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Nickel-Catalyzed Allylic C(sp^2)-H Activation: Stereoselective Allyl Isomerization and Regiospecific Allyl Arylation of Allylarenes

Qiang Wu,[a, b] Lanlan Wang,[a, b] Rizhe Jin,[a] Chuanqing Kang,*[a] Zheng Bian,[a] Zhijun Du,[a] Xiaoye Ma,[a] Haiquan Guo,[a] and Lianxun Gao[a]

Abstract: Stereoselective allyl isomerization and regiospecific allyl arylation of allylarenes with a catalytic system comprising nickel(II) with aryl Grignard reagent are studied. Both reactions are triggered by allylic internal C(sp^2)-H activation by in situ-formed Ni(0), which is inserted into the C-H bond at the 2-position of the allyl without a directing group. The isomerization of allylarene to 1-propenylarene favors the *E*-isomer with a quantitative conversion. The arylation through oxidative cross-coupling of allylarenes with excess Grignard reagents is regiospecific at the position of C(sp^2)-H activation, which provides a new method for synthesizing 1,1-disubstituted olefins. Investigations with deuterium labelling experiments reveal an alkenyl-alkyl mechanism involving the allylic internal C(sp^2)-H activation and multiple intermolecular 1,2-, 1,3-, and 2,3-hydride shifts. These results provide new approaches to olefin functionalization and the mechanistic investigations would be helpful for the discovery and design of new strategy for olefin functionalization.

Introduction

Isomerization and functionalization of olefins are the most simple and efficient approaches to building highly substituted olefins in academic and industrial chemistry.[1] In this field, allylarenes, which are a type of special olefins, have attracted much attention for their biological activity and wide applications for pesticide, fragrance, cosmetics, flavors, pharmaceuticals, and materials.[2] Transition metal-catalyzed isomerization of allylarenes has proven to be an effective method for the synthesis of 1-propenylarenes, molecules with the same application as allylarenes.[3] Besides noble transition metals,[4] inexpensive first-row transition metals (Fe, Co, and Ni) have also shown high catalytic activity and good-to-excellent *E*/*Z* selectivity for olefin isomerization,[5] they are considered to have significant potential to transform this field owing to their abundance and their ability to be easily removed. Past mechanistic studies on olefin isomerization have revealed that the alkyl and π-allyl mechanisms are dependent on the reagents and reaction conditions.[3, 6] According to H/D exchange and crossover experiments, the former functions via metal hydride addition-elimination while the latter functions through a 1,3-hydride shift induced by coordination of π-allyl to a metal. The metal hydride for the addition-elimination is generated from reductive reagents or from ligands by H-abstraction.[5c, 6, 7] No metal hydride should be present in the π-allyl mechanism, or the alkyl mechanism will take place instead. Recently, a few reports have presented olefin isomerizations catalyzed with Co(II) and Fe(III) in the presence of Grignard reagent through a 1,3-hydride shift or an unspecified mechanism.[5a, 8] Previously, olefin isomerizations catalyzed by Ni(0) were carried out under aqueous conditions showing poor-to-good *E*/*Z* selectivity, those studies proposed that nickel hydride is generated from the aqueous medium during the addition-elimination.[5e, 5f] More recently, a Ni(I)-catalyzed olefin isomerization with excellent *Z*-selectivity has been published,[5g] where the hydride addition-elimination is mediated by diphenylphosphane coordinating to Ni(I). Coversely, Ni(0) has also been used to mediate isomerization of allylamides through 1,3-hydride shift with poor-to-excellent *E*/*Z* selectivity depending on the substrate structures.[9] However, no report has ever demonstrated olefin isomerization through olefinic C(sp^2)-H activation or through the alkyl mechanism without pre-formed metal hydride.

Arylation of allyl compounds through well-known Heck-type cross coupling with aryl halides and triflates is an efficient path to linear 1,2-disubstituted ethylene or branched 1,1-disubstituted ethylene determined by regioselective formation of the C-C bond at terminal or internal C(sp^2).[10] The oxidative Heck-type cross coupling of olefins with aryl Grignard reagents shows exclusive regioselectivity at terminal C(sp^2) to form linear olefins.[11, 12] To the best of our knowledge, no report has been published on oxidative cross coupling with internal C(sp^2) selectivity to form branched olefins. In most cases, oxidative cross coupling undergoes coordinative addition of the aryl Grignard reagent to form a complex of a transition metal and a heteroatom-containing olefin followed by β-hydride elimination.[11] In a few other cases, the cross coupling is enabled by transition metal-mediated terminal olefinic C-H activation utilizing a heteroatom in the substrate as a directing group followed by reductive elimination.[12] Both mechanisms have been extensively exploited for the Heck-type cross coupling of olefins with other nucleophilic substrates, in which a heteroatom in the olefin is essential for coordination with the transition metal.[13]

Recently, we have been interested in the C-C bond formation and transformation mediated with inexpensive transition metals. During our studies on Ni(II)-catalyzed cross coupling of the aryl Grignard reagent with aryl halides,[14] we noticed the cross coupling of aryl Grignard reagent with the

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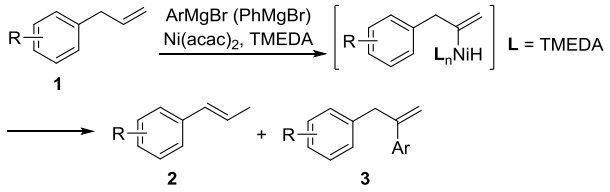
olefin of an olefin-containing substrate, resulting in the olefin arylation. Further studies showed the presence of the olefin isomerization along with the olefin arylation. We then started elaborate studies on the olefin arylation and the olefin isomerization of allylarenes mediated with a Ni(II)-aryl Grignard reagent system. Here we presented the results. Our studies demonstrated the isomerization of allylarenes with excellent *E*/*Z* selectivity and the regiospecific arylation of allylarenes to 1,1-disubstituted olefins (Scheme 1). The reaction conditions subtly control the direction of the transformation of allylarenes to the exclusive isomerization or a combination with arylation. Investigations into the mechanism disclosed a new catalysis method involving allylic internal C(sp^2)-H activation of allylarenes without a directing group followed by an alkenyl-alkyl catalytic cycle for allyl isomerization. These results provide new approaches to olefin functionalization and the mechanistic investigations are helpful for the discovery and design of new strategy for olefin functionalization.



Conditions and yields
a: **1** (1.0 eq), $Ni(acac)_2$ (5 mol%), TMEDA (5 mol%), PhMgBr (30 mol%), THF yield of **2** up to 98%, *E*/*Z* up to 52/1
b: ArMgBr (1.0 eq), **1** (4.0 eq), $Ni(acac)_2$ (5 mol%), TMEDA (20 mol%), neat isolated yield of **3** up to 58%

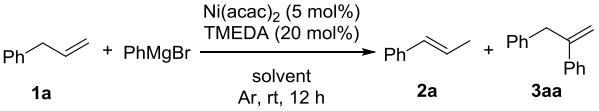
Scheme 1. Conditions-controlled isomerization and arylation of allylarenes.

Results and Discussion

Optimization of the reaction conditions

The optimization of the conditions for isomerization and arylation was carried out with a model reaction between allylbenzene (**1a**) and phenylmagnesium bromide (PhMgBr). First, we determined the conditions that favored the olefin arylation to 1,1-disubstituted ethylene **3aa** (Table 1). Initial experiments with $Ni(acac)_2$ as the catalyst using equimolar **1a** and PhMgBr showed the formation of 1-propenylbenzene (**2a**) from the isomerization and of **3aa** from the arylation (Table 1, entries 1-3), meanwhile, none of these products was formed without nickel (Table 1, entry 4). $NiCl_2$ showed similar catalytic activity, but NiF_2 was a poor catalyst (Table 1, entries 5-6). The yield of the arylation increased to 22% by the use 2 equivalents of **1a** (Table 1, entry 7). Toluene as the solvent gave the same result as THF, but the replacement of the Grignard reagent solvent of THF with toluene (THF-free) led to an increase of 32% in the arylation yield (Table 1, entries 8-9). A higher ratio of **1a** to PhMgBr under neat conditions increased the arylation yield to 56% and decreased the isomerization yield to 30% (Table 1, entries 10-12). Nonpolar conditions benefitted the arylation and suppressed the isomerization. Thus, we could determine the optimized conditions for regiospecific olefin arylation of **1a** to 1,1-disubstituted ethylene with a moderate yield (Table 1, entry 11). $Ni(COD)_2$ as a catalyst gave similar results to $Ni(acac)_2$ (Table 1, entries 13), which suggests that Ni(0) can be used as an active catalyst for arylation and the isomerization.[5e-g, 9, 15] Apart from its use as a substrate, PhMgBr is also used to activate the Ni(II) precatalyst by reducing it to Ni(0),[16] which can be confirmed by the formation of biphenyl according to GC-MS analysis of the reaction mixture. The olefin arylation of **1a** with PhMgBr appeared to be an oxidative cross coupling accompanied by the removal of hydride and magnesium salt. However, the introduction of oxidative reagents such as oxygen, copper(II) triflate, and silver carbonate, completely inhibited both arylation and the isomerization. Ni(0) or active species from Ni(0) likely decomposed in the presence of oxidatives before being able to trigger the catalytic cycles. We further found the formation of propanylbenzene by GC-MS analysis of the reaction mixture, suggesting that **1a** acts as a weak oxidant to receive hydride or hydride-containing species produced during olefin arylation.[11a]

Table 1. Optimization of the olefin arylation conditions.[a]



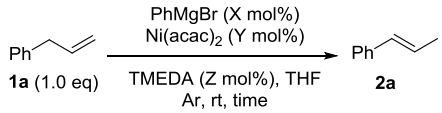
Entry	**1a** : PhMgBr[b]	solvent and other conditions	Yield	
			2a (**1a**)[c]	**3aa**[d]
1	1 : 1	THF	65% (0%)	15%
2	1 : 1	THF, 30 mol% TMEDA	70%(0%)	12%
3	1 : 1	THF, 10 mol% TMEDA	75%(0%)	8%
4	1 : 1	THF, no $Ni(acac)_2$	0% (100%)	0%
5	1 : 1	THF, $NiCl_2$ (5 mol%)	69%(0%)	13%
6	1 : 1	THF, NiF_2 (5 mol%)	34%(44%)	7%
7	2 : 1	THF	65% (5%)	22%
8	2 : 1	toluene	60% (10%)	22%
9	2 : 1	toluene (THF-free)[e]	60% (3%)	32%
10	3 : 1	neat (THF-free)[e]	55% (2%)	39%
11	**4 : 1**	**neat (THF-free)**[e]	**30% (10%)**	**56%**
12	5 : 1	neat (THF-free)[e]	32% (12%)	50%
13	4 : 1	neat (THF-free),[e] $Ni(COD)_2$ (5 mol%)	40% (10%)	40%

[a] Reaction conditions: otherwise indicated, **1a** (as indicated), PhMgBr (1.0 mmol, THF solution for entries 1-9, toluene solution for others indicated as THF-free), TMEDA (20 mol%), $Ni(acac)_2$ (5 mol%), solvent (5 ml or neat), argon atmosphere, rt, 12 h, yields are determined by GC. [b] In molar ratio. [c] Yield based on allylbenzene, yield in bracket is recovered **1a**. [d] Yield based on PhMgBr. [e] Using toluene solution of PhMgBr. TMEDA = tetramethylethylenediamine.

According to above results, isomerization occurs in synchronization with arylation. We therefore shift our focus to optimizing the conditions that favor of allyl isomerization. The reactions with reduced amount of Grignard reagent in tetrahydrofuran (THF), a polar solvent, were examined, where the *E*/*Z* selectivity of isomerization was considered (Table 2). In theory, 10 mol% of PhMgBr is enough to reduce 5 mol% of Ni(II) to Ni(0). However, the reactions with 20 mol% or less of PhMgBr showed poor results and those with more than 25 mol% of PhMgBr resulted in excellent yields and *E*/*Z* values (Table 2, entries 1-4). No trace of **3aa** was detected in those experiments. Tetramethylethylenediamine (TMEDA) is essential but remains effective when used with the same loading amount as that of the nickel catalyst (Table 2, entries 5-7). Lower catalyst loadings also gave excellent results with a very limited decrease in *E*/*Z* selectivity (Table 2, entries 8-9). The time evolution of the experimental data confirmed the rapid isomerization of **1a** (Table 2, entries 6 and 10-12). The high *E*/*Z* ratio at 0.5 h and limited increase within the subsequent 2 h indicate the intrinsic tendency of isomerization to *E*-form selectivity. However, an *E*/*Z* mixture (1/10) of **2a** under catalytic conditions displayed the transformation of *Z*- to *E*-form within 2 h with an *E*/*Z* ratio of 41/1 (Scheme 2). Thus, we cannot reach a conclusion on whether *E*/*Z* selectivity is a result of kinetics or thermodynamics.

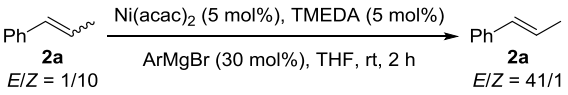
The above results give the optimized conditions for the allyl isomerization of **1a** with excellent yield and *E*/*Z* selectivity catalyzed by 5 mol% of $Ni(acac)_2$ and TMEDA combined with 30 mol% of PhMgBr. No **3aa** from arylation was detected during the optimization of the isomerization conditions. The optimized conditions for both isomerization and arylation had a similar ratio of **1a** to PhMgBr but used different solvents. The isomerization using 1 mol% of $Ni(acac)_2$ in THF had similar catalyst loading as the arylation of **1a** and PhMgBr with a ratio of 4/1 under neat conditions (Table 1, entry 11 and Table 2, entry 9). However, the two reactions gave distinct results, which indicates the solvent plays an essential role in controlling the direction of the conversions to either exclusive isomerization or competitive arylation and isomerization.

Table 2. Optimization of the isomerization conditions.[a]



Entry	X (mol%)	Y (mol%)	Z (mol%)	Time (h)	Yield (*E*/*Z*)[b]
1	15	5	20	2	2% (n.d.)
2	20	5	20	2	55% (15/1)
3	25	5	20	2	95% (28/1)
4	30	5	20	2	98% (32/1)
5	30	5	10	2	96% (44/1)
6	**30**	**5**	**5**	**2**	**96% (52/1)**
7	30	5	0	2	35% (10/1)[c]
8	30	3	3	2	97% (35/1)
9	30	1	1	2	94% (24/1)
10	30	5	5	0.5	96% (28/1)
11	30	5	5	1	96% (42/1)
12	30	5	5	4	96% (52/1)

[a] Reaction conditions: otherwise indicated, **1a** (1.0 mmol), PhMgBr (30 mol%, THF solution), TMEDA (5 mol%), $Ni(acac)_2$ (5 mol%), THF (1 ml), argon atmosphere, rt, 2 h. [b] Determined by GC. [c] 59% of **1a** recovered.

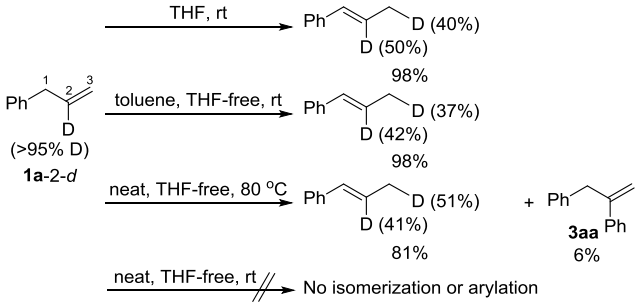


Scheme 2. *E*/*Z*-isomerization of 1-propenylbenzene.

Mechanistic investigations

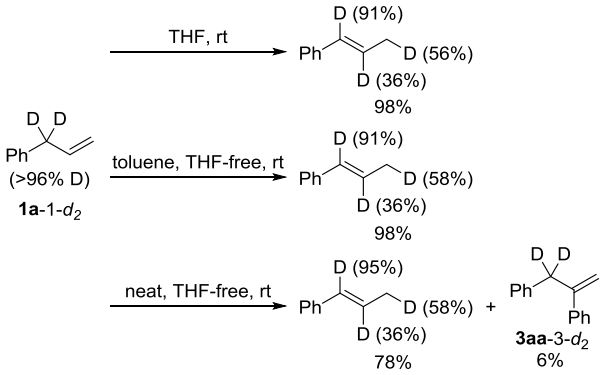
Deep insights into both isomerization and arylation of **1a** with H/D exchange and crossover experiments revealed the mechanistic complexity in the conversions. Substrates with deuteration at the 1- and 2-position of the allyl were studied to sufficiently understand the reactions. All experiments were carried out under the optimized conditions for isomerization. Solvent effects are examined because of the different reactivities of the isomerization and arylation of **1a** in THF, toluene, and under neat conditions.

The olefin isomerization of (allyl-2-*d*)benzene (**1a**-2-*d*) under various conditions showed a 2,3-hydride shift (Scheme 3). In both THF and toluene, the isomerization of **1a**-2-*d* produced **2a** with partial deuteration at the 2- and 3-positions. The hydride shift seemed to be in agreement with the alkyl mechanism.[3, 6] However, isomerization did not proceed under the neat conditions at room temperature, nor did arylation, but successfully yielded **3aa** and **2a** at 80 ºC with partial deuteration at the 2- and 3-positions. These results strongly support that the C-D bond is broken during both isomerization and arylation. Therefore, the activation of $C(sp^2)$-H bond at the 2-position of the allyl of **1a** is essential for both isomerization and arylation. The fact that the arylation product **3aa** using the neat conditions did not show any deuteration suggests that there is no H/D exchange in arylation. We therefore propose that the in situ-formed Ni(0) species from Ni(II) reduction by PhMgBr inserts into the $C(sp^2)$-H bond prior to isomerization and arylation.



Scheme 3. Olefin isomerization with 2,3-hydride shift. Reaction condtions: $Ni(acac)_2$ (5 mol%), TMEDA (5 mol%), PhMgBr (30 mol%), argon, 2 h, others as indicated.

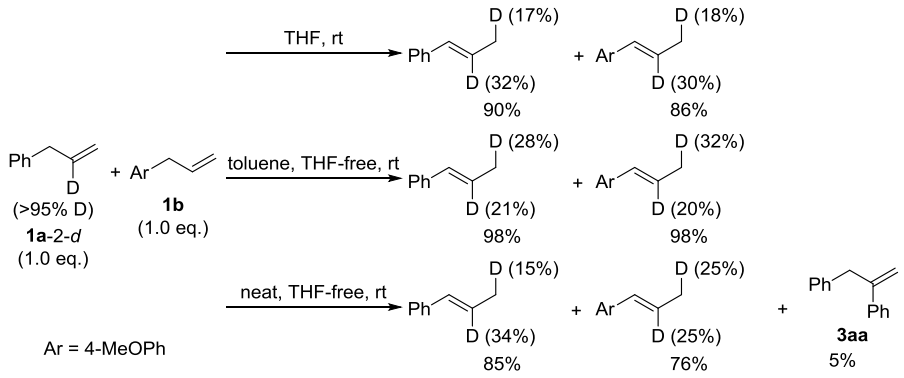
We then examined the isomerization of (allyl-1-d_2)benzene (**1a**-1-d_2) under various conditions, which clearly demonstrates 1,2- and 1,3-hydride shifts that result in partial deuteration at the 2- and 3-positions of **2a** (Scheme 4). The deuterium at the 1-position was abstracted and transfered to the 2- and 3-positions. Under the neat conditions, the arylation product **3aa**-3-d_2 showed no deuterium shift. These observations are in agreement with the results from the isomerization of **1a**-2-*d* (Scheme 3), which support that olefin arylation occurs via a direct cross coupling between C(sp^2)-H-activated **1a** and PhMgBr.



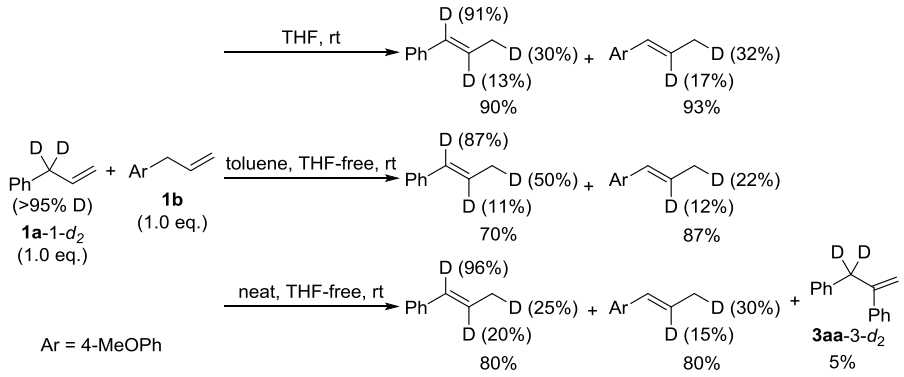
Scheme 4. Olefin isomerization with 1,2- and 1,3-hydride shifts. Reaction condtions: $Ni(acac)_2$ (5 mol%), TMEDA (5 mol%), PhMgBr (30 mol%), argon, 2 h, others as indicated.

Further investigations into the mechanisms were carried out with H/D crossover experiments using deuterated **1a**-2-*d* and **1a**-1-d_2 and undeuterated **1b** as substrates; these experiments clearly demonstrated the presence of multiple intermolecular hydride shifts. In all investigated conditions, the reactions of **1a**-2-*d* and **1b** showed an intermolecular 2,3-hydride shift (Scheme 5), while those of **1a**-1-d_2 and **1b** showed intermolecular 1,2- and 1,3-hydride shifts (Scheme 6). This is the first observation of intermolecular 1,3-hydride shift for olefin isomerization.[3, 6] The intermolecular hydride exchanges led to the deuteration of the 2- and 3-positions of all isomerization products. No allyl arylation was observed in the reactions in THF or toluene, while the allyl arylation worked for the neat conditions but did not show a hydride shift. Cross coupling without a hydride shift suggests that the arylation is independent on isomerization.

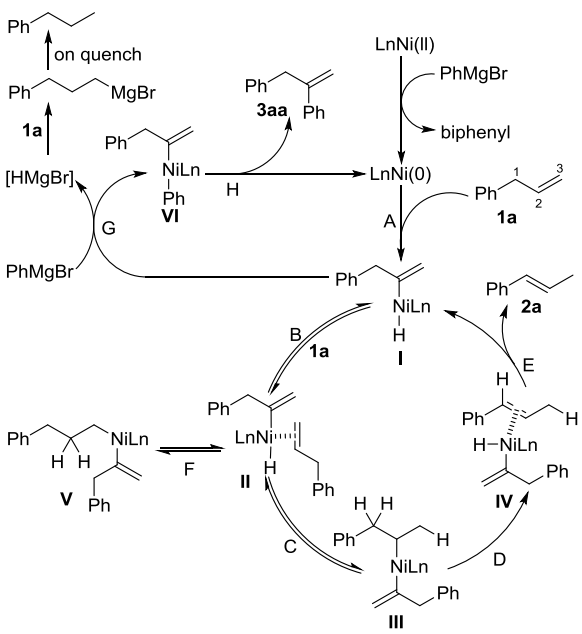
The above result led us to propose mechanisms for allyl isomerization and allyl arylation to address the hydride shifts in the catalytic cycles (Scheme 7). The initial 2-C(sp^2)-H activation of allyl via the oxidative insertion of the in situ-prepared Ni(0) generates alkenyl-nickel-hydride **I**, the activated nickel hydride for forward conversions. Then, the intermolecular 2,3-hydride shift starts with the complexation of **I** into another molecule of **1a** to form **II**. Subsequently, the 2-H of **I** is transferred to another molecule at the 3-position through a nickel-hydride addition in accordance with Markovnikov's rule. The 1,2-elimination of the alkyl molecule trapped in intermediate **III** produces the unstable complex **IV**. Dissociation of **IV** releases product **2a** and regenerates alkenyl-nickel-hydride which takes the 1-H to the 3-position of another molecule of **1a** in the above sequence, which is the 1,3-hydride shift. The complexation of **I** with **1a** and the addition of nickel-hydride to form **III** are reversible, which leads to 2,3-hydride exchange. The combination of 1,3-hydride shift and 2,3-hydride exchange results in the formal 1,2-hydride exchange, which is probably the reason for the lower deuteration rate at the 2-position compared with that at the 3-position (Scheme 6). Another possible pathway for the addition of nickel-hydride to **1a** is via the unfavorable anti-Markovnikov's rule to form **V**. The reversible anti-Markovnikov's addition causes 2,2-hydride exchange. From the catalytic cycle, the alkenyl nickel hydride **I** is the real active species that is trapped in the catalytic cycle and promotes allyl isomerization following the alkyl mechanism,[3, 6] which we refer to as alkenyl-alkyl mechanism.



Scheme 5. Olefin isomerization with intra- and intermolecular 2,3-hydride shift. Reaction condtions: $Ni(acac)_2$ (5 mol%), TMEDA (5 mol%), PhMgBr (30 mol%), argon, 2 h, others as indicated.



Scheme 6. Olefin isomerization with intra- and intermolecular 1,2- and 1,3-hydride shift. Reaction condtions: $Ni(acac)_2$ (5 mol%), TMEDA (5 mol%), PhMgBr (30 mol%), argon, 2 h, others as indicated.



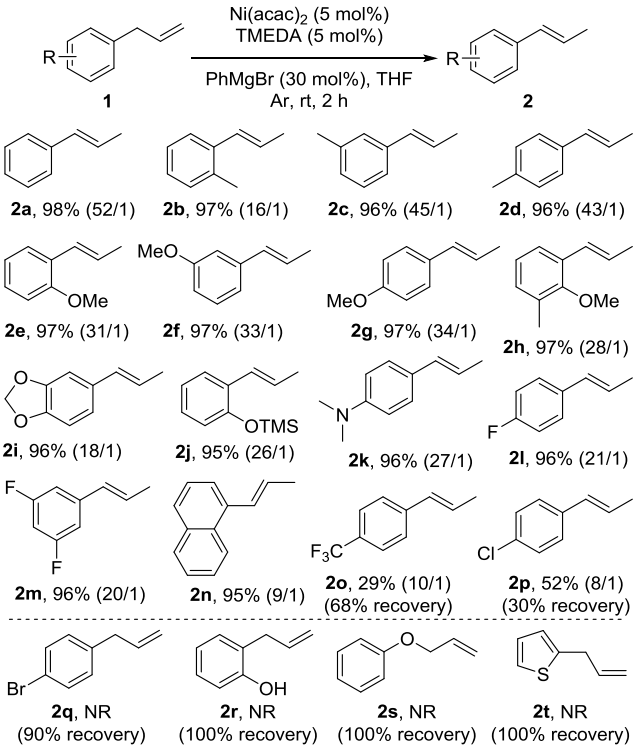
Scheme 7. Proposed alkenyl-alkyl mechanism for the isomerization and cross coupling for the arylation. A: C(sp^2)-H activation; B: complexation; C: addition in Markovnikov's rule; D: 1,2-elimination; E: dissociation; F: addition in anti-Markovnikov's rule; G: transmetalation; H: reductive elimination.

Under neat conditions, the C(sp^2)-H-activated intermediate **I** has a chance to bind with the phenyl from excess PhMgBr through transmetalation to form **VI**, probably because of slightly lower tendency to be complex with and add to **1a** in nonpolar conditions. The transmetalation involves hydride transfer from **I** to a magnesium hydride intermediate captured by **1a** to form phenylpropane upon quenching,[11a, 17] which is confirmed by GC-MS analysis with the detection of phenylpropane in the reaction mixture.‡ Reductive elimination of **VI** releases Ni(0) catalyst and the cross-coupling product **3a**, by which the allyl of **1a** is arylated.

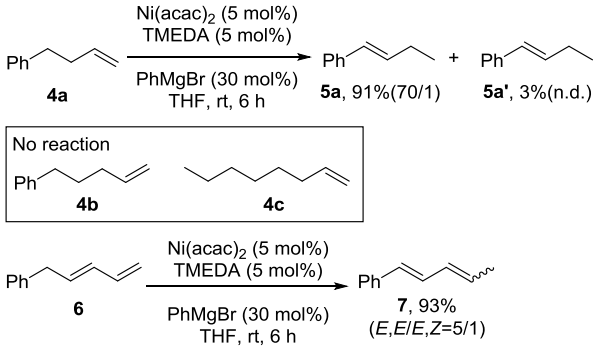
Substrate scope and limitations

Various allylarenes (**1**s) are converted into 1-propenylarenes (**2**s) with excellent yields and *E*/*Z* selectivities (Scheme 8). Under the optimized conditions, the isomerization of allylarenes with methyl, methoxy, dimethylamino, and fluoro gives 1-propenylbenzenes in yields over 95% and *E*/*Z* ratios of up to 52/1. Allylnaphthalene (**1l**) shows a little lower *E*/*Z* selectivity of 9/1 compared with allylbenzene derivatives (*E*/*Z* > 16/1). Although the isomerization of fluoro-substituted substrates **1m** and **1n** demonstrates high reactivity and excellent *E*/*Z* selectivity, the substrates with trifluoromethyl and chloro, **1o** and **1p**, are converted to the products in low-to-moderate yields with a relatively low *E*/*Z* selectivity. Unexpectedly, the bromide substrate **1q** is not suitable for isomerization. The catalytic system is also unable to trigger the conversions of allyl ether **1r** and allylic thiophene **1s**.

We then check the catalytic activity of the $Ni(acac)_2$-PhMgBr system with the isomerization of other terminal alkenes (Scheme 9). Interestingly, but-2-en-1-ylbenzene (**4a**) is converted to but-1-en-1-ylbenzene (**5a**) with a yield of 91% and but-2-en-1-ylbenzene (**5a'**) with a yield of 3%, which indicates a continuous olefin shift along the carbon chain during the olefin isomerization. However, alkenes **4b** and **4c** are inert to the reaction conditions; the latter chemical bears no aryl group. In comparison with **4a**, **4b** has one more CH_2 between the terminal olefin and the phenyl, which suggests that the appropriate distance of an aryl and an olefin in the substrate is a primary factor in forming an activated species for triggering the isomerization. The aryl group in the allylarenes may be involved in the olefin C(sp^2)-H activation as an electron-rich ligand to stabilize nickel-inserted intermediate. Furthermore, diene isomerization is observed for compound **6**, in which diene shifts along the carbon chain to form **7** with an *E*,*E*/*E*,*Z* ratio of 5/1.

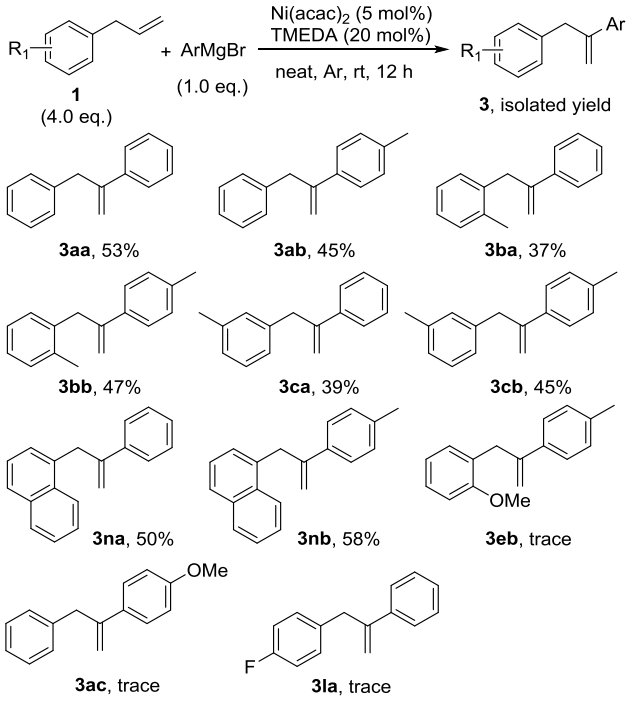


Scheme 8. Scope of the olefin isomerization of allylarenes.



Scheme 9. Olefin isomerization of 1-alkene and diene compounds.

The olefin arylation of a few allylarenes with aryl Grignard reagents provides a method for regiospecific synthesis of 1,1-disubstituted ethylenes in moderate isolated yields (Scheme 10). However, substrates containing methoxy and fluoro inhibit arylation with trace products detected. It is remarkable that methoxy on either allylarene or aryl Grignard reagent results in poor reactivity (**3eb** and **3ac**). In H/D crossover experiments, no cross coupling product from the arylation of **1b** is detected (Schemes 5 and 6). The results suggest that methoxy only influences the cross coupling of the substrate containing it, but does not influence the cross coupling of other substrates in the reaction system.



Scheme 10. Cross coupling of allylarenes with aryl Grignard reagents.

Conclusions

We have developed a novel method for the olefin isomerization and arylation of allylarenes triggered by allylic C(sp^2)-H activation. The method provides new approaches to olefin functionalization, and the proposed mechanism would facilitate the discovery and design of new strategy for olefin functionalization. The inexpensive and wide available nickel is used as catalyst. In situ-formed Ni(0) induces C(sp^2)-H activation by insertion into the allylic internal C(sp^2)-H bond of the allylarenes without a directing group, which results in isomerization and arylation at the activated position. The tendency of allylarene toward exclusive isomerization or a combination of isomerization and arylation is controlled by the solvent, where isomerization is favored by THF, while arylation is favored by neat condtions. The isomerization of allylarenes to 1-propenylarenes shows excellent *E*-form selectivity and yield. The arylation of allylarenes with aryl Grignard reagent is a new method for the synthesis of 1,1-disubstituted ethylene through regiospecific oxidative cross coupling. According to D/H exchange and crossover investigations, we propose an alkenyl-alkyl mechanism in which an alkenyl nickel from C(sp^2)-H activation is used as the active species in the catalytic cycle, similar to the alkyl mechanism. The alkenyl nickel mediates the hydride addition and elimination to form intermolecular 1,2- 1,3-, and 2,3-hydride shifts. Particularly, this is the first observation of intermolecular 1,3-hydride shift for olefin isomerization.[3, 6] The functionalization of allyl using the strategy of allylic C(sp^2)-H activation should benefit this field and are therefore valuable for further investigations.

Experimental Section

General methods

All substrates and reagents are commercial available and used without further purification. The nickel catalysts are purchased from Alfa-Aesar. All the deuterated substrate are prepared from phenylacetic acid and 2,3-dibromopropene according to the literatures.[18] ^{1}H and ^{13}C NMR spectra are recorded on Bruker AVX 300 MHz and 400 MHz spectrometer in $CDCl_3$ with TMS (δ = 0 ppm) and solvent (δ = 77.0 ppm) as internal standard for chemical shift of ^{1}H NMR and ^{13}C NMR, respectively. All known compounds are confirmed with ^{1}H NMR according to respective literatures. GC analyses are performed on Shimidzu GC2010A with DB-WAX column by comparison with authentic compounds. GC-MS analyses are performed on Agilent 5975-6890N system with Agilent 19091G-133 column. Known products of allyl isomerization and allyl arylation are confirmed with ^{1}H and ^{13}C NMR by comparison with literatures. New structures, which are all the products of allyl arylation, are confirmed with ^{1}H and ^{13}C NMR and GC-MS.

General procedure for the allyl isomerization: A 15 mL oven-dried flask was added $Ni(acac)_2$ (12.8 mg, 0.05 mmol) and TMEDA (7.5 μL, 0.05 mmol) in anhydrous THF (1.0 mL) under argon. Then, PhMgBr (0.3 mL, 0.3 mmol, 1M in THF) was added, the solution was turn to black and stirred for 3 minutes at room temperature, and **1a** (132.0 μL, 1.0 mmol) was added. After 3 h at room temperature, the reaction was quenched with aqueous HCl (0.5 M) and extracted with ethyl acetate, the yield and *E*/*Z* ratio was determined by GC analysis.

General procedure for the allyl arylation: A 15 mL oven-dried flask was added $Ni(acac)_2$ (12.8 mg, 0.05 mmol), TMEDA (0.03 mL, 0.20 mmol) and **1a** (0.53 mL, 4.0 mmol) under argon. Then, dropwise addition of PhMgBr (1.0 mL, 1.0 mmol, 1.0 M in toluene) to the stirred solution at room temperature. After 12 h at room temperature, the reaction was quenched with aqueous HCl (0.5 M) and extracted with ethyl acetate. The organic layer was washed with H_2O and brine, dried with anhydrous $MgSO_4$, and concentrated under reduced pressure. The crude material was purified by silica gel column chromatography (petroleum as eluent) to give 87.3 mg product **3aa** as colorless oil in 53% yield.

3ab: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35 (d, J = 8.13 Hz, 2H), 7.28-7.16 (m, 5H), 7.08 (d, J = 7.87 Hz, 2H), 5.47 (s, 1H), 4.96 (s, 1H), 3.82 (s, 1H), 2.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.66, 139.69, 137.87, 137.22, 128.98, 128.95, 128.35, 126.07, 126.02, 113.83, 41.64, 21.12. GC-MS (M/Z): 208.

3ba: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.47 (d, J = 6.90 Hz, 2H), 7.36-7.27 (m, 3H), 7.18-7.11 (m, 4H), 5.44 (s, 1H), 4.72 (s, 1H), 3.76 (s, 2H), 2.29 (s 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.38, 141.51, 137.73, 136.78, 120.17, 129.94, 128.35, 127.54, 126.46, 125.96, 113.92, 38.92,19.45. GC-MS (M/Z): 208.

3bb: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.38 (d, J = 8.15 Hz, 2H), 7.17-7.12 (m, 6H), 5.43 (s, 1H), 4.68 (s, 1H), 3.75 (s, 2H), 2.34 (s, 3H), 2.29 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.11, 138.57, 137.85, 137.28, 136.76, 139.13, 129.90, 129.03, 126.40, 125.97, 125.80, 113.13, 38.90, 21.12, 19.44. GC-MS (M/Z): 222.

3ca: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.44-7.42 (m, 2H), 7.30-7.12 (m, 4H), 7.04-6.97 (m, 3H), 5.49 (s, 1H), 5.00 (s, 1H), 3.79 (s, 2H), 2.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.98, 140.93, 139.46, 137.89, 129.73, 127.45, 126.88, 126.15, 126.00, 114.55, 41.55, 21.44. GC-MS (M/Z): 208.

3cb: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.33 (d, J = 8.07 Hz, 2H), 7.13-6.98 (m, 6H), 5.47 (s, 1H), 4.96 (s, 1H), 3.78 (s, 2H), 2.31 (s, 3H), 2.30 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.72, 139.60, 137.99, 137.86, 137.17, 129.71, 128.97, 128.22, 126.83, 126.00, 113.75, 41.56, 21.44, 21.10. GC-MS (M/Z): 222.

3na: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.80-7.97 (m, 1H), 7.88-7.84 (m, 1H), 7.76-7.30 (m, 1H), 7.56-7.53 (m, 2H), 7.49-7.46 (m, 2H), 7.40-7.28 (m 5H), 5.51 (s, 1H), 4.77 (s, 1H), 4.25 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.23, 141.18, 135.50, 133.82, 132.22, 128.65, 128.36, 127.58, 127.29, 127.07, 125.87, 125.55, 125.50, 124.21, 114.82, 38.33. GC-MS (M/Z): 244.

3nb: colorless liquid; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00-7.97 (m, 1H), 7.87-7.84 (m, 1H), 7.76-7.73 (m, 1H), 7.50-7.35 (m, 6H), 7.14 (d, J = 8.24 Hz, 2H), 5.49 (s, 1H), 4.72 (s, 1H), 4.23 (s, 2H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.05, 138.32, 137.40, 135.70, 133.86, 132.31, 129.10, 128.69, 127.29, 127.06, 125.89, 125.79, 125.60, 125.53, 124.28, 114.07, 38.38, 21.14. GC-MS (M/Z): 258.

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Keywords: C-H activation • isomerization • cross-coupling • allylic compounds • nickel

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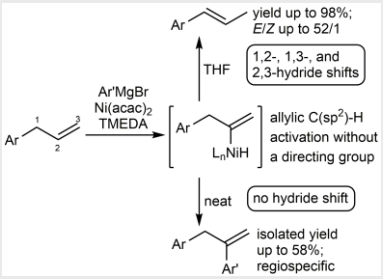
Entry for the Table of Contents (Please choose one layout)

Layout 1:

FULL PAPER

Stereoselective allyl isomerization and regiospecific allyl arylation of allylarenes are triggered by allylic internal C(sp^2)-H activation without a directing group, in which an alkenyl nickel hydride from the C(sp^2)-H activation is the active species trapped in the catalytic cycles.



C-H activation

Q. Wu, L. Wang, R. Jin, C. Kang, Z. Bian, Z. Du, X. Ma, H. Guo, L. Gao*

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Nickel-Catalyzed Allylic C(sp^2)-H Activation: Stereoselective Allyl Isomerization and Regiospecific Allyl Arylation of Allylarenes