Enantioselective functionalisation of the C-2′ position of 1,2,3,4,5-pentamethylazaferrocene *via* sparteine mediated lithiation: potential new ligands for asymmetric catalysis

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The *s*-BuLi–sparteine base combination deprotonated the C-2′ position of 1,2,3,4,5-pentamethylazaferrocene **1** and subsequent reaction with a range of electrophiles gave C-2 substituted products in 76–93% yield and ~80% ee. The products could be recrystallised to enrich ee's to >90%. Resubjection of the initial addition products (~80% ee) to the deprotonation conditions led to a kinetic resolution to give products with >90% ee and superior overall yields compared to recrystallisation for the cases where the electrophiles were Ph_2CO, MeI and Ph_2S_2. Transmetallation of the 2-lithiopentamethylazaferrocene (~80% ee) with $ZnCl_2$ allowed palladium catalysed cross coupling with a variety of C-2 haloaryl, heteroaryl and vinyl groups to give some novel C-2′ substituted pentamethylazaferrocene derivatives in 61–77% yield in 80% ee. Potential *N*,*N*-chelate ligands were recrystallised to >95% ee. A novel C_2-symmetric bis-pentamethylazaferrocene **10** could be synthesised by an iron catalysed oxidative coupling of the enatioenriched C-2 lithio derivative and in the presence of a PhMe–Et_2O solvent mixture proceeded in 97% ee.

Introduction

The ferrocenyl motif is a sturdy platform for the synthesis of planar chiral ligands for asymmetric catalysis. The dominance of the planar chiral element in ferrocenyl derived ligands above centres of chirality for the transmission of asymmetry in chemical reactions has been well documented.[1–5] Purely planar chiral ferrocenes have been less well investigated, possibly due to the challenges associated with enantioselective syntheses compared to the multitude of diastereoselective approaches, for example strategies that start with the ubiquitous Ugi's *N*,*N*-dimethyl-1-ferrocenylethylamine.[6,7] The pioneering work of Fu *et al.*, although relying on resolution to synthesise planar chiral ferrocenes, demonstrated the power of planar chiral metallocene DMAP derivatives in the field of nucleophilic catalysis.[8] These results stimulated other work in the ferrocene field and routes to similar systems[9] and chelate ligands were developed.[2,10–13] In our own work we have used the Sniekus approach of sparteine mediated enantioselective directed *ortho* metallation of *N*,*N*-diisopropyl ferrocenecarboxamide[14] to access a series of N–P, N–N, N–O and N–S planar chiral ferrocene chelate ligands (Fig. 1).[15,16] These were shown to be less efficient than non-ferrocene N–X chiral ligand systems that rely upon centres of chirality in palladium catalysed asymmetric allylic alkylation.[16] Although the 1,2-disubstituted ferrocene systems we surveyed have a sterically large planar chiral element, the nature of the substituents placed the steric bulk of the metallocene some way away from the reaction centre (Fig. 1, 1st generation design). Movement of the ferrocene closer to the catalytically active metal centre would give ligand systems with potentially more efficient chirality transfer. This could be most easily achieved by either synthesising 1,2-bidentate ferrocene systems containing both heteroatoms bonded to one of the cyclopentadienyl rings, or take advantage of a heterometallocene, such as an azaferrocene (Fig. 1, 2nd generation design). Without an obvious asymmetric synthesis to 1,2-heteroatom disubstituted ferrocenes we focussed our attention on azaferrocenes, which can be made planar chiral by substitution at either the C-2′ or C-3′ position

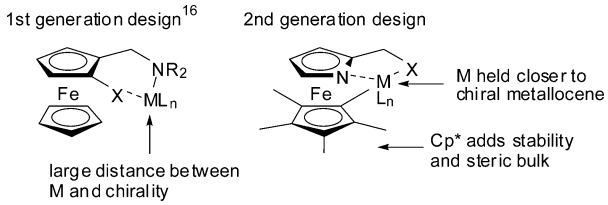

Fig. 1 Design concept.

The investigation of the versatility of planar chiral heterometallocenes in asymmetric catalysis has been dominated by Fu *et al.* who have looked at 2-substituted pentamethylazaferrocenes,[8] pentamethylphosphaferrocenes[17] and (η^5-1,2-azaborolyl)iron derivatives.[18] Their syntheses of planar chiral azaferrocenes have relied upon preparative chiral HPLC to resolve the two enantiomers.[8c,19] We sought an efficient and direct multi-gram enantioselective synthesis of C-2′ substituted azaferrocenes. At the outset of this work there was only one general route to enantiopure 2′-substituted pentamethylazaferrocenes that had been disclosed by Johannsen *et al.*[20] In that work, in a similar manner to the use of chiral sulfoxides by Kagan *et al.* for the diastereoenrichment of planar chiral ferrocenes,[21] regioselective deprotonation at C-2′ of pentamethylazaferrocene and addition of an Andersen reagent[22]

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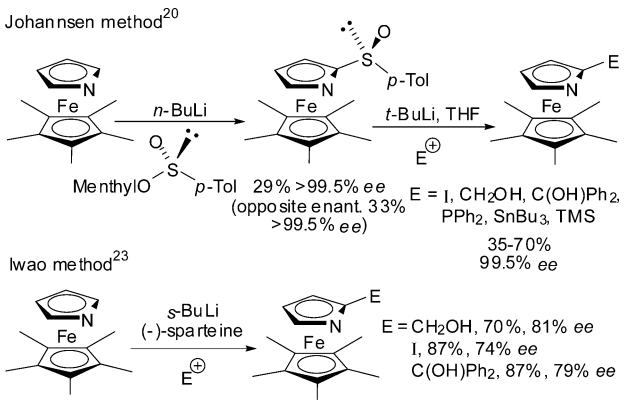
Table 1 Optimisation of enantioselective deprotonation[a]

Entry	*s*-BuLi (equiv.)	(−)-Sparteine (equiv.)	Solvent	Temp/°C	Yield **2** (%)	ee[b] (%)
1	2.2	2.2	Et_2O	−78	84	77
2	2.2	2.2	i-Pr_2O	−78	60	77
3	2.2	2.2	PhMe	−78	70	77
4	2.2	2.2	Hexane	−78	66	77
5	2.2	3.2	Et_2O	−78	68	77
6	2.2	4.2	Et_2O	−78	82	77
7	2.2	5.2	Et_2O	−78	70	70
8	2.2	6.2	Et_2O	−78	84	77
9	3.2	3.2	Et_2O	−78	5	77
10	2.2	1.2	Et_2O	−78	77	77
11	1.2	1.2	Et_2O	−78	84	77
12[c]	1.2	1.2	Et_2O	−90	82	80
13[c]	1.2	1.2	Et_2O	−100	85	83

[a] 4 h then addition of I_2 (1 equiv. to *s*-BuLi). [b] Determined by HPLC on a Chiralcel OD-H column. [c] 6 h.

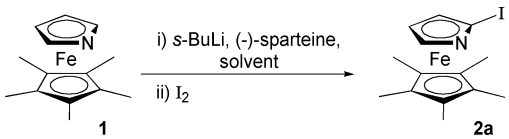
gave separable diastereomeric sulfoxides (Scheme 1). Treatment of either diastereoisomer with ^{t}BuLi led to an enantiomerically pure carbanion that could be quenched with a range of electrophiles. However the overall yield of the process was moderate, ranging between 15–40%. In view of the success of Snieckus' use of enantioselective metallation mediated by sparteine on dialkyl ferrocenecarboxamides[14] we investigated the possibility of using a (−)-sparteine–butyllithium system to differentiate the enantiotopic 2′,5′-pentamethylazaferrocene protons. During our preliminary investigations a communication by Iwao *et al.* also verified that *s*-BuLi–sparteine could be used to enantioselectively metallate pentamethylazaferrocene at the C-2 position and that it reacted with a limited set of electrophiles (Scheme 1).[23] The results we present in this paper considerably extend the preliminary results of Iwao *et al.* in that a broader range of electrophiles were investigated and we show that enantioenrichment can be achieved by kinetic resolution or traditional recrystallisation. We also report our investigations into the synthesis of planar chiral analogues of some privileged ligand structures.



Scheme 1 Direct precedent.

Results and discussion

Treatment of 1,2,3,4,5-pentamethylazaferrocene **1** with *n*-BuLi (2.2 equiv.) in the presence of (−)-sparteine (2.2 equiv.) at −78 °C in THF for 4 hours, followed by the addition of I_2 (2.2 equiv.) gave (−)-(S_p)-2-iodopentamethylazaferrocene[20b] **2a** in a moderate 46% yield and 10% ee [eqn (1)].[24] Preliminary optimisation quickly revealed that using the slightly less coordinating solvent Et_2O and the more reactive *s*-BuLi gave the optimum mixture of rate of reaction and expression of chiral information by competitive coordination of (−)-sparteine[25] to give iodide **2a** in 84% yield and 77% ee (Table 1, entry 1). Less coordinating solvents did not alter the extent of enantioselection, but did have a detrimental effect on the rate of reaction as shown by the isolated yield after 4 h (entries 2–4). Excess (−)-sparteine did not alter the enantioselectivity or the yield to any significant extent (entries 5–8). Although an excess of *s*-BuLi to (−)-sparteine was tolerated (entry 10), 3.2 equiv. of both *s*-BuLi and (−)-sparteine were deleterious to the chemical yield (entry 9). A decrease in temperature gave slightly better yields and enantioselectivites, but at the expense of reaction times and convenience (entries 12 and 13). Based on these results we decided that 1.2 equiv. of both *s*-BuLi and (−)-sparteine at −78 °C were the most practical conditions (entry 11).



(1)

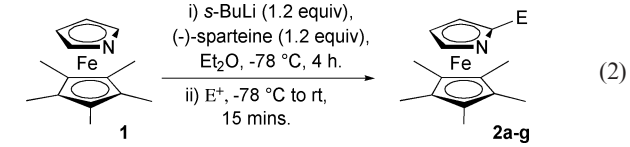
In order to establish the generality of the reaction the optimised procedure was assayed with a variety of electrophiles [eqn (2), Table 2]. The products were isolated in around 90% yield and 80% ee (by chiral HPLC) with the exception of the iodo derivative **2a**, formed in 80% yield, and the diphenylphosphine derivative **2f** that was formed in 57% optical purity. Iodide **2a** was formed in slightly lower yield because of the tendency for it to convert back to **1** in the presence of excess *s*-BuLi. The optical purity of phosphine **2f** is treated as a conservative estimate and, in view of the fact that some of the optical rotations we measured for other derivatives **2** gave lower optical purities than ee's determined by HPLC, the ee of **2f** could be considerably higher. We noticed no erosion of ee in contrast to compound **13** (*vide infra*). We were unable to isolate boronic acid derivative **2g** by standard chromatography or recrystallisation. The enantioselectivities of **2c** and **2d** were extrapolated from derivatives. The enantiopurity of the methyl

Table 2 Scope of reaction

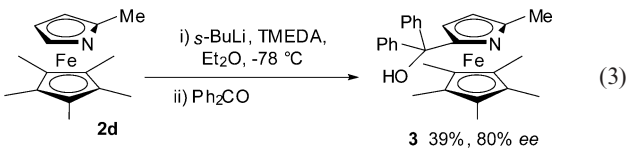
2	E^+	E	Yield (%)	ee (%)	Recryst. yield (%)[f]	ee (%)
a	I_2	I	80	77[b]	52	90[b]
b	Ph_2CO	Ph_2COH	86	82[b]	26	97[b]
c	TMSCl	TMS	86	81[c]	50	>99%[a]
d	MeI	Me	93	80[c]	—[g]	—
e	Ph_2S_2	SPh	93	79[d]	48	96[d]
f	Ph_2PCl	PPh_2	93	57[e]	64	86[e]
g	$B(OMe)_3$	$B(OH)_2$	—[a]	—	—	—

[a] Not isolable. [b] Determined by HPLC on a Chiralcel OD-H column.[20b] [c] Determined by HPLC of a derivative (see text). [d] Determined by HPLC on a Chiralcel AD column.[20b] [e] Optical purity based upon polarimetry data from Ref. 20*b*. [f] Et_2O–hexane mixtures. [g] Soluble in hexane.

derivative **2d** was extrapolated from that of **3**, which was formed by a second *s*-BuLi deprotonation in the presence of *N*,*N*,*N*′,*N*′-tetramethyl-1,2-ethylenediamine (TMEDA) followed by addition of benzophenone [eqn (3)].

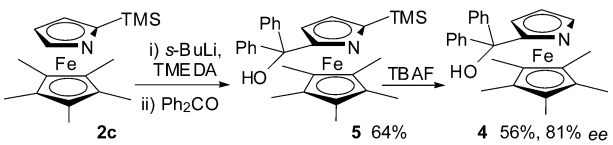


(2)



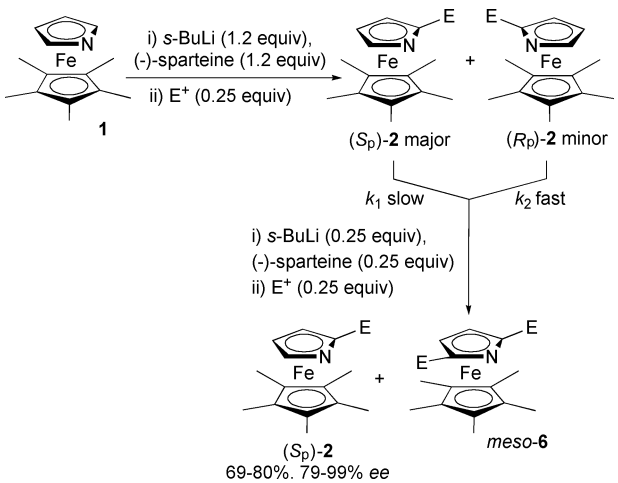
(3)

In a similar manner the enantiopurity of **2c** was extrapolated from alcohol **4**. One of the drawbacks of using (−)-sparteine is that it is only available in one enantiomeric form, although there are some excellent (+)-sparteine-like diamines now available.[26] However Dai *et al.* demonstrated the protection of prochiral protons with a TMS group and subsequent deprotection with tetra-*n*-butylammonium fluoride (TBAF) in ferrocene systems.[27] Deprotonation of a sample of **2c** [from eqn (2)] with *s*-BuLi–TMEDA and addition of benzophenone gave alcohol **5** in 64% yield (Scheme 2). Subsequent treatment with TBAF in refluxing THF gave (−)-(R_p)-alcohol **4** in 56% yield and 81% ee by chiral HPLC.[24]



Scheme 2

In most cases a single recrystallisation of the products enriched the ee's of the 2′-substituted pentamethylazaferrocenes to 90% or more (Table 2). We thought a conceptually more appealing method of enriching the initial enantioselectivity could be by kinetic resolution.[28] Once the products **2** have been formed there exists a preponderance of the S_p product arising from kinetic deprotonation of the pro-*S* proton of **1** (Scheme 3). Assuming that the rate of a second proton abstraction by further treatment with a calculated amount of *s*-BuLi–(−)-sparteine would be faster for the pro-*S* proton of (R_p)-**2** rather then the pro-*R* proton of (S_p)-**2** ($k_2 > k_1$), then a kinetic resolution of **2** could take place and lead to enantioenrichment of the initial product. In addition, deprotonation of the minor enantiomer (R_p)-**2** followed by electrophilic quenching would lead to a *meso* compound which should be readily separable from (S_p)-**2**.



Scheme 3 Kinetic resolution studies.

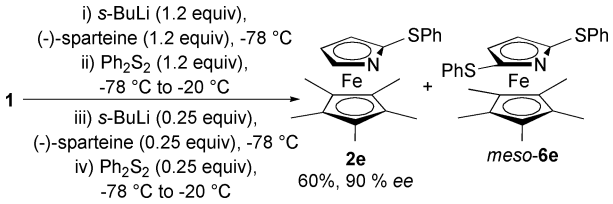
Optimum conditions were based upon resubjection of purified **2**, ~80% ee (Table 2) to sub-stoichiometric quantities of *s*-BuLi–(−)-sparteine (0.25 equiv.). Theoretically around 0.11 equiv. of *s*-BuLi–(−)-sparteine could consume virtually all the minor (R_p)-**2** isomer, but we found 0.25 equiv. to be better both in terms of yield and ee. Substrates in which the ee could be determined easily were examined and an enhancement of ee was observed for **2b**, **d** and **e** (Table 3). The kinetic resolution gives higher material throughput than upgrading ee by recrystallisation. The virtually identical ee and isolated yield obtained for **2a** (Table 3) after attempted kinetic resolution, suggests a non-selective halogen–lithium exchange reaction rather than any deprotonation.[29] It was

Table 3 Kinetic resolution of products **2**

2	E	Yield (%)	Yield *meso*-**6** (%)	Overall yield (%)	ee (%)
a	I	80	—	61	79[a]
b	Ph_2COH	79	—	68	90[a]
d	Me	69	—	64	>99[b]
e	SPh	74	19	69	93[c]

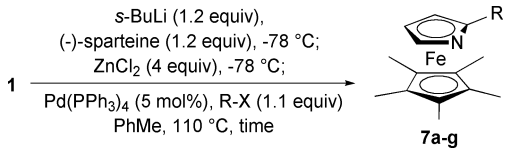
[a] Determined by HPLC on a Chiralcel OD-H column. [b] Determined by HPLC of derivative **3** (see text). [c] Determined by HPLC on a Chiralcel AD column.

only possible to isolate *meso*-**6e**, but we believe this supports the postulated mechanism for this kinetic resolution. Many attempts were made to optimise a one pot process whereby sub-stoichiometric quantities of *s*-BuLi–(−)-sparteine and/or E^+ were added after the initial reaction. We found the reactions with E^+ were temperature dependent and we believe byproducts formed from the first excess of *s*-BuLi reacting with E^+ also reacted with subsequent additions of reagents. These factors, amongst others, greatly complicated the development of a one pot reaction. A process of optimisation did lead to a one pot protocol being developed for the synthesis of **2e** in 60% yield and 90% ee [eqn (4)]. Ultimately the two step protocol provides a very efficient route to highly enantioenriched 2-substituted azaferrocenes and may be a viable route to more complex derivatives.



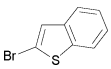
(4)

To increase the structural diversity of potential ligand systems and other derivatives that could be generated by this approach we speculated that certain enantioenriched 2′-substituted pentamethylazaferrocene derivatives could be used as precursors for transition metal catalysed cross coupling reactions. Some preliminary experiments with iodide **2a** revealed that although insertion of Pd(0) was possible, it required microwave conditions and stoichiometric $Pd(PPh_3)_4$. The presumed Pd(II) intermediate (by MS and TLC) was found to be reluctant to undergo any standard coupling reaction. We then speculated that the enantioenriched 2′-lithiopentamethylazaferrocene intermediate could undergo transmetallation in order to participate in a transition metal catalysed cross coupling reaction with a 2-halo heteroaromatic.[30] Isolation of a boron derivative had proven difficult (Table 2), which immediately ruled out investigation of the popular Suzuki cross coupling reaction. However, there are several literature precedents for performing Negishi couplings on ferrocenes.[31] We began a similar study by transmetallating the enantioenriched 2-lithiopentamethylazaferrocene with $ZnCl_2$ (1.2 equiv.) in Et_2O, but quickly found we needed an excess of $ZnCl_2$ (4 equiv.) and PhMe as solvent so we could conduct the reaction at higher temperatures. We speculate that excess $ZnCl_2$ is necessary to sequester (−)-sparteine which could otherwise chelate to the zincated pentamethylazaferrocene and deactivate towards the palladium catalyst. We were able to conduct coupling with aryl, heteroaryl and alkenyl halides in high yield and identical enantioselectivity [eqn (5) and Table 4] to the direct reaction with electrophiles (Table 1). Slightly longer reaction times were necessary for unactivated halides **7b**,**d**,**g**. A larger excess of $ZnCl_2$ (6 equiv.) was needed for the 2-quinoline derivative **7d** as this product may play a similar chelating and deactivating role as mentioned for (−)-sparteine as it is formed in the reaction mixture. The ee of the heteroaryl derivatives **7c–f** were all measured by chiral HPLC and were consistent with previous results. We therefore think it is not unreasonable to assume that aryl **7a**,**b** and alkenyl **7g** derivatives are also formed in 80% ee. In addition the ee of pyridyl **7c** and 2-quinoline **7d** derivatives could be enriched to 95%



(5)

Table 4 Cross coupled products

7	R–X	Time/h	Yield (%)	ee[a] (%)
a	Ph–I	5	77	[c]
b		6	68	[c]
c		2	70	80
d		4	68	80
e		2	62	77
f		2	72[b]	80
g		4	61	[c]

[a] Determined by HPLC on a Chiralcel OD-H column. [b] $ZnCl_2$ (6 equiv.). [c] Assumed ~80% ee, see text.

by a single recrystallisation from Et_2O. Although the overall yield after recrystallisation from azaferrocene for **7c** was disappointing (9%), that for **7d** was much better (36%). The nature of this palladium coupling seems to be robust to a variety of activated and unactivated coupling partners and demonstrates that it is possible to synthesise a range of *N*,*N*- and *N*,*S*-ligands in good yield and enantiomeric excess.

With an efficient cross coupling protocol developed we investigated the synthesis of planar chiral ferrocene analogues of privileged ligand systems. Fu *et al.* have also published the synthesis and utility of methylene bridged bis-pentamethylazaferrocene **8**[8c,32] and we were interested in synthesising an analogue **9** using the *s*-BuLi–(−)-sparteine chemistry developed above (Fig. 2). Both of these bis-azaferrocene skeletons have similarities with the popular and very effective bis-oxazoline type ligands.[33] The synthesis of dimer **9** by classic Ullmann chemistry was found to be inappropriate because of the thermal instability of

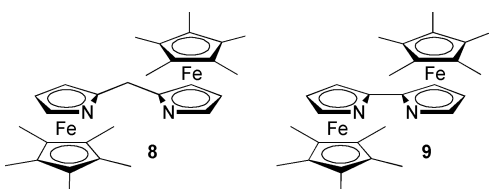
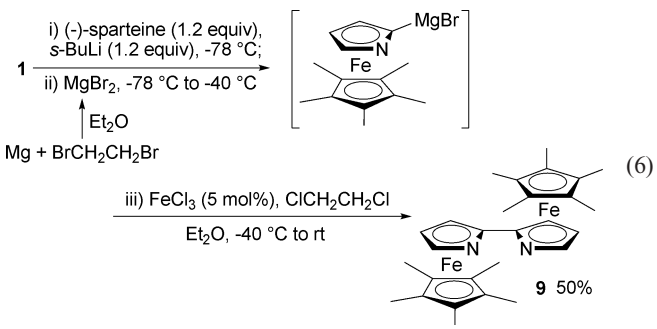


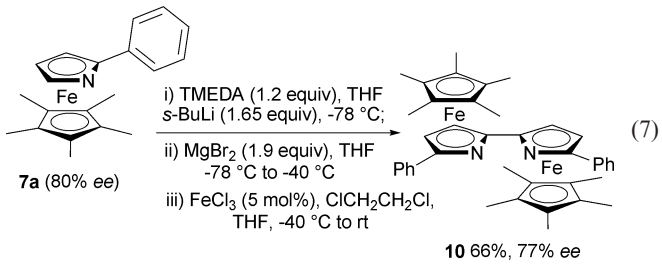
Fig. 2 Bis-pentamethylazaferrocenes.

pentamethylazaferrocene toward the high temperatures involved in such couplings.[34] Stoichiometric Ni coupling failed despite its use in electron rich pyridine dimerisations.[35] During the development of the cross coupling chemistry above we had some success in preparing the *para*-chloro derivative of **7a** from iodopentamethylazaferrocene **2a** *via* iodine–magnesium exchange with i-PrMgCl[36] followed by transmetallation with $ZnCl_2$. Coupling with 1-chloro-4-iodobenzene using $Pd(PPh_3)_4$ as a catalyst in refluxing THF gave coupled product in 49% yield.[37] Attempting an identical procedure but with **2a** also as the electrophile led to no reaction, as did the corresponding Kumada type coupling between the ferrocenyl Grignard, generated *via* halogen–magnesium exchange as above, and **2a** with stoichiometric Ni. Eventually we found we could use an iron catalysed oxidative homocoupling of the ferrocenyl Grignard following a procedure reported by Hayashi and Nagano,[38] but with some optimisation of reaction temperature. The required Grignard reagent could be generated directly from the sparteine derived 2-lithiopentamethylazaferrocene by transmetallation with freshly prepared $MgBr_2$. Warming to −40 °C followed by treatment with catalytic $FeCl_3$ (5 mol%)–$ClCH_2CH_2Cl$ in Et_2O and warming to room temperature gave the homocoupled product **9** which was quickly purified by column chromatography on silica in 50% yield [eqn (6)]. The structure of **9** was characterised by ^1H NMR and mass spectroscopy, but **9** proved to be considerably unstable in solution or its solid form.



(6)

From qualitative observations we had noted that the 2′-phenylpentamethylazaferrocene (**7a**) was significantly more stable than **1**. We attempted the synthesis of a 2′-phenyl analogue of **9** from **7a** (presumed 80% ee) in anticipation that this would be more stable. Initial attempts to synthesise dimer **10** using Et_2O as a solvent were unsuccessful and after some deuterium quenching studies we found the optimum conditions for deprotonation required the combination of *s*-BuLi and TMEDA in THF. Under the optimised coupling conditions we obtained **10** in 66% yield and 77% *ee* [eqn (7)]. As predicted, **10** proved to be significantly more stable than **9**, which bodes well for its future investigation as a chiral ligand in asymmetric reactions. Deprotonation of **7a** under identical conditions, but in PhMe, and continuation of the coupling reaction in Et_2O [as in eqn (6)] for solubility reasons led to the isolation of **10** in 34% yield and 97% ee. This dramatic increase in ee indicated a possible kinetic resolution was operating in this coupling reaction. Although no *meso* product was isolated, we propose that the formation of this product, or intermediates to it, is fast in Et_2O–PhMe and consumes all minor enantiomer of **7a**.



(7)

The C_2-symmetric pyridine-bis-azaferrocene **11** (Fig. 3) is analogous to the successful Pybox type ligands **12**.[33] Attempted Negishi type coupling of zincated pentamethylazaferrocene (2 equiv.) with 2,6-dibromopyridine under our optimised conditions [eqn (5), $ZnCl_2$ (6 equiv.)] led to consumption of starting materials in 2 hours. The ^1H NMR spectrum of the product oil revealed peaks consistent with the formation of **11**, but contaminated with ~10% of **1**. The appearance of a small amount of starting material was apparent in our other coupling reactions (Table 4), but was easily separated by column chromatography. Unfortunately purification of crude **11** by chromatography or recrystallisation was unsuccessful and pure **11** could not be isolated.

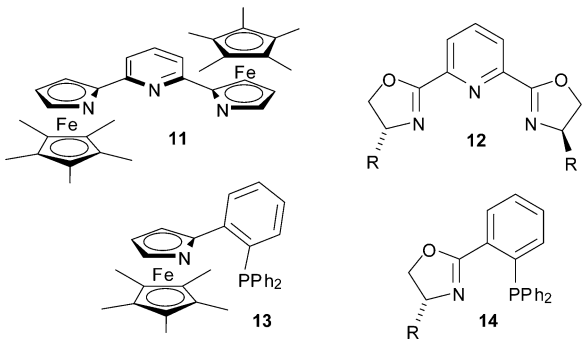
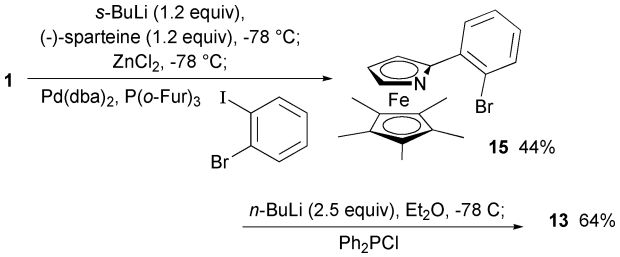


Fig. 3 Chiral planar ferrocene analogues of privileged ligands.

The success of phosphine-containing ligands across a variety of asymmetric catalytic processes encouraged us to investigate the possibility of a *P*,*N*-azaferrocene chelate structure **13** which bears significant similarities to ligand systems **14** independently developed by Sprinz and Helmchen, von Matt and Pfaltz, and Williams *et al.* (Fig. 3).[39] Coupling of zincated pentamethylazaferrocene with 2-bromo-1-iodobenzene proceeded in an unoptimised 44% yield and required a palladium(0) tri-*ortho*-furyl phosphine catalyst (Scheme 4). The aryl bromide substituent was then subjected to halogen–lithium exchange and quenched with Ph_2PCl to give ligand **13** in 64% yield. Unfortunately during recrystallisation, in



Scheme 4

an attempt to upgrade the ee, the compound was found to racemise in solution. After 2 days in Et_2O at −18 °C the enantiopurity of **13** had decreased from 78% to 62% ee as measured by chiral HPLC. A similar phenomenon has been observed for several aromatic phosphine and sulfur substituted ferrocenes by Snieckus *et al.*[14a] and is suggested to be due to Cp–aryl exchange.

Conclusions

The *s*-BuLi–(−)-sparteine mediated deprotonation of pentamethylazaferrocene and addition of a range of electrophiles led to the enantioselective functionalisation of the C-2′ position in around 80% ee for the majority of cases examined. A novel kinetic resolution was developed that enriched the ee of the isolated products (~80% ee) to 90–99% ee in 64–69% overall yield for the cases where the electrophiles Ph_2CO, MeI or Ph_2S_2 were used. This method was higher yielding than upgrading the ee by recrystallisation and may find use for more complex or non-crystalline substrates.

Enantiomerically enriched 2-lithiopentamethylazaferrocene (~80% ee) was used in Negishi cross couplings with a variety of aryl, vinyl and heteroaryl halides and led to the enantioselective synthesis of some C_1-symmetric *N*,*N* (**7c**,**d**) and *N*,*S* (**7e**,**f**) chelate ligands in one step. The *N*,*N*-bidentate ligands **7c** and **7d** were recrystallised to a synthetically useful >95% ee.

The homodimerisation of pentamethylazaferrocene was achieved by an iron catalysed oxidative coupling to give the novel C_2-symmetric ligand **10**. Coupling in a PhMe–Et_2O mixture as opposed to THF resulted in a 34% yield of **10** in 97% ee. The methodology described will be useful for the synthesis of a variety of potential chelate systems that may be useful as chiral ligands in enantioselective catalysis. We are currently investigating the effectiveness of **7c**, **d** and **10** as chiral ligands in asymmetric processes.

Experimental

Our general experimental details have been published previously.[15] Commercial (−)-sparteine was distilled under reduced pressure and stored over 4 Å molecular sieves and $ZnCl_2$ was dried by fusing under vacuum with a Bunsen burner.

(−)-(S_p)-2′-Iodo-1,2,3,4,5-pentamethylazaferrocene 2a

To a solution of 1,2,3,4,5-pentamethylazaferrocene **1** (150 mg, 0.58 mmol) in Et_2O (2.5 mL) was added (−)-sparteine (0.16 mL, 0.70 mmol, 1.2 equiv.). The reaction was cooled to −78 °C and *s*-BuLi (0.70 mL of 1 N in hexanes, 0.70 mmol, 1.2 equiv.) was added dropwise and the reaction was stirred for 4 hours at −78 °C. A solution of I_2 (178 mg, 0.70 mmol, 1.2 equiv.) in Et_2O (7 mL) was added dropwise. The reaction was then warmed to room temperature and left to stir for 15 minutes. A small amount of silica gel was added and the mixture was concentrated *in vacuo*. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **2a** (180 mg, 80%) as an orange solid, mp = 84 °C (hexane), in 77% ee as determined by HPLC analysis[20b] (Daicel Chiralcel OD-H column); $[\alpha]_D$ −20 (benzene, *c* 0.35, 22 °C) [lit[20b] $[\alpha]_D$ = −88 (benzene, *c* 0.12)]. All other data was in exact agreement with those of the literature.[20b]

(+)-(S_p)-2′-Diphenylhydroxymethyl-1,2,3,4,5-pentamethylazaferrocene 2b

Synthesised in an identical manner to **2a** using benzophenone as an electrophile. Purification by flash column chromatography (15% EtOAc–5% Et_3N–pet. ether) gave **2a** (221 mg, 86%) as yellow crystals, mp = 120 °C (50% hexane–50% Et_2O), in 82% ee as determined by HPLC analysis: Daicel Chiralcel OD-H column, 1% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (minor) 10.8 min, t_r (major) 12.3 min; $[\alpha]_D$ = +120 (benzene, *c* 0.33, 22 °C) [lit[20b] $[\alpha]_D$ = +159 (benzene, *c* 0.39)]. All other data was in exact agreement with those of the literature.[20b]

(−)-(S_p)-2′-Trimethylsilyl-1,2,3,4,5-pentamethylazaferrocene 2c

Synthesised in an identical manner to **2a** using TMSCl as an electrophile. Purification by flash column chromatography (15% EtOAc–5% Et_3N–pet. ether) gave **2c** (167 mg, 86%) as a red solid, mp = 110 °C (hexane); $[\alpha]_D$ −70 (benzene, *c* 0.27, 22 °C) [lit[20b] $[\alpha]_D$ = −108 (benzene, *c* 0.37)]. All other data was in exact agreement with those of the literature.[20b]

(−)-(S_p)-2′-Methyl-1,2,3,4,5-pentamethylazaferrocene 2d

Synthesised in an identical manner to **2a** using MeI as an electrophile. Purification by flash column chromatography (30% EtOAc–5% Et_3N–pet. ether) gave **2d** (150 mg, 93%) as an orange solid, mp = 54 °C; $[\alpha]_D$ −17 (benzene, *c* 0.30, 22 °C); IR ν_{max} (solid) 2967, 2907, 2359, 2339, 1380, 1031, 816 cm^{-1}; ^1H NMR δ 1.95 (15H, s, Cp*H), 2.21 (3H, s, Me) 3.95 (1H, s, py-H), 4.08 (1H, s, py-H), 4.89 (1H, s, py-H) ppm; ^{13}C NMR δ 10.8, 13.9, 72.7, 74.8, 80.5, 91.1, 102.3 ppm; *m*/*z* (EI^+) 271 (100% M^+), 190 (51%), 123 (25%); HRMS $C_{15}H_{21}FeN$ calcd 271.1017, found 271.1023.

(−)-(S_p)-2′-Thiophenyl-1,2,3,4,5-pentamethylazaferrocene 2e

Synthesised in an identical manner to **2a** using Ph_2S_2 as an electrophile. Purification by flash column chromatography (30% EtOAc–5% Et_3N–pet. ether) gave **2e**, (150 mg, 93%) as an orange solid, mp = 114 °C (Et_2O), in 79% ee as determined by HPLC analysis: Diacel Chiralcel AD column, 1% i-PrOH–hexane, 0.2 mL min^{-1}; t_r (minor) 8.5 min, t_r (major) 12.3 min; $[\alpha]_D$ +8 (benzene, *c* 0.3, 22 °C); IR ν_{max} (solid) 2953, 2909, 1582, 1382, 1025, 897 cm^{-1}; ^1H NMR δ 1.95 (15H, s, Cp*H), 4.32–4.34 (1H, m, py-H), 4.37 (1H, dd, *J* 2.0, 1.0 Hz, py-H), 5.06 (1H, s, py-H), 7.05–7.10 (3H, m, Ar-H), 7.15–7.21 (2H, m, Ar-H) ppm; ^{13}C NMR δ 10.9, 77.7, 80.0, 82.3, 94.7, 96.7, 125.3, 127.0, 128.6, 138.9 ppm; *m*/*z* (EI^+) 365 (100%), 255 (16%), 134 (16%), 119 (22%); HRMS $C_{20}H_{24}NSFe$ calcd 366.0979, found 366.0947; anal. calcd for $C_{20}H_{24}NSFe$: C, 65.58; H, 6.60; N, 3.82, found C, 65.67; H, 6.43; N, 3.84%.

(−)-(S_p)-2′-Diphenylphosphine-1,2,3,4,5-pentamethylazaferrocene 2f

Synthesised in an identical manner to **2a** using Ph_2PCl as an electrophile. Purification by flash column chromatography (15% EtOAc–5% Et_3N–pet. ether) gave **2f** (239 mg, 93%) as yellow crystals, mp = 161 °C (50% hexane–50% Et_2O), in 57% ee; $[\alpha]_D$ = −20 (benzene, *c* 0.26, 22 °C) [lit[20b] $[\alpha]_D$ = −35 (benzene, *c* 0.26)]. All other data was in exact agreement with those of the literature.[20b]

(−)-(R_p)-2′-Diphenylhydroxymethyl-5-methyl-1,2,3,4,5-pentamethylazaferrocene 3

To a solution of **2d** (100 mg, 0.36 mmol) in Et_2O (2.5 mL) was added TMEDA (49 mg, 0.43 mmol, 1.2 equiv.). The reaction was cooled to −78 °C and *s*-BuLi (358 μL of 1.2 N in hexanes, 0.43 mmol, 1.2 equiv.) was added dropwise and the reaction was stirred for 4 h at −78 °C. A solution of benzophenone (78 mg, 0.43 mmol, 1.2 equiv.) in Et_2O (2 mL) was added dropwise, the reaction was then warmed to room temperature and left to stir for 15 minutes. A small amount of silica gel was added and the mixture was concentrated *in vacuo*. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **3** (64 mg, 39%) as a dark orange oil in 80% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 1% i-PrOH–hexane, 0.15 mL min^{-1}; t_r (major) 22.3 min, t_r (minor) 23.9 min; $[\alpha]_D$ = −78 (benzene, *c* 0.74); IR ν_{max} (film) 3457, 2909, 1658, 1319, 1281, 942 cm^{-1}; ^1H NMR δ 1.74 (15H, s, Cp*H), 1.90 (3H, s, Me), 4.10 (1H, d, *J* 2.2 Hz, py-H), 4.18 (2H, s, py-H and OH), 6.92–6.97 (2H, m, Ar-H), 7.04–7.16 (2H m, Ar-H), 7.27–7.32 (2H, m, Ar-H), 7.41 (2H, t, *J* 7.9 Hz, Ar-H), 7.77–7.80 (2H, m, Ar-H) ppm; ^{13}C NMR δ 11.0, 14.5, 46.7, 73.0, 74.8, 77.9, 81.4, 102.4, 112.9, 126.8, 126.9, 127.0, 127.4, 127.4, 128.0, 145.0, 150.8 ppm; *m*/*z* (ES^+) HRMS: $C_{28}H_{31}NOFe$ calcd 454.1833, found 454.1824.

(−)-(S_p)-2′-Trimethylsilyl-5-diphenylhydroxymethyl-1,2,3,4,5-pentamethylazaferrocene 5

Synthesised in an identical manner to **3**, **2c** (136 mg, 0.41 mmol) gave after purification by flash column chromatography (15% EtOAc–5% Et_3–pet. ether) **5** (135 mg, 64%) as a dark orange solid, mp = 41 °C (Et_2O); $[\alpha]_D$ = −72 (benzene, *c* 0.86, 22 °C); IR ν_{max} (solid) 2956, 2902, 1246, 1032, 838, 760 cm^{-1}; ^1H NMR δ 0.39 (9H, s, TMS), 1.90 (15H, s, Cp*H), 4.28 (1H, d, *J* 2.1 Hz, py-H), 4.43 (1H, d, *J* 2.1 Hz, py-H), 4.56 (1H, s, OH), 6.79 (2H, d, *J* 6.4 Hz, Ar-H), 7.12–7.15 (2H, m, Ar-H), 7.34–7.41 (2H, m, Ar-H), 7.50 (2H, t, *J* 7.7 Hz, Ar-H), 7.85 (2H, d, *J* 7.7 Hz, Ar-H) ppm; ^{13}C NMR δ −0.4, 11.3, 15.4, 73.9, 77.7, 80.8, 81.1, 98.0, 117.2, 126.4, 126.7, 126.8, 127.1, 127.3, 127.4, 127.6, 128.1, 144.7, 151.3 ppm; *m*/*z* (EI^+) 511 (50%), 494 (29%), 493 (47%), 119 (22%), 73 (100%). HRMS: $C_{30}H_{37}SiNOFe$ calcd 511.1994, found 511.1990; anal. calcd for $C_{30}H_{37}SiNOFe$: C, 70.43; H, 7.29; N, 2.74, found C, 70.28; H, 7.39; N, 2.58%.

(−)-(R_p)-2′-Diphenylhydroxymethyl-1,2,3,4,5-pentamethylazaferrocene 4

To a solution of **5** (49 mg, 0.10 mmol) in THF (1 mL) was added TBAF (0.19 mL of 1 N in THF, 0.19 mmol, 1.9 equiv.). The reaction was stirred for 18 h at reflux. The solution was cooled to rt and diluted with Et_2O (10 mL), then washed with H_2O (10 mL) and dried ($MgSO_4$). The crude filtrate was concentrated *in vacuo* to yield an orange oil. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **5** (22 mg, 54%) as yellow crystals, mp = 124 °C, in 81% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 1% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (major) 10.8 min, t_r (minor) 12.3 min; $[\alpha]_D$ = −112 (benzene, *c* 0.33) (lit[20b] $[\alpha]_D$ = −146). All other data was in exact agreement with those of the literature.[20b]

(−)-Sparteine–*s*-BuLi mediated kinetic resolution of 2′-substituted pentamethylazaferrocences 2

To a solution of 2′-substituted-1,2,3,4,5-pentamethylazaferrocene **2** (1 equiv.) in Et_2O (5 mL $mmol^{-1}$) was added (−)-sparteine (0.25 equiv.). The reaction was cooled to −78 °C, *s*-BuLi (0.25 equiv.) was added dropwise and the reaction was stirred for 4 h at −78 °C. The electrophile (0.25 equiv.) was then added dropwise either as a neat liquid or in an ether solution. The reaction was then warmed to rt and left to stir for 15 minutes. A small amount of silica gel was then added and the mixture was concentrated *in vacuo* in preparation for flash column chromatography.

Products **2a**, **2b**, **2d** and **2e** gave identical physical data as to that reported above or in Ref. 20*b*. Magnitude of ee was measured as above.

Data for *meso*-**6e**. Subjection of **2e** (150 mg) to the resolution conditions above gave enantioenriched **2e** (111 mg, 74%) in 93% ee and *meso*-**6e** (53 mg, 19%) as yellow crystals, mp = 137 °C (hexane); IR ν_{max} (solid) 3078, 2910, 1479, 1023, 735 cm^{-1}; ^1H NMR δ 2.55 (15H, s, Cp*H), 4.71 (2H, s, py-H), 6.85–7.01 (10H, m, Ar-H) ppm; ^{13}C NMR δ 10.6, 83.0, 83.7, 99.6, 125.7, 126.4, 127.3, 128.7, 129.1, 138.3 ppm; *m*/*z* (EI^+) 473 (24%, M^+), 147 (32%), 109 (27%), 95 (45%), 83 (52%), 73 (100%), 69 (81%), 57 (98%), 55 (100%). HRMS $C_{26}H_{27}NS_2Fe$ calcd 473.0934, found 473.0936.

One pot (−)-sparteine–*s*-BuLi mediated kinetic resolution to prepare (−)-(S_p)-2′-thiophenyl-1,2,3,4,5-pentamethylazaferrocene 2e

To a solution of 1,2,3,4,5-pentamethylazaferrocene **1** (150 mg, 0.58 mmol) in Et_2O (2.5 mL) was added (−)-sparteine (160 mg, 0.70 mmol, 1.2 equiv.). The reaction was cooled to −78 °C and *s*-BuLi (0.70 mL of 1 N in hexanes, 0.70 mmol, 1.2 equiv.) was added dropwise and the reaction was stirred for 4 h at −78 °C. A solution of Ph_2S_2 (152 mg, 0.70 mmol, 1.2 equiv.) in Et_2O (2 mL) was then added dropwise and the reaction was warmed to rt and left to stir for 15 minutes. After this time (−)-sparteine (34 mg, 0.15 mmol, 0.25 equiv.) was added, the reaction was re-cooled to −78 °C, *s*-BuLi (0.15 mL of 1 N in hexanes, 0.15 mmol, 0.25 equiv.) was added dropwise and the reaction was stirred for 3 h at −78 °C. A solution of Ph_2S_2 (32 mg, 0.15 mmol, 0.25 equiv.) in Et_2O (0.5 mL) was then added dropwise and the reaction was warmed to rt and left to stir for 15 minutes. A small amount of silica gel was added and the mixture was concentrated *in vacuo*. Purification by flash column chromatography (10–20% EtOAc–5% Et_3N–pet. ether) gave **2e** (127 mg, 60%) in 90% ee (determined by HPLC as before) and *meso*-**6e** (47 mg, 17% yield).

(−)-(S_p)-2′-Phenyl-1,2,3,4,5-pentamethylazaferrocene 7a

To a solution of 1,2,3,4,5-pentamethylazaferrocene **1** (1.00 g, 3.90 mmol) in toluene (20 mL) was added sparteine (1.08 mL, 4.68 mmol, 1.2 equiv.). The reaction was cooled to −78 °C and *s*-BuLi (4.68 mL of 1 N in hexanes, 4.68 mmol, 1.2 equiv.) was added dropwise, the reaction was then stirred for 4 hours at −78 °C. After this time a solution of pre-dried $ZnCl_2$ in THF (15.6 mL of 1 N in THF, 15.6 mmol) was added dropwise. The reaction was then warmed to room temperature and left to stir for 15 minutes and a

bright orange precipitate was observed. A solution of $Pd(PPh_3)_4$ (0.23 g, 0.20 mmol, 5 mol%) and PhI (1.19 g, 5.85 mmol, 1.5 equiv.) in THF (15 mL) was stirred at rt for 15 mins and then added to the reaction. The reaction was heated to reflux and followed by monitoring the disappearance of the aromatic halide by TLC. The mixture was diluted with CH_2Cl_2 (40 mL), poured onto a satd aq. solution of NH_4Cl (40 mL), the layers were separated and the combined aqueous layers were washed with CH_2Cl_2 (2 × 20 mL). The organics were combined and washed with $NaHCO_3$ solution (40 mL), brine (40 mL), dried over $MgSO_4$) and concentrated *in vacuo*. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **7a** (1.00 g, 77% yield) as orange crystals, mp = 109 °C (Et_2O); $[\alpha]_D$ −8 (CH_2Cl_2, *c* 0.82, 22 °C); IR ν_{max} (solid) 2971, 2908, 1602, 1452, 1380, 1066, 1033, 801, 762 cm^{-1}; ^1H NMR δ 1.71 (15H, s, Cp*H), 4.34 (1H, d, *J* 1.6 Hz, py-H), 4.58 (1H, d, *J* 2.4 Hz, py-H), 5.13 (1H, s, py-H), 7.26 (1H, d, *J* 7.6 Hz, Ar-H), 7.39 (2H, t, *J* 7.8 Hz, Ar-H), 7.70 (2H, d, *J* 7.2 Hz, Ar-H) ppm; ^{13}C NMR δ 10.3, 69.9, 76.3, 81.2, 92.5, 102.1, 125.3, 126.4, 128.4, 135.7 ppm; *m/z* (EI^+) 333 (100%, M^+), 331 (32%), 190 (27%), 143 (41%). HRMS $C_{20}H_{23}NFe$ calcd 333.1180, found 333.1171; anal. calcd for $C_{20}H_{23}NFe$: C, 72.11; H, 6.96; N, 4.20, found C, 72.22; H, 7.02; N, 4.17%

(−)-(S_p)-2′-(3,5-Difluorophenyl)-1,2,3,4,5-pentamethylazaferrocene 7b

Synthesised in an identical manner to **7a** using 3,5-difluoroiodobenzene as a coupling partner. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **7b** (145 mg, 68% yield) as yellow crystals, mp = 143 °C (Et_2O); $[\alpha]_D$ −35 ($CHCl_3$, *c* 0.28, 22 °C); IR ν_{max} (solid) 2972, 2910, 1621, 1587, 1117, 1083, 1033, 813 cm^{-1}; ^1H NMR δ 1.72 (15H, s, Cp*H), 4.40 (1H, dd, *J* 2.2, 0.8 Hz, py-H), 4.52 (1H, d, *J* 2.5, 0.6 Hz, py-H), 5.15 (1H, s, py-H), 6.71 (1H, tt, *J* 8.8, 2.2 Hz, Ar-H), 7.20 (2H, dd, *J* 9.0, 2.3 Hz, Ar-H) ppm; ^{13}C NMR δ 10.3, 70.6, 81.6, 93.2, 101.4 (t, $J_{C\text{-}F}$ 25.4 Hz), 107.8 (dd, $J_{C\text{-}F}$ 26.1, 7.1 Hz), 164.5, 164.7 ppm; *m/z* (ES^+) HRMS $C_{20}H_{22}NF_2Fe$ calcd 370.1070, found 370.1043; anal. calcd for $C_{20}H_{21}NF_2Fe$: C, 65.02; H, 5.73; N, 3.79, found C, 65.01; H, 5.68; N, 3.78%.

(+)-(S_p)-2′-(2-Pyridyl)-1,2,3,4,5-pentamethylazaferrocene 7c

Synthesised in an identical manner to **7a** using 2-bromopyridine as a coupling partner. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **7c** (395 mg, 68% yield) as orange crystals, mp = 99 °C (Et_2O) in 80% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 10% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (major) 9.5 min, t_r (minor) 24.0 min; $[\alpha]_D$ +140 ($CHCl_3$, *c* 0.30, 22 °C); IR ν_{max} (solid) 2966, 2911, 2855, 2358, 2344, 1587, 1493, 1033, 810, 792 cm^{-1}; ^1H NMR δ 1.69 (15H, s, Cp*H), 4.41 (1H, dd, *J* 2.5, 0.9 Hz, py-H), 5.05 (1H, dd, *J* 2.5, 0.8 Hz, py-H), 5.13 (1H, s, py-H), 7.13 (1H, ddd, *J* 7.6, 4.9, 1.3 Hz, Ar-H), 7.67 (1H, td, *J* 7.7, 1.8 Hz, Ar-H), 7.79 (1H, dt, *J* 8.0, 1.1 Hz, Ar-H), 8.60 (1H, ddd, *J* 5.0, 2.0, 0.9 Hz, Ar-H) ppm; ^{13}C NMR δ 10.3, 72.3, 77.2, 81.5, 101.4, 120.0, 120.9, 136.0, 149.2, 156.3 ppm; *m/z* (EI^+) 334 (92%, M^+), 200 (59%), 144 (100%), 117 (56%), 105 (75%). HRMS $C_{19}H_{22}N_2Fe$ calcd 334.1124, found 334.1132; anal. calcd for $C_{19}H_{22}N_2Fe$: C, 68.24; H, 6.64; N, 8.38, found C, 67.97; H, 6.57; N, 8.10%.

(+)-(S_p)-2′-(8-Quinoline)-1,2,3,4,5-pentamethylazaferrocene 7d

Synthesised in an identical manner to **7a** using 8-bromoquinoline as a coupling partner. Purification by flash column chromatography (15% EtOAc–5% Et_3N–pet. ether) gave **7d** (425 mg, 71% yield) as red crystals, mp = 172 °C (Et_2O) in 80% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 10% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (major) 7.8 min, t_r (minor) 12.4 min.; $[\alpha]_D$ +140 ($CHCl_3$, *c* 0.30, 22 °C); $[\alpha]_D$ +614 ($CHCl_3$, *c* 0.60); IR ν_{max} (solid) 2970, 2901, 1502, 1372, 1069, 1054, 800 cm^{-1}; ^1H NMR δ 1.62 (15H, s, Cp*H), 4.49 (1H, d, *J* 2.4 Hz, py-H), 5.16 (1H, s, py-H), 6.23 (1H, d, *J* 2.3 Hz, py-H), 7.44 (1H, dd, *J* 8.0, 4.0 Hz, Ar-H), 7.56 (1H, t, *J* 8.0 Hz, Ar-H), 7.74 (1H, d, *J* 7.6 Hz, Ar-H), 8.21 (1H, d, *J* 8.4 Hz, Ar-H), 8.48 (1H, d, *J* 7.2 Hz, Ar-H), 9.03 (1H, d, *J* 2.0 Hz, Ar-H) ppm; ^{13}C NMR δ 10.3, 77.7, 81.2, 91.8, 120.6, 126.9, 126.5, 127.7, 128.8, 134.7, 136.4, 138.1, 148.7 ppm; *m/z* (ES^+) HRMS $C_{23}H_{25}N_2Fe$ calcd 385.1373, found 385.1367; anal. calcd for $C_{23}H_{24}N_2Fe$: C, 71.85; H, 6.30; N, 7.29, found C, 71.82; H, 6.29; N, 7.30%.

(−)-(S_p)-2′-(2-Thiophene)-1,2,3,4,5-pentamethylazaferrocene 7e

Synthesised in an identical manner to **7a** using 2-bromothiophene as a coupling partner. Purification by flash column chromatography (15% EtOAc–5% Et_3N–pet. ether) gave **7e** (123 mg, 62% yield) as yellow crystals, mp = 106 °C (Et_2O) in 77% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 10% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (major) 7.8 min, t_r (minor) 12.4 min; $[\alpha]_D$ −167 (acetone, *c* 0.52, 22 °C); IR ν_{max} ($CHCl_3$) 2966, 2905, 1381, 1065, 1034, 841, 806 cm^{-1}; ^1H NMR δ 1.75 (15H, s, Cp*H), 4.27–4.30 (1H, m, py-H), 4.43 (1H, d, *J* 2.4 Hz, py-H), 5.07 (1H, s, py-H), 7.04–7.09 (1H, m, Ar-H), 7.20–7.24 (2H, m, Ar-H) ppm; ^{13}C NMR δ 10.1, 69.9, 75.9, 81.4, 92.1, 99.2, 122.2, 123.4, 127.5, 139.6 ppm; *m/z* (ES^+) HRMS $C_{18}H_{22}NSFe$ calcd 340.0822, found 340.0804; anal. calcd for $C_{18}H_{21}NSFe$: C, 63.70; H, 6.24; N, 4.13, found C, 63.33; H, 6.23; N, 3.93%

(+)-(S_p)-2′-(2-Benzothiophene)-1,2,3,4,5-pentamethylazaferrocene 7f

Synthesised in an identical manner to **7a** using 2-bromobenzothiophene as a coupling partner. Purification by flash column chromatography (20% EtOAc–5% Et_3N–pet. ether) gave **7f** (150 mg, 72% yield) as yellow crystals, mp = 118 °C (Et_2O) in 80% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column; $[\alpha]_D$ +35 ($CHCl_3$, *c* 0.45, 22 °C); IR ν_{max} ($CHCl_3$) 2953, 2908, 1450, 1382, 1307, 1131, 1072, 1030, 881 cm^{-1}; ^1H NMR δ 1.83 (15H, s, Cp*H), 4.38 (1H, d, *J* 1.5 Hz, py-H), 4.63 (1H, d, *J* 2.0 Hz, py-H), 5.21 (1H, s, py-H), 7.30–7.41 (2H, m, Ar-H), 7.43 (1H, s, Ar-H), 7.82 (1H, d, *J* 7.7 Hz, Ar-H), 7.89 (1H, d, *J* 7.9 Hz, Ar-H) ppm; ^{13}C NMR δ 10.2, 70.9, 76.6, 81.6, 92.9, 98.4, 118.2, 122.3, 122.8, 123.6, 124.3, 139.3, 140.5, 140.8 ppm; *m/z* (ES^+) HRMS $C_{22}H_{24}NSFe$ calcd 390.0979, found 390.0954.

(+)-(S_p)-2′-(2-Propene)-1,2,3,4,5-pentamethylazaferrocene 7g

Synthesised in an identical manner to **7a** using 2-bromopropene as a coupling partner. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **7g** (531 mg, 61% yield) as orange crystals, mp = 95 °C (Et_2O); $[\alpha]_D$ −46 ($CHCl_3$, *c* 0.88,

22 °C); IR ν_{max} 3562, 3246, 2949, 2909, 1711, 1627, 1455, 1382, 894 cm^{-1}; ^{1}H NMR δ 1.84 (15H, s, Cp*H), 2.06 (3H, s, Me), 4.21 (1H, d, J 1.8 Hz, C=CH_2), 4.24 (1H, d, J 1.8 Hz, C=CH_2), 5.00 (1H, s, py-H), 5.14 (1H, s, py-H), 5.29 (1H, s, py-H) ppm; ^{13}C NMR δ 10.3, 20.6, 70.5, 76.2, 80.6, 92.4, 103.8, 109.8, 138.4 ppm; m/z (ES$^+$) HRMS $C_{17}H_{24}NFe$ calcd 298.1258, found 298.1233.

(S_p,S_p)-2′-Bis-1,2,3,4,5-pentamethylazaferrocene 9

To a solution of 1,2,3,4,5-pentamethylazaferrocene **1** (150 mg, 0.58 mmol) in Et_2O (3 mL) was added sparteine (162 mg, 0.70 mmol, 1.2 equiv.), the reaction was cooled to −78 °C and *s*-BuLi (538 μL of 1.3 N in hexanes, 0.70 mmol, 1.2 equiv.) was added dropwise. The reaction was then stirred for 4 h at −78 °C before a freshly prepared solution of $MgBr_2$ etherate at −78 °C [0.81 mmol, 1.4 equiv., prepared by adding 1,2-dibromoethane (152 mg, 0.81 mmol) to Mg (21 mg, 0.87 mmol, 1.07 equiv.) in Et_2O (2 mL) and stirring for 30 mins at rt] was added dropwise and the reaction was warmed to −40 °C over 15 min. A solution of $FeCl_3$ (5 mg, 0.03 mmol, 5 mol%) in Et_2O (2 mL) and 1,2-dichloroethane (62 mg, 0.87 mmol, 1.5 equiv.) was added sequentially to the reaction *via* cannula and the reaction was warmed to rt. The reaction was then diluted with Et_2O (15 mL), washed with water (15 mL), dried ($MgSO_4$) and concentrated *in vacuo*. Purification by flash column chromatography (25% EtOAc–5% Et_3N–pet. ether) gave **9** (75 mg, 50% yield) as a yellow solid which decomposed over a few hours. ^{1}H NMR δ 1.77 (30H, s, Cp*H), 4.13 (2H, s, py-H), 4.15 (2H, s, py-H), 5.12 (2H, s, py-H) ppm; m/z (ES$^+$) HRMS $C_{28}H_{36}N_2Fe_2$ calcd 513.1656, found 513.1665.

(+)-(R_p,R_p)-5′-Bis-(2′-phenyl-1,2,3,4,5-pentamethylazaferrocene) 10

To a solution of **7a** (200 mg, 0.60 mmol) in THF (3 mL) was added TMEDA (84 mg, 0.72 mmol, 1.2 equiv.), the reaction was cooled to −78 °C and *s*-BuLi (762 μL of 1.3 N in hexanes, 0.99 mmol, 1.65 equiv.) was added dropwise. The reaction was then stirred for 4 h at −78 °C before a freshly prepared solution of $MgBr_2$ at −78 °C [1.14 mmol, 1.4 equiv., prepared by adding 1,2-dibromoethane (214 mg, 1.14 mmol) to Mg (29 mg, 1.22 mmol, 1.07 equiv.) in THF (2 mL) and stirring for 30 mins at rt] was added dropwise and the reaction was warmed to −40 °C over 15 min. A solution of $FeCl_3$ (10 mg, 0.06 mmol, 5 mol%) in THF (2 mL) and 1,2-dichloroethane (158 mg, 0.90 mmol, 1.5 equiv.) was added sequentially to the reaction *via* cannula and the reaction was warmed to rt. The reaction was then diluted with Et_2O (15 mL), washed with water (15 mL), dried ($MgSO_4$) and concentrated *in vacuo*. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **10** (132 mg, 66% yield) as an orange solid, mp = 121 °C (Et_2O) in 77% ee as determined by HPLC analysis: Diacel Chiralcel OD-H column, 5% i-PrOH–hexane, 0.5 mL min^{-1}; t_r (major) 8.7 min, t_r (minor) 18.6 min; $[\alpha]_D$ + 475 ($CHCl_3$, c 0.41, 22 °C); IR ν_{max} 2907, 1602, 1452, 1382, 1071, 1031, 908, 874 cm^{-1}; ^{1}H NMR δ 1.65 (30H, s, Cp*H), 4.40 (2H, d, J 2.2 Hz, py-H), 4.55 (2H, d, J 2.2 Hz, py-H), 7.26–7.29 (2H, m, Ar-H), 7.38 (4H, t, J 7.7 Hz, Ar-H), 7.66 (4H, d, J 7.4 Hz, Ar-H) ppm; ^{13}C NMR δ 9.6, 70.6, 76.7, 82.6, 97.6, 101.0, 125.4, 127.0, 128.4, 134.3 ppm; m/z (ES$^+$) HRMS $C_{40}H_{45}N_2Fe_2$ calcd 665.2282, found 665.2275.

Repeating the reaction, but initially deprotonating in PhMe and then proceeding with $MgBr_2$ and $FeCl_3$ in Et_2O, in a similar manner as for the preparation of **9**, led to the isolation of **10** in 34% yield and 97% ee by HPLC.

(−)-(S_p)-2′-(2-Bromobenzene)-1,2,3,4,5-pentamethylazaferrocene 15

Synthesised in an identical manner to **7a**, using 1-iodo-2-bromobenzene as coupling partner and $Pd(dba)_2$ (2.5 mol%) premixed with tri-*ortho*-furylphosphine (10 mol%) in THF as a catalyst. Purification by flash column chromatography (10% EtOAc–5% Et_3N–pet. ether) gave **15** (1.05 g, 44% yield) as an orange solid, mp = 113 °C (Et_2O); $[\alpha]_D$ +99 ($CHCl_3$, c 0.55, 22 °C); IR ν_{max} 2952, 2908, 1651, 1622, 1589, 1484, 1453, 1382, 1340, 1030, 1008, 893 cm^{-1}; ^{1}H NMR δ 1.74 (15H, s, Cp*H), 4.34 (1H, dd, J 1.2, 0.4 Hz, py-H), 4.58 (1H, s, py-H), 5.13 (1H, d, J 2.0 Hz, py-H), 7.10 (1H, td, J 6.4, 1.6 Hz, Ar-H), 7.37 (1H, td, J 6.4, 0.8 Hz, Ar-H), 7.67 (1H, dd, J 6.4, 0.8 Hz, Ar-H), 8.24 (1H, dd, J 6.4, 1.2 Hz, Ar-H) ppm; ^{13}C NMR δ 10.5, 73.9, 77.3, 81.4, 92.2, 120.8, 127.1, 127.4, 130.5, 134.6 (10 observed signals); m/z (ES$^+$) HRMS $C_{20}H_{23}NBrFe$ calcd 412.0363, found 412.0378; anal. calcd for $C_{20}H_{22}NBrFe$: C, 58.39; H, 5.39; N, 3.41, found C, 58.26; H, 5.28; N, 3.34%.

(−)-(S_p)-2′-(2-Diphenylphosphine)phenyl-1,2,3,4,5-pentamethylazaferrocene 13

To a solution of **15** (1.00 g, 2.43 mmol) in Et_2O (15 mL) at −78 °C was added *n*-BuLi (2.43 mL of 2.5 N in hexanes, 6.07 mmol, 2.5 equiv.) and the reaction was warmed to −40 °C over a period of 0.5 h. The reaction was cooled to −78 °C, Ph_2PCl (1.61 g, 7.28 mmol, 3.0 equiv.) was added and the reaction was warmed to rt over 15 mins. After addition of H_2O (0.5 mL) the mixture was poured onto neutral alumina and concentrated *in vacuo*. Purification by flash column chromatography (neutral alumina; 15% EtOAc–5% Et_3N–pet. ether) gave **13** (813 mg, 64% yield) as a red solid, mp = 104 °C (Et_2O); $[\alpha]_D$ +164 ($CHCl_3$, c 0.75, 22 °C); IR ν_{max} 2940, 1710, 1587, 1454, 1382, 1122, 1110, 1092, 1070, 1029, 893 cm^{-1}; ^{1}H NMR δ 1.64 (15H, s, Cp*H), 4.23 (1H, s, py-H), 4.83 (1H, s, py-H), 5.07 (1H, s, py-H), 6.94–6.96 (1H, br m, Ar-H), 7.13–7.19 (7H, br m, Ar-H), 7.42–7.43 (5H, br m, Ar-H), 8.19–8.22 (1H, br m, Ar-H) ppm; ^{13}C NMR δ 10.5, 74.6, 75.0, 76.9, 81.2, 126.4, 128.3, 128.3, 128.4, 128.8, 128.8, 128.8, 130.1, 133.7, 133.8, 134.4, 134.5, 134.9 ppm; m/z (ES$^+$) HRMS $C_{32}H_{33}NPFe$ calcd 518.1700, found 518.1704.

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