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Ni(II) Precatalysts Enable Thioetherification of (Hetero)Aryl Halides and Tosylates and Tandem C–S/C–N Couplings

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Abstract: Ni-catalyzed C–S cross-coupling reactions have received less attention compared with other C-heteroatom couplings. Most reported examples comprise the thioetherification of most reactive aryl iodides with aromatic thiols. The use of C–O electrophiles in this context is almost uncharted. Here, we describe that preformed Ni(II) precatalysts of the type NiCl(allyl)(PMe_2Ar') (Ar′ = terphenyl group) efficiently couple a wide range of (hetero)aryl halides, including challenging aryl chlorides, with a variety of aromatic and aliphatic thiols. Aryl and alkenyl tosylates are also well tolerated, demonstrating, for the first time, to be competent electrophilic partners in Ni-catalyzed C–S bond formation. The chemoselective functionalization of the C–I bond in the presence of a C–Cl bond allows for designing site-selective tandem C–S/C–N couplings. The formation of the two C-heteroatom bonds takes place in a single operation and represents a rare example of dual electrophile/nucleophile chemoselective process.

Introduction

Thioethers are prevalent in many natural products,[1] in addition to being valuable intermediates for pharmaceutical[2] and material science[3] applications. Moreover, the rising interest in the activation of C–S bonds by transition metals has opened up new opportunities to transform thioethers into diverse functionalized organic compounds.[4] A general approach for the synthesis of thioethers relies on the use of transition metal-catalyzed C–S cross-coupling reactions between organic halides and thiols under basic conditions.[5] In these transformations, both copper- and palladium-based catalyst systems have proven to be very effective and versatile in terms of functional group tolerance.[5] However, an important limitation of the less expensive copper approach is the inefficiency to couple chloroarenes or phenol-derived electrophiles in a reliable manner.[6] Conversely, thioetherification of challenging aryl chlorides has been successfully accomplished with palladium using bisphosphines[7–8] and N-heterocyclic carbene ligands.[9] However, so far, only limited examples of the use aryl triflates[7a,10] as electrophilic coupling partners and a single case illustrating the coupling between phenyl tosylate[7a] with 1-octanethiol under palladium catalysis have been reported. The synthesis of alkenyl sulfides through Pd-catalyzed coupling of alkenyl tosylates and thiols have been recently described.[11]

Nickel is able to activate those bonds that are less reactive with copper and palladium.[12] However, it is noticeable the scarcity of protocols developed for using aryl chlorides as electrophiles in C–S bond forming reactions.[13] In these reported examples, chelating ligands (i.e. diamines,[13a] Schiff bases,[13e] bisphosphines[13b–d]) were employed to stabilize Ni species and, in some cases, stoichiometric amount of a reductant (i.e. Zn,[13c] organomagnesium or organozinc reagents[13d]) were required to achieve an efficient transformation. Very recently, electrochemical Ni-catalyzed thioetherification of aryl bromides and chlorides has been described,[14] but only electron-deficient chloroarenes are successfully coupled under these conditions.[14a] Regarding the use of phenol-derived electrophiles in Ni-catalyzed C–S cross-coupling, in 1995, Percec and co-workers[15] outlined the first and, to our knowledge, the only application of phenol-derived electrophiles in the synthesis of diaryl sulfides catalyzed by Ni(0) species. High yield of the C–S coupling product was obtained when combining phenyl mesylate with sodium benzenethiolate. However, attempts to extend the scope to *p*-substituted aryl mesylates resulted in low yields of non-symmetrical disulfides together with considerable

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amounts of side products (i.e. diphenyl sulfide and arene resulting from reduction or aryl mesylate).

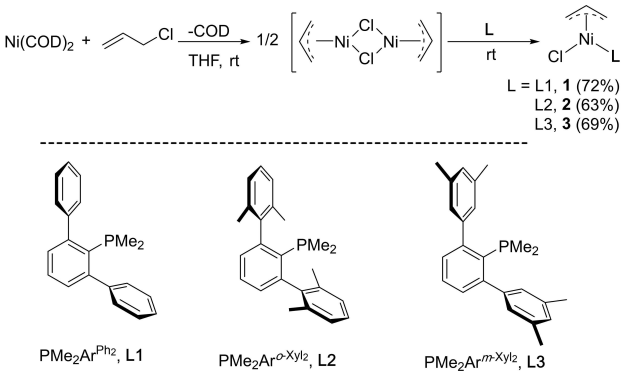
Monodentate ancillary ligands are rarely used to support nickel catalysts for C–S bond forming reactions, the exception being Ni complexes with N-heterocyclic carbenes (NHCs).[16] Among the latter, well-defined complexes of the type (NHC)Ni(allyl)Cl with a 1:1 nickel to ligand ratio described by us[16b] as well as the group of Nolan,[16d] displayed excellent activities in the coupling of aryl iodides and bromides with thiophenols, although aryl chlorides were much less reactive. We wondered whether analogous Ni(II)-allyl complexes ligated by electron-rich and sterically-hindered monophosphine ligands might be better candidates to promote the C–S coupling of problematic substrates such as aryl chlorides and phenol-derived electrophiles. In this vein, it has been recently shown the efficient coupling of aryl bromides with thiols at room temperature promoted by a monophosphine-based Pd catalyst.[17] Our group has recently developed a family of strong electron-donating and sterically demanding dialkylterphenyl phosphine ligands.[18] The bulky terphenyl moiety in these phosphines provides effective steric protection to the metal center along with additional stabilization through weak M–C_{arene} interactions involving one of the flanking aryl rings.[19] These ligand features could improve the Ni catalyst lifetime in C–S cross-coupling, preventing thiolate-mediated deactivation.[20] With this in mind, we prepared and structurally characterized a series of NiCl(allyl)(PMe_2Ar') complexes (Ar′ = terphenyl group). Their catalytic activity have been examined in the S-arylation of aromatic and aliphatic thiols with a variety of electrophiles, including aryl and heteroaryl chlorides, bromides and iodides and, for the first time, tosylates. In addition, a protocol for tandem C–S/C–N couplings in a single reaction has been devised.

Results and Discussion

Synthesis and structural characterization of Ni(II) complexes

The synthesis of NiCl(allyl)(PMe_2Ar') complexes **1**–**3** was accomplished by the addition of one equivalent of the dialkylterphenyl phosphine **L1**–**L3** to a THF solution of (allyl)Ni(II) chloride-bridged dimer, generated in situ via oxidative addition of allyl chloride to $Ni(COD)_2$ (COD = 1,5-cyclooctadiene) (Scheme 1). Compounds **1**–**3** were isolated in good yields (63–72%) as orange crystalline materials by recrystallization from petroleum ether : dichloromethane (2:1) mixtures at −20 °C. They were moderately air stable as solids but decomposed in solution when exposed to air.

Complexes **1**–**3** were characterized by elemental analyses and NMR spectroscopy. In the $^{31}P\{^1H\}$ NMR spectra, the resonances of the P nuclei are significantly shifted (ca. 30–35 ppm) to higher frequencies with respect to the uncoordinated phosphine ligands. The room-temperature ^1H and $^{13}C\{^1H\}$ NMR spectra of these complexes are in agreement with a monodentate coordination mode of the P ligand in conjunction with fast rotation along P–C_{aryl} bond on the NMR time scale. However, the rotation around the P–Ni bond is hindered and



Scheme 1. Synthesis of complexes **1**–**3**.

the two P–Me bound groups give rise to two distinct doublets in the low-frequency region of the spectra ($^2J_{HP} \approx 8$ Hz and $^1J_{CP} \approx 27$ Hz). In turn, all these compounds show five distinct ^1H resonances for the allyl protons, consistent with an η^3-bound allyl ligand in a C_1-symmetric molecule.[21] The terminal allylic protons bound to the carbon atom in pseudo-*trans* position to the phosphine appear at higher frequency (ca. 3.6–2.4 Hz) than those in pseudo-*trans* position to the chloride (ca. 2.3–0.8 Hz).

The molecular structures of **1**–**3** were confirmed by X-ray diffraction studies (Figure 1 and Figure S1). In these compounds, the coordination sphere about the Ni atom is formed by the phosphine ligand, the chloride and the three carbon atoms of an η^3-allyl group. As a result of the *trans* influence exerted by the phosphine ligand, the Ni–C1 bond distances (2.053–2.078 Å) for the allyl carbon atoms pseudo-*trans* to the phosphine are slightly longer than the Ni–C3 bond distances (1.982–1.997 Å) pseudo-*trans* to the chloride. In addition, the C1–C2 separations are ca. 0.04 shorter than the C2–C3 (significant disorder at the allyl group in the structure of **3** precludes an accurate comparison of such bond distances). The Ni–P and Ni–Cl bond lengths are similar to those reported for Ni(II)-allyl complexes.[22]

Catalytic studies

The catalytic activity of compounds **1**–**3** in the C–S coupling of iodobenzene with thiophenol, the model reaction, was evaluated. Complex **1** was selected as the precatalyst to optimize the reaction conditions. Quantitative yield of the diphenyl sulfide product was obtained when the trial was conducted in dioxane at 110 °C for 24 h, using 5 mol% catalyst loading and NaO*t*Bu as the base (see Table 1, entry 1). Decreasing the reaction time up to 16 h does not erode the yield, whereas incomplete conversions were observed when running the C–S coupling for 8 h (Table 1, entries 2 and 3). The yield over the same period of time (16 h) was not affected when the reaction was performed at 100 °C, but at lower temperature inferior results were noted (entries 4 and 5). A set of experiments were accomplished to adjust the catalyst loading. With 3 mol% of **1** full conversion of the iodobenzene was attained (entry 6), but a

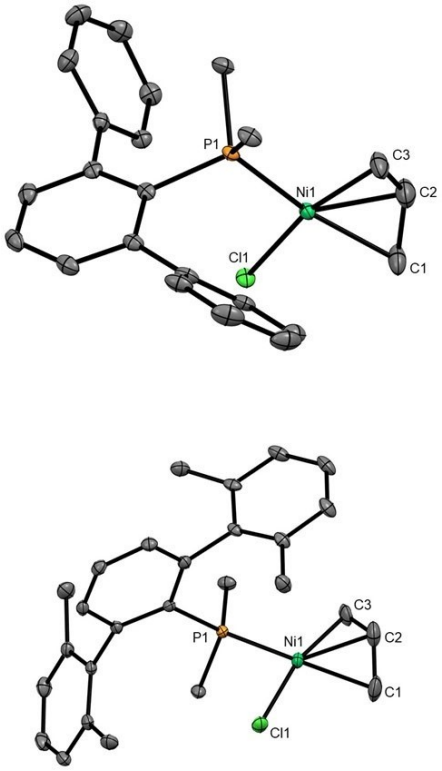


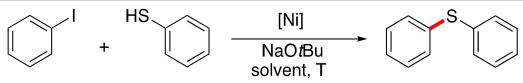
Figure 1. Solid-state structures of complexes **1** (top) and **2** (bottom). Hydrogen atoms are omitted for clarity. Thermal ellipsoids are shown at 50% probability. Selected bond lengths [Å] and angles [°] for **1**: Ni1-P1 2.1904(5), Ni-Cl1 2.2047(5), Ni1-C1 2.078(2), Ni-C2 1.994(2), Ni-C3 1.982(2), C1-C2 1.362(4), C2-C3 1.405(4), C1-C2-C3 120.3(3), P1-Ni-Cl1 102.28(2); for **2**: Ni1-P1 2.1989(5), Ni-Cl1 2.2034(5), Ni1-C1 2.053(2), Ni-C2 1.984(2), Ni-C3 1.997(2), C1-C2 1.377(4), C2-C3 1.409(3), C1-C2-C3 120.2(2), P1-Ni-Cl1 96.17(2).

further reduction of the catalyst loading to 2 mol% led to a substantial drop in the yield (entry 7). Furthermore, the use of DMF as the solvent facilitated the C–S coupling in a shorter time of 6 h (Table 1, entry 8). Among the three Ni(II) precatalysts tested, complex **3** displayed the lower activity (entry 10). Finally, control experiments revealed no reaction in the absence of the nickel complex (entry 13). Interestingly, we do not detect the formation of the disulfide byproduct in any of experiments discussed above.

Having identified the best performing Ni(II) precatalysts and the suitable reaction conditions for the efficient thioetherification of iodobenzene,[23] we tested other haloarenes as potential coupling partners for the C–S coupling with thiophenol (Table 2). Bromobenzene is somewhat less reactive than the parent iodobenzene and a catalyst loading of 5 mol% was required to ensure full conversion (Table 2, entries 1–3). The more challenging chlorobenzene produced a sluggish reaction in DMF even at higher loadings (10 mol%) and extended reaction times (entries 4 and 5). However, we observed that when the C–S coupling was undertaken in NMP (NMP = *N*-methylpyrrolidone) at 120 °C with a catalyst loading of 10 mol%, the expected diphenyl sulfide was obtained in excellent yield with both precatalysts (entries 6 and 7).

Following the optimization studies, complexes **1** and **2** were selected for exploring the scope of these C–S couplings. As summarized in Table 3, a collection of (hetero)aryl chlorides/bromides/iodides reacted with a variety of thiophenols affording the coupling products in good-to-excellent yields. Both, electron-rich (Table 3, **4b–f**, **4h**, **4i** and **4t**) and electron-withdrawing substituents (Table 3, **4g**, **4k**, **4l**) on the aryl halides were well tolerated providing access to the corresponding diarylsulfides in useful synthetic yields under the optimal reaction conditions. Moreover, this catalytic protocol is also compatible with *ortho*-substitution on both coupling partners without the need of increasing the catalyst loading (**4e**, **4h–i**, **4q**, **4t**). Interestingly, aryl iodides could be selectively coupled with thiophenols in the presence of a chloride or a bromide functionality (Table 3, **4k–l**), allowing further derivatizations of the corresponding sulfides (see below). Moreover, (*p*-phenylene) sulfide oligomers (Table 3, **4m–n**) were prepared through two C–S bond formations from the reaction of 1-chloro-4-iodobenzene with two equivalents of the corresponding thiophenol, using the reaction conditions optimized for the thiotherification of aryl chlorides. Compounds of this kind exhibit interesting thermal and conducting properties.[24] Finally, nitrogen-containing heteroaryl halides could be efficiently

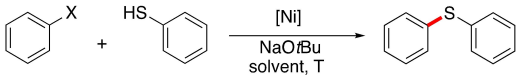
Table 1. Optimization of reaction conditions and screening of precatalysts for the model reaction.[a]



Entry	[Ni]	[Ni] (mol%)	T (°C)	Solvent	Time (h)	Yield (%)[b]
1	**1**	5	110	dioxane	24	99
2	**1**	5	110	dioxane	16	98
3	**1**	5	110	dioxane	8	52
4	**1**	5	100	dioxane	16	98
5	**1**	5	80	dioxane	16	89
6	**1**	3	100	dioxane	16	97
7	**1**	2	100	dioxane	16	61
8	**1**	3	100	DMF	6	98
9	**2**	3	100	dioxane	16	98
10	**3**	3	100	dioxane	16	85
11	-	-	100	DMF	6	0

[a] Reaction conditions: iodobenzene (1.0 mmol), thiophenol (1.1 mmol), NaO*t*Bu (1.2 mmol), solvent (1 mL). [b] Isolated yields (average of two runs).

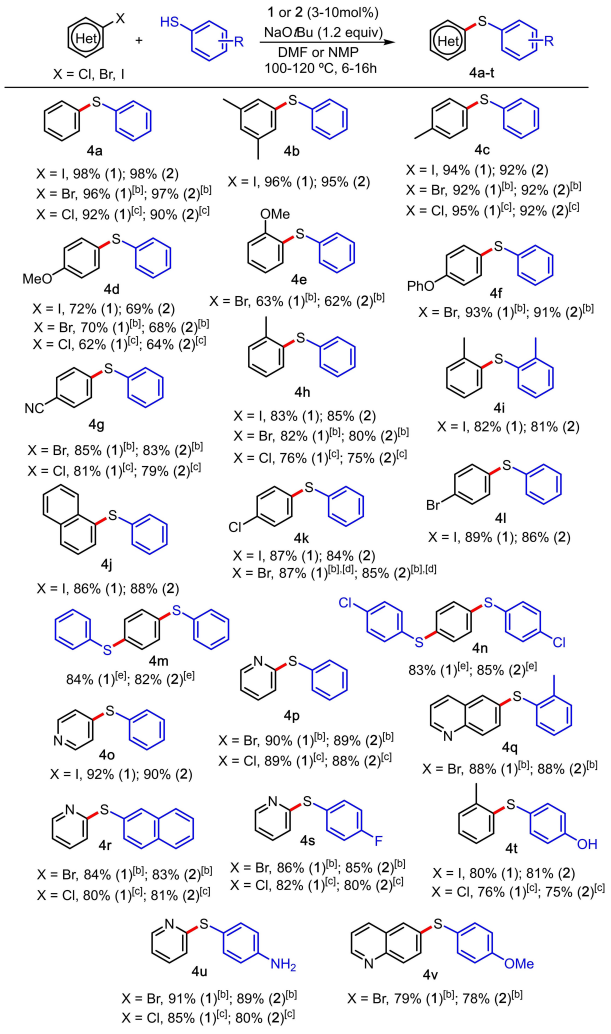
Table 2. Screening of conditions for the coupling of bromobenzene and chlorobenzene with thiophenol catalyzed by complexes **1** and **2**.



Entry	ArX	Deviation from standard conditions[a]	Yield (%)[b]
1	PhBr	None	89
2	PhBr	**1** (5 mol%), 6 h	96
3	PhBr	**2** (5 mol%), 6 h	97
4	PhCl	**1** (5 mol%), 16 h	14
5	PhCl	**1** (10 mol%), 24 h	32
6	PhCl	**1** (10 mol%), NMP, 120 °C, 16 h	92
7	PhCl	**2** (10 mol%), NMP, 120 °C, 16 h	90

[a] Standard conditions: aryl halide (1.0 mmol), thiophenol (1.1 mmol), NaO*t*Bu (1.2 mmol), **1** (3 mol%), DMF (1 mL), 100 °C, 6 h. [b] Isolated yields (average of two runs).

Table 3. Scope of the C–S coupling of (hetero)aryl halides with thiophenols catalyzed by complexes **1** and **2**.[a]



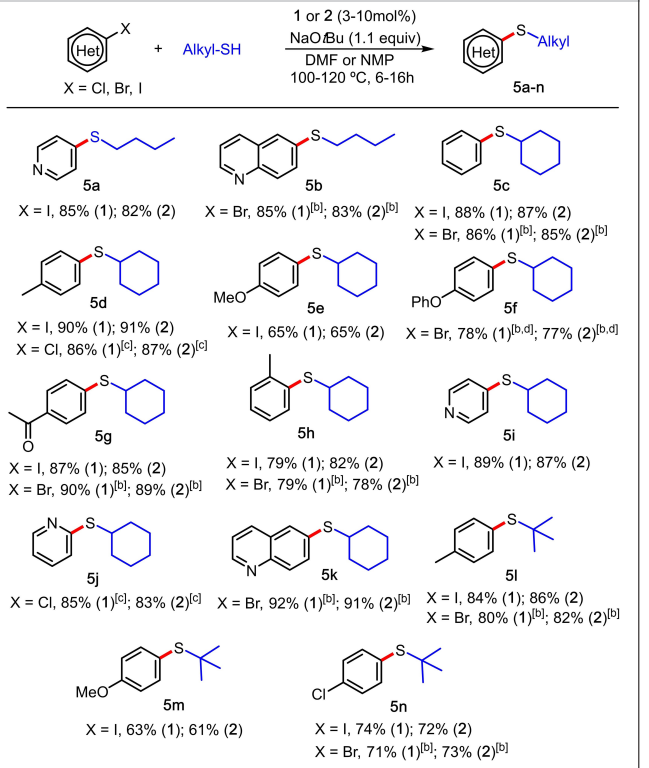
[a] Standard conditions: aryl halide (1.0 mmol), thiophenol (1.1 mmol), NaO*t*Bu (1.2 mmol), **1** or **2** (3 mol%), DMF (1 mL), 100 °C, 6 h. Isolated yields of pure products. [b] Reaction performed with 5 mol% catalyst loading. [c] Reaction performed with 10 mol% catalyst loading in NMP (1 mL), at 120 °C for 16 h. [d] aryl halide (1.1 mmol), thiophenol (1.0 mmol). [e] 1-chloro-4-iodobenzene (0.5 mmol), thiol (1.1 mmol), NaO*t*Bu (1.2 mmol), **1** or **2** (10 mol%) NMP (1 mL), 120 °C, 16 h.

applied as electrophilic coupling partners furnishing the desired products in high yields (Table 3, **4o–s**, **4u–v**).

Concerning the nucleophile scope, aryl thiols bearing either electron-withdrawing (Table 3, **4s**) or electron-donating (Table 3, **4t–4v**) *para*-substituents were equally effective delivering the corresponding products in comparable yields. Perhaps more significantly, reactions involving thiols containing functional groups subjected to being arylated, such as free hydroxyl or amine groups, occurred with complete chemoselectivity towards the C–S coupling products (Table 3, **4t**, **4u**), avoiding the need of protecting groups.

The thioetherification of aliphatic thiols is usually problematic due to their enhanced nucleophilicity compared to that of aromatic thiols.[13c,25] Only few Ni-based catalysts systems that allow the effective coupling of aliphatic thiols with aryl halides, primarily iodides and bromides, have been described in the literature.[13d,26] On that basis, we decided to probe the arylation of aliphatic thiols using the reaction conditions already developed for aromatic thiols. As shown in Table 4, primary (**5a**, **5b**), secondary (**5c–k**) and tertiary alkyl thiols (**5l–n**) could be readily coupled with an array of (hetero)aryl halides, including less reactive chloroarenes (Table 4, **5d**, **5j**), demonstrating the broad utility of this transformation.

Table 4. Scope of the C–S coupling of (hetero)aryl halides with aliphatic thiols catalyzed by complexes **1** and **2**.[a]



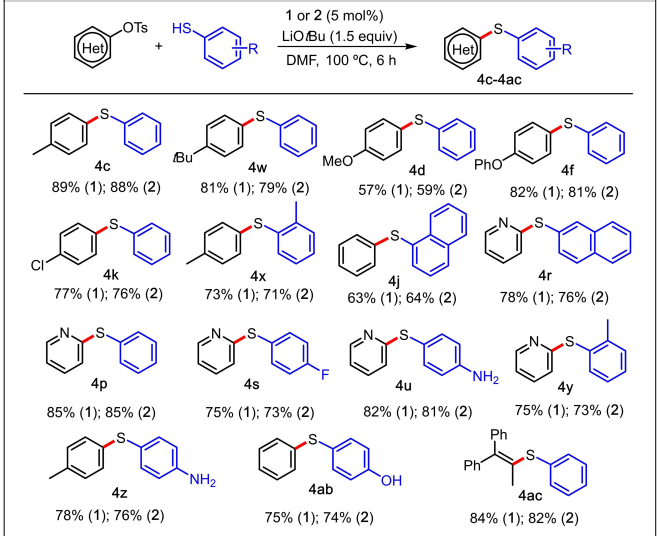
[a] Standard conditions: aryl halide (1.0 mmol), thiophenol (1.1 mmol), NaO*t*Bu (1.2 mmol), **1** or **2** (3 mol%), DMF (1 mL), 100 °C, 6 h. Isolated yields of pure products. [b] Reaction performed with 5 mol% catalyst loading. [c] Reaction performed with 10 mol% catalyst loading in NMP (1 mL), at 120 °C for 16 h. [d] aryl halide (1.1 mmol), thiophenol (1.0 mmol).

To further expand the range of electrophilic partners compatible with this nickel-catalyzed C–S coupling protocol, we focused our attention on aryl sulfonates. Disappointingly, phenyl mesylate, the only phenol-derived electrophile successfully tested in nickel-catalyzed C–S couplings,[15] failed to react with thiophenol under the standard conditions (see Table 2), even in the presence of higher catalyst loadings (10 mol%). However, the coupling of *p*-tolyl tosylate with thiophenol under the standard conditions delivered the corresponding thioether in 58% yield. Further screening experiments revealed that replacing NaO*t*Bu by LiO*t*Bu as the base, the C–S coupling product was isolated in 89% yield with only 5 mol% of the nickel source. Unfortunately, under these optimized conditions other C–O electrophiles, such as aryl mesylates, sulfamates or carbamates, appeared to be completely ineffective.

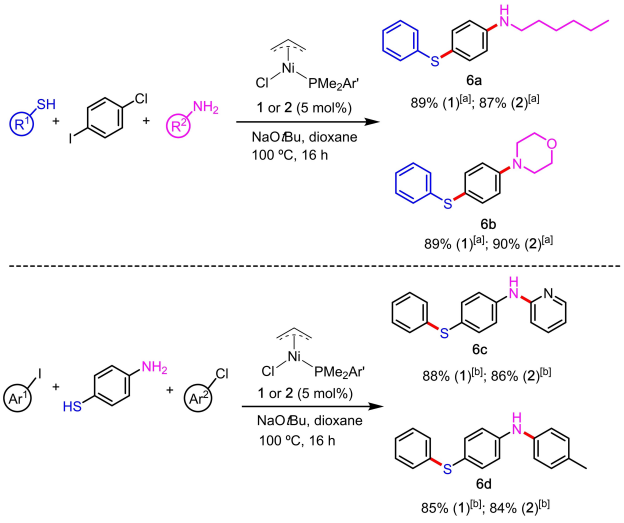
Next, the scope of this novel transformation was evaluated. A variety of aryl tosylates were successfully coupled with a diverse range of thiophenols in yields ranging from 57 to 89% (Table 5). Deactivated aryl tosylates proved to be suitable substrates (Table 5, **4c**, **4f**, **4w–x**, **4z**), although reactions involving strongly deactivated 4-methoxyphenyl tosylate gave the sulfide product **4d** only in moderate yields (57 and 59%). Gratifyingly, thioetherification of 4-chlorophenyl tosylate occurred exclusively at the tosylate group (Table 5, **4k**). Furthermore, 2-pyridyl tosylate underwent efficient coupling with electron-rich (Table 5, **4u**), electron-withdrawing (Table 5, **4s**) and hindered (Table 5, **4y**) thiophenols. It is remarkable the tolerance of potentially reactive functional groups, such as OH (Table 5, **4ab**) and NH_2 (Table 5, **4u**, **4z**) to the reaction conditions. Moreover, the protocol could be applied to the synthesis of alkenyl sulfides, as exemplified by the trisubstituted alkenyl thioether **4ac**. Disappointingly, all attempts to couple aliphatic thiols with aryl tosylates failed.

Taking advantage of the selective thioetherification of C–I bond over C–Cl functionalization and recalling that aryl iodides proved to be problematic in the Buchwald-Hartwig amination,[27] we explored the potential to combine both C–S and C–N couplings in a one-pot reaction using the same Ni-based catalyst precursor. First, we evaluated the performance of complexes **1** and **2** as precatalysts in the Buchwald-Hartwig amination reaction. Taking (4-chlorophenyl)(phenyl)sulfane (see Table 3, **4k**) as the electrophilic partner, the amination of the C–Cl bond with primary and secondary amines (i.e. hexylamine or morpholine) was successfully accomplished in the presence of both Ni precatalysts (see Supporting Information for details). We found that dioxane was the solvent of choice to perform the tandem C–S/C–N couplings since the amination did not work in DMF and, on the other hand, the C–S coupling of aryl chlorides required polar solvents. To our delight, the reaction of 1-chloro-4-iodobenzene with thiophenol and an amine in the presence of 5 mol% of **1** or **2** at 100 °C in dioxane led to the formation of the highly functionalized products in good yields (Scheme 2, **6a–b**). The catalytic efficiency of the one-step catalytic procedure compares well to that of the two-steps reaction (i.e. 90% overall yield for catalyst **1**). Moreover, tandem C–S and C–N bond formations could also be accomplished through two consecutive arylations of 4-aminobenzenethiol with iodo and chloroarenes (Scheme 2, **6c–d**). In all these couplings, the thiolation occurred exclusively on C–I bond and the amination on the C–Cl bond, disclosing an exquisite simultaneous chemoselectivity both at the electrophilic and the nucleophilic sites. Intermolecular cross-coupling reactions taking place in a single step with dual nucleophile and electrophile selectivity are very uncommon.[28] Usually, sequential couplings[29] are accomplished in two steps,[27,30–32] being necessary to change the solvent polarity,[30a–b,31b] use protecting

Table 5. C–S coupling of aryl and alkenyl tosylates with thiophenols catalyzed by complexes **1** and **2**.[a]



[a] Reaction conditions: aryl/alkenyl tosylate (1.0 mmol), thiophenol (1.5 mmol), LiO*t*Bu (1.5 mmol), **1** or **2** (5 mol%), DMF (1 mL), 100 °C, 6 h. Isolated yields of pure products.



Scheme 2. Tandem C–S/C–N couplings. Isolated yields of pure products. [a]. 1-chloro-4-iodobenzene (1.0 mmol), thiol (1.1 mmol), amine (1.2 mmol), NaO*t*Bu (2.4 mmol), **1** or **2** (5 mol%), dioxane (1 mL), T = 100 °C, 16 h. [b] aryl iodide (0.5 mmol), aryl chloride (0.5 mmol), 4-aminobenzenethiol (0.6 mmol), NaO*t*Bu (1.2 mmol), **1** or **2** (5 mol%), dioxane (1 mL), 100 °C, 16 h.

groups, or different catalyst systems[30c,33] to reach high levels of chemoselectivity.

Conclusion

In summary, we have developed a versatile protocol for the arylation of aromatic and aliphatic thiols compatible with a wide variety of electrophiles, including aryl and heteroaryl iodides/bromides/chlorides and, for the first time tosylates. The success of this strategy lies in the use of preformed Ni(II)-allyl precatalysts supported by hindered terphenyl phosphine ligands. No reductant or excess ligand are required to obtain high yields of coupling products. Tandem C–S and C–N couplings of multi-electrophile/nucleophile combinations are achieved in a completely chemoselective manner leading to highly functionalized products. To our knowledge, this is the first example of dual electrophile/nucleophile selectivity in cross-coupling reactions not involving the formation of C–C bonds.

Experimental Section

All preparations and manipulations were carried out under an oxygen-free nitrogen atmosphere using standard Schlenk techniques. Solvents were rigorously dried and degassed before use. Reagents were purchased from commercial suppliers and used without further purification. Dimethylterphenyl phosphines PMe_2Ar^{Ph2},[18a] **L1** and PMe_2Ar^{Xyl2},[18a] **L2** and $Ni(COD)_2$[34] were synthesized following described procedures. Solution NMR spectra were recorded on Bruker Avance DPX-300, Avance DRX-400, Avance DRX-500 and 400 Ascend/R spectrometers. The ^1H and ^{13}C resonances of the solvent were used as the internal standard and the chemical shifts are reported relative to TMS while ^{31}P was referenced to external H_3PO_4. Elemental analyses were performed by the Servicio de Microanálisis of the Instituto de Investigaciones Químicas (IIQ). X-ray diffraction studies were accomplished at Centro de Investigación, Tecnología e Innovación de la Universidad de Sevilla (CITIUS). High resolution mass spectra were registered on Orbitrap Elite Mass Spectrometer at CITIUS (Universidad de Sevilla). Complete synthetic and catalytic procedures are provided in the Supporting Information. A selection of representative synthesis of Ni(II) complexes and catalytic reactions are reported below.

Synthesis of NiCl(allyl)(PMe_2Ar^{Ph2}), 1: To a suspension of $Ni(COD)_2$ (200 mg, 0.722 mmol) in THF (20 mL), allyl chloride (59 μL, 0.724 mmol) was added. The reaction was stirred for 1 h at room temperature, after which a solution of the ligand PMe_2A^{Ph2}, (210 mg, 0.722 mmol) in THF (5 mL) was added. The mixture was stirred for 1 h and then, the solvent was evaporated under vacuum. The solid residue was extracted with CH_2Cl_2, filtered through a Celite plug and the solution was taken to dryness. The complex was purified by recrystallization from CH_2Cl_2: petroleum ether (1:2) mixtures, rendering compound **1** as reddish orange crystals. Yield: 221 mg (72%). Elemental analysis calculated (found) for $C_{27}H_{32}ClNiP$: C, 64.76 (64.58); H, 5.91 (5.75).

General catalytic procedures for the C-S coupling of aryl iodides/bromides/chlorides with aromatic/aliphatic thiols: The catalyst **1** or **2** (0.03–0.1 mmol) and the base NaO*t*Bu (1.2 mmol) were dissolved in the solvent (DMF or NMP, 1 mL) into a vial equipped with a J Young tap containing a magnetic bar. The thiol (1.1 mmol) and the aryl iodide/bromide/chloride (1 mmol) were added, in turn, under a nitrogen atmosphere. The mixture was stirred at certain temperature (100° for aryl iodides/bromides or 120 °C for aryl chlorides) for 6–16 h in an oil bath. The reaction mixture was allowed to cool to room temperature, diluted with ethyl acetate (10 mL) and filtered through a Celite plug. The conversion was determined by GC analysis. Pure products were obtained after purification by flash chromatography on silica gel with petroleum ether.

Crystallographic data: Deposition numbers 2084432 (for **2**), 2084433 (for **3**) and 2084434 (for **1**) contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service www.ccdc.cam.ac.uk/structures.

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Conflict of Interest

The authors declare no conflict of interest.

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