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Nickel-Catalyzed Sonogashira Coupling Reactions of Nonactivated Alkyl Chlorides under Mild Conditions

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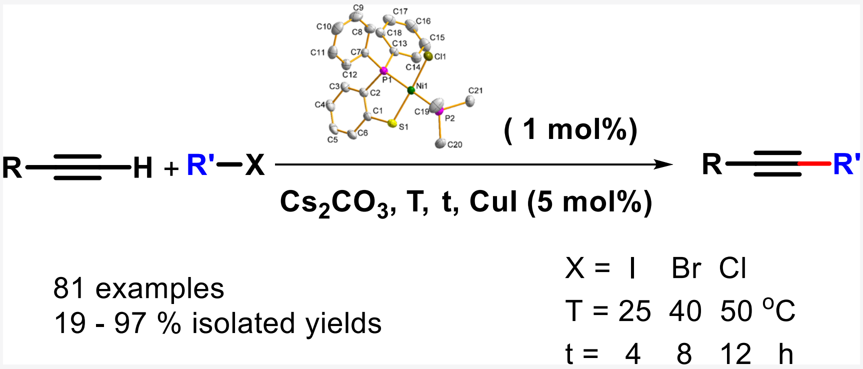

ABSTRACT: The two nickel chlorides **1** and **2** with [P,S] and [P,Se] bidentate ligands, respectively, were synthesized and used as catalysts for Sonogashira coupling reaction. Both **1** and **2** are efficient catalysts for Sonogashira C(sp^3)−C(sp) coupling reactions. Complex **1** has better catalytic activity than complex **2**. In a combination of 1 mol % catalyst loading of **1** and CuI/Cs$_2$CO$_3$/DMSO at 25 °C for the coupling reactions of alkyl iodides with terminal alkynes, the corresponding coupling products were obtained in moderate to excellent yields. This catalytic system is also suitable for alkyl bromides at 40 °C. It must be pointed out that with NaI as an additive complex **1** could effectively catalyze the C(sp^3)−C(sp) coupling of nonactivated alkyl chlorides with alkynes under mild conditions (50 °C) with low catalyst loading (1 mol %). Complex **1** is easy to synthesize and has efficient catalytic activity, especially for alkyl chlorides, under mild conditions.

■ INTRODUCTION

The formation of carbon−carbon bonds is the core of organic chemistry.[1] Traditionally, carbon−carbon bond coupling mainly includes Heck, Suzuki, Kumada, Negishi, and Sonogashira reactions. Through these reactions, C(sp^2)−C(sp^2), C(sp^3)−C(sp^2), or C(sp^2)−C(sp) coupling can be realized. In comparison with other coupling reactions, the Sonongashira coupling reaction has its own unique characteristics, among which alkynes with various functions can be constructed. Various functionalized alkynes are not only important structural units of drug molecules, natural products, and organic materials[2] but also important intermediates in organic synthesis.[3] The transition-metal-catalyzed Sonogashira coupling reaction is one of the important methods to construct functional alkynes. Ever since the palladium-catalyzed C(sp^2)−C(sp) coupling reaction was first reported by Heck, Cassar, and Sonogashira in 1975,[4] the palladium-catalyzed Sonogashira coupling reaction has attracted more and more attention from scientists. There have been many reports on the synthesis of alkynes by C(sp^2)−C(sp) coupling reactions, but there are few examples of alkynes synthesized by C(sp^3)−C(sp) coupling between haloalkanes and alkynes. This is mainly because, on the one hand, the oxidative addition of a C(sp^3)−X bond of haloalkanes is very difficult; on the other hand, β-H elimination can easily occur.[5] Therefore, it is challenging to synthesize functionalized alkynes by C(sp^3)−C(sp) coupling reactions. In 2003, Fu disclosed for the first time a Pd/Cu-catalyzed C(sp^3)−C(sp) coupling reaction between primary bromo- or iodoalkanes and alkynes.[6] Glorius studied the first case of a Pd/Cu-catalyzed C(sp^3)−C(sp) coupling reaction between secondary bromoalkanes and alkynes.[7] In comparison with palladium, nickel in the same group is cheaper and less toxic. Therefore, the Sonogashira coupling reaction catalyzed by nickel complexes has gradually become the focus of chemists. In comparison with the palladium catalyst system, nickel as a catalyst for Sonogashira coupling is rare. In 2009, Hu realized the C(sp^3)−C(sp) coupling reaction of nonactivated haloalkanes

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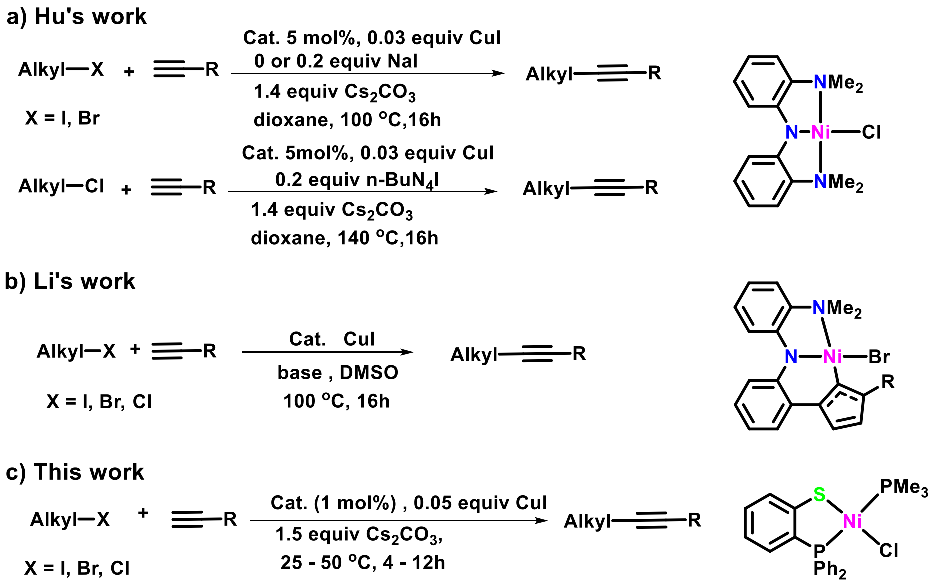
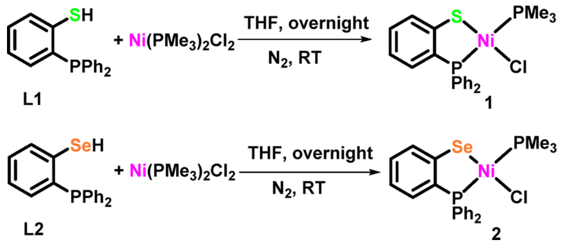
Scheme 1. Nickel-Catalyzed Sonogashira Coupling Reactions



catalyzed by an [NNN] pincer nickel complex. This system not only is suitable for iodoalkanes and bromoalkanes but also has high catalytic yield for chloroalkanes at 140 °C (Scheme 1a).[8] Our group reported that [CNN] pincer nickel complexes could be used as catalysts for C(sp^3)−C(sp) coupling reactions and had a good catalytic effect for secondary haloalkanes at 100 °C (Scheme 1b).[9] This indicates that the activation of a C−Cl bond needs higher reaction temperature (>100 °C). Some other nickel catalysts are only suitable for iodoalkenes and bromoalkanes and are not suitable for chloroalkanes.[10,11] Therefore, C(sp^3)−C(sp) coupling reactions between chlorinated alkanes and alkynes under mild conditions need to be further explored. In addition, most of the nickel catalysts used for Sonogashira coupling reactions are pincer nickel complexes, while nickel chelate complexes are rarely used. In comparison with pincer complexes, chelate complexes are simple and easy to obtain. As we know, [P,O]-chelate nickel complexes have been successfully used in the SHOP process.[12] Because O and S are chalcogenide elements, we explored the [P,S] chelate system and studied the interaction between the [P,S]-chelate nickel hydrides and alkynes.[13] We also found that the [P,S]-chelate iron hydrides have good catalytic effects on the hydrosilylation of aldehydes and ketones.[14] Therefore, as a continuation of our research work in this direction, we have synthesized [P,Y] (Y = S, Se) chelate nickel complexes **1** and **2** and used them to catalyze C(sp^3)−C(sp) coupling reactions. Under mild conditions (25−50 °C), complexes **1** and **2** could catalyze not only the coupling reactions of iodoalkanes and bromoalkanes but also the coupling reactions of chloroalkanes in high yields with a low catalyst loading (Scheme 1c).

Scheme 2. Synthesis of Nickel Chlorides 1 and 2



■ RESULTS AND DISCUSSION

The nickel complex **1** or **2** was prepared from the reaction of 2-(diphenylphosphanyl)benzenethiol (**L1**) or 2-(diphenylphosphanyl)benzeneselenol (**L2**) with $NiCl_2(PMe_3)_2$ in THF in a yield of 70% or 64%, respectively (Scheme 2).[15,16] In the ^{31}P NMR spectrum of complex **1** a signal for the $-PPh_2$ group is situated at 48.95 ppm while the resonance of PMe_3 ligand is registered at −14.74 ppm. A single-crystal X-ray diffraction analysis confirmed that complex **1** has a distorted-square-planar structure with the Ni atom in the center (Figure 1). The two coordinated P atoms are in *trans* positions. Complex **2** has the spectroscopic and structural characteristics similar to those of **1**. Both **1** and **2** in the solid state are air-stable, but **1** is not stable at room temperature in solution and transforms gradually into a bis-chelated nickel complex.[13b]

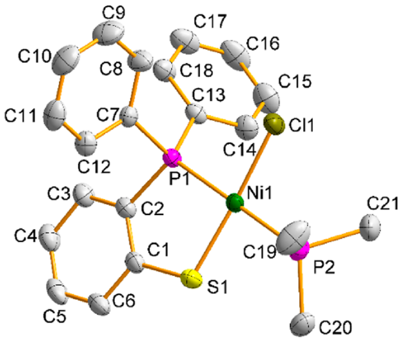
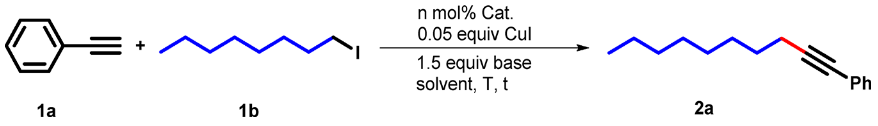


Figure 1. Molecular structure of complex **1**. Thermal ellipsoids are drawn at the 50% probability level. Hydrogen atoms have been omitted for clarity. Selected bond lengths (Å) and angles (deg): Ni1−Cl1 2.19(8), Ni1−S1 2.14 (9), Ni1−P1 2.17(9), Ni1−P2 2.21(9); Cl1−Ni1−S1 174.9(4), P1−Ni1−P2 179.3(4), Cl−Ni1−P1 90.1(3), P1−Ni1−S1 89.2(3), P2−Ni1−Cl1 90.3(4), S1−Ni1−P2 90.5(4).

Table 1. Optimization for Sonogashira Coupling Reaction[a]



entry	catalyst	loading (mol %)	base (1.5 equiv)	solvent	temp (°C)	time (h)	conversn[b] (%)	yield[c] (%)
1	**1**	1	Cs_2CO_3	DMSO	50	2	95	91
2	**1**	1	Cs_2CO_3	DMSO	25	2	87	83
3	**1**	1	Cs_2CO_3	DMSO	25	3	97	92
4	**1**	1	Cs_2CO_3	DMSO	25	4	99	92
5	**2**	1	Cs_2CO_3	DMSO	25	4	87	82
6	**1**	0.5	Cs_2CO_3	DMSO	25	4	58	51
7	**2**	0.5	Cs_2CO_3	DMSO	25	4	47	42
8	**1**	0.5	Cs_2CO_3	DMSO	25	12	73	69
9	**1**	1	K_2CO_3	DMSO	25	4	75	72
10	**1**	1	Na_2CO_3	DMSO	25	4	23	19
11	**1**	1	^{t}BuOK	DMSO	25	4	52	47
12	**1**	1	^{t}BuONa	DMSO	25	4	30	26
13	**1**	1	Cs_2CO_3	dioxane	25	4	51	47
14	**1**	1	Cs_2CO_3	PhMe	25	4	27	23
15	**1**	1	Cs_2CO_3	CH_2Cl_2	25	4	63	58
16	**1**	1	Cs_2CO_3	Et_2O	25	4	53	48
17	**1**	1	Cs_2CO_3	THF	25	4	57	52
18	**1**	1	Cs_2CO_3	CH_3CN	25	4	68	62
19	**1**	1	Cs_2CO_3	DME	25	4	52	47
20	**1**	1	Cs_2CO_3	DMF	25	4	78	73
21			Cs_2CO_3	DMSO	25	4	0	0
22	**1**	1	Cs_2CO_3	DMSO	25	4	0[d]	0

[a] Reaction conditions unless specified otherwise: phenylacetylene (1.0 mmol), 1-iodooctane (1.1 mmol), base (1.5 mmol), and CuI (0.05 mmol) in solvent (2.5 mL). [b] Determined by GC with *n*-dodecane as an internal standard (1.0 mmol). [c] Isolated yields. [d] Without CuI.

Using phenylacetylene and 1-iodooctane as template substrates with complex **1** or **2** as the catalyst, the reaction conditions of Sonogashira coupling were investigated (Table 1). When the catalyst loading was 1 mol % with Cs_2CO_3 as a base, 5 mol % CuI as a cocatalyst, and DMSO as the solvent at 50 °C, 95% conversion could be achieved in 2 h (entry 1, Table 1). When the temperature was reduced to 25 °C, 87% conversion could be achieved in 2 h and the complete conversion was finished in 4 h (entries 2−4, Table 1). According to entries 5−7 in Table 1, the catalytic effect of complex **1** is better than that of complex **2**. When the amount of complex **1** was reduced to 0.5 mol %, the conversion could only reach 73% even when the reaction time was prolonged to 12 h (entry 8, Table 1). In comparison with other bases, such as K_2CO_3, Na_2CO_3, ^{t}BuOK, and ^{t}BuONa, the conversion with Cs_2CO_3 is the highest (entries 4 and 9−12, Table 1). In comparison with other solvents, such as dioxane, PhMe, CH_2Cl_2, Et_2O, THF, CH_3CN, DME, and DMF, the best reaction medium for the catalytic system is DMSO (entries 4 and 13−20, Table 1). It can be seen that the greater the polarity of the solvent, the higher the catalytic efficiency of the system. The control experiments showed that the catalytic reaction could not take place without complex **1** or CuI (entries 21 and 22, Table 1). Therefore, it can be speculated that the catalytic system is a complex **1**/CuI synergetic catalytic system, and Cu plays the role of a cocatalyst in the catalytic system. Finally, we chose catalyst **1** as the catalyst (1 mol %), 150 mol % of Cs_2CO_3 as the base, 5 mol % CuI as the cocatalyst, and DMSO as the solvent at 25 °C for 4 h as the optimized conditions (entry 4, Table 1) to expand the scope of the substrates.

For iodinated alkanes, the isolated yields could reach 88−92% under the optimized reaction conditions (Table 2). The reaction of 2-ethynylpyridine with 1-iodooctane provided the C(sp^3)−C(sp) coupling product in 88% yield. At 25 °C, the catalytic yields with bromoalkanes are not as good as those with iodoalkanes. When the reaction temperature was raised to 40 °C and the reaction time was extended to 8 h, the isolated yields with brominated substrates were 68−94%. Under more demanding conditions (50 °C, 12 h) with the addition of NaI, the catalytic effect with chloroalkane substrates could reach 49−97% isolated yields. No matter whether there was an electron-donating group (−OMe) or electron-withdrawing group (−Cl) in the *para* position of the phenyl ring, the substrates could achieve complete conversion. For both secondary and tertiary chloroalkanes, the yields were good. This catalytic system is also tolerant toward amino, hydroxyl, and ester groups. For the aliphatic alkynes the yields are relatively low (19−47%). In ccomparison with the previously reported pincer nickel compexes,[8−11] this catalytic system has the following advantages: complex **1** is easy to synthesize and has efficient catalytic activity with a lower catalyst loading, especially for alkyl chlorides, under mild conditions.

The gram-scale reaction between phenylacetylene and 1-chlorooctane using 1 mol % of catalyst **1** could be smoothly carried out to give rise to octylphenylacetylene (**2a**) in 91% yield (Scheme 3).

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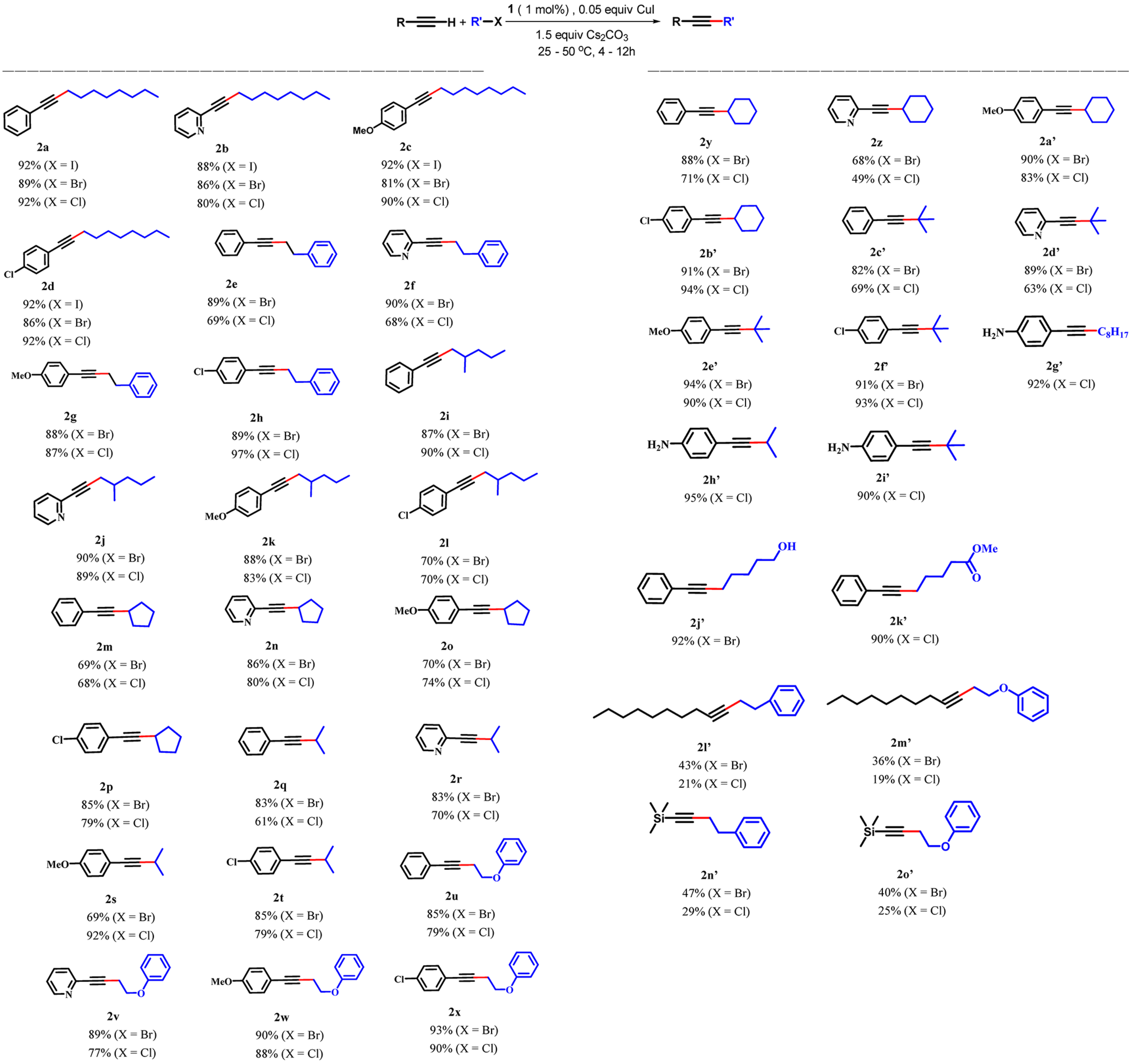
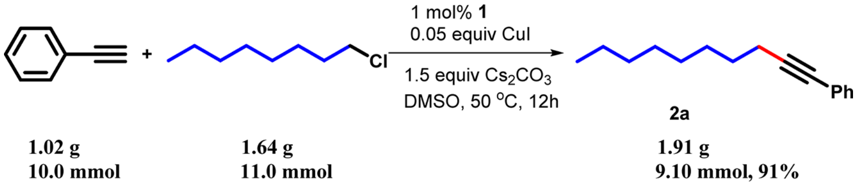
Table 2. Scope of Alkynes and Alkyl Halides[a]



[a] Reaction conditions for X = I: alkynes (1.0 mmol), alkyl iodides (1.1 mmol), Cs_2CO_3 (1.5 mmol), CuI (0.05 mmol), and **1** (0.01 mmol) in 2.5 mL of DMSO, 4 h, 25 °C. Isolated yields. Reaction conditions for X = Br: alkynes (1.0 mmol), alkyl bromides (1.1 mmol), Cs_2CO_3 (1.5 mmol), CuI (0.05 mmol), and **1** (0.01 mmol) in 2.5 mL of DMSO, 8 h, 40 °C. Isolated yields. Reaction conditions for X = Cl: alkynes (1.0 mmol), alkyl chlorides (1.1 mmol), Cs_2CO_3 (1.5 mmol), CuI (0.05 mmol), NaI (0.2 mmol), and **1** (0.01 mmol) in 2.5 mL of DMSO, 12 h, 50 °C. Isolated yields.

Scheme 3. Gram-Scale Reaction of Phenylacetylene with 1-Chlorooctane



CONCLUSIONS

In conclusion, we have synthesized the [P,S]-chelated nickel chloride **1** and the [P,Se]-chelated nickel chloride **2**. The structures of complexes **1** and **2** were confirmed by IR, NMR, and single crystal X-ray diffraction analysis. Both complexes could catalyze the Sonagashira C(sp^3)−C(sp) coupling reactions, but the catalytic effect of complex **1** is better than that of complex **2**. The reaction temperature is mild, and the yields for both secondary and tertiary alkyl halides could reach from above medium to an excellent level. Especially, complex **1** has a good catalytic effect on chloroalkanes under mild conditions (50 °C) with low catalyst loading (1 mol %).

EXPERIMENTAL SECTION

General Considerations. All experiments and manipulations were performed under a N_2 atmosphere utilizing the standard Schlenk techniques. THF, *n*-pentane, diethyl ether, toluene, and dioxane were dried and freshly distilled by Na-benzophenone before use under a nitrogen atmosphere. DMSO, DMF, DME, CH_2Cl_2, and CH_3CN were dried through molecular sieves. $NiCl_2(PMe_3)_2$,[17] **L1**, and **L2** were synthesized according to the literature methods.[15,16] Alkynes and alkyl halides were purchased and used without further purification. Melting points (mp) were measured on a WRR instrument with samples sealed in capillaries. Infrared spectra (4000−400 cm^{-1}) were recorded on a a Bruker ALPHA Fourier transform infrared (FT-IR) instrument from Nujol mulls between KBr disks. The ^1H, ^{31}P, and ^{13}C NMR spectra were recorded with a 300 MHz Bruker instrument. Gas chromatography (GC) was carried out with a Fuli 9790 spectrometer and performed with *n*-dodecane as an internal standard.

Synthesis of Complex 1. A solution of ligand **L1** (1.00 g, 3.40 mmol) in THF (35 mL) was mixed slowly with a solution of $NiCl_2(PMe_3)_2$ (1.10 g, 3.74 mmol) in THF (35 mL) at −78 °C under a N_2 atmosphere. The reaction solution was warmed to room temperature and stirred overnight, and the red solution gradually turned brown-yellow. After removal of the volatiles under vacuum, the brown-yellow residue was extracted with *n*-pentane and diethyl ether and filtered through Celite. Complex **1** (1.10 g) was obtained as square brown-yellow crystals from diethyl ether in 70% yield at −10 °C. Anal. Calcd for $C_{21}H_{23}ClNiP_2S$ (463.57 g mol^{-1}): C, 54.41; H, 5.00. Found: C, 54.00; H, 5.11. Mp: >195 °C. IR (Nujol mull, KBr, cm^{-1}): 951 (PMe_3). ^{31}P NMR (121 MHz, C_6D_6, 298 K, ppm): δ 48.95 (d, J = 346 Hz, 1P, *P*Ph_2), −14.74 (d, J = 346 Hz, 1P, *P*Me_3). ^1H NMR (300 MHz, C_6D_6, 298 K, ppm): δ 7.74−7.28 (m, 11H, Ar-*H*), 7.11−6.83 (m, 3H, Ar-*H*), 1.34 (d, 9H, PCH_3). ^{13}C NMR (75 MHz, C_6D_6, 298 K, ppm): δ 133.9, 133.7, 133.2, 132.0, 131.4, 130.3, 128.5, 128.3, 128.1, 127.8, 127.5, 29.9, 12.7, 12.4.

Synthesis of Complex 2. A solution of ligand **L2** (1.00 g, 2.93 mmol) in THF (35 mL) was mixed slowly with a solution of $NiCl_2(PMe_3)_2$ (0.91 g, 3.22 mmol) in THF (35 mL) at −78 °C under a N_2 atmosphere. The reaction solution was warmed to room temperature and stirred overnight, and the red solution gradually turned brown-yellow. After removal of the volatiles under vacuum, the brown-yellow residue was extracted with *n*-pentane and diethyl ether and filtered through Celite. Complex **2** (0.96 g) was obtained as square brown-yellow crystals from diethyl ether in 64% yield at −10 °C. Anal. Calcd for $C_{21}H_{23}ClNiP_2Se$ (510.47 g mol^{-1}): C, 49.41; H, 4.54. Found: C, 49.12; H, 4.72. Mp: >183 °C. IR (Nujol mull, KBr, cm^{-1}): 954 (PMe_3). ^{31}P NMR (121 MHz, C_6D_6, 298 K, ppm): δ 54.79 (d, J = 276 Hz, 1P, *P*Ph_2), −16.11 (d, J = 290 Hz, 1P, *P*Me_3). ^1H NMR (300 MHz, C_6D_6, 298 K, ppm): δ 8.09−7.86 (m, 5H, Ar-*H*), 7.26−6.75(m, 9H, Ar-*H*), 1.08 (d, 9H, PCH_3). ^{13}C NMR (75 MHz, C_6D_6, 298 K, ppm): δ 133.9, 133.7, 133.2, 132.0, 131.4, 130.3, 128.5, 128.3, 128.1, 127.8, 127.5, 29.9, 12.7, 12.4.

General Procedure for Sonogashira Coupling Reactions. A 25 mL dried Schlenk tube containing Cs_2CO_3 (0.49 g, 1.5 mmol) and CuI (0.01 g, 0.05 mmol) was purged with N_2, and alkyne (1.0 mmol), alkyl halide (1.1 mmol) and anhydrous solvent (2.5 mL) were added. In the case of alkyl chloride, NaI (0.03 g, 0.2 mmol) was added. The catalytic mixture was stirred for 4 h at room temperature for alkyl iodide and heated for 8 h at 40 °C for alkyl bromide and for 12 h at 50 °C for alkyl chloride. After the reaction the solution was cooled to room temperature and quenched with 15 mL of water and 1 mL of 1 mol/L HCl. The mixture was extracted with Et_2O (3 × 20 mL), and a moderate amount of anhydrous Na_2SO_4 was added to the extraction solution. The product could be obtained by flash chromatography on silica gel.

X-ray Crystal Structure Determination. Intensity data and cell parameters were recorded on a Stoe StadiVari diffractometer, employing Ga Kα radiation (λ = 1.34143 Å). The structures were solved using the charge-flipping algorithm, as implemented in the program SUPERFLIP,[18] and refined by full-matrix least-squares techniques against F^2 using the SHELXL[19] program through the OLEX2[20] interface. All non-hydrogen atoms were refined anisotropically, and all hydrogen atoms except for those of the disordered solvent molecules were placed using AFIX instructions. Appropriate restraints or constraints were applied to the geometry and the atomic displacement parameters of the atoms. CCDC 1865451 (complex **1**) contains supplementary crystallographic data for this paper.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.organomet.0c00793.

Spectroscopic data for complexes **1** and **2** and characterization data for the catalytic products (PDF)

Accession Codes

CCDC 1865451 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Knochel, P.; Molander, G. A. *Comprehensive Organic Synthesis*, 2nd ed.; Elsevier: Amsterdam, 2014.

(2) Patai, S. *Chemistry of Triple-Bonded Functional Groups*; Wiley: New York, 1994.

(3) Stang, P. J.; Diederich, F. *Modern Acetylene Chemistry*; VCH: Weinheim, Germany, 1995.

(4) (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. A. convenient synthesis of acetylenes: catalytic substitutions of acetylenic hydrogen with bromoalkenes, iodoarenes and bromopyridines. *Tetrahedron Lett.* **1975**, *16*, 4467−4470. (b) Dieck, H. A.; Heck, F. R. Palladium catalyzed synthesis of aryl, heterocyclic and vinylic acetylene derivatives. *J. Organomet. Chem.* **1975**, *93*, 259−263. (c) Cassar, L. Synthesis of aryl-and vinyl-substituted acetylene derivatives by the use of nickel and palladium complexes. *J. Organomet. Chem.* **1975**, *93*, 253−257.

(5) (a) Eckhardt, M.; Fu, G. C. The First Applications of Carbene Ligands in Cross-Couplings of Alkyl Electrophiles: Sonogashira Reactions of Unactivated Alkyl Bromides and Iodides. *J. Am. Chem. Soc.* **2003**, *125*, 13642−13643. (b) Liu, W.-B.; Li, L.; Li, C.-J. Empowering a transition-metal-free coupling between alkyne and alkyl iodide with light in water. *Nat. Commun.* **2015**, *6*, 6526. (c) Liu, W.-B.; Chen, Z.-W.; Li, L.; Wang, H.-N.; Li, C.-J. Transition-Metal-Free Coupling of Alkynes with a-Bromo Carbonyl Compounds: An Efficient Approach towards b, g-Alkynoates and Allenoates. *Chem. - Eur. J.* **2016**, *22*, 5888−5893.

(6) Eckhardt, M.; Fu, G. C. The First Applications of Carbene Ligands in Cross-Couplings of Alkyl Electrophiles: Sonogashira Reactions of Unactivated Alkyl Bromides and Iodides. *J. Am. Chem. Soc.* **2003**, *125*, 13642−13643.

(7) Altenhoff, G.; Würtzb, S.; Glorius, F. The first palladium-catalyzed Sonogashira coupling of unactivated secondary alkyl bromides. *Tetrahedron Lett.* **2006**, *47*, 2925−2928.

(8) Vechorkin, O.; Barmaz, D.; Proust, V.; Hu, X.-L. Ni-Catalyzed Sonogashira Coupling of Nonactivated Alkyl Halides: Orthogonal Functionalization of Alkyl Iodides, Bromides, and Chlorides. *J. Am. Chem. Soc.* **2009**, *131*, 12078−12079.

(9) Wang, Z.; Zheng, T.; Sun, H.; Li, X.; Fuhr, O.; Fenske, D. Sonogashira reactions of alkyl halides catalyzed by NHC [CNN] pincer nickel(II) complexes. *New J. Chem.* **2018**, *42*, 11465−11470.

(10) Yi, J.; Lu, X.; Sun, Y.-Y.; Xiao, B.; Liu, L. Nickel-Catalyzed Sonogashira Reactions of Non-activated Secondary Alkyl Bromides and Iodides. *Angew. Chem., Int. Ed.* **2013**, *52*, 12409−12413.

(11) Perez Garcia, P. M.; Ren, P.; Scopelliti, R.; Hu, X. Nickel-Catalyzed Direct Alkylation of Terminal Alkynes at Room Temperature: A Hemilabile Pincer Ligand Enhances Catalytic Activity. *ACS Catal.* **2015**, *5*, 1164−1171.

(12) Keim, W. Nickel: Ein Element mit vielflltigen Eigenschaften in der technisch-homogenen Katalyse. *Angew. Chem.* **1990**, *102*, 251−260.

(13) (a) Xue, B.; Sun, H.; Ren, S.; Li, X.; Fuhr, O. Vinyl/Phenyl Exchange Reaction within Vinyl Nickel Complexes Bearing Chelate [P, S]-Ligands. *Organometallics* **2017**, *36*, 4246−4255. (b) She, L.; Li, X.; Sun, H.; Ding, J.; Frey, M.; Klein, H.-F. Insertion of Alkynes into Ni-H Bonds: Synthesis of Novel Vinyl Nickel(II) and Dinuclear Vinyl Nickel(II) Complexes Containing a [P, S]-Ligand. *Organometallics* **2007**, *26*, 566−570.

(14) Xue, B.; Sun, H.; Li, X. Syntheses and catalytic application of hydrido iron(II) complexes with [P,S]-chelating ligands in hydrosilylation of aldehydes and ketones. *RSC Adv.* **2015**, *5*, 52000−52006.

(15) Block, E.; Eswarakrishnan, V.; Gernon, M.; Ofori-Okai, G.; Saha, C.; Tang, K.; Zubieta, J. *o*-Lithiothiophenol equivalents: Generation, Reactions, and Applications in Synthesis of Hindered Thiolate Ligands. *J. Am. Chem. Soc.* **1989**, *111*, 658−665.

(16) Zhou, H.; Sun, H.; Zheng, T.; Zhang, S.; Li, X. Synthesis of Vinylnickel and Nickelacyclopropane Complexes Containing a Chelate [P, Se]-Ligand. *Eur. J. Inorg. Chem.* **2015**, *2015*, 3139−3145.

(17) Jensen, K. A.; Dahl, O.; Lindblom, T.; Schwieter, U.; Paasivirta, J. Nickel(II) complexes of trimethylphosphine. *Acta Chem. Scand.* **1968**, *22*, 1044−1045.

(18) Palatinus, L.; Chapuis, G. SUPERFLIP, A Computer Program for the Solution of Crystal Structures by Charge Flipping in Arbitrary Dimensions. *J. Appl. Crystallogr.* **2007**, *40*, 786−790.

(19) Sheldrick, G. M. A Short History of SHELX. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **2008**, *A64*, 112−122.

(20) Dolomanov, O. V.; Bourhis, L. J.; Gildea, R. J.; Howard, J. A. K.; Puschmann, H. OLEX2: A Complete Structure Solution, Refinement and Analysis Program. *J. Appl. Crystallogr.* **2009**, *42*, 339−341.