN}_2)\mathrm{Ni}\text{-}\mathrm{Bu}^i]$ (**5**) in 73% yield (eq 3, Figure 2). Complexes **3** and **5** could be prepared by direct transmetalation of **1** with *n*-propylMgCl and isobutylMgCl (Figure 2).

The structure of **3** (Figure 3) was confirmed by X-ray analysis.[35] The Ni center is square planar. The Ni–C(1) bond length is 1.965(2) Å, similar to that in **2** and other pincer $\mathrm{Ni}^{\mathrm{II}}$ alkyl complexes.[20,26] No short-distance interaction was observed for Ni–H(β) (3.123 Å). The structure of **5** was also determined, but its quality suffered from disorder. Nevertheless, the connectivity of **5** was confirmed.

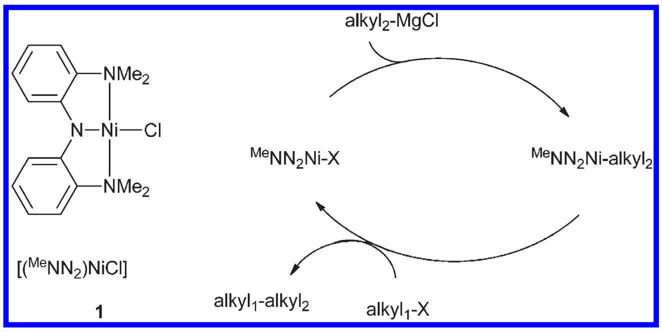
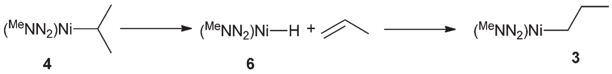
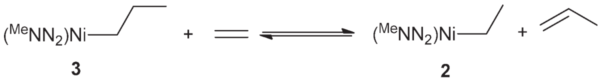


Figure 1. Proposed catalytic cycle for alkyl–alkyl coupling catalyzed by Ni pincer complex **1**.



(4)

The most probable reaction pathway for the isomerization of **4** to **3** is first β-H elimination from **4** to form a Ni–H bond and propene, which reinserts to form the more stable isomer **3** (eq 4). Indeed, DFT computations (at the M06-2X/cc-pVDZ level)[35] show that **3** is more stable than **4** by 5.8 kcal/mol, which agrees with the fact that **3** is the only isolated product in eq 2. The isomerization reaction implies that β-H elimination is kinetically accessible for these Ni alkyl complexes. The stability of the alkyl complexes should arise from a thermodynamic origin.



(5)

To further verify the possibility of β-H elimination, olefin exchange experiments were carried out (eq 5).[35] Reaction of **3** with ethylene (5 to 20 bar) at 80 °C in benzene produced the Ni ethyl complex **2** and 1-propene. The reaction is reversible and reaches equilibrium in ca. 5 h (Figure 4). A concentration equilibrium constant $K_{\mathrm{eq(conc)}}$ of 0.68(3) was found by

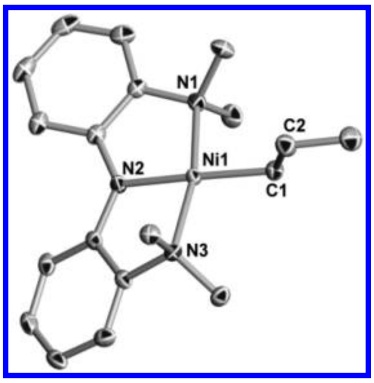


Figure 3. X-ray structure of complex **3**. The thermal ellipsoids are displayed at 50% probability. Selected bond lengths (Å): Ni1–N1, 1.9914(17); Ni1–N2, 1.8906(17); Ni1–N3, 2.0075(17); Ni1–C1, 1.965(2); C1–C2, 1.534(3).

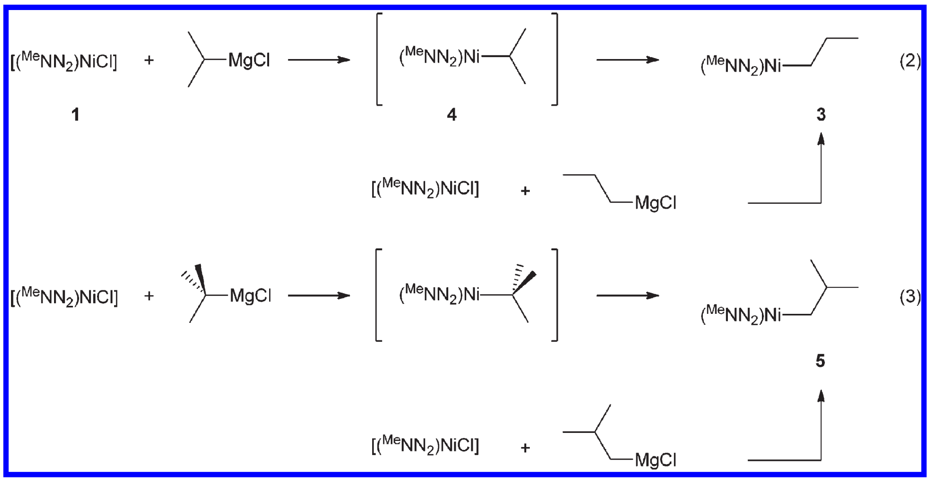


Figure 2. Synthesis and isomerization of Ni alkyl complexes.

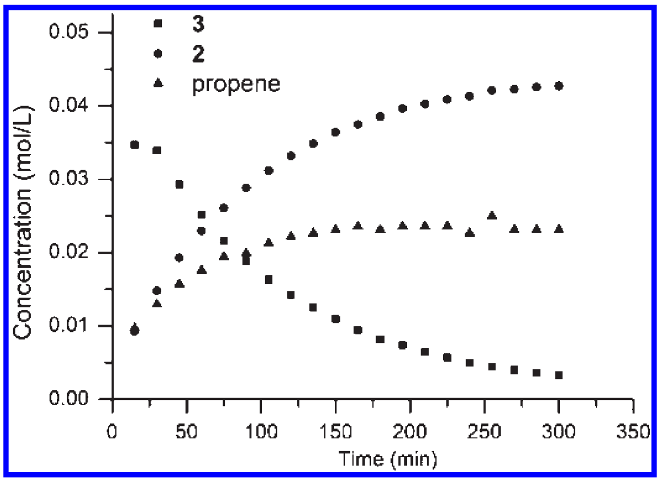
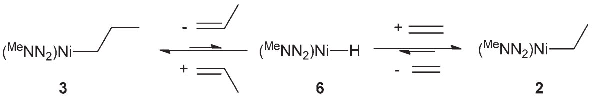


Figure 4. Concentration profile for reaction 5 at 80 °C. The initial ethylene pressure is 5 bar at 25 °C. The concentrations were monitored by NMR.

measuring the concentrations of all species in solution using NMR (Table 1).[35] A similar equilibrium constant $K_{eq(p)}$ of 0.42(11) was obtained if the concentrations of ethylene and 1-propene were expressed as their partial pressures.[35] DFT computations suggest a $\Delta H_r°$(298 K) of -2.69 kcal/mol in the gas phase (-2.64 kcal/mol with benzene treated as a continuum).[35] The small numeric discrepancy between the computed and experimental values may result from the presence of $\pi-\pi$ noncovalent interactions between solvent molecules and olefins, which are not taken into account by implicit solvent models. The reaction followed a pseudo-first-order kinetics on the concentration of **3** when ethylene was in excess. The pseudo-first-order rate constant, however, depends on the pressure of ethylene. The rate constant increases with higher pressure, but not linearly (Table 1).



(6)

The mechanism of olefin exchange is proposed in eq 6. As both **2** and **3** are stable species and do not undergo observable β-H elimination in pure solutions, the elimination step should be reversible and thermodynamically uphill. This hypothesis is supported by DFT computations,[35] which indicate that **2** is more stable than **6** plus ethylene by ca. 22 kcal/mol. This value is comparable to that of three-coordinate β-diketiminate Fe ethyl complex (ΔH = 21.8 kcal/mol).[34] The entropic change ($T\Delta S$) for β-H elimination is favorable, but on the order of 10 kcal/mol.[34] Thus, the overall thermodynamics disfavor β-H elimination for [(^{Me}NN$_2$)Ni-alkyl]. Comparison with related Ni^{II} alkyl complexes indicates that the thermodynamics are strongly influenced by ligands: β-H elimination is also disfavored in pincer [(PNP)Ni-alkyl] complexes,[20] but is favorable in four-coordinate (anilinotropone)(PPh$_3$)Ni-alkyl complexes.[36]

If β-H elimination is the rate-determining step in this reaction, the rate constant should be independent of the concentration of ethylene, as in the isomerization of β-diketiminate Fe alkyl complexes.[33,34] If olefin insertion is rate determining and β-H elimination is a fast pre-equilibrium, then the rate constant should be first-order on the concentration of ethylene. If the rate of β-H elimination is comparable to that of ethylene insertion, a nonlinear dependence of the rate constant on ethylene is expected. The latter was indeed observed for eq 5 (Table 1). Thus, the ethylene exchange reaction with **3** seems not to have a clear rate-determining step.

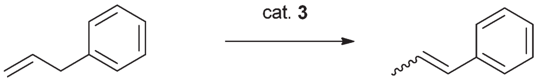
Table 1. Thermodynamic and Kinetics Data for Olefin Exchange (eq 5)

entry	pressure of ethylene (bar)	$K_{eq(conc)}$[a]	$K_{eq\ (p)}$[b]	$k \times 10^4$ (s^{-1})
1	5	0.69	0.50	1.4
2	10	0.71	0.47	1.5
3	15	0.65	0.44	2.4
4	20	0.67	0.26	3.6

[a] Calculated using the concentrations of gases. [b] Calculated using the partial pressures of gases.

The mechanism of β-H elimination is subject to further study. A possibility is that one of amine donors from the tridentate NN$_2$ ligand dissociates from the Ni center, thereby creating a necessary open site. We have yet to observe this type of ligand dissociation in the [(^{Me}NN$_2$)Ni] system. However, such a pathway could not be discounted, as it could occur via high-energy intermediate species or transition states. We are currently employing DFT methods to probe this possibility.

The olefin exchange experiments give more support to the viability of β-H elimination from the [(^{Me}NN$_2$)Ni-alkyl] species. As [(^{Me}NN$_2$)Ni-H] (**6**) would be the product of elimination, we sought to prepare it independently. Reaction of **1** with (^{n}Bu)$_4$NBH$_4$ or LiBH(Et)$_3$ in THF-d_8 at -50 °C produced a species with a ^{1}H signal at -23.16 ppm, attributable to a Ni$-$H moiety. This species is tentatively assigned to complex **6**. It is thermally unstable and escapes isolation efforts. Nonetheless, its existence could be confirmed by a trapping experiment. Reaction of in situ generated **6** with ethylene gave the ethyl complex [(^{Me}NN$_2$)Ni-Et] (**2**), identical to an independently synthesized sample.



(7)

The isomerization and olefin exchange experiments suggest that the [(^{Me}NN$_2$)Ni-alkyl] species may be catalysts for olefin isomerization reactions. Indeed, **3** catalyzed the isomerization of 1-allylbenzene to 2-methylstyrene at 70 °C (10 mol % catalyst, 60% conversion in 30 h, eq 7). The thermodynamically more stable *trans*-isomer was the major product (ca. 90%). Figure 5 shows a possible catalytic cycle. The hydride complex **6** is first generated by β-H elimination from **3**. Allylbenzene then inserts into the Ni$-$H bond to form both terminal and internal Ni alkyl species **7** and **8**, which are in equilibrium via isomerization. Judging from the relative stability of analogous complexes **3** and **4**, the ratio of **8** to **7** must be very small. β-H elimination from **8** then gives 2-methylstyrene and regenerates **6**. Complex **3** also catalyzed the isomerization of *cis*-stilbene to *trans*-stilbene (10 mol % catalyst, 70% conversion in 20 h at 70 °C).

In summary, the isomerization and olefin exchange reactions of [(^{Me}NN$_2$)Ni-alkyl] complexes have been studied to show that β-H elimination of these alkyl complexes is kinetically accessible but thermodynamically unfavorable.

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[35] See Supporting Information.
[36] Jenkins, J. C.; Brookhart, M. *J. Am. Chem. Soc.* **2004**, *126*, 5827–5842.

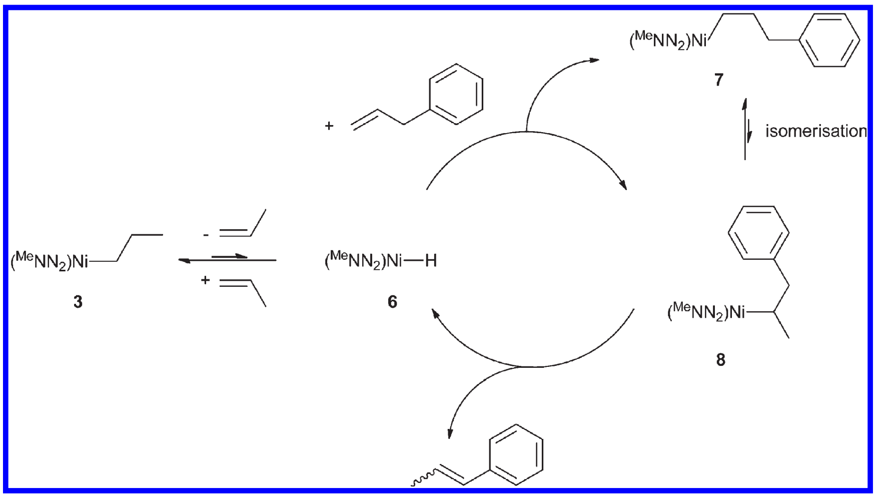

Figure 5. Proposed mechanism for the catalytic isomerization of allylbenzene.

The intermediacy of Ni-hydride species was corroborated by a trapping experiment. The alkyl complex **3** can catalyze olefin isomerization. This work reveals one of the key factors for the efficiency of $(^{Me}NN_2)$Ni pincer complexes in alkyl−alkyl cross-coupling reactions. Work to elucidate further details of the mechanism as shown in Figure 1 is underway.

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Supporting Information Available: Experimental and computational details, crystallographic data in cif format for **3** and **5**, a structural drawing of **5**, and Cartesian coordinates and absolute energies of the computed structures. This material is available free of charge via the Internet at http://pubs.acs.org.