3770 *Organometallics* **1996,** *15,* 3770−3772

Diverse Mechanistic Pathways and Selectivities in Organo-f-Element-Catalyzed Hydroamination. Intermolecular Organolanthanide-Catalyzed Alkyne and Alkene Hydroamination

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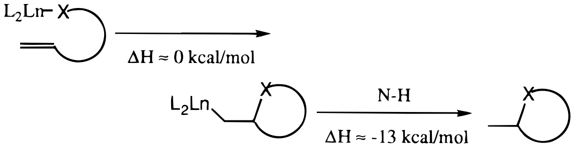
Summary: Lanthanide metallocenes catalyze the regiospecific intermolecular addition of primary amines to acetylenic, olefinic, and diene substrates at rates which are ∼1/1000 those of the most rapid intramolecular analogues. Kinetic and mechanistic data argue for turnover-limiting C≡C/C═C insertion into a Ln−N bond, followed by protonolysis of the resulting Ln−C bond.

Organolanthanides of the type L_2LnR ($L = \eta^5$-cyclopentadienyl-type ancillary ligand) are efficient catalysts for the regiospecific *intramolecular* cyclohydroamination of aminoalkenes[1] and aminoalkynes[2] (eqs 1 and 2; X =



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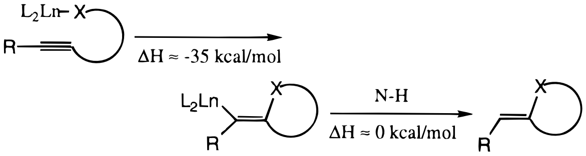

(2)

NH, NR′), as well as sequential hydroamination/bicyclizations involving both C≡C and C═C functionalities.[3] Although these exothermic intramolecular processes (overall $\Delta H_{calcd} \approx -13$ and -35 kcal/mol, respectively)[1,2] are thought to enjoy (heretofore unquantified) entropic advantages (presumably both kinetic and thermodynamic),[4] virtually nothing of a comparative nature is known about the efficiency, scope, and mechanism of the corresponding *intermolecular* processes.[5−7] We communicate here initial observations on the organolanthanide-catalyzed intermolecular hydroamination of alkenes and alkynes.[8] These results present a marked contrast to what is known about the intramolecular cyclizations as well as to actinide-catalyzed intermolecular processes reported by Eisen et al. in the accompanying communication.[9]

The rigorously anhydrous/anaerobic reaction of primary alkyl amines (0.30 M) with various alkynes, alkenes, and dienes (1.2 M) was carried out in hydrocarbon solvents using $Cp'_2LnCH(SiMe_3)_2$ and $Me_2SiCp''_2LnCH(SiMe_3)_2$ complexes ($Cp' = \eta^5$-Me_5C_5; $Cp'' = \eta^5$-Me_4C_5; Ln = Sm, Nd)[10] as precatalysts (6.0 mM).[11] Reaction rates and selectivities were monitored by ^1H/^{13}C NMR, and known products were identified by comparison with literature data[12] and/or with those of authentic samples. New compounds were characterized by 1-D and 2-D ^1H/^{13}C NMR as well as by high-resolution MS.[11] The reactions proceed with >95% regiospecifically, and the results are presented in Table 1. Entry 2 was carried out on a preparative scale, and product **2** was isolated in 62% yield.[13]

A number of aspects of the present intermolecular catalytic transformations are noteworthy and offer informative, quantitative parallels and contrasts to the corresponding organolanthanide-catalyzed intramolecular processes. The present transformations are effective for the hydroamination of both nonfunctionalized (Table 1, entries 4 and 5) and silyl-functionalized/polarized

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[1] (a) Giardello, M. A.; Conticello, V. P.; Brard, L.; Gagné, M. R.; Marks, T. J. *J. Am. Chem. Soc.* **1994**, *116*, 10241−10254. (b) Gagné, M. R.; Stern, C. L.; Marks, T. J. *J. Am. Chem. Soc.* **1992**, *114*, 275−294. (c) Gagné, M. R.; Brard, L.; Conticello, V. P.; Giardello, M. A.; Stern, C. L.; Marks, T. J. *Organometallics* **1992**, *11*, 2003−2005. (d) Gagné, M. R.; Nolan, S. P.; Marks, T. J. *Organometallics* **1990**, *9*, 1716−1718.

[2] (a) Li, Y.; Fu, P.-F.; Marks, T. J. *Organometallics* **1994**, *13*, 439−440. (b) Li, Y.; Marks, T. J. *J. Am. Chem. Soc.*, in press.

[3] Li, Y.; Marks, T. J. *J. Am. Chem. Soc.* **1996**, *118*, 707−708.

[4] (a) Smith, G. M.; Carpenter, J. D.; Marks, T. J. *J. Am. Chem. Soc.* **1986**, *108*, 6805−6807 and references therein. (b) Page, M. I. In *The Chemistry of Enzyme Action*; Page, M. I., Ed.; Elsevier: New York, 1984; pp 1−54. (c) Page, M. I.; Jencks, W. F. *Proc. Nat. Acad. Sci. U.S.A.* **1971**, *68*, 1678−1683.

[5] For hydroamination of olefins using alkali metals at high temperatures and pressures, see: (a) Pez, G. P.; Galle, J. E. *Pure Appl. Chem.* **1985**, *57*, 1917−1926. (b) Howk, B. W.; Little, E. L.; Scott, S. L.; Whitman, G. M. *J. Am. Chem. Soc.* **1954**, *76*, 1899−1902.

[6] For recent examples of hydroamination mediated by early transition metals, see: (a) McGrane, P. L.; Livinghouse, T. *J. Am. Chem. Soc.* **1993**, *115*, 11485−11489. (b) Baranger, A. M.; Walsh, P. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1993**, *115*, 2753−2763. (c) Walsh, P. J.; Hollander, F. J.; Bergman, R. G. *Organometallics* **1993**, *12*, 3705−3723. (d) McGrane, P. L.; Livinghouse, T. *J. Org. Chem.* **1992**, *57*, 1323−1324. (e) Walsh, P. J.; Baranger, A. M.; Bergman, E. G. *J. Am. Chem. Soc.* **1992**, *114*, 1708−1719. This article begins with a review of conventional hydroamination processes for unsaturated carbon−carbon bonds.

[7] For recent examples of hydroamination mediated by middle and late transition metals, see: (a) Brunet, J.-J.; Neibecker, D.; Philippot, K. *Tetrahedron Lett.* **1993**, *34*, 3877−3880. (b) Tamaru, Y.; Hojo, M.; Higashimura, H.; Yoshida, Z.-I. *J. Am. Chem. Soc.* **1988**, *110*, 3994−4002 and references therein. These authors begin by summarizing the strengths and weaknesses of platinum metal-catalyzed transformations. (c) Casalnuovo, A. L.; Calabrese, J. C.; Milstein, D. *J. Am. Chem. Soc.* **1988**, *110*, 6738−6744. (d) Fukuda, Y.; Utimoto, K.; Nozaki, H. *Heterocycles* **1987**, *25*, 297−300.

[8] Communicated in part: (a) Li, Y.; Marks, T. J. *Abstracts of Papers*, 209th National Meeting of the American Chemical Society, Anaheim, CA, **1995**; American Chemical Society: Washington, DC, 1995; INOR 012. (b) Li, Y.; Marks, T. J. Presented at the 34th National Organic Symposium of the American Chemical Society, Williamsburg, VA, 1995; Abstract 44.

[9] Haskel, A.; Straub, T.; Eisen, M. S. *Organometallics* **1996**, *15*, 3773.

[10] (a) Jeske, G.; Lauke, H.; Mauermann, H.; Swepston, P. N.; Schumann, H.; Marks, T. J. *J. Am. Chem. Soc.* **1985**, *107*, 8091−8103. (b) Jeske, G.; Schock, L. E.; Swepston, P. N.; Schumann, H.; Marks, T. J. *J. Am. Chem. Soc.* **1985**, *107*, 8103−8110.

[11] See the Supporting Information for full synthetic details, characterization of new compounds, and kinetic plots.

[12] (a) Nametkin, N. S.; Grushevenko, I. A.; Perchenko, V. N.; Kamneva, G. L.; Kuzovkina, M. E. *Proc. Acad. Sci. USSR*, *Chem. Sect. (Engl. Transl.)* **1972**, *207*, 996−998. (b) Furukawa, J.; Kiji, J.; Mitani, S.-I.; Yoshikawa, S.; Yamamoto, K.; Sasakawa, E. *Chem. Lett.* **1972**, *12*, 1211−1212.

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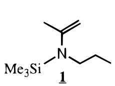
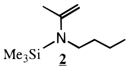
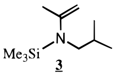
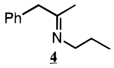
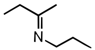
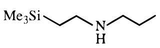
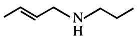
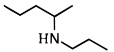
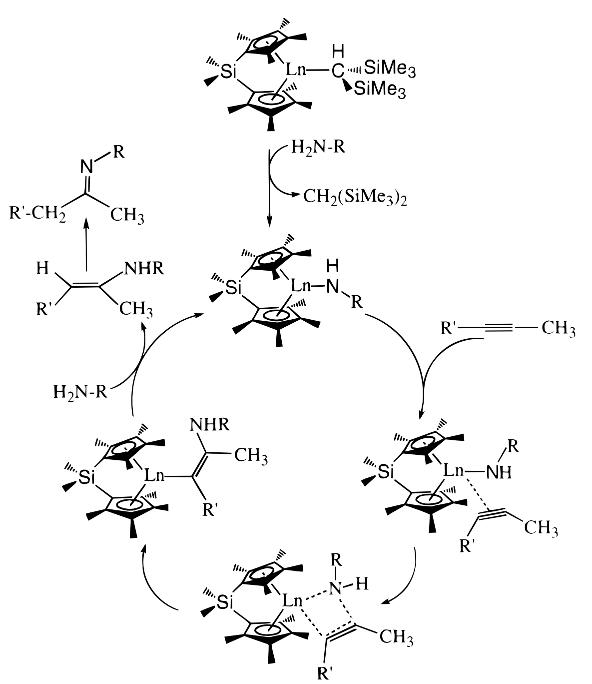
Table 1. Intermolecular Hydroamination Results

Entry	Substrates	Product	N_t,h^{-1}(°C)	Yield(%)
1.	Me_3Si-C≡C-CH_3 $CH_3CH_2CH_2NH_2$	 **1**	< 0.01(60)[a] <0.1(60)[b] 4(60)[c] 14(60)[d]	90[g]
2.	Me_3Si-C≡C-CH_3 $CH_3CH_2CH_2CH_2NH_2$	 **2**	3.4(60)[c] 8(50)[d] 13(60)[d,e]	62[f]
3.	Me_3Si-C≡C-CH_3 $(CH_3)_2CHCH_2NH_2$	 **3**	10(60)[d]	90[g]
4.	Ph-C≡C-CH_3 $CH_3CH_2CH_2NH_2$	 **4**	2(60)[d]	85[g]
5.	CH_3-C≡C-CH_3 $CH_3CH_2CH_2NH_2$	 **5**	1(60)[d]	91[g]
6.	Me_3Si-CH=CH_2 $CH_3CH_2CH_2NH_2$	 **6**	2(60)[d]	93[g]
7.	CH_2=CH-CH=CH_2 $CH_3CH_2CH_2NH_2$	 **7**	0.3(21)[d]	90[g]
8.	$CH_3CH_2CH_2CH$=CH_2 $CH_3CH_2CH_2NH_2$	 **8**	0.4(60)[d]	90[g]

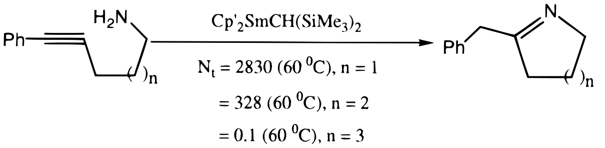
[a] $Cp'_2SmCH(SiMe_3)_2$ as precatalyst. [b] $Me_2SiCp''_2LuCH(SiMe_3)_2$ as precatalyst. [c] $Me_2SiCp''_2SmCH(SiMe_3)_2$ as precatalyst. [d] $Me_2SiCp''_2NdCH(SiMe_3)_2$ as precatalyst. [e] NMR and preparative-scale reactions. [f] Isolated yield. [g] Yield determined by ^1H NMR spectroscopy and GC/MS after vacuum transfer of volatile products.

(entries 1–3) alkynes, as well as a functionalized/polarized alkene (entry 6), a diene (entry 7), and a nonfunctionalized alkene (entry 8). In regard to nonfunctionalized alkynes, the ultimate products are imines, the expected tautomerization products[14] of initially formed enamines (Scheme 1). In regard to comparisons of intermolecular–intramolecular kinetic effects, entries 4 and 5 of Table 1 offer the most realistic comparison to intramolecular analogues (eqs 3 and 4).[2] It can be seen that under comparable conditions of catalyst, concentration, and temperature, the intramolecular hydroamination process is up to ~1000× more rapid. As might be expected for turnover-limiting –C≡C– insertion (cyclization) into the Ln–N bond, the intramolecular kinetic advantage diminishes with increasing ring size.[15] The greatest intermolecular (and intramolecular) alkyne hydroamination rates are observed for silyl-substituted acetylenes (Table 1, entries 1–3) and likely reflect the stabilizing tendency[16] by silicon substituents of α-carbanionic and β-carbocationic centers in what is a reasonable portrayal of the intermolecular insertive transition state (**A**). Note that this mechanistic proposal based on charge stabilization is in good accord with the observed regiochemistry of intermolecular NHR delivery (Table 1).

Scheme 1



R: *n*-propyl, *n*-butyl, *i*-butyl
R': $SiMe_3$, Ph, Me
Ln: Sm, Nd



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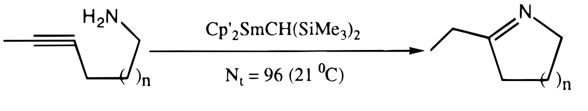

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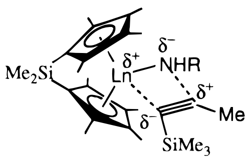
A


In the case of silyl-substituted alkynes, initial imine insertion products are observed by in situ ^1H NMR experiments; however, they undergo subsequent, 1,3-

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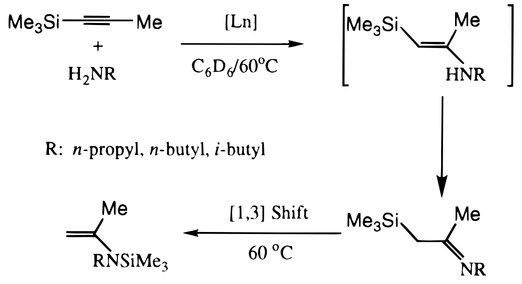
[13] In the glovebox, 20.0 mg (33.2 μmol) of $Me_2SiCp''_2NdCH(SiMe_3)$[10b] was loaded into a storage tube (25.0 mL) equipped with a magnetic stirbar. Next, C_6H_6 (5.0 mL), 1-(trimethylsilyl)-1-propyne (295 mg, 2630 μmol), and *n*-butylamine (183 mg, 2500 μmol) were successively vacuum-transferred onto the precatalyst. The mixture was then freeze–pump–thaw degassed and warmed to room temperature. The resulting solution was stirred with heating at 60 °C for 3 days. Distillation of the C_6H_6 and excess 1-(trimethylsilyl)-1-propyne followed by product vacuum transfer afforded a mixture of *N*-(1-methyl-2-(trimethylsilyl)-ethylidene)butylamine and *N*-(trimethylsilyl)-*N*-(1-(methylethyl)-1-enyl)butylamine. After the mixture was heated at 120 °C for 72 h, the *N*-(1-methyl-2-(trimethylsilyl)ethylidene)butylamine underwent complete isomerization to *N*-(trimethylsilyl)-*N*-(1-(methylethyl)-1-enyl)butylamine (**2**). *N*-(trimethylsilyl)-*N*-(1-(methylethyl)-1-enyl)butylamine, 0.29 g (62% isolated yield), was obtained as a colorless oil. It was >95% pure by ^1H NMR and GC/MS. ^1H NMR (300 MHz, C_6D_6): δ 4.18 (s, 2H, CH_2=), 2.98 (t, 2H, $J = 7.50$ Hz, CH_2N), 1.81 (s, 3H, CH_3C=N), 1.45 (m, 2H, CH_2CH_2N), 1.20 (m, 2H, CH_2Me), 0.84 (t, $J = 7.20$ Hz, 3H, CH_3CH_2), 0.19 (s, 9H, $SiMe_3$). ^{13}C NMR (75 MHz, ^1H-decoupled C_6D_6): δ 148.9, 92.9, 46.6, 32.8, 23.1, 20.9, 14.4, 2.1. ^{13}C NMR (75 MHz, ^1H-coupled, C_6D_6): δ 148.9 (s), 92.7 (t, $J_{CH} = 157.0$ Hz), 46.6 (t, $J_{CH} = 132.5$ Hz), 32.8 (t, $J_{CH} = 123.5$ Hz), 23.1 (q, $J_{CH} = 120.0$ Hz), 20.9 (t, $J_{CH} = 121.5$ Hz), 14.5 (q, $J_{CH} = 123.5$ Hz), 2.1 (q, $J_{CH} = 106.6$ Hz). MS (*m/e* (rel abundance)): M^+ (11), $M^+ - 1$ (2), $M^+ + 1$ (2), 170.2 (66), 156.3 (4), 142.1 (48), 128.1 (18), 114.1 (82), 100.1 (6), 73.0 (100), 59.1 (16), 45.0 (17). High-resolution mass spectrum: Calcd for $C_{10}H_{23}NSi$ (M^+), *m/e* 185.1600; found, *m/e* 185.1602.

[14] Shainyan, B. A.; Mirskova, A. N. *Russ. Chem. Rev.* **1979**, *48*, 107–117 and references therein.

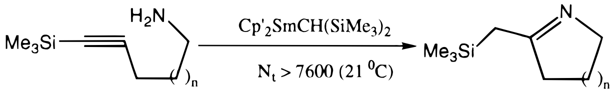
[15] (a) March, J. *Advanced Organic Chemistry*, 4th ed.; Wiley: New York, 1992; pp 211–212 and references therein. (b) DeTar, D. F.; Luthra, N. P. *J. Am. Chem. Soc.* **1980**, *102*, 4505–4512.

[16] (a) Bassindale, A. R.; Taylor, P. G. In *The Chemistry of Organic Silicon Compounds*; Patai, S., Rappaport, Z., Eds.; Wiley: Chichester, U.K., 1989; Chapter 14. (b) Fleming, I. In *Comprehensive Organic Chemistry*; Jones, N. D., Ed.; Pergamon Press: Oxford, U.K., 1979; Chapter 13.

sigmatropic silyl shifts (eq 5);[17] these are rapidly brought to completion at higher temperatures). Regarding inter−intramolecular hydroamination comparisons, the rate of 5-(trimethylsilyl)-4-pentyn-1-amine cyclization (eq 6) is >1000× more rapid than the analogous intermolecular entries 1−3 (Table 1). In the case of terminal alkynes, previously characterized[18] intermolecular alkyne oligomerization processes are considerably more rapid than alkyne hydroamination and dominate the catalytic chemistry under the conditions of Table 1.

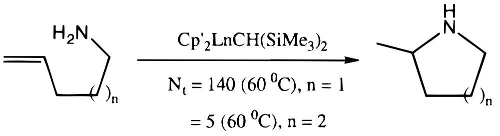


(5)



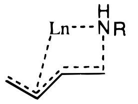
(6)

With respect to olefin hydroamination, entry 6 of Table 1 suggests that silyl-substituted alkenes are slightly less reactive (∼2−5×) than silyl-substituted alkynes (entries 1−3). In contrast, unfunctionalized olefins are sluggishly reactive under the present catalytic conditions (entry 8), in contrast to the analogous, but substantially more rapid, intramolecular transformations (eq 7).[1b] The diene transformation of entry 7 proceeds with complete stereospecificity and reasonably involves protonolysis of an intermediate lanthanide η^3-crotyl structure (**B**). The formation of such species from diene insertion into Ln−C/H bonds has considerable precedent.[10a,19]



(7)

B



A detailed kinetic study[11] of $Me_2SiCp''_2NdCH(SiMe_3)_2$-mediated entry 2 in Table 1 indicates zero-order behavior in amine over a 15-fold concentration range and first-order kinetics in both alkyne and catalyst over 10-fold and 20-fold concentration ranges, respectively. This yields the rate law of eq 8, which contrasts with the

$$\nu = k[\text{amine}]^0[\text{alkyne}]^1[\text{Ln}]^1 \qquad (8)$$

zero-order substrate kinetics observed for both aminoalkyne[2] and aminoalkene[1b] intramolecular hydroamination. In both these cases, turnover-limiting alkyne/alkene insertion is inferred from these results and other evidence (vide infra). Studies of the rate of intermolecular entry 2 over a 45 °C temperature range yield acceptable Eyring plots and the activation parameters $\Delta H^\ddagger = 17.2(1.1)$ kcal/mol and $\Delta S^\ddagger = -25.9(4.0)$ eu. Similar analyses for eq 2 ($H_2NCH_2CH_2CH_2C{\equiv}CH$ cyclization mediated by $Cp'_2SmCH(SiMe_3)_2$) afford $\Delta H^\ddagger = 10.7(8)$ kcal/mol and $\Delta S^\ddagger = -27.4(6)$ eu,[2b] while, for eq 7 ($n = 1$), $\Delta H^\ddagger = 12.7(1.4)$ kcal/mol and $\Delta S^\ddagger = -27.0(4.6)$ eu.[1b] In both cases, the intramolecular process proceeds with a substantially lower enthalpy of activation; however, the large, negative $\Delta S^\ddagger$ values are interestingly comparable in all three cases, arguing that the intramolecular processes do not enjoy a major overall activation entropic advantage and that the transition states are all highly organized/-constrained.

Further mechanistic evidence for steric constraints in the transition state for intermolecular hydroamination is seen in metal and ancillary ligand effects on the rate of entry 1, Table 1. A pattern of falling N_t with constricting metal ion coordination sphere is observed with (N_t(60 °C) values in parentheses) $Me_2SiCp''_2Nd$−(14 h^{-1}) > $Me_2SiCp''_2Sm$− (4 h^{-1}) > $Me_2SiCp''_2Lu$−(≤ 0.1 h^{-1}) > Cp'_2Sm− (<0.01 h^{-1}) and is typical of organolanthanide-catalyzed processes in which olefin insertion into a Ln−C or Ln−N bond is turnover-limiting.[1,10,20] Interestingly, the only significant exception to this pattern that we are aware of is the intramolecular hydroamination/cyclization of aminoalkynes.[2] Further kinetic support for significant steric impediments in the transition state of the present intermolecular process is found in $R''NH_2$ substituent effects where N_t (entries 1−3) declines in the order $R'' = n$-Pr ≥ n-Bu > i-Bu.

The present results contrast with those for Cp'_2An-mediated intermolecular hydroamination processes (An = Th, U).[9] Here, terminal alkynes undergo hydroamination whereas internal alkynes do not, silyl substituent effects are minor, and olefins are unreactive. The 5f work also reveals pronounced metal-dependent effects on regiochemistry not seen here for the lanthanides, and kinetics which are zero-order in [alkyne] and inverse order in [amine], implicating a metal imido (An=NR) intermediate. Together, these results illustrate a rich and diverse intermolecular hydroamination chemistry for 4f and 5f complexes and the most divergent 4f vs 5f catalytic pathways yet identified.

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Supporting Information Available: Text giving synthetic and characterization information for reactants and products and representative kinetic plots (15 pages). Ordering information is given on any current masthead page.

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(17) (a) Hitchcock, P. B.; Lappert, M. F.; Liu, D.-S. *J. Chem. Soc., Chem. Commun.* **1994**, 1699−1700. (b) Brook, A. G.; Bassindale, A. R. *In Rearrangements in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. 2, pp 204−205. (c) Bassindale, A. R.; Brook, A. G. *Can. J. Chem.* **1974**, *52*, 3474−3483. (d) Belavin, I. Yu.; Fedoseeva, N. A. *J. Gen. Chem. USSR* **1973**, *43*, 44.

(18) (a) Heeres, H. J.; Nijhoff, J.; Teuben, J. H. *Organometallics* **1993**, *12*, 2609−2617. (b) Heeres, H. J.; Teuben, J. H. *Organometallics* **1991**, *10*, 1980−1986 and references therein. (c) Heeres, H. J.; Meetsma, A.; Teuben, J. H.; Rogers, R. D. *Organometallics* **1989**, *8*, 2637−2646.

(19) Bunel, E.; Burger, B. J.; Bercaw, J. E. *J. Am. Chem. Soc.* **1988**, *110*, 976−978.

(20) (a) Schumann, H.; Meese-Marktscheffel, J. A.; Esser, L. *Chem. Rev.* **1995**, *95*, 865−986 and references therein. (b) Schaverien, C. J. *Adv. Organomet. Chem.* **1994**, *36*, 283−362 and references therein.