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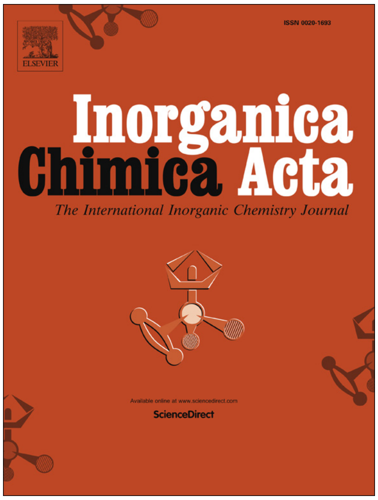

Synthesis of Ni(II) complexes with unsymmetric [O,N,O´]-pincer ligands and their use as precatalysts in carbon–carbon bond formations to access diaryl methanes

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Synthesis of Ni(II) complexes with unsymmetric [O,N,O´]-pincer ligands and their use as precatalysts in carbon–carbon bond formations to access diaryl methanes

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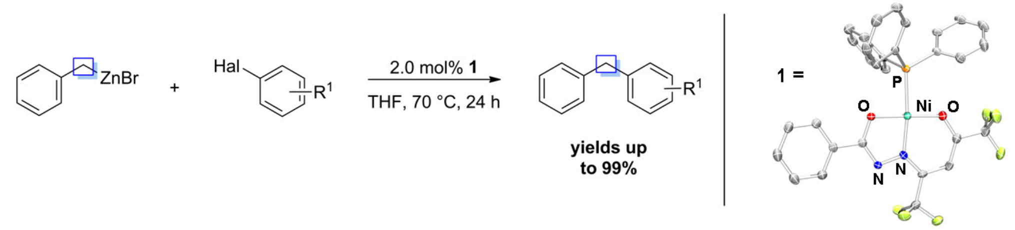
Abstract:

1-Acetyl- [**1a**, 3,5-CF_3, 1-$C(=O)CH_3$] and 1-benzoyl-5-hydroxypyrazolines [**1b**, 3,5-CF_3, 1-$C(=O)C_6H_5$] have been synthesized and reacted with $Ni(OAc)_2$•$4H_2O$ in the presence of PPh_3 to form square planar nickel complexes, which revealed a *O*,*N*,*O´*–coordination. An additional coordination site on the nickel centre is occupied by one triphenylphosphane ligand. After having investigated the properties of the complexes, catalytic experiments have been carried out to synthesize diarylmethanes. Applying the complexes in the nickel-catalyzed carbon–carbon cross coupling of aryl halides with benzylzinc bromide excellent yields and selectivities of the corresponding diarylmethane have been obtained. Moreover, various experiments have been performed to shed light on the underlying reaction mechanism.

Keywords: catalysis / cross coupling / nickel / tridentate ligands / zinc reagents

Graphical Abstract:



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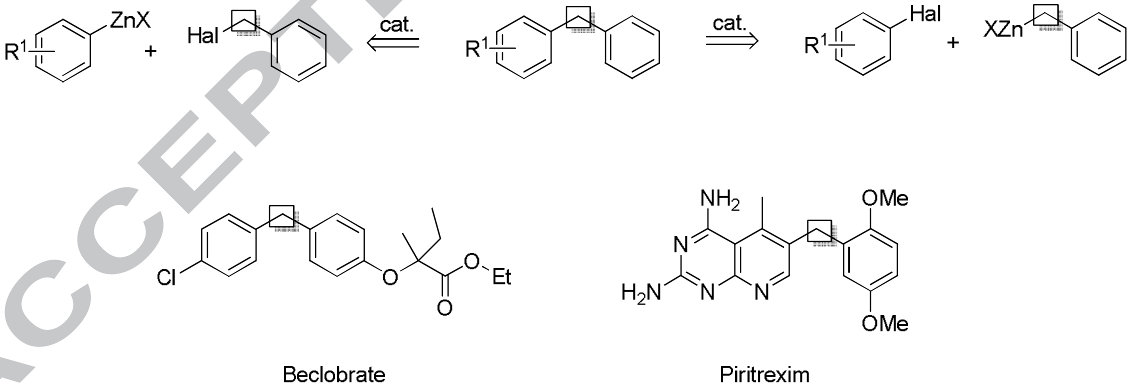
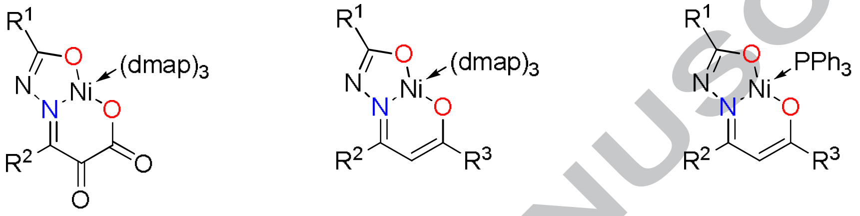
1. Introduction

Nowadays metal-catalyzed transformations are widely used for carbon–carbon bond formations.[1] During the last decades remarkable improvements have been reported for the coupling of sp-, sp^2-, and sp^3-hybridized carbon nucleophiles with sp-, sp^2-, and sp^3-hybridized carbon electrophiles.[2] Based on that, in recent times coupling reactions have become apparent as a methodology of choice with applicability in the production of fine chemicals, pharmaceuticals, agricultural chemicals and natural products.[3] As catalyst core palladium or nickel occupy a central role, performing the coupling reactions with excellent activities, selectivities and high functional-group tolerance.[4] In this regard, the metal-catalyzed C-C bond formation can be an option to access diarylmethanes, which are attractive motifs in pharmaceuticals and biologically active compounds e.g., Beclobrate or Piritrexim (Scheme 1).[5,6] Among the different approaches the application of organometallic zinc reagents as coupling partner allow access to a broad range of products under mild conditions and functional group tolerance.[6a,6b,7] In more detail, the necessity for the design and fine-tuning of the catalyst by ligands was crucial to obtain products in high yields and selectivities. Hence, the development of novel ligands is important for improving the catalyst performance, taking furthermore into account availability, easy synthesis, high tunability, flexibility and stability of the ligands.[8]



Scheme 1. Synthetic strategy to access diarylmethanes via cross coupling reactions and biologically active compounds containing the diarylmethane motif.

Recently we studied the abilities of complexes containing [O,N,O´]-pincer ligands in coordination chemistry (Scheme 2).[9,10] The octahedral nickel complexes were successfully applied as pre-catalyst in cross coupling reactions. Interestingly, the coordination geometry can be easily switched from an octahedral to a square planar geometry by changing the kind of co-ligands from 4-dimethylaminopyridine to phosphanes.[11] In this regard, we became interested in the catalytic abilities of such square planar complexes in cross coupling reactions. Hence, we report herein our ongoing research on the synthesis and characterization of square planar nickel complexes modified by tridentate *O,N,O´*–ligands and a triphenylphosphane as the co-ligand and the application in carbon–carbon cross coupling reactions of aryl halides with benzylzinc bromide to access the diarylmethane motif.



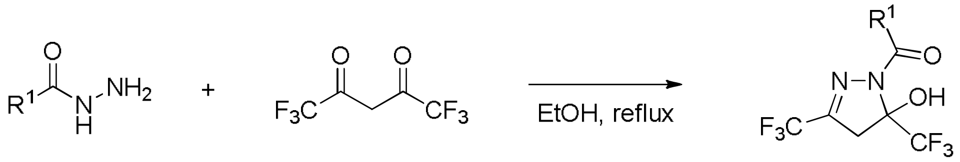
Ref. 10b ***Ref. 10a*** ***this work***

Scheme 2. Nickel complexes modified by *O,N,O´*–ligands (dmap = 4-dimethylaminopyridine).

2. Results and Discussion

2.1. Complex Synthesis, Characterization and Properties

The 1-acetyl- and 1-benzoyl-5-hydroxypyrazoline **1** were synthesized in accordance to the procedure reported in the literature (Scheme 3).[12] Acetohydrazide (**3a**) and benzohydrazide (**3b**) were reacted with equimolar amounts of hexafluoroacetyl acetone (**4**) and refluxed for 24 hours in ethanol. After work-up the desired ligands **1** were obtained as colourless crystalline compounds (83–87%).[9-12]



3a-b **4** **1a-b**

3a: R^1 = Me
3b: R^1 = Ph

1a: R^1 = Me
1b: R^1 = Ph

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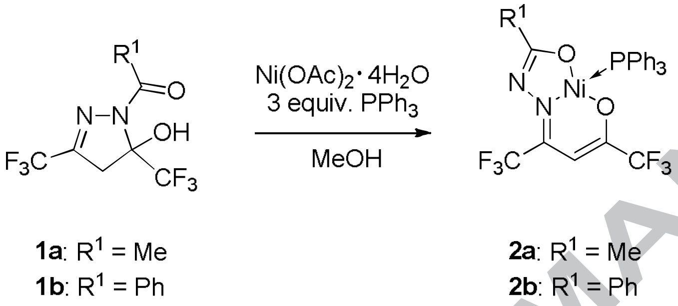
Scheme 3. Synthesis of 1-acetyl- and 1-benzoyl-5-hydroxypyrazoline **1**.

With these chemicals in hand we examined the coordination to nickel salts (Scheme 4). In agreement to our previously established protocol a methanol solution of **1** and an excess of triphenylphosphane (3.0 equiv.) was added to a solution of $Ni(OAc)_2 \bullet 4H_2O$ in methanol at room temperature.[11,13]After stirring overnight, all volatiles were removed to obtain brown powders, which were extracted with ethanol and purified by crystallization to obtain red–brown crystals. Crystals suitable for X–ray measurements were grown from ethanol by slow evaporation of the solvent at room temperature.



Scheme 4. Synthesis of nickel complexes **2a** and **2b**.

The solid–state structures of complexes **2a** and **2b** have been characterized by single–crystal X–ray diffraction analysis. Thermal ellipsoid plots are shown in Figure 1 and selected bond lengths and angles are listed in Table 1. The tridentate ligand is coordinated in a *O*,*N*,*O´*–mode creating a five–membered as well as a six–membered ring system and therefore shielding one side of the metal. The triphenylphosphane ligand is *cis*–positioned to the oxygen donors, while the nitrogen of the ligand is connected to the nickel centre in the *trans*-position. A similar square planar motif was observed by Joshi and co-workers[13a] and more recently by us when applying ammonia instead of triphenylphosphane as the co-ligand, while with dmap an octahedral structure was achieved.[10a,11] The Ni–N1, Ni–O1, Ni–O2 and Ni–P1bond lengths are found in a similar range of those observed in nickel(II) complexes having the same coordinating atoms.[11]

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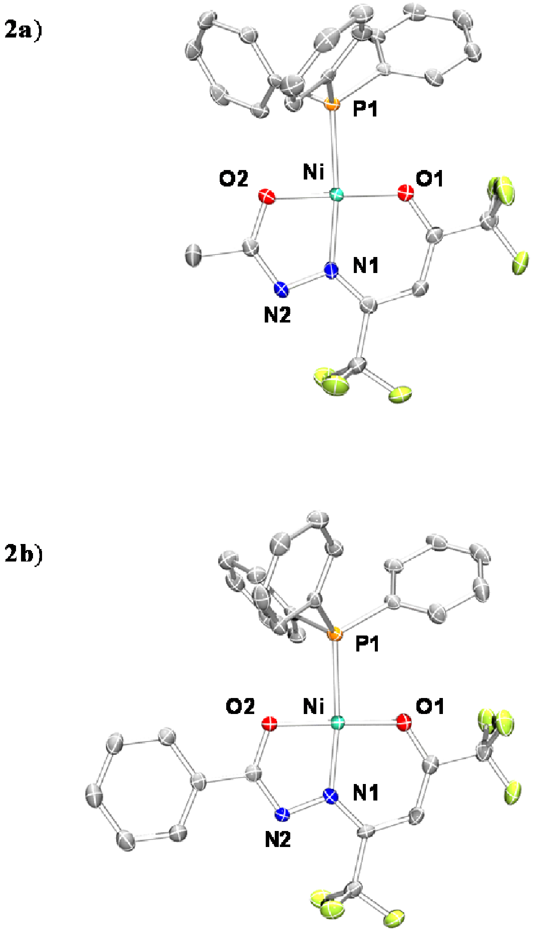

Figure 1. Molecular structures of **2a** (Figure 1a) and **2b** (Figure 1b). Thermal ellipsoids are drawn at the 50% probability level.

Table 1. Selected bond lengths and angles of **2a** and **2b**.

	2a	2b
Ni-N1 [Å]	1.863(3)	1.8602(19)
Ni-O1 [Å]	1.810(3)	1.8154(14)
Ni-O2 [Å]	1.823(3)	1.8355(14)

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Ni-P1 [Å]	2.2252(10)	2.2313(7)
O1-Ni-O2 [º]	179.26(12)	179.00(7)
N1-Ni-P1 [º]	172.15(11)	172.70(6)
N1-Ni-O1 [º]	95.98(13)	95.76(7)
N1-Ni-O2 [º]	83.69(11)	83.40(7)
O1-Ni-P1 [º]	91.68(8)	81.53(5)
O2-Ni-P1 [º]	88.64(8)	89.30(5)

In contrast to our recently reported octahedral paramagnetic complexes the observed square planar structures (diamagnetic properties) allow for NMR investigations. The complexes **2** were characterized by ^{1}H NMR spectroscopy applying $CDCl_3$ as solvent, showing the C–H proton in the six–membered ring at 6.05 ppm for **2a** and 6.13 ppm for **2b**, respectively (Table 2). In the ^{19}F NMR spectrum two sharp signals for the two CF_3 groups at -65.5 ppm and -71.7 ppm for **2a**, and -65.4 ppm, -71.6 ppm for **2b** were observed, which are as expected different from those of ligand **1**. The coordination of the triphenylphosphane was confirmed by ^{31}P{^{1}H} NMR; here a signal at 14.0 ppm for **2a** and 14.8 ppm for **2b**, respectively were detected, while the uncoordinated triphenylphosphane has a chemical shift of -4.75 ppm. Furthermore, the coordination mode of the acetyl and benzoyl functionality was investigated by IR measurements. The absence of signals in the range of 1610–1725 cm^{-1} excludes the possibility for an uncoordinated C=O functionality of the ligand. Strong bands were monitored in the region of 1533–1603 cm^{-1}, which can be attributed to the C=N and C=C functionalities.

Table 2. Analytical properties of **1a**, **1b**, **2a** and **2b**.

	1a	**1b**	**2a**	**2b**
^{1}H NMR 4-C*H*(*H*) [ppm][a]	3.30–3.80	3.00–3.66	6.05	6.13
^{19}F NMR [ppm][a]	-67.7, -81.4	-67.4, -80.5	-65.5, -71.7	-65.4, -71.6
^{31}P{^{1}H} NMR [ppm][a]	-	-	14.0	14.8
IR ν (C=O) [cm^{-1}][b]	1699 (s)	1678 (s)	-	-

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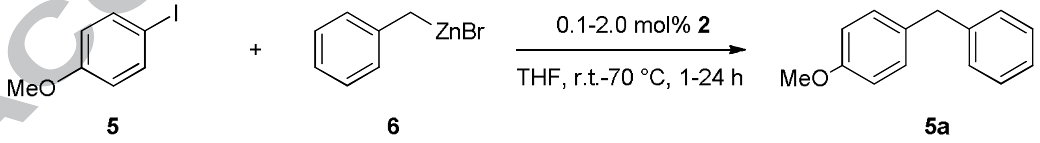
IR ν (C=N/C=C)	1645 (s)	1639 (s)	1603 (s)	1596 (s)
[cm^{-1}][b]	-	-	1543 (s)	1533 (s)

[a] The chemical shift was measured in $CDCl_3$ at 25 °C. [b] Measured in KBr at 25 °C.

2.2. Catalytic investigations

After studying the properties of the complexes, the catalytic abilities of **2** were investigated in the coupling of aryl halides and organometallic zinc reagents to produce diarylmethanes (Table 3).[6b, 14] To find suitable reaction conditions, the coupling of 4-iodoanisole (**5**) with benzylzinc bromide (**6**) was performed in the presence of 2 mol% of **2b** as model reaction (Table 3, entries 1 and 2). First the reaction outcome was examined at different reaction temperatures. Only in the case of elevated temperature (70 °C) the desired coupling product was observed in good yields (Table 3, entry 1). A similar result (yield: >99%) was achieved with the pre-catalyst **2a** (Table 3, entry 4). Noteworthy, the nickel complexes did operate as the pre-catalyst, whilst in its absence no reaction took place (Table 3, entry 3). Furthermore, the catalyst loading was reduced (Table 3, entries 5-8). The cross coupling reaction in the presence of 1.0 mol% or 0.1 mol% of the pre-catalyst **2b** resulted in the formation of **5a** in 46% and 29% yield after one hour (Table 3, entries 7 and 8). However, after 24 hours in both cases excellent yields of the coupling product were observed (Table 3, entries 5 and 6). Note, the obtained result for 0.1 mol% catalyst loading corresponds to a turnover frequency of 290 h^{-1}.

Table 3. Nickel–catalyzed C–C bond formation of benzylzinc bromide with 4-iodoanisole – optimization of the reaction conditions.[a]



Entry	pre-catalyst (mol%)	T [°C]	Yield [%][b]
1	**2b** (2)	70	>99
2	**2b** (2)	r.t.	<1
3	-	70	<1
4	**2a** (2)	70	>99

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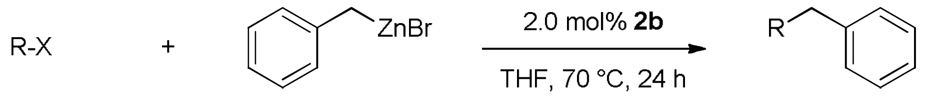
5	**2b** (1)	70	>99
6	**2b** (0.1)	70	>99
7	**2b** (1)	70	46[c]
8	**2b** (0.1)	70	29[c]
9	**2b** (2)	70	>99[d]

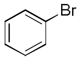
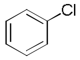
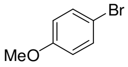
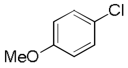
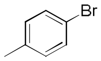
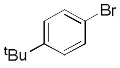
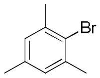
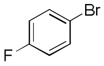
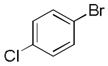
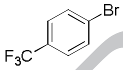
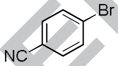
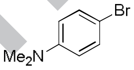
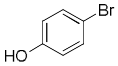
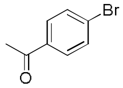
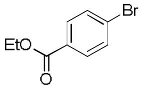
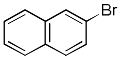
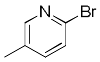
[a] Reaction conditions: 4-iodoanisole (0.77 mmol), benzylzinc bromide (1.15 mmol, 0.5 M in THF), pre-catalyst (2.0 mol%), 70 °C, 24 h. [b] Yield determined by GC-MS. [c] Reaction time: 1 hour. [d] 3 h.

Moreover, the complex **2b** was applied as pre-catalyst in the reaction of benzylzinc bromide and different aryl halides (Table 4). Excellent yields (>99%) were observed for various aryl bromides in the presence of 2.0 mol% pre-catalyst at 70 °C within 24 hours (Table 4, entries 1, 3, 5 and 6).[15] Along with aryl bromides aryl chlorides were investigated. However, a lower activity of the catalyst was found (Table 4, entries 2 and 4). In contrast, aryl fluorides were not converted to the corresponding cross coupling product, probably due to the high bond dissociation energy of the C-F bond.[16] The reaction of aryl dihalides exhibited a higher reactivity and excellent chemoselectivity towards the bromo functionality (Table 4, entries 8 and 9). On the other hand, for 2-bromomesitylene (**13**) a poor reactivity was detected for complex **2b**, probably because of steric hindrance (Table 4, entry 7). In the case of the challenging electron withdrawing trifluoromethyl or dimethyl amino group, excellent yields and selectivities for the coupling products were monitored (Table 4, entries 10-12). Furthermore, the reaction of heteroarenes with benzylzinc bromide resulted in good to excellent formation of the desired products (Table 4, entries 18-20). Noteworthy, in case of 2,6-dibromopyridine an excellent selectivity was found for the mono-benzylation (Table 4, entry 19).

Table 4. Nickel–catalyzed C–C bond formation of aryl halides with benzylzinc bromide – scope and limitations.[a]



7-27 **6** **5a, 7a, 11a-27a**

Entry	Substrate	Product	Yield [%][b]
1	 **7**	**7a**	>99
2	 **8**	**7a**	35
3	 **9**	**5a**	>99
4	 **10**	**5a**	79
5	 **11**	**11a**	>99
6	 **12**	**12a**	>99
7	 **13**	**13a**	5
8	 **14**	**14a**	>99
9	 **15**	**15a**	>99
10	 **16**	**16a**	>99
11	 **17**	**17a**	>99
12	 **18**	**18a**	>99
13	 **19**	**19a**	70
14	 **20**	**20a**	<1
15	 **21**	**21a**	>99
16	 **22**	**22a**	>99
17	$\mathrm{Ph{-}{\equiv}{-}Br}$ **23**	**23a**	28
18	 **24**	**24a**	>99

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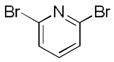
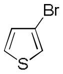
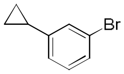
19[c]	 **25**	**25a**	48
20	 **26**	**26a**	79
21	 **27**	**27a**	>99

[a] Reaction conditions: substrate (0.77 mmol), benzylzinc bromide (1.15 mmol, 0.5 M in THF), pre-catalyst (2.0 mol%), 70 °C, 24 h. [b] Yield determined by GC-MS and ^{1}H NMR. [c] 1.5 equiv. of benzylzinc bromide was used. 2-Benzyl-6-bromopyridine was observed as product.

Moreover, the influence of the organometallic zinc reagent was studied (Table 5). First, the coupling reaction of dimethyl zinc, diethyl zinc, di-*iso*-propyl zinc and di-*tert*-butyl zinc was examined (Table 5, entries 1-3, 6-7). A good yield was observed for the production of *p*-methylanisole (74%), while for sterically demanding alkyl functionalities a decreased activity was monitored. For studying the effect of β-hydride elimination 4-iodoanisole was reacted with α-methylbenzylzinc bromide (Table 5, entry 4). The desired coupling product was obtained in a yield of 59%. However, non-negligible amount of the homocoupling products 4,4'-dimethoxybiphenyl (17%) and 2,3-diphenylbutane (15%). Furthermore, styrene (10%) was monitored as the β-hydride elimination product. Interestingly, the complex **2b** was capable to transform a heteroaryl organometalic zinc reagent to the desired 2-aryl pyridine in good yield (Table 5, entry 5). On the other hand changing the source of halide source from aryl bromide to alkyl bromide, revealed not the formation of the desired product (Table 5, entries 8-9). Moreover, the set-up of the reaction was modified by *in situ* pre-generation of the organometallic zinc reagent. Based on that, the corresponding benzyl magnesium bromide reagents **36a** or **36b** were formed by reacting benzyl bromide **35a** or benzyl bromide-d2 **35b** and magnesium in THF at room temperature for 2 hours.[17] To the stirred solution of **36a** or **36b** was added $ZnBr_2$ at room temperature and after stirring for 1 hour benzylzinc bromide **6** or **37** was generated.[18] The reaction mixture of **6** or **37** was filtered and the solution was used in the cross coupling reaction of 4-iodoanisole and **2b** as pre-catalyst. The coupling product **5a** was obtained in a yield of 86%, and **37a** was obtained in 84% yield.

Table 5. Nickel–catalyzed C–C bond formation of aryl halides with organometallic zinc compounds – scope and limitations.[a]

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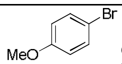
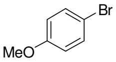
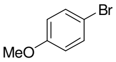
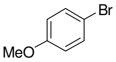
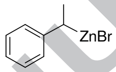
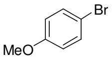
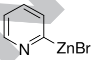
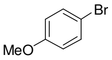
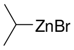
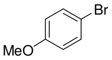
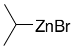
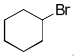
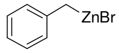
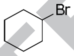
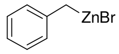
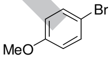
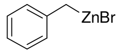
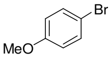
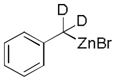
R–X + Zn source (1.5 equiv.) $\xrightarrow[\text{THF, 70 °C, 24 h}]{\text{2.0 mol\% }\mathbf{2b}}$ coupling product

9, 34 **6, 28-33, 37** **28a-34a, 37a**

Entry	Substrate	Zn-source	Yield [%][b]
1	 **9**	$ZnMe_2$ **28**	74
2	 **9**	$ZnEt_2$ **29**	23
3	 **9**	Zn^tBu_2 **30**	9
4	 **9**	 **31**	59[c]
5	 **9**	 **32**	75
6	 **9**	 **33**	<1
7[d]	 **9**	 **33**	15
8	 **34**	 **6**	<1
9[d]	 **34**	 **6**	<1
10[e]	 **9**	 **6**	86
11	 **9**	 **37**	84

[a] Reaction conditions: substrate (0.77 mmol), zinc source (1.15 mmol), pre-catalyst (2.0 mol%), 70 °C, 24 h. [b] Yield determined by GC-MS and ^1H NMR. [c] 15% of 2,3-diphenylbutane and 17% of 4,4'-dimethoxybiphenyl were observed as homocoupling products. 10% of styrene was detected. [d] Addition of Bu_4NI (2.31 mmol). See Ref. 19. [e] *in situ* pre-generation of the organometallic zinc reagent.

Moreover, the reaction in the course of time applying the cross coupling of 4-iodoanisole (**5**) and benzylzinc bromide (**6**) as model reaction was examined (Figure 2). The abilities of the pre-catalyst **2b** in THF were studied at different reaction temperatures (55 °C, 60 °C, 65 °C

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and 70 °C). By comparison the time to reach 50% yield, e.g., 80 min (70 °C), 120 min (65 °C), 190 min (60 °C), and 310 min (55 °C), a decrease in activity was observed with reduced reaction temperature. However, at the investigated temperatures full conversion was reached within 150-480 min. Worth of note is that at each temperature an induction period of several minutes was detected, which is probably required to produce the active catalyst. To enhance the formation of the catalyst the pre-catalyst **2b** was pretreated on the one hand with benzylzinc bromide and on the other hand with 4-iodoanisole **5** for 10 minutes at 70 °C (Figure 3). Subsequently, 4-iodoanisole or benzylzinc bromide, respectively, was added and the reaction proceeding was investigated. In case of the pretreatment of **2b** with benzyl zinc bromide no induction period was observed, whereas for treatment of **2b** with **5** an induction period was noticed. On the other hand, the time to reach 50% yield showed 25 min (a) pretreatment with benzylzinc bromide, 80 min (b) without any pretreatment, and 180 min (c) with pretreatment with **5**. A comparison of the rate constants showed an increased catalytic activity for the pretreatment with benzylzinc bromide.

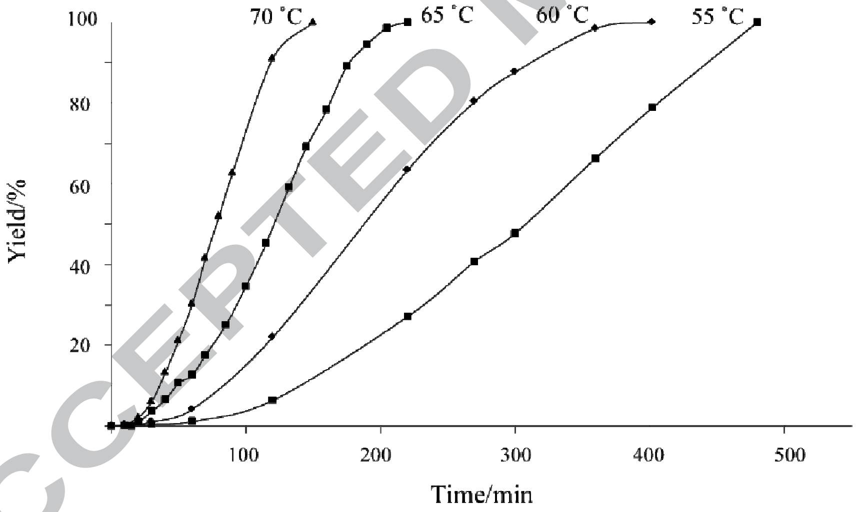

Figure 2. Reaction process of the coupling reactions of 4-iodoanisole (**5**) with benzylzinc bromide (**6**) using the pre-catalyst **2b** (2.0 mol%) in THF at different temperature (55 °C, 60 °C, 65 °C and 70 °C).

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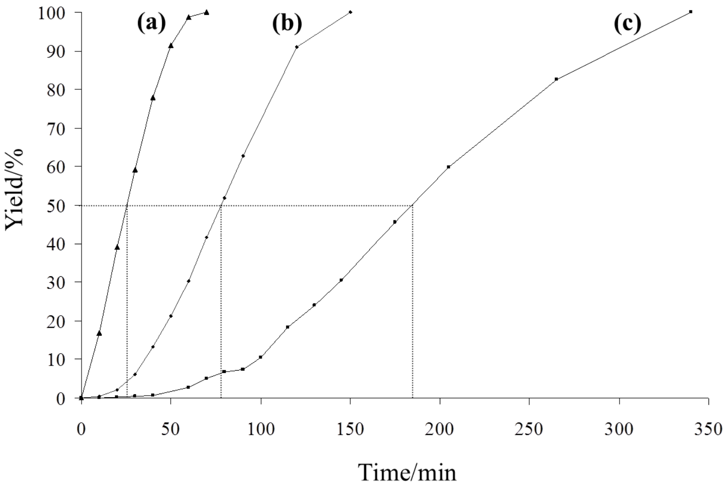
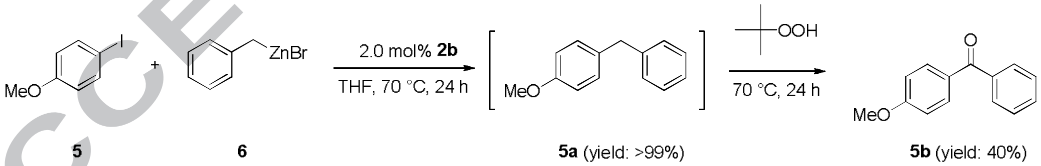


Figure 3. Time courses of the coupling reactions of a) after pretreatment of **2b** with benzylzinc bromide, b) Reaction conditions: substrate (0.77 mmol), benzylzinc bromide (1.15 mmol, 0.5 M in THF), pre-catalyst (2.0 mol%), 70 °C, and c) after pretreatment of **2b** with 4-iodoanisole.

In addition, the established cross coupling protocol was embedded as key reaction in the synthesis of diaryl ketones, which are attractive motifs for pharmaceutical and material-science (Scheme 6).[20] In more detail, the cross coupling of **5** and **6** was carried out in the presence of **2b** as precatalyst resulting in full conversion after 24 hours. Subsequently *tert*-butyl peroxide was added to the solution and heating was continued for 24 hours. After work-up the ketone **5b** was obtained in 40% yield.



Scheme 6. Synthesis of diaryl ketones via nickel-catalyzed cross coupling reaction and subsequent oxidation.

After having studied the scope and limitation of the nickel complexes **2** in cross coupling reactions, additional investigations were carried out to gain insight into the reaction mechanism. First, the behaviour of the complex **2b** was investigated in the coordinating

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solvent THF by NMR spectroscopy, since THF was applied as reaction medium for the catalytic reactions (Figure 4). The ^{19}F NMR spectrum of **2b** in [D$_8$]THF revealed two sets of broad signals, at -67.6 and -73.8 ppm, which can probably be assigned to the complex **2b**, and at -6.3 and -41.7 ppm, which can probably be assigned to complex 2b-1. Moreover, in the ^{31}P{^{1}H} NMR spectrum one signal with a chemical shift of 14.8 ppm was observed in CDCl$_3$, whereas in THF a broad signal at -8.1 ppm was detected. These broad NMR signals could be due to the coordination of THF to the nickel consequently by this creating an octahedral paramagnetic species. Furthermore, low temperature ^{31}P{^{1}H} NMR analysis in [D$_8$]THF at 194 K showed a sharp signal at -10.5 ppm, which can probably be assigned to free triphenylphosphane, and a minor signal at 12.7 ppm, which can be assigned as coordinated triphenylphosphane in complex **2b**. Noteworthy, an addition of an excess of triphenylphosphane (5 equiv.) to the dissolved complex **2b** in [D$_8$]THF showed an increase of the signal at -10.5 ppm, which further proves the presence of free triphenylphosphane on the NMR time scale. The broadness of the signals at room temperature can be either explained by presence of the paramagnetic species or by exchange reactions between coordination and dissociation processes. Based on that, we speculate a dissociation of PPh$_3$ and the formation of an octahedral nickel THF complex. Remarkably, the straightforward exchange of the triphenylphosphane can be a useful tool for catalysis, due to easy creation of an active site for metal-substrate interactions. Moreover, the difference of the structure of **2b** depending on the solvent was also confirmed by UV-Vis spectroscopy. The spectra of **2b** in dichloromethane (325.5 nm, 370.5 nm, 399.0 nm) and THF (380.0 nm, 397.0 nm, 417.5 nm) showed different absorption maxima.

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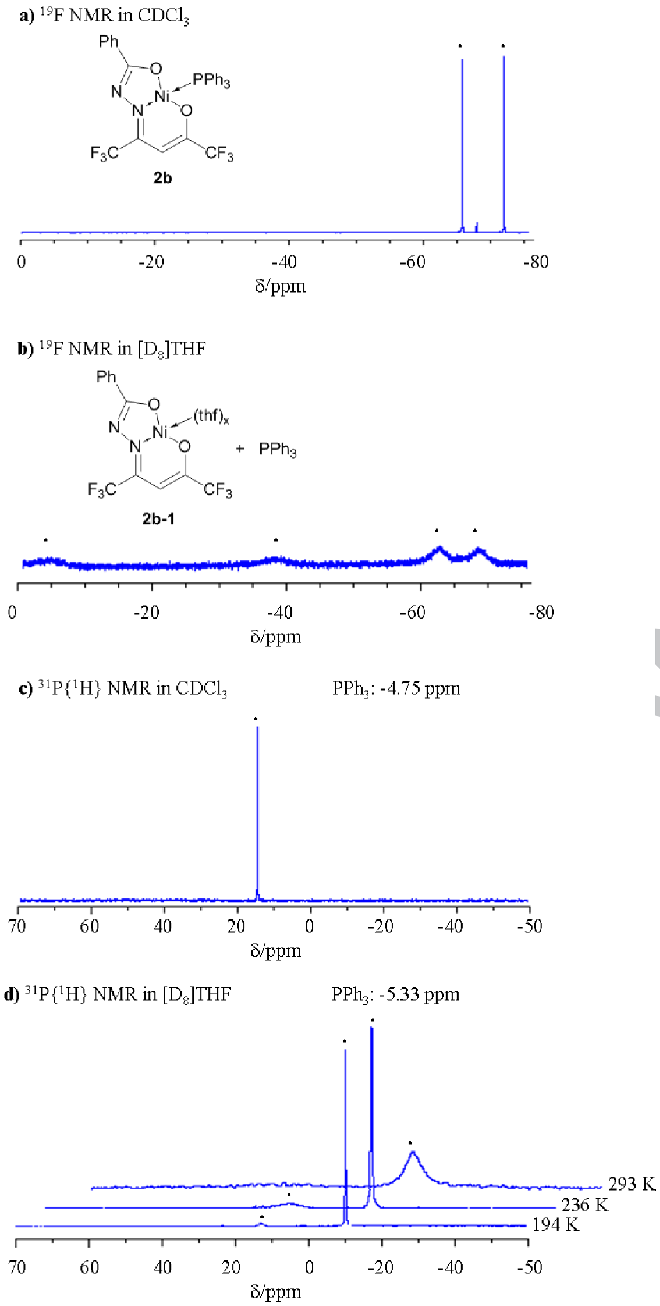

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Figure 4. a) ^{19}F NMR spectrum in $CDCl_3$, b) ^{19}F NMR spectrum in [D$_8$]THF, c) $^{31}P\{^1H\}$ NMR spectrum in $CDCl_3$, and d) $^{31}P\{^1H\}$ NMR spectrum at different temperature in [D$_8$]THF.

To further verify the exchange of triphenylphosphane by other donor systems, we investigated the stability of the complex **2b** in the presence of phosphane ligands in a 1:1

ratio (Figure 5).[21] First, the reaction of **2b** and the phosphane $P(2,6\text{-}(MeO)_2Ph)_3$ **38** lead to the formation of the new complex **38a**, as observed by NMR techniques.[11d] For instance in the ^{19}F NMR spectrum a new set of signals were detected along with the signals of **2b** (**2b**:**38a** = 2:1), which were assigned to the complex **38a**, in which triphenylphosphane is replaced by **38**. Moreover, phosphanes **39** and **40** were added to complex **2b**, and revealed that triphenylphosphane tend to exchange with more basic phosphanes, like $P(2,6\text{-}(MeO)_2Ph)_3$ **38** or *n*-tributylphosphane (**39**), while no exchange was observed for the reaction with tris(phenylethynyl)phosphane (**40**), which has a weaker basicity than triphenylphosphane.

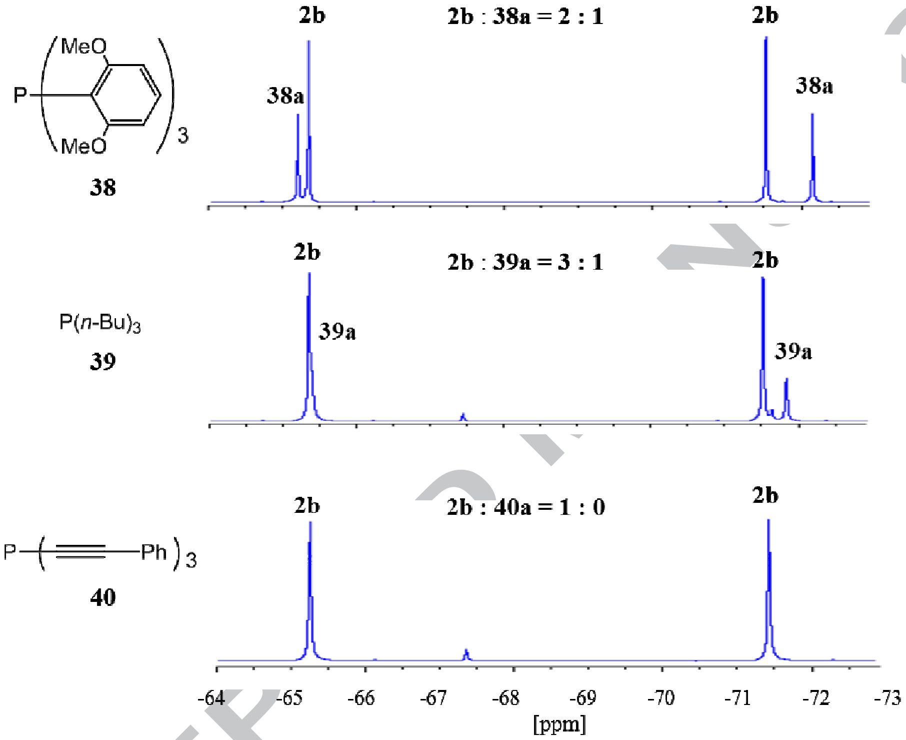

Figure 5. ^{19}F NMR spectra of the reaction mixture of **2b** with phosphanes **38**-**40** in $CDCl_3$.

To rule out the existence of nickel particles as the active catalyst, a large excess of Hg(0) was added to the stirred reaction mixture of benzylzinc bromide (**6**) and 4-iodoanisole (**5**) after the reaction had proceeded for 3 minutes to allow the generation of the "real" catalyst (Scheme 7).[22] The reaction was continued and after 3 hours a sample was taken. In case of a heterogeneous catalyst the addition of Hg will hamper the proceeding of the reaction. However no significant suppression of the reaction rate in the coupling reaction was observed (>99% yield after 3 h). This observation indicates the presence of a homogeneous catalyst. Furthermore, the formation of a heterogeneous catalyst could be excluded by the addition of a large excess of triphenylphosphane, since no negative effect on the reaction outcome was

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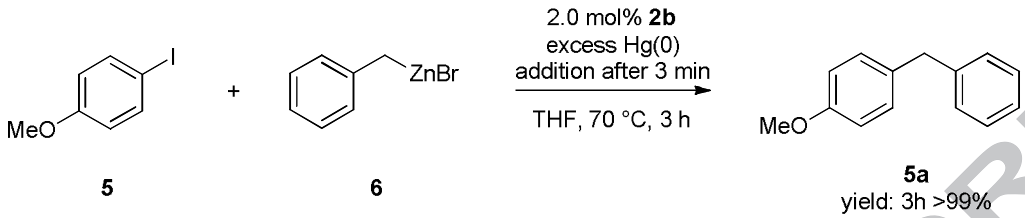
noticed and full conversion was reached within 3 hours. Noteworthy, the tridentate *O*,*N*,*O´*-ligand was stable under cross coupling reactions and was not effected by the addition of an excess of triphenylphosphane, for instance by formation of nickel-phosphane species.



Scheme 7. Evaluation for homogeneous vs. heterogeneous nickel catalysis.

Based on the performed experiments we proposed a reaction mechanism as stated in Scheme 8.[11] First the triphenylphosphane ligand dissociates from complexes **2b** to create open coordination sites. In the NMR study the dissociation was monitored by $^{31}P\{^1H\}$ NMR and the free coordination sites were occupied by the solvent THF to form the complex **A**. The complex **A** reacts with the zinc reagents to create complex **2b-2**, **2b-3**, **2b-4** or **2b-5** which contains a 4-membered ring system.[23] Afterwards the organic halide approaches the coordination sphere of the nickel and mediates a single electron transfer (SET) to oxidize the complex and produce a radical. The one-electron oxidized complex can on the one hand oxidized at the metal center (**2b-6** or **2b-7**) or on the other hand the electron can be stored in the ligand (non-inocent ligand, **2b-8** or **2b-9**). Subsequently, ZnBrX is eliminated and the radical recombines with the nickel species to form the species **2b-10**. Finally, an elimination of the organic product occurs and complex **2b-1** is regenerated.

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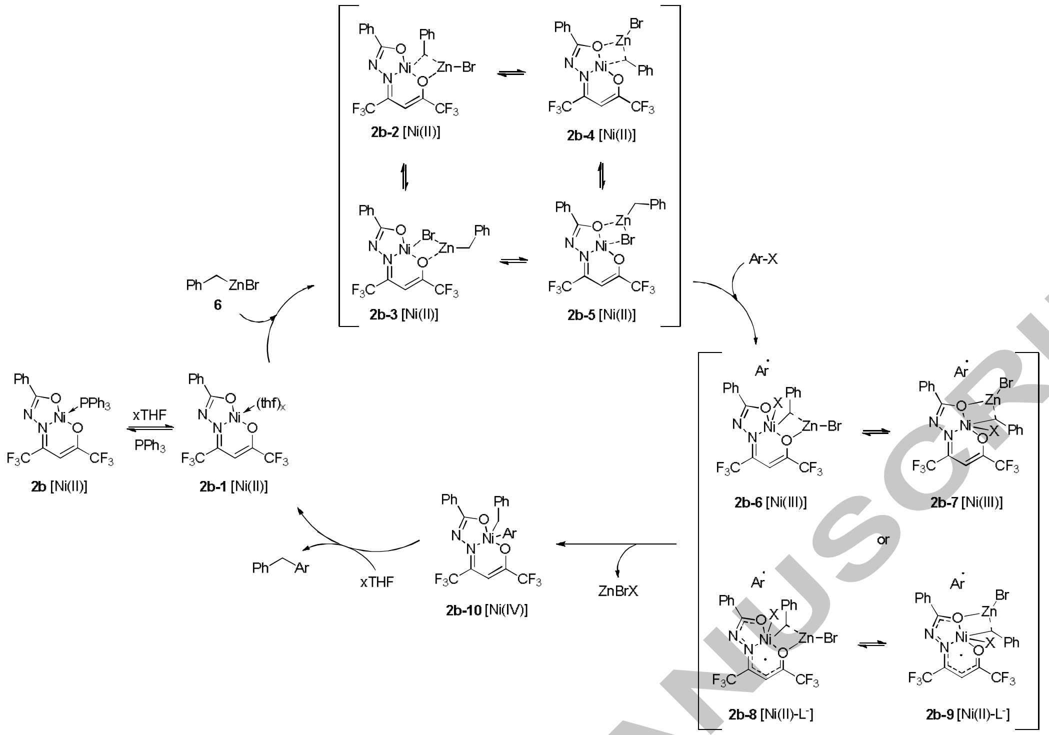

Scheme 8. Proposed reaction mechanism for the nickel-catalyzed cross coupling.

3. Conclusion

In summary, we have synthesized and characterized nickel complexes with the highly flexible [O,N,O´]-pincer ligands (**1a-**2H and **1b-**2H). As co–ligand triphenylphosphane is coordinated to the nickel. Moreover, the properties of the square planar complexes were examined with various techniques. The complexes were applied as pre-catalysts in carbon–carbon bond formations demonstrating an excellent performance to access diaryl methanes. For a better understanding of the system various investigations were carried to understand the underlying reaction mechanism.

4. Experimental Section

Synthesis of 2a: To a mixture of **1a** (1.86 mmol) and triphenylphosphane (5.57 mmol) in methanol (10 mL) was added a solution of $Ni(OAc)_2 \cdot 4H_2O$ (1.86 mmol) at room temperature. The solution was stirred over night. After stirring overnight, the volatiles were removed in vacuo to obtain brown powders, which were extracted with ethanol and purified by

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crystallization to obtain crystals. Crystals suitable for single-crystal X-ray diffraction analysis were obtained from ethanol solution at room temperature. Yield = 450 mg (42%, red crystals). Mp: 150–151 °C. ^{1}H NMR (200 MHz, $CDCl_3$, 25 °C) δ = 7.44–7.62 (m, 15H, Ar), 6.05 (s, br, 1H, C*H*), 1.88 (s, 3H, C(=O)C*H*$_3$) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, 25 °C) δ = 176.9, 157.0 (q, $^2J_{C\text{-}F}$ = 33.8 Hz), 141.6 (q, $^2J_{C\text{-}F}$ = 30.2 Hz), 134.4, 132.2 (q, $^1J_{C\text{-}P}$ = 9.4 Hz), 131.1, 128.7, 118.6 (q, $^1J_{C\text{-}F}$ = 280.8 Hz), 117.9 (q, $^1J_{C\text{-}F}$ = 279.6 Hz), 90.5, 16.5 ppm. ^{19}F NMR (188 MHz, $CDCl_3$, 25 °C) δ = -65.5, -71.7 ppm. $^{31}P\{^1H\}$ NMR (81 MHz, $CDCl_3$, 25°C) δ = 14.8 ppm. IR (KBr): ν = 3417 (br), 3048 (w), 1603 (m), 1580 (w), 1543 (m), 1522 (m), 1482 (w), 1460 (w), 1433 (m), 1384 (w), 1349 (m), 1342 (m), 1311 (w), 1267 (s), 1204 (s), 1180 (s), 1163 (s), 1152 (s), 1125 (s), 1095 (m), 1063 (m), 1026 (w), 1000 (w), 919 (w), 819 (w), 792 (m), 752 (m), 744 (m), 728 (w), 711 (w), 693 (s), 646 (w) cm^{-1}. HRMS calc. for $C_{25}H_{19}F_6N_2O_2NiP$+H: 583.05201, found: 583.05149. Anal. Calcd. for $C_{25}H_{19}F_6N_2O_2NiP$: C, 51.50; H, 3.28; N, 4.80. Found: C, 52.14; H, 3.21; N, 4.84. UV-Vis [nm, (ε, M^{-1}cm^{-1})]: 316.5 (1900), 352.5 (1500) nm in dichloromethane. 370.0 (1400), 384.5 (1180) nm in THF.

Synthesis of 2b: To a methanol solution of $Ni(OAc)_2\cdot 4H_2O$ (3.05 mmol) was added the methanol solution (10 mL) of **1b** (3.05 mmol) and triphenylphosphane (9.15 mmol). The solution was stirred over night. After stirring overnight, the volatiles were removed in vacuo to obtain brown powders, which were extracted with ethanol and purified by crystallization to obtain crystals. Crystals suitable for single-crystal X-ray diffraction analysis were obtained from ethanol solution at room temperature. Yield = 1.0 g (51%, red crystals). Mp: 141–142 °C. ^{1}H NMR (200 MHz, $CDCl_3$, 25 °C) δ = 7.16–7.68 (m, 20H, Ar), 6.13 (s, 1H, C*H*) ppm. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, 25 °C) δ = 172.9, 157.2 (q, $^2J_{C\text{-}F}$ = 34.4 Hz), 142.3 (q, $^2J_{C\text{-}F}$ = 30.6 Hz), 134.4, 134.3, 132.3 (q, $^1J_{C\text{-}P}$ = 10.0 Hz), 130.9, 130.6, 128.8, 128.7, 128.1, 118.9 (q, $^1J_{C\text{-}F}$ = 281.1 Hz), 118.0 (q, $^1J_{C\text{-}F}$ = 279.6 Hz), 91.0 ppm. ^{19}F NMR (188 MHz, C_6D_6, 25 °C) δ = -65.4, -71.6 ppm. $^{31}P\{^1H\}$ NMR (81 MHz, $CDCl_3$, 25°C) δ = 14.5 ppm. IR (KBr): ν = 3432 (br), 3049 (w), 2965 (w), 1596 (m), 1533 (m), 1512 (m), 1493 (w), 1480 (w), 1453 (w), 1437 (m), 1358 (m), 1346 (m), 1268 (s), 1198 (s), 1177 (s), 1155 (m), 1133 (m), 1116 (w), 1097 (m), 1065 (m), 1030 (w), 999 (w), 890 (w), 853 (w), 806 (m), 787 (w), 751 (m), 710 (m), 704 (m), 693 (m), 647 (w), 619 (w), 586 (w), 532 (m), 508 (m) cm^{-1}. HRMS calc. for $C_{30}H_{21}F_6N_2O_2NiP$+H: 645,06766, found 645,06706. Anal. Calcd. for $C_{30}H_{21}F_6N_2O_2NiP$: C, 55.85; H, 3.28; N, 4.34. Found: C, 56.11; H, 3.30; N, 4.33. UV-Vis [nm, (ε, M^{-1}cm^{-1})]:

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325.5 (2800), 370.5 (3000), 399.0 (2800) nm in dichloromethane. 380.0 (2700), 397.0 (3500), 417.5 (2800) nm in THF.

Single-crystal X-ray structure determination[24]: Crystals were each mounted on a glass capillary in perfluorinated oil and measured in a cold N_2 flow. The data were collected using an Oxford Diffraction Xcalibur S Sapphire at 150(2) K ($Mo_{K\alpha}$ radiation, $\lambda = 0.71073$ Å). The structures were solved by direct methods and refined on F^2 with the SHELX-97 software package. The positions of the hydrogen atoms were calculated and considered isotropically according to a riding model.

CCDC-872012 (for **2a**), and -872013 (for **2b**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

General procedure for the catalytic C-C coupling reaction: A Schlenk flask was charged with an appropriate amount of complex **2b** (0.016 mmol, 2.0 mol%) and the corresponding bromo or iodo arene (0.77 mmol). The flask was cycled with nitrogen and vacuum. Afterwards a THF solution of benzylzinc bromide (2.2 mL, 1.1 mmol, 0.5 M in THF) was added. The flask was sealed and heated at 70 °C for 24 hours. After that time, the mixture was cooled, and dichloromethane and water were added. The aqueous layer was extracted with dichloromethane and the collected organic layers were washed with water and dried with Na_2SO_4. The coupling product was confirmed by GC-MS (with *n*-dodecane as internal standard) and NMR analysis. The analytical properties of the products are in agreement with literature data.[6a, 25]

5. Acknowledgements

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Highlights

- Ni(II) complexes with unsymmetric [O,N,O´]-pincer ligands have been studied
- A square planar geometry was observed with triphenylphosphane as co-ligand have been observed
- The Ni(II) complexes were applied as precatalysts in cross-coupling reactions to access diaryl methanes

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