OUKA
The University of Osaka
Institutional Knowledge Archive

Title	Studies on Coupling Reactions of Carbonyl Compounds with Alkenes via Oxa-Nickelacycle Intermediates
Author(s)	林, 由香里
Citation	大阪大学, 2017, 博士論文
Version Type	VoR
URL	https://doi.org/10.18910/61746
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

The University of Osaka

Doctoral Dissertation

Studies on Coupling Reactions of Carbonyl Compounds with Alkenes via Oxa-Nickelacycle Intermediates

Yukari Hayashi

January 2017

Graduate School of Engineering

Osaka University

Preface and Acknowledgements

The study in this thesis has been carried out under the direction of Professor Sensuke Ogoshi at the Department of Applied Chemistry, Faculty of Engineering, Osaka University from April 2012 to March 2017. The thesis describes the coupling reactions of carbonyl compounds with alkenes via oxa-nickelacycle intermediates.

For accomplishment of my works, there were really lots of help, advice, and support. I owe all of them a great debt of gratitude. However, I regret to say that I cannot all of them here.

I wish to express my greatest gratitude to Professor Dr. Sensuke Ogoshi for a great number of invaluable suggestions, discussions, and hearty encouragement throughout this work. In addition, his enthusiasm for chemistry always filled me with a feeling of respect. I would like to express my appreciation to Professor Dr. Naoto Chatani and Professor Dr. Tetsuro Majima for their stimulating discussions. I would like to give my special thanks to Professor Dr. Tetsuro Murahashi at Tokyo Institute of Technology, Associate Professor Dr. Masato Ohashi, Assistant Professor Dr. Yoichi Hoshimoto, Project Assistant Professor Dr. Ravindra Kumar, and Project Assistant Professor Dr. Kotaro Kikushima for their continuous guidance, advice and assistance.

I would like to express my heartfelt appreciation to Secretary Ms. Noriko Fujimoto for her kind help and heart-warming encouragement.

I am deeply indebted to my respectful seniors in the Ogoshi Group, Dr. Takashi Tamaki, Dr. Akira Nishimura, Dr Hiroki Saijo, Ms. Haruka Suzuki, Mr. Kohei Takase, Mr. Ippei Takeda, Dr. Ryohei Doi, Mr. Ryohei Kamura, Mr. Yuki Tachibana, and Mr. Hiromu Tokura for their kindness and helpful advice. As colleagues for the master's course, Mr. Tomoya Ohata, Mr. Seita Kimura, Mr. Mitsutoshi Shibata, and Mr. Atsushi Tanaka always worked hard and improved together. In addition, they always helped my laboratory life. I am much obliged to all of my juniors in the Ogoshi Group, Mr. Hironobu Sakaguchi, Mr. Hiroaki Saito, Mr. Hayato Yabuki, Ms. Eri Tamai, Mr. Takuya Kawashima, Mr. Takuya Kinoshita, Ms. Yukari Sasaoka, Mr. Hiroshi Shirataki, Mr. Takuya Adachi, Mr. Takahiro Asada, Mr. Kyogo Maeda, Mr. Akira Ohnishi, Mr. Yuta Ueda, Mr. Keita Ashida, Mr. Takaya Hinogami, Mr. Naoyoshi Ishida, Mr. Kazuya Ishimoto, Mr. Ryohei

Suzuki, Mr. Yasuhiro Yamauchi, Mr. Kota Ando, Mr. Yu Hashimoto, Ms. Shiori Kusaka, Mr. Takafumi Ono, Mr. Yugo Ueda, and Ms. Tinghui Yu, for their helpful assistance and dedication. I also thank to Dr. Sunit Hazra who works in the Ogoshi Group as a postdoctoral fellow.

I would like to thank Dr. Nobuko Kanehisa for her helpful assistance for X-ray crystallographic analysis. Thanks are also due to the Instrumental Analysis Center, Graduate School of Engineering, Osaka University, for the measurement of spectral and analytical data.

I acknowledge the Research Fellowship from the Japan Society for the Promotion of Science for Young Scientists (April 2014–May 2017).

Finally, I would like to express my utmost gratitude to my parents, Mr. Koichi Hayashi and Ms. Sayuri Hayashi, and my brother, Mr. Hiroki Hayashi for their affectionate support and warm encouragement.

January 2017

Yukari Hayashi

Contents

General Introduction 1

Chapter 1
Mechanistic Studies on Nickel(0)-Catalyzed Intramolecular Hydroacylation 9

Chapter 2
Nickel(0)-Catalyzed Reductive Coupling Reactions of Carbonyl Compounds with Alkenes 47

Chapter 3
Development of Practical Synthesis of (η^6-Arene)Ni(N-Heterocyclic Carbene) Complexes 81

Conclusion 113

List of Publications / Supplementary Publication 115

Abbreviations

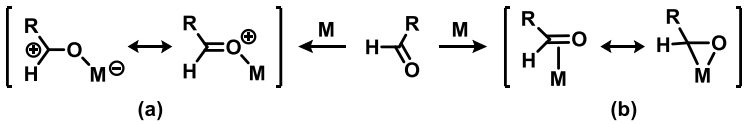
The following abbreviations are used in the thesis.

anal.	Elemental analysis
aq.	aqueous
Ar	aryl
atom	atmospheric pressure
br	broad
Bn	benzyl
Bu	butyl
calcd	calculated
cat.	catalyst
CI	chemical ionization
COA	cyclooctane
cod/COD	1,5-cyclooctadiene
COE	cyclooctene
COSY	correlated spectroscopy
Cy	cyclohexyl
°C	degrees Celcius
d	doublet
δ	chemical shift of NMR signal in ppm
DFT	density functional theory
DME	1,2-dimethoxyethane
dr	diastereomeric ratio
ee	enantiomeric excess
EI	electron ionization
eq(s).	equation(s)
equiv	equivalent
Et	ethyl
Et_2O	diethylether
FAB	fast atom bombardment
GC	gas chromatography
h	hour(s)
Hex	hexyl
HMBC	hetero-nuclear multiple-bond connectivity
HMQC	hetero-nuclear multiple quantum coherence
HPLC	high-performance liquid chromatography
HRMS	high resolution mass spectrometry

Hz	hertz
i	iso
IPr	1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene
IPr*	1,3-bis(2,6-bis(diphenylmethyl)-4-methylphenyl)imidazol-2-ylidene
IMes	1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene
I^{t}Bu	1,3-di-*tert*-butylimidazol-2-ylidene
J	coupling constant in NMR
KIE	kinetic isotope effect
L	ligand
M	metal
m	meta
Me	methyl
min	minute(s)
mL	milliliter
μL	microliter
MS	mass spectral
n	normal
NHC	N-heterocyclic carbene
NMR	nuclear magnetic resonance
o	ortho
ORTEP	Oak Ridge thermal ellipsoid plot
p	para
Ph	phenyl
Pr	propyl
PR_3	trialkyl- or triaryl-phosphine
q	quartet
quant	quantitative
rt	room temperature
s	second(s)
s	singlet
SFC	supercritical fluid chromatography
SIPr	1,3-bis(2,6-diisopropylphenyl)imidazolin-2-ylidene
SIMes	1,3-bis(2,4,6-trimethylphenyl)imidazolin-2-ylidene
t (*tert*)	tertiary
t	triplet
Tf	trifluoromethylsulfonyl
THF	tetrahydrofuran
TMS	trimethylsilyl
vs.	versus

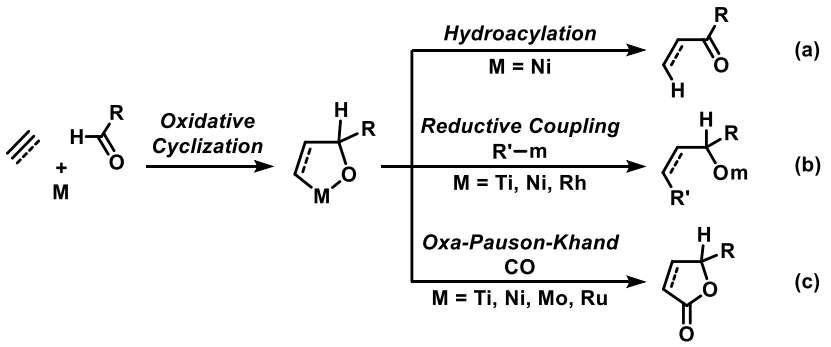
General Introduction

Aldehydes are common carbonyl compounds, and often need to be activated for their use in organic synthesis. Coordination of aldehydes to various typical- and transition-metals has been reported as a method to activate aldehydes. An η^1 coordination of carbonyl oxygen to Lewis acidic metals is accepted as a particularly important method (Scheme 1a).[1] The electrophilicity at the carbonyl carbon is enhanced via this η^1 coordination, which promotes the addition of a variety of nucleophiles to aldehydes. An η^2 coordination of aldehydes to low-valent transition-metals has also been reported (Scheme 1b).[2] Both the carbonyl oxygen and carbon demonstrate nucleophilic reactivity due to the contribution of an oxametallacyclopropane resonance form, which would enhance an interest in the reactivity of η^2-aldehyde complexes.



Scheme 1. Activation of aldehydes via a) η^1 coordination to Lewis acidic metals and b) η^2 coordination to low-valent transition-metals.

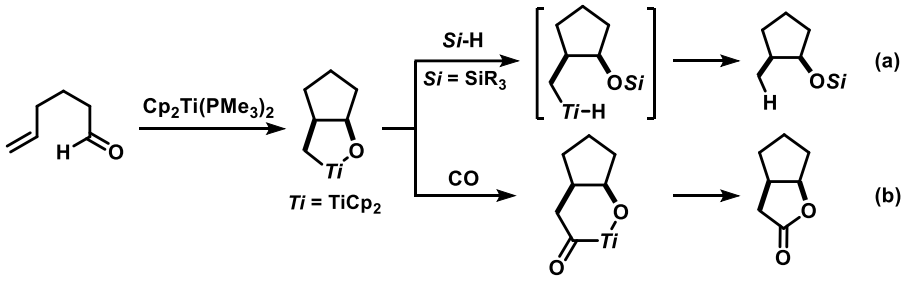
In addition, simultaneous coordination of aldehydes and unsaturated compounds such as alkynes, allenes, dienes, and alkenes to transition-metals are known. Oxidative cyclization then takes place to provide five-membered oxa-metallacycles with the formation of C–C, C–M, and O–M bonds (Scheme 2).[3–5] These five-membered oxa-metallacycles are often proposed as key intermediates in transition-metal-catalyzed synthesis of oxygen-containing compounds via formation of a C–C bond between aldehydes and unsaturated compounds,[5] e.g., hydroacylation reaction (Scheme 2a),[5a–c] reductive coupling reaction (Scheme 2b),[5d–g] and oxa-Pauson-Khand reaction (Scheme



Scheme 2. Transformation of aldehydes via five-membered oxa-metallacycles: a) hydroacylation, b) reductive coupling, and c) oxa-Pauson-Khand reactions.

2c).[5h] Therefore, the development of efficient methods to generate metallacycles would offer further opportunities to access a variety of organic compounds.

Five-membered oxa-metallacycles containing early transition-metals such as titanium and zirconium are well-known, and these complexes are stabilized by a strong interaction between oxygen and metals.[3a–c,e,f] For example in 1990s, Whitby reported the formation of oxa-titanacycles given by δ,ε-unsaturated carbonyl compounds and $TiCp_2(PMe_3)_2$ (Scheme 3).[3a] Furthermore, Buchwald and Crowe independently reported titanium-mediated/-catalyzed reductive coupling (Scheme 3a)[6] and oxa-Pauson-Khand reactions (Scheme 3b).[7] However, the strong interaction between oxygen and titanium in oxa-titanacycle intermediates significantly limits the catalytic turnover. Late transition-metal-catalyzed coupling reactions have also been well-investigated. In order to generate five-membered oxa-metallacycle intermediates in late transition-metal-catalyzed coupling reactions, strong back-donation from a metal center to η^2-aldehyde and η^2-unsaturated ligands is essential. Thus, the combination of an electron-rich transition-metal and a strong electron-donating ligand such as phosphine or N-heterocyclic carbene (NHC) ligands would be ideal.



Scheme 3. Titanium-mediated a) reductive coupling reaction with hydrosilanes and b) oxa-Pauson-Khand reaction via five-membered oxa-titanacycles.

Nickel(0) species would be a promising candidate since several reports on the isolation of five-membered oxa-nickelacycles[4] and on nickel(0)-catalyzed coupling reactions via oxa-nickelacycle intermediates have been reported.[5a–g] In 1970s, Stone and co-workers reported the first example on isolation of five-membered oxa-nickelacycles **a** and **b** formed by reactions of hexafluoroacetone with either hexafluoroacetone or hexafluoroacetone imine on tetrakis-(*tert*-butyl isocyanide)nickel,[4a,b] and Penfold and co-workers reported the first crystallographic identification of the five-membered oxa-

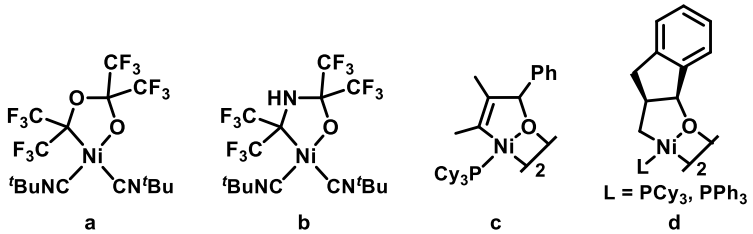
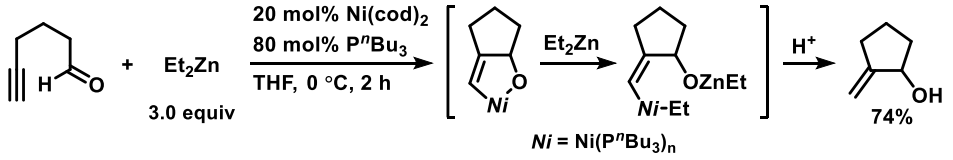


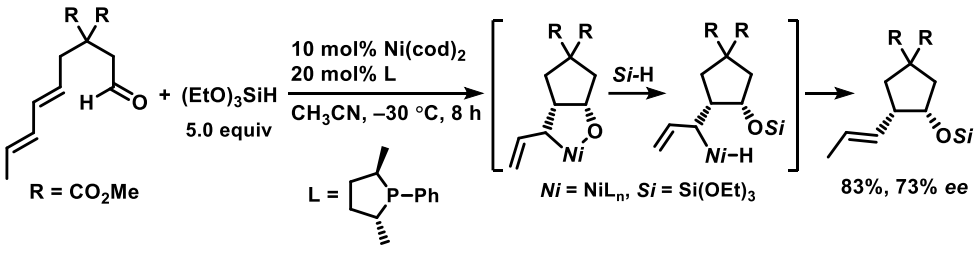
Figure 1. Examples of the reported five-membered oxa-nickelacycles.

nickelacycle **b** (Figure 1).[8] Our group has also contributed to these developments by the direct observation of the formation of oxa-nickelacycles **c** and **d** from (η^2-aldehyde:η^2-alkyne)nickel and (η^2-aldehyde:η^2-alkene)nickel complexes via oxidative cyclization (Figure 1), and observation of the following quantitative transformation into the corresponding oxygen-containing organic compounds.[4e–h]

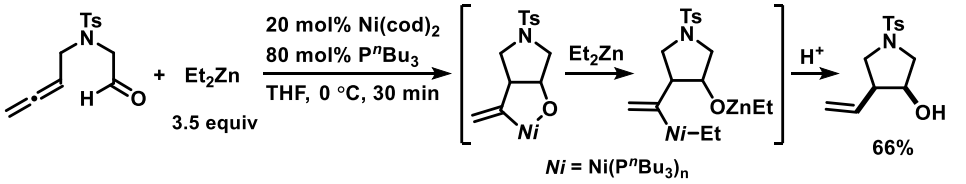
Oxa-nickelacycle is proposed as a key intermediate in a nickel(0)-catalyzed coupling reaction of aldehydes and unsaturated compounds (Scheme 1). Especially, nickel(0)-catalyzed reductive coupling reactions have been well-developed. In 1997, Montgomery and co-worker reported the first example on nickel(0)-catalyzed intramolecular reductive coupling reaction of aldehydes and alkynes with organozinc reagents (Scheme 4).[9] They proposed the reaction pathway proceeding via transmetallation between the oxa-nickelacycle with the organozinc reagent. After their first report, the reactions of aldehydes with alkynes have been well-developed.[5c–g] The use of 1,3-dienes[10] or allenes[11] instead of alkynes was also reported. In 2000, Mori, Sato, and co-workers reported the nickel(0)-catalyzed intramolecular reductive coupling of aldehydes and 1,3-dienes with hydrosilanes (Scheme 5).[10e,f] Montgomery and co-worker developed the nickel(0)-catalyzed intramolecular reductive coupling of aldehydes and allenes with organozinc reagents (Scheme 6).[11d] Nevertheless, the use of alkenes has been rare, which



Scheme 4. Nickel(0)-catalyzed reductive coupling of aldehyde and alkyne.

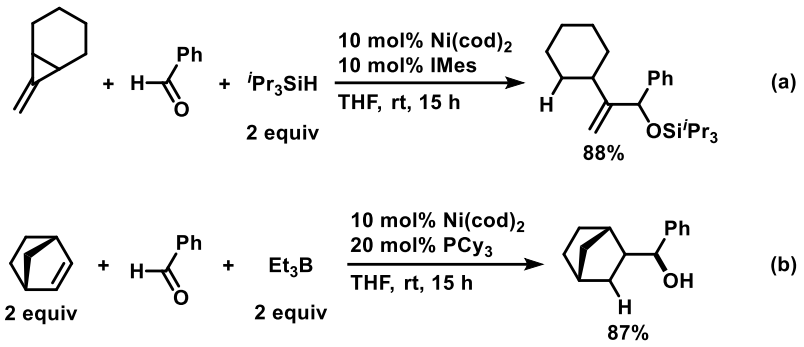


Scheme 5. Nickel(0)-catalyzed reductive coupling of aldehyde and 1,3-diene.

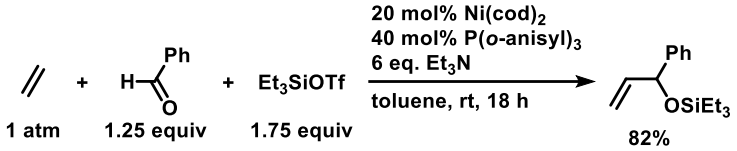


Scheme 6. Nickel(0)-catalyzed reductive coupling of aldehyde and allene.

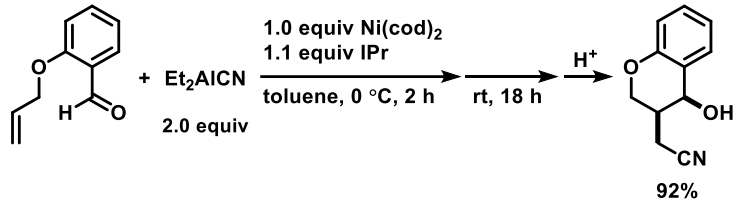
might be due to the difficulty of both the simultaneous coordination of these two components to nickel(0) and the following oxidative cyclization.[4e] Thus far, the use of alkenes has been limited to the highly reactive ones such as methylenecyclopropane (Scheme 7a),[12] norbornene (Scheme 7b).[13] The reaction using ethylene and silyl triflates was also reported by Jamison and co-workers (Scheme 8).[14] In addition, nickel(0)-mediated intramolecular reductive coupling reaction of aldehydes and alkenes with diethylaluminum cyanide was reported by Ho (Scheme 9).[15]



Scheme 7. Nickel(0)-catalyzed reductive coupling of aldehydes and alkenes.



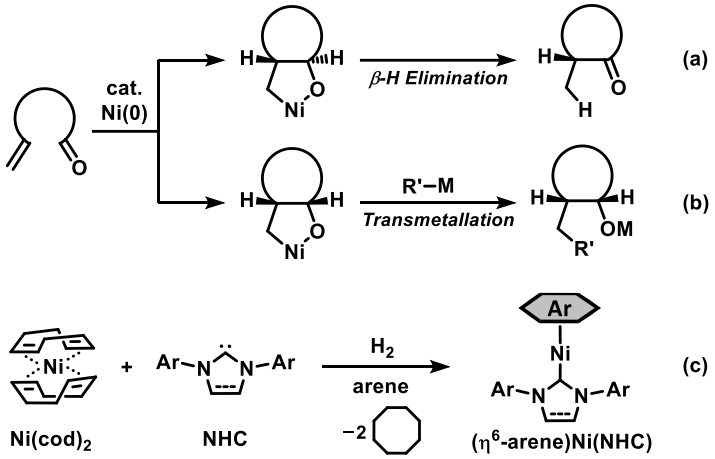
Scheme 8. Nickel(0)-catalyzed reductive coupling of aldehyde and ethylene with silyl triflate.



Scheme 9. Nickel(0)-mediated reductive coupling of aldehyde and alkene with diethylaluminum cyanide.

The purpose of this study is the development of intramolecular coupling reactions of simple alkenes with carbonyl compounds such as aldehydes and ketones via oxa-nickelacycle key intermediates. In addition, the development of practical method to synthesize a highly reactive and versatile Ni(0)–NHC precursor, where NHC stands for N-heterocyclic carbene, and utilization of these nickel(0) complex in organic synthesis are also the aim of this study.

This thesis consists of the general introduction in this chapter and the following three chapters (Scheme 10). In chapter 1, the mechanistic studies on the nickel(0)-catalyzed intramolecular hydroacylation of alkenes are described (Scheme 10a). Chapter 2 deals with the nickel(0)-catalyzed intramolecular reductive coupling reactions of carbonyl compounds with alkenes (Scheme 10b). During the course of the studies on nickel(0)-catalyzed coupling reactions through chapters 1 and 2, I focused on a versatile Ni(0)–NHC precursor with labile and less noxious η^6-arene ligand. In chapter 3, the development of practical preparation method for (η^6-arene)Ni(NHC) complexes is discussed (Scheme 10c). Finally, this thesis is summarized in conclusion.



Scheme 10. This thesis: a) nickel(0)-catalyzed intramolecular hydroacylation, b) nickel(0)-catalyzed intramolecular reductive coupling reaction, and c) practical preparation method for (η^6-arene)Ni(NHC) complexes.

References and notes

[1] For books, see: a) S. Shambayati, S.L. Schreiber in *Comprehensive Organic Synthesis*, *Vol. 1* (Eds.: B. M. Trost, I. Fleming), Pergamon, Oxford, UK, **1991**, chapter 1; b) R. H. Crabtree, *The Organometallic Chemistry of the Transition Metals*, 4th ed. Wiley-Interscience, New York, **2003**; c) J. P. Collman, L. S. Hegedus, J. R. Norton, R. G. Finke, *Principles and Applications of Organotransition-Metal Chemistry*, University Science Books, Mill Valley, CA, **1987**; also see: d) Y.-H. Huang, J. A. Gladysz, *J. Chem. Educ.* **1988**, *65*, 298; e) D. M. Schuster, P. S. White, J. L. Templeton, *Organometallics* **1996**, *15*, 5467 and references therein.

[2] For selected examples of η^2-aldehyde complexes, see: **Ti**: a) L. Li, K. E. Kristian, A. Han, J. R. Norton, W. Sattler, *Organometallics* **2012**, 31, 8218; **V**: b) S. Gambarotta, C. Floriani, A. Chiesi-Villa, C. Guastini, *Organometallics* **1986**, *5*, 2425; **Fe**: c) H. Lei, A. M. Royer, T. B. Rauchfuss, Danielle Gray, *Organometallics*

2012, *31*, 6408; **Co**: d) C. P. Lenges, M. Brookhart, P. S. White, *Angew. Chem. Int. Ed*. **1999**, *38*, 552; e) J. J. Schneider, D. Wolf, D. Bläser, R. Boese, *Eur. J. Inorg. Chem*. **2000**, 713; **Ni**: f) D. Walther, *J. Organomet. Chem*. **1980**, *190*, 393; g) J. Kaiser, J. Sieler, D. Walther, E. Dinjus, L. Golić, Acta Cryst. **1982**, *B38*, 1584; **Zr**: h) S. Gambarotta, C. Floriani, A. Chiesi-Villa, C. Guastini, *J. Am. Chem. Soc.* **1983**, *105*, 1690; **Nb**: i) B. Thiyagarajan, M. E. Kerr, J. C. Bollinger, V. G. Young, Jr., J. W. Bruno, *Organometallics* **1997**, *16*, 1331; **Mo**: j) H. Brunner, J. Wachter, I. Bernal, M. Creawick, *Angew. Chem. Int. Ed*. **1979**, *18*, 861; k) C. S. Chen, C. S. Lin, W. Y. Yeh, *J. Organomet. Chem*. **2011**, *696*, 1474; l) T. Jiménez, E. Barea, J. E. Oltra, J. M. Cuerva, J. Justica, *J. Org. Chem*. **2010**, *75*, 7022; **W**: m) W. Y. Yeh, C. S. Lin, *Organometallics* **2004**, *23*, 917; **Re**: n) W. E. Buhro, A. T. Patton, C. E. Strouse, J. A. Gladysz, *J. Am. Chem. Soc*. **1983**, *105*, 1056; **Os**: o) K. L. Brown, G. R. Clark, C. E. L. Headford, K. Marsden, W. R. Roper, *J. Am. Chem. Soc*. **1979**, *101*, 503; **Pt**: p) R. A. Head, *J. Chem. Soc. Dalton Trans*. **1982**, 1637.

[3] For selected examples of five-membered oxa-metallacycles, see: **Ti**: a) D. F. Hewlett, R. J. Whitby, *J. Chem. Soc., Chem. Commun.* **1990**, 16874; b) H. G. Alt, G. S. Herrmann, M. D. Rausch, D. T. Mallin, *J. Organomet. Chem.* **1988**, *356*, C53; c) V. B. Shur, V. V. Burlakov, A. I. Yanovsky, P. V. Petrovsky, Y. T. Struchkov, M. E. Vol'pin, *J. Organomet. Chem.* **1985**, *297*, 51; **Fe**: d) H. Lei, A. M. Royer, T. B. Rauchfuss, D. Gray, *Organometallics* **2012**, *31*, 6408; **Zr**: e) K. Kropp, V. Skibbe, G. Erker, *J. Am. Chem. Soc.* **1983**, *105*, 3353; f) G. Erker, F. Rosenfeldt, *J. Organomet. Chem.* **1982**, *224*, 29; **Ru**: g) J. F. Hartwig, R. A. Andersen, R. G. Bergman, *J. Am. Chem. Soc.* **1989**, *111*, 2717; **Ta**: h) J. R. Strickler, M. A. Bruck, P. A. Wexler, D. E. Wigley, *Organometallics* **1990**, *9*, 266; **W**: i) M. L. H. Green, G. Parkin, *J. Chem. Soc., Chem. Commun.* **1986**, 90.

[4] For selected examples of five-membered oxa-nickelacycles, see: a) M. Green, S. K. Shakshooki, F. G. A. Stone, *J. Chem. Soc. (A)* **1971**, 2828; b) A. Greco, M. Green, S. K. Shakshooki, F. G. A. Stone, *Chem. Commun.* **1970**, 1374; c) H. Hoberg, Y. Peres, C. Krüger, Y.-H. Tsay, *Angew. Chem. Int. Ed. Engl.* **1987**, *26*, 771; d) H. Hoberg, B. W. Oster, *J. Organomet. Chem.* **1984**, *266*, 321; for contributions by our group, see: e) Y. Hoshimoto, Y. Hayashi, H. Suzuki, M. Ohashi, S. Ogoshi, *Angew. Chem. Int. Ed.* **2012**, *51*, 10812; f) S. Ogoshi, T. Arai, M. Ohashi, H. Kurosawa, *Chem. Commun.* **2008**, 1347; g) S. Ogoshi, M. Ueta, T. Arai, H. Kurosawa, *J. Am. Chem. Soc.* **2005**, *127*, 12810; h) S. Ogoshi, M.-a. Oka, H. Kurosawa, *J. Am. Chem. Soc.* **2004**, *126*, 11802.

[5] For selected recent reviews, see: a) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *Acc. Chem. Res.* **2015**, *48*, 1746; b) M. C. Willis, *Chem. Rev.* **2010**, *110*, 725; c) K. Tanaka, Y.

Tajima, *Eur. J. Org. Chem.* **2012**, 3715; d) H. A. Reichard, M. McLaughlin, M. Z. Chen, G. C. Micalizio, *Eur. J. Org. Chem.* **2010**, 391; e) S.-S. Ng, C.-Y. Ho, K. D. Schleicher, T. F. Jamison, *Pure Appl. Chem.* **2008**, *80*, 929; f) E. Skucas, M.-Y. Ngai, V. Komanduri, M. J. Krische, *Acc. Chem. Res.* **2007**, *40*, 1394; g) J. Montgomery, *Angew. Chem. Int. Ed.* **2004**, *43*, 3890; h) N. Chatani, *Chem. Rec.* **2008**, *8*, 201.

[6] a) N. M. Kablaoui, S. L. Buchwald, *J. Am. Chem. Soc.* **1996**, *118*, 3182; b) N. M. Kablaoui, S. L. Buchwald, *J. Am. Chem. Soc.* **1995**, *117*, 6785; c) W. E. Crowe, M. J. Rachita, *J. Am. Chem. Soc.* **1995**, *117*, 6787.

[7] a) N. M. Kablaoui, F. A. Hicks, S. L. Buchwald, *J. Am. Chem. Soc.* **1997**, *119*, 4424; b) N. M. Kablaoui, F. A. Hicks, S. L. Buchwald, *J. Am. Chem. Soc.* **1996**, *118*, 5818; c) W. E. Crowe, A. T. Vu, *J. Am. Chem. Soc.* **1996**, *118*, 1557; d) K. Mashima, H. Haraguchi, A. Ohyoshi, N. Sakai, H. Takaya, *Organometallics* **1991**, *10*, 2731.

[8] R. Countryman, B. R. Penfold, *Chem. Commun.* **1971**, 1598.

[9] E. Oblinger, J. Montgomery, *J. Am. Chem. Soc.* **1997**, *119*, 9065.

[10] a) Y. Sato, Y. Hinata, R. Seki, Y. Oonishi, N. Saito, *Org. Lett.* **2007**, *9*, 5597; b) R. Sawaki, Y. Sato, M. Mori, *Org. Lett.* **2004**, *6*, 1131; c) Y. Sato, T. Takanashi, M. Hoshiba, M. Mori, *J. Organomet. Chem.* **2003**, *688*, 36; d) Y. Sato, N. Saito, M. Mori, *J. Org. Chem.* **2002**, *67*, 9310; e) Y. Sato, N. Saito, M. Mori, *J. Am. Chem. Soc.* **2000**, *122*, 2371; f) Y. Sato, M. Takimoto, M. Mori, *J. Am. Chem. Soc.* **2000**, *122*, 1624; g) Y. Sato, M. Takimoto, K. Hayashi, T. Katsuhara, K. Takagi, M. Mori, *J. Am. Chem. Soc.* **1994**, *116*, 9771.

[11] a) S.-S. Ng, T. F. Jamison, *Tetrahedron* **2006**, *62*, 11350; b) S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2005**, *127*, 7320; c) S.-K. Kang, S.-K. Yoon, *Chem. Commun.* **2002**, 2634; d) J. Montgomery, M. Song, *Org. Lett.* **2002**, *4*, 4009.

[12] K. Ogata, Y. Atsuumi, S.-i. Fukuzawa, *Org. Lett.* **2010**, *12*, 4536.

[13] a) K. Ogata, A. Toh, D. Shimada, S.-i. Fukuzawa, *Chem. Lett.* **2012**, *41*, 157; b) K. Ogata, Y. Atsuumi, D. Shimada, S.-i. Fukuzawa, *Angew. Chem. Int. Ed.* **2011**, *50*, 5896.

[14] a) C.-Y. Ho, T. F. Jamison, *Angew. Chem. Int. Ed.* **2007**, *46*, 782; b) S.-S. Ng, C.-Y. Ho, T. F. Jamison, *J. Am. Chem. Soc.* **2006**, *128*, 11513; c) C.-Y. Ho, S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2006**, *128*, 5362; d) S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2005**, *127*, 14194.

[15] C.-Y. Ho, *Chem. Commun.* **2010**, *46*, 466.

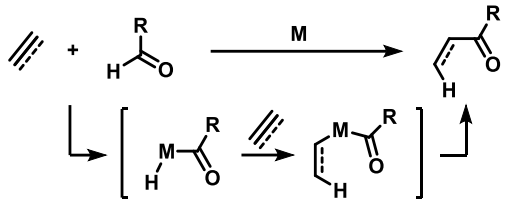
Chapter 1

Mechanistic Studies on Nickel(0)-Catalyzed Intramolecular Hydroacylation

Abstract: Our group previously reported the first example of a nickel(0)-catalyzed intramolecular hydroacylation of alkenes. No decarbonylation took place in our hydroacylation system while the decarbonylation has been an undesired, albeit unavoidable, side reaction in a long history of transition-metal-catalyzed hydroacylation. Thus, our hydroacylation system would be accepted as a practical and novel development in this field. Although some preliminary mechanistic studies using stoichiometric experiments were already reported, further studies were required to clarify all details of the reaction mechanism. Herein, a combined experimental and theoretical studies of nickel(0)-catalyzed intramolecular hydroacylation of alkenes is described. The results support the hypothesis that this intramolecular hydroacylation proceeds via an oxa-nickelacycle key intermediate.

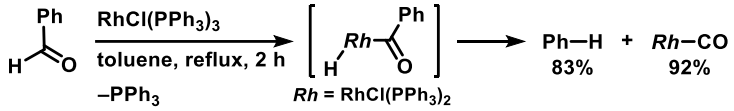
1.1. Introduction

Transition-metal-catalyzed hydroacylation has been accepted as a promising synthetic method to form C–C bonds between an aldehyde and unsaturated compounds, such as alkynes and alkenes (Scheme 1.1). In 1972, Sakai and co-workers reported the first



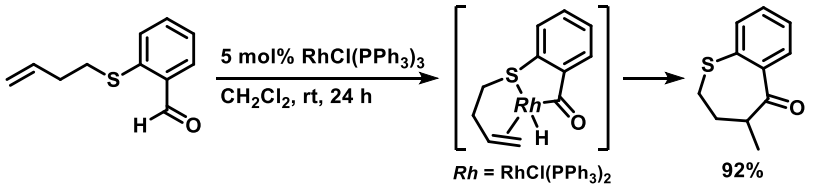
Scheme 1.1. Transition-metal-catalyzed hydroacylation.

example of intramolecular hydroacylation of alkenes by using a stoichiometric amount of Wilkinson's complex $RhCl(PPh_3)_3$.[1] The first example of rhodium-catalyzed intramolecular hydroacylation of alkenes was reported by Miller and co-worker in 1976.[2] Since these reports, significant advances have been achieved.[3] The reaction mechanism is believed to proceed via an acyl metal intermediate generated by oxidative addition of the aldehyde to the metal center. The acyl metal complex is also proposed as a key intermediate in transition-metal-catalyzed decarbonylation of aldehydes. For example, Tsuji reported that decarbonylation of benzaldehyde took place in the present of $RhCl(PPh_3)_3$ to give benzene and rhodium carbonyl complex $RhCl(PPh_3)_2(CO)$ (Scheme 1.2).[4] Thus, decarbonylation causes a decrease in the yield of the target product



Scheme 1.2. Decarbonylation of benzaldehyde with $RhCl(PPh_3)_3$.

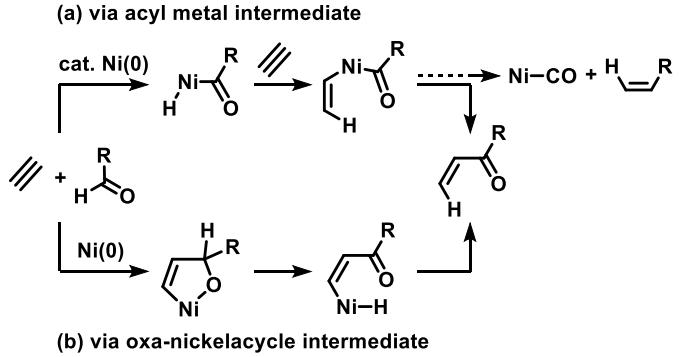
in hydroacylation and a deactivation of the catalyst via the coordination of carbon monoxide. In order to enhance the efficiency of the hydroacylation process, many strategies have been developed to suppress undesired decarbonylation from the acyl metal intermediate. In particular, chelation-assisted systems have significantly progressed, and these systems have become a major strategy in the design of novel hydroacylation systems.[3,5] For example, Bendorf and co-workers reported rhodium-catalyzed chelation-assisted intramolecular hydroacylation of alkenes (Scheme 1.3).[5a] In this reaction, coordination of both the sulfur tether atom and the alkene to a vacant site of the acyl



Scheme 1.3. Rhodium-catalyzed chelation-assisted hydroacylation of alkenes.

rhodium intermediate suppress the decarbonylation.

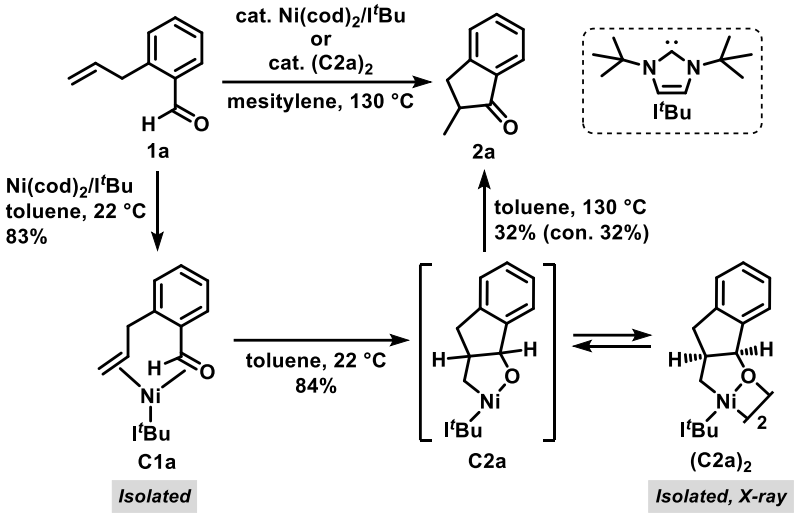
Nickel(0)-catalyzed intermolecular hydroacylation of alkyne was reported by Tsuda, Saegusa, and co-worker in 1990.[6,7] They proposed two possible reaction pathways: a) proceeds via an acyl nickel intermediate, and b) proceeds via an oxa-nickelacycle intermediate (Scheme 1.4). They concluded that the former was more plausible because



Scheme 1.4. Nickel-catalyzed hydroacylation of alkyne via a) an acyl nickel intermediate or b) an oxa-nickelacycle intermediate.

of observation of the formation of nickel carbonyl complex and decarbonylated olefinic side products in the reaction with benzaldehyde. On the other hand, during the course of our research on hetero-nickelacycles,[8] our group demonstrated that an oxa-nickelacycle prepared by oxidative cyclization of an alkyne and an aldehyde with nickel(0) slowly decomposed to furnish a hydroacylated product and no decarbonylated product.[8b] This result indicated that the oxa-nickelacycle can act as a potential intermediate in nickel(0)-catalyzed hydroacylation alkyne (Scheme 1.4b). The formation of dimeric oxa-nickelacycles in the stoichiometric reaction of *o*-allylbenzaldehyde (*o*-ABA), $Ni(cod)_2$, and tertiary phosphines has been reported as well.[8a] Thus, the construction of a catalytic hydroacylation of alkene via the oxa-nickelacycle seemed quite effective for the generation of a hydroacylated product without decarbonylation. Recently, we have developed the first example on Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of alkenes (Scheme 1.5).[9] Remarkably, no decarbonylation was observed under our catalytic conditions, and thus this Ni(0)/I^{t}Bu-catalyzed hydroacylation represents 100% atom efficiency. A plausible reaction mechanism was proposed as shown in Scheme 1.5 based on the results of preliminary mechanistic studies using *o*-ABA (**1a**): i) (η^2-aldehyde:η^2-alkene)nickel complex **C1a** and dimeric oxa-nickelacycle **(C2a)$_2$** were isolated by stoichiometric experiments of **1a**, $Ni(cod)_2$, and I^{t}Bu; and, ii) transformation of **(C2a)$_2$** into 2-methylindanone (**2a**) was confirmed under both stoichiometric and catalytic conditions.

Herein, additional results obtained by kinetic and theoretical studies and detailed insights into the reaction mechanism are described.



Scheme 1.5. Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of alkene. A reaction mechanism previously proposed is shown.

1.2. Result and Discussion

1.2.1. Kinetic Experiments

The reaction of **1a** (0.40 mol m^{-3}) with Ni(cod)$_2$ (2.0×10^{-2} mol m^{-3}) and I^{t}Bu (2.0×10^{-2} mol m^{-3}) in mesitylene at 130 °C was monitored by means of GC (Figure 1.1a). The rate constants of the disappearance of **1a** (k_S) and the production of **2a** (k_P) were evaluated by the least-squares fitting of the time–concentration profiles to zeroth-order rate equations (Eqs. 1 and 2):

$$-d[\mathbf{1a}]/dt = k_S = 3.39(11) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (1)$$

$$d[\mathbf{2a}]/dt = k_P = 2.66(7) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (2)$$

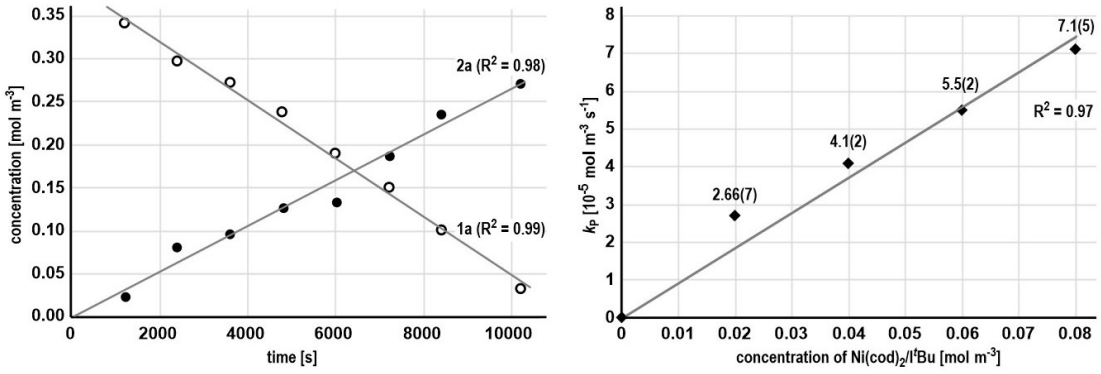


Figure 1.1. a) The profiles of the concentration of the disappearance of **1a** (○) and the production of **2a** (●) with respect to reaction time. Reaction was monitored by GC using pentadecane as an internal standard. b) The profile of k_P with respect to the concentration of Ni(cod)$_2$/I^{t}Bu. All reactions were monitored by GC using pentadecane as an internal standard.

The zeroth-order dependence on the concentration of **1a** indicates that the coordination of **1a** to a Ni(0)/I^{t}Bu complex yielding **C1a** is not involved in the rate-determining event. Next, the k_P values were estimated by varying the concentrations of Ni(cod)$_2$ and I^{t}Bu from 2.0×10^{-2} to 8.0×10^{-2} mol m^{-3} (Figure 1.1b). Thus, the kinetic order in the Ni(0)/I^{t}Bu catalyst is the first-order.

1.2.2. Theoretical Experiments

Two reaction mechanisms for the hydroacylation of **1a** were evaluated with DFT calculation, which proceeds via i) oxidative cyclization giving **C2a** (Figure 1.2) and ii) cleavage of the aldehyde C–H bond giving acyl nickel intermediate **C8a** (Figure 1.3). All minima and transition state geometries were optimized with B3PW91 function implemented in Gaussian 09.[10] For calculation of the potential energies, the SDD basis set was used for Ni with an f polarization function, and 6-311+G(d,p) was used for other atoms. The SCRF (mesitylene) with IEF-PCM solvation model was used in all calculations. All relative energies presented herein are Gibbs free energies in kilocalories per mole (kcal mol^{-1}) at 403.15 K with respect to **Ni(0)/I^{t}Bu+1a**. Zero-point vibration energies and thermodynamic corrections at 403.15 K were calculated at the same level as the geometry optimization.

The calculation results on the transformation of **1a** to (η^2-**2a**)Ni(I^{t}Bu) (**C6a**) via oxidative cyclization giving oxa-nickelacycle intermediate **C2a** are shown in Figure 1.2. The optimized molecular structures for ***anti*-C1a**, ***trans*-TS1**, ***trans*-C2a**, **TS2**, **C3a**, and **TS4** are also given. Coordination of **1a** to Ni(0)/I^{t}Bu yields two isomers, ***anti*-C1a** (–29.5 kcal mol^{-1}) and ***syn*-C1a** (–31.5 kcal mol^{-1}), depending on the orientation of the C1–H1 bond with respect to the C5–H5 bond. The molecular structure of (η^2:η^2-*o*-homoallylbenzaldehyde)Ni(I^{t}Bu) was previously confirmed by X-ray analysis, and the corresponding *syn* orientation was determined.[9a] Oxidative cyclization from ***anti*-C1a** produces monomeric oxa-nickelacycle ***trans*-C2a** (–22.3 kcal mol^{-1}) via ***trans*-TS1** (–6.5 kcal mol^{-1}), and the activation barrier in this step is thus $\Delta G^{\ddagger}$ = 23.0 kcal mol^{-1}. The interatomic distance between C1 and C5 varies from 2.74 Å in ***anti*-C1a** to 1.52 Å in ***trans*-C2a** via ***trans*-TS1** (C1···C5 1.68 Å), which shows the formation of the C1–C5 bond during this oxidative cyclization process. The monomeric oxa-nickelacycle complex ***cis*-C2a** (–29.5 kcal mol^{-1}) and dimeric ***cis*-(C2a)$_2$** (–30.6 kcal mol^{-1} without BSSE correction; –26.3 kcal mol^{-1} with BSSE) are also accessible from ***syn*-C1a** via ***cis*-TS1** (–7.6 kcal mol^{-1}). Thus, the oxidative cyclization to form ***cis*-C2a** (and the following dimerization to give ***cis*-(C2a)$_2$**) could occur easily under the catalytic conditions, which is consistent with the experimental result wherein ***cis*-(C2a)$_2$** was isolated in 88% yield as a precipitation from toluene solution of **C1a** after 33 days at room temperature.[9a]

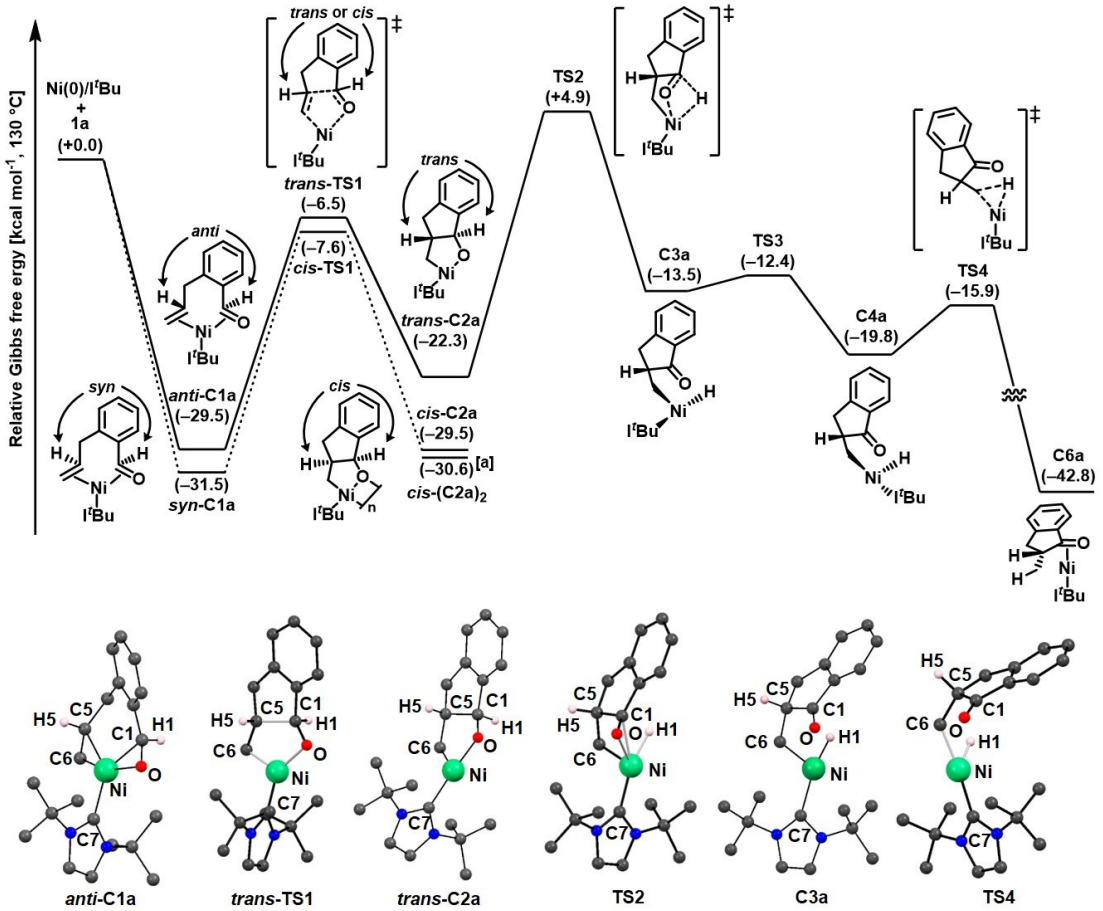


Figure 1.2. Gibbs free energy surface of the pathways via oxidative cyclization followed by β-hydride elimination. Relative Gibbs free energies in mesitylene (IEF-PCM solvation model) with respect to **Ni(0)/I^{t}Bu+1a** (= +0.0) are shown, calculated by DFT at the B3PW91/SDD(f) for Ni and 6-311+G(d,p) for other atoms (403.15 K). Optimized structures of ***anti*-C1a**, ***trans*-TS1**, ***trans*-C2s**, **TS2**, **C3a**, and **TS4** are also given. Hydrogen atoms except H1 and H5 are omitted for alacrity. Selected distances [Å] and angles [°]: (***anti*-C1a**) O–Ni 1.96, C1–Ni 1.94, C1···C5 2.74, C5–Ni 2.03, C6–Ni 2.02, C1–O 1.30, C5–C6 1.40, Ni–C7 1.99; (***trans*-TS1**) O–Ni 1.96, C1···Ni 2.24, C1···C5 1.68, C5···Ni 2.27, C6–Ni 1.88, C1–O 1.37, C5–C6 1.51, Ni–C7 1.85, C6–Ni–O 117.1, C6–Ni–C7 103.3, O–Ni–C7 139.4, O–C1–C5 119.7, C6–C5–C1 114.5; (***trans*-C2a**) O–Ni 1.83, C1···Ni 2.63, C1–C5 1.52, C5···Ni 2.67, C6–Ni 1.94, C1–O 1.39, C5–C6 1.52, Ni–C7 1.92, C6–Ni–C7 99.3, C7–Ni–O 169.4, O–Ni–C6 91.0; (**TS2**) O···Ni 2.36, C1···Ni 2.22, H1···Ni 1.56, C1···H1 1.61, C1–O 1.27, C1–C5 1.57, C5–C6 1.52, C6–Ni 1.93, Ni–C7 1.93, C6–Ni–H1 82.6, C6–Ni–C7 103.6, H1–Ni–C7 163.9; (**C3a**) H1–Ni 1.46, H1···C6 2.23, Ni–C6 1.90, C7–Ni 2.01, C6–Ni–C7 111.0, C7–Ni–H1 166.9, H1–Ni–C6 82.2; (**TS4**) C6···H1 1.63, H1–Ni 1.43, C6–Ni 1.91, Ni–C7 1.92, C6–Ni–H1 56.2, C6–Ni–C7 175.1, H1–Ni–C7 126.8. [a] Energy value without BSSE correction (–26.3 kcal mol^{-1} with BSSE).

A rational structure for **TS2** (+4.9 kcal mol^{-1}) is found in the β-hydride elimination step from ***trans*-C2a** forming nickel hydride intermediate **C3a** (–13.5 kcal mol^{-1}); however, an activation complex in β-hydride elimination from ***cis*-C2a** was not found under the present calculation conditions. Thus, ***trans*-C2a** is key for the production of **2a**. After the formation of **C3a**, isomerization to **C4a** (–19.8 kcal mol^{-1}) followed by reductive

elimination via **TS4** (−15.9 kcal mol^{-1}) affords **C6a**. The overall activation barrier for this reaction mechanism is $\Delta G^{\ddagger}$ = 36.4 kcal mol^{-1}, which is calculated using the steps from ***syn*-C1a** to **TS2**.

The reaction pathways via cleavage of the aldehyde C–H bond were also evaluated under the same calculation conditions. The results and optimized structures of ***anti*-TS5**, ***anti*-C7a**, ***trans*-TS6**, **C8a**, and **TS7** are shown in Figure 1.3, wherein the participation of a ligand-to-ligand hydrogen transfer process via ***cis*-** or ***trans*-TS6** is revealed.[11] First, the formation of ***anti*/*syn*-C1a** occurs followed by a change in the coordination mode of

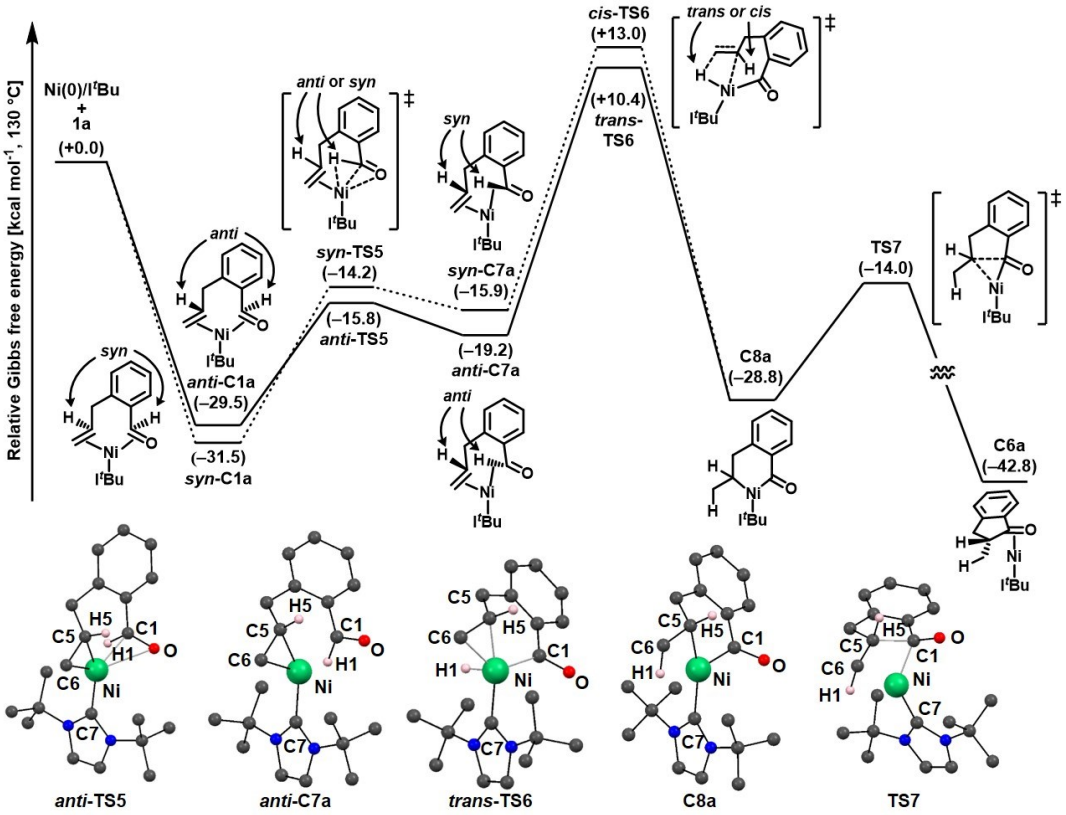
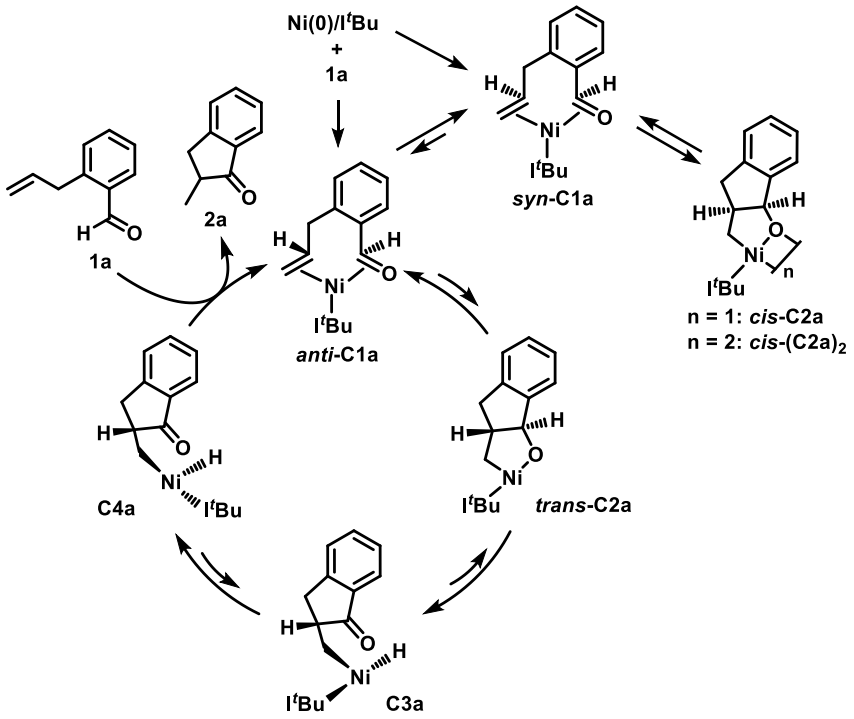


Figure 1.3. Gibbs free energy surface of the pathways via cleavage of the aldehyde C–H bond giving an acyl nickel intermediate. Relative Gibbs free energies in mesitylene (IEF-PCM solvation model) with respect to **Ni(0)/I^{t}Bu+1a** (= +0.0) are shown, calculated by DFT at the B3PW91/SDD(f) for Ni and 6-311+G(d,p) for other atoms (403.15 K). Optimized structures of ***anti*-TS5**, ***anti*-C7a**, ***trans*-TS6**, **C8a**, and **TS7** are also given. Hydrogen atoms except H1 and H5 are omitted for alacrity. Selected distances [Å] and angles [°]: (***anti*-TS5**) O···Ni 2.59, C1–Ni 2.08, H1···Ni 1.79, C1–H1 1.15, C1–O 1.24, C5–Ni 1.99, C6–Ni 1.96, Ni–C7 1.96, Ni–C1–H1 59.2, O–C1–H1 118.2; (***anti*-C7a**) O···Ni 2.76, C1–Ni 2.01, H1–Ni 1.62, C1–H1 1.22, C1–O 1.24, C5–Ni 1.98, C6–Ni 1.97, Ni–C7 1.96, Ni–C1–H1 53.6, O–C1–H1 115.7; (***trans*-TS6**) O···Ni 2.87, C1–Ni 2.01, H1–Ni 1.37, C1···H1 2.73, C6···H1 2.25, C5–Ni 1.98, C6···Ni 2.08, Ni–C7 1.94, C1–Ni–H1 106.0, C6–Ni–H1 78.5, C6–Ni–C7 127.7, C7–Ni–C1 104.2, C6–Ni–C1 128.0, C5–Ni–C1 87.1; (**C8a**) C1–Ni 1.84, C5–Ni 1.90, C6···Ni 2.34, Ni–C7 1.97, C5–Ni–C7 163.9, C7–Ni–C1 109.1, C5–Ni–C1 87.0; (**TS7**) O···Ni 2.66, C1–Ni 1.88, C1···C5 1.74, C5···Ni 2.16, Ni–C7 1.89, C5–Ni–C7 175.2, C7–Ni–C1 127.4, C5–Ni–C1 50.6.

the aldehyde group from η^2-(κ-C,O) to η^2-(κ-C,H) to give ***anti*-C7a** (−19.2 kcal mol^{-1}) and ***syn*-C7a** (−15.9 kcal mol^{-1}). The optimized molecular structures of ***anti*-TS5** and ***anti*-C7a** illustrate this change in coordination mode from ***anti*-C1a** to ***anti*-C7a** via ***anti*-TS5**. The interatomic distances between Ni to H1 and Ni to O vary from 2.45 to 1.62 Å and from 1.96 to 2.76 Å, respectively, via ***anti*-TS5** (Ni···H1 1.79 Å, Ni···O 2.59 Å). A rational transition state for the oxidative addition of the aldehyde C1−H1 bond in ***anti*/*syn*-C7a** to the nickel(0) center affording a nickel hydride intermediate was not found under the present calculation conditions. Alternatively, the pathways were predicted to proceed via the hydrogen transfer from the η^2-(κ-C,H)-aldehyde ligand in ***syn*-** or ***anti*-C7a** to the η^2-alkene ligand via ***cis*-** (+13.0 kcal mol^{-1}) or ***trans*-TS6** (+10.4 kcal mol^{-1}), respectively. As a result, an acyl nickel intermediate **C8a** (−28.8 kcal mol^{-1}) is formed. In the optimized structure of ***trans*-TS6**, the C1−H1 bond is cleaved (C1···H1 2.73 Å) to form a Ni−H1 bond (Ni−H1 1.37 Å), and then the covalent bonds between C6 and H1, C5 and Ni, and C1 and Ni form simultaneously. From **C8a**, reductive elimination via **TS7** (−14.0 kcal mol^{-1}) furnishes the product **C6a**. Thus, the overall activation barrier is $\Delta G^{\ddagger}$ = 41.9 kcal mol^{-1}, which is given by the steps from ***syn*-C1a** to ***trans*-TS6**.

Given the lower overall activation barrier of 36.4 kcal mol^{-1} for the former versus 41.9 kcal mol^{-1} for the latter, it is likely that the former pathways proceed via the oxidative cyclization depicted in Figure 1.2. Furthermore, this former reaction mechanism is consistent with the following experimental results: i) the transformation of **1a** to **2a** showed the zeroth- and first-order dependence upon the concentrations of **1a** and Ni(0)/I^{t}Bu, respectively (Figure 1.1); ii) the isolation of ***cis*-(C2a)$_2$** and its conversion into **C2a** took place under both stoichiometric and catalytic conditions (Scheme 1.5); and, iii) no decarbonylation was observed under the optimized catalytic conditions.[9a]

Details of the catalytic cycle are summarized in Scheme 1.6. First, the coordination of **1a** to Ni(0)/I^{t}Bu gives ***anti*-C1a** and/or ***syn*-C1a**, in which **1a** coordinates to the Ni(0) center in an η^2-alkene and an η^2-aldehyde fashion. Under the present calculation conditions, ***syn*-C1a** is predicted to be energetically more stable. The oxa-nickelacycles ***trans*-C2a** and ***cis*-C2a** are generated from ***anti*-C1a** and ***syn*-C1a**, respectively, via oxidative cyclization processes. The dimeric complex ***cis*-(C2a)$_2$** was previously experimentally isolated;[9a] however, the present calculations show that ***trans*-C2a** is the key intermediate for the production of **2a**. β-Hydride elimination occurs from ***trans*-C2a** to afford nickel hydride intermediate **C3a**. The transition state with the highest relative Gibbs free energy is given in this β-hydride elimination process. Thus, the reaction rate is determined by the pathways from ***syn*-C1a** to **C3a**. Isomerization to **C4a** and reductive elimination occur to give **2a**, along with regeneration of ***anti*-C1a** and/or ***syn*-C1a** by coordination of **1a** to Ni(0)/I^{t}Bu.



Scheme 1.6. Catalytic pathways for Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of *o*-allylbenzaldehyde **1a**.

1.3. Conclusion

In conclusion, experimental and theoretical studies on the Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of alkenes were performed. Two plausible reaction mechanisms were fully evaluated by DFT calculation. The mechanism proceeding via i) an oxa-nickelacycle intermediate given by the oxidative cyclization of η^2-alkene and η^2-aldehyde ligands on nickel(0) is likely when compared to the mechanism proceeding via ii) an acyl nickel intermediate given by a ligand-to-ligand hydrogen transfer from η^2-(κ-C,H)-aldehyde to η^2-alkene ligands. Kinetic experiments of the reaction showed the zeroth- and first-order dependence on the concentrations of the substrate and the Ni(0)/I^{t}Bu catalyst, respectively. All theoretical predictions and experimental results are well consistent with the conclusion that the Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of *o*-allylbenzaldehyde proceeds via the oxa-nickelacycle with *trans*-conformation as a key intermediate.

1.4. Experimental Section

1.4.1. General

All manipulations were conducted under a nitrogen atmosphere using standard Schlenk or dry box techniques. Analytical gas chromatography (GC) was carried out on a Shimadzu GC-2014 gas chromatograph, equipped with a flame ionization detector.

1.4.2. Materials

Mesitylene was distilled from sodium benzophenone ketyl prior to use. Pentadecane was distilled over CaH_2 under reduced pressure prior to use. 1,3-Di-*tert*-butylimidazol-2-ylidene (I^{t}Bu) was furnished by the known procedures.[12] *o*-Allylbenzaldehyde (**1a**) was prepared by the procedure reported previously.[9a]

1.4.3. Kinetic Studies

Determination of order in substrate (Figure 1.1a)

Determination of the reaction rate constant for the hydroacylation with 1a: To a solution of $Ni(cod)_2$ (22.0 mg, 0.08 mmol) and I^{t}Bu (14.4 mg, 0.08 mmol) in mesitylene (4 mL) was added **1a** (235.6 mg, 1.61 mmol) and pentadecane (207.7 mg) as an internal standard. Initially the reaction mixture was heated at 128–130 °C for 15 min, and then the monitoring of the reaction started at the indicated temperature by GC. The results were summarized in Figure 1.4. k_S and k_P were evaluated by the least-squares fitting of the time–concentration profiles to zeroth-order rate equations (Eqs. 1 and 2):

$$-d[\mathbf{1a}]/d\mathrm{t} = k_\mathrm{S} = 3.39(11) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (1)$$

$$d[\mathbf{2a}]/d\mathrm{t} = k_\mathrm{P} = 2.66(7) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (2)$$

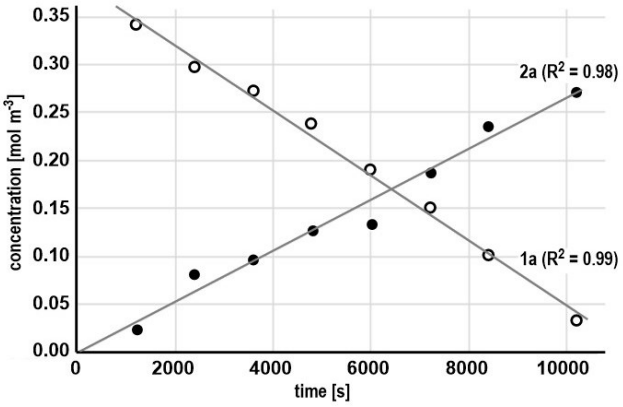


Figure 1.4. The profiles of the concentration of **1a** (○) and **2a** (●) with respect to reaction time. Reaction was monitored by GC using pentadecane as an internal standard.

Determination of the order of the reaction in catalyst (Figure 1.1b)

[Ni(cod)$_2$/I^{t}Bu] = 0.08 M: To a solution of $Ni(cod)_2$ (88.0 mg, 0.32 mmol) and I^{t}Bu (57.6 mg, 0.32 mmol) in mesitylene (4 mL) was added **1a** (234.0 mg, 1.60 mmol) and

pentadecane (177.4 mg) as an internal standard. Initially the reaction mixture was heated at 130 °C for 15 min, and then the monitoring of the reaction started at the indicated temperature by GC. The results were summarized in Figure 1.5. k_{P} at [cat] = 0.08 M was evaluated by the least-squares fitting of the time–concentration profile to zeroth-order rate equation (Eq. 3).

$$k_{\mathrm{P}} = d[\mathbf{2a}]/d\mathrm{t} = 7.1(5) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (3)$$

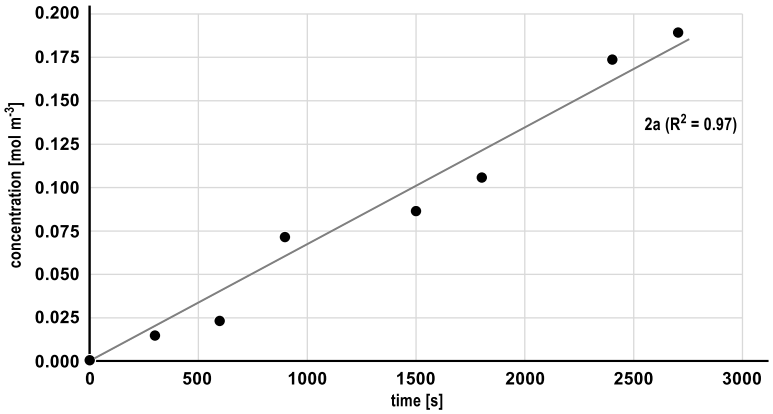


Figure 1.5. The profile of the concentration of **2a** with respect to reaction time when [Ni(cod)$_2$/I^{t}Bu] is 0.08 M. Reaction was monitored by GC using pentadecane as an internal standard.

[Ni(cod)$_2$/I^{t}Bu] = 0.06 M: To a solution of Ni(cod)$_2$ (33.0 mg, 0.12 mmol) and I^{t}Bu (21.6 mg, 0.12 mmol) in mesitylene (2 mL) was added **1a** (116.5 mg, 0.80 mmol) and pentadecane (99.9 mg) as an internal standard. Initially the reaction mixture was heated at 130 °C for 15 min, and then the monitoring of the reaction started at the indicated temperature by GC. The results were summarized in Figure 1.6. k_{P} at [cat] = 0.06 M

$$k_{\mathrm{P}} = d[\mathbf{2a}]/d\mathrm{t} = 5.5(2) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (4)$$

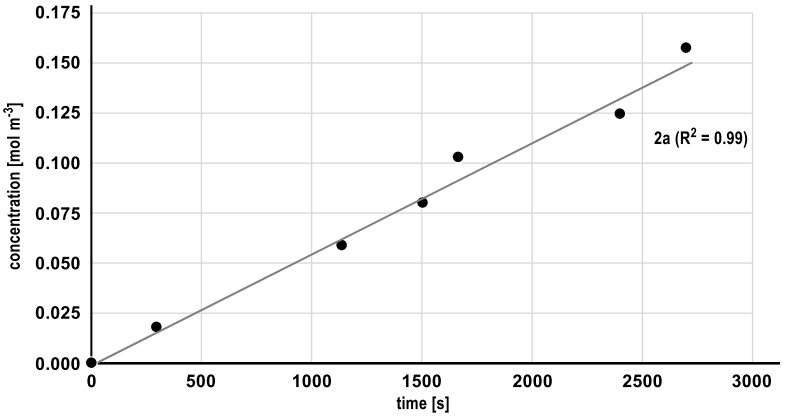


Figure 1.6. The profile of the concentration of **2a** with respect to reaction time when [Ni(cod)$_2$/I^{t}Bu] is 0.06 M. Reaction was monitored by GC using pentadecane as an internal standard.

was evaluated by the least-squares fitting of the time–concentration profile to zeroth-order rate equation (Eq. 4).

[Ni(cod)$_2$/I^{t}Bu] = 0.04 M: To a solution of Ni(cod)$_2$ (22.0 mg, 0.08 mmol) and I^{t}Bu (14.4 mg, 0.08 mmol) in mesitylene (2 mL) was added **1a** (118.6 mg, 0.81 mmol) and pentadecane (103.7 mg) as an internal standard. Initially the reaction mixture was heated at 130 °C for 15 min, and then the monitoring of the reaction started at the indicated temperature by GC. The results were summarized in Figure 1.7. k_{P} at $[\mathrm{cat}] = 0.04$ M was evaluated by the least-squares fitting of the time–concentration profile to zeroth-order rate equation (Eq. 5).

$$k_{\mathrm{P}} = d[\mathbf{2a}]/d\mathrm{t} = 4.1(2) \times 10^{-5}\ [\mathrm{mol\ m^{-3}\ s^{-1}}] \qquad (5)$$

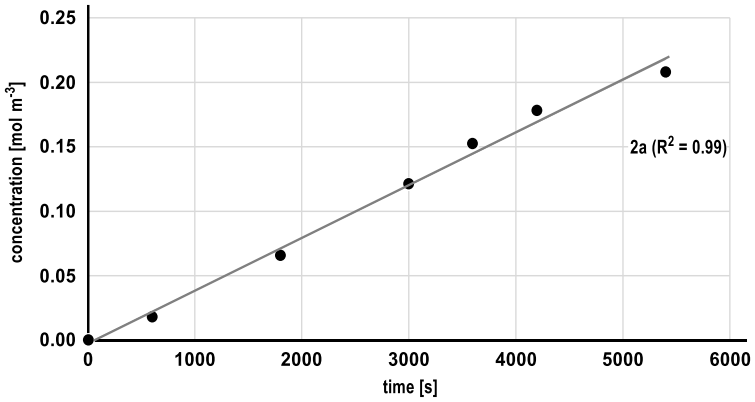


Figure 1.7. The profile of the concentration of **2a** with respect to reaction time when [Ni(cod)$_2$/I^{t}Bu] is 0.04 M. Reaction was monitored by GC using pentadecane as an internal standard.

Order in catalyst: From these results, the profile of k_P with respect to the concentration of Ni(cod)$_2$/I^{t}Bu gave a straight line (R^2 = 0.97), suggesting the kinetic order in the Ni(0)/I^{t}Bu catalyst is the first-order (Figure 1.8).

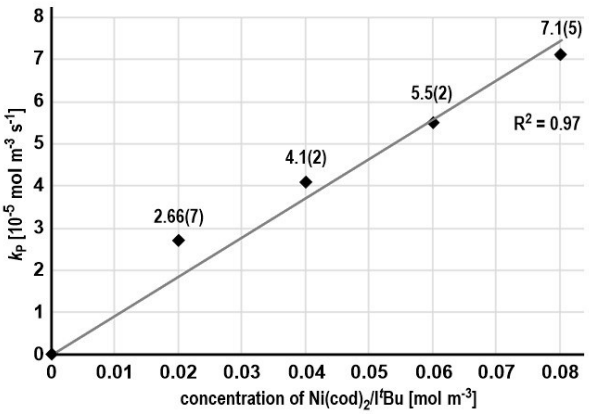


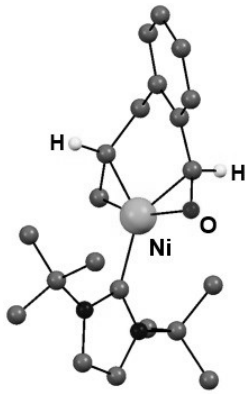
Figure 1.8. The profile of k_{P} with respect to the concentration of Ni(cod)$_2$/I^{t}Bu. All reactions were monitored by GC using pentadecane as an internal standard.

1.4.4. Theoretical Study

Computational details (Figure 1.2 and 1.3): All calculations were performed with the Gaussian 09 package[10] of programs with the hybrid B3PW91 function.[13] For initial geometry optimization, Ni was represented by the effective core potentials (ECPs) of Hay and Wadt with a double-ζ basis set (LANL2DZ)[14] augmented with an f-type polarization function.[15] The 6-31G(d,p) basis set was used for C, H, N, and O. The geometry optimizations were performed without any symmetry constraint followed by analytical frequency calculations to confirm that a minimum or a transition state had been reached. The nature of the species connected by a given transition state structure was checked by IRC. The Gibbs free energies were calculated at 403.15 K and 1 atm from the harmonic approximation for frequencies. Potential energies were also obtained by performing single point calculations using the above optimized geometries with the following basis sets: The SDD[16] augmented by an f polarization function for the outer ones for Ni, the 6-311+G(d,p) basis set for all the other atoms. Solvent effects (mesitylene; $\varepsilon = 2.2650$) were introduced through the single-point calculation at the optimized gas-phase geometries for all the minima and transition states by means of the polarizable continuum model (IEFPCM) implemented in Gaussian 09.[17] Relative Gibbs free energies were obtained by adding the Gibbs free energy corrections derived from the analytical frequency calculations to the single-point energies. These calculations involve a certain margin error. The molecular geometries for the transition states **TS3**, ***anti*-TS5**, and ***syn*-TS5** were first estimated by Reaction plus software package,[18] based on the nudged elastic band (NEB) method,[19] and were and were subsequently re-optimized using Gaussian 09 software package.

Table 1.1. Computed Cartesian coordinates (x,y,z) and energies for the optimized structures.

***anti*-C1a**

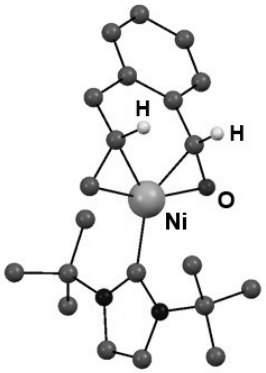


E [a.u.] = −1173.426318

G [a.u.] = −1173.512814

Ni	-0.175000	-0.361000	0.172000	H	-2.383000	-2.528000	1.056000
O	-0.759000	-0.109000	-1.680000	H	-3.233000	-1.729000	2.377000
N	2.831000	-0.513000	-0.231000	H	-5.384000	-0.852000	1.667000
N	2.191000	1.518000	0.111000	H	-6.701000	0.529000	0.080000
C	-0.196000	-1.107000	2.051000	H	-5.639000	1.387000	-1.997000
C	-1.478000	-0.678000	1.699000	H	-3.270000	0.799000	-2.511000
C	-2.695000	-1.545000	1.436000	H	-1.556000	-1.923000	-1.112000
C	-3.602000	-0.828000	0.465000	H	4.954000	-0.103000	-0.460000
C	-4.928000	-0.506000	0.741000	H	4.143000	2.460000	-0.053000
C	-5.667000	0.282000	-0.147000	H	1.701000	-3.628000	-1.073000
C	-5.071000	0.764000	-1.311000	H	1.343000	-2.080000	-1.878000
C	-3.744000	0.441000	-1.601000	H	0.757000	-2.381000	-0.237000
C	-3.011000	-0.361000	-0.725000	H	4.130000	-2.206000	1.431000
C	-1.629000	-0.819000	-1.029000	H	3.252000	-3.677000	0.974000
C	1.716000	0.236000	0.027000	H	2.385000	-2.323000	1.728000
C	3.965000	0.281000	-0.281000	H	5.026000	-2.139000	-0.924000
C	3.562000	1.555000	-0.076000	H	3.916000	-1.862000	-2.287000
C	2.901000	-1.998000	-0.357000	H	4.005000	-3.447000	-1.502000
C	1.593000	-2.549000	-0.924000	H	0.970000	2.416000	2.366000
C	3.184000	-2.585000	1.031000	H	-0.267000	1.731000	1.289000
C	4.035000	-2.369000	-1.325000	H	-0.201000	3.482000	1.558000
C	1.343000	2.741000	0.245000	H	-0.088000	3.814000	-0.974000
C	0.405000	2.579000	1.442000	H	-0.082000	2.054000	-1.253000
C	0.547000	2.925000	-1.052000	H	1.227000	3.064000	-1.900000
C	2.232000	3.966000	0.481000	H	2.858000	3.853000	1.373000
H	0.038000	-2.172000	2.049000	H	1.586000	4.834000	0.636000
H	0.443000	-0.491000	2.677000	H	2.871000	4.189000	-0.379000
H	-1.757000	0.338000	1.991000				

***syn*-C1a**

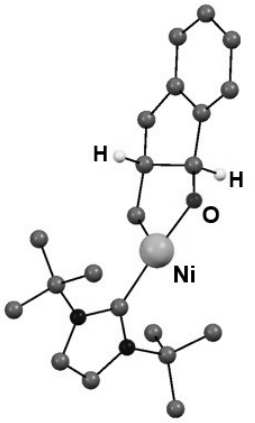


E [a.u.] = −1173.430867

G [a.u.] = −1173.516090

Ni	-0.175000	-0.361000	0.172000	H	-2.383000	-2.528000	1.056000
O	-0.759000	-0.109000	-1.680000	H	-3.233000	-1.729000	2.377000
N	2.831000	-0.513000	-0.231000	H	-5.384000	-0.852000	1.667000
N	2.191000	1.518000	0.111000	H	-6.701000	0.529000	0.080000
C	-0.196000	-1.107000	2.051000	H	-5.639000	1.387000	-1.997000
C	-1.478000	-0.678000	1.699000	H	-3.270000	0.799000	-2.511000
C	-2.695000	-1.545000	1.436000	H	-1.556000	-1.923000	-1.112000
C	-3.602000	-0.828000	0.465000	H	4.954000	-0.103000	-0.460000
C	-4.928000	-0.506000	0.741000	H	4.143000	2.460000	-0.053000
C	-5.667000	0.282000	-0.147000	H	1.701000	-3.628000	-1.073000
C	-5.071000	0.764000	-1.311000	H	1.343000	-2.080000	-1.878000
C	-3.744000	0.441000	-1.601000	H	0.757000	-2.381000	-0.237000
C	-3.011000	-0.361000	-0.725000	H	4.130000	-2.206000	1.431000
C	-1.629000	-0.819000	-1.029000	H	3.252000	-3.677000	0.974000
C	1.716000	0.236000	0.027000	H	2.385000	-2.323000	1.728000
C	3.965000	0.281000	-0.281000	H	5.026000	-2.139000	-0.924000
C	3.562000	1.555000	-0.076000	H	3.916000	-1.862000	-2.287000
C	2.901000	-1.998000	-0.357000	H	4.005000	-3.447000	-1.502000
C	1.593000	-2.549000	-0.924000	H	0.970000	2.416000	2.366000
C	3.184000	-2.585000	1.031000	H	-0.267000	1.731000	1.289000
C	4.035000	-2.369000	-1.325000	H	-0.201000	3.482000	1.558000
C	1.343000	2.741000	0.245000	H	-0.088000	3.814000	-0.974000
C	0.405000	2.579000	1.442000	H	-0.082000	2.054000	-1.253000
C	0.547000	2.925000	-1.052000	H	1.227000	3.064000	-1.900000
C	2.232000	3.966000	0.481000	H	2.858000	3.853000	1.373000
H	0.038000	-2.172000	2.049000	H	1.586000	4.834000	0.636000
H	0.443000	-0.491000	2.677000	H	2.871000	4.189000	-0.379000
H	-1.757000	0.338000	1.991000				

***trans*-C2a**

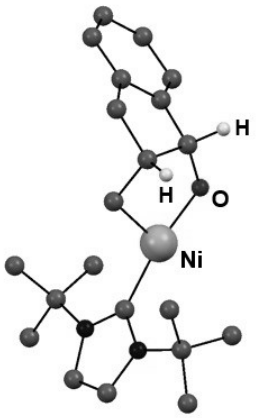


E [a.u.] = –1173.416029

G [a.u.] = –1173.501379

H	-2.277000	-1.776000	-0.381000	H	-1.927000	0.912000	0.941000
Ni	0.260000	-0.112000	-0.578000	H	-3.041000	-1.680000	2.121000
O	-1.404000	-0.167000	-1.327000	H	-3.185000	-0.059000	2.820000
N	3.110000	-0.781000	0.049000	H	-5.952000	-0.108000	2.216000
N	2.690000	1.338000	0.142000	H	-7.516000	0.362000	0.342000
C	-0.461000	-0.639000	1.141000	H	-6.696000	0.417000	-1.991000
C	-1.902000	-0.188000	0.991000	H	-4.291000	-0.020000	-2.491000
C	-3.096000	-0.608000	1.876000	H	5.220000	-0.666000	0.545000
C	-4.245000	-0.334000	0.914000	H	4.695000	2.000000	0.647000
C	-5.587000	-0.100000	1.191000	H	1.949000	-3.714000	-1.276000
C	-6.466000	0.168000	0.134000	H	2.308000	-2.206000	-2.139000
C	-6.003000	0.199000	-1.182000	H	0.989000	-2.258000	-0.950000
C	-4.655000	-0.045000	-1.466000	H	3.282000	-2.581000	2.059000
C	-3.783000	-0.308000	-0.418000	H	2.480000	-3.924000	1.223000
C	-2.311000	-0.658000	-0.400000	H	1.582000	-2.434000	1.572000
C	2.097000	0.126000	-0.085000	H	5.099000	-2.763000	0.346000
C	4.291000	-0.147000	0.385000	H	4.762000	-2.377000	-1.361000
C	4.030000	1.181000	0.437000	H	4.239000	-3.916000	-0.663000
C	2.995000	-2.267000	-0.075000	H	1.397000	2.653000	2.133000
C	1.996000	-2.625000	-1.177000	H	0.190000	1.964000	1.022000
C	2.555000	-2.834000	1.280000	H	0.432000	3.721000	1.092000
C	4.362000	-2.850000	-0.458000	H	0.901000	3.765000	-1.462000
C	1.994000	2.659000	0.041000	H	0.542000	2.038000	-1.469000
C	0.937000	2.752000	1.145000	H	2.087000	2.629000	-2.137000
C	1.347000	2.773000	-1.345000	H	3.481000	3.779000	1.199000
C	3.012000	3.790000	0.210000	H	2.484000	4.742000	0.111000
H	-0.386000	-1.736000	1.146000	H	3.791000	3.762000	-0.558000
H	0.089000	-0.228000	1.993000				

***cis*-C2a**

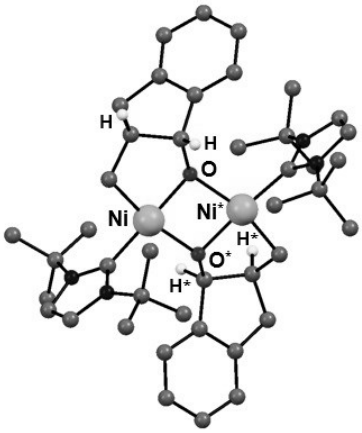


E [a.u.] = −1173.426995

G [a.u.] = −1173.512886

H	2.628000	-2.514000	-0.899000	H	1.286000	-2.555000	1.109000
Ni	-0.205000	-0.386000	-0.619000	H	2.785000	-0.874000	2.737000
O	1.250000	-1.083000	-1.405000	H	3.499000	-2.329000	2.041000
N	-2.339000	1.570000	0.138000	H	5.372000	0.285000	2.261000
N	-3.039000	-0.475000	0.140000	H	6.574000	1.523000	0.474000
C	0.746000	-0.453000	1.024000	H	5.792000	1.410000	-1.872000
C	1.769000	-1.593000	0.902000	H	3.787000	0.041000	-2.462000
C	3.019000	-1.373000	1.788000	H	-4.215000	2.505000	0.703000
C	3.917000	-0.546000	0.894000	H	-5.099000	-0.066000	0.693000
C	5.032000	0.220000	1.229000	H	0.058000	3.608000	-1.202000
C	5.705000	0.918000	0.223000	H	-1.088000	2.564000	-2.067000
C	5.263000	0.855000	-1.101000	H	0.161000	1.849000	-1.020000
C	4.145000	0.086000	-1.436000	H	-1.403000	3.022000	2.223000
C	3.480000	-0.614000	-0.435000	H	-0.089000	3.834000	1.352000
C	2.267000	-1.524000	-0.557000	H	-0.068000	2.071000	1.542000
C	-1.919000	0.284000	-0.065000	H	-3.000000	4.245000	0.732000
C	-3.675000	1.599000	0.491000	H	-3.024000	3.917000	-1.020000
C	-4.115000	0.318000	0.488000	H	-1.737000	4.896000	-0.303000
C	-1.485000	2.796000	0.061000	H	-2.512000	-2.367000	2.018000
C	-0.532000	2.690000	-1.132000	H	-1.163000	-2.306000	0.858000
C	-0.713000	2.935000	1.378000	H	-2.248000	-3.714000	0.890000
C	-2.380000	4.026000	-0.142000	H	-2.766000	-3.385000	-1.626000
C	-3.106000	-1.959000	-0.035000	H	-1.603000	-2.055000	-1.613000
C	-2.198000	-2.626000	1.001000	H	-3.263000	-1.780000	-2.202000
C	-2.658000	-2.309000	-1.459000	H	-4.910000	-2.238000	1.178000
C	-4.547000	-2.438000	0.166000	H	-4.571000	-3.521000	0.018000
H	1.263000	0.516000	1.050000	H	-5.235000	-1.990000	-0.558000
H	0.103000	-0.538000	1.907000				

***cis*-(C2a)$_2$**



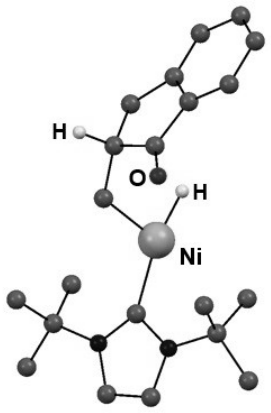
E [a.u.] = –2346.892603

G [a.u.] = –2347.029410

Ni	1.050000	0.385000	1.150000	C	0.941000	-2.892000	-3.384000
O	-0.848000	0.439000	1.003000	C	2.359000	-2.416000	-3.208000
N	3.812000	-0.236000	2.009000	C	3.429000	-2.557000	-4.092000
N	3.707000	1.533000	0.761000	C	4.693000	-2.105000	-3.714000
C	0.873000	1.345000	2.824000	C	4.883000	-1.522000	-2.458000
C	-0.621000	1.476000	3.125000	C	3.809000	-1.373000	-1.579000
C	-1.245000	0.357000	3.988000	C	2.539000	-1.808000	-1.961000
C	-2.695000	0.389000	3.575000	C	1.243000	-1.790000	-1.162000
C	-3.824000	-0.061000	4.253000	C	-2.829000	0.093000	-1.282000
C	-5.086000	0.150000	3.689000	C	-4.752000	0.978000	-2.095000
C	-5.213000	0.804000	2.462000	C	-5.056000	-0.219000	-1.552000
C	-4.076000	1.241000	1.774000	C	-2.680000	2.329000	-2.540000
C	-2.819000	1.025000	2.329000	C	-1.417000	2.685000	-1.761000
C	-1.443000	1.423000	1.822000	C	-2.330000	1.950000	-3.986000
C	2.933000	0.531000	1.296000	C	-3.609000	3.552000	-2.530000
C	5.093000	0.287000	1.933000	C	-3.842000	-2.134000	-0.475000
C	5.027000	1.385000	1.151000	C	-3.710000	-3.124000	-1.640000
C	3.554000	-1.474000	2.807000	C	-2.682000	-2.296000	0.504000
C	2.137000	-1.998000	2.598000	C	-5.149000	-2.399000	0.286000
C	3.775000	-1.143000	4.290000	H	1.397000	0.844000	3.650000
C	4.543000	-2.557000	2.347000	H	1.335000	2.334000	2.727000
C	3.258000	2.589000	-0.210000	H	-0.844000	2.428000	3.636000
C	2.080000	3.379000	0.362000	H	-0.796000	-0.613000	3.734000
C	2.856000	1.918000	-1.526000	H	-1.098000	0.514000	5.063000
C	4.411000	3.566000	-0.470000	H	-3.733000	-0.548000	5.222000
Ni	-1.009000	-0.198000	-0.882000	H	-5.976000	-0.181000	4.219000
O	0.862000	-0.550000	-0.617000	H	-6.201000	0.982000	2.044000
N	-3.390000	1.171000	-1.917000	H	-4.180000	1.752000	0.819000
N	-3.881000	-0.752000	-1.049000	H	-1.465000	2.404000	1.316000
C	-0.686000	-1.052000	-2.567000	H	5.941000	-0.151000	2.434000
C	0.171000	-2.262000	-2.194000	H	5.813000	2.056000	0.854000

H	2.021000	-2.912000	3.191000	H	5.534000	-2.212000	-4.395000
H	1.952000	-2.245000	1.550000	H	5.873000	-1.181000	-2.164000
H	1.380000	-1.278000	2.914000	H	3.960000	-0.911000	-0.609000
H	4.793000	-0.787000	4.478000	H	1.333000	-2.545000	-0.358000
H	3.615000	-2.039000	4.897000	H	-5.396000	1.699000	-2.569000
H	3.075000	-0.372000	4.622000	H	-6.010000	-0.712000	-1.473000
H	5.585000	-2.291000	2.548000	H	-0.942000	3.545000	-2.243000
H	4.436000	-2.750000	1.276000	H	-1.654000	2.955000	-0.729000
H	4.334000	-3.486000	2.885000	H	-0.701000	1.857000	-1.745000
H	2.342000	3.844000	1.318000	H	-3.232000	1.694000	-4.551000
H	1.211000	2.734000	0.513000	H	-1.841000	2.792000	-4.486000
H	1.810000	4.171000	-0.344000	H	-1.653000	1.094000	-4.003000
H	2.493000	2.681000	-2.224000	H	-4.464000	3.444000	-3.204000
H	2.071000	1.173000	-1.364000	H	-3.977000	3.765000	-1.522000
H	3.713000	1.416000	-1.985000	H	-3.043000	4.423000	-2.874000
H	4.750000	4.060000	0.447000	H	-4.544000	-3.019000	-2.342000
H	4.049000	4.342000	-1.149000	H	-2.777000	-2.957000	-2.184000
H	5.264000	3.084000	-0.957000	H	-3.712000	-4.151000	-1.260000
H	-0.090000	-0.327000	-3.143000	H	-2.726000	-3.305000	0.925000
H	-1.543000	-1.349000	-3.185000	H	-1.714000	-2.168000	0.012000
H	-0.470000	-3.020000	-1.729000	H	-2.739000	-1.568000	1.315000
H	0.515000	-2.599000	-4.352000	H	-6.021000	-2.464000	-0.372000
H	0.907000	-3.990000	-3.348000	H	-5.065000	-3.364000	0.794000
H	3.283000	-3.021000	-5.065000	H	-5.326000	-1.630000	1.043000

C3a

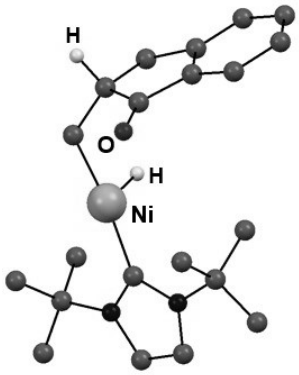


E [a.u.] = −1173.397072

G [a.u.] = −1173.487378

Ni	0.244000	-0.175000	-0.570000	H	-2.333000	-1.977000	-1.141000
O	-2.177000	0.755000	2.051000	H	-3.217000	-3.029000	-0.024000
N	3.317000	-0.538000	0.011000	H	-5.385000	-2.022000	-1.733000
N	2.591000	1.487000	-0.046000	H	-7.075000	-0.213000	-1.640000
C	-0.529000	-1.374000	0.688000	H	-6.749000	1.761000	-0.187000
C	-2.032000	-1.428000	0.936000	H	-4.684000	1.943000	1.227000
C	-2.903000	-1.994000	-0.203000	H	-1.098000	-0.227000	-1.143000
C	-4.079000	-1.057000	-0.302000	H	5.414000	-0.074000	0.339000
C	-5.228000	-1.162000	-1.086000	H	4.495000	2.489000	0.254000
C	-6.176000	-0.140000	-1.033000	H	2.594000	-3.647000	-1.195000
C	-5.993000	0.981000	-0.209000	H	3.015000	-2.204000	-2.140000
C	-4.851000	1.089000	0.576000	H	1.543000	-2.211000	-1.151000
C	-3.908000	0.061000	0.521000	H	3.441000	-2.174000	2.160000
C	-2.639000	-0.063000	1.271000	H	2.905000	-3.653000	1.342000
C	2.170000	0.189000	-0.128000	H	1.810000	-2.264000	1.469000
C	4.410000	0.288000	0.202000	H	5.465000	-2.217000	0.694000
C	3.953000	1.563000	0.161000	H	5.304000	-2.051000	-1.074000
C	3.392000	-2.030000	-0.008000	H	4.867000	-3.563000	-0.270000
C	2.581000	-2.553000	-1.197000	H	1.358000	2.853000	1.953000
C	2.849000	-2.560000	1.324000	H	0.167000	1.808000	1.143000
C	4.849000	-2.474000	-0.173000	H	0.077000	3.569000	0.955000
C	1.671000	2.651000	-0.189000	H	0.246000	3.360000	-1.658000
C	0.763000	2.721000	1.044000	H	0.113000	1.638000	-1.388000
C	0.847000	2.464000	-1.470000	H	1.492000	2.288000	-2.335000
C	2.488000	3.941000	-0.308000	H	3.062000	4.148000	0.600000
H	-0.168000	-2.375000	0.413000	H	1.798000	4.777000	-0.453000
H	-0.026000	-1.061000	1.614000	H	3.169000	3.917000	-1.164000
H	-2.214000	-2.037000	1.840000				

C4a

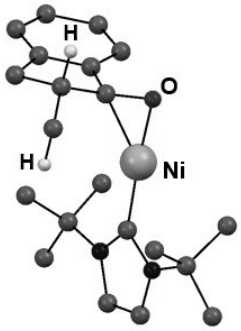


E [a.u.] = −1173.407177

G [a.u.] = −1173.497497

Ni	0.609000	-0.905000	0.340000	H	-1.846000	-1.830000	-1.477000
O	-2.350000	-0.359000	2.382000	H	-3.077000	-3.041000	-1.105000
N	3.326000	0.146000	-0.282000	H	-4.639000	-1.191000	-2.753000
N	1.921000	1.768000	-0.077000	H	-6.161000	0.730000	-2.396000
C	-0.620000	-2.270000	0.816000	H	-6.104000	2.027000	-0.292000
C	-2.128000	-2.092000	0.657000	H	-4.491000	1.392000	1.523000
C	-2.666000	-2.076000	-0.790000	H	0.170000	-1.105000	-0.998000
C	-3.705000	-0.983000	-0.811000	H	5.077000	1.346000	-0.750000
C	-4.603000	-0.633000	-1.820000	H	3.302000	3.394000	-0.488000
C	-5.457000	0.451000	-1.616000	H	3.760000	-2.943000	-1.667000
C	-5.425000	1.189000	-0.423000	H	3.613000	-1.384000	-2.504000
C	-4.534000	0.843000	0.586000	H	2.258000	-1.996000	-1.528000
C	-3.686000	-0.246000	0.378000	H	3.875000	-1.461000	1.813000
C	-2.673000	-0.815000	1.296000	H	4.001000	-2.983000	0.903000
C	2.011000	0.407000	-0.015000	H	2.449000	-2.136000	0.981000
C	4.026000	1.314000	-0.521000	H	5.868000	-0.603000	0.400000
C	3.142000	2.334000	-0.391000	H	5.760000	-0.652000	-1.379000
C	3.909000	-1.226000	-0.354000	H	5.841000	-2.150000	-0.455000
C	3.348000	-1.931000	-1.594000	H	0.820000	2.324000	2.316000
C	3.535000	-1.993000	0.919000	H	-0.191000	1.078000	1.542000
C	5.434000	-1.135000	-0.453000	H	-0.811000	2.719000	1.731000
C	0.658000	2.530000	0.154000	H	-1.271000	2.729000	-0.808000
C	0.091000	2.136000	1.521000	H	-0.540000	1.115000	-0.971000
C	-0.332000	2.189000	-0.965000	H	0.074000	2.474000	-1.941000
C	0.951000	4.032000	0.144000	H	1.666000	4.316000	0.923000
H	-0.328000	-3.245000	0.401000	H	0.017000	4.566000	0.341000
H	-0.387000	-2.302000	1.903000	H	1.324000	4.374000	-0.826000
H	-2.659000	-2.900000	1.196000				

C6a

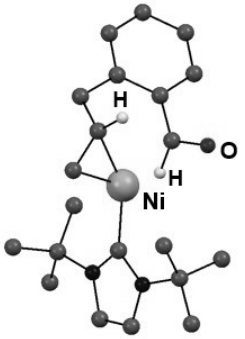


E [a.u.] = –1173.446439

G [a.u.] = –1173.534051

Ni	-0.336000	-0.844000	-0.483000	H	0.816000	0.901000	1.272000
N	-2.936000	0.304000	-0.044000	H	0.144000	2.047000	2.457000
N	-1.476000	1.858000	0.283000	C	-2.723000	2.431000	0.455000
C	-1.583000	0.529000	-0.022000	H	-2.872000	3.468000	0.703000
C	-3.547000	-1.026000	-0.324000	C	-3.640000	1.456000	0.250000
C	-3.000000	-1.551000	-1.656000	H	-4.714000	1.507000	0.288000
H	-1.911000	-1.718000	-1.614000	O	0.756000	-2.214000	-0.969000
H	-3.206000	-0.849000	-2.469000	C	1.504000	-1.559000	-0.125000
H	-3.461000	-2.514000	-1.895000	C	1.875000	-2.121000	1.261000
C	-3.195000	-1.980000	0.823000	C	2.640000	-0.697000	-0.527000
H	-3.591000	-1.607000	1.773000	C	0.717000	-2.450000	2.189000
H	-2.108000	-2.077000	0.912000	C	2.903000	-1.112000	1.816000
H	-3.620000	-2.971000	0.633000	H	2.417000	-3.056000	1.041000
C	-5.068000	-0.888000	-0.432000	C	3.459000	-0.441000	0.583000
H	-5.519000	-0.561000	0.511000	C	2.972000	-0.198000	-1.789000
H	-5.489000	-1.868000	-0.671000	H	0.137000	-1.550000	2.420000
H	-5.361000	-0.196000	-1.227000	H	1.073000	-2.884000	3.130000
C	-0.182000	2.595000	0.379000	H	0.043000	-3.172000	1.718000
C	0.532000	2.497000	-0.972000	H	2.404000	-0.376000	2.462000
H	1.496000	3.011000	-0.925000	H	3.679000	-1.589000	2.425000
H	-0.072000	2.958000	-1.761000	C	4.607000	0.334000	0.443000
H	0.708000	1.449000	-1.231000	C	4.125000	0.572000	-1.926000
C	-0.442000	4.066000	0.713000	H	2.338000	-0.418000	-2.644000
H	0.522000	4.577000	0.779000	C	4.936000	0.842000	-0.817000
H	-0.945000	4.188000	1.678000	H	5.250000	0.532000	1.298000
H	-1.028000	4.568000	-0.063000	H	4.404000	0.961000	-2.902000
C	0.654000	1.959000	1.492000	H	5.835000	1.441000	-0.940000
H	1.625000	2.457000	1.562000				

***anti*-C7a**

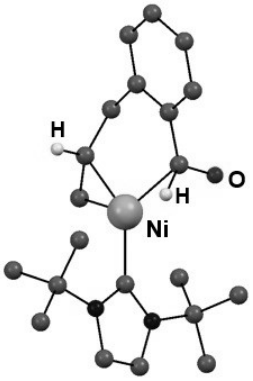


E [a.u.] = −1173.409441

G [a.u.] = −1173.496521

Ni	0.101000	-0.246000	0.507000	H	2.232000	1.621000	1.606000
O	1.383000	-2.378000	-0.688000	H	3.274000	0.612000	2.588000
N	-2.231000	1.427000	-0.423000	H	5.155000	1.366000	1.184000
N	-2.773000	-0.652000	-0.206000	H	6.588000	0.781000	-0.744000
C	0.210000	0.090000	2.444000	H	5.732000	-0.757000	-2.509000
C	1.457000	-0.347000	1.949000	H	3.421000	-1.666000	-2.318000
C	2.611000	0.594000	1.709000	H	0.748000	-0.420000	-0.968000
C	3.456000	0.239000	0.503000	H	-4.172000	2.154000	-1.079000
C	4.765000	0.723000	0.397000	H	-4.846000	-0.466000	-0.832000
C	5.577000	0.386000	-0.683000	H	0.432000	3.549000	-0.739000
C	5.099000	-0.475000	-1.672000	H	0.004000	2.197000	-1.808000
C	3.807000	-0.980000	-1.569000	H	0.468000	1.882000	-0.125000
C	2.975000	-0.614000	-0.503000	H	-2.668000	3.397000	1.374000
C	1.580000	-1.173000	-0.496000	H	-1.122000	4.241000	1.158000
C	-1.718000	0.209000	-0.057000	H	-1.148000	2.574000	1.773000
C	-3.568000	1.319000	-0.770000	H	-3.200000	4.020000	-0.995000
C	-3.903000	0.016000	-0.644000	H	-2.253000	3.327000	-2.336000
C	-1.525000	2.740000	-0.358000	H	-1.596000	4.644000	-1.352000
C	-0.066000	2.576000	-0.784000	H	-2.532000	-2.101000	2.092000
C	-1.622000	3.270000	1.078000	H	-0.973000	-2.163000	1.242000
C	-2.196000	3.731000	-1.320000	H	-1.991000	-3.610000	1.324000
C	-2.706000	-2.141000	-0.077000	H	-1.970000	-3.796000	-1.260000
C	-2.007000	-2.521000	1.229000	H	-0.895000	-2.394000	-1.265000
C	-1.944000	-2.702000	-1.284000	H	-2.407000	-2.370000	-2.219000
C	-4.127000	-2.717000	-0.054000	H	-4.733000	-2.277000	0.745000
H	0.061000	1.144000	2.676000	H	-4.058000	-3.792000	0.133000
H	-0.424000	-0.589000	3.010000	H	-4.646000	-2.590000	-1.009000
H	1.748000	-1.382000	2.137000				

***syn*-C7a**

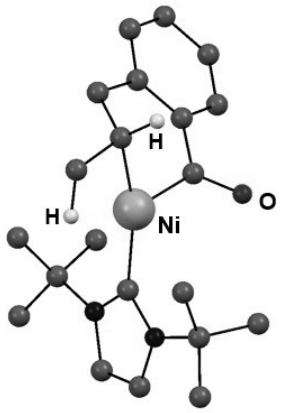


E [a.u.] = −1173.403262

G [a.u.] = −1173.491188

Ni	-0.155000	-0.040000	0.426000	H	0.648000	2.400000	-2.018000
O	-1.326000	-2.059000	-0.829000	H	0.080000	3.719000	-0.970000
N	2.420000	1.324000	-0.272000	C	1.569000	3.042000	1.274000
N	2.750000	-0.807000	-0.169000	H	2.504000	3.004000	1.841000
C	-0.326000	-0.064000	2.390000	H	0.860000	2.343000	1.721000
H	-0.242000	-1.080000	2.777000	H	1.157000	4.053000	1.353000
H	0.361000	0.646000	2.844000	C	2.759000	3.714000	-0.820000
C	-1.537000	0.355000	1.807000	H	3.683000	3.831000	-0.246000
H	-1.713000	1.432000	1.732000	H	2.259000	4.686000	-0.825000
C	-2.814000	-0.459000	1.830000	H	3.011000	3.462000	-1.855000
H	-3.414000	-0.201000	2.714000	C	2.544000	-2.289000	-0.156000
H	-2.564000	-1.524000	1.921000	C	1.674000	-2.684000	1.037000
C	-3.634000	-0.223000	0.587000	H	1.565000	-3.773000	1.054000
C	-4.972000	0.171000	0.623000	H	0.679000	-2.243000	0.959000
H	-5.462000	0.300000	1.586000	H	2.131000	-2.363000	1.979000
C	-5.683000	0.406000	-0.555000	C	1.873000	-2.693000	-1.475000
H	-6.723000	0.717000	-0.508000	H	1.796000	-3.784000	-1.531000
C	-5.056000	0.245000	-1.790000	H	2.465000	-2.348000	-2.329000
H	-5.604000	0.427000	-2.711000	H	0.862000	-2.282000	-1.532000
C	-3.721000	-0.155000	-1.840000	C	3.900000	-2.992000	-0.028000
H	-3.229000	-0.292000	-2.801000	H	3.721000	-4.065000	0.081000
C	-3.010000	-0.382000	-0.660000	H	4.454000	-2.654000	0.854000
C	-1.585000	-0.853000	-0.710000	H	4.527000	-2.861000	-0.916000
H	-0.810000	-0.080000	-1.165000	C	3.965000	-0.224000	-0.484000
C	1.770000	0.139000	-0.031000	H	4.871000	-0.782000	-0.640000
C	1.809000	2.685000	-0.197000	C	3.761000	1.111000	-0.539000
C	0.493000	2.706000	-0.979000	H	4.462000	1.899000	-0.749000
H	-0.247000	2.036000	-0.525000				

C8a

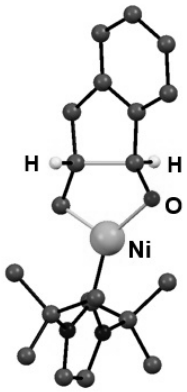


E [a.u.] = −1173.423407

G [a.u.] = −1173.511835

Ni	0.029000	-0.598000	0.672000	H	2.447000	0.354000	2.234000
O	0.659000	-1.592000	-1.752000	H	3.388000	-1.105000	2.449000
N	-1.720000	1.741000	-0.096000	H	5.197000	0.039000	1.268000
N	-2.765000	-0.131000	-0.336000	H	6.286000	0.450000	-0.912000
C	0.380000	-1.201000	2.909000	H	4.993000	0.161000	-3.024000
C	1.344000	-1.425000	1.758000	H	2.599000	-0.555000	-2.897000
C	2.636000	-0.636000	1.792000	H	-0.540000	-0.623000	2.587000
C	3.272000	-0.431000	0.433000	H	-3.331000	3.048000	-0.741000
C	4.623000	-0.068000	0.350000	H	-4.644000	0.687000	-1.053000
C	5.239000	0.157000	-0.878000	H	1.192000	3.405000	-0.738000
C	4.515000	-0.004000	-2.062000	H	-0.013000	2.810000	-1.899000
C	3.184000	-0.393000	-1.995000	H	0.882000	1.663000	-0.879000
C	2.551000	-0.601000	-0.760000	H	-0.847000	2.559000	2.336000
C	1.100000	-1.006000	-0.766000	H	0.684000	3.275000	1.784000
C	-1.555000	0.389000	0.036000	H	0.410000	1.530000	1.606000
C	-2.984000	2.045000	-0.565000	H	-2.090000	4.274000	0.869000
C	-3.638000	0.870000	-0.718000	H	-1.649000	4.433000	-0.851000
C	-0.663000	2.762000	0.175000	H	-0.500000	4.887000	0.403000
C	0.417000	2.651000	-0.905000	H	-2.751000	-1.991000	1.661000
C	-0.072000	2.514000	1.565000	H	-1.338000	-2.307000	0.615000
C	-1.278000	4.165000	0.143000	H	-2.717000	-3.418000	0.604000
C	-3.100000	-1.583000	-0.451000	H	-2.866000	-3.140000	-1.937000
C	-2.433000	-2.364000	0.682000	H	-1.525000	-1.968000	-1.895000
C	-2.610000	-2.083000	-1.815000	H	-3.092000	-1.522000	-2.623000
C	-4.620000	-1.763000	-0.333000	H	-5.012000	-1.309000	0.583000
H	0.797000	-0.591000	3.719000	H	-4.840000	-2.833000	-0.301000
H	-0.017000	-2.131000	3.326000	H	-5.159000	-1.354000	-1.192000
H	1.525000	-2.485000	1.557000				

***trans*-TS1**



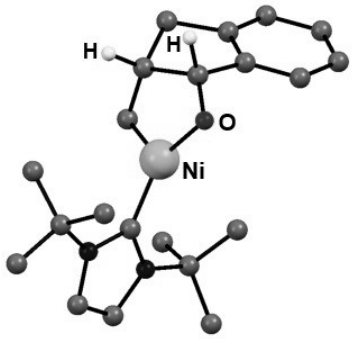
E [a.u.] = –1173.391929

G [a.u.] = –1173.476230

194.41*i* [cm^{-1}]

Ni	0.135000	-0.082000	-0.161000	H	-2.838000	-2.015000	1.682000
O	-1.309000	0.289000	-1.438000	H	-3.154000	-0.641000	2.747000
N	2.956000	-0.843000	-0.124000	H	-5.879000	-0.659000	1.949000
N	2.628000	1.291000	0.103000	H	-7.339000	0.164000	0.113000
C	-0.366000	-0.674000	1.550000	H	-6.369000	0.797000	-2.073000
C	-1.736000	-0.220000	1.115000	H	-3.900000	0.592000	-2.459000
C	-2.978000	-0.923000	1.704000	H	-1.953000	-1.520000	-0.665000
C	-4.079000	-0.495000	0.765000	H	5.125000	-0.790000	-0.081000
C	-5.449000	-0.397000	0.985000	H	4.715000	1.881000	0.189000
C	-6.269000	0.069000	-0.050000	H	1.478000	-3.730000	-1.216000
C	-5.721000	0.426000	-1.283000	H	1.678000	-2.211000	-2.114000
C	-4.344000	0.317000	-1.506000	H	0.636000	-2.263000	-0.684000
C	-3.539000	-0.146000	-0.476000	H	3.493000	-2.682000	1.786000
C	-2.045000	-0.412000	-0.525000	H	2.491000	-3.986000	1.122000
C	1.968000	0.098000	-0.027000	H	1.736000	-2.475000	1.665000
C	4.200000	-0.243000	-0.033000	H	4.910000	-2.874000	-0.265000
C	3.996000	1.086000	0.102000	H	4.238000	-2.455000	-1.862000
C	2.777000	-2.323000	-0.238000	H	3.831000	-3.992000	-1.085000
C	1.566000	-2.644000	-1.116000	H	1.574000	2.545000	2.269000
C	2.612000	-2.900000	1.173000	H	0.235000	1.979000	1.246000
C	4.021000	-2.931000	-0.901000	H	0.576000	3.713000	1.375000
C	1.978000	2.640000	0.132000	H	0.780000	3.855000	-1.192000
C	1.033000	2.719000	1.334000	H	0.406000	2.128000	-1.307000
C	1.218000	2.852000	-1.184000	H	1.898000	2.768000	-2.038000
C	3.053000	3.722000	0.273000	H	3.631000	3.612000	1.196000
H	-0.278000	-1.759000	1.677000	H	2.554000	4.694000	0.310000
H	0.078000	-0.139000	2.391000	H	3.737000	3.738000	-0.581000
H	-1.854000	0.858000	1.292000				

***cis*-TS1**



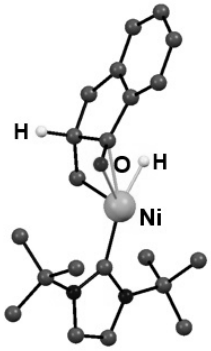
E [a.u.] = −1173.393293

G [a.u.] = −1173.477982

260.47*i* [cm $^{-1}$]

Ni	-0.088000	-0.550000	-0.165000	H	2.896000	-1.031000	2.761000
O	0.932000	-1.530000	-1.479000	H	3.372000	-2.464000	1.850000
N	-1.945000	1.699000	0.049000	H	5.232000	0.275000	1.886000
N	-2.920000	-0.239000	0.000000	H	6.150000	1.489000	-0.080000
C	0.527000	-0.532000	1.589000	H	5.085000	1.260000	-2.303000
C	1.476000	-1.640000	1.178000	H	3.062000	-0.204000	-2.580000
C	2.902000	-1.473000	1.759000	H	2.245000	-2.761000	-0.505000
C	3.645000	-0.643000	0.742000	H	-3.746000	2.905000	0.166000
C	4.766000	0.164000	0.909000	H	-4.966000	0.480000	0.088000
C	5.280000	0.846000	-0.199000	H	0.980000	3.309000	-0.709000
C	4.678000	0.718000	-1.453000	H	0.014000	2.267000	-1.773000
C	3.554000	-0.097000	-1.617000	H	0.814000	1.583000	-0.351000
C	3.048000	-0.773000	-0.514000	H	-1.460000	3.326000	2.154000
C	1.862000	-1.718000	-0.493000	H	0.145000	3.879000	1.642000
C	-1.686000	0.358000	-0.005000	H	-0.127000	2.166000	2.014000
C	-3.310000	1.923000	0.111000	H	-2.375000	4.488000	0.135000
C	-3.917000	0.717000	0.074000	H	-1.964000	3.902000	-1.496000
C	-0.945000	2.811000	0.103000	H	-0.802000	4.851000	-0.557000
C	0.288000	2.462000	-0.732000	H	-2.887000	-2.127000	1.954000
C	-0.574000	3.057000	1.570000	H	-1.423000	-2.326000	0.965000
C	-1.575000	4.080000	-0.489000	H	-2.716000	-3.537000	0.886000
C	-3.172000	-1.707000	-0.163000	H	-2.854000	-3.218000	-1.674000
C	-2.506000	-2.468000	0.986000	H	-1.528000	-2.047000	-1.572000
C	-2.616000	-2.160000	-1.519000	H	-3.070000	-1.585000	-2.333000
C	-4.680000	-1.972000	-0.125000	H	-5.131000	-1.662000	0.823000
H	1.028000	0.413000	1.824000	H	-4.839000	-3.049000	-0.228000
H	-0.195000	-0.799000	2.362000	H	-5.207000	-1.484000	-0.951000
H	1.046000	-2.612000	1.435000				

TS2



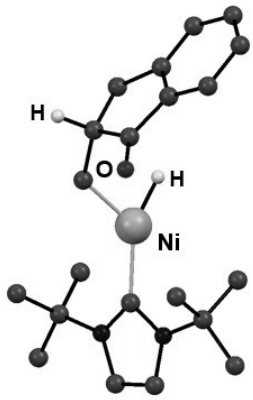
E [a.u.] = −1173.372686

G [a.u.] = −1173.458008

430.05*i* [cm^{-1}]

Ni	0.036000	-0.263000	-0.106000	H	-2.781000	-1.437000	2.040000
O	-1.388000	1.511000	-0.744000	H	-3.516000	-0.061000	2.855000
N	2.838000	-1.078000	-0.099000	H	-5.904000	-1.017000	1.575000
N	2.741000	1.078000	0.051000	H	-7.135000	-0.751000	-0.564000
C	-0.502000	-0.207000	1.741000	H	-5.994000	0.136000	-2.573000
C	-1.851000	0.456000	1.487000	H	-3.576000	0.785000	-2.455000
C	-3.079000	-0.388000	1.905000	H	-1.400000	-0.849000	-0.298000
C	-4.044000	-0.287000	0.750000	H	5.000000	-1.264000	-0.071000
C	-5.392000	-0.636000	0.695000	H	4.880000	1.443000	0.112000
C	-6.082000	-0.484000	-0.510000	H	1.247000	-3.722000	-1.563000
C	-5.438000	0.016000	-1.647000	H	1.896000	-2.256000	-2.330000
C	-4.090000	0.373000	-1.591000	H	0.531000	-2.151000	-1.179000
C	-3.409000	0.210000	-0.389000	H	2.547000	-2.891000	1.900000
C	-2.000000	0.625000	-0.067000	H	1.578000	-4.065000	0.985000
C	1.952000	-0.036000	-0.029000	H	0.938000	-2.434000	1.287000
C	4.139000	-0.621000	-0.042000	H	4.435000	-3.341000	0.272000
C	4.077000	0.729000	0.049000	H	4.216000	-3.008000	-1.466000
C	2.465000	-2.520000	-0.242000	H	3.411000	-4.385000	-0.707000
C	1.477000	-2.664000	-1.405000	H	1.530000	2.483000	2.012000
C	1.842000	-3.006000	1.070000	H	0.270000	2.211000	0.763000
C	3.717000	-3.347000	-0.553000	H	0.940000	3.825000	1.012000
C	2.266000	2.499000	-0.037000	H	1.423000	3.778000	-1.563000
C	1.182000	2.757000	1.011000	H	0.826000	2.115000	-1.615000
C	1.714000	2.729000	-1.449000	H	2.472000	2.498000	-2.205000
C	3.444000	3.445000	0.217000	H	3.902000	3.277000	1.198000
H	-0.593000	-1.198000	2.191000	H	3.064000	4.470000	0.201000
H	0.228000	0.388000	2.293000	H	4.214000	3.375000	-0.557000
H	-1.915000	1.464000	1.922000				

TS3



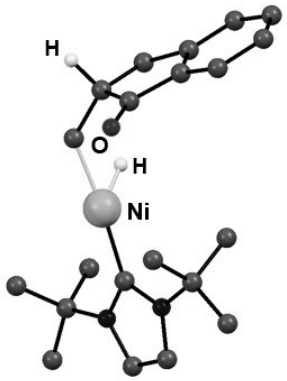
E [a.u.] = −1173.395985

G [a.u.] = −1173.485611

65.23*i* [cm^{-1}]

Ni	0.302000	-0.472000	-0.308000	H	-2.394000	-2.186000	-1.049000
O	-2.276000	0.587000	2.167000	H	-3.455000	-3.094000	0.034000
N	3.403000	-0.374000	-0.119000	H	-5.336000	-1.916000	-1.919000
N	2.507000	1.583000	-0.114000	H	-6.859000	0.037000	-1.985000
C	-0.668000	-1.605000	0.848000	H	-6.499000	1.983000	-0.503000
C	-2.184000	-1.587000	1.032000	H	-4.570000	1.990000	1.102000
C	-3.024000	-2.104000	-0.154000	H	-0.937000	-0.657000	-1.009000
C	-4.092000	-1.061000	-0.367000	H	5.479000	0.264000	-0.069000
C	-5.165000	-1.069000	-1.259000	H	4.344000	2.741000	-0.077000
C	-6.019000	0.034000	-1.294000	H	2.915000	-3.539000	-1.301000
C	-5.816000	1.139000	-0.454000	H	3.202000	-2.061000	-2.245000
C	-4.750000	1.151000	0.437000	H	1.743000	-2.198000	-1.239000
C	-3.900000	0.043000	0.469000	H	3.572000	-1.964000	2.062000
C	-2.723000	-0.186000	1.335000	H	3.149000	-3.486000	1.253000
C	2.192000	0.256000	-0.129000	H	1.970000	-2.161000	1.324000
C	4.438000	0.539000	-0.086000	H	5.642000	-1.855000	0.617000
C	3.873000	1.773000	-0.088000	H	5.494000	-1.818000	-1.160000
C	3.573000	-1.858000	-0.111000	H	5.150000	-3.300000	-0.265000
C	2.809000	-2.449000	-1.300000	H	1.302000	2.681000	2.047000
C	3.030000	-2.399000	1.216000	H	0.133000	1.621000	1.224000
C	5.057000	-2.211000	-0.237000	H	-0.087000	3.379000	1.188000
C	1.485000	2.673000	-0.121000	H	-0.138000	3.314000	-1.400000
C	0.659000	2.579000	1.166000	H	0.034000	1.554000	-1.312000
C	0.593000	2.501000	-1.356000	H	1.188000	2.515000	-2.275000
C	2.183000	4.034000	-0.187000	H	2.812000	4.216000	0.689000
H	-0.341000	-2.625000	0.597000	H	1.417000	4.814000	-0.207000
H	-0.194000	-1.305000	1.798000	H	2.789000	4.142000	-1.093000
H	-2.434000	-2.185000	1.925000				

TS4



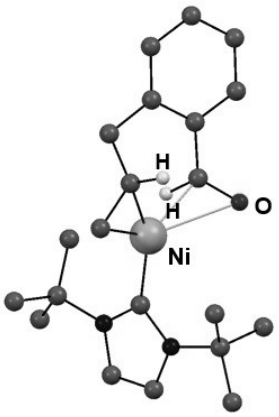
E [a.u.] = –1173.400213

G [a.u.] = –1173.491196

732.79*i* [cm^{-1}]

Ni	0.633000	-0.841000	0.394000	H	-2.063000	-2.056000	-1.360000
O	-2.328000	0.004000	2.287000	H	-3.278000	-3.150000	-0.702000
N	2.027000	1.735000	-0.129000	H	-4.892000	-1.538000	-2.546000
N	3.367000	0.057000	-0.321000	H	-6.365000	0.449000	-2.409000
C	-0.681000	-2.125000	0.915000	H	-6.174000	2.049000	-0.535000
C	-2.196000	-1.955000	0.814000	H	-4.472000	1.664000	1.268000
C	-2.829000	-2.159000	-0.580000	H	-0.179000	-1.570000	-0.531000
C	-3.850000	-1.055000	-0.711000	H	3.461000	3.297000	-0.607000
C	-4.796000	-0.845000	-1.714000	H	5.151000	1.179000	-0.852000
C	-5.623000	0.276000	-1.634000	H	0.218000	4.608000	0.186000
C	-5.516000	1.186000	-0.571000	H	1.487000	4.310000	-1.002000
C	-4.574000	0.979000	0.431000	H	1.875000	4.345000	0.738000
C	-3.753000	-0.147000	0.347000	H	-0.022000	1.191000	1.595000
C	-2.701000	-0.589000	1.288000	H	-0.619000	2.853000	1.711000
C	2.064000	0.371000	-0.035000	H	1.026000	2.467000	2.265000
C	3.263000	2.247000	-0.479000	H	-0.471000	1.105000	-0.900000
C	4.105000	1.192000	-0.600000	H	0.135000	2.395000	-1.966000
C	0.797000	2.547000	0.102000	H	-1.162000	2.744000	-0.801000
C	1.130000	4.037000	-0.004000	H	3.429000	-1.591000	-2.480000
C	0.267000	2.244000	1.507000	H	2.127000	-2.082000	-1.370000
C	-0.242000	2.174000	-0.962000	H	3.570000	-3.112000	-1.572000
C	3.895000	-1.337000	-0.370000	H	3.987000	-3.048000	0.953000
C	3.212000	-2.078000	-1.524000	H	2.511000	-2.070000	1.132000
C	3.596000	-2.026000	0.966000	H	4.057000	-1.485000	1.798000
C	5.409000	-1.313000	-0.595000	H	5.675000	-0.873000	-1.561000
H	-0.415000	-3.175000	0.737000	H	5.776000	-2.343000	-0.593000
H	-0.368000	-1.879000	1.957000	H	5.933000	-0.773000	0.200000
H	-2.675000	-2.668000	1.508000				

***anti*-TS5**



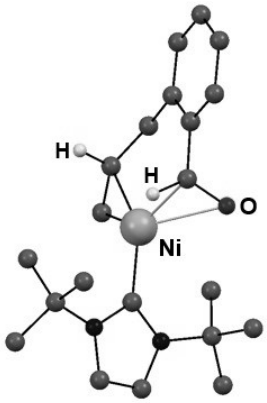
E [a.u.] = –1173.405550

G [a.u.] = –1173.491137

93.73*i* [cm^{-1}]

Ni	0.112000	-0.032000	0.436000	H	2.187000	2.065000	0.998000
O	1.291000	-1.753000	-1.092000	H	3.217000	1.469000	2.287000
N	-2.541000	1.129000	-0.448000	H	5.354000	1.488000	1.253000
N	-2.672000	-0.993000	-0.063000	H	6.947000	0.418000	-0.308000
C	0.308000	0.563000	2.294000	H	6.124000	-1.198000	-2.014000
C	1.562000	0.166000	1.788000	H	3.680000	-1.684000	-2.158000
C	2.646000	1.150000	1.403000	H	1.065000	0.291000	-1.045000
C	3.614000	0.556000	0.406000	H	-4.623000	1.442000	-0.985000
C	4.985000	0.812000	0.484000	H	-4.779000	-1.231000	-0.536000
C	5.885000	0.200000	-0.388000	H	-0.387000	3.742000	-0.950000
C	5.426000	-0.706000	-1.343000	H	-0.518000	2.258000	-1.917000
C	4.064000	-0.980000	-1.426000	H	0.008000	2.168000	-0.224000
C	3.155000	-0.343000	-0.573000	H	-3.355000	3.071000	1.243000
C	1.705000	-0.628000	-0.766000	H	-2.015000	4.196000	0.951000
C	-1.782000	0.053000	-0.055000	H	-1.697000	2.594000	1.653000
C	-3.854000	0.756000	-0.678000	H	-4.027000	3.434000	-1.147000
C	-3.932000	-0.573000	-0.450000	H	-2.976000	2.858000	-2.465000
C	-2.118000	2.560000	-0.475000	H	-2.587000	4.342000	-1.583000
C	-0.662000	2.683000	-0.920000	H	-1.748000	-2.177000	2.226000
C	-2.308000	3.141000	0.932000	H	-0.396000	-2.099000	1.075000
C	-2.989000	3.331000	-1.478000	H	-1.148000	-3.659000	1.448000
C	-2.347000	-2.437000	0.150000	H	-1.578000	-4.069000	-1.049000
C	-1.348000	-2.593000	1.297000	H	-0.833000	-2.499000	-1.407000
C	-1.773000	-2.997000	-1.157000	H	-2.487000	-2.862000	-1.977000
C	-3.627000	-3.196000	0.525000	H	-4.130000	-2.744000	1.385000
H	0.078000	1.622000	2.406000	H	-3.354000	-4.220000	0.795000
H	-0.244000	-0.092000	2.966000	H	-4.335000	-3.266000	-0.307000
H	1.941000	-0.817000	2.078000				

***syn*-TS5**



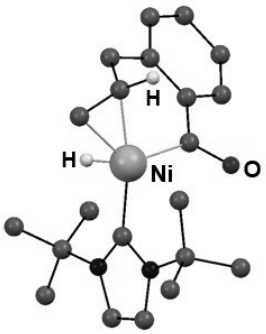
E [a.u.] = −1173.401548

G [a.u.] = −1173.488472

132.46*i* [cm^{-1}]

Ni	-0.142000	0.119000	0.401000	H	2.271000	2.440000	-2.394000
O	-1.194000	-1.153000	-1.478000	H	1.290000	3.754000	-1.713000
N	2.663000	1.085000	-0.090000	C	1.327000	2.916000	0.919000
N	2.611000	-1.074000	-0.044000	H	1.804000	2.762000	1.892000
C	-0.306000	0.047000	2.361000	H	0.406000	2.325000	0.887000
H	-0.206000	-0.969000	2.740000	H	1.066000	3.974000	0.823000
H	0.382000	0.765000	2.803000	C	3.514000	3.412000	-0.148000
C	-1.528000	0.467000	1.804000	H	4.070000	3.260000	0.783000
H	-1.736000	1.540000	1.782000	H	3.191000	4.456000	-0.177000
C	-2.773000	-0.388000	1.811000	H	4.187000	3.259000	-0.997000
H	-3.345000	-0.221000	2.735000	C	2.170000	-2.500000	-0.159000
H	-2.486000	-1.449000	1.818000	C	1.017000	-2.789000	0.800000
C	-3.672000	-0.114000	0.631000	H	0.734000	-3.842000	0.700000
C	-5.057000	0.003000	0.774000	H	0.140000	-2.179000	0.568000
H	-5.494000	-0.084000	1.767000	H	1.313000	-2.605000	1.837000
C	-5.881000	0.227000	-0.328000	C	1.739000	-2.742000	-1.611000
H	-6.955000	0.322000	-0.191000	H	1.457000	-3.791000	-1.746000
C	-5.324000	0.328000	-1.602000	H	2.563000	-2.519000	-2.298000
H	-5.959000	0.499000	-2.467000	H	0.879000	-2.115000	-1.859000
C	-3.946000	0.204000	-1.761000	C	3.339000	-3.426000	0.203000
H	-3.503000	0.270000	-2.752000	H	2.969000	-4.455000	0.229000
C	-3.116000	0.000000	-0.653000	H	3.752000	-3.191000	1.189000
C	-1.642000	-0.147000	-0.894000	H	4.145000	-3.398000	-0.537000
H	-1.045000	0.846000	-0.988000	C	3.932000	-0.703000	-0.227000
C	1.797000	0.026000	0.038000	H	4.742000	-1.406000	-0.309000
C	2.268000	2.521000	-0.219000	C	3.965000	0.647000	-0.254000
C	1.589000	2.710000	-1.581000	H	4.809000	1.305000	-0.359000
H	0.698000	2.081000	-1.656000				

***trans*-TS6**



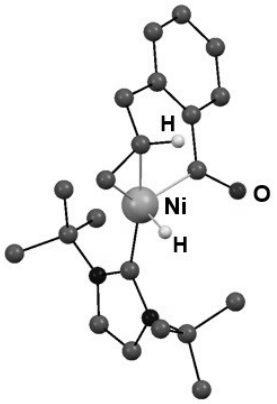
E [a.u.] = −1173.363178

G [a.u.] = −1173.449301

571.46*i* [cm^{-1}]

Ni	-0.001000	-0.507000	0.837000	H	2.512000	0.640000	2.210000
O	0.769000	-1.464000	-1.756000	H	3.498000	-0.776000	2.496000
N	-1.959000	1.581000	-0.250000	H	5.249000	0.289000	1.285000
N	-2.595000	-0.480000	-0.404000	H	6.361000	0.629000	-0.892000
C	0.427000	-0.805000	2.846000	H	5.100000	0.248000	-3.010000
C	1.471000	-1.200000	1.969000	H	2.709000	-0.499000	-2.879000
C	2.722000	-0.371000	1.829000	H	0.301000	0.769000	1.245000
C	3.338000	-0.238000	0.447000	H	-3.662000	2.465000	-1.270000
C	4.686000	0.138000	0.365000	H	-4.452000	-0.134000	-1.470000
C	5.317000	0.324000	-0.861000	H	0.737000	3.690000	-0.335000
C	4.611000	0.111000	-2.048000	H	0.092000	2.705000	-1.665000
C	3.285000	-0.293000	-1.981000	H	0.757000	1.917000	-0.231000
C	2.633000	-0.460000	-0.749000	H	-2.149000	3.106000	2.008000
C	1.182000	-0.875000	-0.749000	H	-0.576000	3.912000	1.839000
C	-1.582000	0.305000	0.072000	H	-0.660000	2.154000	2.075000
C	-3.174000	1.573000	-0.917000	H	-2.944000	4.176000	-0.077000
C	-3.570000	0.286000	-1.016000	H	-2.038000	3.991000	-1.603000
C	-1.208000	2.837000	0.069000	H	-1.371000	4.944000	-0.277000
C	0.182000	2.778000	-0.576000	H	-1.577000	-2.085000	1.512000
C	-1.141000	3.007000	1.593000	H	-0.566000	-2.318000	0.005000
C	-1.949000	4.047000	-0.514000	H	-1.611000	-3.587000	0.588000
C	-2.676000	-1.963000	-0.361000	H	-2.607000	-3.593000	-1.784000
C	-1.536000	-2.500000	0.499000	H	-1.569000	-2.207000	-2.198000
C	-2.541000	-2.500000	-1.791000	H	-3.337000	-2.121000	-2.440000
C	-4.018000	-2.365000	0.265000	H	-4.124000	-1.941000	1.269000
H	0.520000	0.107000	3.431000	H	-4.071000	-3.455000	0.343000
H	-0.248000	-1.548000	3.263000	H	-4.870000	-2.039000	-0.339000
H	1.595000	-2.263000	1.758000				

***cis*-TS6**



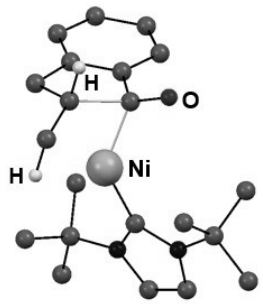
E [a.u.] = –1173.359204

G [a.u.] = –1173.445114

579.37*i* [cm^{-1}]

Ni	-0.022000	-0.551000	0.751000	H	-2.454000	-2.032000	-2.315000
O	0.735000	-1.422000	-1.908000	H	-2.698000	-3.377000	-1.183000
N	-2.820000	-0.051000	-0.398000	C	-3.473000	-1.959000	1.026000
N	-1.629000	1.722000	-0.069000	H	-4.192000	-1.342000	1.574000
C	0.292000	-1.199000	2.681000	H	-2.522000	-1.925000	1.562000
H	0.354000	-0.331000	3.337000	H	-3.835000	-2.992000	1.024000
H	-0.369000	-1.986000	3.029000	C	-4.725000	-1.494000	-1.064000
C	1.362000	-1.498000	1.795000	H	-5.466000	-0.926000	-0.494000
H	1.445000	-2.525000	1.437000	H	-5.058000	-2.535000	-1.087000
C	2.659000	-0.732000	1.792000	H	-4.709000	-1.134000	-2.097000
H	3.383000	-1.256000	2.434000	C	-0.512000	2.657000	0.213000
H	2.506000	0.244000	2.275000	C	0.488000	1.975000	1.141000
C	3.322000	-0.521000	0.440000	H	1.284000	2.675000	1.412000
C	4.688000	-0.211000	0.417000	H	1.011000	1.155000	0.609000
H	5.232000	-0.150000	1.359000	H	0.011000	1.625000	2.059000
C	5.363000	0.017000	-0.779000	C	0.162000	3.025000	-1.115000
H	6.420000	0.268000	-0.765000	H	0.997000	3.710000	-0.939000
C	4.680000	-0.088000	-1.993000	H	-0.545000	3.516000	-1.791000
H	5.201000	0.081000	-2.932000	H	0.546000	2.128000	-1.609000
C	3.332000	-0.423000	-1.985000	C	-1.063000	3.906000	0.913000
H	2.771000	-0.542000	-2.909000	H	-0.232000	4.561000	1.189000
C	2.636000	-0.631000	-0.784000	H	-1.607000	3.637000	1.824000
C	1.147000	-0.926000	-0.857000	H	-1.729000	4.486000	0.269000
H	-0.835000	-1.654000	0.831000	C	-2.814000	2.139000	-0.646000
C	-1.605000	0.361000	0.082000	H	-3.034000	3.170000	-0.868000
C	-3.334000	-1.459000	-0.418000	C	-3.560000	1.031000	-0.846000
C	-2.395000	-2.327000	-1.263000	H	-4.546000	0.941000	-1.265000
H	-1.349000	-2.230000	-0.967000				

TS7



E [a.u.] = −1173.401594

G [a.u.] = −1173.488265

175.89*i* [cm^{-1}]

Ni	0.018000	-0.426000	0.882000	H	-2.339000	-1.646000	-2.634000
O	0.772000	-2.721000	-0.235000	H	-2.364000	-3.232000	-1.838000
N	-2.597000	-0.127000	-0.444000	C	-2.519000	-2.277000	0.781000
N	-1.618000	1.779000	-0.153000	H	-3.048000	-1.824000	1.625000
C	0.952000	-1.323000	3.018000	H	-1.439000	-2.220000	0.953000
H	1.617000	-1.359000	3.893000	H	-2.795000	-3.335000	0.722000
H	0.306000	-2.205000	3.060000	C	-4.397000	-1.788000	-0.776000
C	1.796000	-1.314000	1.734000	H	-5.003000	-1.301000	-0.006000
H	2.339000	-2.265000	1.740000	H	-4.610000	-2.860000	-0.741000
C	2.819000	-0.182000	1.591000	H	-4.714000	-1.431000	-1.761000
H	3.723000	-0.366000	2.190000	C	-0.636000	2.834000	0.238000
H	2.402000	0.772000	1.943000	C	0.664000	2.607000	-0.537000
C	3.149000	-0.112000	0.118000	H	1.407000	3.358000	-0.250000
C	4.185000	0.604000	-0.478000	H	0.490000	2.685000	-1.615000
H	4.862000	1.201000	0.130000	H	1.065000	1.612000	-0.325000
C	4.353000	0.545000	-1.863000	C	-1.193000	4.219000	-0.103000
H	5.157000	1.106000	-2.333000	H	-0.454000	4.968000	0.196000
C	3.504000	-0.242000	-2.649000	H	-2.120000	4.438000	0.438000
H	3.654000	-0.289000	-3.724000	H	-1.366000	4.340000	-1.176000
C	2.480000	-0.976000	-2.055000	C	-0.399000	2.752000	1.750000
H	1.825000	-1.613000	-2.643000	H	0.312000	3.524000	2.060000
C	2.299000	-0.896000	-0.673000	H	0.013000	1.771000	2.013000
C	1.245000	-1.618000	0.107000	H	-1.334000	2.896000	2.301000
H	0.321000	-0.430000	3.147000	C	-2.835000	2.039000	-0.752000
C	-1.440000	0.431000	0.039000	H	-3.183000	3.028000	-0.994000
C	-2.895000	-1.590000	-0.534000	C	-3.444000	0.846000	-0.940000
C	-2.101000	-2.177000	-1.706000	H	-4.405000	0.633000	-1.373000
H	-1.028000	-2.121000	-1.510000				

1.5. References and Notes

[1] K. Sakai, J. Ide, O. Oda, N. Nakamura, *Tetrahedron Lett.* **1972**, 1287.

[2] C. F. Lochow, R. G. Miller, *J. Am. Chem. Soc.* **1976**, *98*, 1281.

[3] For selected recent reviews on hydroacylation, see: a) M. C. Willis, *Chem. Rev.* **2010**, *110*, 725; b) J. C. Leung, M. J. Krische, *Chem. Sci.* **2012**, *3*, 2202; c) I. D. G. Watson, F. D. Toste, *Chem. Sci.* **2012**, *3*, 2899; d) S. K. Murphy, V. M. Dong, *Chem. Commun.* **2014**, *50*, 13645; e) B. Liu, F. Hu, B.-F. Shi, *ACS Catal.* **2015**, *5*, 1863; f) A. Ghosh, K. F. Johnson, K. L. Vickerman, J. A. Walker, L. M. Stanley, *Org. Chem. Front.* **2016**, *3*, 639; for a review on intramolecular variants, see: g) Y. Oonishi, M. Mori, Y. Sato, *J. Synth. Org. Chem., Jpn.* **2007**, *65*, 183; for a book, see: h) "A ctivation of C–H Bonds: Catalytic Reactions": F. Kakiuchi, S. Murai in *Topics in Organometallic Chemistry. Activation of Unreactive Bonds and Organic Synthesis, Vol.3* (Eds.: S. Murai), Springer, New York, **1999**, chapter 3.

[4] a) J. Tsuji, K. Ohno, *Tetrahedron Lett.* **1965**, *6*, 3969; b) J. Tsuji, K. Ohno, *Synthesis* **1969**, 157.

[5] For selected examples of chelation-assisted intramolecular alkene hydroacylations, see: a) H. D. Bendorf, C. M. Colella, E. C. Dixon, M. Marchetti, A. N. Matukonis, J. D. Musselman, T. A. Tiley, *Tetrahedron Lett.* **2002**, *43*, 7031; b) Z. Shen, P. K. Dornan, H. A. Khan, T. K. Woo, V. M. Dong, *J. Am. Chem. Soc.* **2009**, *131*, 1077; c) H. D. Bendorf, K. E. Ruhl, A. J. Shurer, J. B. Shaffer, T. O. Duffin, T. L. LaBarte, M. L. Maddock, O. W. Wheeler, *Tetrahedron Lett.* **2012**, *53*, 1275; for selected examples of chelation-assisted intermolecular alkene hydroacylation, see: d) C. P. Lenges, M. Brookhart, *J. Am. Chem. Soc.* **1997**, *119*, 3165; e) K. Kokubo, K. Matsumasa, M. Miura, M. Nomura, *J. Org. Chem.* **1997**, *62*, 4564; f) M. von Delius, C. M. Le, V. M. Dong, *J. Am. Chem. Soc.* **2012**, *134*, 15022; g) J. F. Hooper, R. D. Young, A. S. Weller, M. C. Willis, *Chem. Eur. J.* **2013**, *19*, 3125; h) T. Zhang, Z. Qi, X. Zhang, L. Wu, X. Li, *Chem. Eur. J.* **2014**, *20*, 3283.

[6] T. Tsuda, T. Kiyoi, T. Saegusa, *J. Org. Chem.* **1990**, *55*, 2554.

[7] For other examples of Ni(0)/PR_3-catalyzed hydroacylation of alkyne, see: a) L.-J. Xiao, X.-N. Fu, M.-J. Zhou, J.-H. Xie, L.-X. Wang, X.-F. Xu, Q.-L. Zhou, *J. Am. Chem. Soc.* **2016**, *138*, 2957; b) F. Yang, T. Jin, Y. Yamamoto, *Tetrahedron* **2012**, *68*, 5223; c) H. Taniguchi, T. Ohmura, M. Suginome, *J. Am. Chem. Soc.* **2009**, *131*, 11298.

[8] For examples of our related works, see: a) S. Ogoshi, M. Oka, H. Kurosawa, *J. Am. Chem. Soc.* **2004**, *126*, 11802; b) S. Ogoshi, T. Arai, M. Ohashi, H. Kurosawa, *Chem. Commun.* **2008**, 1347; c) S. Ogoshi, Y. Hoshimoto, M. Ohashi, *Chem. Commun.* **2010**, *46*, 3354; d) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2011**,

133, 4668.

[9] a) Y. Hoshimoto, Y. Hayashi, H. Suzuki, M. Ohashi, S. Ogoshi, *Angew. Chem. Int. Ed.* **2012**, *51*, 10812; b) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *Acc. Chem. Res.* **2015**, *48*, 1746. See also the related report; c) A. Ghosh, J. A. Walker, Jr., A. Ellern, L. M. Stanley, *ACS Catal*. **2016**, *6*, 2673.

[10] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, *Gaussian 09, Revision A.02*, Gaussian, Inc., Wallingford CT, 2009.

[11] J. Guihaumé, S. Halbert, O. Eisenstein, R. N. Perutz, *Organometallics* **2012**, *31*, 1300.

[12] a) E. A. Mistryukov, *Mendeleev Commun*. **2006**, *16*, 258; b) P. Lara, O. Rivada-Wheelaghan, S. Conejero, R. Poteau, K. Philippot, B. Chaudret, *Angew. Chem. Int. Ed.* **2011**, *50*, 12080.

[13] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648.

[14] a) P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 270; b) P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 284; c) P. J. Hay, W. R. Wadt, *J. Chem. Phys.* **1985**, *82*, 299.

[15] Z. Barandiarán, L. Seijo, S. Huzinaga, M. Klobukowski, *Int. J. Quant. Chem.* **1986**, *29*, 1047.

[16] a) P. Schwerdtfeger, M. Dolg, W. H. E. Schwarz, G. A. Bowmaker, P. D. W. Boyd, *J. Chem. Phys.* **1989**, *91*, 1762; b) D. Andrae, U. Häußermann, M. Dolg, H. Stoll, H. Preuβ, *Theor. Chim. Acta* **1990**, *77*, 123; c) A. Bergner, M. Dolg, W. Küchle, H. Stoll, H. Preuβ, *Mol. Phys.* **1993**, *80*, 1431.

[17] a) B. Mennucci, E. Cancès, J. Tomasi, *J. Phys. Chem. B* **1997**, *101*, 10506; b) E. Cancès, B. Mennucci, J. Tomasi, *J. Chem. Phys.* **1997**, *107*, 3032; for a recent review, see: c) J. Tomasi, B. Mennucci, R. Cammi, *Chem. Rev.* **2005**, *105*, 2999.

[18] Software to optimize reaction paths along the user's expected ones, HPC Systems Inc., http://www.hpc.co.jp/chem/react1.html (written in Japanese).

[19] a) H. Jónsson, G. Mills, K. W. Jacobsen, *Nudged Elastic Band Method for Finding Minimum Energy Paths of Transitions, in Classical and Quantum Dynamics in Condensed Phase Simulations*, (Eds. B. J. Berne, G. Ciccotti and D. F. Coker), World Scientific, 1998, pp. 385–404; b) G. Henkelman, H. Jónsson, *J. Chem. Phys.* **2000**, *113*, 9978.

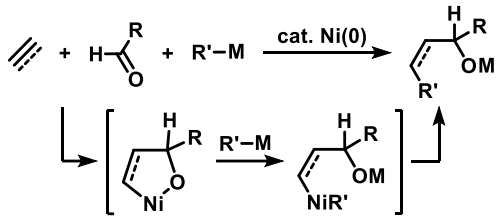
Chapter 2

Nickel(0)-Catalyzed Reductive Coupling Reactions of Carbonyl Compounds with Alkenes

Abstract: Nickel(0)-catalyzed intramolecular reductive coupling reactions of carbonyl compounds and alkenes with reducing reagents are described. The reductive coupling reaction of *o*-allylbenzaldehyde derivatives with triethylsilane provided silyl-protected indanol derivatives. On the other hand, the reaction of *o*-homoallylbenzaldehyde derivatives with triethylsilane gave silyl-protected cyclic allyl alcohol derivatives. In addition, this catalyst system could be applied to the synthesis of a seven-membered cyclic allyl alcohol. When triethylborane was employed instead of triethylsilane, tetralol derivatives were obtained. The results of mechanistic studies including deuterium-labeling experiments are also demonstrated.

2.1. Introduction

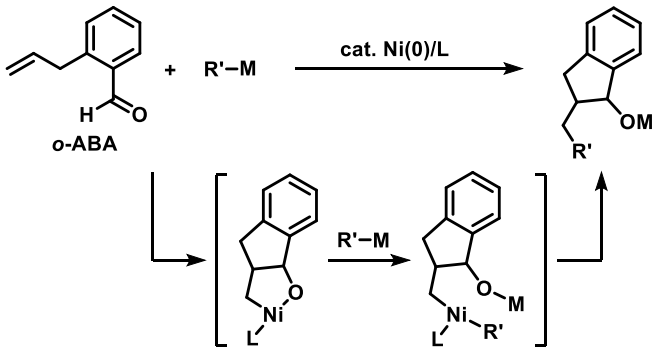
Reactions of oxa-nickelacycles comprising of carbonyl compounds and unsaturated compounds like alkynes, 1,3-dienes, and allenes with reducing reagents such as hydrosilanes, organoaluminiums, organoboranes, and organozincs were extensively studied so far, which have been also proposed as the key process in nickel(0)-catalyzed reductive coupling reactions (Scheme 2.1).[1] Among them, the reaction of aldehydes and



Scheme 2.1. Reductive coupling reaction of aldehydes and unsaturated compounds via oxa-nickelacycle.

alkynes was especially well-developed.[2] The first example on nickel(0)-catalyzed reductive coupling reaction was reported by Montgomery and co-workers in 1997 (see Scheme 3 in General Introduction).[2f] So far, the use of 1,6-enyne,[3] 1,3-dienes,[4] or allenes[5] instead of alkynes was also reported. Nevertheless, the use of alkenes has been rare, which probably is due to the difficulty of both the simultaneous coordination of these two components to nickel(0) and the following oxidative cyclization.[1e] Thus far, the use of alkenes has been limited to the highly reactive ones such as methylenecyclopropane,[6] norbornene[7] and tetrafluoroethylene.[8] The reaction using ethylene and silyl triflates was also reported by Jamison and co-workers.[1e,9] In addition, intramolecular reductive coupling reaction of aldehydes and alkenes with diethylaluminum cyanide was reported by Ho.[10]

In the previous chapter, the nickel(0)-catalyzed intramolecular hydoacylation proceeding via oxa-nickelacycle intermediate was reported. This oxa-nickelacycle could give a reductive coupling product by reaction with reducing reagents. Herein, nickel(0)-



Scheme 2.2. Intramolecular reductive coupling reaction of *o*-ABA via oxa-nickelacycle.

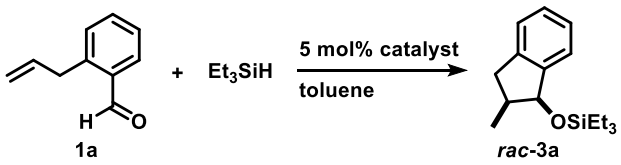
catalyzed intramolecular reductive coupling reactions of *o*-ABA derivatives with reducing reagents are described (Scheme 2.2).

2.2. Result and Discussion

2.2.1. Reaction of *o*-Allylbenzalehyde Derivatives with Hydrosilanes

The results on optimization of the reaction conditions using *o*-allylbenzaldehyde (*o*-ABA: **1a**) and triethylsilane are summarized in Table 2.1. The formation of 1-triethylsiloxy-2-methylindan (**3a**) was confirmed when NHC ligands were employed, whereas PPh_3 and PCy_3 were not effective (entries 1–6). Among the examined NHCs, SIPr gave **3a** in a better yield at room temperature (69%, entry 5). In this reaction system, (η^6-toluene)Ni(SIPr) (**TNSI**) was generated as a precursor for an active nickel(0)/SIPr catalyst (see Chapter 3 for details about this nickel(0) complex). Indeed, the reaction conducted with **TNSI** provided **3a** without a loss of the yield compared with the system comprising $Ni(cod)_2$ and SIPr (entry 7 vs. 5). Thus, **TNSI** was used for a further optimization since **TNSI** can be prepared by a single-step, one-pot, and gram-scale method, and it readily dissolves in a variety of solvents including alkane mediums, unlike $Ni(cod)_2$. In addition, the experimental manipulations were simplified and made more accurate by using the prepared nickel(0) complex. The reaction at 40 °C resulted in

Table 2.1. Optimization of reaction conditions using **1a** and triethylsilane.



1a *rac*-3a

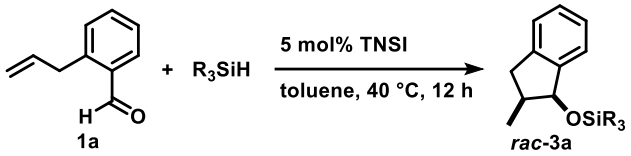
entry	catalyst	solvent	temp. [°C]	time [h]	yield [%][a]	*dr* (*syn*:*anti*)[a]
1[b]	$Ni(cod)_2/PCy_3$	toluene	rt	24	<1	–
2[b]	$Ni(cod)_2/PPh_3$	toluene	rt	24	<1	–
3	$Ni(cod)_2$/IPr	toluene	rt	24	14	86:14
4	$Ni(cod)_2$/IMes	toluene	rt	24	5	70:30
5	$Ni(cod)_2$/SIPr	toluene	rt	24	69	94:6
6	$Ni(cod)_2$/SIMes	toluene	rt	24	20	69:31
7	TNSI	toluene	rt	24	69	93:7
8	TNSI	toluene	40	12	94 (99)[c]	>99:1
9	TNSI	THF	40	12	83	>99:1
10	TNSI	1,4-dioxane	40	12	92	>99:1
11	TNSI	cyclohexane	40	12	80	92:8

[a] Determined by GC using *n*-pentadecane as an internal standard.
[b] Employment of 5 mol% of $Ni(cod)_2$ and 10 mol% of phosphine ligand.
[c] Isolated yield.

improvements in both yield and diastereoselectivity giving **3a** in 99% isolated yield (entry 8). Among the various solvents, toluene gave the highest yield and diastereoselectivity (entries 8–11). The *syn*-conformation between the silyl ether and the methyl groups in **3a** was confirmed by comparison with reports in the literature after desilylation with TBAF (94% isolated yield, see Experimental Section for detail).[11]

The impact of the steric and electronic nature of silanes on both the yield and diastereoselectivity was not significant (Table 2.2). Good to excellent yields and diastereoselectivities were obtained across a broad range of hydrosilanes, with the exception of $(EtO)_3SiH$ (entry 7). Other reducing reagents such as diethylzinc or triethylborane were less effective in this reaction (Table 2.3).

Table 2.2. Scope of hydrosilanes.

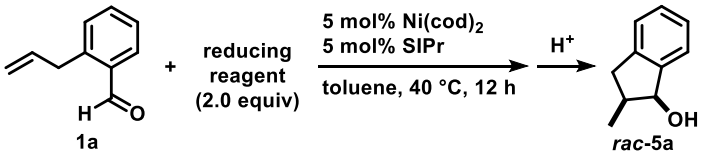


1a *rac*-3a

entry	R_3SiH	yield [%][a]	*dr* (*syn*:*anti*)[a]
1	Et_3SiH	94 (99)[b]	>99:1
2	$(^iPr)_3SiH$	98	96:4
3	$^tBuMe_2SiH$	86	>99:1
4	$PhMe_2SiH$	90	96:4
5	Ph_2MeSiH	86	>99:1
6	Ph_3SiH	98	>99:1
7	$(EtO)_3SiH$	49	96:4

[a] Determined by GC using *n*-pentadecane as an internal standard.
[b] Isolated yield.

Table 2.3. Scope of reducing reagents.



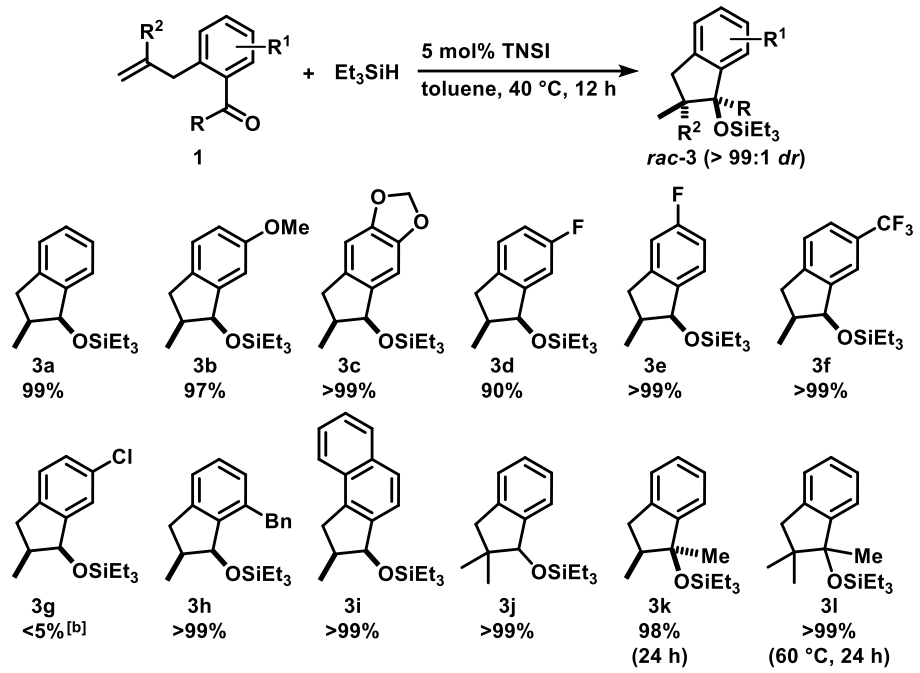
1a *rac*-5a

entry	reducing reagent	conv. [%][a]	yield [%][a]	*dr* (*syn*:*anti*)[a]
1	Et_3B (1.0 M in pentane)	>99	91[b]	>99:1
2	Et_2Zn (1.0 M in heptane)	>99	63	>99:1

[a] Determined by GC using *n*-pentadecane as an internal standard.
[b] Isolated yield.

The scope of the reaction was investigated with respect to *o*-ABA derivatives (**1a**–**j**) (Table 2.4). When an electron-donating group was bonded to the benzene ring (**1b** and **1c**), the reaction proceeded well to give the corresponding silyl-protected 1-indanol derivatives (**3b** and **3c**) in >97% isolated yields. The fluorine substituted products (**3d**–**f**) were obtained in >89% isolated yields; however, a trace amount of chlorine-substituted

Table 2.4. Intramolecular reductive coupling reaction of *o*-ABA derivatives with triethylsilane.[a]

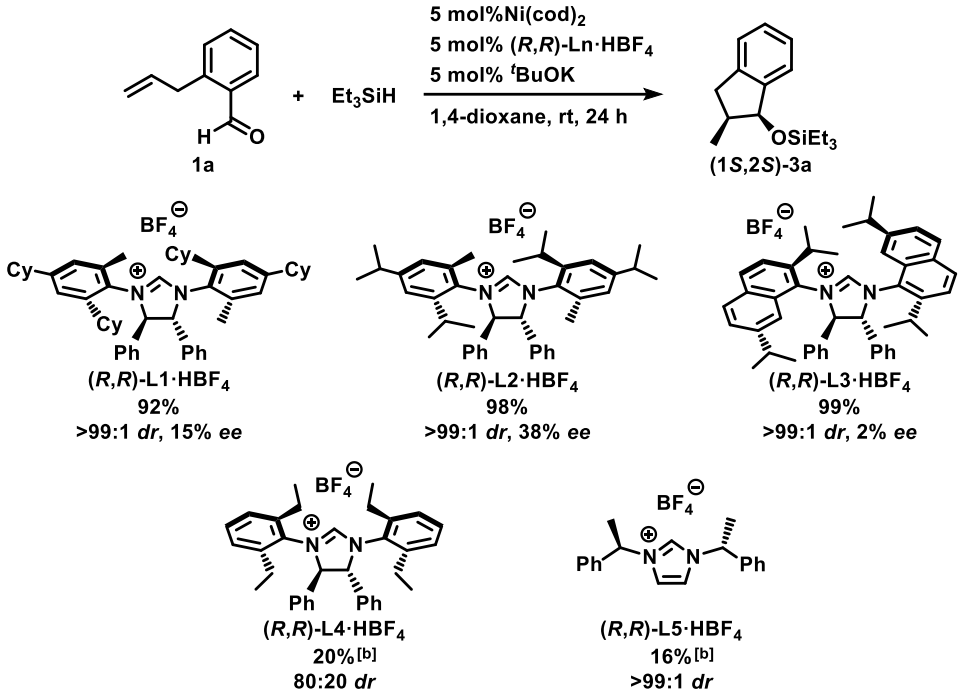


[a] Isolated yields of **3** are presented. Diastereoselectivity was determined by GC.
[b] Determined by GC using *n*-pentadecane as an internal standard.

product **3g** was obtained. Both products with the *o*-benzyl group (**3h**) and the naphthyl structure (**3i**) were obtained in >99% isolated yields. In all of these reactions, the *syn*-isomer was obtained with >99:1 *dr*. The substituted allyl group was also employed to afford **3j** in >99% isolated yield. In addition, this catalyst system could be applied to a reductive coupling reaction of ketones and alkenes with triethylsilane. The reaction of *o*-allylacetophenone (**1k**) took place efficiently to afford the corresponding silyl-protected 1-methyl-1-indanol (**3k**) in 98% isolated yield and >99:1 *dr*. The *syn*-conformation between the silyl ether and the methyl groups in **3k** was confirmed by comparison with reports in the literature after desilylation with TBAF (see Experimental Section for detail).[12] The substituted allyl group was also employed at 60 °C, giving **3l** in >99% isolated yield.

Preliminary results of the expansion of the presented reaction to an enantioselective version are given in Table 2.5. Chiral NHC ligands (**L1**–**L5**) generated in situ by treating the imidazolinium salts (**Ln**·HBF_4) with ^{t}BuOK were applied in this reaction. The reductive coupling reaction of **1a** and triethylsilane was catalyzed by 5 mol% of $Ni(cod)_2$ and chiral NHC ligand at room temperature for 24 h in 1,4-dioxane and provided **3a**. The enantiomeric excess of **3a** was determined using supercritical fluid chromatography (SFC) after converting it into 2-methyl-1-indanol (**5a**) via desilylation using TBAF (see Experimental Section for detail). A novel ligand **L2** was prepared according to the

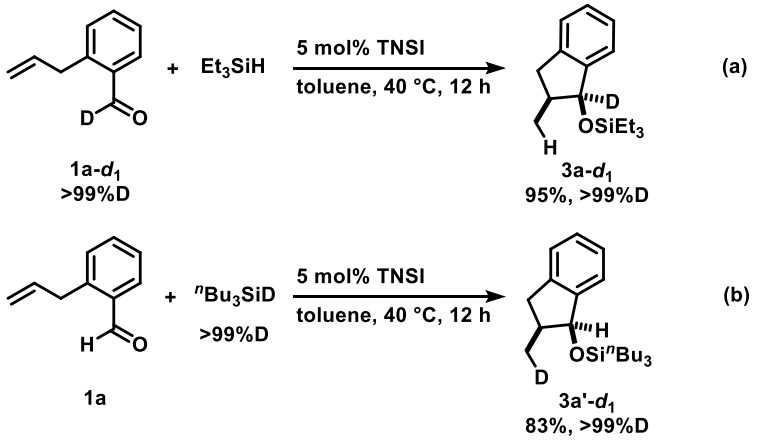
Table 2.5. Enantioselective intramolecular reductive coupling reaction of **1a** with triethylsilane.[a]



[a] Isolated yields of **3a** are presented. Diastereoselectivity was determined by GC, and enantioselectivity was determined by SFC after converting into **5a** by desilylation.
[b] Determined by GC using *n*-pentadecane as an internal standard.

procedures of **L1** reported by Montgomery and co-workers,[13] and the system utilizing **L2** afforded further improved results (98% isolated yield, >99:1 *dr*, and 38% *ee*). The absolute configuration of (1*S*,2*S*)-**3a** was confirmed by comparing the specific rotation of corresponding desilylation product (1*S*,2*S*)-**5a** with data found in the literature.[11b]

To gain insight into the reaction mechanism, deuterium labeling experiments were conducted (Scheme 2.3). In the presence of 5 mol% of **TNSI**, the reaction of **1a**-d_1



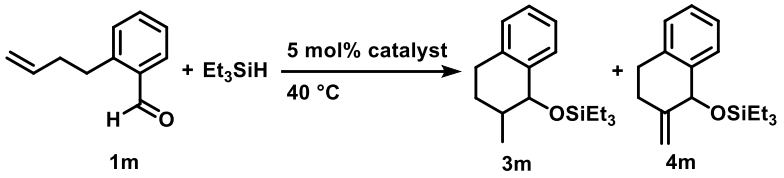
Scheme 2.3. Deuterium labeling experiments.

(>99% D) and triethylsilane proceeded to give **3a-*d*1** in 95% yield, and no H/D exchange was observed (Scheme 2.3a). The reaction of **1a** and tributylsilane-d_1 (>99% D) was also conducted in the presence of 5 mol% of **TNSI** to provide **3a'-*d*1** in 83% yield with >99% deuterium incorporation at the methyl group (Seheme 2.3b). Thus, this intramolecular reductive coupling would proceed via oxidative cyclization of an aldehyde and an alkene affording an oxa-nickelacycle intermediate as shown in Scheme 2.2. The oxidative cyclization process might be promoted by a Lewis acidic silane reagent,[1e,10,14] followed by σ-bond metathesis and reductive elimination giving the product.[15]

2.2.2. Reaction of *o*-Homoallylbenzalehyde Derivatives with Triethylsilane

The results on optimization of the reaction conditions using *o*-homoallylbenzaldehyde (*o*-homoABA: **1m**) and triethylsilane are summarized in Table 2.6. In the presence of 5 mol% of **TNSI**, the reaction of **1m** and triethylsilane proceeded to give a cyclic allyl alcohol **4m** as a major product with a trace amount of **3m** (entries 1 and 2). The reaction conducted with $Ni(cod)_2$/SIPr instead of **TNSI** provided **4m** in 64 % yield (entry 3). Employment of 2 equivalents of SIPr with respect to $Ni(cod)_2$ resulted in the improvement of the yield of **4m** (entry 4). Among various solvents, 1,2-dimethoxyethane (DME) gave the highest yield (entries 5–8).

Table 2.6. Optimization of reaction conditions using **1m** and triethylsilane.



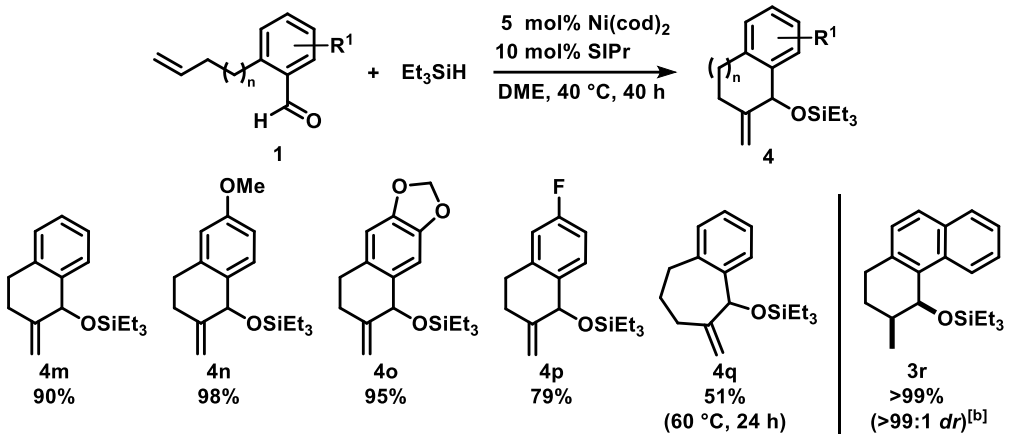
1m 3m 4m

entry	catalyst	solvent	time [h]	yield [%][a] 3m	4m
1	TNSI	toluene	24	<1	22
2	TNSI	toluene	40	2	53
3	$Ni(cod)_2$/SIPr	toluene	40	3	64
4[b]	$Ni(cod)_2$/SIPr	toluene	40	3	76
5[b]	$Ni(cod)_2$/SIPr	THF	40	3	60
6[b]	$Ni(cod)_2$/SIPr	1,4-dioxane	40	5	93
7[b]	$Ni(cod)_2$/SIPr	Et_2O	40	2	45
8[b]	$Ni(cod)_2$/SIPr	DME	40	5	96

[a] Determined by GC using *n*-pentadecane as an internal standard.
[b] Employment of 5 mol% of $Ni(cod)_2$ and 10 mol% of SIPr.

The scope of the reaction was investigated with respect to *o*-homoABA derivatives (**1m**–**r**) (Table 2.7). The reaction of **1m** and triethylsilane took place to give **4m** in 90% isolated yield. When an electron-donating group was bonded to the benzene ring (**1n** and **1o**), the reaction proceeded efficiently to provide the corresponding cyclic allyl alcohols

Table 2.7. Intramolecular reductive coupling reaction of *o*-homoABA derivatives with triethylsilane.[a]



[a] Isolated yields of **3** and **4** are presented. [b] Diastereoselectivity was determined by GC.

(**4n** and **4o**) in >95% isolated yields. The fluorine substituted product (**4p**) was obtained in 79% isolated yield. In addition, this catalyst system could be applied to a synthesis of a seven-membered cyclic allyl alcohol (**4q**). The reaction conducted at 60 °C for 24 h giving **4q** in 51% isolated yield. However, naphthyl substituted derivative (**1r**) provided simple reductive coupling product **3r** in >99% isolated yield and >99:1 *dr*. The steric hindrance repulsing among nickel/SIPr, silyl ether, and naphthyl units might significantly promote reductive elimination (Figure2.1).[10]

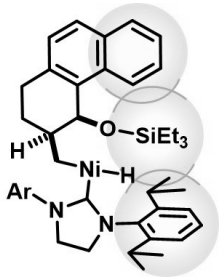
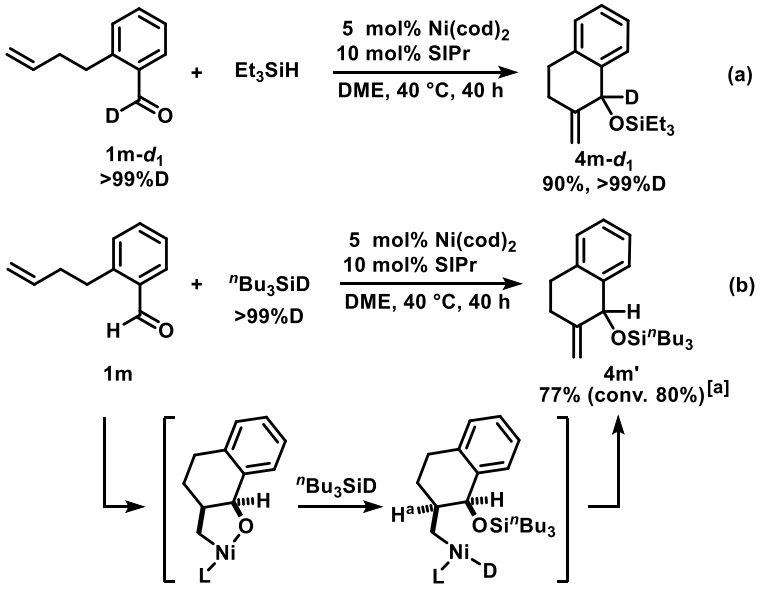


Figure 2.1. Steric hindrance around nickel.



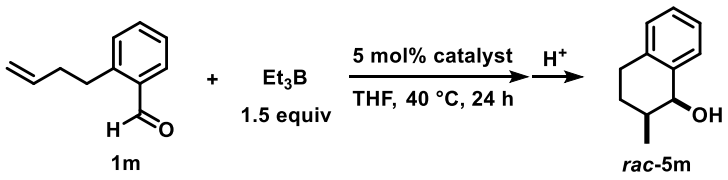
Scheme 2.4. Deuterium labeling experiments. A plausible reaction mechanism is shown. [a] Determined by GC using *n*-pentadecane as an internal standard.

To gain insight into the reaction mechanism, deuterium labelling experiments were conducted (Scheme 2.4). In the presence of 5 mol% of $Ni(cod)_2$ and 10 mol% of SIPr, the reaction of **1m-*d*$_1$** (>99% D) and triethylsilane proceeded to give **4m-*d*$_1$** in 90% yield, and no H/D exchange was observed (Scheme 2.4a). The reaction of **1m** and tributylsilane-d_1 (>99% D) was also conducted in the presence of 5 mol% of $Ni(cod)_2$ and 10 mol% of SIPr to provide **4m'** in 77% yield (conv. 80%) (Scheme 2.4b). These results support that this intramolecular reductive coupling would proceed via an oxa-nickelacycle intermediate followed by σ-bond metathesis with Si–H, β-hydride elimination of H^a, and reductive elimination.

2.2.3. Reaction of *o*-Homoallylbenzalehyde Derivatives with Triethylborane

The results on optimization of the reaction conditions using **1m** and triethylborane are summarized in Table 2.8. The formation of 2-methyl-1-tetralol (**5m**) was confirmed in high yield and diastereoselectivity when both phosphine and NHC ligands were employed (entries 1–7). Especially, the reaction with 5 mol% of $Ni(cod)_2$ and P^nBu_3 proceeded to give **5m** >99% yield and >99:1 *dr* (entry 8). The *syn*-conformation between the hydroxyl and the methyl groups in **5m** was confirmed by comparison with reports in the literature.[16]

Table 2.8. Optimization of reaction conditions using **1m** and triethylborane.



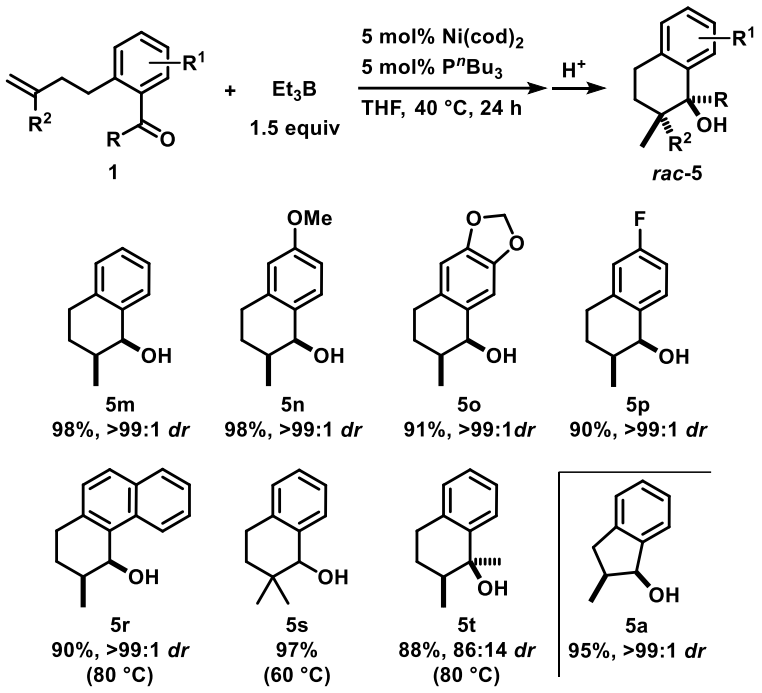
1m *rac*-5m

entry	catalyst	yield [%][a]	*dr* (*syn*:*anti*)[a]
1[b]	$Ni(cod)_2/PCy_3$	93	96:4
2[b]	$Ni(cod)_2/P^nBu_3$	95	97:3
3[b]	$Ni(cod)_2/PPh_3$	89	93:7
4	$Ni(cod)_2$/IPr	94	95:5
5	$Ni(cod)_2$/IMes	95	96:4
6	$Ni(cod)_2$/SIPr	93	96:4
7	$Ni(cod)_2$/SIMes	93	95:5
8	$Ni(cod)_2/P^nBu_3$	>99	>99:1

[a] Determined by NMR after treatment with sat. NH_4Cl aq.
[b] Employment of 5 mol% of $Ni(cod)_2$ and 10 mol% of phosphine ligand.

The scope of the reaction was investigated with respect to *o*-homoallylbenzaldehyde derivatives (**1m**–**p**, **r**–**t**) (Table 2.9). When an electron-donating group was bonded to the benzene ring (**1n** and **1o**), the reaction proceeded well to give the corresponding tetralol derivatives (**5n** and **5o**) in >91% isolated yields. The fluorine substituted product (**5p**)

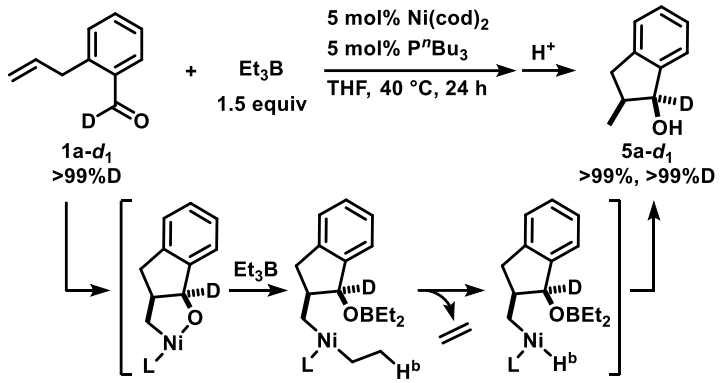
Table 2.9. Intramolecular reductive coupling reaction of *o*-homoABA derivatives with triethylborane.[a]



[a] Isolated yield of **5** are presented. Diastereoselectivity was determined by NMR.

was obtained in 90% isolated yield. The product with the naphthyl structure (**5r**) was also obtained in 90% isolated yield. In all of these reactions, the *syn*-isomer was obtained with >99:1 *dr*. The substituted allyl group was also employed to afford **5s** in 97% isolated yield. In addition, this catalyst system could be applied to a reductive coupling reaction of ketones and alkenes with triethylborane. The reaction of *o*-homoallylacetophenone (**1t**) took place to afford the corresponding tetralol derivative (**5t**) in 88% isolated yield and 86:14 *dr*. The reaction of **1a** proceeded to give the corresponding reductive coupling product **5a** in 95% isolated yield and >99:1 *dr*, so this catalyst system would be also applied to the reaction of *o*-ABA derivatives.

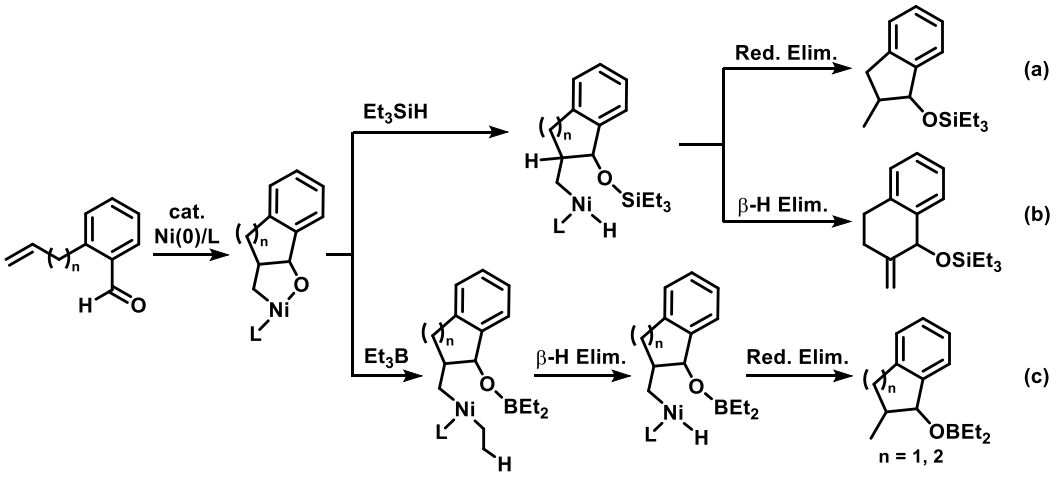
To gain insight into the reaction mechanism, deuterium labelling experiments were conducted (Scheme 2.5). In the presence of 5 mol% of $Ni(cod)_2$ and P^{n}Bu$_3$, the reaction of **1a-*d*$_1$** (>99% D) and triethylborane proceeded to give **5a-*d*$_1$** in >99% yield, >99:1 *dr*, and no H/D exchange was observed. During the reaction, generation of ethylene was confirmed by ^{1}H NMR spectroscopy. Therefore, this intramolecular reductive coupling reaction would proceed via oxidative cyclization of an aldehyde and an alkene affording an oxa-nickelacycle intermediate in Scheme 2.2. The oxidative cyclization process might be promoted by a Lewis acidic organoborane reagent,[1e,10,14] followed by σ-bond metathesis, β-hydride elimination of H^b at the ethyl group on the nickel, and reductive elimination giving the product.[15]



Scheme 2.5. Deuterium labeling experiment. A plausible reaction mechanism is shown.

2.3. Conclusion

Nickel(0)-catalyzed intramolecular reductive coupling reactions of carbonyl compounds and alkenes with reducing reagents were developed (Scheme 2.6). Mechanistic studies including stoichiometric and deuterium-labeling experiments were demonstrated. The reductive coupling reaction of *o*-ABA derivatives with triethylsilane provided silyl-protected indanol derivatives in excellent yields and diastereoselectivities via oxidative cyclization of an aldehyde and an alkene affording an oxa-nickelacycle intermediate followed by σ-bond metathesis with hydrosilane and reductive elimination (Scheme 2.6a). On the other hand, the reaction of *o*-homoABA derivatives with triethylsilane gave silyl-protected cyclic allyl alcohol derivatives in high yields via oxidative cyclization affording an oxa-nickelacycle intermediate followed by σ-bond metathesis with hydrosilane, β-hydride elimination, and reductive elimination (Scheme 2.6b). In addition, this catalyst system could be applied to the synthesis of a seven-membered cyclic allyl alcohol. When triethylborane was employed instead of triethylsilane, tetralol derivatives were obtained



Scheme 2.6. Plausible reaction pathways.

in high yields and diastereoselectivities via oxidative cyclization affording an oxa-nickelacycle intermediate followed by σ-bond metathesis with triethylborane, β-hydride elimination, and reductive elimination (Scheme 2.6c).

2.4. Experimental Section

2.4.1. General

All manipulations were conducted under a nitrogen atmosphere using standard Schlenk or dry box techniques. ^{1}H, ^{13}C, and ^{19}F nuclear magnetic resonance (NMR) spectra were recorded on Bruker AVANCE III 400, Bruker AVANCE III 600, and JEOL AL-400 spectrometers at 25 °C unless otherwise noted. The chemical shifts in the ^{1}H NMR spectra were recorded relative to Me_4Si or residual protonated solvent ($CHCl_3$ (δ 7.26)). The chemical shifts in the ^{13}C NMR spectra were recorded relative to Me_4Si or residual protonated solvent ($CDCl_3$ (δ 77.16)). The chemical shifts in ^{19}F NMR spectra were recorded relative to α,α,α-trifluorotoluene (δ –65.64). Assignment of the resonances in the ^{1}H and ^{13}C NMR spectra was based on ^{1}H-^{1}H COSY, HMQC and HMBC experiments. Mass spectra were obtained using a Shimadzu GCMS-QP 2010 instrument with an ionization voltage of 70 eV. Analytical gas chromatography (GC) was carried out on a Shimadzu GC-2014 gas chromatograph, equipped with a flame ionization detector. Medium-pressure column chromatography was carried out on a Biotage Flash Purification System Isolera, equipped with a 254 nm UV detector. High resolution mass spectrometry (HRMS) was performed at Instrumental Analysis Center, Faculty of Engineering, Osaka University. Enantioselectivities were recorded by means of JASCO-Supercritical Fluid chromatography (SFC) equipped with PU-2080-CO_2 plus CO_2 delivery pump and MD-2018 plus as a photodiode array detector. Optical rotations were measured in JASCO-DIP 1000 polarimeter with a path length of 1 dm using the sodium D line, 589 nm.

2.4.2. Materials

Toluene, 1,4-dioxane, THF, Et_2O, DME, and cyclohexane were distilled from sodium benzophenone ketyl prior to use. All commercially available reagents were distilled over CaH_2 under reduced pressure prior to use. $Ni(cod)_2$ was recrystallized from toluene prior to use. All synthesized starting materials were purified either by distillation over CaH_2 or recrystallization prior to use for catalytic reactions. NHCs shown in Figure 2.2 were prepared according to the reported procedures.[17] (η^6-Toluene)Ni(SIPr) (**TNSI**) was prepared according to the procedure in the Chapter 3. The preparation procedures for chiral imidazolinium salts (**Ln**·HBF_4) are shown in Section 2.4.3.7. The preparation

procedures for substrates (**1a**–**t**, **1a-*d*1**, **1m-*d*1**, tributylsilane-d_1) are shown in Section 2.4.3.8, Section 2.4.4.4, and Section 2.4.5.4.

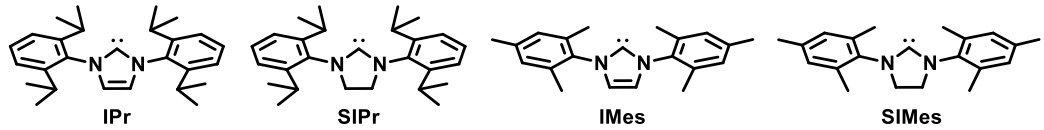
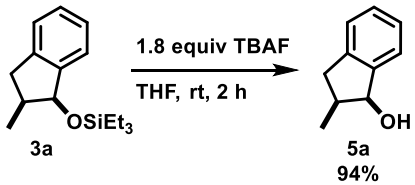


Figure 2.2. NHCs employed in this chapter.

2.4.3. Reaction of *o*-Allylbenzalehyde Derivatives with Hydrosilanes

2.4.3.1. Optimization of Reaction Conditions (Table 2.1)

General procedures: A reaction tube was charged with **1a** (0.80 mmol) and triethylsilane (0.80 mmol) in the presence of catalyst (0.04 mmol) in solvent (3.0 mL). The reaction mixture was stirred at room temperature or 40 °C. The reaction was monitored by GC, and GC yield of **3a** was determined by using *n*-pentadecane as an internal standard.



Desilylation of 3a with TBAF: To a solution of **3a** (221.2 mg, 0.84 mmol) in THF (2.0 mL) was added TBAF (1M in THF, 2.0 mL, 2.0 mmol) at room temperature and stirred for 2 h to complete the reaction. Then, the reaction was quenched by sat. NH_4Cl aq., and the organic layer was extracted with ethyl acetate and dried over anhydrous Na_2SO_4. After the filtration, the solvent was removed under reduced pressure followed by the purification by the silica gel column chromatography to give **5a** (117.0 mg, 0.80 mmol, 94%) as a colorless solid. Spectroscopic data of **5a** were identical to that previously reported.[11]

2.4.3.2. Scope of Hydrosilanes (Table 2.2)

General procedures: A reaction tube was charged with **1a** (0.40 mmol) and hydrosilane (0.40–0.45 mmol) in the presence of **TNSI** (0.02 mmol) in toluene (1.5 mL). The reaction mixture was stirred at 40 °C. The reaction was monitored by GC, and GC yield of **3a** was determined by using *n*-pentadecane as an internal standard.

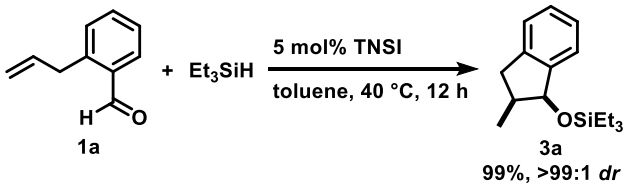
2.4.3.3. Scope of Other Reducing Reagents (Table 2.3)

General procedures: A reaction tube was charged with **1a** (0.80 mmol) and reducing reagent (1.6 mmol) in the presence of $Ni(cod)_2$ (0.04 mmol) and SIPr (0.04 mmol) in toluene (3.0 mL). The reaction mixture was stirred at 40 °C for 12 h and quenched with sat. NH_4Cl aq. followed by 1M HCl aq. The organic layer was extracted with ethyl acetate,

and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure. The reaction was monitored by GC, and GC yield of **5a** was determined by using *n*-pentadecane as an internal standard.

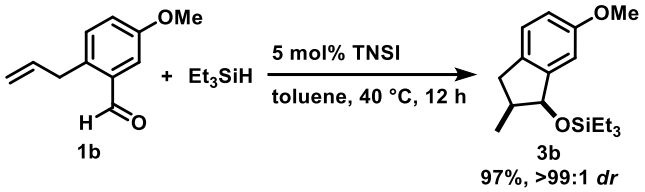
2.4.3.4. Scope of Substrates (Table 2.4)

General procedures: A reaction tube was charged with **1a–l** (0.80 mmol) and triethylsilane (0.80 mmol) in the presence of **TNSI** (0.04 mmol) in toluene (3.0 mL). The reaction mixture was stirred at 40 °C for 12 h. The reaction was monitored by GC. The products were isolated either by silica gel column chromatography or Kugelrohr distillation.



1a → **3a**, 99%, >99:1 *dr*

Reaction of 1a giving 3a: The general procedure was followed with **1a** (118.0 mg, 0.81 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 120 °C) gave **3a** (209.9 mg, 0.80 mmol, 99 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.30 (t, *J* = 3.2 Hz, 1H, Ar-*H*), 7.20–7.19 (m, 3H, Ar-*H*), 5.11 (d, *J* = 6.4 Hz, 1H, C*H*OSi), 2.91 (dd, *J* = 15.2, 6.4 Hz, 1H, ArCH_2CH), 2.64 (dd, *J* = 15.2, 4.8 Hz, 1H, ArCH_2CH), 2.56–2.50 (m, 1H, CH_2CHCH_3), 1.01 (t, *J* = 7.2 Hz, 12H, CHCH_3 and Si(CH_2CH_3)$_3$), 0.69 (apparent q, *J* = 7.2 Hz, 6H, Si(CH_2CH_3)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ145.2, 142.3, 127.6, 126.4, 125.0, 124.5, 77.8, 40.3, 38.0, 14.1, 7.1, 5.3. **HRMS** (EI): *m/z* Calcd for $C_{16}H_{26}OSi$: (M^+) 262.1753, found 262.1752.

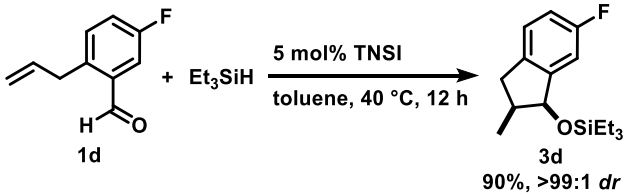


1b → **3b**, 97%, >99:1 *dr*

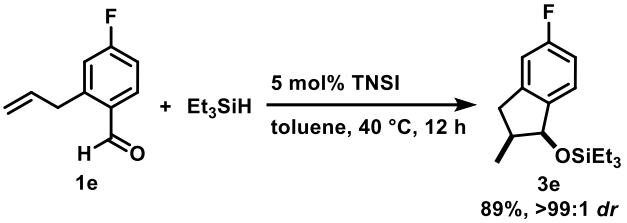
Reaction of 1b giving 3b: The general procedure was followed with **1b** (142.4 mg, 0.81 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 150 °C) gave **3b** (229.5 mg, 0.79 mmol, 97 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.08 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 6.86 (d, *J* = 2.0 Hz, 1H, Ar-*H*), 6.75 (dd, *J* = 8.0, 2.0 Hz, 1H, Ar-*H*), 5.08 (d, *J* = 5.6 Hz, 1H, C*H*OSi), 3.80 (s, 3H, OCH_3), 2.85 (dd, *J* = 15.6, 7.4 Hz, 1H, ArCH_2CH), 2.56–2.53 (m, 2H, ArCH_2CH and CH_2CHCH_3), 1.03–0.97 (m, 12H, CHCH_3 and Si(CH_2CH_3)$_3$), 0.70 (q, *J* = 7.4 Hz, 6H, Si(CH_2CH_3)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 158.9, 146.6, 134.0, 125.7, 113.7, 109.8, 78.0, 55.5, 40.7, 37.1, 14.2, 7.1, 5.3. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{28}O_2Si$: (M^+)

292.1859, found 292.1865.

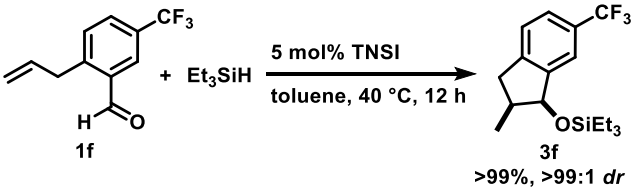
Reaction of 1c giving 3c: The general procedure was followed with **1c** (153.0 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 180 °C) gave **3c** (244.6 mg, 0.80 mmol, >99 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 6.75 (s, 1H, Ar-*H*), 6.65 (s, 1H, Ar-*H*), 5.91 (d, *J* = 2.8 Hz, 2H, OCH_2O), 5.00 (d, *J* = 6.0 Hz, 1H, C*H*OSi), 2.80 (dd, *J* = 16.4, 8.0 Hz, 1H, $ArCH_2CH$), 2.54–2.51 (m, 2H, $ArCH_2CH$ and CH_2CHCH_3), 1.02–0.98 (m, 12H, $CHCH_3$ and $Si(CH_2CH_3)_3$), 0.68 (q, *J* = 7.6 Hz, 6H, $Si(CH_2CH_3)_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ147.5, 146.5, 138.3, 135.6, 105.6, 105.2, 101.0, 77.6, 40.7, 37.9, 14.3, 7.1, 5.3. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{26}O_3Si$: (M^+) 306.1651, found 306.1650.



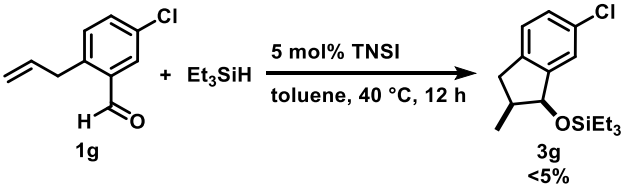
Reaction of 1d giving 3d: The general procedure was followed with **1d** (132.1 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 150 °C) gave **3d** (201.6 mg, 0.72 mmol, 90 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.12–7.09 (m, 1H, Ar-*H*), 6.96 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 6.90–6.85 (m, 1H, Ar-*H*), 5.08 (d, *J* = 5.6 Hz, 1H, C*H*OSi), 2.86 (dd, *J* = 16.0, 7.2 Hz, 1H, $ArCH_2CH$), 2.58–2.55 (m, 2H, $ArCH_2CH$ and CH_2CHCH_3), 1.03–0.96 (m, 12H, $CHCH_3$ and $Si(CH_2CH_3)_3$), 0.70 (q, *J* = 8.0 Hz, 6H, $Si(CH_2CH_3)_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 162.3 (d, J_{CF} = 240.8 Hz), 147.3 (d, J_{CF} = 7.6 Hz), 137.3 (d, J_{CF} = 2.5 Hz), 126.0 (d, J_{CF} = 8.3 Hz), 114.4 (d, J_{CF} = 22.3 Hz), 111.4 (d, J_{CF} = 21.7 Hz), 77.7 (d, J_{CF} = 2.0 Hz), 40.9, 37.1, 14.0, 7.0, 5.2. **^{19}F NMR** (376 MHz, $CDCl_3$): δ –117.2. **HRMS** (EI): *m/z* Calcd for $C_{16}H_{25}FOSi$: (M^+) 280.1659, found 280.1659.



Reaction of 1e giving 3e: The general procedure was followed with **1e** (131.0 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 150 °C) gave **3e** (198.9 mg, 0.72 mmol, 89 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.24–7.20 (m, 1H, Ar-*H*), 6.88–6.86 (m, *2*H, Ar-*H*), 5.04 (d, *J* = 6.0 Hz, 1H, C*H*OSi), 2.87 (dd, *J* = 15.6, 7.2 Hz, 1H, ArC*H*$_2$CH), 2.62 (dd, *J* = 15.6, 4.8 Hz, 1H, ArC*H*$_2$CH), 2.56–2.51 (m, 1H, CH_2CHCH_3), 1.01–0.97 (m, 12H, $CHCH_3$ and $Si(CH_2CH_3)_3$), 0.68 (q, *J* = 7.6 Hz, 6H, $Si(CH_2CH_3)_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 162.9 (d, J_{CF} = 242.2 Hz), 144.8 (d, J_{CF} = 8.7 Hz), 140.9 (d, J_{CF} = 2.0 Hz), 125.6 (d, J_{CF} = 8.7 Hz), 113.3 (d, J_{CF} = 22.1 Hz), 112.0 (d, J_{CF} = 21.4 Hz), 77.0, 40.8, 38.0 (d, J_{CF} = 2.0 Hz), 14.1, 7.1, 5.2. **^{19}F NMR** (376 MHz, $CDCl_3$): δ –115.8. **HRMS** (EI): *m/z* Calcd for $C_{16}H_{25}FOSi$: (M^+) 280.1659, found 280.1657.

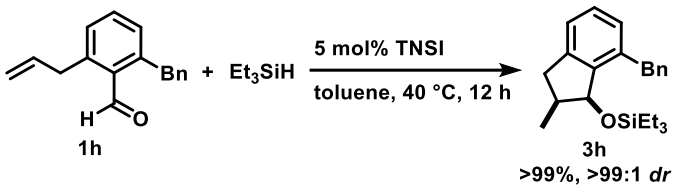


Reaction of 1f giving 3f: The general procedure was followed with **1f** (171.9 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 150 °C) gave **3f** (267.8 mg, 0.81 mmol, >99 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.51 (s, 1H, Ar-*H*), 7.46 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 7.28 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 5.12 (d, *J* = 6.0 Hz, 1H, C*H*OSi), 2.94 (dd, *J* = 15.6, 6.8 Hz, 1H, ArC*H*$_2$CH), 2.67 (dd, *J* = 15.6, 4.0 Hz, 1H, ArC*H*$_2$CH), 2.61–2.55 (m, 1H, CH_2CHCH_3), 1.02–0.98 (m, 12H, $CHCH_3$ and $Si(CH_2CH_3)_3$), 0.70 (apparent q, *J* = 8.0 Hz, 6H, $Si(CH_2CH_3)_3$). **^{13}C{^{1}H,^{19}F} NMR** (100 MHz, $CDCl_3$): δ 146.4, 146.0, 129.0, 125.4, 124.8, 124.7, 121.4, 77.3, 40.5, 37.8, 13.9, 7.0, 5.2. **^{19}F NMR** (376 MHz, $CDCl_3$): δ –61.9. **HRMS** (CI): *m/z* Calcd for $C_{17}H_{26}F_3OSi$: $[M+H]^+$ 331.1705, found 331.1700.

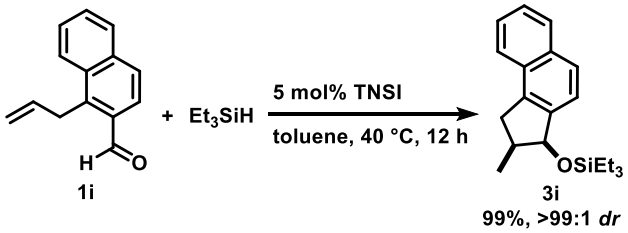


Reaction of 1g giving 3g: The general procedure was followed with **1g** (70.2 mg, 0.39 mmol), triethylsilane (70.0 μL, 0.44 mmol), and TNSI (10.8 mg, 0.02 mmol) in toluene

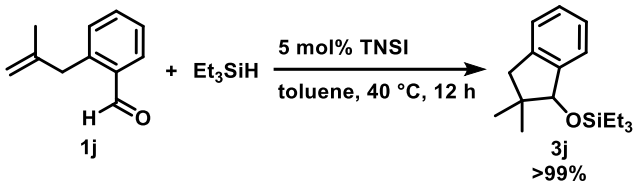
(2.0 mL). The reaction was monitored by GC, and GC yield of **3g** was determined by using *n*-pentadecane as an internal standard.



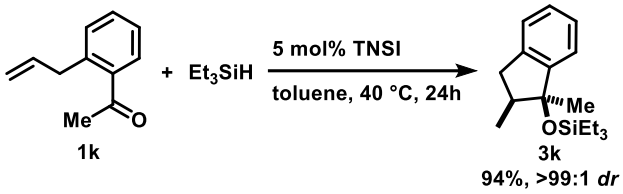
Reaction of 1h giving 3h: The general procedure was followed with **1h** (189.4 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by silica gel column chromatography gave **3h** (285.4 mg, 0.81 mmol, >99 %, >99:1 *dr*) as pale yellow oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.30–7.05 (m, 7H, Ar-*H* overlapped with residual $CHCl_3$), 6.81 (d, *J* = 7.2 Hz, 1H, Ar-*H*), 5.23 (d, *J* = 5.6 Hz, 1H, C*H*OSi), 4.15 (s, 2H, ArCH_2Ph), 2.84 (dd, *J* = 15.2, 6.8 Hz, 1H, ArCH_2CH), 2.72 (dd, *J* = 15.2, 6.8 Hz, 1H, ArCH_2CH), 2.42–2.39 (m, 1H, CH_2CHCH_3), 1.10 (d, *J* = 6.8 Hz, 3H, CHCH_3), 0.95 (t, *J* = 8.0 Hz, 9H, Si(CH_2CH_3)$_3$), 0.65 (q, *J* = 8.0 Hz, 6H, Si(CH_2CH_3)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 143.7, 143.4, 141.3, 137.6, 129.2, 128.5, 128.2, 127.7, 126.0, 122.9, 77.9, 40.9, 38.1, 37.9, 14.6, 7.2, 5.7. **HRMS** (FAB): *m/z* Calcd for $C_{23}H_{32}OSiNa$: $[M+Na]^+$ 375.2120, found 375.2133.



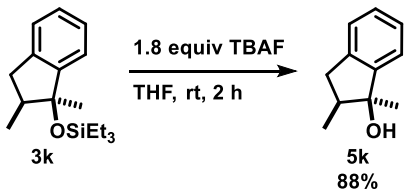
Reaction of 1i giving 3i: The general procedure was followed with **1i** (158.2 mg, 0.81 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by silica gel column chromatography gave **3i** (250.6 mg, 0.80 mmol, 99 %, >99:1 *dr*) as pale yellow oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.86 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 7.81 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 7.73 (d, *J* = 8.4 Hz, 1H, Ar-*H*), 7.51–7.43 (m, 3H, Ar-*H*), 5.30 (d, *J* = 6.4 Hz, 1H, C*H*OSi), 3.23 (dd, *J* = 15.8, 7.0 Hz, 1H, ArCH_2CH), 2.99 (dd, *J* = 15.8, 4.6 Hz, 1H, ArCH_2CH), 2.76–2.70 (m, 1H, CH_2CHCH_3), 1.10 (d, *J* = 7.2 Hz, 3H, CHCH_3), 1.03 (t, *J* = 8.0 Hz, 9H, Si(CH_2CH_3)$_3$), 0.84 (q, *J* = 8.0 Hz, 6H, Si(CH_2CH_3)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 141.8, 138.5, 133.6, 130.7, 128.6, 127.2, 125.9, 125.4, 124.5, 122.9, 78.5, 39.9, 36.3, 14.8, 7.1, 5.3. **HRMS** (EI): *m/z* Calcd for $C_{20}H_{28}OSi$: (M^+) 312.1909, found 312.1905.



Reaction of 1j giving 3j: The general procedure was followed with **1j** (129.8 mg, 0.81 mmol) and triethylsilane (130.0 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 160 °C) gave **3j** (227.3 mg, 0.82 mmol, >99 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.26–7.14 (m, 4H, Ar-*H* overlapped with residual $CHCl_3$), 4.76 (s, 1H, C*H*OSi), 2.71 (d, *J* = 15.2 Hz, 1H, ArCH_2C$(CH_3)_2$), 2.61 (d, *J* = 15.2 Hz, 1H, ArCH_2C$(CH_3)_2$), 1.17 (s, 3H, C(CH_3)), 1.02 (t, *J* = 8.0 Hz, 9H, Si$(CH_2CH_3)_3$), 0.94 (s, 3H, C(CH_3)), 0.71 (q, *J* = 8.0 Hz, 6H, Si(C$H_2CH_3)_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 145.6, 141.5, 127.4, 126.3, 125.0, 124.3, 83.7, 45.7, 45.0, 26.8, 21.8, 7.1, 5.4. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{28}OSi$: (M^+) 276.1909, found 276.1911.

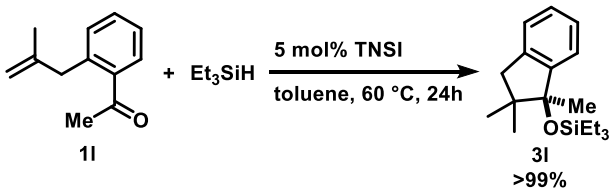


Reaction of 1k giving 3k: The general procedure was followed with **1k** (128.4 mg, 0.80 mmol) and triethylsilane (130.0 μL, 0.82 mmol), and reaction was conducted at 40 °C for 24 h. The reaction mixture was stirred at 40 °C for 24 h. Purification by Kugelrohr distillation (0.4 mmHg, 160 °C) gave **3k** (208.6 mg, 0.75 mmol, 94 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.32 (d, *J* = 6.8 Hz, 1H, Ar-*H*), 7.22–7.17 (m, 3H, Ar-*H*), 2.79 (dd, *J* = 15.2, 7.2 Hz, 1H, ArCH_2CH), 2.67 (dd, *J* = 15.2, 9.6 Hz, 1H, ArCH_2CH), 2.10–2.04 (m, 1H, CH_2C*H*CH_3), 1.55 (s, 3H, C(CH_3)OSi), 1.12 (d, *J* = 6.8 Hz, 3H, CHCH_3), 0.79 (t, *J* = 8.0 Hz, 9H, Si$(CH_2CH_3)_3$), 0.32 (apparent q, *J* = 8.0 Hz, 6H, Si(C$H_2CH_3)_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 148.4, 144.3, 128.1, 125.9, 124.9, 123.2, 82.1, 47.8, 38.2, 25.2, 12.9, 7.1, 6.3. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{28}OSi$: (M^+) 276.1909, found 276.1906.



Desilylation of 3k with TBAF: To a solution of **3k** (386.2 mg, 1.4 mmol) in THF (4.0 mL) was added TBAF (1M in THF, 3.0 mL, 3.0 mmol) at room temperature and stirred for 2 h to complete the reaction. Then, the reaction was quenched by sat. NH_4Cl aq., and the organic layer was extracted with ethyl acetate and dried over anhydrous Na_2SO_4. After

the filtration, the solvent was removed under reduced pressure followed by the purification by the silica gel column chromatography to give **5k** (198.9 mg, 1.2 mmol, 88%) as pale yellow oil. Spectroscopic data of **5k** were identical to that previously reported.[12]



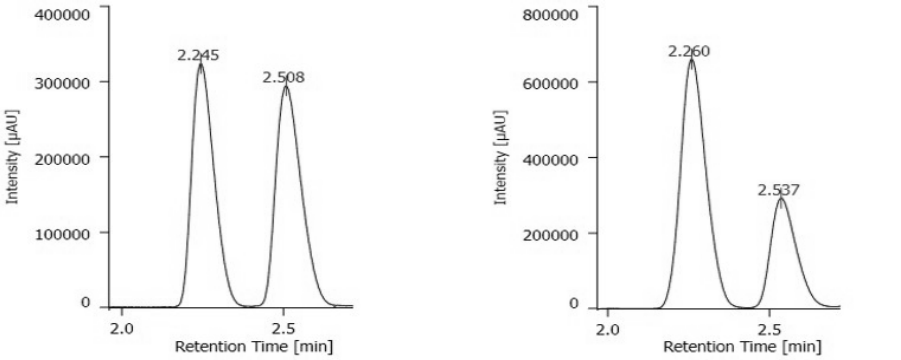
1l 3l >99%

Reaction of 1l giving 3l: The general procedure was followed with **1l** (140.6 mg, 0.81 mmol) and triethylsilane (130.0 μL, 0.82 mmol), and reaction was conducted at 60°C for 24 h. Purification by Kugelrohr distillation (0.4 mmHg, 180 °C) gave **3l** (233.6 mg, 0.80 mmol, >99%) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.28–7.26 (m, 1H, Ar-*H* overlapped with residual $CHCl_3$), 7.20–7.15 (m, 3H, Ar-*H*), 2.95 (d, *J* = 15.2 Hz, 1H, ArCH_2C$(CH_3)_2$), 2.42 (d, *J* = 15.2 Hz, 1H, ArCH_2C$(CH_3)_2$), 1.42 (s, 3H, C(CH_3)OSi), 1.13 (s, 3H, ArCH_2C(CH_3)$_2$), 0.83–0.79 (m, 12H, Si(CH_2CH_3)$_3$ and ArCH_2C(CH_3)$_2$), 0.38–0.32 (m, 6H, Si(CH_2CH_3)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 148.0, 143.6, 127.9, 125.8, 125.2, 123.5, 85.0, 48.6, 45.6, 25.0, 21.8, 21.1, 7.2, 6.4. **HRMS** (EI): *m/z* Calcd for $C_{18}H_{30}OSi$: (M^+) 290.2066, found 290.2066.

2.4.3.5. Enantioselective Reductive Coupling Reaction (Table 2.5)

General procedures: A reaction tube was charged with **Ln**·HBF_4 (0.04 mmol) and ^{t}BuOK (0.04 mmol) in 1,4-dioxane (3.0 mL). After stirring for 5 min, the reaction mixture was added $Ni(cod)_2$ (0.04 mmol), **1a** (0.80 mmol), and triethylsilane (0.82 mmol). The reaction mixture was stirred at room temperature for 24 h. The reaction was monitored by GC, and GC yield of **3a** was determined by using *n*-pentadecane as an internal standard. **3a** was isolated by Kugelrohr distillation. The enantioselectivity of **3a** was determined by using SFC after converting it into desilylated product **5a.** Desilylation was conducted by the same procedure as mentioned above (see Section 2.4.3.1).

Chiral separation (Figure 2.3): The enantioselectivity was measured by using SFC with Chiralpak IC (back pressure = 15 MPa, flow (CO_2) = 4.0 mL/min, flow (isopropanol) = 0.3 mL/min, 25 °C, λ = 264 nm). Retention time: t_R = 2.3 min (1*S*,2*S*-enantiomer) and 2.5 min (1*R*,2*R*-enantiomer).



peak #	tR (min)	area (μV·sec)	hight (μV)	area (%)
1	2.245	1600938	325914	49.036
2	2.508	1663882	296433	50.964

peak #	tR (min)	area (μV·sec)	hight (μV)	area (%)
1	2.260	3683446	661107	69.005
2	2.537	1654482	293032	30.995

Figure 2.3. Chiral separation by using SFC.

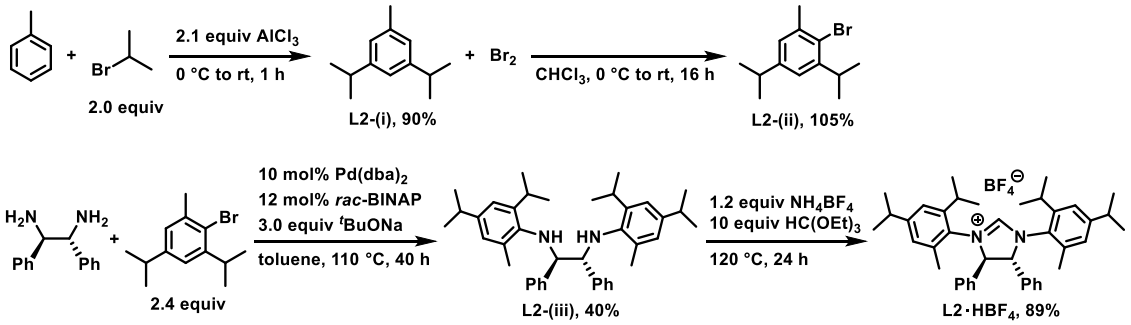
2.4.3.6. Deuterium Labeling Experiments (Scheme 2.3)

Reaction of 1a-*d*$_1$ with triethylsilane: A reaction tube was charged with **1a-*d*$_1$** (59.5 mg, 0.40 mmol) and triethylsilane (70.0 μL, 0.44 mmol) in the presence of **TNSI** (10.8 mg, 0.02 mmol) in toluene (4.0 mL). The reaction mixture was stirred at 40 °C for 12 h. Purification by silica gel column chromatography gave **3a-*d*$_1$** (101.4 mg, 0.38 mmol, 95 %, >99% D) as pale yellow oil.

Reaction of 1a with tributylsilane-*d*$_1$: A reaction tube was charged with **1a** (58.7 mg, 0.40 mmol) and tributylsilane-*d*$_1$ (85.5 mg, 0.42 mmol) in the presence of **TNSI** (10.8 mg, 0.02 mmol) in toluene (4.0 mL). The reaction mixture was stirred at 40 °C for 12 h. Purification by silica gel column chromatography gave **3a'-*d*$_1$** (115.6 mg, 0.33 mmol, 83 %, >99% D) as pale yellow oil.

2.4.3.7. Preparation of Chiral Imidazolinium Salt (Ln·HBF$_4$)

Chiral imidazolinium salt **Ln**·HBF$_4$ was prepared by literature procedures.[18] A novel chiral imidazolinium salt **L2**·HBF$_4$ was prepared according to the procedures reported for **L1**·HBF$_4$ by Montgomery and co-workers.[18a]

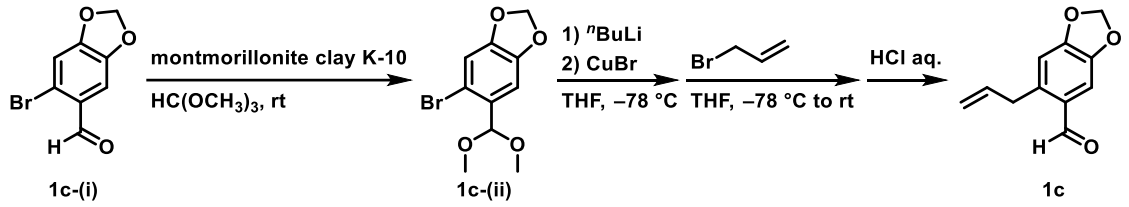


Preparation of (4*R*,5*R*)-1,3-bis(2,4-diisopropyl-6-methylphenyl)-4,5-diphenyl-4,5-dihydro-1*H*-imidazol-3-iumtetrafluoroborate (L2·HBF$_4$): Synthesis of 3,5-

diisopropyl toluene (**L2-(i)**),[19] 2-bromo-3,5-diisopropyl toluene (**L2-(ii)**),[20] and 1*R*,2*R*-N^1,N^2-bis(2,4-diisopropyl-6-methylphenyl)-1,2-diphenylethane-1,2-diamine (**L2-(iii)**)[20] were previously reported. To a solution of **L2-(iii)** (4.5 g, 8.0 mmol) in triethyl orthoformate (12.0 g, 80.0 mmol) was added ammonium tetrafluoroborate (1.0 g, 9.6 mmol) and formic acid (3 drops). The reaction mixture was stirred at 120 °C for 24 h. The crude reaction mixture was purified by silica gel column chromatography (with 5% methanol/CH_2Cl_2) to give (4*R*,5*R*)-1,3-bis(2,4-diisopropyl-6-methylphenyl)-4,5-diphenyl-4,5-dihydro-1*H*-imidazol-3-iumtetrafluoroborate (**L2**·HBF_4) (4.7 g, 7.1 mmol, 89%) as a pale yellow solid. The complicated spectroscopic data suggest an existence of rotamers. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 8.80 (s, 0.13H), 8.58 (s, 0.60H), 8.31 (s, 0.29H) (correspond to the three rotamers of a single proton: NC*H*N), 7.39–7.26 (m, 10H, Ar-*H* overlapped with residual $CHCl_3$), 7.09 (bs, 2H, Ar-*H*), 6.86–6.80 (m, 2H, Ar-*H*), 6.09–6.06 (m, 1H), 5.85–5.77 (m, 1H) (correspond to three rotamers of two protons: NC*H*Ph), 3.30–3.18 (m, 1H, C*H*$(CH_3)_2$), 2.84–2.65 (m, 8H, C*H*$(CH_3)_2$ and C*H*$_3$), 1.90–1.08 (m, 21H), 0.57 (d, *J* = 6.4 Hz, 2H, CH(C*H*$_3$)$_2$), 0.47 (d, *J* = 6.4 Hz, 2H, CH(C*H*$_3$)$_2$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 158.5, 157.9, 152.1, 151.8, 151.7, 147.4, 146.4, 145.2, 137.6, 135.0, 134.6, 131.4, 131.3, 131.0, 130.9, 130.8, 130.4, 129.8, 129.8, 129.6, 129.4, 129.4, 129.0, 127.9, 127.8, 127.7, 127.5, 127.4, 127.2, 127.0, 123.2, 122.7, 122.7, 77.4, 74.8, 72.9, 72.7, 34.1, 34.0, 29.9, 29.3, 25.8,. 25.6, 25.2, 24.7, 23.8, 23.8, 22.6, 22.3, 19.4, 19.1, 18.8. **HRMS** (FAB^+): *m/z* Calcd for $C_{41}H_{51}BF_4N_2$: $[M–BF_4]^+$ 571.4047, found 571.4039.

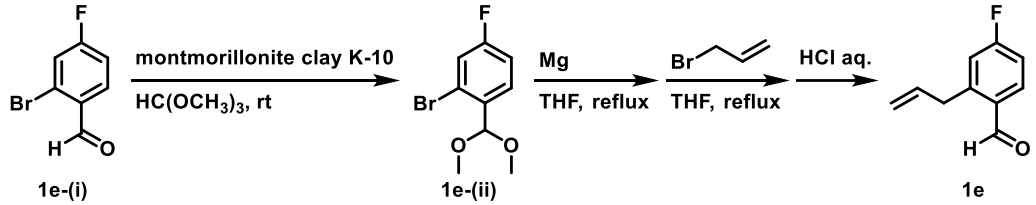
2.4.3.8. Preparation of Substrates

1a–**b**, **1d**, **1g**–**j**, and **1a-*d*$_1$** were prepared by following the procedure reported previously.[21,22]

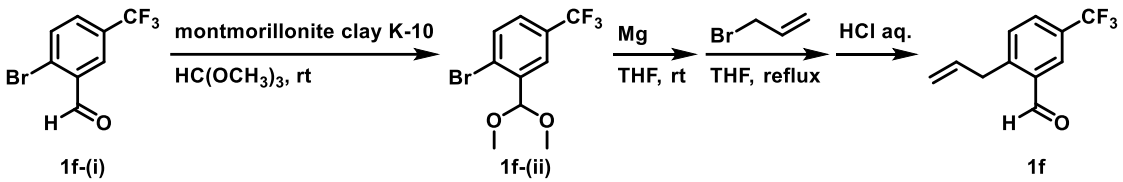


Preparation of 1c: A mixture of montmorillonite K-10 (20 g) and trimethyl orthoformate (30 mL) was stirred for 10 min at room temperature. Then, **1c-(i)** (10.0 g, 43.7 mmol) was added and the resultant mixture was stirred for 1 h. After filtration, all volatiles were removed under reduced pressure to give **1c-(ii)** (12.0 g, 43.6 mmol, >99%) as pale yellow oil, which was employed in the next step without further purification. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.09 (s, 1H, Ar-*H*), 7.00 (s, 1H, Ar-*H*), 5.98 (s, 2H, OC*H*$_2$O), 5.46 (s, 1H, C*H*$(OCH_3)_2$), 3.37 (s, 6H, CH(OC*H*$_3$)$_2$).

To a solution of **1c-(ii)** (12.0 g, 43.6 mmol) in THF (40 mL) was added dropwise a solution of ^{n}BuLi (2.6 M in hexane, 20.0 mL, 56.0 mmol) in THF (40 mL) at −78 °C, and the reaction mixture was stirred at −78 °C for 1 h. CuBr (6.3 g, 43.7 mmol) was added portionwise and the reaction mixture was stirred at −78 °C for 4 h. To this reaction mixture was added dropwise a solution of allyl bromide (6.3 g, 52.0 mmol) in THF (30 mL), and then the resultant mixture was allowed to warm to room temperature with stirring overnight. 1 M HCl aq. was added to the reaction mixture, and stirred for 10 min. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1c** (8.2 g, 43.1 mmol, 99%) as pale yellow oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 10.12 (s, 1H, C*H*O), 7.33 (s, 1H, Ar-*H*), 6.72 (s, 1H, Ar-*H*), 6.09–5.98 (m, 3H, OC*H*$_2$O and CH$_2$C*H*=CH$_2$), 5.11 (d, *J* = 10.4 Hz, 1H, CH$_2$CH=C*H*$_2$), 4.98 (d, *J* = 16.8 Hz, 1H, CH$_2$CH=C*H*$_2$), 3.72 (d, *J* = 6.0 Hz, 2H, C*H*$_2$CH=CH$_2$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 189.6, 152.7, 147.1, 139.9, 137.1, 128.6, 116.7, 110.7, 108.6, 102.1, 36.1. **HRMS** (EI): *m/z* Calcd for $C_{11}H_{10}O_3$: (M^+) 190.0630, found 190.0628.

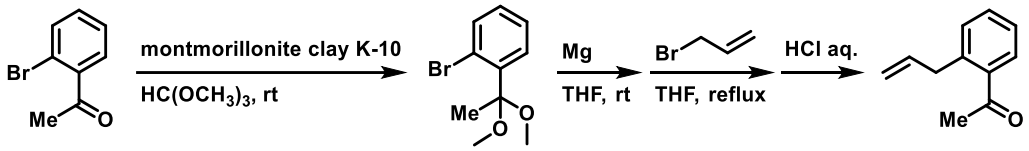


Preparation of 1e: Synthesis of **1e-(ii)** was conducted by the same procedure as mentioned above. To a suspension of Mg (3.8 g, 157.0 mmol), which had been activated by stirring under reduced pressure for 3 h, in THF (40 mL) was added slowly a solution of **1e-(ii)** (36.2 g, 145.3 mmol) in THF (100 mL) at 0 °C. The reaction mixture was stirred at 80 °C for 2 h. Then, to this solution was added dropwise a solution of allyl bromide (19.0 g, 157.0 mmol) in THF (80 mL) at 0 °C. The reaction mixture was stirred at 80 °C for 16 h. After cooling to room temperature, 5 M HCl aq. was added to the reaction mixture, and stirred for 4 h. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1e** (24.0 g, 146.2 mmol, >99%) as orange oil. Spectroscopic data of **1e** were identical to that previously reported.[23]

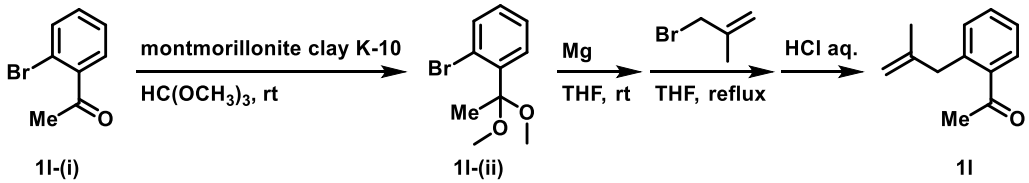


Preparation of 1f: Synthesis of **1f-(ii)** was conducted by the same procedure as mentioned above. To a suspension of Mg (0.6 g, 24.7 mmol), which had been activated

by stirring under reduced pressure for 3 h, in THF (10 mL) was added slowly a solution of **1f-(ii)** (5.7 g, 19.1 mmol) in THF (30 mL) at 0 °C. The reaction mixture was stirred at room temperature for 3 h. Then, to the solution was added dropwise a solution of allyl bromide (3.4 g, 28.5 mmol) in THF (20 mL) at 0 °C. The reaction mixture was stirred at 80 °C for 6 h. After cooling to room temperature, 5 M HCl aq. was added to the reaction mixture, and stirred for 3 days. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1f** (3.9 g, 18.0 mmol, 94%) as pale yellow oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 10.29 (s, 1H, C*H*O), 8.12 (s, 1H, Ar-*H*), 7.78 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 7.45 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 6.07–5.97 (m, 1H, CH_2CH=CH_2), 5.15 (d, *J* = 10.0 Hz, 1H, CH_2CH=CH_2), 5.00 (d, *J* = 16.8 Hz, 1H, CH_2CH=CH_2), 3.87 (d, *J* = 6.0 Hz, 2H, CH_2CH=CH_2). **^{13}C{^{1}H,^{19}F} NMR** (100 MHz, $CDCl_3$): δ 190.9, 146.1, 136.0, 134.2, 131.9, 130.3, 129.8, 128.2, 123.7, 117.5, 36.5. **^{19}F NMR** (376 MHz, $CDCl_3$): δ −62.8. **HRMS** (CI): *m/z* Calcd for $C_{11}H_{10}F_3O$: $[M+H]^+$ 215.0684, found 215.0682.

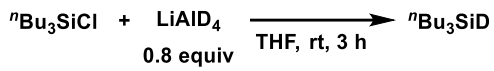


Preparation of 1k: Synthesis of **1k-(ii)** was conducted by the same procedure as mentioned above. To a suspension of Mg (3.0 g, 126.5 mmol), which had been activated by stirring under reduced pressure for 3 h, in THF (20 mL) was added slowly a solution of **1k-(ii)** (28.2 g, 115.1 mmol) in THF (50 mL) at 0 °C. The reaction mixture was stirred at room temperature for 3 h. Then, to the solution was added dropwise a solution of allyl bromide (16.7 g, 138.0 mmol) in THF (30 mL) at 0 °C. The reaction mixture was stirred at 80 °C for 2 h. After cooling to room temperature, 1 M HCl aq. was added to the reaction mixture, and stirred for 1 h. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1k** (18.1 g, 113.0 mmol, 98%) as pale yellow oil. Spectroscopic data of **1k** were identical to that previously reported.[24]



Preparation of 1l: Synthesis of **1l-(ii)** was conducted by the same procedure as mentioned above. To a suspension of Mg (1.0 g, 43.0 mmol), which had been activated by stirring under reduced pressure for 3 h, in THF (10 mL) was added slowly a solution of **1l-(ii)** (9.8 g, 40.0 mmol) in THF (50 mL) at 0 °C. The reaction mixture was stirred at

room temperature for 3 h. To the solution was added dropwise a solution of methallyl bromide (6.5 g, 48.0 mmol) in THF (40 mL) at 0 °C. The reaction mixture was stirred at 80 °C for 2 h. After cooling to room temperature, 3 M HCl aq. was added to the reaction mixture, and stirred for overnight. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1l** (6.9 g, 39.6 mmol, 99%) as pale yellow oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.61 (d, *J* = 7.6 Hz, 1H, Ar-*H*), 7.39 (dd, *J* = 7.6 Hz, 1H, Ar-*H*), 7.30–7.24 (m, 2H, Ar-*H* overlapped with residual $CHCl_3$), 4.77 (s, 1H, $CH_2C(CH_3)=CH_2$), 4.42 (s, 1H, $CH_2C(CH_3)=CH_2$), 3.59 (s, 2H, $CH_2CH=CH_2$), 2.54 (s, 3H, $ArCOCH_3$), 1.72 (s, 3H, $CH_2C(CH_3)=CH_2$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 202.6, 145.6, 139.1, 139.0, 131.8, 131.3, 128.8, 126.3, 111.7, 41.4, 30.0, 23.1. **HRMS** (EI): *m/z* Calcd for $C_{12}H_{14}O$: (M^+) 174.1045, found 174.1044.



Preparation of tributylsilane-*d*$_1$: A mixture of chlorotributylsilane (2.5 g, 10.6 mmol), lithium aluminum deuteride (325 mg, 7.7 mmol, 98% isotopic purity), and THF (40 mL) was stirred for 3 h at room temperature. After cooling to 0 °C, sat. potassium sodium tartrate tetrahydrate aq. was added to the reaction mixture, and stirred for 1 h at room temperature. Then, organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **tributylsilane-*d*$_1$** (2.0 g, 9.9 mmol, 93%, >99%D) as pale yellow oil. Purification by Kugelrohr distillation gave colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 1.36–1.28 (m, 12H), 0.90–0.87 (m, 9H), 0.60–0.56 (m, 6H). **HRMS** (EI): *m/z* Calcd for $C_{12}H_{27}DSi$: (M^+) 201.2023, found 201.2025.

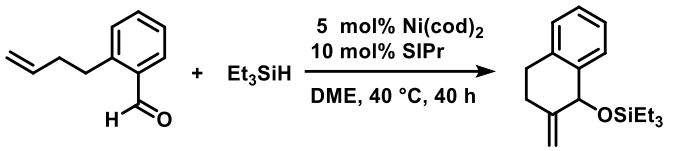
2.4.4. Reaction of *o*-Homoallylbenzalehyde Derivatives with Triethylsilane

2.4.4.1. Optimization of Reaction Conditions (Table 2.6)

General procedures: A reaction tube was charged with **1m** (0.40 mmol) and triethylsilane (0.40 mmol) in the presence of catalyst (0.02 mmol) in solvent (3.0 mL). The reaction mixture was stirred at 40 °C. The reaction was monitored by GC, and GC yield of **4m** was determined by using *n*-pentadecane as an internal standard.

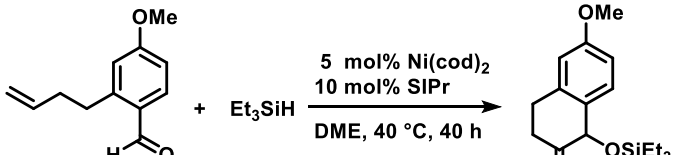
2.4.4.2. Scope of Substrates (Table 2.7)

General procedures: A reaction tube was charged with **1m–r** (0.80 mmol) and triethylsilane (0.80 mmol) in the presence of $Ni(cod)_2$ (0.04 mmol) and SIPr (0.08 mmol) in DME (4.0 mL). The reaction mixture was stirred at 40 °C for 40 h. The reaction was monitored by GC. The products were isolated either by silica gel column chromatography or Kugelrohr distillation.



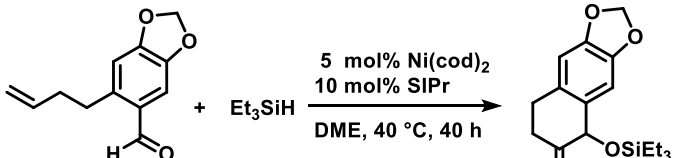
1m 4m 90%

Reaction of 1m giving 4m: The general procedure was followed with **1m** (128.2 mg, 0.80 mmol) and triethylsilane (130 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 120 °C) gave **4m** (198.9 mg, 0.72 mmol, 90 %) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.37 (d, *J* = 6.8 Hz, 1H, Ar-*H*), 7.23–7.16 (m, 2H, Ar-*H*), 7.09 (d, *J* = 6.8 Hz, 1H, Ar-*H*), 5.12 (s, 1H, C*H*OSi), 5.10 (s, 1H, C=CH_2), 4.94 (s, 1H, C=CH_2), 3.00–2.93 (m, 1H, ArCH_2CH$_2$), 2.88–2.80 (m, 1H, ArCH_2CH$_2$), 2.72–2.65 (m, 1H, ArCH$_2$CH_2), 2.51–2.44 (m, 1H, ArCH$_2$CH_2), 1.00 (t, *J* = 7.6 Hz, 9H, Si(CH$_2$CH_3)$_3$), 0.71 (q, *J* = 7.6 Hz, 6H, Si(CH_2CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 148.3, 140.1, 136.9, 128.3, 127.3, 127.2, 126.3, 108.5, 72.7, 30.8, 28.6, 7.1, 5.2. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{26}OSi$: (M^+) 274.1753, found 274.1751.



1n 4n 98%

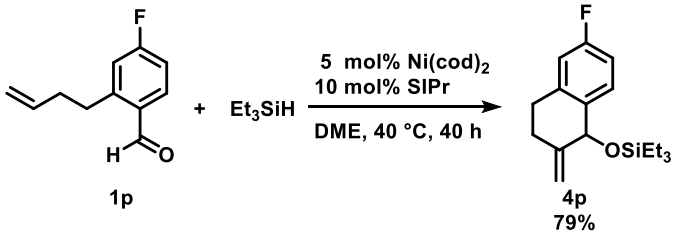
Reaction of 1n giving 4n: The general procedure was followed with **1n** (153.7 mg, 0.81 mmol) and triethylsilane (130 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 130 °C) gave **4n** (241.2 mg, 0.79 mmol, 98 %) as colorless oil. **^{1}H NMR** (400 MHz, $CHCl_3$): δ 7.25 (1H, Ar-*H*, overlapped with $CDCl_3$), 6.76 (dd, *J* = 8.4, 2.4 Hz, 1H, Ar-*H*), 6.61 (d, *J* = 2.4 Hz, 1H, Ar-*H*), 5.07 (s, 1H, C*H*OSi), 5.06 (s, 1H, C=CH_2), 4.91 (s, 1H, C=CH_2), 3.77 (s, 3H, OCH_3), 2.98–2.91 (m, 1H, ArCH_2CH$_2$), 2.84–2.76 (m, 1H, ArCH_2CH$_2$), 2.73–2.66 (m, 1H, ArCH$_2$CH_2), 2.45–2.39 (m, 1H, ArCH$_2$CH_2), 0.99 (t, *J* = 8.0 Hz, 9H, Si(CH$_2$CH_3)$_3$), 0.69 (q, *J* = 8.0 Hz, 6H, Si(CH_2CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 158.9, 148.6, 138.3, 132.5, 128.9, 113.1, 112.4, 108.6, 72.5, 55.3, 31.3, 28.4, 7.1, 5.2. **HRMS** (EI): *m/z* Calcd for $C_{18}H_{28}O_2Si$: (M^+) 304.1859, found 304.1857.



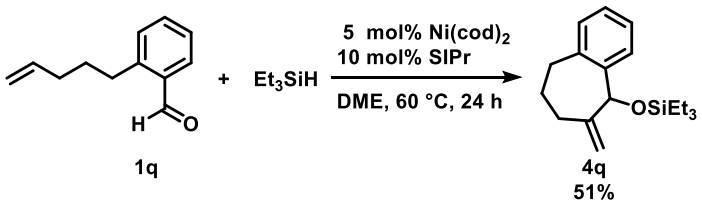
1o 4o 95%

Reaction of 1o giving 4o: The general procedure was followed with **1o** (163.9 mg, 0.80

mmol) and triethylsilane (130 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 150 °C) gave **4o** (241.8 mg, 0.76 mmol, 95 %) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 6.81 (s, 1H, Ar-*H*), 6.54 (s, 1H, Ar-*H*), 5.90–5.89 (m, *2*H,OCH_2O), 5.05 (s, 1H, C=CH_2), 5.00 (s, 1H, C*H*OSi), 4.91 (s, 1H, C=CH_2), 2.89–2.83 (m, 1H, ArCH_2CH$_2$), 2.77–2.61 (m, 2H, ArCH_2CH$_2$ and ArCH$_2$CH_2), 2.44–2.38 (m, 1H, ArCH$_2$CH_2), 0.99 (t, *J* = 7.6 Hz, 9H, Si(CH$_2$CH_3)$_3$), 0.70 (q, *J* = 7.6 Hz, 6H, Si(CH_2CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 148.3, 146.2, 133.2, 130.4, 108.6, 108.2, 107.6, 100.9, 77.4, 72.7, 31.1, 28.5, 7.1, 5.2. **HRMS** (EI): *m/z* Calcd for $C_{18}H_{26}O_3Si$: (M^+) 318.1651, found 318.1655.

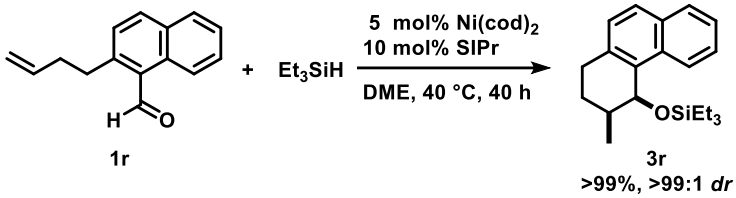


Reaction of 1p giving 4p: The general procedure was followed with **1p** (145.7 mg, 0.82 mmol) and triethylsilane (130 μL, 0.82 mmol). Purification by Kugelrohr distillation (0.4 mmHg, 130 °C) gave **4p** (190.3 mg, 0.65 mmol, 79 %) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.31 (dd, *J* = 8.4, 6.4 Hz, 1H, Ar-*H*), 6.89 (ddd, *J* = 8.4, 8.4, 2.0 Hz, 1H, Ar-*H*), 6.78 (d, *J* = 9.2 Hz, 1H, Ar-*H*), 5.09 (s, 1H, C=CH_2), 5.07 (s, 1H, C*H*OSi), 4.94 (s, 1H, C=CH_2), 2.98–2.91 (m, 1H, ArCH_2CH$_2$), 2.85–2.77 (m, 1H, ArCH_2CH$_2$), 2.72–2.65 (m, 1H, ArCH$_2$CH_2), 2.48–2.42 (m, 1H, ArCH$_2$CH_2), 0.99 (t, *J* = 8.0 Hz, 9H, Si(CH$_2$CH_3)$_3$), 0.70 (q, *J* = 8.0 Hz, 6H, Si(CH_2CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 162.1 (d, J_{CF} = 243.5 Hz), 147.9, 139.2 (d, J_{CF} = 7.4 Hz), 135.9 (d, J_{CF} = 2.7 Hz), 129.1 (d, J_{CF} = 8.7 Hz), 114.7 (d, J_{CF} = 20.7 Hz), 113.3 (d, J_{CF} = 20.7 Hz), 109.0, 72.3, 30.9 (d, J_{CF} = 1.3 Hz), 28.2, 7.1, 5.1. **^{19}F NMR** (376 MHz, $CDCl_3$): δ –119.2. **HRMS** (EI): *m/z* Calcd for $C_{17}H_{25}FOSi$: (M^+) 292.1659, found 292.1662.



Reaction of 1q giving 4q: The general procedure was followed with **1q** (139.4 mg, 0.80 mmol) and triethylsilane (130 μL, 0.82 mmol), and reaction was conducted at 60 °C for 24 h. Purification by silica gel column chromatography gave **4q** (118.6 mg, 0.41 mmol, 51 %) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.38 (dd, *J* = 7.2, 1.6 Hz, 1H, Ar-*H*), 7.18–7.10 (m, 2H, Ar-*H*), 7.05 (dd, *J* = 7.2, 1.6 Hz, 1H, Ar-*H*), 5.18 (s, 1H, C*H*OSi), 4.96 (d, *J* = 1.6 Hz, 1H, C=CH_2), 4.75 (d, *J* = 1.6 Hz, 1H, C=CH_2), 3.24–3.18 (m, 1H,

ArC*H*$_2$CH$_2$CH$_2$), 2.86–2.79 (m, 1H, ArCH$_2$CH$_2$C*H*$_2$), 2.77–2.70 (m, 1H, ArC*H*$_2$CH$_2$CH$_2$), 2.41–2.35 (m, 1H, ArCH$_2$CH$_2$C*H*$_2$), 1.75–1.69 (m. 2H, ArCH$_2$C*H*$_2$CH$_2$), 0.93 (t, *J* = 8.0 Hz, 9H, Si(CH$_2$C*H*$_3$)$_3$), 0.59 (q, *J* = 8.0 Hz, 6H, Si(C*H*$_2$CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, CDCl$_3$): δ 151.2, 143.3, 140.8, 129.8, 127.1, 126.3, 125.8, 109.6, 78.8, 36.5, 35.1, 29.3, 7.0, 5.0. **HRMS** (EI): *m/z* Calcd for C$_{18}$H$_{28}$OSi: (M$^+$) 288.1909, found 288.1906.



1r 3r

>99%, >99:1 *dr*

Reaction of 1r giving 3r: The general procedure was followed with **1r** (171.7 mg, 0.82 mmol) and triethylsilane (130 μL, 0.82 mmol). Purification by silica gel column chromatography gave **3r** (266.5 mg, 0.82 mmol, 99 %, >99:1 *dr*) as colorless oil. **^{1}H NMR** (400 MHz, CDCl$_3$): δ 8.17 (d, *J* = 8.8 Hz, 1H, Ar-*H*), 7.79 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 7.68 (d, *J* = 8.8 Hz, 1H, Ar-*H*), 7.51 (t, *J* = 7.2 Hz, 1H, Ar-*H*), 7.42 (t, *J* = 7.2 Hz, 1H, Ar-*H*), 7.22 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 5.41 (s, 1H, C*H*OSi), 3.09–2.89 (m, 2H, ArC*H*$_2$CH$_2$), 2.10–1.99 (m, 1H, ArCH$_2$C*H*$_2$), 1.88–1.82 (m, 1H, C*H*CH$_3$), 1.65–1.60 (m, 1H, ArCH$_2$C*H*$_2$), 1.22 (d, *J* = 6.8 Hz, 3H, CHC*H*$_3$), 0.75 (t, *J* = 8.0 Hz, 9H, Si(CH$_2$C*H*$_3$)$_3$), 0.41 (q, *J* = 8.0 Hz, 6H, Si(C*H*$_2$CH$_3$)$_3$). **^{13}C{^{1}H} NMR** (100 MHz, CDCl$_3$): δ 134.9, 134.2, 132.4, 131.9, 128.6, 128.3, 127.8, 125.8, 124.8, 123.2, 68.2, 35.6, 30.3, 24.0, 19.1, 7.1, 6.1. **HRMS** (EI): *m/z* Calcd for C$_{21}$H$_{30}$OSi: (M$^+$) 326.2066, found 326.2067.

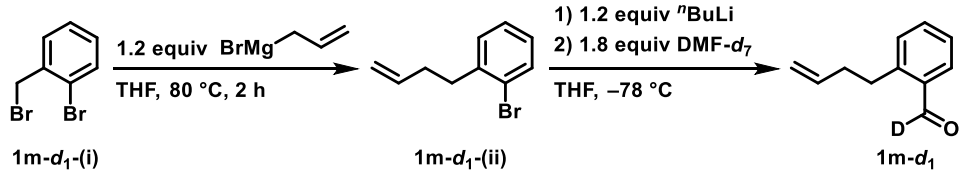
2.4.4.3. Deuterium Labeling Experiments (Scheme 2.4)

Reaction of 1m-*d*$_1$ with triethylsilane: A reaction tube was charged with **1m-*d*$_1$** (66.4 mg, 0.41 mmol) and triethylsilane (80.0 μL, 0.50 mmol) in the presence of Ni(cod)$_2$ (5.5 mg, 0.02 mmol) and SIPr (15.6 mg, 0.04 mmol) in DME (4.0 mL). The reaction mixture was stirred at 40 °C for 40 h. Purification by silica gel column chromatography gave **4m-*d*$_1$** (102.8 mg, 0.37 mmol, 90 %, >99% D) as pale yellow oil.

Reaction of 1m with tributylsilane-*d*$_1$: A reaction tube was charged with **1m** (67.8 mg, 0.42 mmol) and tributylsilane-*d*$_1$ (84.8 mg, 0.42 mmol) in the presence of Ni(cod)$_2$ (5.5 mg, 0.02 mmol) and SIPr (15.6 mg, 0.04 mmol) in DME (4.0 mL). The reaction mixture was stirred at 40 °C for 40 h. The reaction was monitored by GC, and GC yield of **4m'** was determined by using *n*-pentadecane as an internal standard (conv. 88%, yield 77%). After the purification by silica gel column chromatography, deuterium content was determined by NMR.

2.4.4.4. Preparation of Substrates

1m–**q** were prepared by following the procedure reported previously.[21,22]



1m-d_1-(i) 1m-d_1-(ii) 1m-d_1

Preparation of 1m-d_1: 1m-d_1-(ii) were prepared by following the procedure reported previously.[22] To a solution of **1m-d_1-(ii)** (4.6 g, 21.8 mmol) in THF (10 mL) was added dropwise a solution of ^{n}BuLi (2.6 M in THF, 10 mL, 26.2 mmol) in THF (15 mL) at −78 °C, and the reaction mixture was stirred at −78 °C for 30 min. DMF-d_7 (3 mL, 39.3 mmol) was added dropwise and the reaction mixture was warmed up to room temperature for 16 h. Then, sat. NH_4Cl aq. was added to the reaction mixture, and stirred for 10 min. The organic layer was extracted with ether and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure to give **1m-d_1** as pale yellow oil. Purification by Kugelrohr distillation gave **1m-d_1** (3.2 g, 19.8 mmol, 91%, >99%D) as colorless oil. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.84 (d, J = 7.6 Hz, 1H, Ar-*H*), 7.51 (dd, J = 7.6, 7.6 Hz, 1H, Ar-*H*), 7.38 (dd, J = 7.6, 7.6 Hz, 1H, Ar-*H*), 7.28 (d, J = 7.6 Hz, 1H, Ar-*H*), 5.92–5.81 (m, 1H, CH_2CH=CH_2), 5.06–4.98 (m, 2H, CH_2CH=CH_2), 3.13 (t, J = 7.8 Hz, 2H, $ArCH_2CH_2$), 2.38 (dt, J = 7.8, 6.8 Hz, 2H, $ArCH_2CH_2$). **HRMS** (EI): *m/z* Calcd for $C_{11}H_{11}DO$: (M^+) 161.0951, found 161.0949.

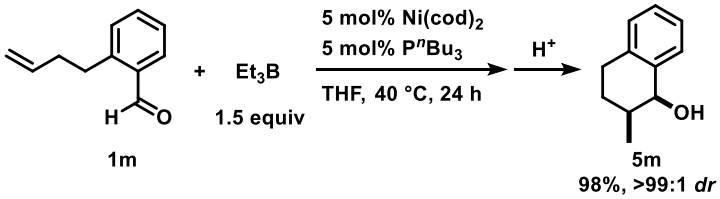
2.4.5. Reaction of *o*-Homoallylbenzalehyde Derivatives with Triethylboranes

2.4.5.1. Optimization of Reaction Conditions (Table 2.9)

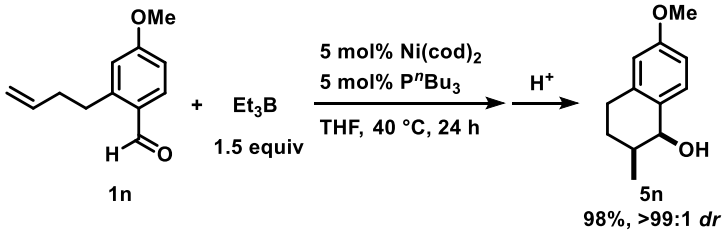
General procedures: A reaction tube was charged with **1m** (0.40 mmol) and triethylborane (1.0 M in hexane, 0.40 mmol) in the presence of catalyst (0.02 mmol) in THF (4.0 mL). The reaction mixture was stirred at 40 °C for 24 h. After treatment with sat. NH_4Cl aq., the organic layer was extracted with ethyl acetate and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure. The yields and diastereoselectivities of **5m** were determined by NMR.

2.4.5.2. Scope of Substrates (Table 2.10)

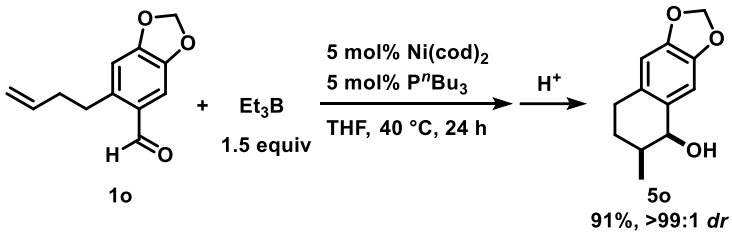
General procedures: A reaction tube was charged with **1m**–**p**, **1r**–**t**, **1a** (0.80 mmol) and triethylborane (1.0 M in hexane, 0.40 mmol) in the presence of $Ni(cod)_2$ (0.04 mmol) and P^{n}Bu$_3$ (0.04 mmol) in THF (4.0 mL). The reaction mixture was stirred at 40 °C for 24 h. After treatment with sat. NH_4Cl aq., the organic layer was extracted with ethyl acetate and dried over anhydrous Na_2SO_4. After filtration, the solvent was removed under reduced pressure. The products were isolated by silica gel column chromatography.



Reaction of 1m giving 5m: The general procedure was followed with **1m** (130.2 mg, 0.81 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol). Purification by silica gel column chromatography gave **5m** (127.7 mg, 0.79 mmol, 98 %, >99:1 *dr*) as colorless oil. Spectroscopic data of **5m** were identical to that previously reported.[11]

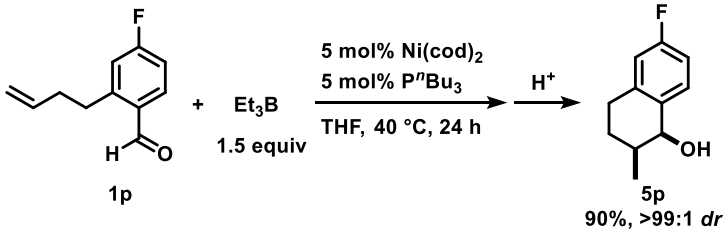


Reaction of 1n giving 5n: The general procedure was followed with **1n** (154.7 mg, 0.81 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol). Purification by silica gel column chromatography gave **5n** (153.6 mg, 0.80 mmol, 98 %, >99:1 *dr*) as a colorless solid. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.28 (d, *J* = 8.0 Hz, 1H, Ar-*H*), 6.76 (dd, *J* = 8.0, 2.8 Hz, 1H, Ar-*H*), 6.64 (d, *J* = 2.8 Hz, 1H, Ar-*H*), 4.52 (dd, *J* = 5.6, 3.2 Hz, 1H, C*H*OH), 3.79 (s, 3H, OCH_3), 2.85–2.71 (m, 2H, ArCH_2CH$_2$), 1.90–1.83 (m, 1H, ArCH$_2$CH_2), 1.79–1.69 (m, 1H, C*H*CH$_3$), 1.65–1.60 (m, 1H, ArCH$_2$CH_2), 1.36 (d, *J* = 5.6 Hz, 1H, CHO*H*), 1.13 (d, *J* = 6.8 Hz, 3H, CHCH_3). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 159.2, 138.3, 131.5, 131.2, 113.4, 112.5, 71.1, 55.3, 34.6, 29.5, 24.7, 17.3. **HRMS** (EI): *m/z* Calcd for $C_{12}H_{16}O_2$: (M^+) 192.1150, found 192.1147.

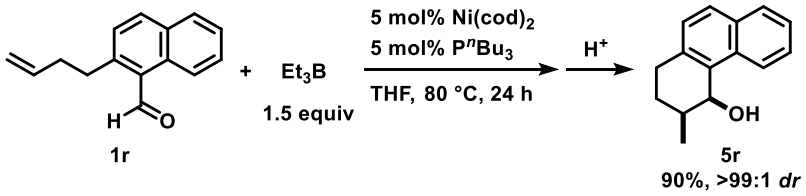


Reaction of 1o giving 5o: The general procedure was followed with **1o** (163.1 mg, 0.80 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol). Purification by silica gel column chromatography gave **5o** (149.7 mg, 0.73 mmol, 91 %, >99:1 *dr*) as a colorless solid. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 6.81 (s, 1H, Ar-*H*), 6.57 (s, 1H, Ar-*H*), 5.91–5.90 (m, 2H,OCH_2O), 4.45 (dd, *J* = 6.0, 3.6 Hz, 1H, C*H*OH), 2.78–2.63 (m, 2H, ArCH_2CH$_2$), 1.89–1.82 (m, 1H, ArCH$_2$CH_2), 1.75–1.57 (m, 1H, C*H*CH$_3$ and ArCH$_2$CH_2), 1.41 (d, *J* = 6.0 Hz, 1H, CHO*H*), 1.11 (d, *J* = 6.8 Hz, 3H, CHCH_3). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 147.4, 146.0, 131.9, 130.5, 109.5, 108.6, 100.9, 71.6, 34.4, 29.3, 24.8, 17.1. **HRMS**

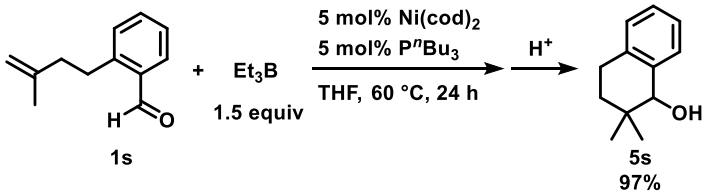
(EI): *m/z* Calcd for $C_{12}H_{14}O_3$: (M^+) 206.0943, found 206.0940.



Reaction of 1p giving 5p: The general procedure was followed with **1p** (145.9 mg, 0.82 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol). Purification by silica gel column chromatography gave **5p** (133.1 mg, 0.74 mmol, 90 %, >99:1 *dr*) as a colorless solid. **^{1}H NMR** (400 MHz, $CDCl_3$): δ 7.32 (dd, *J* = 8.4, 5.6 Hz, 1H, Ar-*H*), 6.89 (ddd, *J* = 8.4, 8.4, 2.8 Hz, 1H, Ar-*H*), 6.81 (dd, *J* = 9.6, 2.8 Hz, 1H, Ar-*H*), 4.55–4.53 (m, 1H, C*H*OH), 2.88–2.71 (m, 2H, ArCH_2CH$_2$), 1.94–1.84 (m, 1H, ArCH$_2$CH_2), 1.80–1.69 (m, 1H, C*H*CH$_3$), 1.67–1.61 (m, 1H, ArCH$_2$CH_2), 1.47 (d, *J* = 5.6 Hz, 1H, CHO*H*), 1.13 (d, *J* = 6.8 Hz, 3H, CHCH_3). **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$): δ 162.3 (d, J_{CF} = 244.3 Hz), 139.3 (d, J_{CF} = 7.3 Hz), 134.6 (d, J_{CF} = 2.9 Hz), 131.7 (d, J_{CF} = 8.8 Hz), 115.2 (d, J_{CF} = 20.4 Hz), 113.4 (d, J_{CF} = 21.2 Hz), 71.0, 34.4, 29.2 (d, J_{CF} = 1.5 Hz), 24.4, 17.0. **^{19}F NMR** (376 MHz, $CDCl_3$): δ −114.7. **HRMS** (EI): *m/z* Calcd for $C_{11}H_{13}FO$: (M^+) 180.0950, found 180.0948.

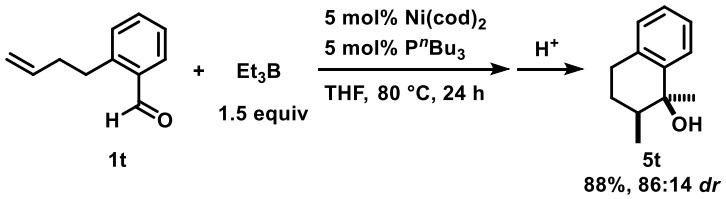


Reaction of 1r giving 5r: The general procedure was followed with **1r** (168.7 mg, 0.80 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol), and reaction was conducted at 80 °C for 24 h. Purification by silica gel column chromatography gave **5r** (153.8 mg, 0.72 mmol, 90 %, >99:1 *dr*) as a pale yellow solid. Spectroscopic data of **5r** was identical to that previously reported.[25]

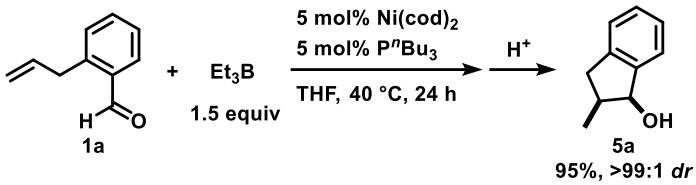


Reaction of 1s giving 5s: The general procedure was followed with **1s** (141.2 mg, 0.81 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol), and reaction was conducted at 60 °C for 24 h. Purification by silica gel column chromatography gave **5s** (138.5 mg, 0.79 mmol, 97 %) as colorless oil. Spectroscopic data of **5s** were identical to

that previously reported.[26]



Reaction of 1t giving 5t: The general procedure was followed with **1t** (142.6 mg, 0.82 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol), and reaction was conducted at 80 °C for 24 h. Purification by silica gel column chromatography gave **5t** (127.4 mg, 0.72 mmol, 88 %, 86:14 *dr*) as a pale yellow solid. Spectroscopic data of **5t** were identical to that previously reported.[27]



Reaction of 1a giving 5a: The general procedure was followed with **1a** (117.2 mg, 0.80 mmol) and triethylborane (1.0 M in hexane, 1.2 mL, 1.2 mmol). Purification by silica gel column chromatography gave **5a** (112.6 mg, 0.76 mmol, 95 %, >99:1 *dr*) as a colorless solid. Spectroscopic data of **5a** were identical to that previously reported.[11]

2.4.5.3. Deuterium Labeling Experiments (Scheme 2.5)

Reaction of 1a-*d*$_1$ with triethylbarane: A reaction tube was charged with **1a-*d*$_1$** (60.2 mg, 0.41 mmol) and triethylborane (1.0 M in hexane, 0.6 mL, 0.6 mmol) in the presence of $Ni(cod)_2$ (5.5 mg, 0.02 mmol) and P^nBu_3 (5.0 μL, 0.02 mmol) in THF (4.0 mL). The reaction mixture was stirred at 40 °C for 24 h. Purification by silica gel column chromatography gave **5a-*d*$_1$** (61.3 mg, 0.41 mmol, >99 %, >99% D) as colorless oil.

2.4.5.4. Preparation of Substrates

All of the substrates (**1a**, **1m**–**p**, **1r**, **1s**, and **1t**) were prepared by following the procedure reported previously.[21,28]

2.5. References and Notes

[1] For selected recent reviews on nickel(0)-catalyzed reductive coupling reactions, see: a) E. A. Standley, S. Z. Tasker, K. L. Jensen, T. F. Jamison, *Acc. Chem. Res.* **2015**, *48*, 1503; b) E. P. Jackson, H. A. Malik, G. J. Sormunen, R. D. Baxter, P. Liu, H. Wang, A.-R. Shareef, J. Montgomery, *Acc. Chem. Res.* **2015**, *48*, 1736; c) K.

Tanaka, Y. Tajima, *Eur. J. Org. Chem.* **2012**, *20*, 3715; d) M. Jeganmohan, C.-H. Cheng, *Chem. –Eur. J.* **2008**, *14*, 10876; e) S.-S. Ng, C.-Y. Ho, K. D. Schleicher, T. F. Jamison, *Pure Appl. Chem.* **2008**, *80*, 929; f) R. M. Moslin, K. Miller-Moslin, T. F. Jamison, *Chem. Commun.* **2007**, 4441; g) J. Montgomery, *Angew. Chem. Int. Ed.* **2004**, *43*, 3890; h) S.-i. Ikeda, *Angew. Chem. Int. Ed.* **2003**, *42*, 5120; i) J. Montgomery, *Acc. Chem. Res.* **2000**, *33*, 467.

[2] a) C.-Y. Zhou, S.-F. Zhu, L.-X. Wang, Q.-L. Zhou, *J. Am. Chem. Soc.* **2010**, *132*, 10955; b) K. M. Miller, W.-S. Huang, T. F. Jamison, *J. Am. Chem. Soc.* **2003**, *125*, 3442; c) W.-S. Huang, J. Chan, T. F. Jamison, *Org. Lett.* **2000**, *2*, 4221; d) X.-Q. Tang, J. Montgomery, *J. Am. Chem. Soc.* **2000**, *122*, 6950; e) X.-Q. Tang, J. Montgomery, *J. Am. Chem. Soc.* **1999**, *121*, 6098; f) E. Oblinger, J. Montgomery, *J. Am. Chem. Soc.* **1997**, *119*, 9065.

[3] R. M. Moslin, K. M. Miller, T. F. Jamison, *Tetrahedron* **2006**, *62*, 7598 and references therein.

[4] N. Saito, Y. Sugimura, Y. Sato, *Org. Lett.* **2010**, *12*, 3494 and references therein.

[5] a) S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2005**, *127*, 7320; b) S.-K. Kang, S.-K. Yoon, *Chem. Commun.* **2002**, 2634; c) J. Montgomery, M. Song, *Org. Lett.* **2002**, *4*, 4009.

[6] K. Ogata, Y. Atsuumi, S.-i. Fukuzawa, *Org. Lett.* **2010**, *12*, 4536.

[7] a) J. S. E. Ahlin, N. Cramer, *Org. Lett.* **2016**, *18*, 3242; b) K. Ogata, A. Toh, D. Shimada, S.-i. Fukuzawa, *Chem. Lett.* **2012**, *41*, 157; c) K. Ogata, Y. Atsuumi, D. Shimada, S.-i. Fukuzawa, *Angew. Chem. Int. Ed.* **2011**, *50*, 5896.

[8] a) M. Ohashi, T. Kawashima, T. Taniguchi, K. Kikushima, S. Ogoshi, *Organometallics* **2015**, *34*, 1604; b) M. Ohashi, H. Shirataki, K. Kikushima, S. Ogoshi, *J. Am. Chem. Soc.* **2015**, *137*, 6496.

[9] a) C.-Y. Ho, T. F. Jamison, *Angew. Chem. Int. Ed.* **2007**, *46*, 782; b) S.-S. Ng, C.-Y. Ho, T. F. Jamison, *J. Am. Chem. Soc.* **2006**, *128*, 11513; c) C.-Y. Ho, S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2006**, *128*, 5362; d) S.-S. Ng, T. F. Jamison, *J. Am. Chem. Soc.* **2005**, *127*, 14194.

[10] C.-Y. Ho, *Chem. Commun.* **2010**, *46*, 466.

[11] a) P. A. Marshall, R. H. Prager, *Aust. J. Chem.* **1979**, *32*, 1251; b) R. Fernández, A. Ros, A. Magriz, H. Dietrich, J. M. Lassaletta, *Tetrahedron* **2007**, *63*, 6755.

[12] N. M. Kablaoui, S. L. Buchwald, *J. Am. Chem. Soc.* **1996**, *118*, 3182.

[13] M. R. Chaulagain, G. J. Sormunen, J. Montgomery, *J. Am. Chem. Soc.* **2007**, *129*, 9568.

[14] S. Ogoshi, M.-a. Oka, H. Kurosawa, *J. Am. Chem. Soc.* **2004**, *126*, 11802.

[15] a) E. P. Jackson, J. Montgomery, *J. Am. Chem. Soc.* **2015**, *137*, 958; b) M. T. Haynes

II, P. Liu, R. D. Baxter, A. J. Nett, K. N. Houk, J. Montgomery, *J. Am. Chem. Soc.* **2014**, *136*, 17495; c) P. Liu, P. McCarren, P. H.-Y. Cheong, T. F. Jamison, K. N. Houk, *J. Am. Chem. Soc.* **2010**, *132*, 2050; d) N. Saito, T. Katayama, Y. Sato, *Org. Lett.* **2008**, *10*, 3829.

[16] a) R. Fernández, A. Ros, A. Magriz, H. Dietrich, J. M. Lassaletta, *Tetrahedron* **2007**, *63*, 6755; b) S. Buksha, G. S. Coumbarides, M. Dingjan, J. Eames, M. J. Suggate, N. Weerasooriya, *J. Label. Compd. Radiopharm.* **2005**, *48*, 337.

[17] The NHCs employed in this paper are as follows: IPr, 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene; SIPr, 1,3-bis(2,6-diisopropylphenyl) imidazolin-2-ylidene; IMes, 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene; SIMes, 1,3-bis(2,4,6-trimethylphenyl)imidazolin-2-ylidene. The preparation methods of these NHCs, see: A. J. Arduengo, III, R. Krafczyk, R. Schmutzler, *Tetrahedron* **1999**, *55*, 14523.

[18] Preparation of **L1**·HBF_4, see: a) M. R. Chaulagain, G. J. Sormunen, J. Montgomery, *J. Am. Chem. Soc.* **2007**, *129*, 9568; Preparation of **L3**·HBF_4, see: b) X. Luan, R. Mariz, C. Robert, M. Gatti, S. Blumentritt, A. Linden, R. Dorta, *Org. Lett.* **2008**, *10*, 5569; Preparation of **L4**·HBF_4, see: c) L. Xu, Y. Shi, *J. Org. Chem.* **2008**, *73*, 749; Preparation of **L5**·HBF_4, see: d) C. D. Campbell, C. Concellón, A. D. Smith, *Tetrahedron: Asymmetry* **2011**, *22*, 797.

[19] M. Ghiaci, J. Asghari, Synth. Commun. **1998**, *28*, 2213.

[20] G. J. Mercer, M. Sturdy, D. R. Jensen, M. S. Sigman, *Tetrahedron* **2005**, *61*, 6418.

[21] Y. Hoshimoto, Y. Hayashi, H. Suzuki, M. Ohashi, S. Ogoshi, *Angew. Chem. Int. Ed.* **2012**, *51*, 10812.

[22] I. D. G. Watson, S. Ritter, F. D. Toste, *J. Am. Chem. Soc.* **2009**, *131*, 2056.

[23] S. Fustero, E. Rodríguez, R. Lázaro, L. Herrera, S. Catalán and P. Barrio, *Adv. Synth. Catal.* **2013**, *355*, 1058.

[24] K. T. Tarantino, P. Liu, R. R. Knowles, *J. Am. Chem. Soc.* **2013**, *135*, 10022.

[25] N. Harada, N. Koumura, B. L. Feringa, *J. Am. Chem. Soc.* **1997**, *119*, 7256.

[26] T. Ohkuma, C. A. Sandoval, R. Srinivasan, Q. Lin, Y. Wei, K. Muñiz, R. Noyori, *J. Am. Chem. Soc.* **2005**, *127*, 8288.

[27] B. T. Kelley, J. C. Walters, S. E. Wengryniuk, *Org. Lett.* **2016**, *18*, 1896.

[28] S. Lin, C.-X. Song, G.-X. Cai, W.-H. Wang, Z.-J. Shi, *J. Am. Chem. Soc.* **2008**, *130*, 12901.

Chapter 3

Development of Practical Synthesis of (η^6-Arene)Ni(N-Heterocyclic Carbene) Complexes

Abstract: The combination of nickel(0) and NHCs has been paid special attention because of its high reactivity toward the activation of unreactive bonds and the bond-forming reactions. Thus, it would be worthwhile to provide a highly reactive, easily accessible, and versatile Ni(0)–NHC precursor. Herein, a practical preparation method for (η^6-arene)Ni(NHC) complexes from commercially available $Ni(cod)_2$ and NHCs (or its salt) via hydrogenation of COD is described. The structure and bonding situations of (η^6-arene)Ni(NHC) complexes were evaluated by NMR, X-ray, and DFT studies. Applications of (η^6-arene)Ni(NHC) complexes as the source for a Ni(0)–NHC unit are also demonstrated.

3.1. Introduction

N-Heterocyclic carbenes (NHCs) are cyclic carbenes bearing at least one nitrogen atom within the ring structure (Figure 3.1).[1] Early work on these compounds carried out independently by Wanzlick and co-worker and Öfele in 1968,[2] and was followed by important organometallic studies by Lappert and co-workers in 1970s.[3] The breakthrough came from the Arduengo group with the isolation of "free carbene" IAd, which opened up a novel opportunities for NHCs to be employed in organic synthesis.[4]

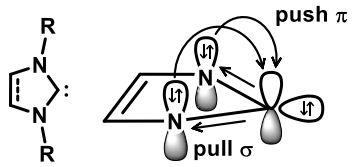


Figure 3.1. N-Heterocyclic carbene.

Over the past couple of decades, a wide range of fields in chemistry, including synthetic, organometallic, and inorganic, have benefited from the development of the chemistry of NHCs. Because of their distinctive electronic and steric properties, NHCs have been widely employed as auxiliary ligands and as organocatalysts in the field of organic synthesis.[1,5] As a part of these pursuits, the combination of palladium and NHCs has been well established.[5,6] In contrast, the application of NHCs toward nickel-catalyzed/-mediated reactions has been less developed, although nickel is a more inexpensive and ubiquitous element.[5,7] Thus, it would be worthwhile to provide a readily accessible, highly reactive, and widely applicable Ni(0)–NHC source from commercially available $Ni(cod)_2$.

A variety of Ni(0)–NHC complexes have been synthesized to date, such as $Ni(CO)_3$(NHC), bis(η^2-alkene)Ni(NHC), (η^2:η^2-diene)Ni(NHC), and $Ni(NHC)_2$ (Figure 3.2).[8] These complexes have been used as a source of Ni(0)–NHC reactive species;

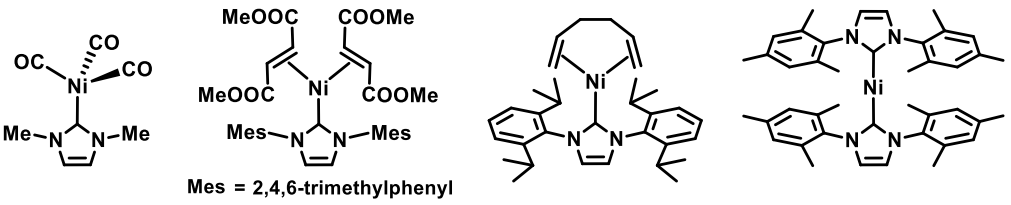
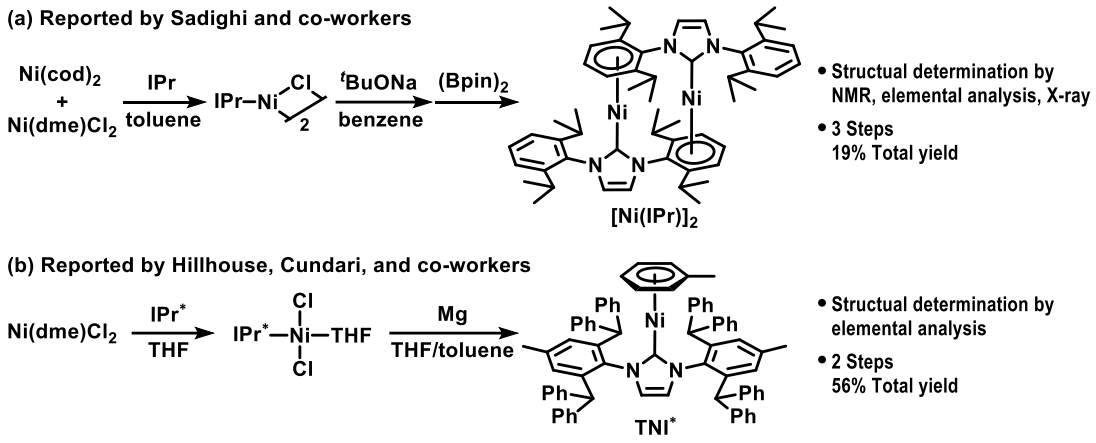


Figure 3.2. Examples of reported Ni(0)–NHC complexes.

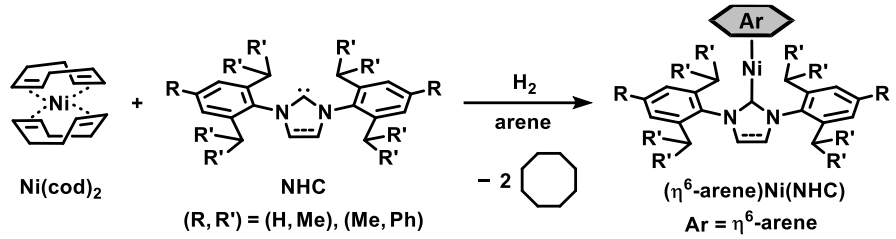
however, difficulties in preparation and ligand substitution may make chemists hesitant to use them. In contrast to these well-known Ni(0)–NHC complexes, less is known about (η^6-arene)Ni(NHC) complexes.[9–11] Two examples of (η^6-arene)Ni(NHC) complexes have been reported (Scheme 3.1). One is $[Ni(IPr)]_2$, in which one of the 2,6-diisopropylphenyl rings in the Ni(0)–IPr moiety coordinates with the other nickel(0) atom to form a dimeric structure.[10] The complex was synthesized from $Ni(cod)_2$ and $Ni(dme)Cl_2$ in 19% overall yields (Scheme 3.1a). The other is (η^6-toluene)Ni(IPr*) (**TNI***), which was synthesized from $Ni(dme)Cl_2$ in 56% yield (Scheme 3.1b).[11] The



Scheme 3.1. Reported synthetic methods of (η^6-arene)Ni(NHC) complexes: a) $[Ni(IPr)]_2$ reported by Sadighi and co-workers, and b) **TNI*** reported by Hillhouse, Canduri, and co-workers.

formation of **TNI*** was confirmed by elementary analysis. The reactivity of these (η^6-arene)Ni(NHC) complexes is very intriguing, since the η^6-arene ligand would be more labile and less noxious than olefins, carbon monoxide, and other donor ligands. Therefore, developing a simple and practical preparation method for (η^6-arene)Ni(NHC) complexes would expand the range of applications for them as catalyst precursors in organic synthesis and as a source of Ni(0)–NHC units in organometallic chemistry.

Herein, the single-step, one-pot, and gram-scale synthesis of a series of (η^6-arene)Ni(NHC) complexes is described. The hydrogenation of a mixture of $Ni(cod)_2$ and NHC in an arene medium at room temperature gave an (η^6-arene)Ni(NHC) complex in nearly quantitative yield (Scheme 3.2). This is the first crystallographic structure of a monomeric (η^6-arene)Ni(NHC) complex with the solid evidence of the η^6 coordination mode of an arene ring. In addition, the applications of (η^6-arene)Ni(NHC) complexes as the source for a Ni(0)–NHC unit are also demonstrated.

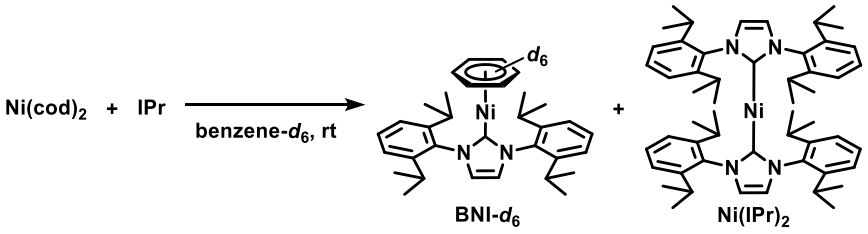


Scheme 3.2. Synthesis of (η^6-arene)Ni(NHC) complexes.

3.2. Result and Discussion

3.2.1. Synthesis of (η^6-Arene)Ni(NHC) Complexes

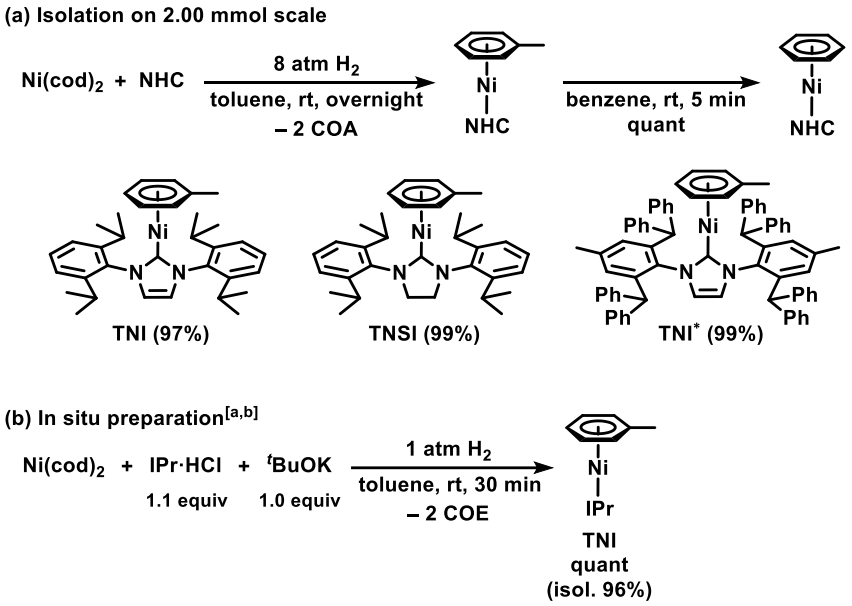
During the course of the present research on Ni(0)–NHC catalysis,[12] I found the generation of (η^6-benzene-d_6)Ni(IPr) (**BNI-*d*$_6$**) by mixing Ni(cod)$_2$ and IPr in benzene-d_6 at room temperature (Scheme 3.3). After 31 h, the concomitant formation of Ni(IPr)$_2$ (9%) was also observed, while the major product was **BNI-*d*$_6$** (72%). Neither **BNI-*d*$_6$** nor Ni(IPr)$_2$ was obtained as a single product, even when the reaction time was prolonged for several days, which indicates that **BNI-*d*$_6$** and Ni(IPr)$_2$ exist in equilibrium with Ni(cod)$_2$, IPr, and 1,5-cyclooctadiene (COD) in benzene-d_6.[13] In order to prepare **BNI-*d*$_6$** selectively, it is important to remove COD before the formation of Ni(IPr)$_2$. However, an attempt to isolate **BNI-*d*$_6$** via the evaporation of COD failed to give an inseparable mixture of Ni(cod)$_2$, IPr, **BNI-d$_6$**, and Ni(IPr)$_2$.



	conversion of IPr	yield of BNI-d_6	yield of Ni(IPr)$_2$
5 min	56%	56%	<1%
31 h	90%	72%	9%
evaporation	53%	34%	19%

Scheme 3.3. Generation of **BNI-*d*$_6$**.

Next, I tried the hydrogenation of COD to cyclooctane (COA), a compound that would no longer have the ability to coordinate to Ni(0).[14] The treatment of a toluene solution of Ni(cod)$_2$ and IPr with H_2 (8 atm) at room temperature resulted in the formation of (η^6-toluene)Ni(IPr) (**TNI**) as a single product via the hydrogenation of COD to COA. The reaction mixture was filtered through a Celite followed by concentration in vacuo to give **TNI** as a reddish brown solid in 97% isolated yield with >99% purity. This simple operation can afford **TNI** on a 2.00 mmol scale (>1.00 g). (η^6-Toluene)Ni(SIPr) (**TNSI**), (η^6-toluene)Ni(IPr*) (**TNI***), and their benzene-coordinated complexes (**BNI**, **BNSI**, and **BNI***) were also prepared (Scheme 3.4a). Gram-scale preparation of **TNI** and **TNSI** would be particularly noteworthy, since IPr and SIPr are one of the most frequently employed NHCs to date, and they are commercially available.[5,7] Furthermore, an in situ preparation of **TNI** was successfully achieved by the reaction of Ni(cod)$_2$ (0.080 mmol), IPr·HCl (1.1 equiv), ^{t}BuOK (1.0 equiv), and H_2 (1 atm) in toluene for 30 min, which was confirmed by ^{1}H NMR in benzene-d_6 via transformation into **BNI-*d*$_6$** (Scheme 3.4b). In



Scheme 3.4. Single-step, one-pot, gram-scale, and selective synthesis of (η^6-arene)Ni(NHC) complexes via hydrogenation of COD: a) preparation on 2.00 mmol scale with isolated yields; b) *in situ* preparation. [a] 0.08 mmol scale. [b] Determined by ^{1}H NMR in C_6D_6 via transformation into **BNI-*d*$_6$**.

this case, the formation of cyclooctene (COE) was observed while **BNI-*d*$_6$** was formed as a single nickel complex in an arene medium. Thus, this method would be suitable for the generation of (η^6-arene)Ni(NHC) complexes in situ prior to the Ni(0)–NHC catalysis or organonickel complex synthesis. Under these reaction conditions, the reduction of COD to COA was completed within 30 h. The preparation of (η^6-arene)Ni(IMes) failed under the present hydrogenation conditions, and the formation of Ni(IMes)$_2$ was observed as a major product.

3.2.2. Identification of (η^6-Benzene)Ni(IPr*) Complex

The molecular structure of **BNI*** was unambiguously determined by X-ray crystallography, which clearly shows that the coordination mode of the benzene ring

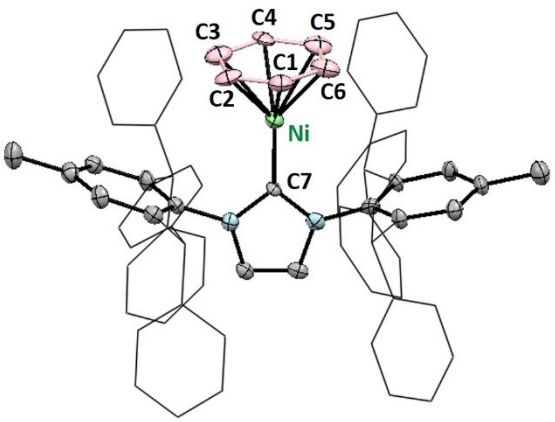


Figure 3.3. Molecular structure of **BNI*** (ellipsoids set at 30% probability). Hydrogen atoms are omitted for clarity. Selected bond distances [Å]: Ni–C_6H_6 (centroid of the ring) 1.588(4), Ni–C1 2.123(8), Ni–C2 2.128(8), Ni–C3 2.15(1), Ni–C4 2.117(8), Ni–C5 2.120(6), Ni–C6 2.132(9), Ni–C7 1.836(6).

is η^6 (Figure 3.3). The distance between Ni and the η^6-benzene ring is 1.588(4) Å, which is almost the same value as that observed in (η^6-benzene)Ni[bis(di-*tert*-butylphosphino)methane] (1.606(5) Å)[9c] and (η^6-toluene)Ni(R^H_2Si), (R^H_2 = 1,1,4,4-tetrakis(trimethylsilyl)butane-1,4-diyl substituent) (1.617(1) Å).[9a] The angle C7–Ni–(centroid of the coordinated benzene ring) is 177°, which also supports its η^6 coordination. To the best of our knowledge, this is the first crystallographic identification of a monomeric (η^6-arene)Ni(NHC) complex. This result supports the proposed structure of **TNI***, as reported by Hillhouse, Cundari, and co-workers.[11]

In the ^{1}H and ^{13}C NMR spectra measured in THF-d_8 at −60 °C, resonances of the coordinated benzene of **BNI*** were observed at δ_H 5.26 and δ_C 89.9, respectively. These chemical shifts were shifted upfield in comparison with those of non-coordinated benzene (δ_H 7.29 and δ_C 129.0). Moreover, they were comparable to those of the structurally well-defined (η^6-benzene)Ni[bis(di-*tert*-butylphosphino)methane] (δ_H 5.95 and δ_C 92.0 in THF-d_8 at −60 °C).[9c] A significant change was not observed in the ^{1}H NMR spectra measured in THF-d_8 from −60 to −5 °C (Figure 3.11). The coordination of the arene ring in all of the complexes presented in Scheme 3.4, with the exception of **BNI***, was validated by ^{1}H and ^{13}C NMR spectra in cyclohexane-d_{12} at 25 °C. For example, resonances of the arene moiety of the coordinated toluene in **TNI** were observed at δ_H 5.07 (1H) and 5.17–5.22 (4H) and δ_C 88.5, 89.9, 90.7, and 101.6 in the ^{1}H and ^{13}C NMR spectra, which were shifted upfield in comparison with those of non-coordinated toluene (δ_H 7.1–7.3 and δ_C 125.8, 128.7, 129.4, 137.9). These results are consistent with the results of the X-ray analysis.

3.2.3. Calculated Molecular Orbitals of (η^6-Benzene)Ni(IPr) Complex

In order to gain insight into the bonding situation in **BNI**, a DFT calculation was conducted (see Section 3.4.7 for detail). The highest occupied molecular orbital (HOMO) of BNI consists of two degenerate orbitals (–3.67 eV), which involve both contribution of the back-donation from the electron-rich nickel(0) center to IPr (Figure 3.4a, left) and the donation from IPr to the nickel(0) center (Figure 3.4a, right). The energy levels of HOMO–1, HOMO–2, and HOMO–3 are –3.80, –4.35, and –4.37 eV, respectively. Although HOMO–1 is antibonding, HOMO–2 and HOMO–3, both of which would be almost degenerate, show the back-donation from the nickel(0) to the π^* orbital of benzene (Figure 3.4b). The LUMO was calculated to consist mainly of *N*-2,6-diisopropylphenyl moieties on IPr (–0.05 eV; Figure 3.16).

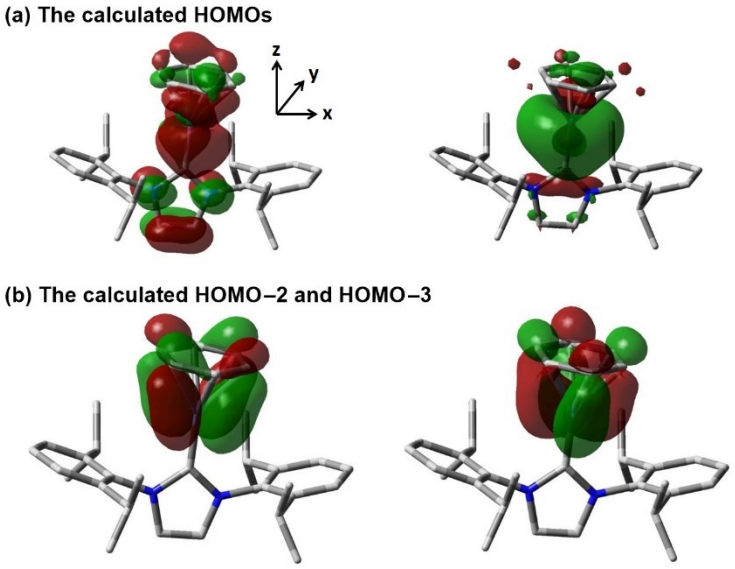
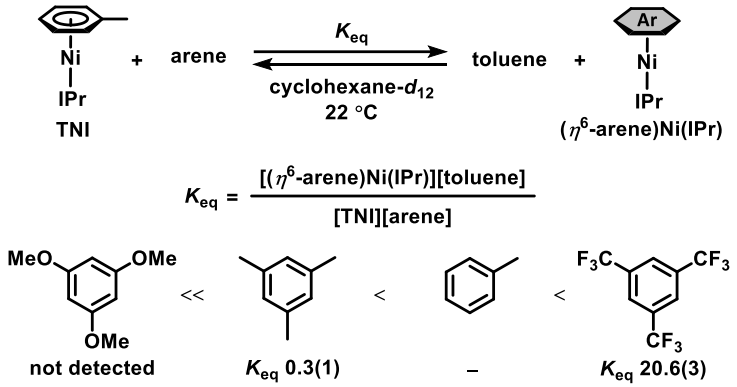


Figure 3.4. Selected calculated molecular orbitals of **BNI**: a) HOMOs; b) HOMO–2 (left) and HOMO–3 (right).

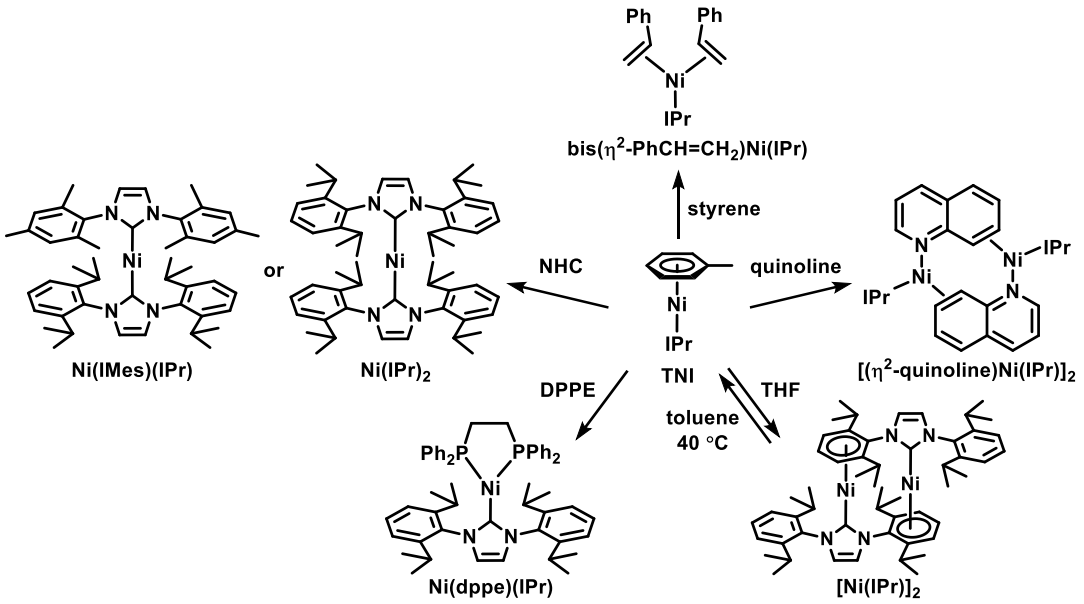
3.2.4. Ligand Exchange Reactions of (η^6-Toluene)Ni(IPr) Complex

The equilibrium constants of the exchange reaction between the coordinated toluene in **TNI** and arenes were determined by means of NMR in cyclohexane-d_{12}, showing that a more electron poor arene ring can strongly coordinate to the Ni(0)–IPr unit, since such an arene can efficiently accept back-donation from the electron-rich nickel(0) center (Scheme 3.5).[15]



Scheme 3.5. Equilibrium constant of arene exchange reaction.

An interconversion between mononuclear **TNI** and binuclear $[Ni(IPr)]_2$ was examined (Scheme 3.6). The conversion of **TNI** into $[Ni(IPr)]_2$ took place in THF at room temperature, and $[Ni(IPr)]_2$ was isolated in 77% yield after 48 h. In addition, $[Ni(IPr)]_2$ was reversibly converted into **TNI** quantitatively in toluene at 40 °C after 2 days.[16] The preparation of bis(η^2-$PhCH{=}CH_2$)Ni(IPr),[8k] Ni(dppe)(IPr),[8l] $Ni(IPr)_2$,[8n] [(η^2-quinoline)Ni(IPr)]$_2$, and Ni(IMes)(IPr) was also demonstrated via a ligand substitution



Scheme 3.6. Preparation of Ni(0)–IPr complexes from **TNI** via ligand exchange reactions. The reaction was carried out in *n*-pentane at room temperature, and quantitative formation of the products was observed within 30 min except for the interconversion between **TNI** and $[Ni(IPr)]_2$.

reaction with **TNI**. These reactions were completed within 30 min in *n*-pentane at room temperature to afford the products quantitatively and also took place in arene mediums such as benzene and toluene. The quantitative formation of $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ is especially noteworthy, because the selective preparation of $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ from $Ni(cod)_2$ is quite challenging. In fact, $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ was generated as an inseparable equilibrium mixture of $[(\eta^2\text{-quinoline})Ni(IPr)]_2$, $Ni(cod)_2$, IPr, quinoline, and COD in the reaction of quinoline, $Ni(cod)_2$, and IPr. The structure of $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ was unambiguously determined by NMR and X-ray analyses. As shown in Figure 3.5, $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ forms a dimeric structure with a 16-electron nickel center in which the nitrogen atom of the quinoline ligand coordinates to the Ni(0)–IPr fragment and one of the C=C bonds (C7–C8) coordinates to the other nickel. The C7–C8 bond distance is elongated to 1.445(5) Å in comparison with that of non-coordinated quinoline (1.36–1.38 Å).[17] In addition, both the ^1H and ^{13}C NMR spectra of $[(\eta^2\text{-quinoline})Ni(IPr)]_2$ clearly indicate the η^2 coordination of the C7–C8 double bond to the nickel(0) center, as shown by the upfield shift of those signals (δ_H 3.62 and 3.68, and δ_C 45.9 and 52.9, respectively). These results indicate that the elongation of the C7–C8 bond in quinoline is due to the back-donation from the Ni(0)–IPr unit. A variety of coordination modes of quinoline to transition metals have been reported to date;[18] however, the direct observation of the η^2 coordination of its benzene moiety is quite rare.[19] The heteroleptic bis-NHC nickel(0) complex Ni(IMes)(IPr) was also identified by X-ray analysis (Figure

3.6). To the best of our knowledge, this is the first example of a heteroleptic bis-NHC nickel(0) complex.[20]

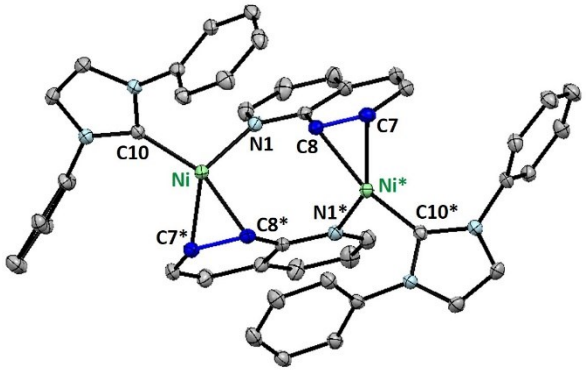


Figure 3.5. Molecular structure of [(η^2-quinoline)Ni(IPr)]$_2$ (ellipsoids set at 30% probability). Hydrogen atoms and ^{i}Pr groups are omitted for clarity. Selected bond distances [Å]: Ni–N1 1.973(3), Ni–C7* 1.981(3), Ni–C8* 2.009(3), Ni–C10 1.887(3), C7–C8 1.445(5).

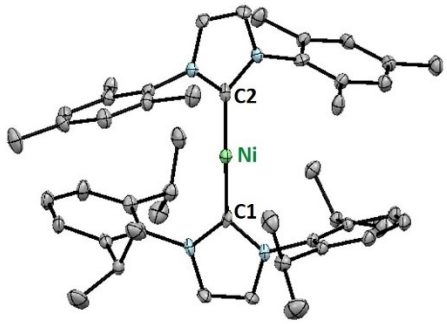
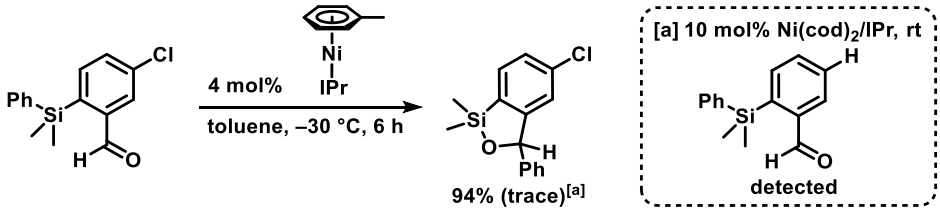


Figure 3.6. Molecular structure of Ni(IMes)(IPr) (ellipsoids set at 30% probability). Hydrogen atoms are omitted for clarity. Selected bond distances [Å]: Ni–C1 1.815(8), Ni–C2 1.830(9). Selected bond angle [°]: C1-Ni-C2 179.6(3).

3.2.5. Catalytic Application of TNI

Recently, our group reported the nickel(0)-catalyzed synthesis of 3-aryl-2,1-benzoxasiloles from benzaldehydes with arylsilyl moiety at the *ortho* position, which proceed via an activation of organosilanes with (η^2-aldehyde)Ni(IPr) complex.[21] The reaction of chlorine-substituted *o*-dimethylphenylsilylbenzaldehyde did not take place in the presence of 10 mol % Ni(cod)$_2$ and IPr at room temperature or 100 °C due to the deactivation of the catalyst by oxidative addition of the Ar–Cl bond to the nickel(0) center (Scheme 3.7). Although lowering the reaction temperature might have been effective in preventing this deactivation pathway, this would have caused a significant decrease in the solubility of Ni(cod)$_2$ toward toluene. Thus, **TNI** was employed as a Ni(0)–IPr source since **TNI** dissolves easily into toluene even at −78 °C. With 4 mol % **TNI**, the target chlorine-substituted benzoxasilole was obtained in 99% yield at –30 °C. This result suggests the utility of (η^6-arene)Ni(NHC) complexes as a precursors of a Ni(0)–NHC unit.[22]



Scheme 3.7. Catalytic application of **TNI** for synthesis of benzoxasiloles.

3.3. Conclusion

A practical method for the synthesis of (η^6-arene)Ni(NHC) complexes was developed. (η^6-Arene)Ni(NHC) complexes having IPr, SIPr, and IPr* can be prepared on a gram scale from commercially available $Ni(cod)_2$ via simple, single-step, and one-pot procedures. The key feature of the present method is the hydrogenation of COD. The products were fully characterized by NMR, which would support the coordination of arene to a Ni(0)–NHC unit. Moreover, the first crystallographic structure of a monomeric (η^6-arene)Ni(NHC) complex is reported, providing solid evidence for the η^6 coordination of the arene. A study of the equilibrium between the coordinated toluene in **TNI** and the arenes in a ligand exchange reaction showed that a (η^6-arene)Ni(IPr) with a more electron-poor arene would be thermodynamically favored. The preparation of some Ni(0)–IPr complexes was demonstrated via a ligand substitution reaction from **TNI**. In particular, the selective preparation of $[(\eta^2$-quinoline)Ni(IPr)$]_2$, in which the C7–C8 double bond coordinates to the nickel(0) center, and Ni(IMes)(IPr), a nickel(0) complex having two different NHCs, was achieved for the first time. (η^6-Arene)Ni(NHC) complexes could be very useful precursors of a Ni(0)–NHC unit in the field of organic and organometallic chemistry. Thus, I hope the present work and the methodology will lead to further developments in these fields of chemistry.

3.4. Experimental Section

3.4.1. General

All manipulations were conducted under a nitrogen atmosphere using standard Schlenk or dry box techniques. The ^1H, ^{13}C, ^{31}P and ^{19}F nuclear magnetic resonance spectra were recorded on JEOL AL-400, Bruker DPX 400, and Bruker AVANCE III spectrometers at 25 °C unless otherwise stated. The chemical shifts in ^1H nuclear magnetic resonance spectra were recorded relative to Me_4Si or residual protonated solvent (C_6D_5H (δ 7.16), C_7D_7H (δ 2.09), THF-d_7 (δ 1.72) or $C_6D_{11}H$ (δ 1.38)). The chemical shifts in the ^{13}C spectra were recorded relative to Me_4Si or deuterated solvent (C_6D_6 (δ 128.06), C_7D_8 (δ 137.48), THF-d_8 (δ 67.21) or C_6D_{12} (δ 26.43)). The chemical shifts in the ^{31}P NMR spectra were recorded using 85% H_3PO_4 as external standard. The chemical shifts in the ^{19}F NMR spectra were recorded relative to α,α,α-trifluorotoluene (δ −65.64). Assignment of the resonances in ^1H and ^{13}C NMR spectra was based on ^1H-^1H COSY, HMQC and HMBC experiments. Elementary analyses were performed at Instrumental Analysis Center, Faculty of Engineering, Osaka University. X-ray crystal data were collected by a Rigaku RAXIS-RAPID Imaging Plate diffractometer.

3.4.2. Materials

Benzene, toluene, hexane, pentane, cyclohexane, benzene-d_6, toluene-d_8, THF-d_8, and cyclohexane-d_{12} were distilled from sodium benzophenone ketyl prior to use. All commercially available reagents were distilled over CaH_2 under reduced pressure prior to use. NHCs shown in Figure 3.7 were furnished by the known procedures.[23]

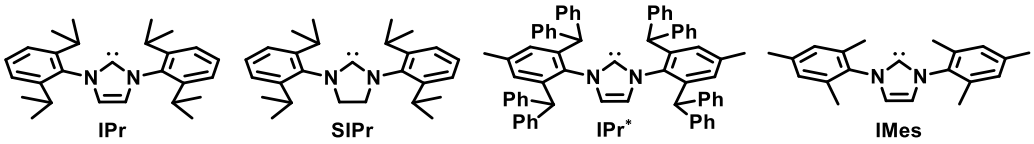
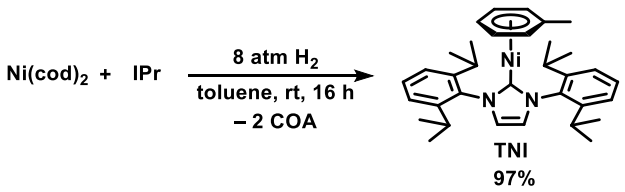


Figure 3.7. NHCs employed in this chapter.

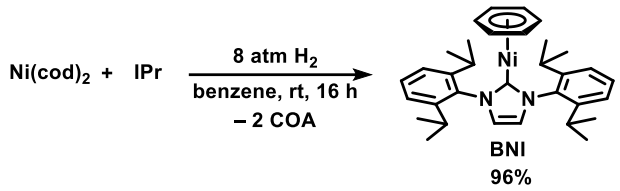
3.4.3. Synthesis of (η⁶-Arene)Ni(NHC) Complexes

Note: Employing well-dried and -degased solvents should be essential to generate (η⁶-arene)Ni(NHC) complexes quantitatively. Commercially available dehydrated solvents may cause a decrement of purity of the products.

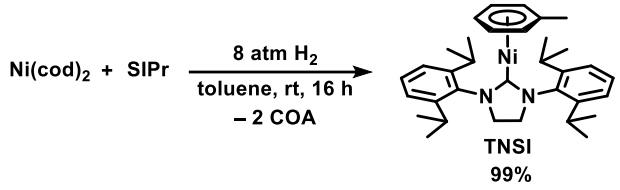
General procedures: A reaction tube was charged with $Ni(cod)_2$ (2.0 mmol), NHC (2.0 mmol), and solvent (20 mL). The resulting solution was transferred into an autoclave reactor, and then H_2 was pressurized quickly (within 5 min recommended) into the reactor at 5–8 atm. After the reaction mixture was stirred at room temperature for overnight (~16 h), the resultant brown solution was quickly filtered, and all volatiles were removed under the reduced pressure to give (η⁶-arene)Ni(NHC) as a reddish-brown solid.



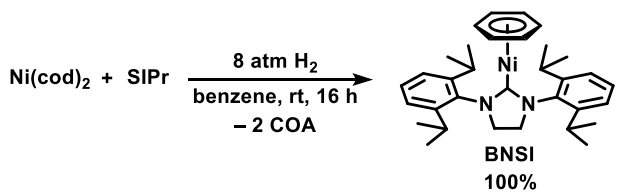
Synthesis of (η⁶-toluene)Ni(IPr) (TNI): The general procedure was followed with $Ni(cod)_2$ (549 mg, 2.00 mmol), IPr (778 mg, 2.00 mmol), and toluene (20 mL), and reaction was conducted at room temperature for 16 h to give **TNI** (1.05 g, 1.94 mmol, 97%) as a reddish-brown solid. **^{1}H NMR** (400 MHz, C_6D_{12}): δ 7.27 (t, J = 7.4 Hz, 2H, Ar-*H*), 7.16 (d, J = 7.4 Hz, 4H, Ar-*H*), 6.58 (s, 2H, NC_2H_2N), 5.22–5.17 (m, 4H, η⁶-$C_6H_5CH_3$), 5.07 (t, J = 5.4 Hz, 1H, η⁶-$C_6H_5CH_3$), 2.88–2.81 (m, 4H, $CH(CH_3)_2$), 1.53 (s, 3H, η⁶-$C_6H_5CH_3$), 1.31 (d, J = 6.8 Hz, 12Hz, $CH(CH_3)_2$), 1.07 (d, J = 6.8 Hz, 12H, $CH(CH_3)_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_{12}): δ 196.2, 147.0, 139.8, 128.6, 123.6, 119.6, 101.6 (η⁶-$C_6H_5CH_3$), 90.7 (η⁶-$C_6H_5CH_3$), 89.9 (η⁶-$C_6H_5CH_3$), 88.5 (η⁶-$C_6H_5CH_3$), 29.1, 24.7, 23.7, 21.4 (η⁶-$C_6H_5CH_3$). **Anal. Calcd for $C_{34}H_{44}N_2Ni$**: C, 75.70; H, 8.22; N, 5.19. Found: C, 75.27; H, 8.53; N, 5.51.



Synthesis of (η^6-benzene)Ni(IPr) (BNI): The general procedure was followed with $Ni(cod)_2$ (551 mg, 2.00 mmol), IPr (779 mg, 2.00 mmol), and benzene (20 mL), and reaction was conducted at room temperature for 16 h to give **BNI** (1.01 g, 1.92 mmol, 96%) as a reddish-brown solid. **^{1}H NMR** (400 MHz, C_6D_{12}, Figure 3.8a): δ 7.29 (t, *J* = 7.6 Hz, 2H, Ar-*H*), 7.16 (d, *J* = 7.6 Hz, 4H, Ar-*H*), 6.59 (s, 2H, NC_2H_2N), 5.22 (s, 6H, η^6-C_6H_5), 2.84–2.77 (m, 4H, C*H*$(CH_3)_2$), 1.30 (d, *J* = 6.8 Hz, 12Hz, CH(C*H*$_3)_2$), 1.07 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_{12}, Figure 3.8b): δ 195.9, 147.1, 139.6, 128.8, 123.6, 119.6, 89.1 (η^6-*C*$_6H_6$), 29.2, 24.7, 23.7. **Anal. Calcd for $C_{33}H_{42}N_2Ni$**: C, 75.44; H, 8.06; N, 5.33. Found: C, 75.25; H, 8.17; N, 5.90. The ^{1}H NMR spectrum of **BNI-*d*$_6$** (400 MHz, C_6D_6) is also shown in Figures 3.9. The synthesis of **BNI** was also possible by the reaction of **TNI** with benzene (excess) quantitatively.

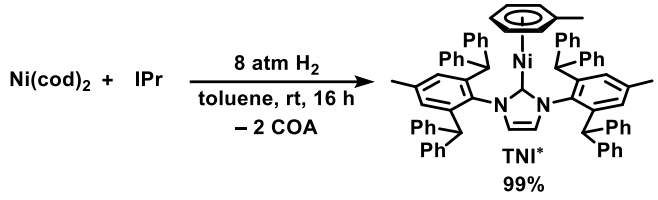


Synthesis of (η^6-toluene)Ni(SIPr) (TNSI): The general procedure was followed with $Ni(cod)_2$ (550 mg, 2.00 mmol), IPr (780 mg, 2.00 mmol), and toluene (20 mL), and reaction was conducted at room temperature for 16 h to give **TNSI** (1.07 g, 1.98 mmol, 99%) as a reddish-brown solid. **^{1}H NMR** (400 MHz, C_6D_{12}): δ 7.20 (t, *J* = 7.2 Hz, 2H, Ar-*H*), 7.11 (d, *J* = 7.2 Hz, 4H, Ar-*H*), 5.18–5.12 (m, 4H, η^6-$C_6H_5CH_3$), 5.05 (t, *J* = 5.4 Hz, 1H, η^6-$C_6H_5CH_3$), 3.64 (s, 4H, NC_2H_4N), 3.13–3.08 (m, 4H, C*H*$(CH_3)_2$), 1.49 (s, 3H, η^6-$C_6H_5CH_3$), 1.18 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$). The resonances of ^{i}Pr-*H*s (12H) are obscured by $C_6D_{11}H$ (δ 1.38). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_{12}): δ 214.2, 148.2, 140.6, 127.9, 124.0, 103.4 (η^6-*C*$_6H_5CH_3$), 91.7 (η^6-*C*$_6H_5CH_3$), 91.2 (η^6-*C*$_6H_5CH_3$), 89.5 (η^6-*C*$_6H_5CH_3$), 52.5, 29.3, 25.3, 24.4, 21.2 (η^6-C_6H_5*C*H_3). **Anal. Calcd for $C_{34}H_{46}N_2Ni$**: C, 75.42; H, 8.56; N, 5.17. Found: C, 74.95; H, 8.73; N, 5.65.

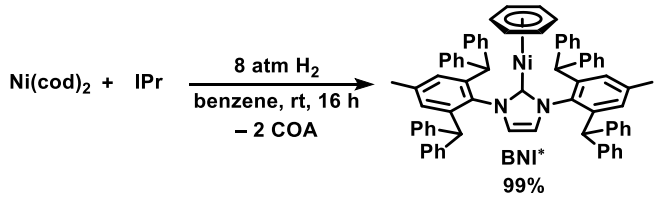


Synthesis of (η^6-benzene)Ni(SIPr) (BNSI): The general procedure was followed with

$Ni(cod)_2$ (550 mg, 2.00 mmol), SIPr (781 mg, 2.00 mmol), and benzene (20 mL), and reaction was conducted at room temperature for 16 h to give **BNSI** (1.06 g, 2.00 mmol, 100%) as a reddish-brown solid. **^{1}H NMR** (400 MHz, C_6D_{12}): δ 7.21 (t, J = 7.6 Hz, 2H, Ar-*H*), 7.11 (d, J = 7.6 Hz, 4H, Ar-*H*), 5.19 (s, 6H, η^6-C_6H_6), 3.64 (s, 4H, NC_2H_4N), 3.12–3.05 (m, 4H, $CH(CH_3)_2$), 1.37 (d, J = 6.8 Hz, 12H, $CH(CH_3)_2$, partially overlapped with $C_6D_{11}H$), 1.18 (d, J = 6.8 Hz, 12H, $CH(CH_3)_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_{12}): δ 214.2, 148.2, 140.4, 128.0, 123.9, 90.2 (η^6-C_6H_6), 52.5, 29.3, 25.3, 24.4. **Anal. Calcd for $C_{33}H_{44}N_2Ni$**: C, 75.15; H, 8.41; N, 5.31. Found: C, 74.61; H, 8.61; N, 5.69.



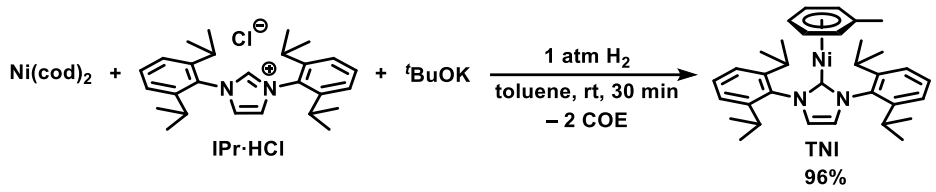
Synthesis of (η^6-toluene)Ni(IPr*) (TNI*): A reaction tube was charged with $Ni(cod)_2$ (22.2 mg, 0.08 mmol), IPr* (73.2 mg, 0.08 mmol), and toluene (15 mL). The resulting solution was transferred into an autoclave reactor, and then H_2 was pressurized at 8 atm. After the reaction mixture was stirred at room temperature for 12 h, the resultant brown solution was quickly filtered, and all volatiles were removed under the reduced pressure to give **TNI*** (82.8 mg, 0.079 mmol, 99%) as a reddish-brown solid. Identification of **TNI*** was conducted by ^{1}H NMR in C_6D_6 as **BNI*-*d*$_6$**, which is identical to that previously reported.[11]



Synthesis of (η^6-benzene)Ni(IPr*) (BNI*): A reaction tube was charged with $Ni(cod)_2$ (10.8 mg, 0.04 mmol), IPr* (36.2 mg, 0.04 mmol), and benzene (0.5 mL). The resulting solution was transferred into an autoclave reactor, and then H_2 was pressurized at 5 atm. After the reaction mixture was stirred at room temperature for 3 h, the resultant brown solution was quickly filtered, and all volatiles were removed under the reduced pressure to give **BNI*** (40.3 mg, 0.038 mmol, 99%) as a reddish-brown solid. A single crystal suitable for X-ray diffraction analysis was prepared by recrystallization from benzene/hexane at –35 °C. The crystal structure of **BNI*** can be obtained from Cambridge Crystallography Data Centre (CCDC 957443). **^{1}H NMR** (400 MHz, THF-d_8, –60 °C, Figure 3.10): δ 7.41–7.35 (m, 16H, Ar-*H*), 7.26 (t, J = 6.2 Hz, 4H, Ar-*H*), 7.08–7.01 (m, 16H, Ar-*H*), 6.82 (d, J = 7.2 Hz, 8H, Ar-*H*), 5.40 (s, 4H, $CHPh_2$), 5.26 (s, 6H, η^6-C_6H_6), 4.96 (s, 2H, NC_2H_2N), 2.29 (s, 6H, CH_3). **^{13}C{^{1}H} NMR** (100 MHz, THF-d_8, –60 °C): δ

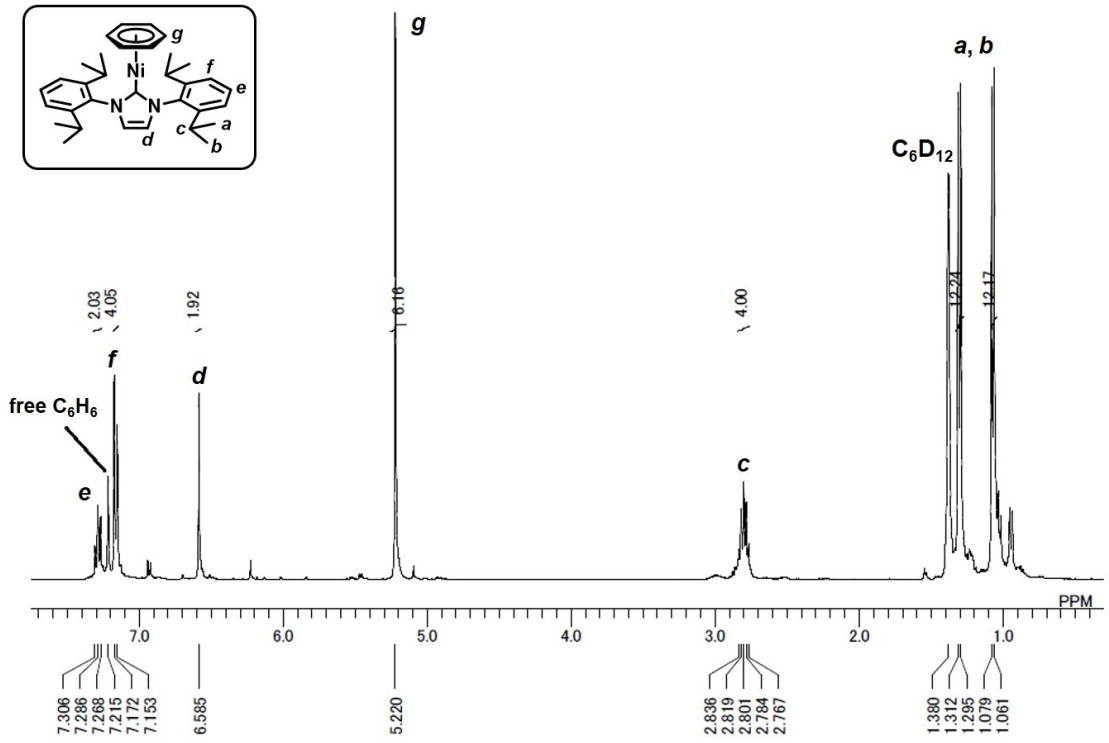
194.2, 145.6, 144.8, 142.5, 138.7, 138.1, 131.2, 130.1, 129.7, 128.9, 128.8, 127.1, 126.8, 120.1, 89.9 (η^6-C_6H_6), 52.2, 21.8. **Anal. Calcd for $C_{75}H_{62}N_2Ni$**: C, 85.79; H, 5.95; N, 2.67. Found: C, 85.42; H, 6.03; N, 3.05.

*Note: **BNI*** was found to be rather unstable in THF. Thus, signals of an unidentified chemical species were observed in NMR spectra due to decomposition (Figures 3.10 and 3.11)*



Synthesis of TNI via *in situ* generation of IPr from IPr·HCl: A reaction tube was charged with IPr · HCl (37.4 mg, 0.088 mmol), ^{t}BuOK (9.0 mg, 0.080 mmool), and toluene (10 mL), and then the reaction mixture was stirred at room temperature for 10 min. Then, $Ni(cod)_2$ (22.0 mg, 0.080 mmol) was added to the reaction mixture. The resulting solution was transferred into an autoclave reactor, and the reaction mixture was stirred at room temperature for 30 min under H_2 atmosphere (1 atm). The resultant brown solution was quickly filtered, and all volatiles were removed under the reduced pressure. At this moment, the quantitative formation of **BNI-*d*$_6$** and the concomitant formation of cyclooctene were confirmed by ^{1}H NMR in C_6D_6. Several dozen times of azeotropic removal of COE with toluene gave **TNI** (41.8 mg, 0.077 mmol, 96%) as a reddish-brown solid.

(a) ^{1}H NMR



(b) ^{13}C NMR

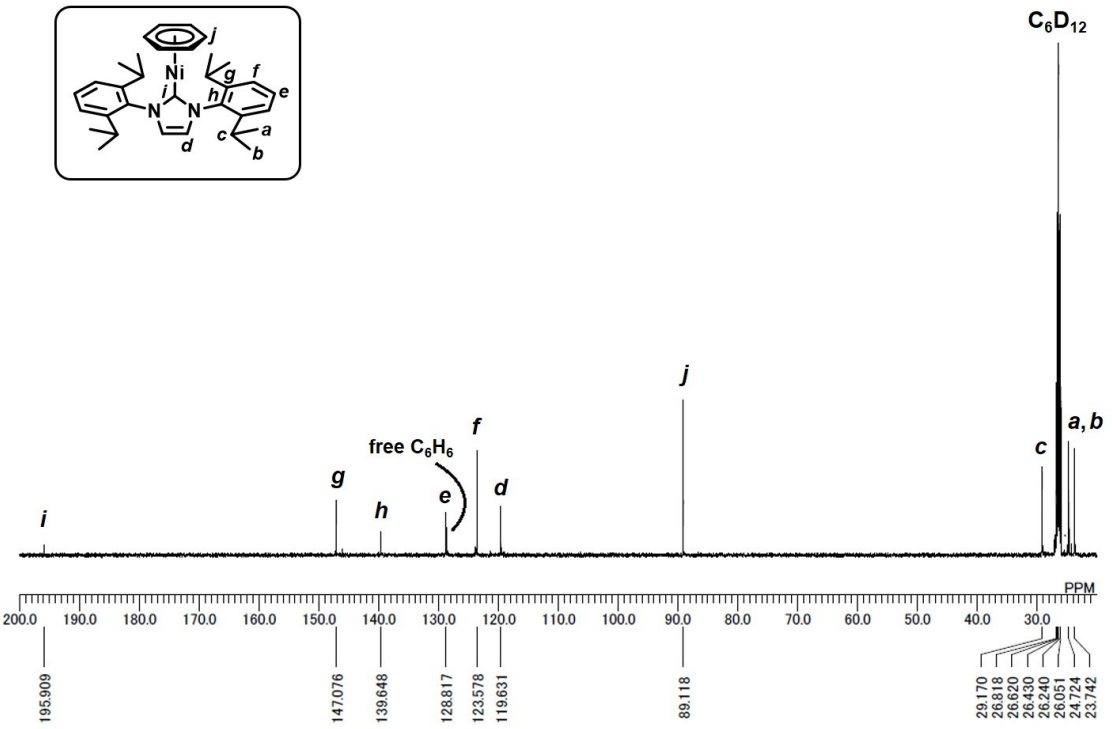


Figure 3.7. a) ^{1}H NMR (pulse delay = 50 s) and b) ^{13}C NMR spectra of **BNI** in C_6D_{12}.

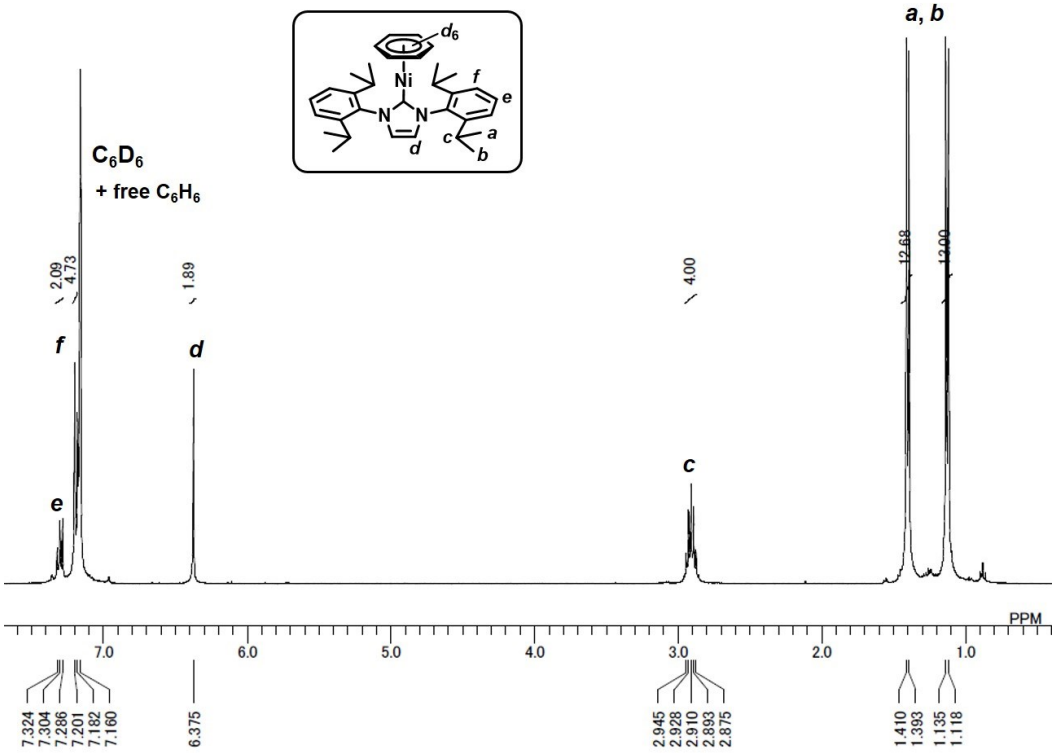


Figure 3.8. ^{1}H NMR spectrum of **BNI-*d*$_6$** in C_6D_6.

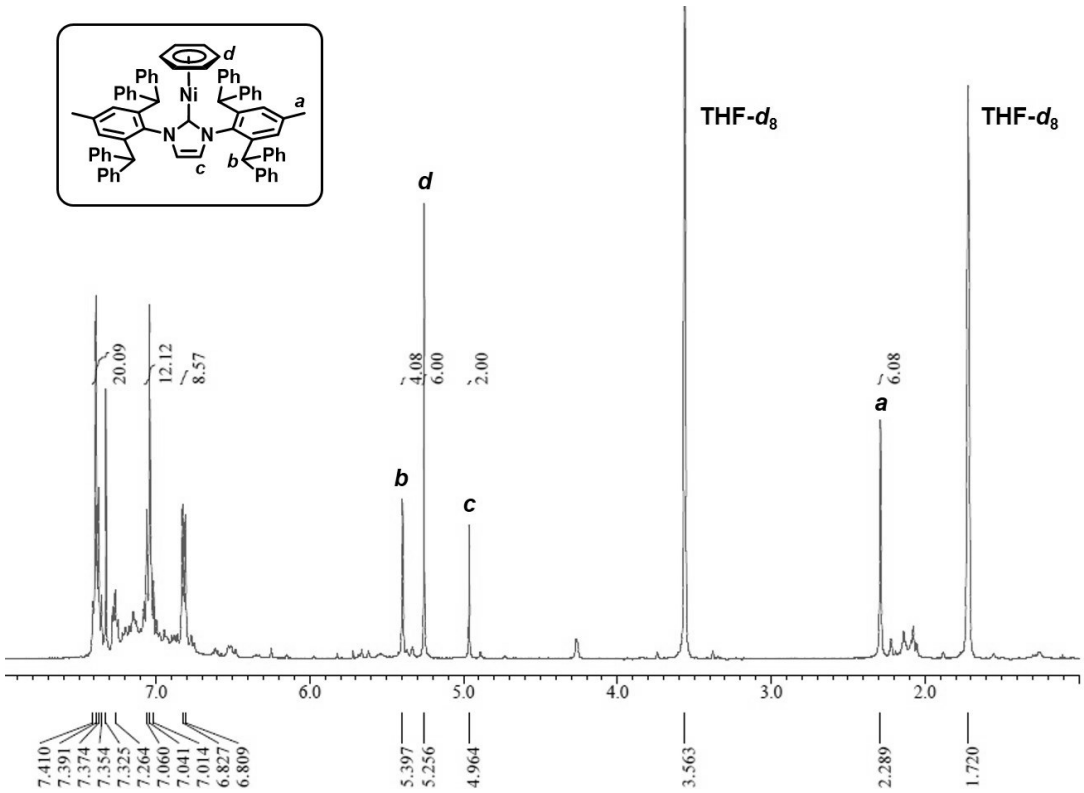


Figure 3.9. ^{1}H NMR spectrum of **BNI*** in THF-d_8 at −60 °C.

3.4.4. The Variable Temperature Measurement of BNI*

Variable temperature NMR experiment was conducted from −60 °C to 15 °C by using **BNI*** in THF-d_8, and the result is shown in Figure 3.11. Resonance of the coordinated benzene was observed at δ_H 5.26 at −60 °C. The signal was slightly shifted downfield (from δ_H 5.26 at −60 °C to 5.33 at −5 °C) and broadening along with an elevation of temperature to −5 °C. At 15 °C, the resonances of **BNI*** were observed as broad signals. This might be due to instability of **BNI*** in non-arene medium at 15 °C, and therefore, decomposition would occur under these conditions. However I cannot rule out the possibility of a change of the coordination mode of benzene at 15 °C.

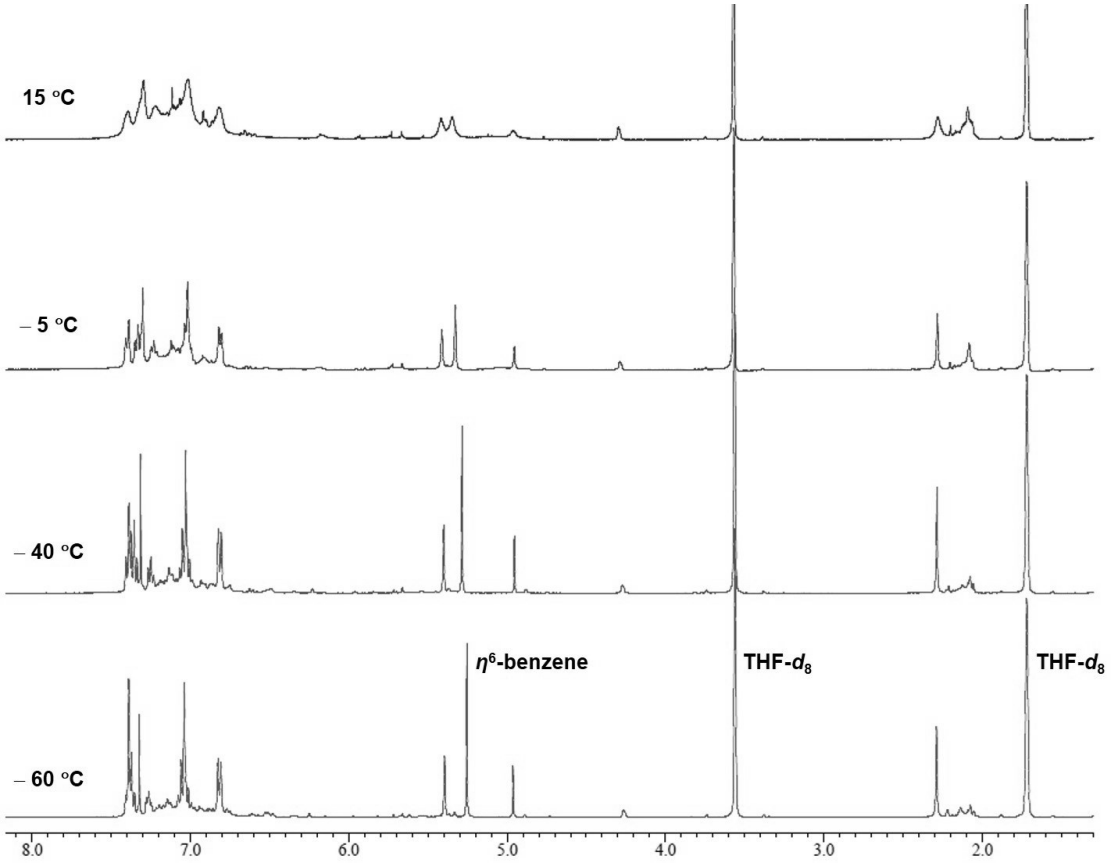
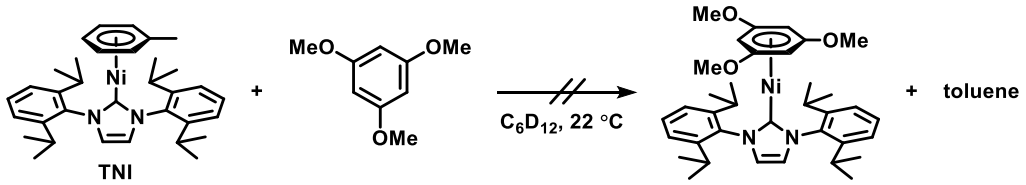


Figure 3.11. VT NMR spectra for **BNI*** in THF-d_8 from −60 °C to 15 °C.

3.4.5. Determination of Equilibrium Constants of Arene Exchange Reaction (Scheme 3.5)

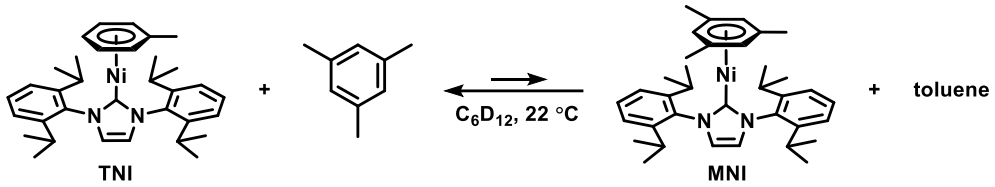
Reaction with 1,3,5-tris(trimethoxybenzene)



1 equiv of 1,3,5-Tris(trimethoxybenzene): To a solution of **TNI** (21.3 mg, 0.04 mmol) in C_6D_{12} (0.5 mL) was added 1,3,5-tris(trimethoxy)benzene (7.1 mg, 0.04 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR. No formation of [η^6-(1,3,5-tris(trimethoxy)benzene)]Ni(IPr) was observed.

10 equiv of 3,5-Tris(trimethoxybenzene): To a solution of **TNI** (22.0 mg, 0.04 mmol) in C_6D_{12} (0.5 mL) was added 1,3,5-tris(trimethoxy)benzene (67.4 mg, 0.40 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR. No formation of [η^6-(1,3,5-tris(trimethoxy)benzene)]Ni(IPr) was observed.+-

Reaction with mesitylene



1 equiv of Mesitylene: To a solution of **TNI** (20.0 mg, 0.04 mml) in C_6D_{12} (0.5 mL) was added mesitylene (4.5 mg, 0.04 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.12a. From the profile of the $K_{\mathbf{MNI}}$, where $K_{\mathbf{MNI}} = [\mathbf{MNI}][\text{toluene}]/[\mathbf{TNI}][\text{mesitylene}]$, with respect to reaction time, an equilibrium constant (K_{eq}) was estimated as 0.252(1).

3 equiv of Mesitylene: To a solution of **TNI** (21.1 mg, 0.04 mml) in C_6D_{12} (0.5 mL) was added mesitylene (14.2 mg, 0.12 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.12b. From the profile of the $K_{\mathbf{MNI}}$, where $K_{\mathbf{MNI}} = [\mathbf{MNI}][\text{toluene}]/[\mathbf{TNI}][\text{mesitylene}]$, with respect to reaction time, K_{eq} was estimated as 0.2573(8).

5 equiv of Mesitylene: To a solution of **TNI** (21.4 mg, 0.04 mml) in C_6D_{12} (0.5 mL) was added mesitylene (23.8 mg, 0.20 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.12c. From the profile of the $K_{\mathbf{MNI}}$, where $K_{\mathbf{MNI}} = [\mathbf{MNI}][\text{toluene}]/[\mathbf{TNI}][\text{mesitylene}]$, with respect to reaction time, K_{eq} was estimated as 0.2594(8).

Based on the average value of these results, K_{eq} in the ligand exchange reaction of **TNI** and mesitylene was estimated as 0.26(1).

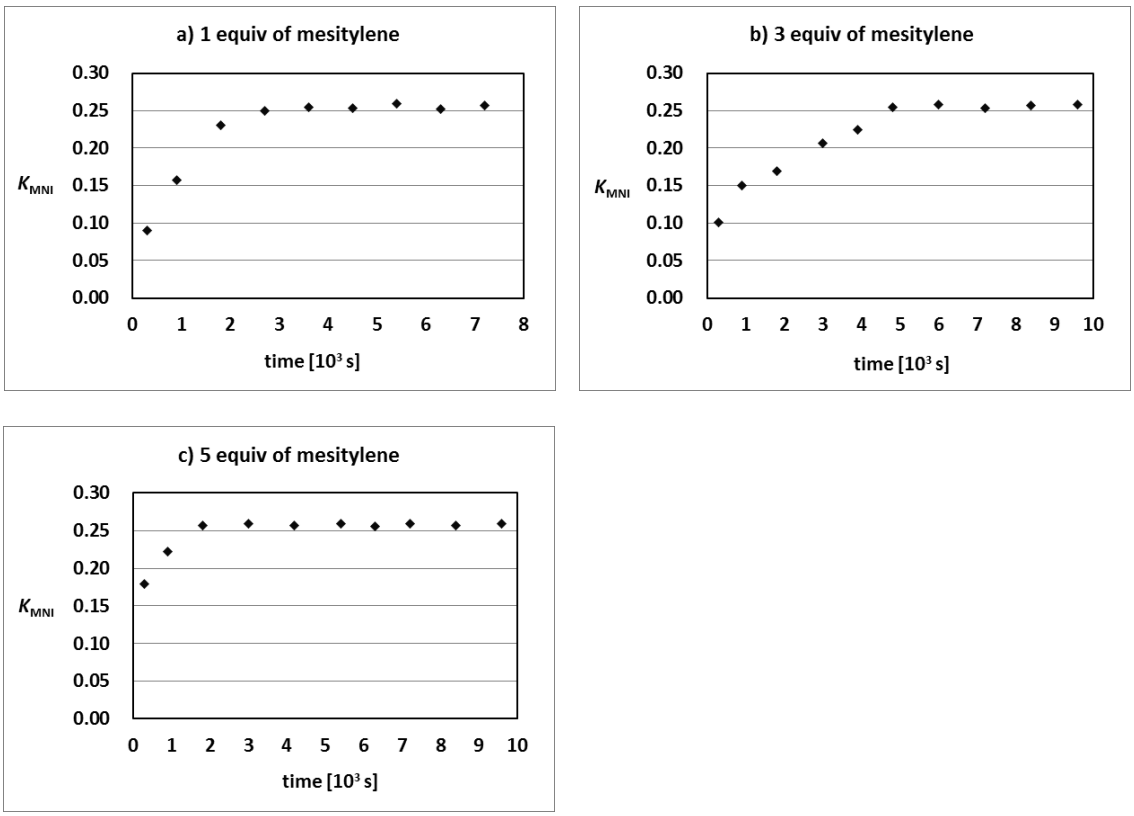
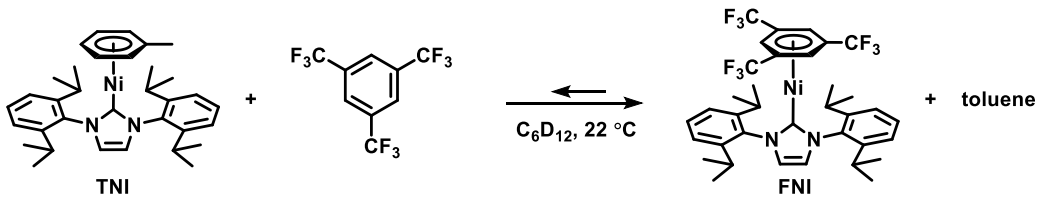


Figure 3.12. The profiles of K_{MNI} with respect to reaction time.

Isolation of (η^6-mesitylene)Ni(IPr) (MNI): To a solution or **TNI** (22.2 mg, 0.04 mmol) in pentane (0.5 mL) was added mesitylene (110 μL, 0.80 mmol, 20 equiv) at room temperature. After the reaction mixture was stirred for several minutes, all volatiles were removed under the reduced pressure to give **MNI** as a reddish brown solid (24.5 mg, 0.04 mmol, 100%). ^{1}H NMR (400 MHz, C_6D_{12}): δ 7.26–7.24 (m, 2H, Ar-*H*), 7.16 (d, J = 7.2 Hz, 4H, Ar-*H*), 6.54 (s, 2H, NC_2H_2N), 5.08 (s, 3H, η^6-$C_6H_3(CH_3)_3$), 2.98–2.95 (m, 4H, $CH(CH_3)_2$), 1.58 (s, 9H, η^6-$C_6H_3(CH_3)_3$), 1.33 (d, J = 6.4 Hz, 12H, $CH(CH_3)_2$, partially overlapped with $C_6D_{11}H$), 1.06 (d, J = 6.4 Hz, 12H, $CH(CH_3)_2$). $^{13}C\{^1H\}$ NMR (100 MHz, C_6D_{12}): δ 196.0, 147.0, 140.2, 128.5, 123.7, 119.9, 100.0 (η^6-$C_6H_3(CH_3)_3$), 93.5 (η^6-$C_6H_3(CH_3)_3$), 29.0, 24.7, 23.9, 21.4 (η^6-$C_6H_3(CH_3)_3$).

Reaction with 1,3,5-tris(trifluoromethyl)benzene



1 equiv of 1,3,5-tris(trifluoromethyl)benzene: To a solution of **TNI** (22.6 mg, 0.04 mmol) in C_6D_{12} (0.5 mL) was added 1,3,5-tris(trifluoromethyl)benzene (11.8 mg, 0.04 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.13a. From the profile of the $K_{\mathbf{FNI}}$, where $K_{\mathbf{FNI}} = [\mathbf{FNI}][\text{toluene}]/[\mathbf{TNI}][1,3,5\text{-tris(trifluoromethyl)benene}]$, with respect to reaction time, K_{eq} was estimated as 21.71(9).

3 equiv of 1,3,5-tris(trifluoromethyl)benzene: To a solution of **TNI** (21.5 mg, 0.04 mmol) in C_6D_{12} (0.5 mL) was added 1,3,5-tris(trifluoromethyl)benzene (33.5 mg, 0.12 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.13b. From the profile of the $K_{\mathbf{FNI}}$, where $K_{\mathbf{FNI}} = [\mathbf{FNI}][\text{toluene}]/[\mathbf{TNI}][1,3,5\text{-tris(trifluoromethyl)benene}]$, with respect to reaction time, K_{eq} was estimated as 21.4(1).

5 equiv of 1,3,5-tris(trifluoromethyl)benzene: To a solution of **TNI** (21.3 mg, 0.04 mmol) in C_6D_{12} (0.5 mL) was added 1,3,5-tris(trifluoromethyl)benzene (56.0 mg, 0.20 mmol) at 22 °C. The reaction was monitored by means of ^{1}H NMR, and the result is summarized in Figure 3.13c. From the profile of the $K_{\mathbf{FNI}}$, where $K_{\mathbf{FNI}} = [\mathbf{FNI}][\text{toluene}]/[\mathbf{TNI}][1,3,5\text{-tris(trifluoromethyl)benene}]$, with respect to reaction time, K_{eq} was estimated as 18.53(7).

Based on the average value of these results, K_{eq} in the ligand exchange reaction of **TNI** and 1,3,5-tris(trifluoromethyl)benzene was estimated as 20.6(3).

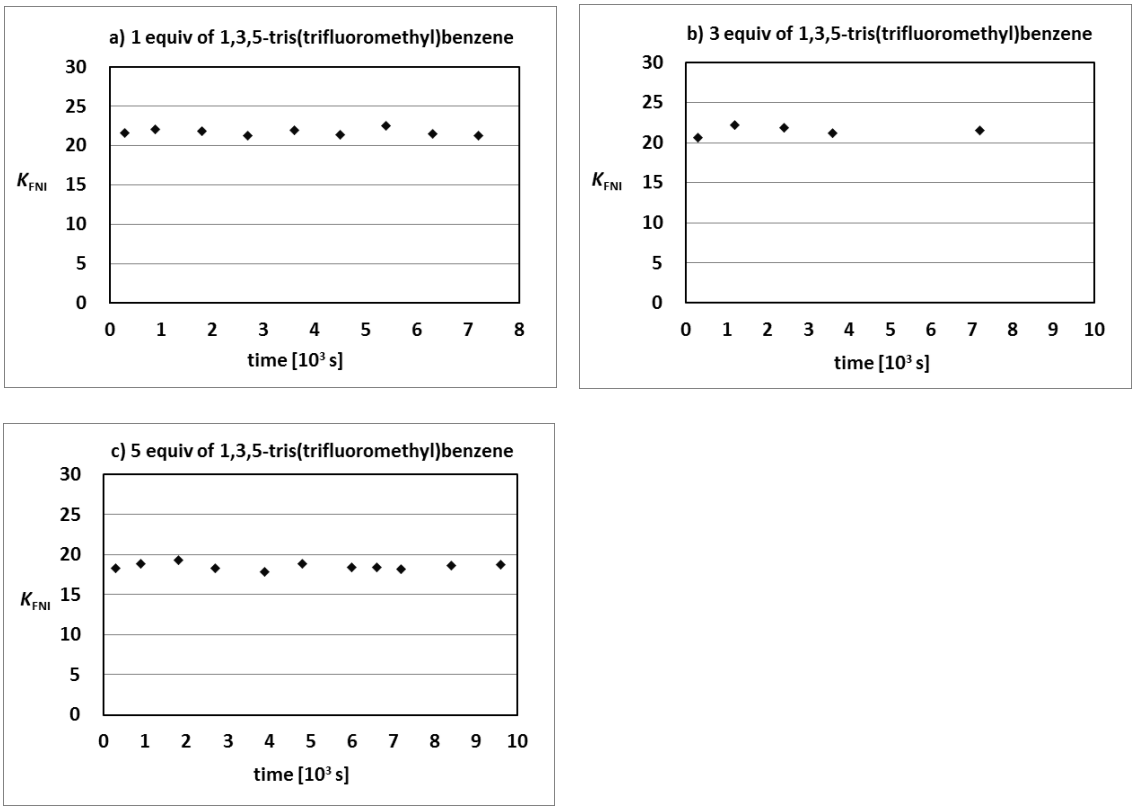
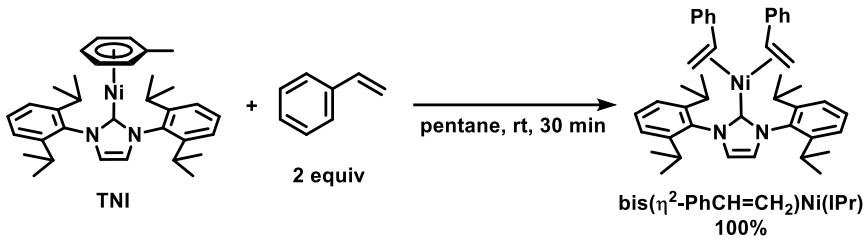


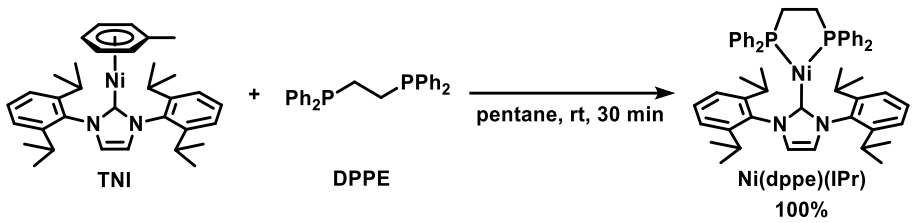
Figure 3.13. The profiles of K_{FNI} with respect to reaction time.

Isolation of [η^6-(1,3,5-tris(trifluoromethyl)benzene)]Ni(IPr) (FNI): To a solution or **TNI** (22.5 mg, 0.04 mmol) in pentane (0.5 mL) was added 1,3,5-tris(trifluoromethyl) benzene (75 μL, 0.40 mmol, 10 equiv) at room temperature. After the reaction mixture was stirred for several minutes, all volatiles were removed under the reduced pressure to give **FNI** as a purple solid (25.1 mg, 0.03 mmol, 83%). **^{1}H NMR** (400 MHz, C_6D_{12}): δ 7.36 (t, J = 7.8 Hz, 2H, Ar-*H*), 7.22 (d, J = 7.8 Hz, 4H, Ar-*H*), 6.65 (s, 2H, NC_2H_2N), 5.89 (s, 3H, η^6-$C_6H_3(CF_3)_3$), 2.65–2.61 (m, 4H, $CH(CH_3)_2$), 1.34 (d, J = 6.4 Hz, 12H, $CH(CH_3)_2$, partially overlapped with $C_6D_{11}H$), 1.04 (d, J = 6.4 Hz, 12H, $CH(CH_3)_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_{12}): δ 188.9, 146.1, 137.5, 130.2, 125.2 (q, J_{CF} = 271 Hz, η^6-$C_6H_3(CF_3)_3$), 124.3, 122.8, 92.4 (q, J_{CF} = 35 Hz, η^6-$C_6H_3(CF_3)_3$), 81.7 (η^6-$C_6H_3(CF_3)_3$), 29.1, 25.1, 23.6 . **^{19}F NMR** (372 MHz, C_6D_{12}): δ −62.6.

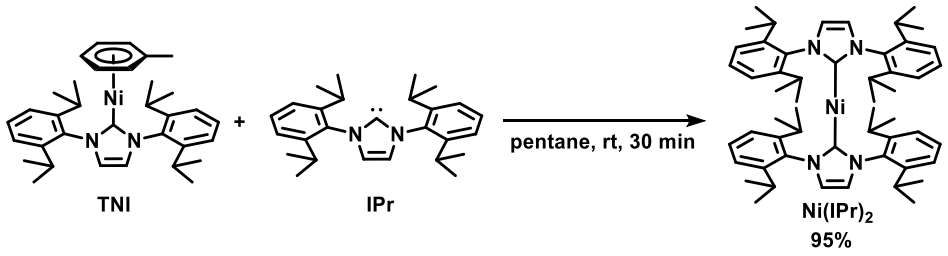
3.4.6. Conversion of TNI into Ni(0)–IPr Complexes via Ligand Exchange Reactions



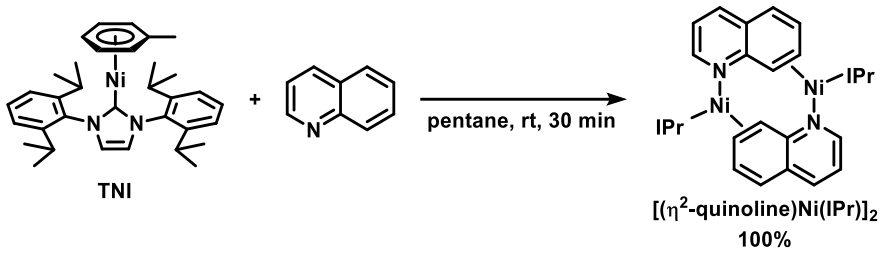
Conversion into bis(η^2-PhCH=CH_2)Ni(IPr): To a solution of **TNI** (21.6 mg, 0.04 mmol) in *n*-pentane (5.0 mL) was added styrene (9.4 μL, 0.08 mmol) at room temperature. After the reaction mixture was stirred for 30 min, all volatiles were removed under the reduced pressure to give bis(η^2-PhCH=CH_2)Ni(IPr) as a dark green solid (28.4 mg, 0.04 mmol, 100%). Spectroscopic data of bis(η^2-PhCH=CH_2)Ni(IPr) were identical to that previously reported.[8k]



Conversion into Ni(dppe)(IPr): To a solution of **TNI** (21.6 mg, 0.04 mmol) in *n*-pentane (5.0 mL) was added 1,3-bis (diphenylphosphino)ethane (DPPE) (15.9 mg, 0.04 mmol) at room temperature. After the reaction mixture was stirred for 5 min, all volatiles were removed under the reduced pressure. The residue was washed with cold *n*-pentane to give Ni(dppe)(IPr) as a reddish brown solid (34.3 mg, 0.04 mmol, 100%). Spectroscopic data of Ni(dppe)(IPr) were identical to that previously reported.[8l]



Conversion into Ni(IPr)$_2$: To a solution of **TNI** (21.6 mg, 0.04 mmol) in *n*-pentane (5.0 mL) was added IPr (15.6 mg, 0.04 mmol) at room temperature. After the reaction mixture was stirred for 30 min, all volatiles were removed under the reduced pressure to give Ni(IPr)$_2$ as a deep blue solid (32.1 mg, 0.038 mmol, 95%). Spectroscopic data of Ni(IPr)$_2$ were identical to that previously reported.[8n]



Conversion into [(η^2-quinolone)Ni(IPr)]$_2$: To a solution of **TNI** (21.6 mg, 0.04 mmol) in *n*-pentane (5.0 mL) was added quinolone (4.9 μL, 0.04 mmol) at room temperature. After the reaction mixture was stirred for 30 min, all volatiles were removed under the reduced pressure to give [(η^2-quinolone) Ni(IPr)]$_2$ as a dark brown solid (45.8 mg, 0.04 mmol, 100%). A single crystal suitable for X-ray diffraction analysis was prepared by recrystallization from C_6H_{12} at room temperature. **^{1}H NMR** (400 MHz, C_6D_6, Figure 3.14a): δ 8.06 (d, *J* = 5.6 Hz, 2H, quinoline-C2*H*), 7.33–7.27 (m, 8H, Ar-*H*), 7.11 (d, *J* = 7.0 Hz, 4H, Ar-*H*), 6.75 (d, *J* = 6.8 Hz, 2H, quinoline-C4*H*), 6.48 (s, 4H, NC_2H_2N), 6.13 (dd, *J* = 5.6, 6.8 Hz, 2H, quinoline-C3*H*), 5.85 (d, *J* = 8.4 Hz, 2H, quinoline-C5*H*), 4.74 (dd, *J* = 5.4, 8.4 Hz, 2H, quinoline-C6*H*), 3.68 (dd, *J* = 5.4, 6.0 Hz, 2H, quinoline-C7*H*), 3.61 (d, *J* = 6.0 Hz, 2H, quinoline-C8*H*), 3.39–3.32 (m, 4H, C*H*$(CH_3)_2$), 2.81–2.75 (m, 4H, C*H*$(CH_3)_2$), 1.63 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$), 1.15 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$), 1.06 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$), 1.00 (d, *J* = 6.8 Hz, 12H, CH(C*H*$_3)_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_6, Figure 3.14b): δ 199.8, 156.6 (*C10*), 147.1, 146.2, 145.2 (*C2*), 138.5, 129.2, 127.2 (*C9*), 124.1, 123.8, 123.7 (*C4*), 122.6, 113.5 (*C5*), 112.7 (*C3*), 52.9 (*C8*), 45.9 (*C7*), 28.9, 28.8, 26.4, 25.9, 23.4, 22.1. One Ar-*C* (*C6*) is obscured by C_6D_6. **Anal. Calcd for $C_{72}H_{86}N_6Ni_2$**: C, 75.01; H, 7.52; N, 7.29. Found: C, 73.34; H, 7.43; N, 7.32.

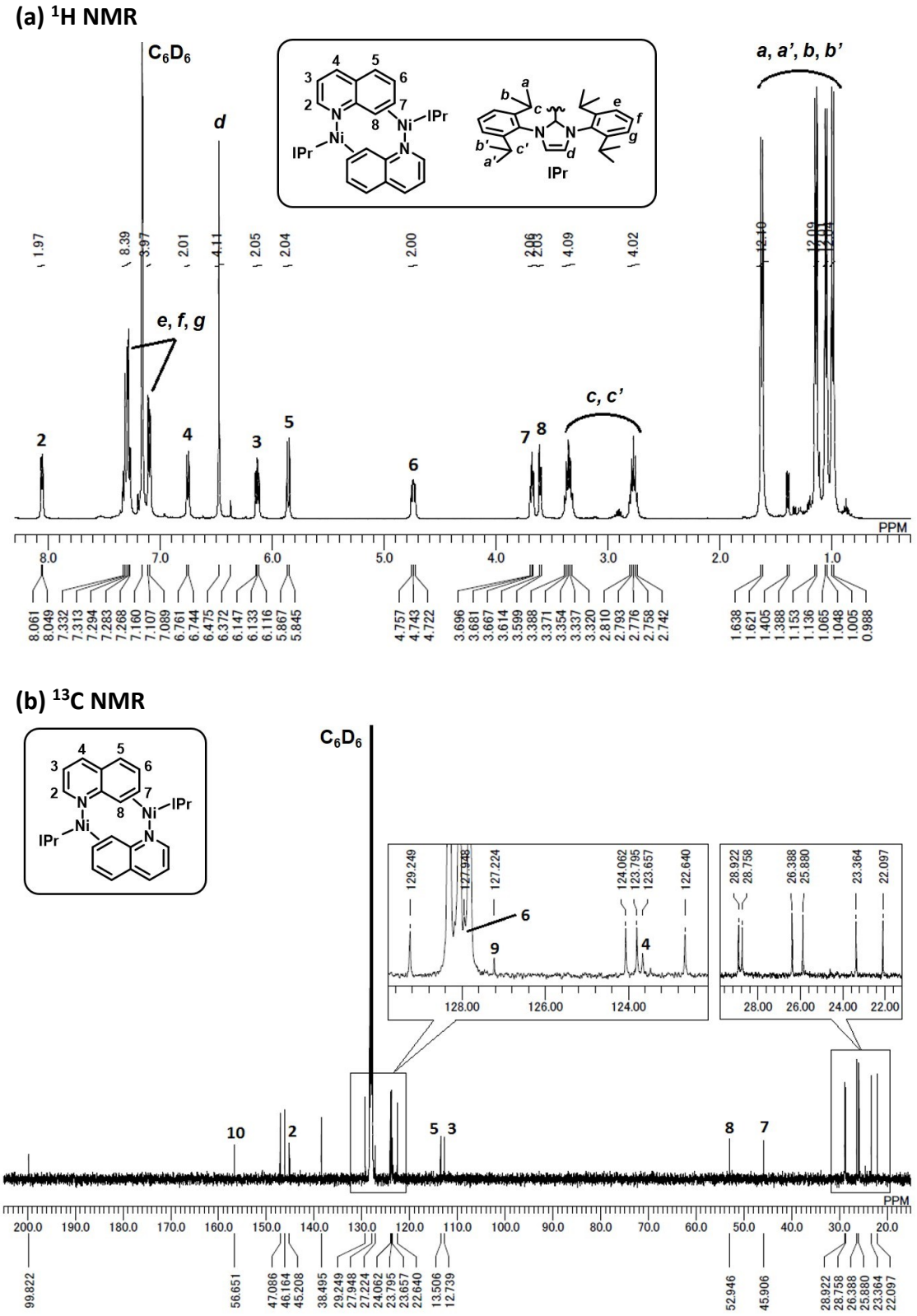
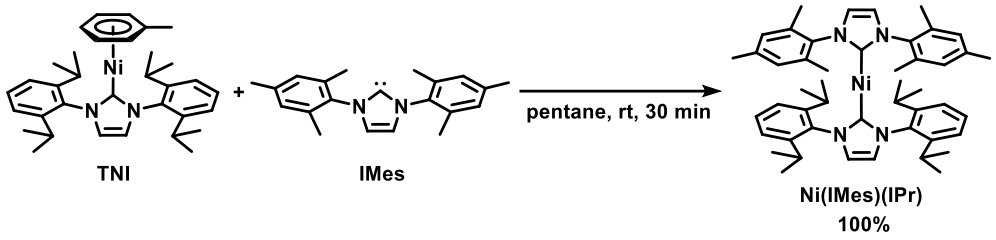
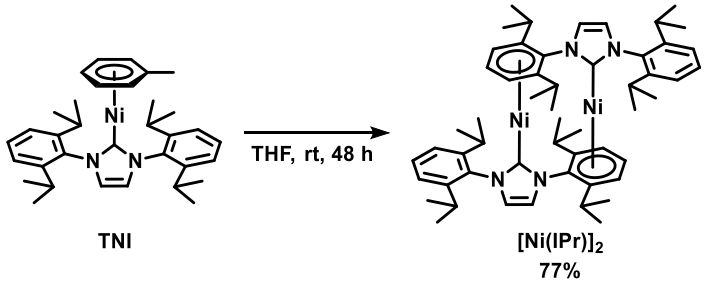


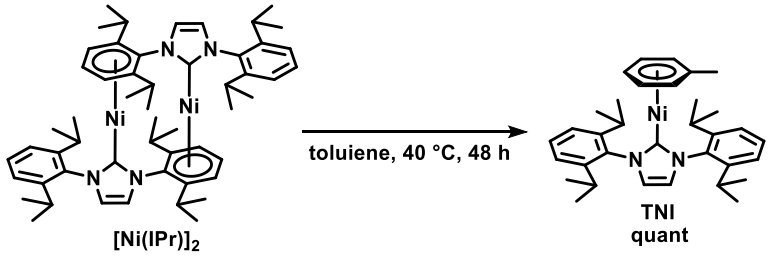
Figure 3.14. a) ^{1}H and b) ^{13}C NMR spectra of $[(\eta^{2}\text{-quinoline})Ni(IPr)]_2$ in C_6D_6.



Conversion into Ni(IMes)(IPr): To a solution of **TNI** (21.6 mg, 0.04 mmol) in *n*-pentane (5.0 mL) was added IMes (12.2 mg, 0.04 mmol) at room temperature. After the reaction mixture was stirred for 30 min, all volatiles were removed under the reduced pressure to give Ni(IMes)(IPr) as a deep blue solid (31.7 mg, 0.04 mmol, 100%). A single crystal suitable for X-ray diffraction analysis was prepared by recrystallization from toluene/hexane at –35 °C. **^{1}H NMR** (400 MHz, C_6D_6): δ 7.33 (t, *J* = 7.6 Hz, 2H, IPr-Ar-*H*), 7.13 (d, *J* = 7.6 Hz, 4H, IPr-Ar-*H*), 6.72 (s, 4H, IMes-Ar-*H*), 6.22 (s, 2H, IPr-NC_2H_2N), 5.95 (s, 2H, IMes-NC_2H_2N), 3.05–2.98 (m, 4H, IPr-C*H*$(CH_3)_2$), 2.30 (s, 6H, IMes-CH_3), 2.02 (s, 12H, IMes-CH_3), 1.35 (d, *J* = 6.8 Hz, 12H, IPr-CH(CH_3)$_2$), 1.17 (d, *J* = 6.8 Hz, 12H, IPr-CH(CH_3)$_2$). **^{13}C{^{1}H} NMR** (100 MHz, C_6D_6): δ 194.9, 191.8, 145.8, 139.0, 138.6, 135.9, 135.1, 129.1, 127.9, 123.4, 119.6, 118.5, 28.8, 24.6, 23.7, 21.3, 18.5. **Anal. Calcd for $C_{48}H_{60}N_4Ni$**: C, 76.69; H, 8.05; N, 7.45. Found: C, 76.41; H, 8.08; N, 7.50.



Conversion of TNI into [Ni(IPr)]$_2$: A solution of **TNI** (20.7 mg, 0.038 mmol) in THF (5.0 mL) was stirred for 48 h (2 days) at room temperature, all volatiles were removed under the reduced pressure to give [Ni(IPr)]$_2$ (13.1 mg, 0.015 mmol, 77%). Spectroscopic data of [Ni(IPr)]$_2$ were identified to that previously reported.[10]



Conversion of [Ni(IPr)]$_2$ into TNI: A solution of [Ni(IPr)]$_2$ (18.5 mg, 0.021 mmol) in toluene (8.0 mL) was stirred for 48 h (2 days) at room temperature. The quantitative

formation of **TNI** was confirmed by ^{1}H NMR in C_6D_6 via transformation into **BNI-*d*$_6$**. After removing all volatiles under the reduced pressure, **TNI** (18.3 mg, 0.034 mmol, 83%) was given.

3.4.7. DFT Calculation Study

The structure of **BNI** was optimized with B3LYP implemented in Gaussian 09, Revision A.02.[24]The LANL2DZ basis set was used for nickel, and 6-31G(d) was used for other atoms. The optimized structure of **BNI** and its information are shown in Figure 3.15 and Table 3.1. The selected calculated molecular orbitals are shown in Figure 3.16.

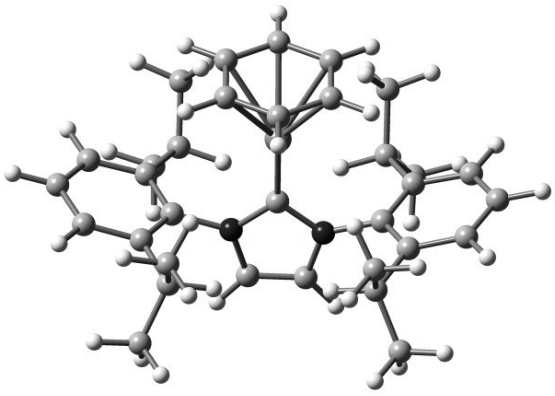


Figure 3.15. Optimized structure of **BNI**.

Table 3.1. Computed Cartesian coordinates (x,y,z) for the optimized structure of **BNI**.

Ni	0.001021	-0.001414	1.484102	C	4.468871	1.199453	-0.291651
N	1.078366	-0.001512	-1.246985	H	5.003909	2.135164	-0.153365
N	-1.076333	0.002640	-1.247763	C	3.120871	1.228784	-0.670530
C	1.189227	0.755778	3.249192	C	2.411707	-2.574558	-0.870585
C	1.249310	-0.654074	3.250407	H	1.366149	-2.367792	-1.113791
C	0.054826	-1.408699	3.244308	C	2.427106	2.567654	-0.900392
C	-1.198939	-0.757055	3.248010	H	1.383666	2.364105	-1.155356
C	-1.258959	0.652599	3.247958	C	-2.455231	0.004007	-0.842015
C	-0.064618	1.407334	3.243117	C	-3.119052	-1.228383	-0.673408
C	0.000708	-0.000226	-0.369831	C	-4.467267	-1.199437	-0.295258
C	0.678003	0.000234	-2.583124	H	-5.002255	-2.135294	-0.157782
H	1.388286	-0.000474	-3.395583	C	-4.460345	1.211617	-0.279245
C	-0.674979	0.003129	-2.583627	H	-4.990113	2.148615	-0.129786
H	-1.384662	0.005142	-3.396606	C	-3.111919	1.237882	-0.656714
C	2.456963	-0.003408	-0.840193	C	-2.425090	-2.567031	-0.903976
C	3.113312	-1.237479	-0.655036	H	-1.381416	-2.363253	-1.157791
C	4.461525	-1.211604	-0.276790	C	-2.410454	2.575175	-0.871432
H	4.991036	-2.148762	-0.127420	H	-1.364773	2.368712	-1.114390

H	-2.220855	1.155237	3.243965	H	2.980766	-2.748812	-2.980906
H	-2.114774	-1.339542	3.246693	C	-3.052721	-3.325754	-2.089889
H	0.100514	-2.493420	3.237255	H	-2.513309	-4.262682	-2.274197
H	-0.110337	2.492038	3.235144	H	-4.102116	-3.578262	-1.896090
H	2.105061	1.338264	3.249405	H	-3.018702	-2.728848	-3.008503
H	2.211184	-1.156739	3.249222	C	-2.416882	-3.432349	0.369853
C	2.417700	3.431615	0.374365	H	-3.432723	-3.688831	0.694334
H	3.433235	3.687743	0.700071	H	-1.879587	-4.371198	0.188049
H	1.880562	4.370655	0.193071	H	-1.916394	-2.902161	1.185717
H	1.916468	2.900556	1.189213	C	-2.412933	3.434673	0.406316
C	3.055754	3.327693	-2.084920	H	-1.868680	4.371396	0.234553
H	2.516439	4.264778	-2.268717	H	-3.430881	3.695537	0.720421
H	4.104953	3.580074	-1.889905	H	-1.924375	2.898828	1.225728
H	3.022623	2.731776	-3.004210	C	-3.022477	3.342027	-2.060392
C	2.413594	-3.434537	0.406841	H	-4.073641	3.595212	-1.877237
H	1.869262	-4.371115	0.234526	H	-2.479129	4.278911	-2.233036
H	3.431392	-3.695665	0.721218	H	-2.978788	2.750237	-2.981890
H	1.924798	-2.898899	1.226249	C	-5.133818	0.006707	-0.095764
C	3.024022	-3.341010	-2.059647	H	-6.180746	0.007773	0.197007
H	4.075074	-3.594467	-1.876225	C	5.135118	-0.006898	-0.092402
H	2.480573	-4.277725	-2.232896	H	6.181888	-0.008283	0.200935

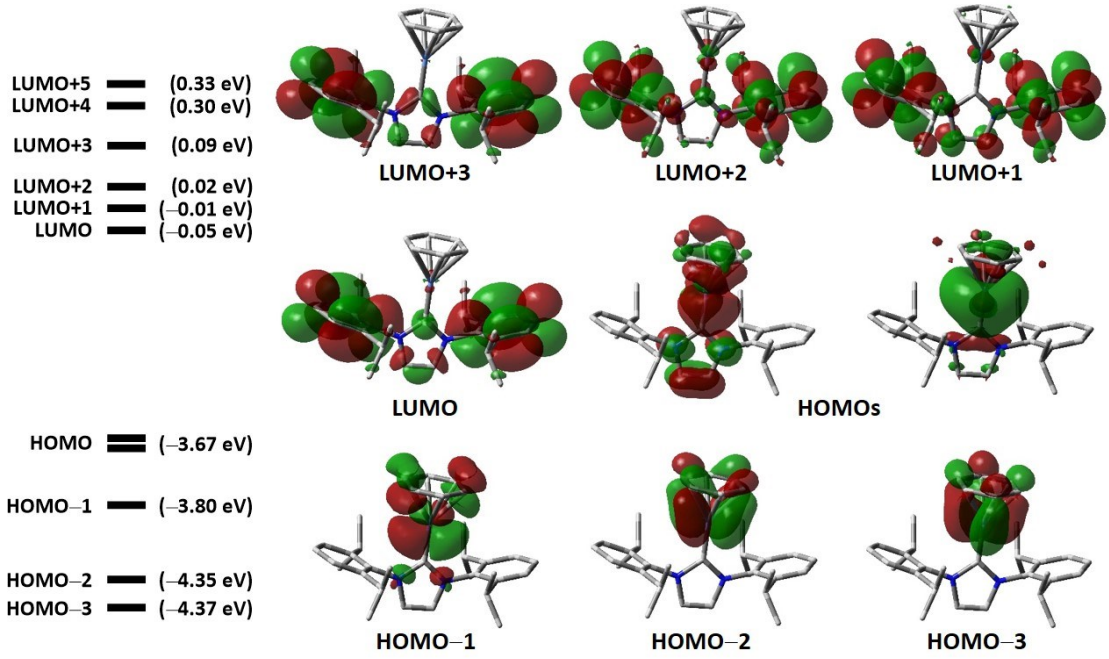


Figure 3.16. Selected calculated molecular orbitals of **BNI**.

3.5. References and Notes

[1] For selected revies, see: a) M. N. Hopkinson, C. Richter, M. Schedler, F. Glorius, *Nature*, **2014**, *510*, 485; b) L. Benhamou, E. Chardon, G. Lavigne, S. Bellemin-Laponnaz, V. César, *Chem. Rev.* **2011**, *111*, 2705; c) T. Dröge, F. Glorius, *Angew. Chem. Int. Ed.* **2010**, *49*, 6940; d) D. Bourissou, O. Guerret, F. P. Gabbaï, G. Bertrand, *Chem. Rev.* **2000**, *100*, 39; e) W. A. Herrmann, C. Köcher, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2162.

[2] a) H. W. Wanzlick, H. J. Schönherr, *Angew. Chem. Int. Ed. Engl*. **1968**, *7*, 141; b) K. Öfele, *J. Organomet. Chem.* **1968**, *12*, 42.

[3] a) D. J. Cardin, B. Çetinkaya, M. F. Lappert, *Chem. Rev.* **1972**, *72*, 545; b) M. F. Lappert, *J. Organomet. Chem.* **1988**, *358*, 185.

[4] a) A. J. Arduengo, III, R. L. Harlow, M. Kline, *J. Am. Chem. Soc.* **1991**, *113*, 361.

[5] For books, see: a) C. S. Cazin, *N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis*; Springer: Heidelberg, London, New York, **2010**; b) F. Glorius, *N-Heterocyclic Carbenes in Transition Metal Catalysis*; Springer: Berlin, **2007**; c) S. P. Nolan, *N-Heterocyclic Carbenes in Synthesis*; Wiley-VCH: Weinheim, Germany, **2006**; for selected reviews on NHCs in coordination chemistry, see: d) P. de Frémont, N. Marion, S. P. Nolan, *Coord. Chem. Rev.* **2009**, *253*, 862; e) F. E. Hahn, M. C. Jahnke, *Angew. Chem. Int. Ed.* **2008**, *47*, 3122.

[6] For selected recent reviews on Pd/NHC catalysis, see: a) C. Valente, S. Çalimsiz, K. H. Hoi, D. Mallik, M. Sayah, M. G. Organ, *Angew. Chem. Int. Ed.* **2012**, *51*, 3314; b) G. C. Fortman, S. P. Nolan, *Chem. Soc. Rev.* **2011**, *40*, 5151; c) J. A. Meta, M. Poyatos, *Curr. Org. Chem.* **2011**, *15*, 3309; d) E. A. B. Kantchev, C. J. O'Brien, M. G. Organ, *Angew. Chem. Int. Ed.* **2007**, *46*, 2768.

[7] For selected recent reviews on Ni(0)–NHC catalysis, see: a) F.-S. Han, *Chem. Soc. Rev.* **2013**, *42*, 5270; b) Z.-X. Wang, N. Liu, *Eur. J. Inorg. Chem.* **2012**, 901; c) B. M. Rosen, K. W. Quasdorf, D. A. Wilson, N. Zhang, A.-M. Resmerita, N. K. Garg, V. Percec, *Chem. Rev.* **2011**, *111*, 1346; d) S. Gu, P. Ni, W. Chen, *Chin. J. Catal.* **2010**, *31*, 875.

[8] For selected examples of $Ni(CO)_3(NHC)$ or $Ni(CO)_2(NHC)$, see: a) A. Collado, J. Balogh, S. Meiries, A. M. Z. Slawin, L. Falivene, L. Cavallo, S. P. Nolan, *Organometallics* **2013**, *32*, 3249; b) J. Balogh, A. M. Z. Slawin, S. P. Nolan, *Organometallics* **2012**, *31*, 3259; c) R. Dorta, E. D. Stevens, N. M. Scott, C. Costabile, L. Cavallo, C. D. Hoff, S. P. Nolan, *J. Am. Chem. Soc.* **2005**, *127*, 2485; d) R. Dorta, E. D. Stevens, C. D. Hoff, S. P. Nolan, *J. Am. Chem. Soc.* **2003**, *125*, 10490; e) W. A. Herrmann, L. J. Gooβen, G. R. J. Artus, C. Köcher, *Organometallics* **1997**, *16*, 2472; f) M. F. Lappert, P. L. Pye, *J. Chem. Soc., Dalton*

Trans. **1977**, 2172; for selected examples of $Ni(NHC)_2(CO)_2$, see: g) N. M. Scott, H. Clavier, P. Mahjoor, E. D. Stevens, S. P. Nolan, *Organometallics* **2008**, *27*, 3181; h) T. Schaub, U. Radius, *Chem. Eur. J.* **2005**, *11*, 5024; i) T. Schaub, M. Backes, U. Radius, *Organometallics* **2006**, *25*, 4196; j) K. Öfele, W. A. Herrmann, D. Mihalios, M. Elison, E. Herdtweck, W. Scherer, J. Mink, *J. Organomet. Chem.* **1993**, *459*, 177; for selected examples of olefin-coordinated Ni(0)–NHC complexes, see: k) M. J. Iglesias, J. F. Blandez,M. R. Fructos, A. Prieto, E. Álvarez, T. R. Belderrain, M. C. Nicasio, *Organometallics* **2012**, *31*, 6312; l) J. Wu, J. W. Faller, N. Hazari, T. J. Schmeier, *Organometallics* **2012**, *31*, 806 and references therein; m) N. D. Clement, K. J. Cavell, L.-L. Ooi, *Organometallics* **2006**, *25*, 4155 and references therein; for selected examples of $Ni(NHC)_2$, see: n) A. A. Danopoulos, D. Pugh, *Dalton Trans.* **2008**, 30; o) S. Caddick, F. G. N. Cloke, P. B. Hitchcock, A. K. de K. Lewis, *Angew. Chem. Int. Ed.* **2004**, *43*, 5824; p) A. J. Arduengo, III, S. F. Gamper, J. C. Calabrese, F. Davidson, *J. Am. Chem. Soc.* **1994**, *116*, 4391.

[9] For reported η^6-arene Ni(0) complexes, see: a) C. Watanabe, Y. Inagawa, T. Iwamoto, M. Kira, *Dalton Trans.* **2010**, *39*, 9414; b) A. Meltzer, C. Präsang, C. Milsmann, M. Driess, *Angew. Chem. Int. Ed.* **2009**, *48*, 3170; c) T. Nickel, R. Goddard, C. Krüger, K.-R. Pörschke, *Angew. Chem. Int. Ed.* **1994**, *33*, 879; see also the following reports on η^2-arene Ni(0) complexes: d) J. A. Hatnean, R. Beck, J. D. Borrelli, S. A. Johnson, *Organometallics* **2010**, *29*, 6077; e) I. Bach, K.-R. Pörschke, R. Goddard,C. Kopiske, C. Krüger, A. Rufińska, K. Seevogel, *Organometallics* **1996**, *15*, 4959.

[10] C. H. Lee, D. S. Laitar, P. Mueller, J. P. Sadighi, *J. Am. Chem. Soc.* **2007**, *129*, 13802.

[11] C. A. Laskowski, A. J. M. Miller, G. L. Hillhouse, T. R. Cundari, *J. Am. Chem. Soc.* **2011**, *133*, 771.

[12] For our selected recent reports on Ni(0)–NHC catalysis, see: a) Y. Hoshimoto, Y. Hayashi, H. Suzuki, M. Ohashi, S. Ogoshi, *Angew. Chem. Int. Ed.* **2012**, *51*, 10812; b) A. Nishimura, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2012**, *134*, 15692; c) Y. Hoshimoto, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2011**, *133*, 4668; d) T. Tamaki, M. Ohashi, S. Ogoshi, *Chem. Lett.* **2011**, *40*, 248; e) S. Ogoshi, Y. Hoshimoto, M. Ohashi, *Chem. Commun.* **2010**, *46*, 3354; f) T. Tamaki, M. Nagata, M. Ohashi, S. Ogoshi, *Chem. Eur. J.* **2009**, *15*, 10083.

[13] It has been reported that $Ni(cod)_2$ and IPr (2 equiv) exist in equilibrium with $Ni(IPr)_2$ and COD in THF ($K_{eq} = 1$), see: J. Louie, J. E. Gibby, M. V. Farnworth, T. N. Tekavec, *J. Am. Chem. Soc.* **2002**, *124*, 15188.

[14] Recently, hydrogenation of olefins in the presence of Ni(0)–NHC was reported by

Hazari and co-workers, see: ref 8l for details.

[15] a) S. Sakaki, K. Kitaura, K. Maruoka, K. Ohkubo, *Inorg. Chem.* **1983**, *22*, 104; b) F. Delbecq, S. Sautet, *J. Am. Chem. Soc.* **1992**, *114*, 2446.

[16] Sadighi et al. reported that heating $[Ni(IPr)]_2$ in C_6D_6 at 60 °C for 7 days gave an unidentified product. On the basis of our result, their product would be **BNI-*d*$_6$**, see: ref 10 for details.

[17] For a book, see: a) T. Eicher, S. Hauptmann, A. Speicher, *The Chemistry of Heterocycles: Structures, Reactions, Synthesis, and Applications*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2003; for a theoretical study, see: b) E. E. Ebenso, M. M. Kabanda, T. Arslan, M. Saracoglu, F. Kandemirli, L. C. Murulana, A. K. Singh, S. K. Shukla, B. Hammouti, K. F. Khaled, M. A. Quraishi, I. B. Obot, N. O. Eddy, *Int. J. Electrochem. Sci.* 2012, 7, 5643.

[18] For selected examples, see: a) J. J. Garcia, N. M. Brunkan, W. D. Jones, *J. Am. Chem. Soc.* **2002**, *124*, 9547; b) G. Zhu, J. M. Tanski,D. G. Churchill, K. E. Janak, G. Parkin, *J. Am. Chem. Soc.* **2002**, *124*, 13658; c) C. Bianchini, A. Meli, F. Vizza, *Eur. J. Inorg. Chem.* **2001**, 43 and references therein.

[19] Rh(NHC)-catalyzed selective functionalization of quinolines at the 8-position was reported, see: J. Kwak, M. Kim, S. Chang, *J. Am. Chem. Soc.* **2011**, *133*, 3780.

[20] For examples of M(NHC)(NHC′) type complexes, see: **Pd(0)**: a) S. Fantasia, S. P. Nolan, *Chem. Eur. J.* **2008**, *14*, 6987; **Cu(I)**: b) S. Guo, M. H. Lim, H. V. Huynh, *Organometallics* **2013**, *32*, 7225; c) V. César, C. Barthes, C. Farré, S. V. Cuisiat, B. Y. Vacher, R. Brousses, N. Lugan, G. Lavigne, *Dalton Trans.* **2013**, *42*, 7373; d) F. Lazreg, A. M. Z. Slawin, C. S. J. Cazin, *Organometallics* **2012**, *31*, 7969; **Au(I)**: e) S. Gaillard, P. Nun, A. M. Z. Slawin, S. P. Nolan, *Organometallics* **2010**, *29*, 5402.

[21] Y. Hoshimoto, H. Yabuki, R. Kumar, H. Suzuki, M. Ohashi, S. Ogoshi, *J. Am. Chem. Soc.* **2015**, *136*, 16752.

[22] For examples on catalytic utilization, see: a) Y. Makida, E. Marelli, A. M. Z. Slawin, S. P. Nolan, *Chem. Commun.* **2014**, *50*, 8010; b) Y. Schramm, M. Takeuchi, K. Semba, Y. Nakao, J. F. Hartwig, *J. Am. Chem. Soc.* **2015**, *137*, 12215; for example on proposing as a reaction intermediate, see: c) B. Sawatlon, T. Wititsuwannakul, Y. Tantirungrotechai, P. Surawatanawong, *Dalton Trans.* **2014**, *43*, 18123.

[23] The NHCs employed in this paper are as follows: IPr, 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene; SIPr, 1,3-bis(2,6-diisopropylphenyl) imidazolin-2-ylidene; IPr*, 1,3-bis(2,6-bis(diphenylmethyl)-4-methylphenyl) imidazol-2-ylidene; IMes, 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene. The preparation methods of these NHCs, see: a) A. J. Arduengo, III, R. Krafczyk, R. Schmutzler, *Tetrahedron* **1999**, *55*, 14523; b) G. Berthon-Gelloz, M. A. Siegler, A.

L. Spek, B. Tinant, J. N. H. Reek, I. E. Markó, *Dalton Trans.* **2010**, *39*, 1444.

[24] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, *Gaussian 09*, *Revision A.02*, Gaussian, Inc., Wallingford CT, 2009.

Conclusion

Described in this thesis are the studies on coupling reactions of carbonyl compounds with alkenes via oxa-nickelacycle intermediates. The use of alkenes with carbonyl compounds in the catalytic reactions proceeding via a metallacycle intermediate has been limited to the highly reactive alkenes, which might be due to the difficulty of the efficient formation of the metallacycle. Then, I envisioned that the combination of an electron-rich nickel and a strong electron-donating ligand would promote the formation of metallacycle. In addition, I envisioned that a highly reactive and versatile Ni(0)–NHC precursor with labile and less noxious η^6-arene ligand would help the coupling reactions of carbonyl compounds with alkenes.

In chapter 1, the mechanistic studies on a Ni(0)/I^{t}Bu-catalyzed intramolecular hydroacylation of alkenes were described. All theoretical predictions and experimental results are well consistent with the conclusion that this intramolecular hydroacylation proceeds via an oxa-nickelacycle with *trans*-conformation as a key intermediate.

In chapter 2, a nickel(0)-catalyzed intramolecular reductive coupling reactions of carbonyl compounds with alkenes were demonstrated. The reductive coupling reaction of *o*-allylbenzaldehyde derivatives with triethylsilane provided silyl-protected indanol derivatives. On the other hand, the reaction of *o*-homoallylbenzaldehyde derivatives with triethylsilane gave silyl-protected cyclic allyl alcohol derivatives. In addition, this catalyst system could be applied to the synthesis of a seven-membered cyclic allyl alcohol. When triethylborane was employed instead of triethylsilane, tetralol derivatives were obtained. These studies would provide new strategies for the utilize simple alkenes for nickel(0)-catalyzed coupling reactions via oxa-nickelacycle intermediates.

During the course of the studies on nickel(0)-catalyzed coupling reactions through chapters 1 and 2, I focused on a highly reactive and versatile Ni(0)–NHC precursor: (η^6-arene)Ni(NHC) complex. In chapter 3, a practical method for the synthesis of (η^6-arene)Ni(NHC) complexes from commercially available Ni(cod)$_2$ and NHCs was developed. The key feature of this method is the hydrogenation of COD. The η^6-arene ligand would be more labile and less noxious than other donor ligands, so (η^6-arene)Ni(NHC) complexes could be very useful precursors of Ni(0)–NHC units in the field of organic and organometallic chemistry.

In this thesis, the development of the intramolecular coupling reactions of carbonyl compounds with simple alkenes via oxa-nickelacycle intermediates by using the combination of an electron-rich nickel and a strong electron-donating ligand as a catalyst

has been achieved. This result provided that the combination of an electron-rich transition-metal and a strong electron-donating ligand would promote the formation of oxa-metallacycles and following transformation into oxygen-containing organic compounds. In addition, the development of the practical preparation method for highly reactive and versatile Ni(0)–NHC precursor, (η^6-arene)Ni(NHC) complex, has also been achieved. This result expanded the utility of nickel(0) catalyst. Thus, these studies will give a significant development in the field of organic and organometallic chemistry.

List of Publications

1. One-Pot, Single-Step, and Gram-Scale Synthesis of Mononuclear [(η^6-arene)Ni(N-heterocyclic carbene)] Complexes: Useful Precursors of the Ni^0–NHC Unit
   Yoichi Hoshimoto, Yukari Hayashi, Haruka Suzuki, Masato Ohashi, Sensuke Ogoshi
   Organometallics **2014**, *33*, 1276–1282.
2. Nickel(0)-catalyzed intramolecular reductive coupling of alkenes and aldehydes or ketones with hydrosilanes
   Yukari Hayashi, Yoichi Hoshimoto, Ravindra Kumar, Masato Ohashi, Sensuke Ogoshi
   Chem. Commun. **2016**, *52*, 6237–6240.
3. Kinetic and Theoretical Studies on Ni(0)/N-Heterocyclic Carbene-Catalyzed Intramolecular Alkene Hydroacylation
   Yoichi Hoshimoto, Yukari Hayashi, Masato Ohashi, Sensuke Ogoshi
   Chem. Asian J. **2017**, *12*, 278–282.
4. Synthesis of Benzocycloalkanols through Nickel(0)-Catalyzed Intramolecular Reductive Coupling of Carbonyl Compounds and Alkenes
   Yukari Hayashi, Yoichi Hoshimoto, Ravindra Kumar, Masato Ohashi, Sensuke Ogoshi
   Manuscript under preparation

Supplementary Publication

1. Synthesis of Five- and Six-Membered Benzocyclic Ketones through Intramolecular Alkene Hydroacylation Catalyzed by Nickel(0)/N-Heterocyclic Carbenes
   Yoichi Hoshimoto, Yukari Hayashi, Haruka Suzuki, Masato Ohashi, Sensuke Ogoshi
   Angew. Chem. Int. Ed. **2012**, *51*, 10812–10815.