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Nickel: The “Spirited Horse” of Transition Metal Catalysis

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1. INTRODUCTION

In 1922, the famous scientist and Nobel Laureate Paul Sabatier reviewed the state of the art of catalysis in organic chemistry and highlighted the specific behavior of nickel catalysts. Of particular interest is his observation that nickel “has an excessive activity along with maximum alterability”.[1] Inspired by its unusual combination of properties, he wrote about the nickel catalyst: “It can be compared to a spirited horse, delicate, difficult to control, and incapable of sustainable work”. In the next paragraph, however, Sabatier described that changing the catalyst preparation conditions produces another type of nickel, and “Such a nickel can do all kinds of work and maintains its activity for a long time”.[1] Almost a century ago, Sabatier ingeniously noticed the outstanding catalytic power of nickel, together with its Achilles heel: a critical weakness in some practical applications. This dual nature was already recognized during the early days of nickel catalysis and largely influenced progress in this field.

Since that time, the development of organonickel chemistry has led to the discovery of several outstanding catalytic systems and powerful practical applications.[2−5] Nickel polymerization catalysts have contributed to both the academic and industrial areas of material science.[6,7] Fine tuning of the ligands has been the key to the design of homogeneous nickel catalysts,[8] and understanding the role of the nanoscale environment has played a leading role in the development of solid nickel catalysts.[9]

Ni-catalyzed cross-coupling of electrophiles (organic halides and pseudohalides) with carbon nucleophiles (organometallic compounds) has had a prominent impact on organic synthesis.[10] Different organometallic compounds were successfully employed in the Kumada−Corriu (magnesium), Suzuki−Miyaura (boron), Negishi (zinc), and Hiyama (silicon) reactions.[11−14] The selection of ligands has made it possible to utilize a variety of reagents with very simple and inexpensive catalyst precursors.[10−16] Diverse reactivity and cost efficiency have provided a valuable driving force for the remarkable progress of nickel catalysts in this area,[17] with more challenges coming in the modern design of process equipment.[18,19] Further development of the field has involved rapid progress in Ni-catalyzed C−X cross-coupling reactions[20−22] and the Mizoroki−Heck reaction.[23]

The utility of very simple catalyst precursors, such as $Ni(acac)_2$, in a variety of transformations deserves special mention. In combination with a suitable ligand, nickel acetylacetonate has been proven to be an excellent catalyst for the above-mentioned cross-coupling reactions as well as for asymmetric reactions.[24]

The prominent achievements of nickel catalysis include cyclizations, cycloaddition reactions, and multicomponent couplings.[25−27] In these transformations, nickel species demonstrated outstanding ability to coordinate and activate unsaturated organic molecules (alkenes, dienes, alkynes, etc.). Indeed, the coordination of unsaturated molecules with the nickel centers “activates” them toward unusual reactivity, which is not possible otherwise.

An ultimate ability of nickel species to mediate transformations of π-electronic systems was revealed upon the development of nanotechnology.[28] Nickel catalysts have shown outstanding performance in the growth of carbon nanotubes and graphene.[28,29] Because of the strong affinity of Ni for unsaturated carbon systems, incorporation of nickel clusters into graphene sheets[30] and the mastering of graphene layers in Ni/C systems under heating may take place.[31]

In recent years, we have observed tremendous activity in the development of new Ni-catalyzed reactions, resulting in numerous fascinating applications in synthetic organic chemistry. The ongoing renaissance in nickel catalysis has brought new life to old and well-known nickel salts, whereas gaining more insight into the mechanistic nature of catalytic cycles has inspired new reactivity patterns. A remarkable number of articles, >40 000, have mentioned the concept of nickel catalysis in the current literature.[32] In this Viewpoint, selected literature examples are considered to draw attention to important fundamental aspects of nickel chemistry and to highlight promising directions of catalyst development. A comprehensive analysis of the literature is not attempted here, as detailed reviews are available elsewhere.

2. NICKEL CATALYSTS IN ORGANIC CHEMISTRY

The important fundamental properties of organonickel compounds (Section 2.1) and a brief summary of their pros and cons for catalytic applications (Section 2.2) are considered first. A few selected transformations that highlight specific advantages of nickel catalysts are discussed next (Section 2.3), followed by a short survey of catalyst availability (Section 2.4).

2.1. Fundamental Properties of Nickel Catalysts. As far as organic chemistry is concerned, the construction of molecular frameworks requires flexible tools for the formation and breakage of carbon−carbon (C−C) bonds. This is difficult to achieve because of the high strength of the C−C bond. The noncatalytic rearrangement of molecular fragments in organic molecules (Figure 1) requires overcoming high activation barriers and harsh reaction conditions. The power of transition metal catalysis enables the assembly of fragments in the coordination sphere of metal complexes as a stepwise process in which each step has a much smaller activation barrier (Figure 1). Weaker metal−carbon (M−C) bonding provides the necessary fundamental basis for catalytic transformations. In particular, the bond dissociation energy changes from 87.4

Received: January 15, 2015
Published: February 17, 2015

DOI: 10.1021/acscatal.5b00072

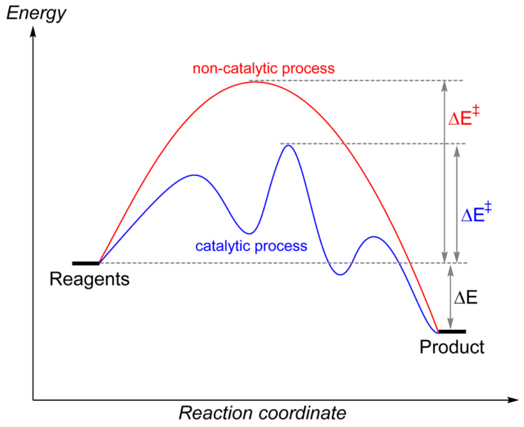


Figure 1. A general energy surface of noncatalytic and catalytic processes.

kcal/mol for the C−C bond to much lower values of 38.0−66.5 kcal/mol for M−C bonds (Table 1).[33,34] The rearrangement of organic groups in the coordination sphere of the metal involves the breakage of M−C bonds, and it is therefore less energetically demanding.

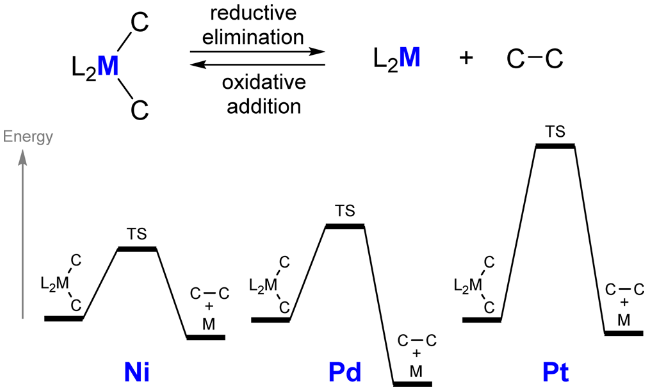
Table 1. Carbon−carbon and Metal−Carbon Bond Dissociation Energies (BDE) in Ethane and in $L_2(X)M^{II}$-CH_3 Complexes (M = Ni, Pd, Pt)[33,34]

bond	BDE, kcal/mol
C−C	87.4
Ni−C	38.0−51.1
Pd−C	48.3−55.2
Pt−C	60.8−66.5

Within the group 10 metals, the M−C bond strength changes in the order Ni−C < Pd−C < Pt−C (Table 1).[35] The trend gives a clue to the exceptional reactivity of organonickel species. Indeed, the higher reactivity of nickel species should naturally be expected among the platinum group metals. Their exceptional reactivity provides a valuable advantage for the design of highly active catalysts, but at the same time, it gives rise to the unavoidable disadvantage of making the catalytic system difficult to control.

The formation of the C−C bond via reductive elimination and the reverse process of oxidative addition are the primary elementary steps in the catalytic transformations of organic molecules. The reductive elimination in nickel complexes proceeds most easily with a small activation barrier of $\Delta E^{‡}_{(RE)}$ = 16.8 kcal/mol (Table 2) (RE = reductive elimination; OA = oxidative addition). The reaction is slightly exothermic with $\Delta E_{(RE)}$ = −4.1 kcal/mol, so the rather small activation barrier for the inverse process of oxidative addition, $\Delta E^{‡}_{(OA)}$ is 20.9 kcal/mol. The picture is noticeably different for palladium, which has a slightly larger activation barrier for reductive elimination, $\Delta E^{‡}_{(RE)}$ = 24.9 kcal/mol, that is accompanied by a much more exothermic transformation, $\Delta E_{(RE)}$ = −19.0 kcal/mol, resulting in a high barrier for the backward process, $\Delta E^{‡}_{(OA)}$ = 43.9 kcal/mol. For the platinum complexes, both the forward and backward reactions possess large activation barriers, $\Delta E^{‡}$ > 45 kcal/mol. Comparison between the group 10 metals shows that, indeed, nickel complexes should be the most reactive in both directions. Palladium is excellently suitable for C−C bond formation, whereas platinum should form the least reactive and most stable complexes. A similar reactivity trend was observed for C−N and C−O bond formation.[33] The difference between Pd and Pt was demonstrated on various organic groups (alkyl, vinyl, phenyl, and alkynyl),[34] and the ligand effect[36] and oxidation state effect[37] were evaluated in more detail.

Table 2. Activation and Reaction Energies of C−C Reductive Elimination and Oxidative Addition Processes (in kcal/mol)[33]



M	$\Delta E^{‡}$ (RE)	ΔE (RE)	$\Delta E^{‡}$ (OA)	ΔE (OA)
Ni−C	16.8	−4.1	20.9	4.1
Pd−C	24.9	−19.0	43.9	19.0
Pt−C	45.8	−3.5	49.3	3.5

Homolytic bond cleavage shows the following trend: Ni−C > Pd−C > Pt−C, in which the reactivity decreases from nickel to palladium and then to platinum (Figure 2).[33,34,36,37] Therefore, among the group 10 metals, the contribution of radical processes is most probable for the nickel species. Homolytic bond cleavage is less probable for palladium and the most energetically demanding for platinum. An important difference of the nickel species is the easy involvement of 1 e⁻ processes.[2,38] For nickel species, the M^{I} and M^{III} oxidation states are much more accessible than for palladium and platinum complexes, where M^{0}, M^{II}, and M^{IV} oxidation states are more common.

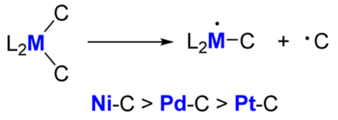


Figure 2. Homolytic M−C bond cleavage.

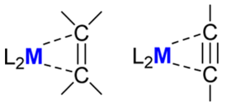
The cleavage of the metal−ligand bond is an important mechanistic factor responsible for accessing low-ligated metal species. For a widely used phosphine-ligand-based catalysis, the cleavage of metal−phosphorus (M−P) bonds was evaluated for M^{0} and M^{II} complexes.[39] In the $M^{II}L_2X_2$ complexes, the binding energy of the phosphine ligand increases in the following order: Ni−P (24.5 kcal/mol) < Pd−P (32.1 kcal/mol) < Pt−P (40.3 kcal/mol). The trend was different in the $M^{0}L_2$ species, following the order Pd−P (33.6 kcal/mol) < Ni−P (39.7 kcal/mol) < Pt−P (45.5 kcal/mol). The data suggests that the coordination vacancy should be accessible in the Ni^{II} species, whereas Ni^{0} species tend to bind phosphine ligands more strongly.

The binding picture dramatically changes upon considering the coordination of unsaturated compounds to the metal

DOI: 10.1021/acscatal.5b00072
ACS Catal. 2015, 5, 1964−1971

center.[40,41,34,37] The binding of alkene and alkyne units to nickel complexes is exceptionally strong: $\Delta E = 34.3$ and 41.6 kcal/mol for C═C and C≡C bonds, respectively (Table 3). In contrast, the binding of double and triple carbon−carbon bonds to palladium and platinum is less energetically favored, $\Delta E = 16.1{-}23.7$ kcal/mol.

Table 3. Binding Energies of Alkyne and Alkene Units to Metal Centers (in kcal/mol)[41]



M	ΔE (C═C)	ΔE (C≡C)
Ni	34.3	41.6
Pd	16.1	17.9
Pt	19.6	23.7

The binding of unsaturated molecules involves the donation of electron density to the metal and back-donation from the metal. Electron density delocalization induces significant changes into the coordinated unsaturated molecules, which are reflected by the altered geometry, charges, and spectral properties of the alkyne and alkene units. Such changes lead to the appearance of new reactivity in coordinated organic molecules, which would not be possible in the absence of metals. Coordination to nickel most significantly changes the properties of unsaturated molecules and causes activation to a certain type of reactivity.

Unusual behavior was also observed in the study of acetylene binding on a metal surface.[42] Anomalous adsorption of acetylene was found in the case of Ni compared with the other metals considered in the study (Pd, Pt, Rh).[42]

It should be noted that the interaction of metal centers with π-electronic systems is much more flexible than M−C σ-bonding. Variations in the structure of ligands may significantly affect the binding of double and triple bonds to metal centers.[40,41,43]

2.2. Pros and Cons of Nickel Catalysts. On the basis of the key fundamental properties discussed above and on the detailed studies of various catalytic transformations mentioned in the introduction, a few important features deserve particular mention (Table 4). Catalytic cycles with organonickel species as intermediates in many cases demonstrate high performance and involve unreactive organic molecules as substrates, but the inability to predict all pathways and the difficulty of control are a known price for greater reactivity.

Ni catalysts demonstrate outstanding diversity of reactivity patterns: several different reactions may take place from the same starting materials. This provides an excellent opportunity to discover new reactions, but only if the catalytic system would be possible to tune to a favored transformation while suppressing unwanted reactions. In the worst case, several pathways taking place in parallel is a critical diminishing factor that induces side reactions and leads to the formation of byproducts.

For palladium and platinum complexes, 2 e^- chemistry is usually expected, whereas for nickel complexes, 1 e^- processes are not uncommon. Typical Pd and Pt catalytic cycles include M^0/M^{II} and M^{II}/M^{IV} transformations. For Ni catalysts, such transformations are also anticipated, but they are not limiting. Reactivity of the Ni species is enriched by the availability of the M^I and M^{III} states as well as the possible involvement of radical processes. This difference may result in the appearance of fascinating catalytic transformations involving Ni^I/Ni^{III} or $Ni^0/Ni^I/Ni^{II}$.

Thus, the fundamental properties of nickel species are exhibited on the level of elementary steps. To name a few, Ni complexes may be readily tuned for reductive elimination and for oxidative addition, whereas in Pd complexes, reductive elimination is easier to promote. Slow β-hydride elimination was found for Ni complexes as well as facile migratory insertion. In contrast, Pd complexes are known for their rapid and widely accessible β-hydride elimination. The comparison shows that Ni may show features complementary to those of the other transition metal catalysts, promoting different transformations.

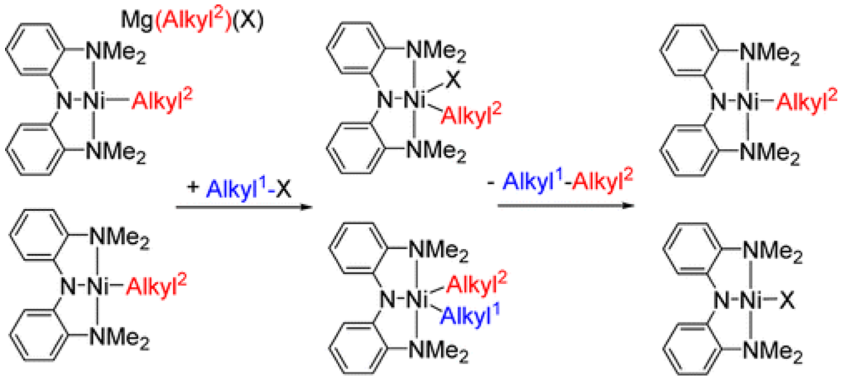
Design of ligands and fine-tuning of the ligand structure is crucial for Ni-catalyzed reactions. Without a suitable ligand, many Ni-mediated transformation are likely to fail because of the influence of the limiting factors (Table 4). This is in sharp contrast with palladium, as many Pd-catalyzed reactions can usually be efficiently catalyzed by the metal catalyst in various forms. For example, Pd-catalyzed cross-coupling and Heck reactions can be catalyzed with virtually any source of palladium (including several types of ligands, ligand-less, metal clusters, nanoparticles, and trace-impurities) and even by a cocktail of Pd catalysts.[44]

2.3. Exploring Nickel Catalysts in Selected Transformations. The cross-coupling of nonactivated alkyl halides is a challenging case of transition metal catalysis with valuable potential in synthetic transformations.[11,12,45] A powerful nickel catalyst containing an N_2N ligand with a bis(aryl)amido framework was developed to promote the reaction and suppress the problematic β-hydride elimination.[46] Under optimized conditions, high yields and good selectivity were observed in the Ni-catalyzed transformations for a wide substrate scope.

Table 4. Advantages and Disadvantages Typically Faced in the Development of Nickel Catalytic Systems

features of Ni catalysts	advantages	disadvantages
highly reactive organometallic species	active catalytic systems; efficient catalysis with extraordinarily high performance; transformations involving unreactive substrates	catalytic system is difficult to control and to predict; strong dependence of performance on several minor factors and substituents
facile homolytic bond cleavage	readily accessible cascade reactions, cyclizations, and couplings; photocatalysis	generation of radicals and initiation of side reactions leading to byproducts; lower selectivity
easier accessibility of $Ni^0/Ni^I/Ni^{II}/Ni^{III}$ oxidation states	new reactivity patterns beyond traditional framework of noble metals; novel types of catalytic cycles that can be tuned by selection of ligands	great alterability of the catalyst; easy catalyst deactivation; poor functional group tolerance; paramagnetic contribution inhibits NMR studies
strong affinity to unsaturated systems and coordination (activation) of multiple bonds	exceptional activation of unsaturated molecules; a variety of unusual transformations involving multiple bonds	easy oligomerization of unsaturated molecules; a number of side reactions and low product yield; poor selectivity

Scheme 1. Bimetallic Pathway Involving Radical Intermediates in Ni-Catalyzed Alkyl−Alkyl Cross-Coupling[a]



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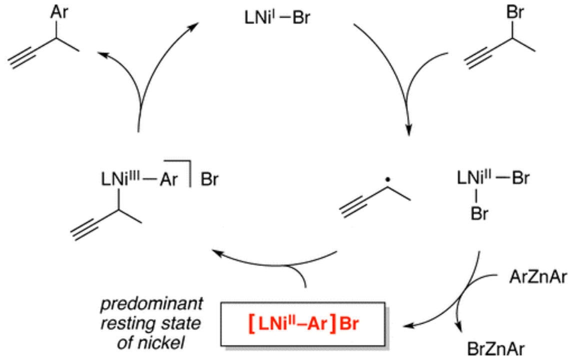
A mechanistic study of alkyl−alkyl Kumada cross-coupling has shown that the reaction proceeds via a radical process with the involvement of two Ni centers (Scheme 1).[47] One of the nitrogen groups of the pincer N_2N ligand was proposed to assist in the binding of the Mg species to the catalyst. The formation of the $[(N_2N)Ni{-}alkyl^2](alkyl^2{-}MgCl)$ complex was found to be a turnover-determining step in the catalytic cycle. The oxidative addition stage was suggested to involve two metal atoms with the formal Ni^{III} oxidation state in the organonickel intermediates. Clearly, such transformations should be specific to Ni complexes and highlight the power of their unusual reactivity patterns.

The diverse reaction pathways characteristic for the nickel complexes and their compatibility with the radical route have been shown in the study of propargylic derivatives (Scheme 2).[48] A radical chain pathway with the involvement of a bimetallic mechanism for the oxidative addition of a C−Br bond was proposed. The overall catalytic cycle contains $Ni^I/Ni^{II}/Ni^{III}$ intermediates in which the Ni^{II}−Ar species represents a dominant resting state of nickel during the catalytic process. The study shows that the usage of other ligands, conditions, and reagents may cause significant differences in the reaction mechanism of nickel-catalyzed transformations.

Scheme 2. Mechanism of the Ni-Catalyzed Negishi Arylation of Propargylic Bromides[a]



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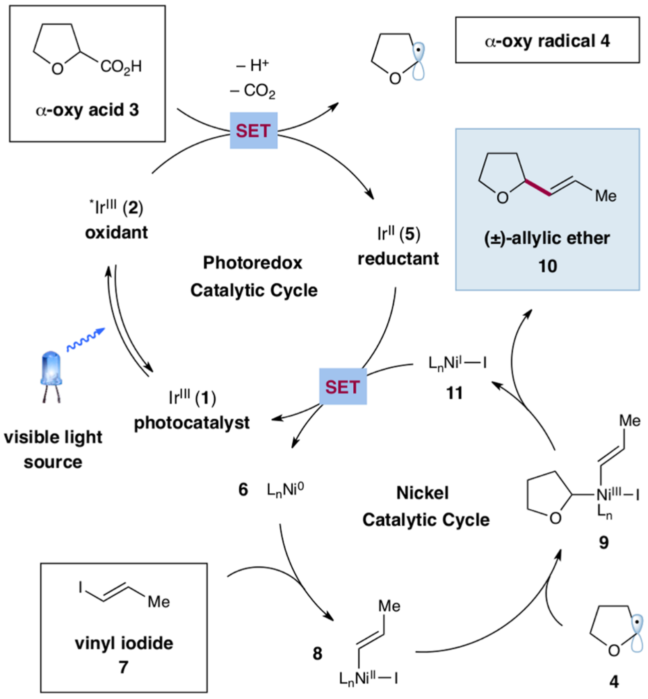
A mechanistic study of other C−C cross-coupling reactions revealed the involvement of observable Ni^I, Ni^{II}, and Ni^{III} intermediates.[49] It is important to note that Ni^{III}−alkyl species have been isolated and characterized.

The unique properties of nickel have been utilized in the photoredox catalytic approach.[50,51] Decarboxylative cross-coupling between carboxylic acids and organic halides is a very promising methodology in organic synthesis because it allows the replacement of specific transmetalation reagents with easily available substrates. A dual catalyst platform with Ir complexes for visible light photoredox catalysis and Ni complexes for cross-coupling catalysis was successfully designed (Scheme 3).[52] The outstanding synergetic action of both metals led to development of a convenient synthetic protocol with a wide substrate scope.

The photoexcitation of the iridium catalyst and the generation of the carboxyl radical initiate the elimination of CO_2 and the formation of the α-oxy radical (Scheme 3). In parallel with the photoredox cycle, the nickel catalyst undergoes

Scheme 3. Photoredox and Nickel Catalysis in the Decarboxylative Cross-Coupling of Carboxylic Acids and Vinyl Halides[a]



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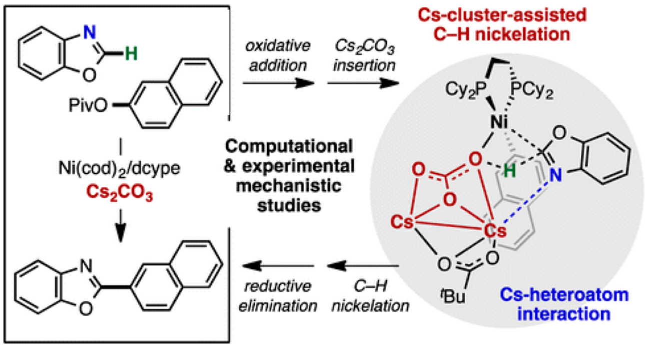
the oxidative addition of a vinyl halide, followed by the trapping of an α-oxy radical and allylic ether formation after reductive elimination. Regeneration of both catalysts is performed by the reduction of the Ni^{I} complex with the reduced state of the Ir^{III} photocatalyst. It is the exceptional ability of nickel complexes to maintain $Ni^{0}/Ni^{II}/Ni^{III}/Ni^{I}$ states in one catalytic cycle that rendered the organic transformation in a synergetic manner.

Nickel catalysts have shown high efficiency in several coupling reactions that benefit from the elimination of predesigned molecular fragments.[53] An advantage of the facile oxidative addition of nickel species into C−H, C−O, and C−N bonds is utilized in the catalytic cycles.

An interesting finding was revealed in the mechanistic study of Ni-catalyzed C−H/C−O coupling between benzoxazole and naphthalen-2-yl pivalate (Scheme 4).[54] In the proposed catalytic cycle, the Ni^{0} species undergoes C−O oxidative addition, followed by the coordination of Cs_2CO_3 and cluster formation. The subsequent step of C−H activation was facilitated by the cluster structure, which reduced the activation barrier and enhanced the reaction rate. The addition of Cs_2CO_3 to the reaction mixture resulted in a 3-fold increase in the reaction rate. The proposed Cs-cluster-assisted C−H nickelation is a new mechanistic proposal that accounts for supramolecular interactions in nickel catalysis. It would be of much interest to explore the role of supramolecular interactions in other Ni-catalyzed transformations.

Scheme 4. Key Intermediate in the Ni-Catalyzed C−H/C−O Coupling of Biaryls[a]



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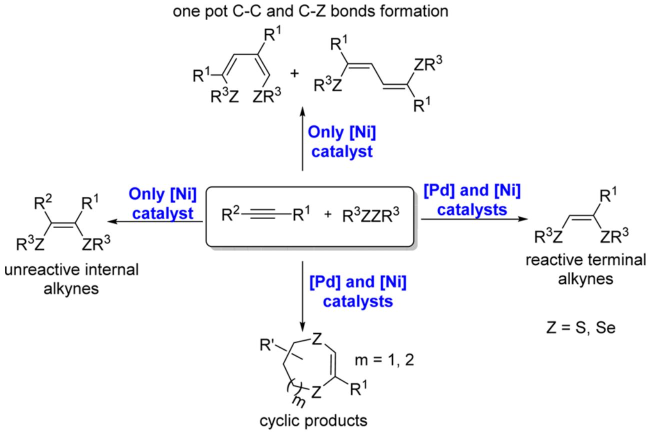
The high affinity of nickel complexes to unsaturated organic molecules led to the discovery of numerous fascinating transformations involving alkynes, alkenes, and dienes, with several bright examples appearing in ongoing development.[25−27,55] Our group has developed atom-economic addition reactions of alkynes, in which the superior catalytic properties of the Ni catalyst were employed for selective carbon−heteroatom bond formation.[56]

In the simple case of Z−Z bond addition to reactive terminal alkynes, both Ni and Pd catalysts have shown the desired activity in the synthesis of linear and cyclic products (Scheme 5);[57,58] however, only the Ni catalyst mediated the transformation in the case of unreactive internal alkynes.[59] Moreover, only the Ni catalyst facilitated one-pot C−C and C−Z bond formation furnishing 1,3-dienes as the final products.[60] These examples clearly highlight the advantages of the Ni catalyst: superior catalytic activity and new types of reactivity. It should be emphasized that the practical utilization of the advantages of the Ni catalyst in these reactions was possible only after elimination (or minimization) of the negative influence of the corresponding shortcomings. Particularly, radical side-reactions were suppressed by the addition of radical traps, alkyne oligomerization was suppressed by optimizing the reaction conditions, and the formation of byproducts was avoided by tuning the ligand structure.

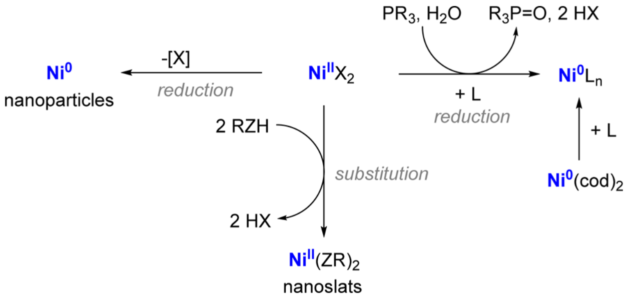
Scheme 5. Ni- and Pd-Catalyzed Atom-Economic Addition Reactions to Alkynes



2.4. Catalyst Availability.

Many of the catalytic reactions discussed in the present article were mediated by NiX_2 precatalysts, usually represented by simple nickel salts (Scheme 6). Convenient protocols were developed for the generation of soluble Ni^{0} species, Ni^{0} nanoparticles, and Ni^{II} nanosalts. $Ni(cod)_2$ is most commonly utilized to generate the NiL_n species because of the rapid and quantitative replacement of the cod ligands. The reduction in the solution phase to the Ni^{0} species can be achieved by several reagents; for example, by phosphines in the presence of traces of water (Scheme 6).[61] Nickel nanoparticles can be prepared by reduction and were used for catalytic carbon−carbon bond formation.[62] Nickel nanosalts can be readily accessed by substitution reactions and were utilized as catalysts for carbon-heteroatom bond formation.[63]

Scheme 6. Possible Transformations of Nickel Catalyst Precursors



Various simple nickel salts NiX_2 (X = Cl, Br, OAc, acac, etc.) have been used as catalyst precursors. In many cases, $Ni(acac)_2$ was found to be the catalyst precursor of choice. Solubility in organic solvents and easy transformation of $Ni(acac)_2$ to the catalyst active form ensure important preferences for practical applications. An interesting issue concerns generation of Ni_2X_2 superatomic core starting from $Ni(acac)_2$ solutions.[64] Possible involvement of such superatomic units in the catalytic transformations is unclear and deserves further study.

Comparing the cost of catalyst precursors for nickel and noble metals shows a dramatic difference (Table 5).[65] Cost efficiency is an indisputable driving force for selecting nickel for catalytic applications. It is therefore natural to expect not only the development of new nickel-catalyzed transformations but also the replacement of known noble-metal-based catalysts by reliable nickel analogs. Easy availability of Ni salts is an unquestionable advantage; however, an important issue concerns possible influence on the environment. The subject deserves more attention because nickel complexes have shown noticeable toxicity and possible carcinogenic properties.[66]

Table 5. Estimates of the Costs of Ni, Pd, Pt, Au and Rh Catalyst Precursors[65]

	compd				
	$NiCl_2$	$PdCl_2$	$PtCl_2$	$AuCl_3$	$RhCl_3$
price per 1 mmol, USD	0.1	5.8	32.2	35.6	51.8

3. SUMMARY AND OUTLOOK

An evaluation of the current state of transition-metal-catalyzed transformations shows an amazing picture. Pd-catalyzed reactions have been tremendously developed over recent decades, and it is now the most widely used metal in organic synthesis (Table 6). Synthetic applications of palladium catalysts are of paramount importance in modern organic chemistry. From the point of view of activity, palladium represents an optimal balance that allows efficient catalysis as well as rational control and predictability.

Table 6. Brief Comparison of Ni, Pd and Pt-Catalyzed Reactions in Organic Synthesis

catalyst	activity[a]	application in organic synthesis	no. of publications[b]
Ni	high	good area of application; potential of several reactions to be explored	44 000
Pd	moderate	outstanding area of application; leading catalyst for organic transformations	72 000
Pt	less active	good area of application; excellent models for mechanistic studies	50 000

[a] A rough estimation of the relative chemical activity of the organometallic species (an estimate only, may depend on compound class). [b] Approximate number of publications mentioning the corresponding metal and catalysis.[32]

Nickel and platinum did not show as much catalytic transformations, but for different reasons (Table 6). Higher stability is a fundamental property of platinum complexes. In many cases, platinum complexes were studied as model compounds that can be easily isolated, characterized and applied in stoichiometric reactions. In contrast, nickel complexes are very reactive, and design/control of their catalytic systems requires much more effort. Nickel catalysts retain significant synthetic potential, which will be unveiled upon gaining more insight and understanding into their character. Indeed, in the majority of known Ni-mediated reactions, the active catalyst remains unknown.

Its great alterability, difficulty of control, and inability to predict the outcome—the main difficulties correctly identified by Sabatier in the previous century—have hampered progress in the field of nickel catalysis. In many aspects, the field still remains terra incognita in chemical science; however, the development of a new generation of analytical equipment and rapid progress in computational studies have provided outstanding systematic tools for mechanistic investigations. At the moment, we can clearly observe the emergence of nickel catalysis and have no doubts about the remarkable synthetic applications to be explored soon.

To achieve this goal, the following key questions need to be addressed in the near future:

(i) the joint application of experimental and theoretical studies of complex reaction mechanisms
(ii) the development of general reactivity trends and characterization of elementary steps
(iii) insight into the structure and reactivity of various Ni^0/Ni^I/Ni^{II}/Ni^{III}/Ni^{IV} states
(iv) a comparative analysis of 2 e^- vs 1 e^- chemistry and exploration of radical pathways
(v) the development of new ligands to create well-defined and robust Ni catalysts
(vi) the suppression of side-reactions and elimination of byproduct formation

The increasing price of Pd, Pt, and other noble metals even further stimulates search for inexpensive and easily available catalysts. This provides a remarkable opportunity to develop new nickel catalysts. However, nickel not only is an inexpensive replacement for noble metals but also enables new reactions and novel catalytic frameworks. If properly understood and treated, such a "spirited horse" can drive some of the greatest breakthroughs in catalysis. As with any spirited horse, nickel is a challenge. Obtaining a deep mechanistic understanding of Ni-catalyzed reactions is much more challenging compared with Pd and Pt.

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Notes

The author declares no competing financial interest.

■ ACKNOWLEDGMENTS

Financial support of the Russian Science Foundation is acknowledged (RSF Grant 14-50-00126).

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