Ferrocenylindium reagents in palladium-catalyzed cross-coupling reactions: asymmetric synthesis of planar chiral 2-aryl oxazolyl and sulfinyl ferrocenes

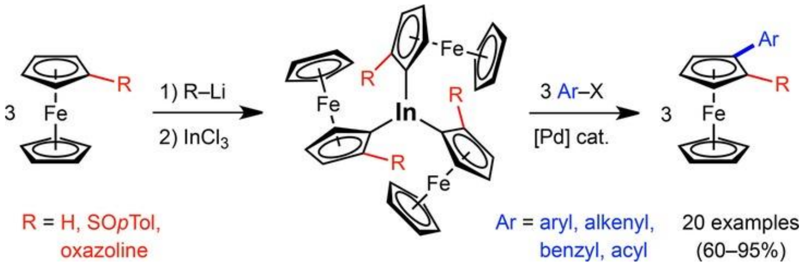
Mauro Mato, Cristina Pérez-Caaveiro, Luis A. Sarandeses and José Pérez Sestelo*

Centro de Investigaciones Científicas Avanzadas (CICA) and Departamento de Química Fundamental,
Universidade da Coruña, Spain

Advanced Synthesis & Catalysis, volume 359, issue 8, pages 1388–1393, 17 April 2017
Received 21 December 2016, revised 30 January 2017, published online 16 February 2017, issue online12 April 2017

Ferrocenylindium Reagents in Palladium-Catalyzed Cross-Coupling Reactions: Asymmetric Synthesis of Planar Chiral 2-Aryl Oxazolyl and Sulfinyl Ferrocenes. M. Mato, C. Pérez-Caaveiro, L. A. Sarandeses, J. Pérez Sestelo, *Adv. Synth. Catal.* **2017**, *359*, 1388

Abstract



The preparation of ferrocenylindium species and palladium-catalyzed cross-coupling reactions for the synthesis of monosubstituted and planar chiral 1,2-disubstituted ferrocenes is described. Triferrocenylindium reagents (Fc_3In) are efficiently prepared in a one-pot procedure from ferrocenes by lithiation and transmetallation to indium using $InCl_3$. The palladium-catalyzed cross-coupling reactions of Fc_3In (40 mol%) with a variety of organic electrophiles (aryl, heteroaryl, benzyl, alkenyl and acyl halides) in THF at 80 °C overnight provided a wide variety of monosubstituted ferrocenes in good to excellent yields. This methodology allowed the stereoselective synthesis of planar chiral 2-aryl-1-oxazolylferrocenes and 2-aryl-1-sulfinylferrocenes, which are of interest in asymmetric catalysis.

Keywords: asymmetric synthesis; cross-coupling; ferrocene ligands; indium; palladium

Ferrocene and derivatives are compounds of great interest in different areas of chemistry due to their fascinating structural and electronic properties.[1] The applications of ferrocene derivatives are constantly increasing, especially in organic synthesis,[2] materials science[3] and medicinal chemistry.[4] Ferrocene, for its aromatic character, can be considered a bioisotere of a phenyl ring, and established drugs such as anticancer taxol, or antimalarial artemisinin, have been modified by using ferrocene as a substituent in their core structure.[5] On the other hand, the inherent electrochemical properties of the ferrocene unit have led to its introduction in complex structures to provide new molecules with novel nonlinear optical or ferromagnetic properties.[6] In addition, the planar chirality of 1,2-disubstituted ferrocenes makes them important ligands in asymmetric catalysis. In this field, chiral ferrocenylphosphines such as ppfa (*N*,*N*-dimethyl-1-[2-

(diphenylphosphino)ferrocenyl]ethyl-amine), 2-aryl-monophosphine ferrocenes (aryl-MOPF), or ferrocenyl phosphino-oxazolines (Fc-PHOX) are privileged ferrocene ligands (Figure 1).[2a,7] Therefore, the development of efficient methods for the synthesis of functionalized and enantiomerically pure ferrocenes is of great importance.[2,8]

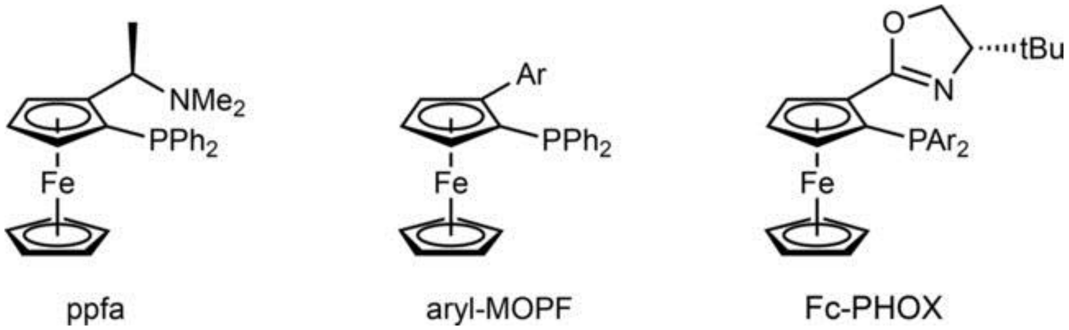


Figure 1. Privileged ferrocene ligands in asymmetric catalysis.

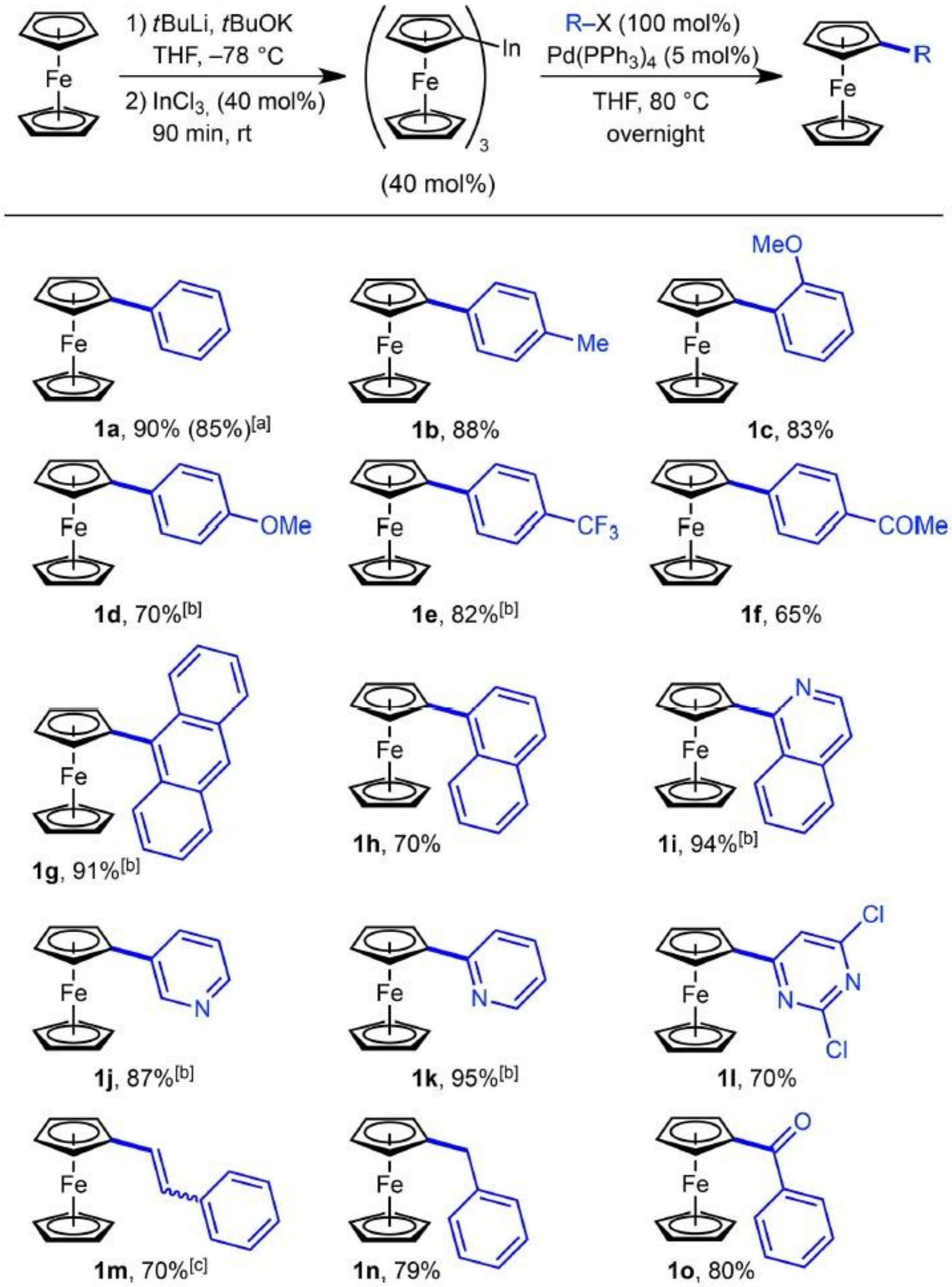
Metal-catalyzed cross-coupling reactions are amongst the most powerful tools available for the construction of new carbon-carbon bonds.[9] Although this methodology has already been applied to the synthesis of ferrocenes,[8e–8g,10] it often suffers from limitations such as low atom efficiency, the need for harsh reaction conditions or the use of highly toxic compounds. Over the last two decades, triorganoindium compounds (R_3In), which can be easily prepared from the corresponding organolithium or organic halide, have emerged as alternative reagents in metal-catalyzed reactions.[11] The palladium-catalyzed cross-coupling reaction using R_3In, which was discovered by our group,[12] is the most useful reaction of these reagents and its utility in organic synthesis is increasing steadily.[13] Besides their high atom efficiency due to the transfer of all three organic groups from indium to the electrophile, R_3In reagents show excellent selectivity, high versatility and, in general, low toxicity. In this communication we describe the novel preparation of triferrocenylindium reagents and their application in palladium-catalyzed cross-coupling reactions for the synthesis of monosubstituted and planar chiral 1,2-disubstituted ferrocenes.

Our investigation started with the one-pot procedure involving lithiation of ferrocene, transmetallation to indium and palladium-catalyzed coupling. It was found that direct lithiation of ferrocene using standard reaction conditions (*t*BuLi/*t*BuOK at −78 °C in THF),[14] followed by addition of anhydrous $InCl_3$ (40 mol%) and coupling with bromobenzene (100 mol%), using $Pd(PPh_3)_4$ (5 mol%) as catalyst in THF at 80 °C overnight, gave phenylferrocene (**1 a**) in 90% yield (Table 1). This result supports the formation of the Fc_3In intermediate and the efficient transfer of the three ferrocene units attached to indium. It should be noted that the coupling reaction is not efficient if indium is not used. Interestingly, the reaction can be monitored by observing the colour of the reaction mixture, which shows the different steps in this chemical transformation.[15] The reaction can be performed using palladium(II) complexes such as $Pd(dppf)Cl_2$ to afford the coupling product in similar yield. The reaction was easily scaled up to gram-scale obtaining a similar yield (85%).

To exploit the scope of this protocol, the palladium-catalyzed coupling reaction using Fc_3In was evaluated with a variety of organic halides (Table 1). During this research we found that the metallation/transmetallation/coupling works efficiently with aryl halides bearing electron-rich substituents such as 4-bromotoluene, 2-bromoanisole and 4-iodoanisole to give the corresponding phenyl substituted ferrocenes **1 b–d** in high yields (70–88%). Analogously, the cross-coupling using electron-deficient arenes such as 4-trifluoromethyl bromobenzene and 4-bromoacetophenone also afforded the phenylferrocenes **1 e** and **1 f** in

85% and 65% yields, respectively. It is remarkable that the coupling is not sensitive to the nature of the substituent on the phenyl halide and all of the reactions proceeded efficiently at 80 °C overnight. It was observed, however, that in some examples the highest yield was obtained on using Pd(dppf)Cl_2 as the catalyst.

Table 1. Pd-catalyzed cross-coupling of Fc_3In with organic electrophiles.



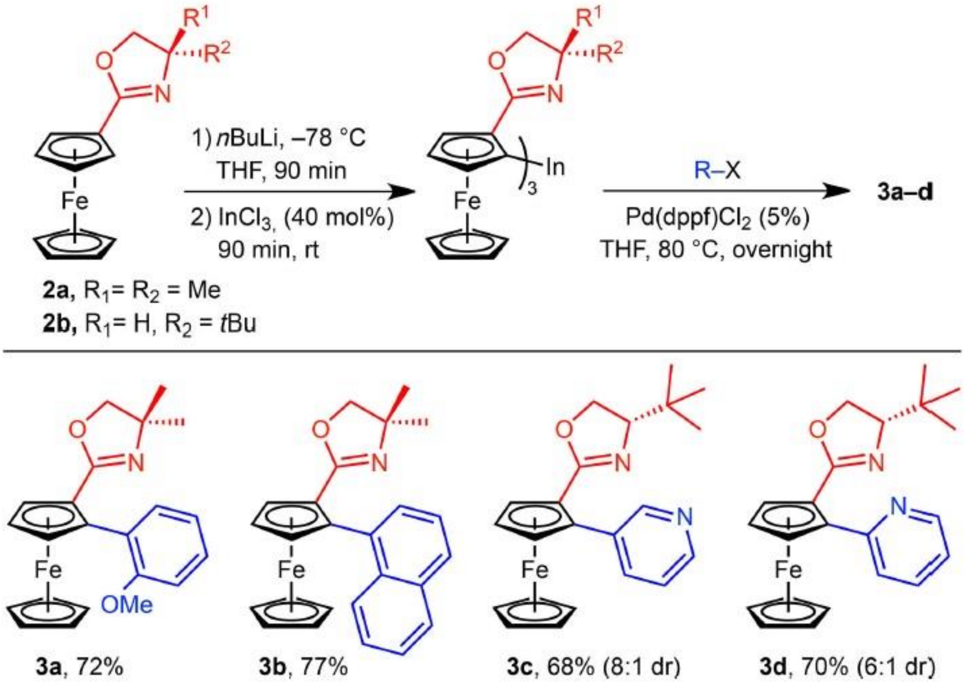
[a] In parenthesis, isolated yield at gram-scale. [b] Pd(dppf)Cl_2 (5 mol%) used as the catalyst. [c] *E*:*Z* 80:20.

The reaction of Fc$_3$In with bulky electrophiles such as 9-bromoanthracene or 1-bromonaphthalene, which usually require specific reaction conditions (high temperature, excess of the organometallic or additives),[16] also gave the corresponding 9-anthranylferrocene (**1 g**) and 1-naphthylferrocene (**1 h**) at 80 °C overnight in high yields (91% and 70%, respectively). Analogously, the coupling with heteroaryl halides allowed the synthesis of interesting substituted ferrocenes bearing nitrogen donor atoms, e. g., 3-pyridylferrocene (**1 j**), 2-pyridylferrocene (**1 k**), 1-isoquinolinylferrocene (**1 i**) and 2,6-dichloro-4-pyrimidylferrocene (**1 l**).[17] This study was also extended to organic electrophiles other than aryl halides and these allow further chemical transformations that are useful for the synthesis of new ferrocene derivatives. The cross-coupling of Fc$_3$In with β-bromostyrene (*E:Z*80:20) allowed the introduction of the alkene functionality (**1 m**) and the reaction with benzyl bromide and benzoyl chloride gave the corresponding monosubstituted ferrocenes **1 n** and **1 o** in good yields (70—80%). It is noteworthy that all reactions take place with only 40 mol% of Fc$_3$In in THF at 80 °C to afford the coupling product in good to excellent yields.

The synthetic utility of ferrocenylindium reagents in palladium-catalyzed cross-coupling reactions was also tested for the stereoselective synthesis of planar chiral 1,2-disubstituted ferrocenes. Ferrocene derivatives that contain a chiral directing group such as an oxazoline,[18] or a sulfoxide,[19] can be *ortho*-lithiated diastereoselectively under the appropriate conditions. In this study we envisioned that the resulting organolithium species could be transformed into the corresponding triferrocenylindium reagents and used in palladium-catalyzed cross-coupling reactions.

We began by exploring the lithiation/transmetallation/coupling protocol using the achiral ferrocenyl oxazoline **2 a**. As described in the literature, lithiation of **2 a** (100 mol%) with *n*BuLi in THF at −78 °C [20] followed by addition of InCl$_3$ (40 mol%) and coupling with 2-bromoanisole (100 mol%) in the presence of Pd(dppf)Cl$_2$ (5 mol%) in THF at 80 °C gave the 2-aryl-1-oxazolylferrocene **3 a** in 72% yield (Table 2). Analogously, the reaction using 1-bromonaphthalene afforded the 2-(1-naphthyl)-1-oxazolylferrocene **3 b** in 77% yield. To the best of our knowledge, these results represent the first examples of palladium-catalyzed cross-coupling reactions involving an organometallic ferrocenyloxazoline.

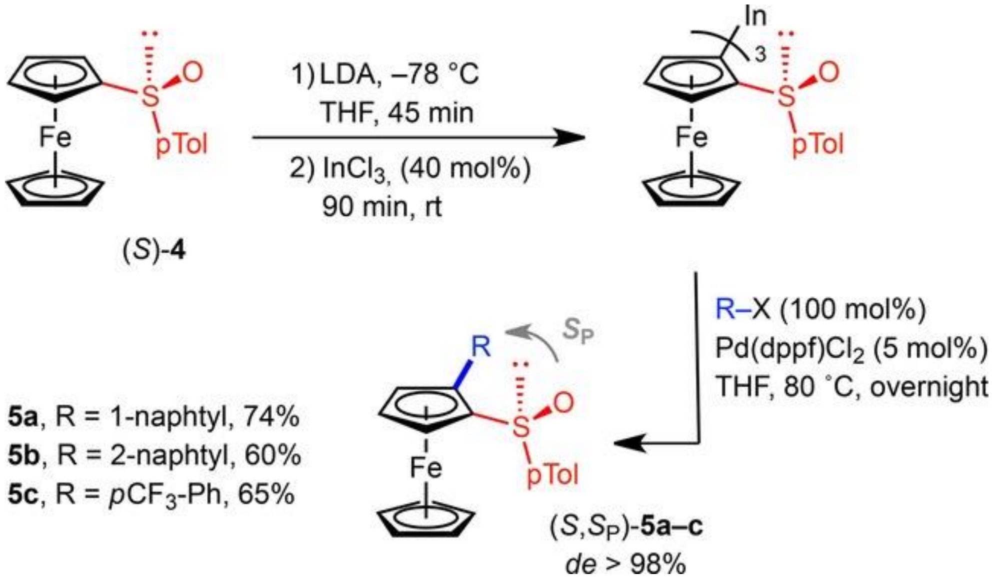
Table 2. Synthesis of 2-aryl-1-oxazolylferrocenes.



3a, 72% **3b**, 77% **3c**, 68% (8:1 dr) **3d**, 70% (6:1 dr)

These encouraging results led us to study the stereoselective synthesis of 2-aryl-1-oxazolylferrocenes. For this purpose, substrates bearing donor atoms such as pyridines were selected as electrophiles. Under the previously developed reaction conditions, lithiation of the enantiomerically pure ferrocenyl oxazoline **2 b** with *n*BuLi, transmetallation with indium and palladium-catalyzed cross-coupling with 3-bromopyridine using Pd(dppf)Cl$_2$(5 mol%) in THF under reflux gave (R_P)-2-(3-pyridyl)-1-oxazolylferrocene **3 c** in 68% yield with an 8:1 diastereomeric ratio, as determined by ^{1}H NMR spectroscopy (Table 2). This *dr* value is equal or slightly higher than that previously reported for the lithiation step, which indicates that the transmetallation-coupling steps take place without loss of diastereoselectivity. The two diastereoisomers were separated by flash column chromatography. The analogous protocol using 2-bromopyridine afforded the chiral (R_P)-2-pyridyl-1-oxazolylferrocene **3 d** in 70% yield (6:1 *dr* by ^{1}H NMR). Apart from the existing synthetic methods for the preparation of ferrocenyloxazolines,[7a] these cross-coupling reactions are the first examples in which oxazolylferrocenyl organometallics have been used for the enantioselective synthesis of 2-pyridyl-1-oxazolylferrocene ligands with planar and central chirality.

Our next objective was the enantioselective synthesis of 2-aryl-1-sulfinylferrocenes using an enantiopure ferrocenyl sulfoxide. The sulfoxide functionality can be used as a chiral *ortho*metallating group with high diastereoselectivity and its subsequent conversion allows the stereoselective synthesis of 1,2-disubstituted ferrocenes.[10d,21] Accordingly, lithiation of enantiopure *p*-tolyl ferrocenyl sulfoxide (*S*)-**4** using LDA in THF at −78 °C,[14] followed by addition of InCl$_3$ solution (40 mol%) gave the tri(2-sulfinylferrocenyl)indium intermediate (Scheme 2). Palladium-catalyzed cross-coupling with 1-bromonaphthalene using Pd(dppf)Cl$_2$(5 mol%) afforded the planar chiral (S,S_P)-2-(1-naphthyl)-1-sulfinylferrocene **5 a** in 74% yield as a single enantiomer (>99:1 by HPLC). Therefore, the lithiation step takes place with high diastereoselectivity and both the transmetallation and coupling steps proceed without affecting the stereoselectivity. In a similar manner, the procedure carried out with 2-bromonaphthalene and 4-trifluoromethylbromobenzene as organic electrophiles gave the enantiomerically rich (S,S_P)-2-aryl-1-sulfinyl ferrocenes **5 b** and **5 c** with high diastereomeric excess (*de* >98%) in 60% and 65% yield, respectively.

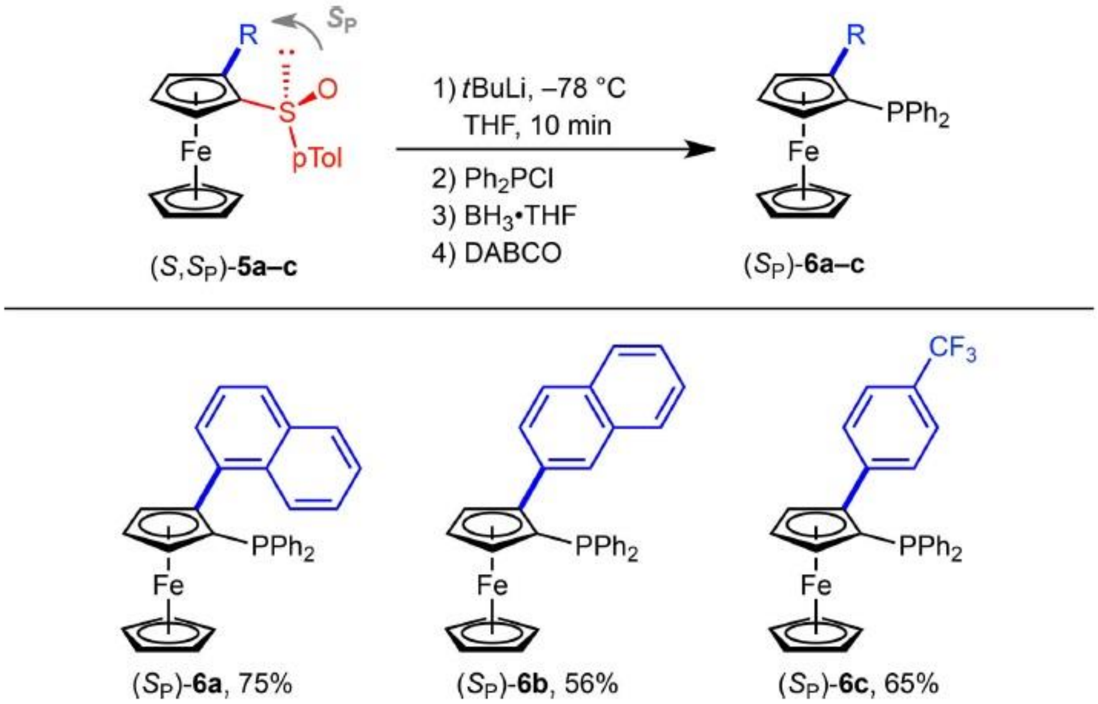


Scheme 1. Synthesis of (S,S_P)-2-aryl-1-sulfinylferrocenes.

Finally, and taking advantage of the versatility of the sulfoxide group, the enantiomerically rich (S,S_P)-2-aryl-1-sulfinylferrocenes **5 a–c** were transformed into the corresponding 2-aryl-1-monophosphine ferrocenes.

Following a reported procedure,[19] the sulfoxide group was converted into a diphenylphosphine group to give the planar-chiral phosphines (S_P)-**6 a**–**c** in good yields (Table 3). The enantiomeric purity of phosphines **6 a**–**c** was established based on the enantiomeric excess of the chiral sulfoxides **5 a**–**c** since the transformation is stereospecific.[19b–19d,21] It is worth noting that the (S_P)-2-(1- naphthyl)-diphenylphosphine ferrocene **6 a** exhibits high catalytic activity in the hydrosilylation of styrene.[21b] The utility of the novel chiral phosphines **6 b**–**c** in asymmetric catalysis is still unknown.

Table 3. Synthesis of planar chiral (S_P)-2-aryl-1-diphenylphosphine ferrocenes.



In summary, a practical and efficient procedure for the synthesis of monosubstituted and planar chiral 1,2-disubstituted ferrocenes by palladium-catalyzed cross-coupling reactions using triferrocenlylindium reagents has been developed. Fc_3In reagents can be efficiently prepared from ferrocene and derivatives by lithiation and transmetallation with indium(III). Fc_3In reagents (40 mol%) react with an array of organic electrophiles to provide an interesting range of monosubstituted ferrocenes in good yields under mild reaction conditions. The diastereoselective lithiation, transmetallation to indium and cross-coupling of chiral (S)-ferrocenyloxazolines led to the synthesis of planar chiral (R_P)-2-aryl-1-oxazolylferrocenes. Analogously, the coupling reaction in which tri(2-sulfinylferrocenyl)indium was used led to (S,S_P)-2-aryl-1-sulfinylferrocenes in good yields and with high diastereoselectivity. These compounds were efficiently converted into the corresponding *N*,*P*-2-aryl-1-diphenylphosphine ferrocenes (MOPF), which are of interest in asymmetric catalysis. Further applications of this synthetic method for novel planar chiral ferrocenes are underway.

Experimental Section

Full experimental details are available in the Supporting Information.

Preparation of triferrocenylindium solution (Fc_3In)

A flame-dried round-bottomed flask under an argon atmosphere, equipped with a Teflon-coated magnetic stirring bar, was charged with ferrocene (1.0 g, 5.375 mmol, 1.0 equiv.). The ferrocene was dissolved in dry THF (40 mL, 0.134 M for ferrocene) and *t*BuOK solution (0.65 mL, 1.0 M in THF, 0.12 equiv.) was added by syringe. The mixture was cooled to −78 °C. The resulting yellow solution was treated with *t*BuLi solution (6.3 mL, 1.64 M in pentane, 2.0 equiv.) over 15 minutes by syringe and the resulting orange suspension was stirred at −78 °C for 90 min. Then, $InCl_3$ solution (4.8 mL, 0.45 M in THF, 0.4 equiv.) was added dropwise and the reaction mixture was allowed to warm up to 0 °C and stirred for 1 h to give triferrocenylindium (1.79 mmol, 0.034 M in THF) as an orange homogeneous solution, which was immediately used for the cross-coupling step.

General procedure for the palladium-catalyzed cross-coupling reaction

A flame-dried Schlenk flask under an argon atmosphere, equipped with a Teflon-coated magnetic stirring bar, was charged with the organic halide (1.0 equiv.) and $Pd(PPh_3)_4$ (5 mol%) or $Pd(dppf)Cl_2$(5 mol%). The mixture was dissolved in dry THF (ca. 0.3 M) and freshly prepared Fc_3In solution (0.034 M in THF, 0.4 equiv.) was added dropwise by syringe or cannula. The mixture was heated at 80 °C overnight (16–18 h). The reaction was monitored by TLC and, after completion, quenched by the addition of a few drops of methanol and then tap water. The mixture was extracted with Et_2O or EtOAc three times and the combined organic phases were washed with brine and dried over anhydrous $MgSO_4$. The crude product was obtained by removal of the solvent under reduced pressure and it was purified by flash column chromatography (silica gel) to give the corresponding functionalized ferrocenes (65–95% yield).

Acknowledgements

We gratefully acknowledge the Spanish Ministerio de Economía y Competitividad (CTQ2015-68369-P), Xunta de Galicia (GRC2014/042) and EDRF funds for financial support..

References

[1] a) *Ferrocenes* (Eds.: T. Hayashi, A. Togni), VCH, Weinheim, **1995**. 1b) *Ferrocenes: Ligands, Materials and Biomolecules* (Ed.: P. Stepnicka), Wiley, West Sussex, **2008**.

[2] a) *Chiral Ferrocenes in Asymmetric Catalysis*, (Eds.: L.-X. Dai, X.-L. Hou), Wiley-VCH, Weinheim, **2010**. For selected references: b) M. Pérez, M. Fañanás-Mastral, P. H. Bos, A. Rudolph, S. R. Harutyunyan, B. L. Feringa, *Nat. Chem.* 2011, **3**, 377–381. c) B. Ye, N. Cramer, *Science* 2012, **338**, 504–506. d) D. Schaarschmidt, H. Lang, *Organometallics* 2013, **32**, 5668–5704. e) C. T. Check, K. P. Jang, C. B. Schwamb, A. S. Wong, M. H. Wang, K. A. Scheidt, *Angew. Chem. Int. Ed.* 2015, **54**, 4264–4268. f) A. M. del Hoyo, A. Urbano, A. Latorre, R. Díaz, M. C. Carreño, *Adv. Synth. Catal.* 2015, **357**, 1154–1160.

[3] a) *Electron Transfer and Radical Processes in Transition-Metal Chemistry* (Ed.: D. Astruc), VCH, New York, **1995**. For selected references: b) Z. M. Hudson, I. Manners, *Science* 2014, **344**, 482–483. c) L. Xu, Y.-X. Wang, L.-J. Chen, H.-B. Yang, *Chem. Soc. Rev.* 2015, **44**, 2148–2167. d) M. S. Inkpen, S. Scheerer, M. Linseis, A. J. P. White, R. F. Winter, T. Albrecht, N. J. Long, *Nat. Chem.* 2016, **8**, 825–830.

[4] For reviews: a) D. R. van Staveren, N. Metzler-Nolte, *Chem. Rev.* 2004, **104**, 5931–5986. b) G. Jaouen, A. Vessières, S. Top, *Chem. Soc. Rev.* 2015, **44**, 8802–8817. For selected examples: c) G. Gasser, I. Ott, N. Metzler-Nolte, *J. Med. Chem.* 2011, **54**, 3–25. c) H. V. Nguyen, Z. Zhao, A. Sallustrau, S. L. Horswell, L.

Male, A. Mulas, J. H. R. Tucker, *Chem. Commun.* 2012, **48**, 12165–12167. d) S. S. Braga, A. M. S. Silva, *Organometallics* 2013, **32**, 5626–5639.

[5] a) F. Dubar, C. Slomianny, J. Khalife, D. Dive, H. Kalamou, Y. Guerardet, P. Grellier, C. Biot, *Angew. Chem. Int. Ed.* 2013, **52**, 7690–7693. b) D. Plazuk, A. Wieczorek, A. Blauz, B. Rychlik, *Med. Chem. Comm.* 2012, **3**, 498–501. c) L. Delhaes, C. Biot, L. Berry, L. A. Maciejewski, D. Camus, J. S. Brocard, D. Dive, *Bioorg. Med. Chem.* 2000, **8,** 2739–2745.

[6] a) M. Hmyene, A. Yassar, M. Escorne, A. Percheron-Guegan, F. Garnier, *Adv. Mater.* 1994, **6**, 564–568. b) N. Tsuboya, R. Hamasaki, M. Ito, M. Mitsuishi, T. Miyashita, Y. Yamamoto, *J. Mater. Chem.* 2003, **13**, 511–513. c) R. Horikoshi, T. Mochida, *Eur. J. Inorg. Chem.* 2010, 5355–5371. d) S. Kaur, S. Dhoun, G. Depotter, P. Kaur, K. Claysb, K. Singh, *RSC Adv.* 2015, **5**, 84643–84656.

[7] For reviews see: a) R. Gómez Arrayás, J. Adrio, J. C. Carretero, *Angew. Chem. Int. Ed.* 2006, **45**, 7674–7715. b) Y. Miyake, Y. Nishibayashi, S. Uemura, *Synlett* 2008, 1747–1758. c) S. Toma, J. Csizmadiová, M. Meciarová, R. Šebesta, *Dalton Trans.* 2014, **43**, 16557–16579.

[8] For some recent representative examples: a) M. Ogasawara, S. Watanabe, K. Nakajima, T. Takahashi, *J. Am. Chem. Soc.* 2010, **132**, 2136–2137. b) C. Pi, Y. Li, X. Cui, H. Zhang, Y. Han, Y. Wu, *Chem. Sci.* 2013, **4**, 2675–2679. c) T. Shibata, T. Shizuno, T. Sasaki, *Chem. Commun.* 2015, **51**, 7802–7804. d) M. Murai, K. Matsumoto, Y. Takeuchi, K. Takai, *Org. Lett.* 2015, **17**, 3102–3105. e) D.-Y. Zhu, P. Chen, J.-B. Xia, *ChemCatChem* 2016, **8**, 68–73. f) D−W. Gao, Q. Gu, S.-L. You, *J. Am. Chem. Soc.* 2016, **138**, 2544–2547. g) S. B. Wang, J. Zheng, S. L. You, *Organometallics* 2016, **35**, 1420–1425. h) A. Urbano, G. Hernández-Torres, A. M. del Hoyo, A. Martínez-Carrión, M. C. Carreño, *Chem. Commun.* 2016, **52**, 6419–6422.

[9] *Metal-Catalyzed Cross-Coupling Reactions* (Eds.: F. Diederich, P. Stang), Wiley-VCH, New York, **2008**.

[10] For a review see: a) V. Mamane, *Mini-Rev. Org. Chem.* 2008, **5**, 303–312. For representative examples, see: b) M. T. Lee, B. M. Foxman, M. Rosenblum, *Organometallics* 1985, **4**, 539–547. c) M. Enders, G. Kohl, H. Pritzkow, *J. Organomet. Chem.* 2001, **622**, 66–73. d) J. F. Jensen, I. Søtofte, H. O. Sørensen, M. Johannsen, *J. Org. Chem.* 2003, **68**, 8332–8337. e) H. Song, X. Li, Y. Long, G. Schatte, H.-B. Kraatz, *Dalton. Trans.* 2006, 4696–4701. f) T. Mochida, H. Shimizu, S. Suzuki, T. Akasaka, *J. Organomet. Chem.* 2006, **691**, 4882–4889. g) R. J. Kloetzing, P. Knochel, *Tetrahedron: Asymmetry* 2006, **17**, 116–123. h) H. V. Nguyen, M. Motevalli, C. J. Richards, *Synlett* 2007, 725–728. i) V. C. Gibson, N. J. Long, P. J. Oxford, A. J. P. White, D. J. Williams *Organometallics* 2006, **25**, 1932–1939. j) J. Xia, S.-L. You, *Organometallics* 2007, **26**, 4869. k) D.-W. Gao, Y.-C. Shi, Q. Gu, Z.-L. Zhao, S.-L. You, *J. Am. Chem. Soc.* 2013, **135**, 86–89.

[11] For a review on the preparation and applications of organoindium reagents, see: Z.-L. Shen, S.-Y. Wang, Y.-K. Chok, Y.-H. Xu, T.-P. Loh, *Chem. Rev.* 2013, **113**, 271–401.

[12] a) I. Pérez, J. Pérez Sestelo, L. A. Sarandeses, *Org. Lett.* 1999, **1**, 1267–1269. b) I. Pérez, J. Pérez Sestelo, L. A. Sarandeses, *J. Am. Chem. Soc.* 2001, **123**, 4155–4160. c) D. Rodríguez, J. Pérez Sestelo, L. A. Sarandeses, *J. Org. Chem.* 2004, **69**, 8136–8139. d) R. Riveiros, D. Rodríguez, J. Pérez Sestelo, L. A. Sarandeses, *Org. Lett.* 2006, **8**, 1403–1406.

[13] For key references from this group: a) M. M. Martinez, C. Perez-Caaveiro, M. Peña-López, L. A. Sarandeses, J. Pérez Sestelo, *Org. Biomol. Chem.* 2012, **10**, 9045–9051. b) C. Pérez-Caaveiro, J. Pérez Sestelo, M. M. Martínez, L. A. Sarandeses, *J. Org. Chem.* 2014, **79**, 9586–9593. c) Á. Mosquera, M. I. Fernández, M. Canle López, J. Pérez Sestelo, L. A. Sarandeses, *Chem. Eur. J.*2014, **20**, 14524–14530. For additional examples: d) K. Takami, H. Yorimitsu, H. Shinokubo, S. Matsubara, K. Oshima, *Org. Lett.* 2001, **3**, 1997–1999. e) P. H. Lee, S.-Y. Sung, K. Lee, *Org. Lett.* 2001, **3**, 3201–3204. f) K. Lee, D.

Seomoon, P. H. Lee, *Angew. Chem. Int. Ed.* 2002, **41**, 3901–3903. g) U. Lehmann, S. Awasthi, T. Minehan, *Org. Lett.* 2003, **5**, 2405–2408. h) K. Takami, S. Mikami, H. Yorimitsu, H. Shinokubo, K. Oshima, *J. Org. Chem.* 2003, **68**, 6627–6631. i) L. Baker, T. Minehan, *J. Org. Chem.* 2004, **69**, 3957–3960. j) L. Jin, Y. Zhao, L. Zhu, H. Zhang, A. Lei, *Adv. Synth. Catal.* 2009, **351**, 630–634. k) Y.-H. Chen, M. Sun, P. Knochel, *Angew. Chem. Int. Ed.* 2009, **48**, 2236–2239. l) J. Mo, S. H. Kim, P. H. Lee, *Org. Lett.* 2010, **12**, 424–427. m) Z.-L. Shen, K. K. K. Goh, Y.-S. Yang, Y.-C. Lai, C. H. A. Wong, H.-L. Cheong, T.-P. Loh, *Angew. Chem. Int. Ed.* 2011, **50**, 511–514. n) Z.-L. Shen, Y.-C. Lai, C. H. A. Wong, K. K. K. Goh, Y.-S. Yang, H.-L. Cheong, T.-P. Loh, *Org. Lett.*2011, **13**, 422–425. o) L. Adak, N. Yoshikai, *J. Org. Chem.* 2011, **76**, 7563–7568. p) K. Lee, H. Kim, J. Mo, P. H. Lee, *Chem. Asian J.* 2011, **6**, 2147–2157. q) S. Bernhardt, Z.-L. Shen, P. Knochel, *Chem. Eur. J.* 2013, **19**, 828–833. r) D. Lee, T. Ryu, Y. Park, P. H. Lee, *Org. Lett.* 2014, **16**, 1144–1147. s) S. Thapa, S. K. Gurung, D. A. Dickie, R. Giri, *Angew. Chem. Int. Ed.* 2014, **53**, 11620–11624. t) S. Kim, C.-E. Kim, B. Seo, P. H. Lee, *Org. Lett.* 2014, **16**, 5552–5555. u) Y. Park, J. Min, D. Eom, P. H. Lee, *Org. Lett.* 2015, **17**, 3934–3937.

[14] O. Riant, G. Argouarch, D. Guillaneux, O. Samuel, H. B. Kagan, *J. Org. Chem.* 1998, **63**, 3511–3514, and references therein.

[15] See Supporting Information.

[16] a) K. Nikitin, H. Müller-Bunz, Y. Ortin, J. Muldoon, M. J. McGlinchey, *J. Am. Chem. Soc.* 2010, **132**, 17617–17622. b) A. M. Del Hoyo, A. Urbano, M. C. Carreño *Org. Lett.* 2016, **18**, 20–23.

[17] F. Fache, E. Schulz, M. L. Tommasino, M. Lemaire, *Chem. Rev.* 2000, **100**, 2159–2232.

[18] a) C. Bolm, K. Muñiz, A. Seger, G. Raabe, K. Günther, *J. Org. Chem.* 1998, **63**, 7860–7867. b) S. A. Herbert, D. C. Castell, J. Clayden, G. E. Arnott, *Org. Lett.* 2013, **15**, 3334–3337. c) M. Ayerbe Garcia, W. Frey, R. Peters, *Organometallics* 2014, **33**, 1068–1078. d) C. Nottingham, R. Benson, H. Müller-Bunz, P. J. Guiry, *J. Org. Chem.* 2015, **80**, 10163–10176.

[19] For a review, see: a) B. Ferber, H. B. Kagan, *Adv. Synth. Catal.* 2007, **349**, 493–507. b) J. F. Jensen, M. Johannsen, *Org. Lett.* 2003, **5**, 3025–3028. c) J. F. Jensen, I. Søtofte, H. O. Sørensen, M. Johannsen, *J. Org. Chem.* 2003, **68**, 1258–1265. d) M. Lotz, K. Polborn, P. Knochel, *Angew. Chem. Int. Ed.* 2002, **41**, 4708–4711.

[20] a) T. Sammakia, H. A. Latham, D. R. Schaad, *J. Org. Chem.* 1995, **60**, 10–11. b) T. Sammakia, H. A. Latham, *J. Org. Chem.* 1995, **60**, 6002–6003. c) T. Sammakia, A. H. A. Latham, *J. Org. Chem.* 1996, **61**, 1629–1635.

[21] a) M. Lotz, G. Kramer, P. Knochel, *Chem. Commun.* 2002, 2546–2547. b) V. E. Albrow, A. J. Blake, R. Fryatt, C. Wilson, S. Woodward, *Eur. J. Org. Chem.* 2006, 2549–2557.

---

[*] sestelo@udc.es