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Chiral Transient Directing Groups in Transition Metal-Catalyzed Enantioselective C–H Bond Functionalization

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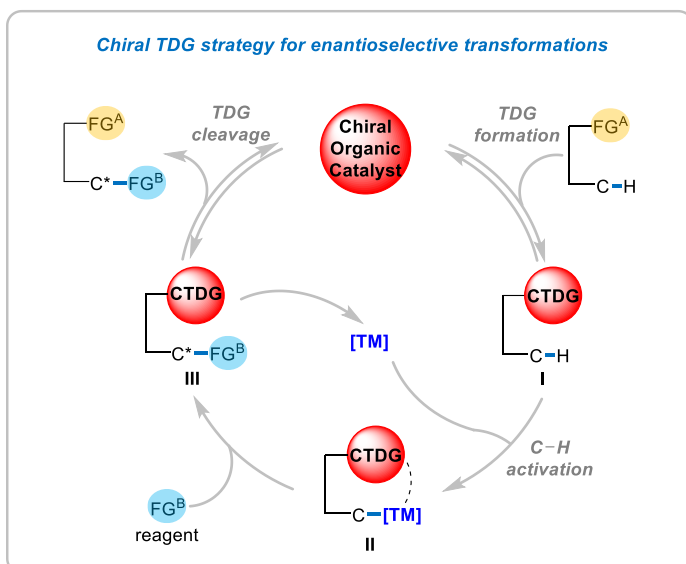
E-mail: tatiana.besset@insa-rouen.fr

Abstract: Transition metal-catalyzed C–H bond functionalization has known a rapid evolution in the last years, offering new strategies for reaching high molecular complexity in a step- and atom-economical way. Despite the indisputable advances, selectivity issues still remain given the ubiquity of C–H bonds on molecules, thus several approaches have been developed to tackle this challenge. Among them, the use of a transient directing group has emerged as an effective tool, circumventing the need of extra synthetic steps to install and then cleave a directing group on the molecule. More recently, this strategy has been successfully applied to the even more challenging transition metal-catalyzed enantioselective C–H bond functionalization. This review will highlight and discuss the main advances made in the use of a chiral transient directing group for the enantioselective functionalization of C(sp²)–H and C(sp³)–H bonds by transition metal catalysis.

1. INTRODUCTION

In the last decades, the transition metal-catalyzed C–H bond functionalization has emerged as a powerful strategy for achieving unprecedented transformations in a step- and atom-economical way.¹ This was illustrated, for instance, by the huge number of applications of this synthetic tool for the preparation of highly complex molecules.² Despite the unarguably advances, some limitations still remain: the selectivity is one of the most relevant challenges to be addressed since C–H bonds are ubiquitous on a molecule. This issue has been elegantly circumvented with the aid of a directing group (DG), which is able to coordinate to the metal center and to place it close to the C–H bond to be functionalized.³ Hence, various monodentate and bidentate directing groups have been efficiently used for the selective functionalization of different positions over aromatic⁴ and aliphatic derivatives.⁵ Nevertheless, solutions to avoid the extra synthetic steps required to install and cleave the directing group on the molecules were needed. Therefore, several strategies have arisen, such as the use of traceless directing groups⁶ and transient mediators.^{7,8} More recently, other promising alternatives emerged, based on the use of non-covalent interactions between the substrates and designed catalysts^{5e,9} and transient directing groups (TDGs).^{10,11} Since the pioneering example described by Jun and co-workers in 1997,¹² the latter strategy was successfully applied in several transition metal-catalyzed regioselective C–H bond functionalization, appearing as a modern and sustainable solution. Encouraged by this new synthetic tool, the scientific community showed a real endeavor towards the design and the use of chiral transient directing groups to achieve the highly challenging enantioselective C–H bond functionalization.^{1a,13} Indeed, the chiral transient directing group (CTDG) strategy, which relied on the reversible and temporary formation of a chiral directing group from a functional group, was particularly appealing. Taking benefit from the fact that the transient directing group also played the role of a chiral ligand, the number of species in the reaction media remained limited, reducing the possibilities for side reactions. Conceptually, a suitable functional group (FG^A) on the substrate would first react with a chiral organic catalyst to afford the aforementioned CTDG (I). After its coordination with the transition metal center in a monodentate or bidentate fashion, the metallacycle II would be formed. This latter would then react with the coupling partner leading to the species III and allowing the regeneration of the transition metal catalyst. A final hydrolysis would release the product along with the organo-catalyst (Scheme 1).

Scheme 1. The chiral transient directing group strategy in transition metal-catalyzed C–H bond activation reactions.



The aim of this review is to showcase and discuss the recent advances made in the cutting-edge C–H activation field based on the use of chiral transient directing groups to address transition metal-catalyzed enantioselective C–H bond functionalization. First, major advances regarding the atroposelective C(sp²)-H functionalization for the synthesis of enantioenriched chiral biaryls will be described. Then, the application of the transient directing group strategy to the preparation of enantioenriched heterocycles and carbocycles along with miscellaneous reactions will be highlighted. Finally, a last part of the review will be dedicated to the recent developments on the transition metal-catalyzed enantioselective C(sp³)-H bond functionalization.

2. Asymmetric C(sp²)-H bond activation for atropisomer synthesis

2.1. from biaryl derivatives

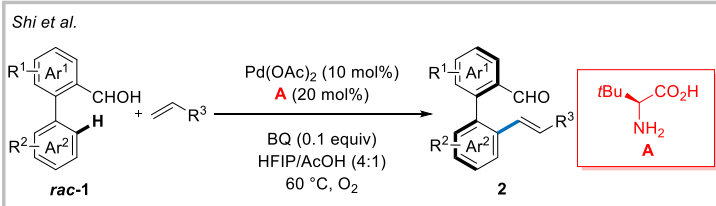
Given the significance and the abundance of the axially chiral biaryls in bioactive natural products,¹⁴ advanced material sciences,¹⁵ chiral ligands¹⁶ and catalysts,¹⁷ groundbreaking advances were made towards a straightforward access to these scaffolds.^{14c,18} Existing methods to synthesize such derivatives generally relied on stereoselective cross-coupling reactions,¹⁹ asymmetric cycloadditions,²⁰ transition metal-catalyzed atroposelective C–H bond functionalization,²¹ among others.²² Recently, the chiral transient directing group strategy appeared as a potent tool for the atroposelective synthesis of chiral biaryls. Therefore, the major advances made to access these high-value added axially chiral biaryl backbones thanks to this approach will be highlighted and discussed in this section.

a) Olefination and allylation reactions

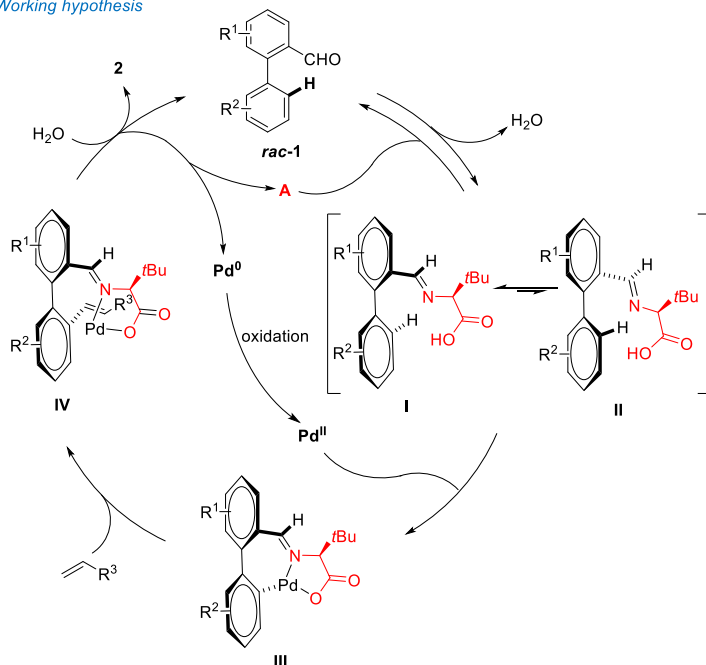
In 2017, Shi and co-workers studied the chiral transient directing group-assisted Pd-catalyzed atroposelective olefination of biaryl aldehydes based on the following working hypothesis²³ First, reaction of the racemic biaryl aldehyde (*rac*-1) with the chiral amino acid A would reversibly afford the two imines I and II. Then, formation of the axially enantioenriched biaryl palladacycle III derived from the diastereoisomer imine I would take place, presumably driven by steric interactions. The latter intermediate III would then undergo a Heck-type reaction with the alkene. After a reductive elimination and an *in situ* hydrolysis, the enantioenriched product 2 would be released along with the organocatalyst A. Finally, the palladium (II) catalyst would be regenerated after oxidation. Using the readily available chiral amino acid, L-*tert*-leucine (A), as a pivotal transient directing group precursor, a panel of aromatic aldehydes (*rac*-1) were olefinated through a dynamic kinetic resolution pathway (Scheme 2). When using substrates bearing electron-donating groups, the expected alkenylated products (2a-d) were obtained in yields up to 94% and high enantioselectivities (up to >99%). The transformation was tolerant to functional groups such as a halogen (1e) and an ester (1f). Pleasingly, a styrene derivative was a suitable coupling partner as showed by the synthesis of the compound 2g. In the case of biaryl derivatives bearing bulky

substituents at both 6- and 2'-positions, the reaction proceeded *via* a kinetic resolution pathway, furnishing the enantiopure products (2h-k) in 30-45% yields along with the enantioenriched starting biaryl aldehydes (1h-k). It is worth to mention that in this case the reaction also went smoothly with other acrylate and electron-poor styrene derivatives as demonstrated with the synthesis of compounds 2l-n.

Scheme 2. Pd(II)-catalyzed atroposelective C–H olefination reaction by using a chiral transient directing group.

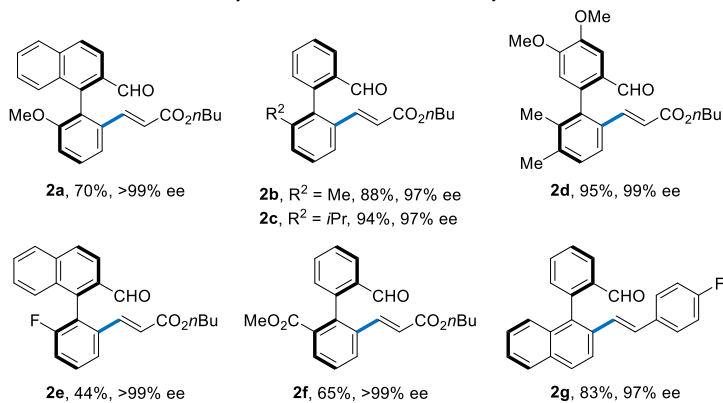


Working hypothesis

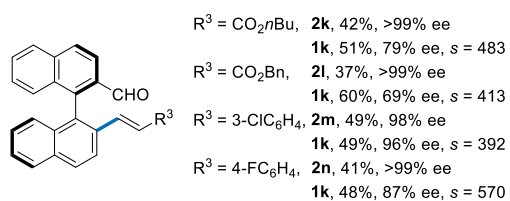
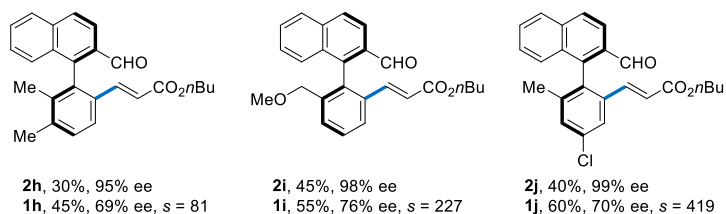


Selected examples

Dynamic Kinetic Resolution Pathway

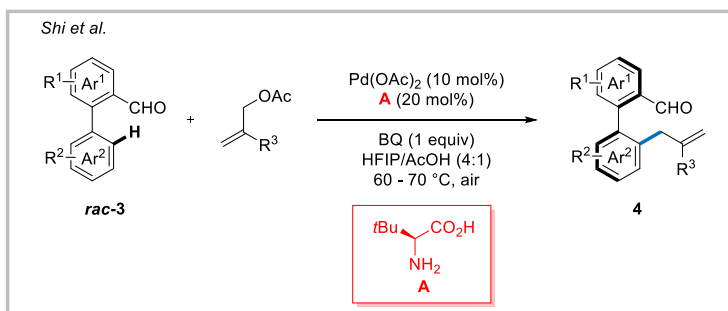


Kinetic Resolution Pathway

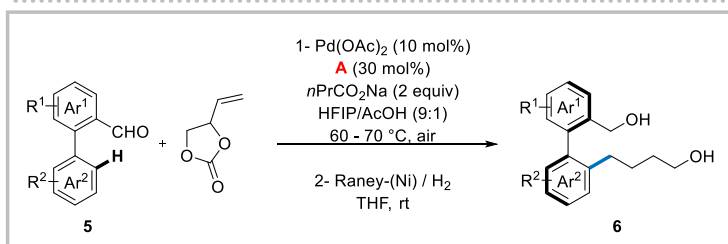
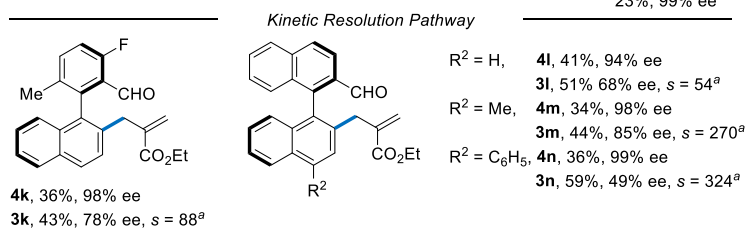
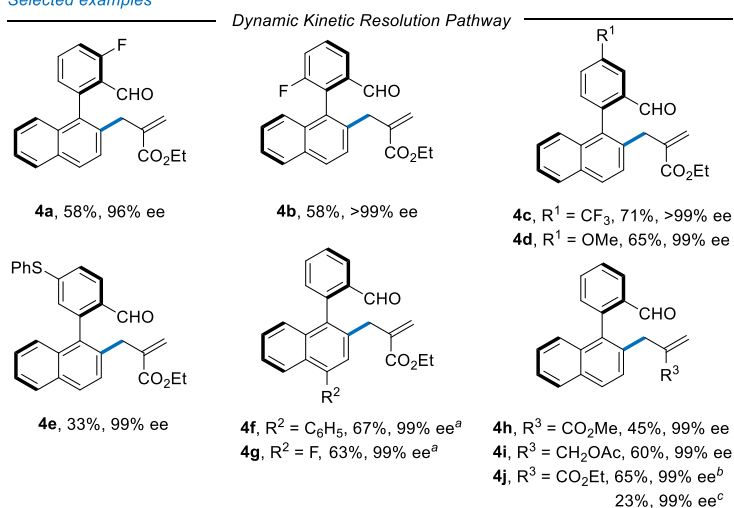


A year later, a Pd-catalyzed asymmetric allylation of biaryl aldehydes *via* a (dynamic) kinetic resolution reaction was developed by the same group (Scheme 3).²⁴ Using the L-*tert*-leucine (A) as a chiral organo-catalyst, an array of biaryl aldehydes *rac*-3 was functionalized with the allylic acetate reagent in the presence of benzoquinone in a HFIP/AcOH mixture. It turned out that the presence of an oxidant under acidic reaction conditions was crucial for the efficiency of the reaction. With substrates bearing a substituent at either the phenyl (3a-e) or the naphthyl part (3f-g), the corresponding allylated products were obtained efficiently through a dynamic kinetic resolution pathway in yields ranging between 33% and 71% and in high enantioselectivities (96% to >99% ee). Allylated biaryls bearing either halogens or electron-withdrawing groups (4a-c) as well as electron-donating groups (4d-f) were efficiently synthesized. In addition, the substitution pattern did not have a significant impact on the outcome of the reaction (4a, 4b and 4g). Worth mentioning that other coupling partners were also successfully used (4h-i) and replacing the leaving group of the allylation reagent with OBz or OBoc led to the corresponding product (4j) in 65% and 23% yields, respectively. With 2'- and 6-disubstituted racemic biaryls, the reaction proceeded in the presence of the allylic acetate reagent *via* a kinetic resolution process, affording the enantioenriched allylated products (4k-n) along with the enantioenriched starting materials (3k-n). Then, a Pd-catalyzed olefination of non-C2-symmetric biaryl aldehydes was achieved using the vinyl ethylene carbonate followed by a reduction step, offering an efficient access to the corresponding diols 6a-g in moderate to good yields and high enantioselectivities (>99%) (Scheme 3).

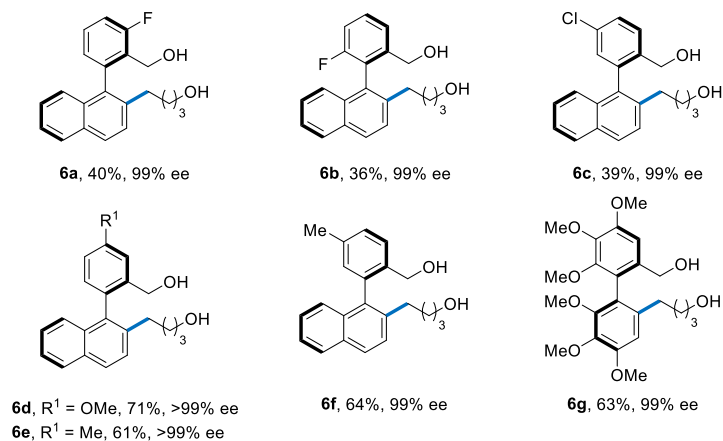
Scheme 3. Synthesis of axially chiral biaryls via a Pd(II)-catalyzed asymmetric allylation reaction.



Selected examples



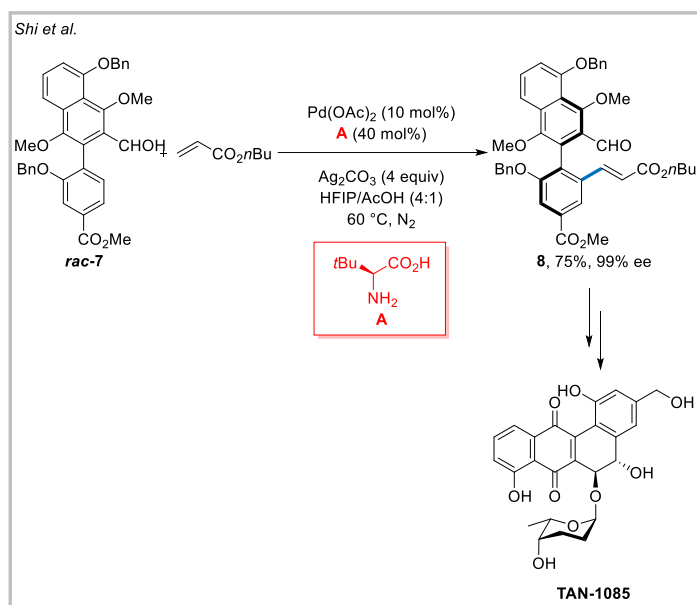
Selected examples



^a A (30 mol%). ^b The leaving group of the coupling partner (OAc) was replaced by a OBz group. ^c The leaving group of the coupling partner (OAc) was replaced by a OBoc group.

Applying the enantioselective C–H functionalization strategy to natural products synthesis,^{2a,c,d,k,25} the group of Shi reported a concise and highly enantioselective total synthesis of TAN-1085,²⁶ an angucycline antibiotic isolated from *Streptomyces* species (Scheme 4).²⁷ Taking benefit from their pioneering work,²³ a scalable and efficient construction of the axially chiral biaryl scaffold 8 was achieved in 75% yield with a high level of enantioselectivity (99% ee).

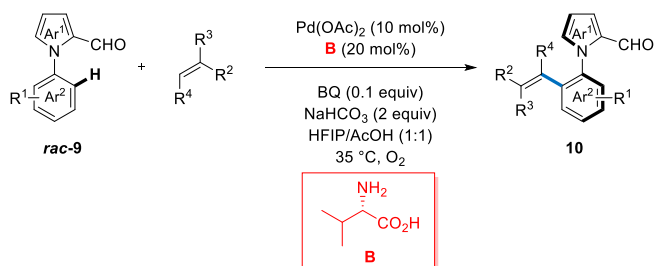
Scheme 4. Application of the transient directing group strategy to access a key intermediate 8 for the total synthesis of TAN-1085.



In 2019, Zhang and Xie extended this appealing strategy to the synthesis of unprecedented N–C axially chiral *N*-arylindoles by means of a transition metal-catalyzed atroposelective C–H alkenylation reaction (Scheme 5).²⁸ Using a catalytic amount of $\text{Pd}(\text{OAc})_2$ and L-Valine (B) in the presence of benzoquinone, the olefination of a panel of aryl-1*H*-indole-2-carbaldehyde derivatives *rac*-9 with the *n*-butyl acrylate was achieved in a high regio- and stereocontrol leading to the corresponding alkenylated products 10a-g. Various *N*-arylindoles bearing electron-donating and electron-withdrawing groups at either the indole (9a-c) or the phenyl part (9d-g) were functionalized in good yields *via* a desymmetrization process. The transformation also went smoothly with a phenyl vinyl sulfone, a styrene derivative and with the 3-methylenedihydrofuran-2(3*H*)-one affording the compounds 10h-j. Moreover, a dynamic kinetic resolution pathway was reported allowing the functionalization of *N*-arylindoles bearing a halogen or an alkyl chain in good yields with excellent enantioselectivities (10k-l). The transformation was not restricted to the use of the *n*-butyl acrylate as several olefins were suitable (10m-n). The olefination of the bulkier substrates *rac*-11a-i with various activated olefins as coupling partners was achieved in the presence of L-*tert*-leucine and silver triflate *via* a kinetic resolution process furnishing a range of enantioenriched heterobiaryl derivatives in moderate to good yields and excellent enantioselectivities (12a-i).

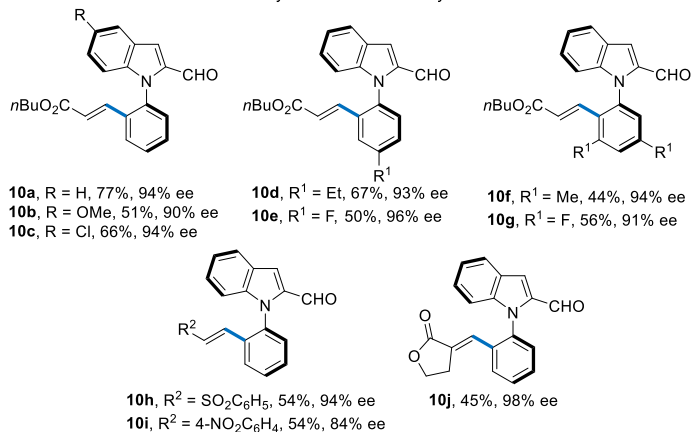
Scheme 5. Atroposelective Pd(II)-catalyzed olefination of *N*-arylindoles.

Zhang, Xie et al.

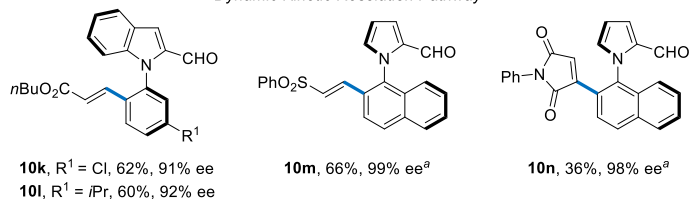


Selected examples

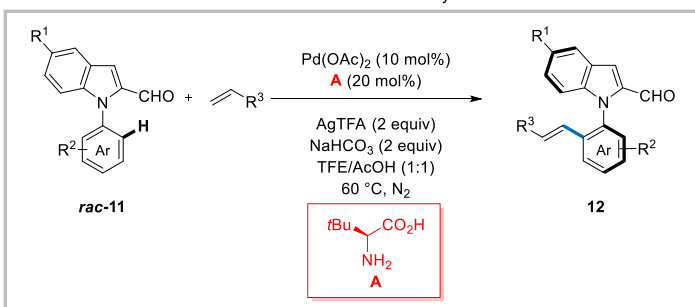
Desymmetrization Pathway



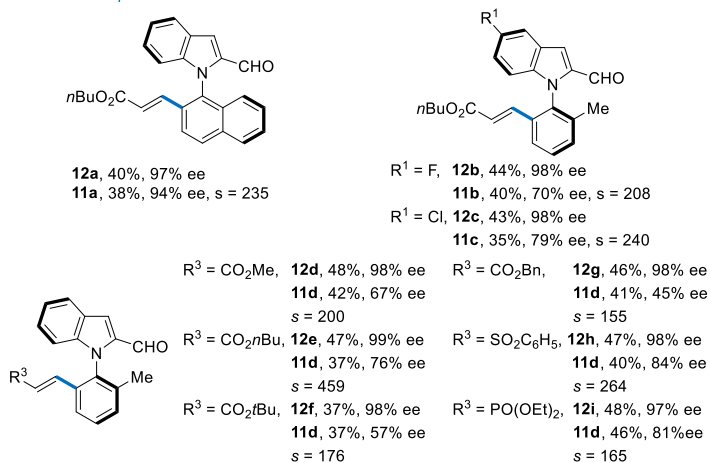
Dynamic Kinetic Resolution Pathway



Kinetic Resolution Pathway



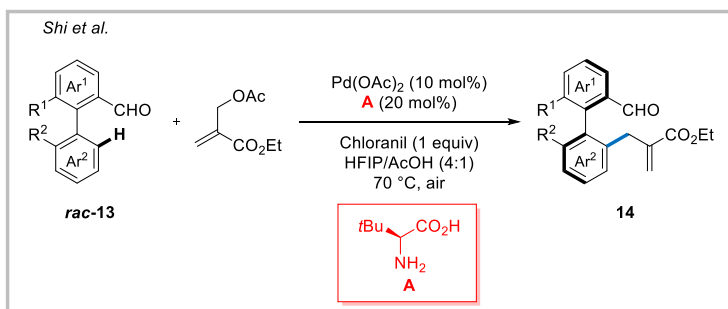
Selected examples



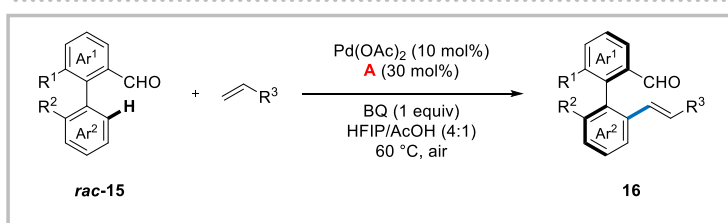
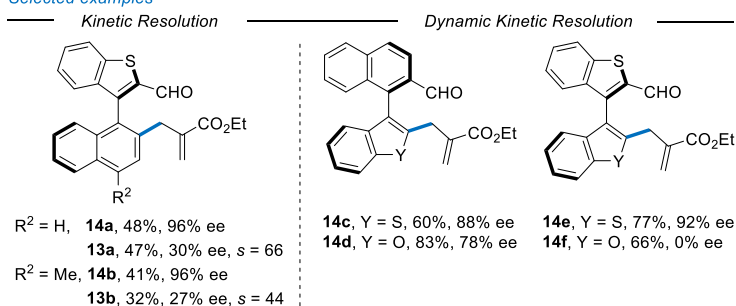
^a Pd(OAc)₂ (10 mol%), A (20 mol%), AgTFA (2 equiv), NaHCO₃ (2 equiv), TFE/AcOH (1:1), 60 °C, N₂.

The same year, the Shi group depicted the atroposelective Pd-catalyzed allylation and olefination of biaryl aldehydes, offering a straightforward access to the challenging five-membered axially chiral biaryls (Scheme 6).²⁹ For this purpose, a catalytic amount of *L*-*tert*-leucine and Pd(OAc)₂ along with chloranil as the oxidant were used for the allylation of a broad range of heterocycles *rac*-13 with the allylic acetate reagent leading to enantioenriched atropoisomers featuring a heteroaryl part. Importantly, it is worth to mention that the position of the heteroarenes on the biaryl scaffold did have an influence on the mechanism pathway involved in the transformation. When the benzothiophene was at the upper part of the biaryls (13a-b), the transformation proceeded via a kinetic resolution affording the expected products (14a-b) in good yields and high selectivities. While for substrates bearing heteroarenes in the lower part (13c-d), the enantiopure allylated biaryls (14c-d) were obtained through a dynamic kinetic resolution pathway in moderate to good yields. The synthesis of the allylated 3,3'-bisbenzothiophene (14e) was straightforward (77% yield, 92% ee), while no enantioselectivity was observed with a biaryl bearing a benzothiophene and a benzofuran residue (14f). This approach was then applied to the alkenylation of heteroarenes with various acrylate derivatives and styrene under similar reaction conditions. While a set of biaryls bearing a benzothiophene part (15a-e) were functionalized *via* a kinetic resolution process, the olefination of the benzofuran-based biaryl 15f and the 3,3'-bisbenzothiophene 15g proceeded according to a dynamic kinetic resolution pathway.

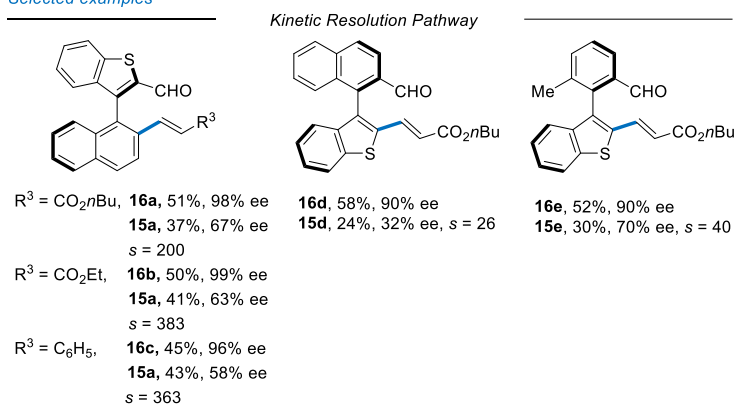
Scheme 6. Synthesis of enantioenriched atropoisomers featuring a heteroaryl part by Pd(II)-catalysis.



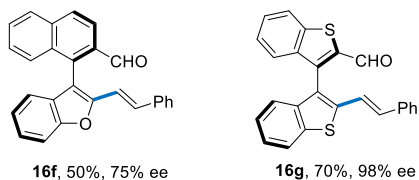
Selected examples



Selected examples



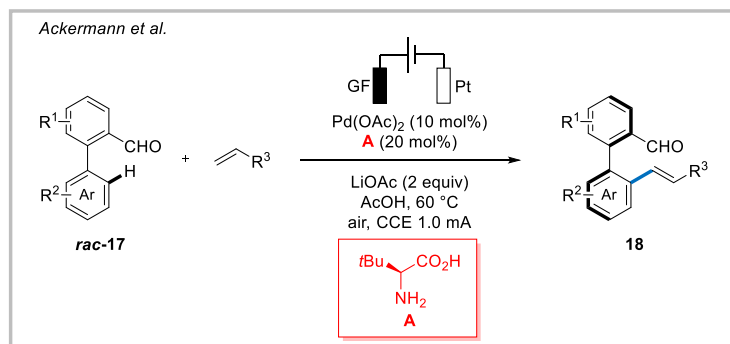
Dynamic Kinetic Resolution Pathway



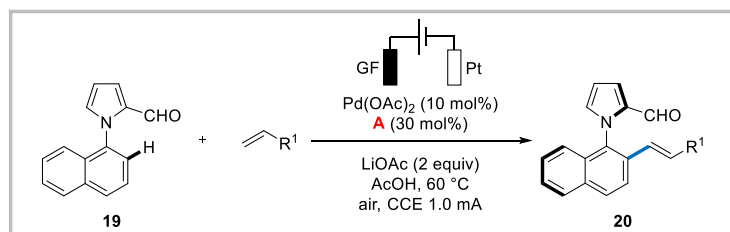
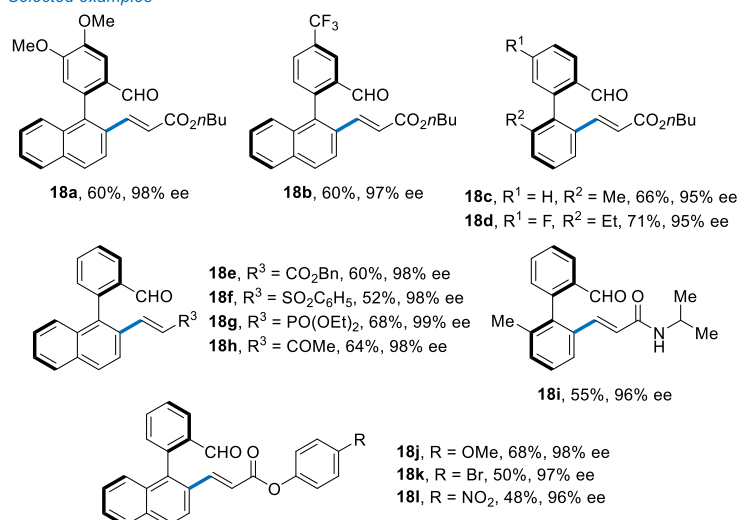
This year, the Ackermann group described the first atroposelective palladoelectro-catalyzed olefination of biaryl aldehydes by C–H bond activation under mild reaction conditions (Scheme 7).³⁰ A panel of biaryl derivatives *rac-17* was olefinated using the *L-tert*-Leucine as chiral organo-catalyst and LiOAc as the electrolyte, furnishing the corresponding products in moderate to good yields (up to 71%) and high enantioselectivities (up to 98% ee). Both electron-rich (17a) and electron-poor (17b) substrates reacted well under these conditions showcasing the robustness of this approach. Besides, disubstituted biphenyls proved to be suitable substrates for this functionalization (17c-d). Notably, a series of electron-deficient olefins was successfully used as coupling partners offering an atroposelective access to the corresponding biaryls in up to 68% yield (18e-l). More interestingly, this transformation turned out to be efficient also with *N*-arylpyrrole

derivatives. Hence, an access to N–C axially chiral heteroaryls 20a-e was achieved in a complete regio- and stereoselective manner. Finally, the strategy was further applied to access key compounds such as chiral BINOLs, dicarboxylic acids and helicenes.

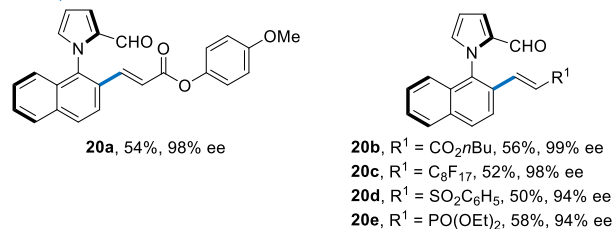
Scheme 7. Electrochemical enantioselective olefination of biaryl aldehydes by Pd(II)-catalyzed C–H bond activation using the chiral transient directing group strategy.



Selected examples



Selected examples

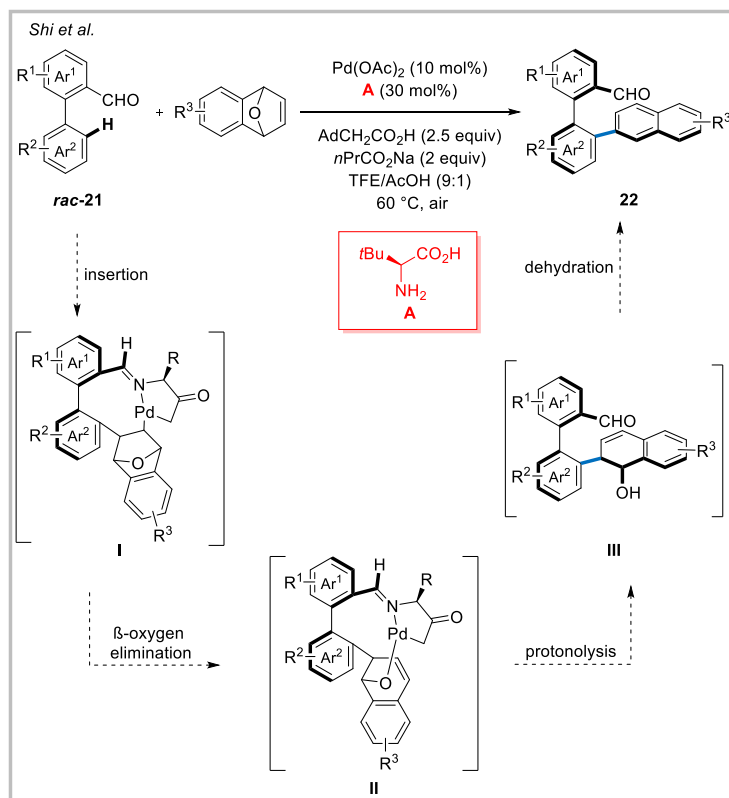


b) Naphthylation reaction

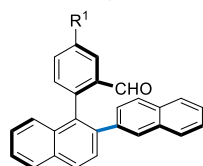
In 2019, the Shi group reported the atroposelective Pd-catalyzed *ortho* C–H naphthylation of racemic biaryl aldehydes **rac-21** with 7-oxabenzonorboranadienes (Scheme 8)³¹ leading to key scaffolds, known to be efficient chiral catalysts.^{17d,32} For this transformation, a four-step process was designed: insertion of a 7-oxabenzonorboranadiene derivative within the palladacycle intermediate (I) followed by a β -oxygen elimination would lead to the intermediate II. The latter would then undergo a protonolysis to afford the dihydronaphthol III, which after a dehydration step would furnish the expected product

22. By employing *L-tert*-leucine, 1-adamantaneacetic acid and sodium butyrate, an array of the desired naphthylated products (22a-h) was obtained efficiently in good yields and enantioselectivities. Indeed, this reaction was compatible with substrates bearing at the aryl ring either an electron-donating functional group (21a) or an electron-withdrawing one (21b) and with difunctionalized substrates (21c-d). Also, the methodology was successfully applied to substrates with electron-rich naphthyl parts (21e-f). Nonetheless, a lower reactivity was observed once the naphthalene ring is functionalized with an electron-withdrawing group (22g). Besides, an access to the chiral poly-substituted biaryl compound 22h was possible by this methodology. Notably, the desymmetrization of prochiral substrates was achieved in good to moderate yields and high enantioselectivities (22i-j). When several analogues of the 7-oxabenzonorboranadiene were used, the desired products (22k-l) were successfully synthesized with electron-rich partners in contrast to electron-poor ones, which only afforded the dihydronaphthol products (22m-n).

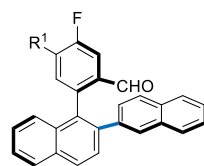
Scheme 8. Atroposelective Pd(II)-catalyzed *ortho* C–H naphthylation of biaryl aldehydes.



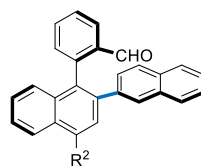
Selected examples



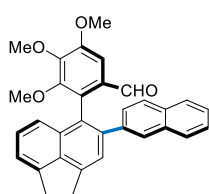
22a, $\text{R}^1 = \text{OMe}$, 59%, 99% ee
22b, $\text{R}^1 = \text{CF}_3$, 52%, 99% ee



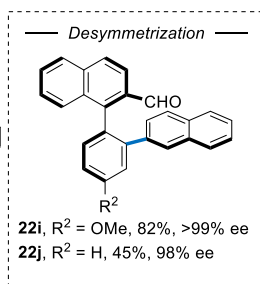
22c, $\text{R}^1 = \text{Me}$, 68%, 98% ee
22d, $\text{R}^1 = \text{F}$, 59%, >99% ee



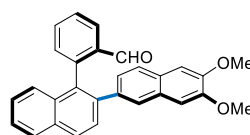
22e, $\text{R}^2 = \text{Me}$, 77%, 97% ee
22f, $\text{R}^2 = \text{C}_6\text{H}_5$, 68%, >99% ee
22g, $\text{R}^2 = \text{F}$, 26%, >99% ee



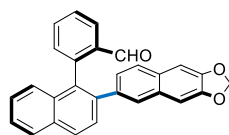
22h, 62%, 98% ee



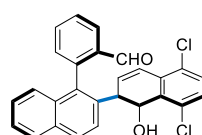
22i, $\text{R}^2 = \text{OMe}$, 82%, >99% ee
22j, $\text{R}^2 = \text{H}$, 45%, 98% ee



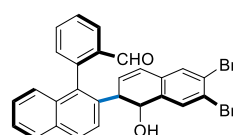
22k, 65%, 99% ee



22l, 31%, 96% ee



22m, 43%, 96% ee



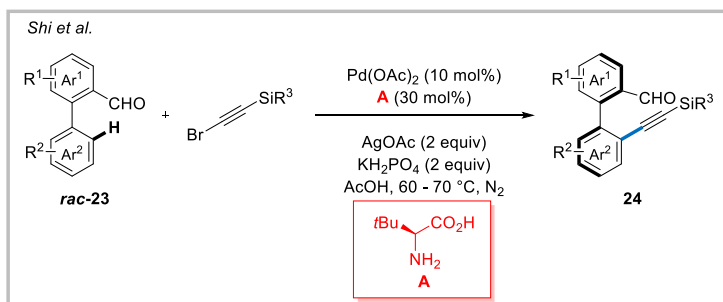
22n, 64%, 99% ee

c) Alkynylation reaction

Aiming at having an efficient access towards advanced intermediates for the synthesis of the bioactive dibenzocyclooctadiene lignans,³³ Shi *et al.* developed a novel Pd-catalyzed C–H alkynylation reaction in the presence of a TIPS-protected alkynyl bromide (Scheme 9).³⁴ The approach displayed a high functional group tolerance since products bearing electron-withdrawing groups and halogens (24a-c) as well as electron-donating groups (24d-e) were obtained

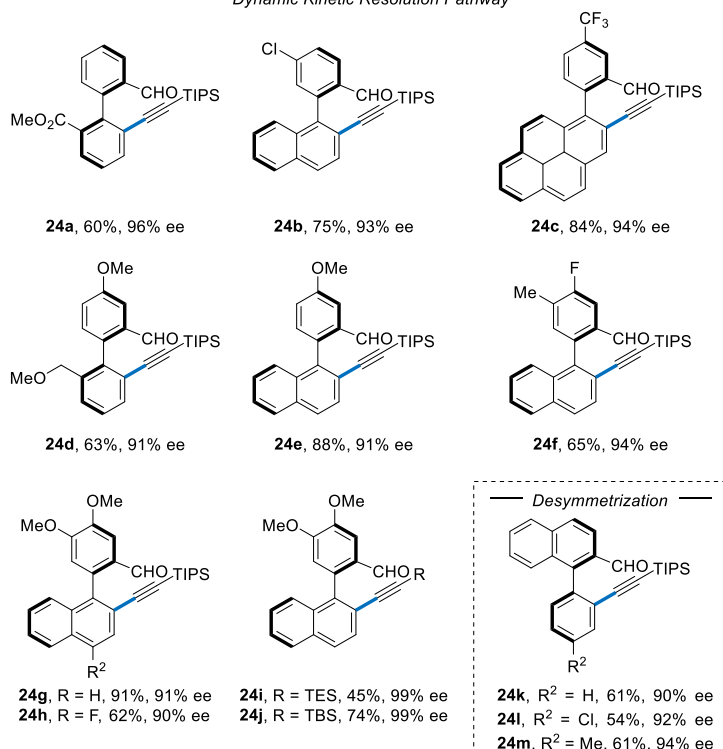
through a dynamic kinetic resolution process. Poly-substituted biaryl aldehydes 23f-h also underwent this reaction successfully. Moreover, different silylated-protected alkynyl bromides turned out to be suitable for this transformation leading to the corresponding compounds 24i-j in up to 74% yield and high selectivities (up to 99% ee). Furthermore, prochiral substrates were desymmetrized in good yields and high enantioselectivities (24k-m) and both halogenated 23l and alkylated biaryl aldehydes 23m were suitable substrates. In case of biaryl aldehydes, substituted at both 6- and 2'-positions (25a-d), the Pd-catalyzed alkynylation reaction proceeded *via* a kinetic resolution pathway under slightly modified reaction conditions (Scheme 9).

Scheme 9. Atroposelective synthesis of alkynylated biaryl scaffolds.

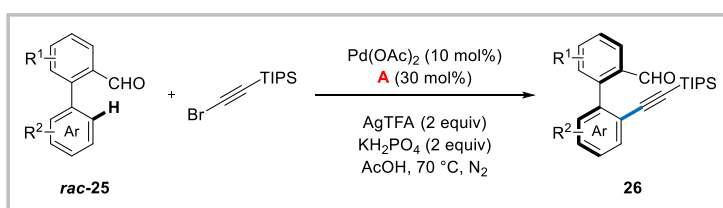


Selected examples

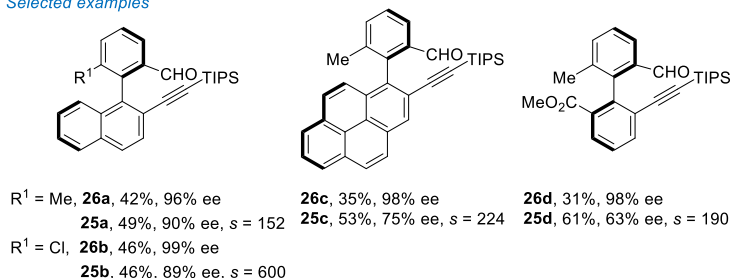
Dynamic Kinetic Resolution Pathway



Kinetic Resolution Pathway



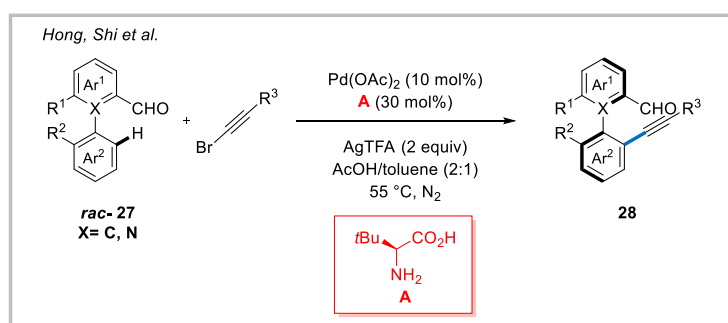
Selected examples



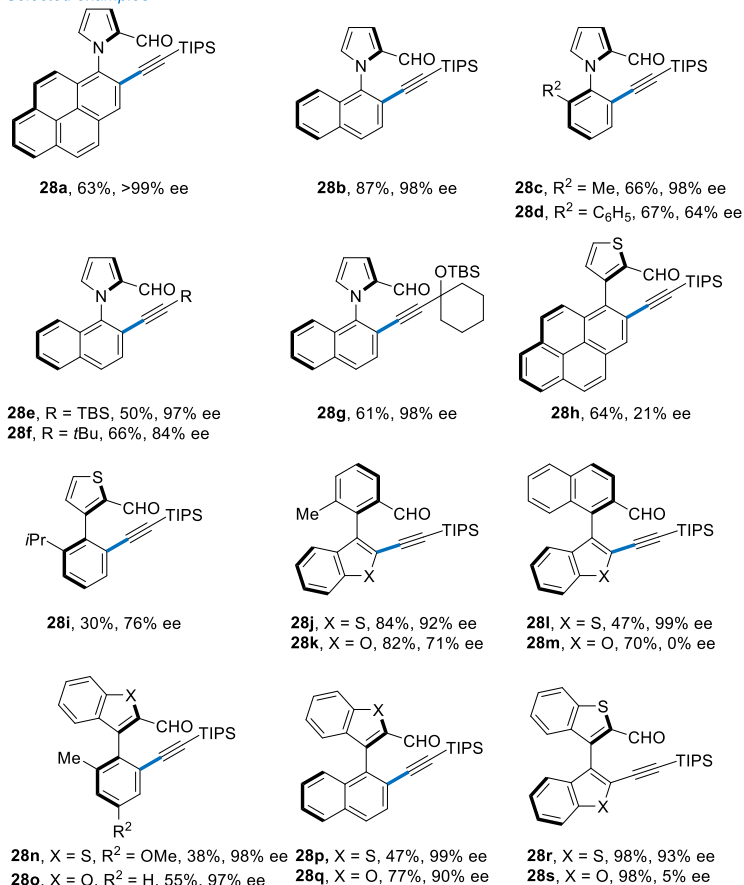
Then, the same group extended their methodology to the challenging atroposelective alkylation of biaryls featuring at least one five-membered heteroarene (Scheme 10).³⁵ Under Palladium catalysis, the enantioselective alkylation of various biaryl aldehydes bearing a C–N and a C–C chiral axis with a TIPS-protected alkyne bromide was realized in an efficient manner. Different *N*-arylpyrroles were functionalized (**28a-d**) and different alkynes were efficient partners in the reaction (**28e-g**), albeit *N*-arylindoles were unreactive. The alkylation of the thiophene derivatives (**27h,i**) was achieved

in moderate to good yields and with enantiomeric excesses ranging from 21% to 76%. Moreover, replacing the benzothiophene in the lower part by a benzofuran had a deleterious effect on the enantioselectivity (28j vs 28k and 28l vs 28m), whereas the nature of the heteroaryl in the upper part of the biaryls had no significant impact on the outcome of the reaction (28n-q). Interestingly, with this approach, the alkylation of substrates having two five-membered heteroarenes was possible and it turned out that the enantioselectivity of the reaction was dependent on the nature of the heteroarene in the lower part (28r vs 28s).

Scheme 10. Pd(II)-catalyzed alkylation of five-membered containing biaryls by C–H bond activation.



Selected examples

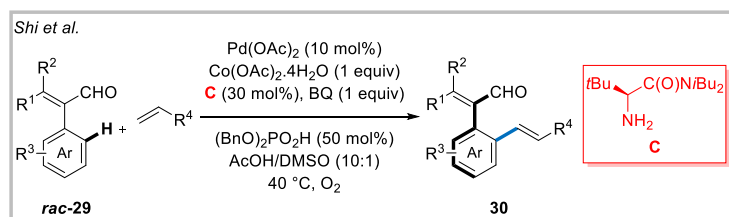


2.2 from styrene derivatives

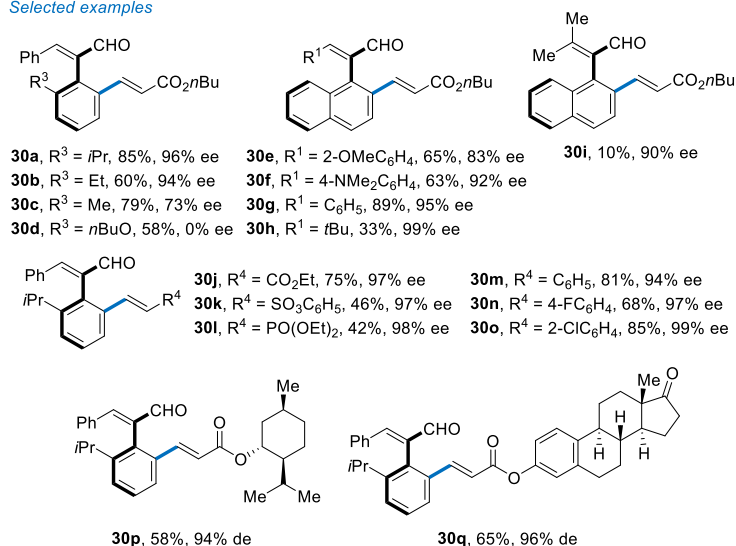
Recently in 2020, Shi and co-workers investigated the challenging synthesis of axially chiral styrenes. To that purpose, the Pd-catalyzed atroposelective C–H olefination of racemic styrenes (*rac*-29) using the bulky amino acid C was developed in the presence of benzoquinone and cobalt acetate in a mixture of AcOH and DMSO, this latter presumably acting as a ligand (Scheme 11).³⁶ With substrates bearing a substituent at the *ortho* position, the expected products were obtained

with a good enantiocontrol (30a-c) except in the case of 30d. By replacing the aryl part by a naphthyl one, the olefination of several derivatives (30e-i) went smoothly. Moreover, several activated olefins and styrenes were suitable coupling partners leading to the synthesis of axially chiral compounds (30j-o) in high enantioselectivities. Interestingly, using acrylates derived from natural products, an access to added-value styrenes (30p-q) was possible with high diastereomeric excesses. Notably, axially chiral styrenes **30** were oxidized to the corresponding carboxylic acids, which showed higher efficiency as chiral ligands in the Co(III)-catalyzed enantioselective (sp^3)-H amidation of a thioamide compared to their biaryl counterparts.

Scheme 11. Synthesis of axially chiral styrenes *via* the transient directing group strategy.



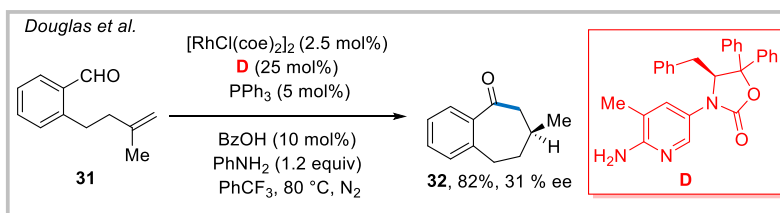
Selected examples



3. Asymmetric synthesis of chiral carbocycles and heterocycles by C–H bond activation

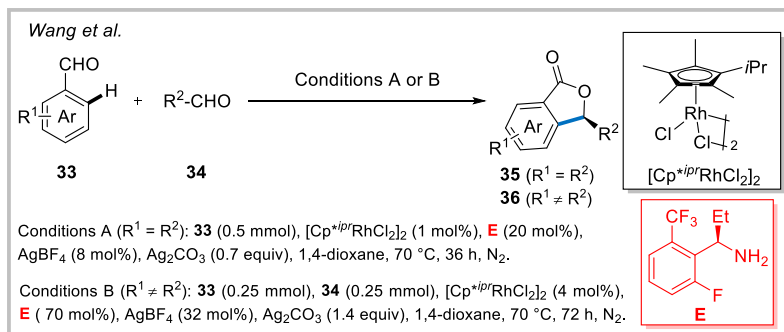
The preparation of chiral carbocycles and heterocycles through transition metal-catalyzed direct C–H bond activation has been considerably studied in the last decades. Indeed, the use of Rhodium complexes, especially those containing cyclopentadienyl (Cp)-derived ligands, allowed many successful enantioselective transformations employing different strategies to induce asymmetry.^{13g,37} In contrast, the utilization of chiral transient directing groups to this end is still in its infancy despite the indisputable advances made in the recent years. In 2012, in the course of their study regarding the Rh(I)-catalyzed intramolecular hydroacylation of disubstituted alkenes, Douglas and co-workers provided the first example applied to the enantioselective cyclization of the aldehyde **31**.³⁸ To this purpose, a chiral derivative of 2-amino-3-picoline (D) was used to achieve the *in situ* formation of the aldimine species from **31** (Scheme 12). Although a unique example was depicted with a modest enantioselectivity, this seminal work paved the way for further developments in catalytic asymmetric transformations using the chiral transient directing group strategy. Note that a theoretical mechanistic study was then published by Zhang, Lei and co-workers in 2014.³⁹

Scheme 12. Rh(I)-catalyzed enantioselective hydroacylation using a chiral TDG.



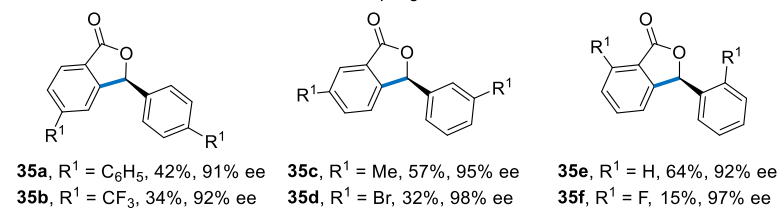
In 2019, Wang and co-workers took benefit from the use of cyclopentadienyl-containing Rh(III) catalysts for the asymmetric synthesis of phthalides.⁴⁰ By employing a combination of the $[\text{Cp}^* \text{RhCl}_2]_2$ catalyst and the chiral amine E, a methodology was developed for the enantioselective homo- and hetero-coupling of benzaldehyde derivatives, offering an access to a large panel of chiral phthalides (yields up to 73% and enantiomeric excesses ranging from 61% to 99.9 %, Scheme 13).⁴¹ For compounds 35a-f, resulting from a homocoupling reaction, the best yields were obtained with phenyl- and alkyl-substituted aromatic aldehydes (33a and 33c) as well as benzaldehyde (33e). On the contrary, the presence of a CF_3 group (33b) or halogens (33d and 33f) had a deleterious effect on the outcome of the reaction. Notably, when *meta*-substituted aldehydes reacted, the functionalization at the less hindered position occurred (35c-d). Regarding the heterocoupling reactions (36a-i), the observed selectivity stemmed from the fact that the transition metal-catalyzed C–H bond activation event was favored with substrates substituted with electron-neutral or electron-donating groups (alkyl, phenyl, OBn), which then reacted with aromatic aldehydes bearing electron-withdrawing substituents (halogens, CF_3 , SO_2Me , CO_2Et , NO_2). Hence, a selective access to only one of the four potential products was possible in most cases. Moreover, heterocoupling of 2,4-dimethoxybenzaldehyde with aliphatic aldehydes was also achieved, leading to the corresponding products 36j-l with good to high enantioselectivities. Regarding the mechanism of the transformation, a plausible pathway was suggested to explain the observed enantioselectivities for both homo- and hetero-couplings. First, the precatalyst $[\text{Cp}^* \text{RhCl}_2]_2$ would react with the silver tetrafluoroborate to afford the active species $[\text{Cp}^* \text{Rh}^{\text{III}}]$. Then, the rhodacycle II formation would take place from the aldimine I *via* a reversible C–H activation event, followed by the coordination of the second coupling partner (intermediate III). Subsequently, the intermediate IV would be obtained after a stereoselective addition of the arene to the second aldehyde, followed by an intramolecular attack of the resulting alkoxide at the imine carbon. After a β -hydride elimination, a Rh(I) species would be released, which after oxidation with the silver salt would regenerate the active Rh(III) catalyst along with the imine V. This latter would be easily hydrolyzed to provide the desired chiral phthalides 35 or 36 and the organo-catalyst.

Scheme 13. Rh(III)-catalyzed preparation of chiral phthalides from aldehydes using a chiral TDG.

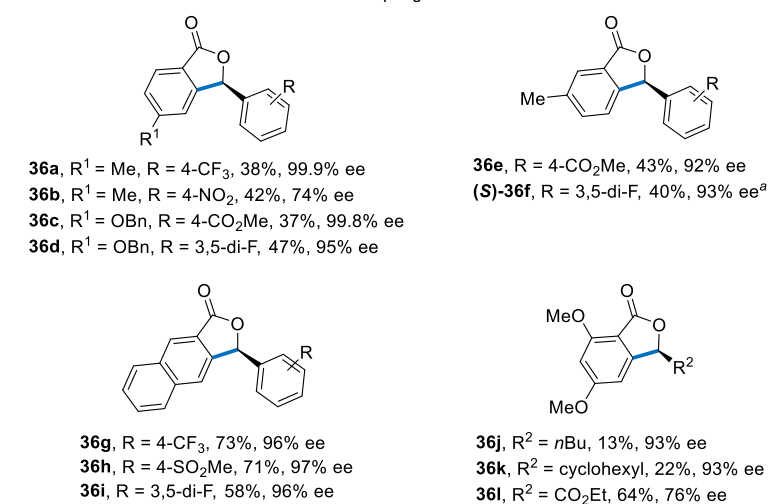


Selected examples

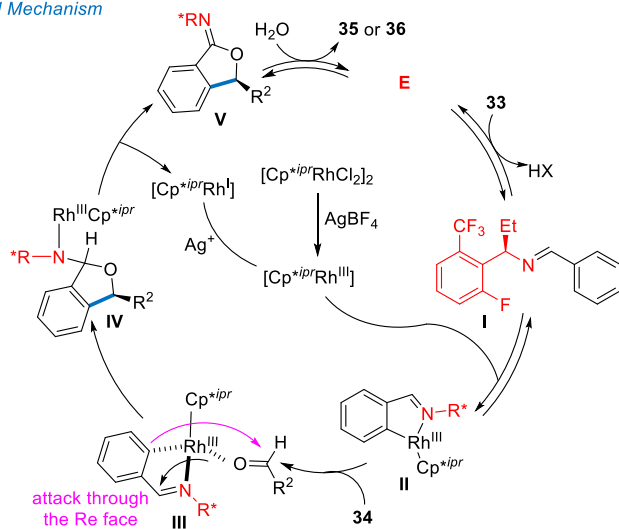
Homocoupling reactions



Heterocoupling reactions



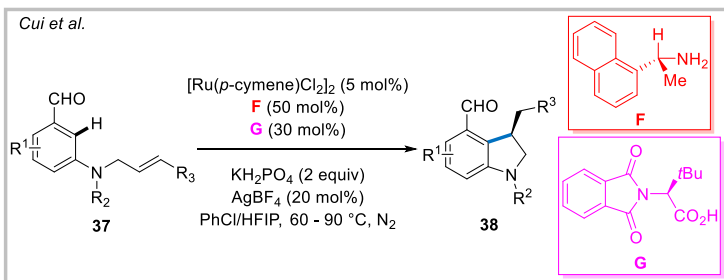
Proposed Mechanism



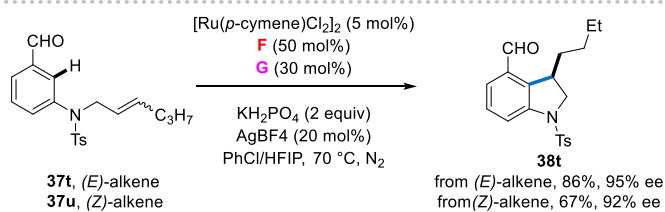
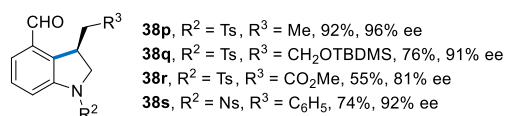
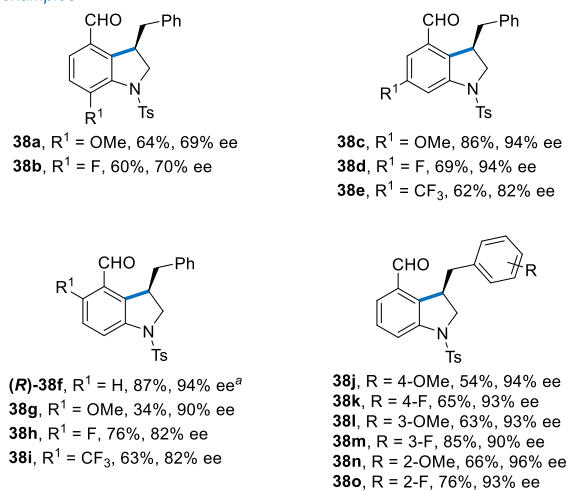
^a Absolute configuration determined by X-ray diffraction.

In contrast to Rhodium based-catalysts, Ruthenium ones have been less employed in asymmetric C–H activation reactions.^{21b,42} In 2019, Cui and co-workers reported the first Ruthenium-catalyzed synthesis of chiral indoline derivatives by means of the chiral transient directing group strategy. Using the $[\text{Ru}(\textit{p}\text{-cymene})\text{Cl}_2]_2$ catalyst combined with the chiral amine F and an additional chiral acid G, the enantioselective intramolecular hydroarylation of aromatic aldehydes 37 was achieved leading to *N*-Tosyl protected indoline derivatives with yields up to 92% and enantiomeric excesses between 69% and 96% (Scheme 14).⁴³ Several benzaldehyde derivatives 37a-i bearing either an electron-donating (OMe, 37a, 37c, 37g) or an electron-withdrawing (CF_3 , 37e and 37h) group were functionalized with moderate to high yields. The substitution pattern on the aromatic aldehydes did not have a strong impact on the outcome of the reaction, except in the presence of a methoxy group at the *ortho* position, as the corresponding product 38g was isolated in only 34% yield with a high enantiomeric excess. The substitution over the alkene counterpart was also investigated (37j-r) and it turned out that various (*E*)-styrenyl groups containing both electron-donating and electron-withdrawing groups (OMe and F, among others) were suitable (37j-o). Moreover, alkenes substituted with different substituents (Me, CH_2OTBDMS , CO_2Et , 37p-r) were well tolerated. Note that the nitrogen-protecting group was not only restricted to tosyl, since the *N*-nosyl indoline 38s was synthesized. Notably, when both *E* and *Z* diastereoisomers of the same alkene were employed as substrates (37t-u), the same product 38t was obtained with high enantiomeric excesses (91% and 92%, respectively), showing that the alkene geometry did not have any influence on the stereocontrol of the transformation. The following plausible mechanism was suggested for the enantioselective synthesis of indoline scaffolds (Scheme 14). First, the active catalyst species $(\text{Ru}(\textit{p}\text{-cymene})(\text{O}_2\text{CR}^*)_2)$ would be generated from $(\text{Ru}(\textit{p}\text{-cymene})(\text{Cl}_2)_2)$ followed by the formation of the ruthenacycle II from the transient aldimine I through a reversible C–H activation step. Coordination of the alkene to the Ruthenium metal center would lead to the cationic intermediate III as an ion pair with the chiral carboxylate G, crucial for the efficiency and the enantioselectivity of the reaction. Then, the insertion of the alkene would occur selectively through the less hindered face of the chiral imine (intermediate IV) presumably due to its conformationally rigid structure. Finally, the product 38f would be obtained after the hydrolysis of the aldimine V and F would be regenerated along with the Ruthenium-based catalyst.

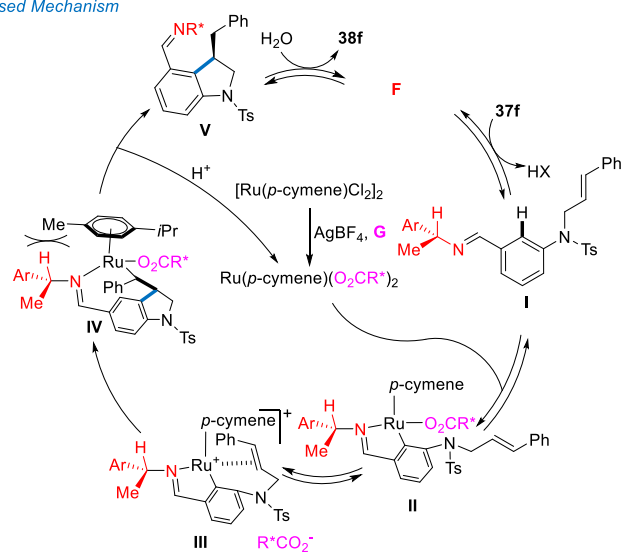
Scheme 14. Preparation of chiral indolines through an enantioselective Ru(II)-catalyzed intramolecular hydroarylation.



Selected examples



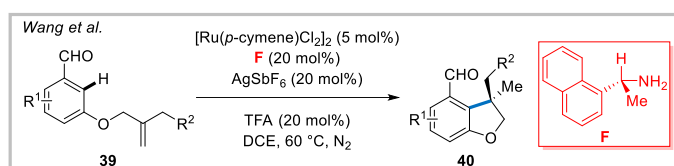
Proposed Mechanism



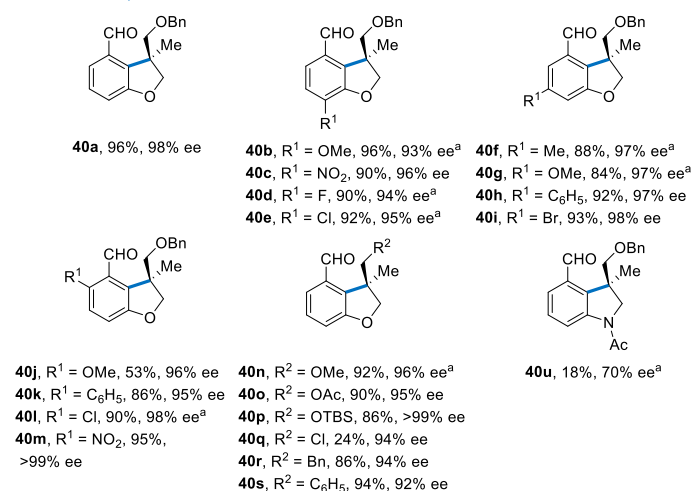
^a Absolute configuration determined by X-ray diffraction.

In 2020, Wang and co-workers reported another application of the chiral transient directing group strategy in a Ru-catalyzed transformation for the synthesis of 2,3-dihydrobenzofurans through an asymmetric intramolecular hydroarylation reaction.⁴⁴ To this end, the combination of $[\text{Ru}(\textit{p}\text{-cymene})\text{Cl}_2]_2$ catalyst with the chiral amine **F** and trifluoroacetic acid were found to be the best for this transformation. Several olefin-tethered aromatic aldehydes were smoothly converted into the corresponding 2,3-dihydrobenzofurans **40** with yields up to 98% and enantiomeric excesses up to >99% (Scheme 15). The reaction proceeded successfully with an unsubstituted aldehyde **39a** as well as with aromatic aldehydes bearing halogens, electron-donating (eg. OMe, Me) and electron-withdrawing groups (NO_2), either at the *para*-, *meta*- or *ortho*-position (**39b-m**). Nevertheless, the presence of a methoxy group at the *ortho* position led to a lower yield (**40j**). Substrates **39n-s**, bearing various substituents at the allylic position were also tested, leading to the expected products **40n-s** with very good yields and enantioselectivities, except for the chlorine-containing product **40q**. Extension of their methodology to the synthesis of the indoline derivative **40u** turned out to be feasible but less efficient (18% yield, 70% ee). A similar mechanism to the one depicted in the Scheme 14 was suggested for this transformation, although the use of a chiral acid was not required to improve yields and enantioselectivities.

Scheme 15. Synthesis of chiral 2,3-dihydrobenzofuranes through a Ru(II)-catalyzed enantioselective intramolecular hydroarylation.



Selected examples



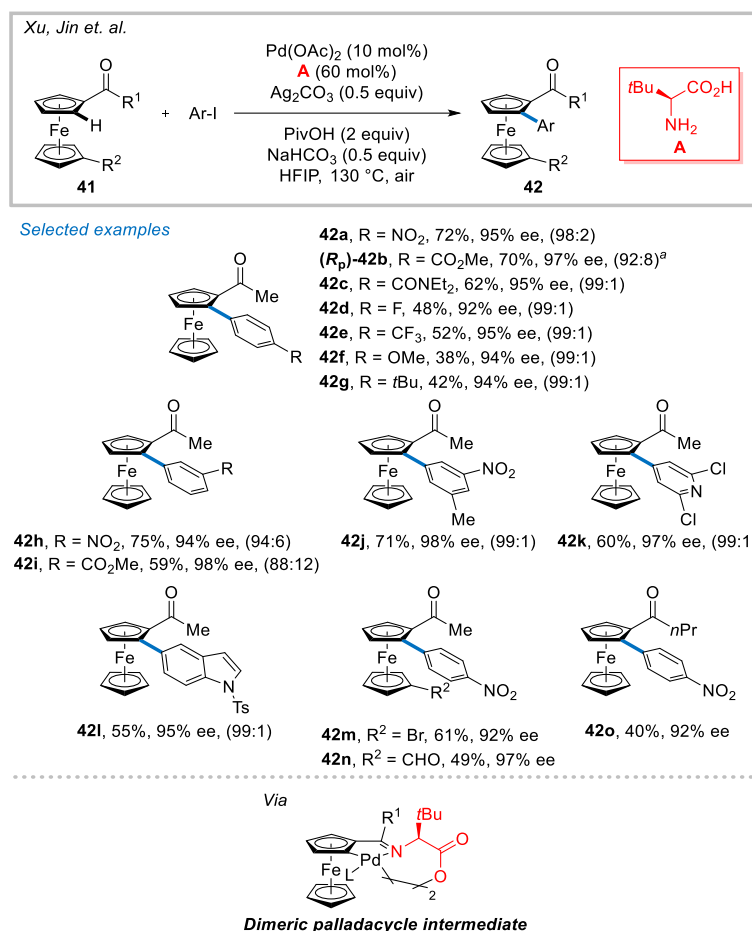
^a F (40 mol%), TFA (40 mol%).

4. Application of the chiral transient directing group strategy for miscellaneous reactions

In 2018, Xu, Jin and co-workers applied the chiral transient directing group strategy in the enantioselective C(sp²)-H arylation of ferrocenyl ketones by Palladium catalysis in order to obtain enantioenriched planar-chiral ferrocenes with yields up to 75%, enantiomeric excesses ranging from 92% to 98% and a ratio of mono- vs di-functionalized products between 88:12 and 99:1 (Scheme 16).⁴⁵ It was found that the reaction of the acetylferrocene with the 1-iodo-4-nitrobenzene was successfully achieved using the *L*-*tert*-leucine as the transient directing group precursor leading to the corresponding product **42a**. Both the pivalic acid and the sodium bicarbonate were essential for the efficiency and the enantioselectivity of the transformation. In particular, the pivalic acid had a dual function as it promoted the transient aldimine formation and played a key role in the rate determining C-H cleavage event. The arylation of **41** was also realized with an array of *para*- and *meta*-substituted aryl iodides (**42b-i**); electron-deficient ones being more efficient coupling partners (**42b-e** and **42h-i**). Aryl iodides bearing electron-donating substituents (OMe, *t*Bu) led to the expected products **42f-g** in lower yields. Note that the reaction went smoothly with disubstituted aryl iodides containing one electron-withdrawing group as demonstrated

with the compound 42j. Additionally, when heteroaryl iodides were used, the expected products 42k-l were obtained in moderate to good yields and high enantioselectivities (up to 97% ee). Notably, in all the cases, an excellent selectivity towards the monoarylation was observed. Substituents over the ferrocene ring were also tolerated, affording the corresponding arylated products 42m-n with moderate to good yields. Finally, the *n*-propyl ketone 41o led to the arylated product 42o in 40% yield and 92% enantiomeric excess. It is worth mentioning that a dimeric palladacycle intermediate was presumably formed in the course of the transformation.

Scheme 16. Enantioselective Pd(II)-catalyzed C(sp²)-H arylation of ferrocenyl ketones.



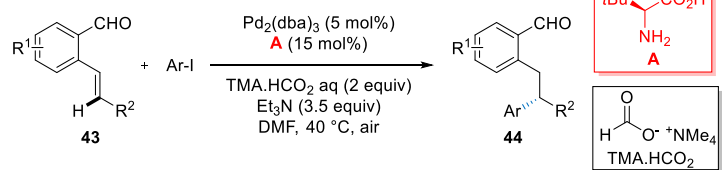
Ratio of mono:di arylated products are indicated in parenthesis. ^a The absolute configuration was assigned to *R_p* on the basis of X-ray diffraction.

In 2020, Liu, Engle and co-workers reported another application of the chiral transient directing group strategy for the enantioselective Pd-catalyzed β -hydroarylation of alkenyl benzaldehydes.⁴⁶ It is worth to mention that the enantioselective β -hydroarylation of substituted alkenyl arenes⁴⁷ is still underdeveloped compared to the asymmetric α -hydroarylation reaction.⁴⁸ Using *L*-*tert*-leucine and in the presence of a hydride donor (TMA.HCO₂), the Pd(0)-catalyzed reductive hydroarylation of alkenyl benzaldehydes with a panel of (hetero)aromatic iodides was achieved with yields up to 94% and enantiomeric excesses between 92% and >99% (Scheme 17). The reaction of the (*E*)-2-(prop-1-en-1-yl)benzaldehyde with several aryl iodides bearing electron-donating groups, electron-withdrawing ones and halogens led to the

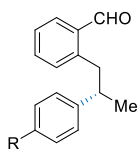
corresponding products 44a-i in moderate to excellent yields. Interestingly, various functional groups were tolerated such as a hydroxyl group (44b), a *N*-Boc-protected amine (44c) and a free carboxylic acid (44f). Heteroaryl iodides were suitable as well (44j-l), although the pyridine derivative 44l was synthesized with a very low yield. Regarding the alkene part, both *E* and *Z* isomers were hydroarylated and it turned out that *E* alkenes gave the best enantiomeric excesses but with lower yields (44m-n). Moreover, when the size of the substituent on the alkene part was increased, lower yields were generally obtained (44g vs. 44m). Finally, benzaldehydes with different substitution patterns were tested leading to the corresponding products 44o-u in good yields. Note that *ortho*-substituted benzaldehyde derivatives 43t-u were also functionalized. The authors suggested the following pathway for the enantioselective hydroarylation. First, aldimine I formation followed by the coordination to the Pd(0) would lead to the species II, which would undergo an oxidative addition with the aryl iodide to afford the intermediate III. Then, the enantioselective carbopalladation would take place (intermediate IV), which would be the key step for enantioinduction. Subsequently, the formate salt would coordinate to the metal center (intermediate V) and after a decarboxylation reaction, a Pd-H species VI would be obtained. A final reductive elimination would regenerate the Pd(0)-catalyst and would furnish VII, which after hydrolysis would release the product 44a along with *L*-*tert*-leucine (A).

Scheme 17. Pd(0)-catalyzed enantioselective reductive Heck arylation of alkenyl benzaldehydes.

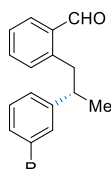
Liu, Engle et al.



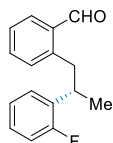
Selected examples



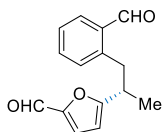
44a, R = H, 94%, >99% ee
44b, R = OH, 55%, 99% ee
44c, R = NHBoc, 56%, >99% ee
44d, R = Br, 82%, >99% ee
44e, R = CF₃, 77%, >99% ee
44f, R = CO₂H, 75%, 99% ee



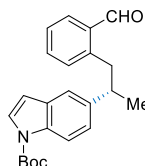
44g, R = OMe, 92%, >99% ee
44h, R = Cl, 75%, >99% ee



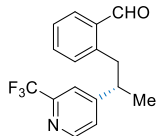
44i, R = F, 76%, >99% ee



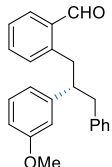
44j, 63%, 97% ee



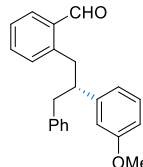
44k, 83%, 99% ee



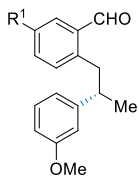
44l, 18%, 95% ee



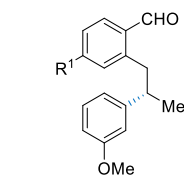
44m, 67%, >99% ee



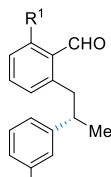
44n, 80%, 97% ee^a



44o, R¹ = CF₃, 53%, >99% ee



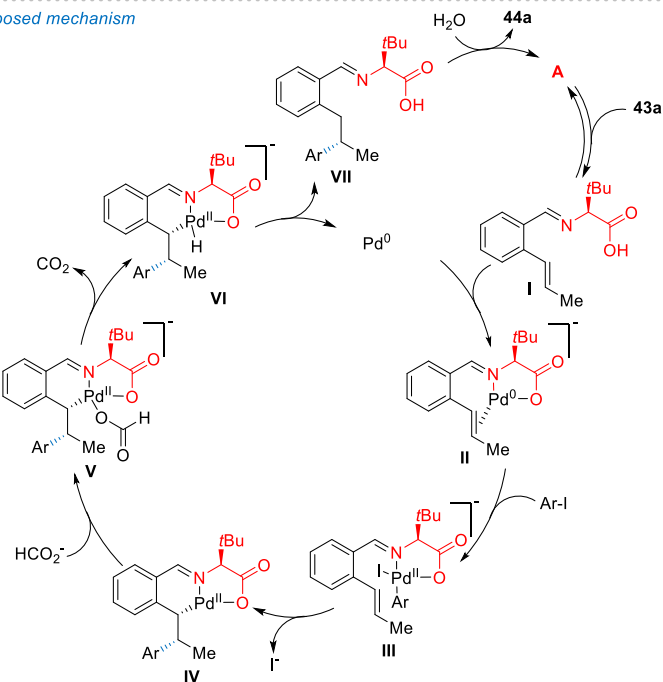
44r, R¹ = Cl, 75%, 99% ee



44s, R¹ = CF₃, 61%, 96% ee

(S)-44t, R¹ = F, 93%, 97% ee^b
44u, R¹ = N(CH₂CH₂)₂O, 58%, 92% ee

Proposed mechanism



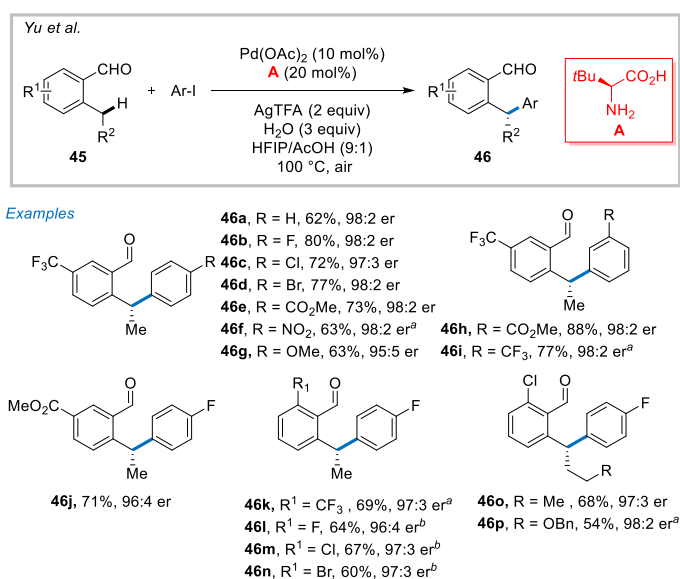
^a From *Z*-alkene. ^b The absolute configuration was assigned through X-ray diffraction.

5. Enantioselective functionalization of C(sp³)–H bonds

Despite their lower reactivity in comparison with C(sp²)–H bonds, groundbreaking advances were made in the enantioselective functionalization of C(sp³)–H bonds by transition metal catalysis in the last decades.^{1a,13g,h,k} Among the existing approaches employed, the use of chiral ligands in Pd-catalyzed directed C–H bond functionalization reactions was broadly exploited.⁴⁹ Therefore, the quest for new approaches to reach highly challenging asymmetric transformations was particularly attractive. In this context, although restricted so far to handful of examples, the use of the chiral transient directing group strategy turned out to be an efficient tool as highlighted in this section.

In 2016, Yu and co-workers pioneered the use of a chiral transient directing group for achieving the Pd-catalyzed enantioselective arylation of benzylic C(sp³)–H bonds.⁵⁰ In the course of their study related to the arylation of C(sp³) centers of ketones and aldehydes by Pd-catalysis, the authors developed a methodology for the preparation of enantioenriched products by using *L*-*tert*-leucine (**A**) with yields up to 88% and enantiomeric ratios between 95:5 and 98:2 (Scheme 18). Taking benefit from the steric interactions between the bulky *tert*-butyl group of the *L*-*tert*-leucine and the benzylic R² group, good enantiomeric ratios were reached for this transformation. With this approach, an array of *meta*- and *para*-substituted aryl iodides was successfully employed for the functionalization of the 2-ethyl-5-(trifluoromethyl)benzaldehyde. Halogens as well as different electron-withdrawing (CO₂Me, NO₂, CF₃) and electron-donating groups (OMe) were well tolerated, as demonstrated with the synthesis of compounds **46a-i**. Several *ortho*- and *meta*-substituted benzaldehydes were suitable substrates in the reaction with 4-fluoriodobenzene and the corresponding products **46j-n** were obtained in 60–71% yields and enantiomeric ratios up to 97:3. Note that the transformation turned out to be tolerant to functional groups such as an ester (**46j**) and halogens (**46l-n**). Moreover, the substituent over the benzylic position (R²) was not restricted to a methyl group since substrates bearing other alkyl chains were also smoothly functionalized (**46o-p**). Note that later in 2018, Dang and co-workers reported a theoretical study to get more insight about the regio- and stereoselectivity observed for the Pd-catalyzed arylation of aldehydes and ketones by C(sp³)–H activation using the chiral transient directing group strategy.⁵¹

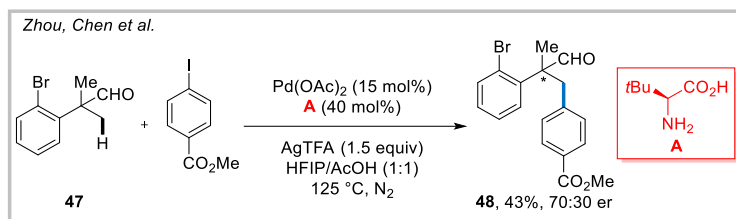
Scheme 18. Pd(II)-catalyzed enantioselective benzylic C(sp³)–H arylation of benzaldehyde derivatives using the *L*-*tert*-leucine as the chiral transient directing group precursor.



^a Reaction performed at 110 °C. ^b 5 mol% Pd(OAc)₂, 10 mol% **A**.

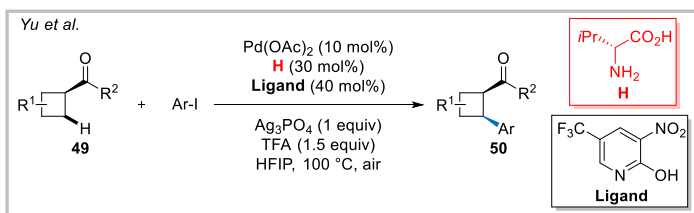
In 2019, during their investigations towards the arylation of phenylacetaldehyde derivatives with aryl iodides under Palladium catalysis, the group of Chen and Zhou applied a similar methodology than the one depicted by the Yu group.⁵² A single example of Pd(II)-catalyzed enantioselective arylation of the 2-bromo- α,α -dimethylbenzaldehyde **47** using the imine derived from L-*tert*-leucine as the transient directing group was achieved leading to the corresponding product **48** in 43% yield and an enantiomeric ratio of 70:30 (Scheme 19).

Scheme 19. Pd(II)-catalyzed C(sp³)-H asymmetric arylation of the phenylacetaldehyde derivative **47**.

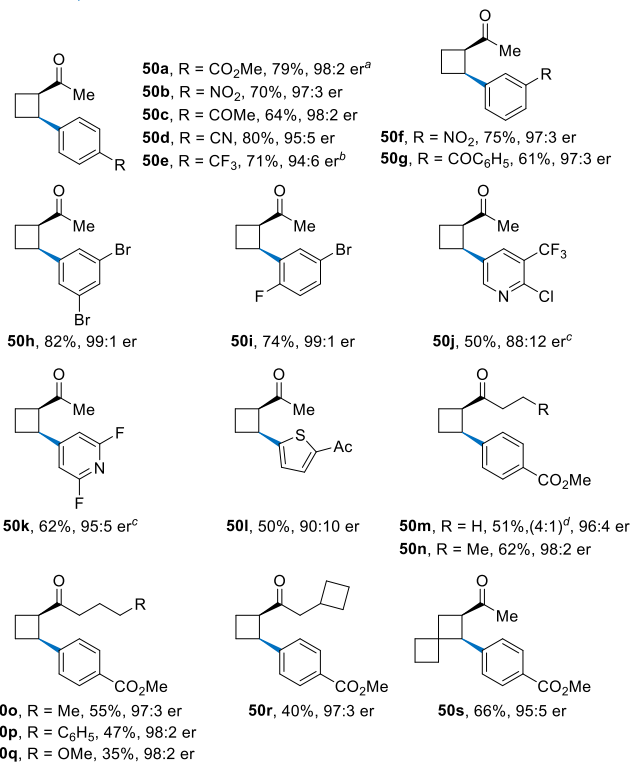


In 2020, Yu and co-workers provided a key contribution to the field by developing the Pd-catalyzed enantioselective arylation of nonactivated secondary C(sp³) centers. By employing a combination of Pd(OAc)₂, D-valine (H), pyridone and Ag₂PO₃, the authors were able to perform the arylation of cyclobutyl ketones **49**, providing the corresponding products **50a-s** with yields up to 82% and enantiomeric ratios up to 99:1 (Scheme 20).⁵³ Remarkably, by replacing Ag₂PO₃ by AgTFA, the products were obtained with a reversed enantioselectivity. Moreover, in this transformation, pyridone ligand, usually known for fastening the cleavage of C-H bonds,^{4k,7f,11k,54} was crucial to achieve the reaction with high enantioselectivities. The arylation proved to be efficient with several *para*- and *meta*-substituted aryl iodides bearing electron-withdrawing groups such as CO₂Me, NO₂, Ac, CN, CF₃ and COC₆H₅ (**50a-g**). Disubstituted electron-poor aryl iodides were also suitable coupling partners (**50h-i**). Although the functionalization was not efficient with electron-neutral or electron-rich iodoarenes, it went smoothly with heteroaromatic iodides (**50k-l**). Moreover, different cyclobutyl alkyl ketones were arylated at the α -position (**50m-r**) and only in the case of the ketone **49m**, a competitive arylation of the methyl group of the alkyl chain was also observed. Note that even the spiro-derivative **50s** was successfully functionalized. After mechanistic studies, a plausible pathway was suggested. First, coordination of the imine **I** derived from **49a** to the palladium catalyst in the presence of the pyridone would afford the intermediate **II**, followed by the formation of the palladacycle **III**. This latter would undergo an oxidative addition with the aryl iodide (intermediate **IV**) and subsequently the iodine abstraction by the silver salt would take place (intermediate **V**). After reductive elimination, the catalyst would be regenerated and the ketimine **VI** would be obtained. A final hydrolysis of **V** would furnish the product **50a** (or *ent*-**50a**) and H. Worth to mention that depending on the nature of the silver salt (AgTFA or Ag₂PO₃), either the C-H activation event or the iodine abstraction was suggested to be the rate determining step.

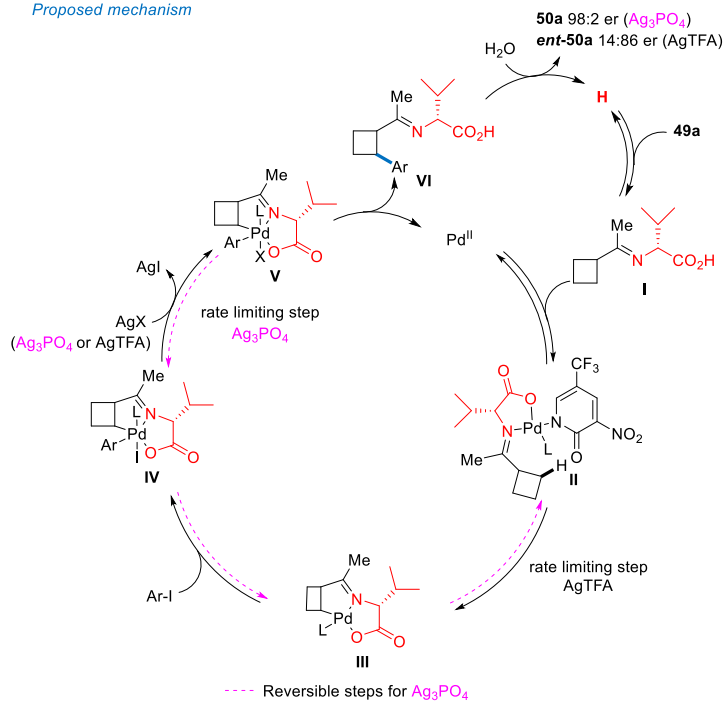
Scheme 20. Pd(II)-catalyzed enantioselective C(sp³)-H arylation of cyclobutyl ketones.



Selected examples



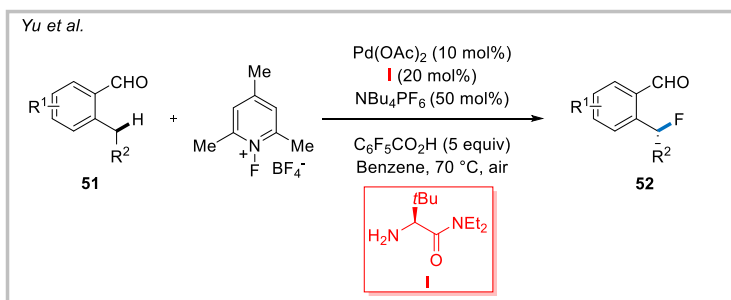
Proposed mechanism



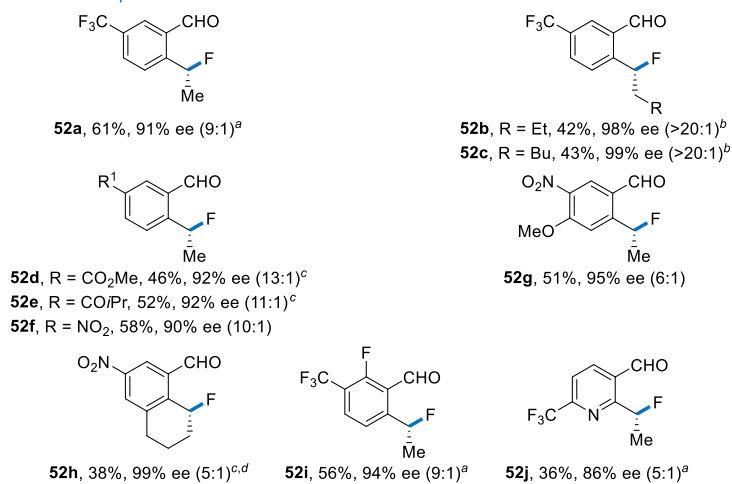
^a Using AgTFA instead of Ag₃PO₄, *ent*-50a was obtained in 34% yield (14:86 er) along with the corresponding diarylated product (50% yield). ^b *D-tert*-leucine was used as TDG precursor. ^c 1 equivalent of H was used. ^d Ratio of the products resulting from the arylation of the cyclobutane ring and the terminal methyl group.

The asymmetric formation of C(sp³)-F bonds has been achieved in the last two decades through different strategies.⁵⁵ In sharp contrast, the transition metal-catalyzed enantioselective direct fluorination of a C(sp³)-H bond is a highly difficult and appealing task and needs to be further investigated. To tackle this synthetic challenge, Yu and co-workers developed a new methodology based on the Pd(II)-catalyzed enantioselective fluorination of C(sp³) centers using a chiral transient directing group.⁵⁶ They anticipated that the design and use of a suitable ligand in this Pd(II)/Pd(IV) process would be crucial to successfully promote the C(sp³)-F bond formation in an enantioselective fashion over the side-competitive reductive eliminations (C-C or C-X bond formation) from Pd(IV) species,⁵⁷ and the undesirable S_N2-type reactions over C(sp³)-Pd(IV)-F intermediates.⁵⁸ Instead of using a traditional amino acid, it was discovered that the combination of the amide **1** (derived from *L-tert*-leucine) along with 2,3,4,5,6-pentafluorobenzoic allowed the fluorination of the trifluoromethylated benzaldehyde derivative **51a** on a secondary C(sp³) center in the presence of *N*-fluoro-2,4,6-trimethylpyridinium tetrafluoroborate as the fluorinating reagent (Scheme 21). A panel of aromatic aldehydes was functionalized leading to the expected products **52b-j** in yields up to 61% and enantiomeric excesses ranging between 86-99%. Even though the competitive pathway that led to the formation of the undesired C(sp³)-O bond formation by an S_N2-type process could not be completely circumvented, moderate to excellent ratios in favor to the fluorinated products were obtained (5:1 to >20:1). Benzaldehydes bearing longer alkyl chains than an ethyl group at the *ortho* position were also suitable and furnished the best enantiomeric excesses and the best C(sp³)-F/C(sp³)-O ratio (>20:1), albeit with lower yields (**52b-c**). Moreover, benzaldehydes substituted with electron-withdrawing groups (CO₂Me, CO_{*i*}Pr, NO₂, **51d-f**) at the *meta* position were successfully functionalized. Although electron-rich substrates turned out to be inefficient in this transformation, the fluorination was achieved when the disubstituted benzaldehyde **51g** was used. Note that the tetraline derivative **51h**, the *ortho*-fluorinated aldehyde **51i** and the pyridine **51j** were also suitable substrates in this transformation. On the basis of mechanistic investigations and literature data,⁵⁹ the authors suggested that a cationic Pd(IV) intermediate would be the key intermediate in this transformation and would favor the fluorination reaction over the C(sp³)-O bond formation.

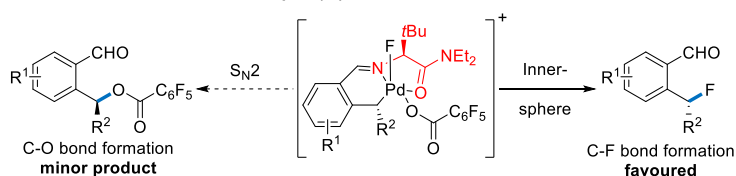
Scheme 21. Pd(II)-catalyzed enantioselective fluorination secondary C(sp³)-H bonds.



Selected examples



Key Pd(IV) cationic intermediate



Isolated yields were reported as a mixture of the product **52** with the starting material **51**. The numbers in parenthesis indicated the ratio of products resulting from either a C(sp³)-F or C(sp³)-O bond formation and were determined by ¹H NMR analysis. ^a ¹H NMR yields were given due to the volatility of the products. ^b 1-Fluoro-2,4,6-trimethylpyridinium hexafluorophosphate (1.5 equiv) was used as the fluorine source. ^c CH₂Cl₂ was used instead of benzene. ^d 25 mol% of **I** were used.

6. SUMMARY

Over the past few years, transition metal-catalyzed enantioselective transformations by C-H bond activation have been developed as a powerful tool for the construction of interesting chiral molecules. In particular, the use of the chiral transient directing group strategy was appealing, offering potent synthetic solutions to the challenging asymmetric transformations. In this review, a general overview of the recent groundbreaking advances made in this field was given. Original methodologies based on the astute use of chiral transient directing groups for the enantioselective synthesis of biaryls, as well as chiral heterocycles and carbocycles were developed. In addition, this strategy was successfully applied to the challenging enantioselective C(sp³)-H bond functionalization. Even though major breakthroughs were achieved, this modern and sustainable strategy is still in its infancy. Indeed, so far only aldehyde and ketone derivatives were used as substrates to provide the chiral transient directing group by the reversible formation of an imine and in most cases, acidic reaction conditions were necessary; which hampered the general use of this strategy. To widen the scope of these transformations, the use of amine derivatives as substrates and more generally, the reversible formation of other functional groups playing the role of chiral transient directing groups are expected to be explored. Moreover, most of the transformations were limited to the formation of C-C or C-F bonds, although in the last case, only a single example was reported. Therefore, there is an urgent need to further explore other transformations. Finally, the enantioselective

functionalization of unactivated aliphatic derivatives and the use of earth-abundant 3d transition metals were not achieved yet, and any advances using the chiral transient directing group strategy will bring significant breakthroughs. We do believe that this novel tool will be inspiring for the scientific community and milestones will be reached in the forthcoming years, expanding the chemical space for asymmetric transformations.

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Keywords: Transition Metal, Chiral Transient Directing Group, Asymmetric Transformations, Dual Catalysis, Synthetic Methodology, C–H Bond Functionalization

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