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Design, Synthesis and Catalytic Activity of (Cyclopentadienone)iron Complexes Containing a Stereogenic Plane and a Stereogenic Axis

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Herein, we report the synthesis and characterization of several chiral (cyclopentadienone)iron complexes (CICs) featuring either two (*R*)-BINOL-derived stereoaxes or a combination of one (*R*)-BINOL-derived stereoaxis and a stereogenic plane. The stereoplane-containing CICs were obtained as epimer mixtures, which were separated by flash column chromatography and assigned an absolute configuration based on XRD analysis, NMR and order of elution. The library was tested in the asymmetric hydrogenation of ketones showing good catalytic activity and a moderate stereoselectivity which, notably, is mostly imparted by the stereogenic plane. Indeed, the two epimers of each CIC possessing a stereoplane show opposite and equally strong stereochemical preference.

Introduction

Control of the stereochemistry during a transition metal-catalyzed organic transformation is imparted by the asymmetric environment around the metal, which directs substrate approach to the catalytically active metal center. In this way one type of approach of the substrate is preferred over the others, and the catalytic transformation occurs favoring one enantiomer of the product. In many chiral complexes (typically in the presence of C_2-symmetric bidentate ligands), the catalytic metal center is non-stereogenic, while in others the metal itself is a stereogenic element. To date, in most chiral organometallic catalysts the chiral environment is imparted by ligands containing stereogenic centers or axes, which shape in a chiral pocket the space around the metal.[1] On the other hand, stereogenic planes have so far been rather neglected as source of stereochemical information. A stereogenic plane is generated when a planar motif possessing enantio- or diastereofaces is modified by a substituent located above or below the plane.[2] This stereogenic element is typically displayed in *p*-cyclophane derivatives, in *trans*-cyclooctene and, more commonly, in metal complexes in which a planar ligand (e.g., a cyclopentadienyl anion or a planar aromatic moiety), is η- coordinated to the metal, such as in *sandwich* and *piano-stool* complexes. In this case, coordination of the metal to either face of the ligand affords two enantiomeric or diastereoisomeric complexes (depending on the possible presence of additional stereogenic elements) potentially suitable for enantioselective catalysis.

An interesting example of chiral hydroxycylopentadienyl ruthenium, Shvo-type catalysts[3] with a stereogenic plane was developed by Hayashi and co-workers.[4] The complexes (Figure 1A) were obtained by reaction of unsymmetrically substituted achiral cyclopentadienones with $Ru_3(CO)_{12}$, and the two enantiomers arising from ruthenium complexation on the two enantiofaces were separated by chiral HPLC. The catalysts were tested in the transfer hydrogenation of activated ketones (such as 2,2,2-trifluoroacetophenone) and ketimines, yielding excellent conversions and moderate enantioselectivities ($ee \leq 56\%$ with 2,2,2-trifluoroacetophenone and $ee \leq 64\%$ with the *N*-phenyl imine of acetophenone).

More recently, chiral (cyclopentadienone)iron complexes (CICs)[5,6] with a stereogenic plane (Figure 1A) were developed as pre-catalysts for the asymmetric hydrogenation of polar double bonds with moderate enantioselectivities ($ee \leq 48\%$ with 2,2,2-trifluoroacetophenone).[7] A major drawback of this approach is the need for chiral HPLC separation of the racemic mixture of the two enantiomeric complexes arising from the unbiased complexation of the $Fe(CO)_3$ moiety on both enantiofaces of the achiral cyclopentadienone ligand. To get by this issue, Wills and co-workers synthesized a few CICs containing a stereocenter in addition to the stereogenic plane (Figure 1B). The two diastereomers formed upon complexation with iron could be separated and tested in ketone reduction,

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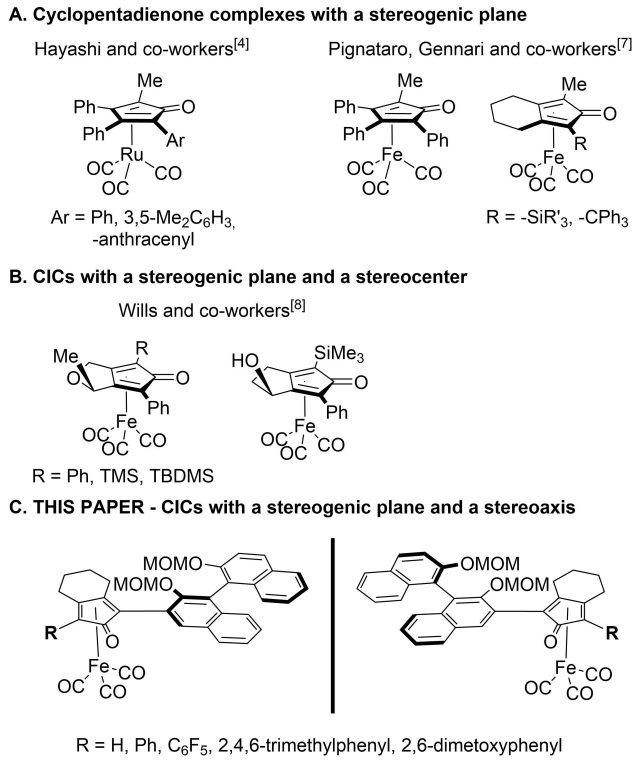


Figure 1. Cyclopentadienone complexes featuring a stereogenic plane. CIC = (cyclopentadienone)iron complex.

showing moderate reactivity and enantioselectivity ($ee \leq$ 25 %).[8]

Herein we describe synthesis, characterization and catalytic properties of several chiral CICs in which the cyclopentadienone moiety is functionalized at the position 2 by an enantiomerically pure binaphthyl substituent (Figure 1C). Thanks to the latter, upon coordination of $Fe(CO)_3$, two diastereomeric complexes containing a stereogenic plane and a stereogenic axis were formed (Figure 1) and easily separated by silica gel chromatography. These complexes were tested in the asymmetric hydrogenation of C=O double bonds, affording enantiomerically enriched chiral alcohols.

Results and Discussion

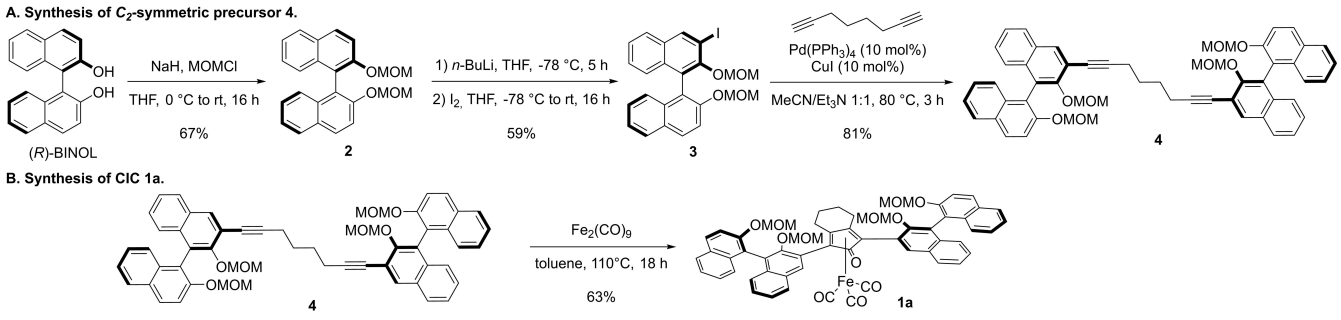
Synthesis of the iron complexes containing C_2-symmetric cyclopentadienone ligands

Our investigation started from the synthesis of new chiral CIC derivatives bearing 1,1′-binaphthalene-based substituents at both C2 and C5 of the cyclopentadienone ring.[9] Since these chiral complexes are formally derived from C_2-symmetric cyclopentadienones, they possess no stereogenic plane, and the binaphthyl stereoaxes are the only stereogenic elements. Studying the catalytic properties of these complexes in enantioselective reduction allowed a first insight in the structure and geometry of the new binaphthalene-based iron complexes. A similar strategy had already been followed by some of us with the synthesis of a family of chiral CICs featuring an (*R*)-BINOL-derived backbone at C3 and C4 of the cyclopentadienone moiety, and their application in the asymmetric hydrogenation of ketones afforded *ee* values up to 77 %, which are still the highest reported so far using chiral CICs.[10]

In order to obtain the desired structure, we planned to perform a carbonylative cyclization/complexation reaction on a properly functionalized diyne. The synthesis of the desired precursor **4** was achieved through the Sonogashira coupling between 1,7-octadiyne and two equivalents of the chiral iodide **3**, which was in turn prepared from commercially available (*R*)-BINOL via protection of the two OH groups as MOM ethers[11] followed by regioselective deprotonation/iodination of position C3 of the binaphthyl moiety (Scheme 1A).[12] Treating compound **4** with $Fe_2(CO)_9$ in refluxing toluene led to the isolation of the desired complex **1 a** in 63 % yield (Scheme 1B).

Crystals of **1 a** suitable for X-ray diffraction (XRD) analysis were grown via slow diffusion of *n*-hexane into a solution of the complex in EtOAc. XRD analysis confirmed structure and absolute configuration (*R*,*R*) of the desired complex (Figure 2). The two binaphthalene-derived residues at positions C2 and C5 adopt a conformation in which the steric hindrance is mostly located around the portion of space above the cyclopentadienone ligand.

The MOM acetal groups of complex **1 a** could be easily removed under acidic conditions (HCl in THF), affording compound **1 b** in 77 % yield (Scheme 2). The latter complex possesses four OH groups amenable to be functionalized by alkylation or acylation. However, alkyl substituents could not be



Scheme 1. A: Synthesis of the C_2-symmetric diyne **4**; B: Carbonylative cyclization/complexation to yield CIC **1 a**.

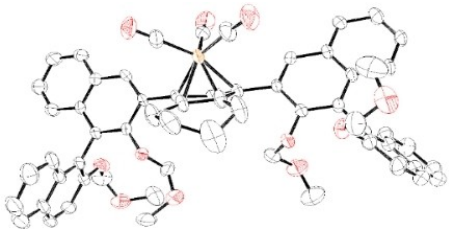
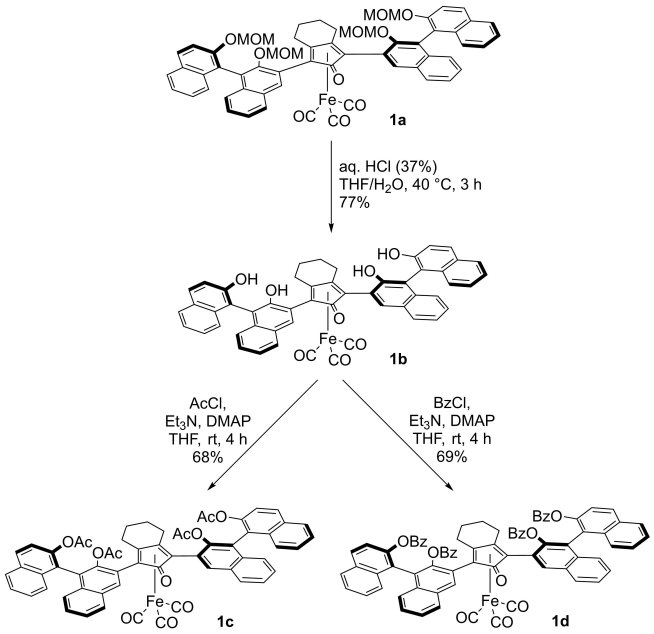


Figure 2. ORTEP representation of the molecular structure of complex **1 a**. Thermal ellipsoids are represented at the 50% probability level. Color code: C (black), O (red) and Fe (orange).



Scheme 2. Cleavage of the four MOM groups of complex **1 a** and synthesis of tetra-acylated ClCs **1 c** and **1 d**.

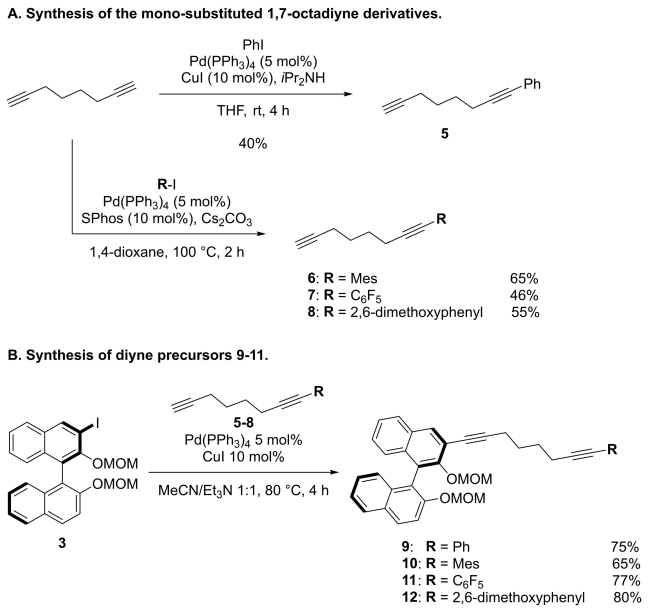
installed, as the reactions with both methyl iodide and benzyl bromide led only to products of partial functionalization or to the degradation of the starting material. In contrast, the tetra-acetylated complex **1 c** and the fully benzoylated complex **1 d** were obtained in 68% and 69% yield, respectively, by treating **1 b** with the corresponding acyl chloride in the presence of triethylamine and catalytic DMAP (Scheme 2).

Synthesis of the iron complexes containing C_1-symmetric cyclopentadienone ligands

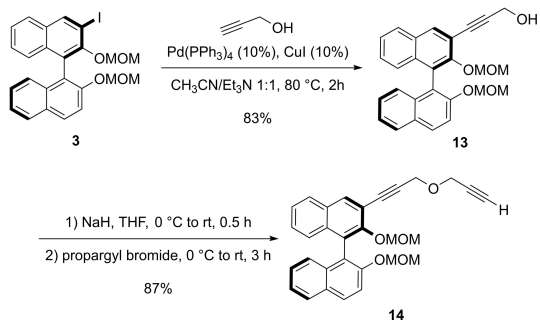
After making chiral complexes **1 a**–**d**, we investigated the synthesis and isolation of a new class of diastereoisomerically pure chiral ClCs starting from iodide **3**, which had been already employed in the preparation of **1 a** (Scheme 1). Cyclative complexation of 1,7-octadiynes bearing different substituents at the terminal positions leads to the formation of a stereogenic plane. Due to the presence of the 1,1′-binaphthalene moiety in the diyne precursors, diastereomeric pairs are formed featuring an uncommon combination of a stereogenic plane and a stereogenic axis. Intermediate **3** was used in the Sonogashira cross-coupling with a small library of mono-functionalized 1,7-octadiyne derivatives (Scheme 3B).

Diyne **5** was in turn obtained in 40% yield from the Sonogashira coupling between 1,7-octadiyne and iodobenzene (Scheme 3A),[13] while products **6**–**8** were isolated in synthetically useful yields from the coupling reaction between 1,7-octadiyne and the corresponding aryl iodides under copper-free conditions (Scheme 3B). Through the use of different aromatic systems, we aimed to investigate the properties of complexes containing residues with diverse steric and electronic properties, starting from the plain phenyl ring and ranging from the bulky and electron-rich mesityl and 2,6-dimethoxyphenyl groups, to the electron-poor pentafluorophenyl group. The reactions between the common intermediate **3** and compounds **5**–**8** were performed under the same conditions used for the preparation of C_2-symmetric diyne **4**, and resulted in the isolation of products **9**–**12** in good yields (Scheme 3B).

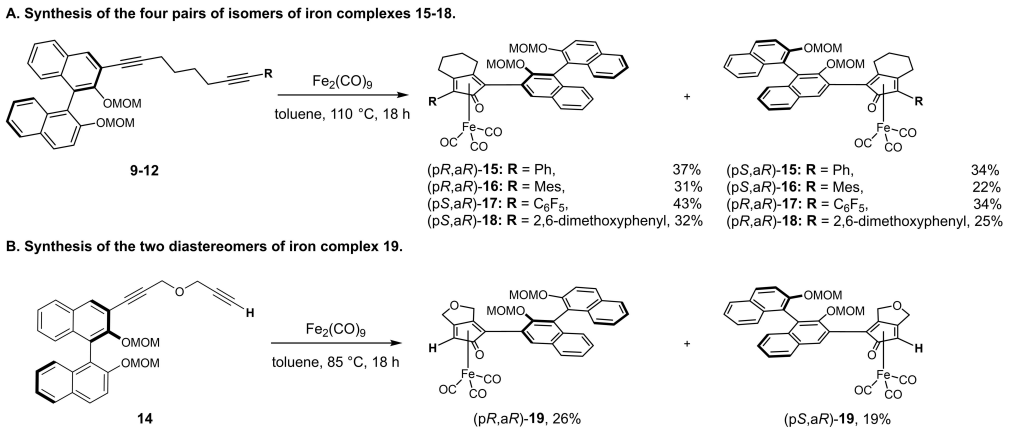
To generate the largest possible difference in hindrance between the position 2 and 5 of the cyclopentadienone ligand,



Scheme 3. A: Synthesis of mono-substituted 1,7-octadiyne derivatives **5**–**8**; B: Synthesis of C_1-symmetric diyne precursors **9**–**12**.



Scheme 4. Synthesis of the diyne functionalized only on one end **13**.



Scheme 5. Carbonylative cyclization/complexation of diynes **9**–**12** and **14**.

we also decided to prepare a diyne with a terminal triple bond. Since the direct coupling between 1,7-octadiyne and one equivalent of iodide **3** led to the mono-functionalization product with poor selectivity, and thus in low yields, we opted for a diyne containing a different tether linking the two triple bonds (compound **14**, Scheme 4). Hence, **3** was treated with propargyl alcohol in the Sonogashira conditions described above, affording compound **13** in 83% yield (Scheme 4). Deprotonation and substitution on propargylic bromide successfully led to product **14**, containing a free terminal alkyne moiety.

The carbonylative cyclization/complexation of diynes **9**–**12** and **14** was performed using $Fe_2(CO)_9$ as iron source and toluene as solvent (Scheme 5).

Formation of the two diastereomers of the desired complexes was observed in all cases, and the separation of each pair was successfully achieved via column chromatography on silica gel. Complexes (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15**[14] were isolated in good yields (37% and 34% respectively), as well as (p*S*,a*R*)-**17** and (p*R*,a*R*)-**17** (43% and 34%). Complexes (p*R*,a*R*)-**16**, (p*S*,a*R*)-**16**, (p*S*,a*R*)-**18** and (p*R*,a*R*)-**18**, containing more electron-rich substituents, were slightly sensitive to air when in solution, but could be nevertheless isolated in >50% yield over the two diastereomers. The preparation of complexes (p*R*,a*R*)-**19** and (p*R*,a*R*)-**19** required a lower reaction temperature of 85 °C and resulted in the isolation of the two isomers in 26% and 19% yield, respectively. Crystals of the second-eluted isomer containing a phenyl ring as substituent (**15**) were grown by slow evaporation of a diethyl ether solution and then subjected to XRD analysis. Structure and diastereoisomeric purity of the complex (Figure 3) were confirmed, and configuration of the stereogenic plane was assigned as *S*, which allowed to identify the compound as (p*S*,a*R*)-**15**.[14]

Slow evaporation of an EtOAc solution of the first-eluted isomer of the pair of complexes without any substituent at C5 (**19**) afforded crystals suitable for XRD analysis. The stereogenic plane was assigned as (*R*)-configured in this case, and the complex was identified as (p*R*,a*R*)-**19** (Figure 4).

While the configuration of the stereoaxis is the same for all the complexes, the configuration of the stereogenic plane had to be determined for each isolated compound. For the attribution we relied mostly on the molecular structures of (p*S*,a*R*)-**15** and (p*R*,a*R*)-**19**, and on the order of elution: for both the pairs of complexes from which we were able to collect X-ray analysis data, the species with a (*R*)-configured plane has a higher R_f value on silica gel, and vice versa a lower R_f is

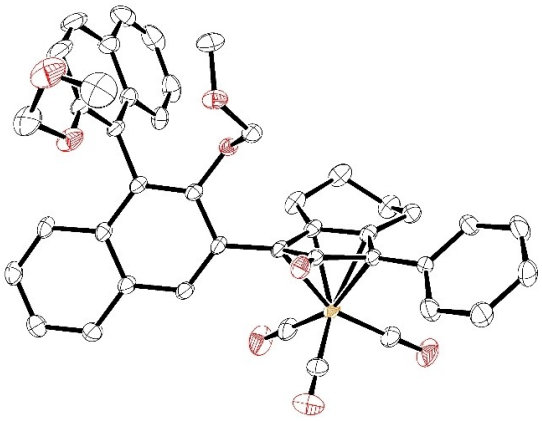


Figure 3. ORTEP representation of the molecular structure of complex (p*S*,a*R*)-**15**. Thermal ellipsoids are represented at the 50% probability level. Color code: C (black), O (red) and Fe (orange).

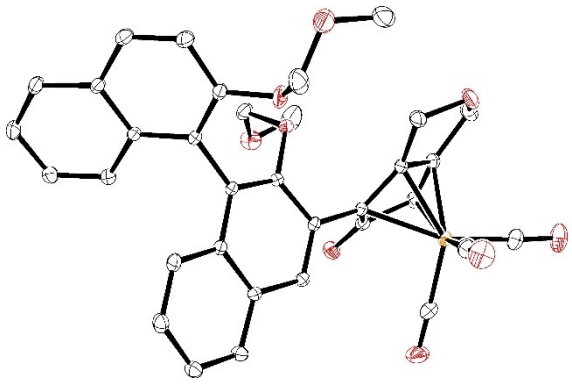


Figure 4. ORTEP representation of the molecular structure of complex (p*R*,a*R*)-**19**. Thermal ellipsoids are represented at the 50% probability level. Color code: C (black), O (red) and Fe (orange).

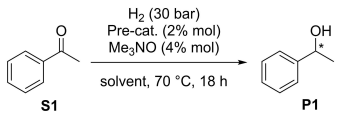
associated to the opposite coordination geometry. Thus, we figured that we could extend the relationship between the absolute configuration of the stereoplane and the order of elution also to the other pairs of diastereomers.[15] Further proof of the validity of the attribution can be found in the pattern of the ^{1}H NMR signals of the MOM groups (see Table S2 in the Supporting Information) and in the stereochemical outcome of the reduction of acetophenone promoted by the new catalysts.

Catalytic activity of the CICs containing C_2-symmetric cyclopentadienone ligands

CICs have found widespread application in the hydrogenation and transfer hydrogenation of polar double bonds such as carbonyls and imines.[16] Several chiral CICs have been prepared, containing stereogenic centers[8b,17] or axes[10] in the cyclopentadienone backbone. In all cases, moderate enantioselectivities were attained both with ketone and imine substrates.

The four new CICs **1a**–**d** were employed in a preliminary test for the enantioselective hydrogenation of acetophenone (Table 1). All the reactions were carried out under 30 bar H_2 pressure at 70 °C, using Me_3NO to activate the pre-catalysts *in situ*.[18] Complex **1a** was initially tested using a 5:2 isopropanol/water solvent mixture, in which only a moderate conversion to 1-phenylethanol was obtained (Table 1, entry 1), probably due to the low solubility of the pre-catalyst. Quantitative conversions were obtained, respectively, in isopropanol and in toluene, where **1a** is soluble (entries 2 and 3). However, the enantiomeric excesses were negligible in all cases. This is not surprising because, as can be seen in the X-ray crystal structure of **1a** (see Figure 2), the pocket around the iron center is almost symmetric, and the steric hindrance is mainly located above the iron atom. Removing the MOM residues resulted in a remarkable decrease in terms of activity: the hydrogenation of acetophenone promoted by pre-catalyst **1b** in isopropanol gave 22% conversion (Table 1, entry 5). Tetra-acylated complexes **1c**–**d** did not afford significantly better results, (*R*)-1-phenylethanol being obtained with very low enantioselectivty (9% *ee* with **1c** – entry 6, and 11% *ee* with **1d** – entry 7).

Table 1. AH of acetophenone (**S1**) catalyzed by complexes **1a**–**d**.[a]



Entry	Pre-cat.	Solvent	Conv. (%)[b]	*ee* (%)[b]
1	**1a**	*i*PrOH/H_2O 5:2	35	<5
2	**1a**	*i*PrOH	99	<5
3	**1a**	Toluene	98	<5
4	**1a**	1,4-Dioxane	91	<5
5	**1b**	*i*PrOH	22	<5
6	**1c**	*i*PrOH	14	9 (*R*)
7	**1d**	*i*PrOH	3	11 (*R*)

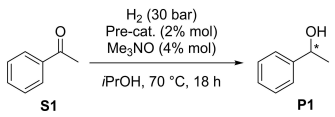
[a] Reaction conditions: **S1**/Pre-cat./Me_3NO = 100:2:4, T = 70 °C, P_{H2} = 30 bar, C_0(**S1**) = 1.43 M. [b] Determined by GC analysis with a chiral capillary column (see the Supporting Information).

Catalytic activity and selectivity of complexes 15–19

Both diastereomers of CICs **15**–**19** were employed in the AH of acetophenone in the best conditions identified for **1a**. The results of the tests are shown in Table 2. Two general aspects of the catalytic activity and selectivity of the new complexes have to be highlighted (Table 2): firstly, the two diastereomers of each complex (having opposite configurations of the stereogenic plane and the same configuration of the stereoaxis) perform similarly in terms of activity. Secondly, the two stereoplane epimers show stereochemical preferences opposite but similar in absolute value: the catalyst isomers with the higher R_f [i.e., (p*R*,a*R*)-**15**, (p*R*,a*R*)-**16**, (p*S*,a*R*)-**17**, (p*S*,a*R*)-**18**, (p*R*,a*R*)-**19**] preferentially form (*R*)-1-phenylethanol, while the complexes with lower R_f ([i.e., (p*S*,a*R*)-**15**, (p*S*,a*R*)-**16**, (p*R*,a*R*)-**17**, (p*R*,a*R*)-**18**, (p*S*,a*R*)-**19**] selectively form (*S*)-1-phenylethanol. Thus, the stereogenic plane seems to play much stronger role than the stereoaxis in determining the stereochemical outcome. Interestingly, assuming the pericyclic outer sphere mechanism commonly accepted for this type of reaction,[19] the product **P1** seems to derive in all cases from a transition state in which the phenyl group is positioned on the same side of the 1,1′-binaphthalene moiety (Figure 5).

The phenyl-substituted complexes (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15** gave almost quantitative conversion of acetophenone, leading to 38% *ee* and 33% *ee* with opposite stereochemical preferences (Table 2, entries 1 and 2).

Table 2. AH of acetophenone (**S1**) catalyzed by the diastereoisomerically pure complexes **15**–**19**.[a]



Entry	Pre-cat.	Conv. (%)[b]	*ee* (%)[b]
1	(p*R*,a*R*)-**15**	98	38 (*R*)
2	(p*S*,a*R*)-**15**	98	33 (*S*)
3	(p*R*,a*R*)-**16**	25	7 (*R*)
4	(p*S*,a*R*)-**16**	18	10 (*S*)
5	(p*S*,a*R*)-**17**	>99	5 (*R*)
6	(p*R*,a*R*)-**17**	>99	5 (*S*)
7	(p*S*,a*R*)-**18**	8	53 (*R*)
8	(p*R*,a*R*)-**18**	2	54 (*S*)
9	(p*R*,a*R*)-**19**	18	39 (*R*)
10	(p*S*,a*R*)-**19**	16	37 (*S*)

[a] Reaction conditions: **S1**/Pre-cat./Me_3NO = 100:2:4, T = 70 °C, P_{H2} = 30 bar, $C_{0,S1}$ = 1.43 M. [b] Determined by GC analysis with a chiral capillary column (see the Supporting Information).

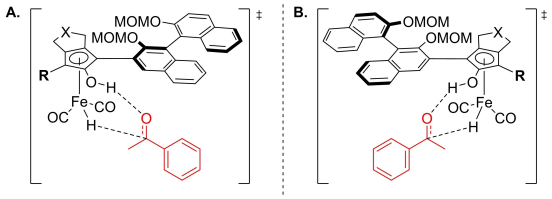


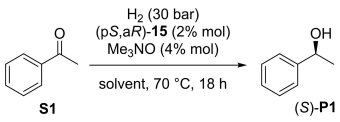
Figure 5. Postulated outer-sphere mechanism of the AH of acetophenone promoted, respectively, by the CIC diastereomers with a higher R_f on silica gel (A), and from those with a lower R_f on silica gel (B).

The two pre-catalysts containing a mesityl group (p*R*,a*R*)-**16** and (p*S*,a*R*)-**16** showed both a lower activity and a lower selectivity in C=O hydrogenation (entries 3 and 4). The presence of a pentafluorophenyl ring imparted a much higher activity to complexes (p*S*,a*R*)-**17** and (p*R*,a*R*)-**17**, but enantioselectivities were negligible (entries 5 and 6). In contrast, the two complexes containing the strongly electron-donor 2,6-dimethoxyphenyl ring promoted the reduction of acetophenone in low conversion but with the highest *ee*'s in the series (53% *ee* towards (*R*)-1-phenylethanol and 54% *ee* towards (*S*)-1-phenylethanol, respectively; entries 7 and 8). Pre-catalysts (p*R*,a*R*)-**19** and (p*S*,a*R*)-**19**, despite showing the largest difference in steric bulk between the two sides of the cyclopentadienone, showed a similar performance to (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15** in terms of selectivity (entries 9 and 10), along with a modest activity.

Conditions optimization and substrate screening with complexes (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15**.

After the first screening performed on the five pairs of diastereoisomerically pure pre-catalysts, we carried out a deeper investigation of pre-catalysts (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15**, which showed the best compromise between activity and selectivity. A solvent screening was performed using the second-eluted isomer of the complex [(p*S*,a*R*)-**15**, Table 3]. Overall, alcohols proved the solvents of choice for the hydrogenation reaction: full conversions to 1-phenylethanol were obtained in both ethanol and isopropanol/water mixture (Table 3, entries 1 and 2), but no improvements were observed in terms of *ee*. Lower conversions and similar *ee*'s were observed in aprotic solvents such as 1,4-dioxane (entry 3), toluene (entry 4) and 1,2-dichloroethane (entry 5).

Table 3. Solvent screening for the AH of acetophenone (**S1**) catalyzed by complex (p*S*,a*R*)-**15**.[a]



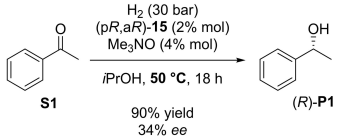
Entry	Solvent	Conv. (%)[b]	*ee* (%)[b]
1	5:2 *i*PrOH/H_2O	>99	33
2	EtOH	>99	30
3	1,4-Dioxane	68	37
4	Toluene	81	32
5	1,2-Dichloroethane	46	32

[a] Reaction conditions: **S1**/Pre-cat./Me_3NO = 100:2:4, T = 70 °C, P_{H2} = 30 bar, $C_{0,S1}$ = 1.43 M. [b] Determined by GC analysis with a chiral capillary column (see Supporting Information).

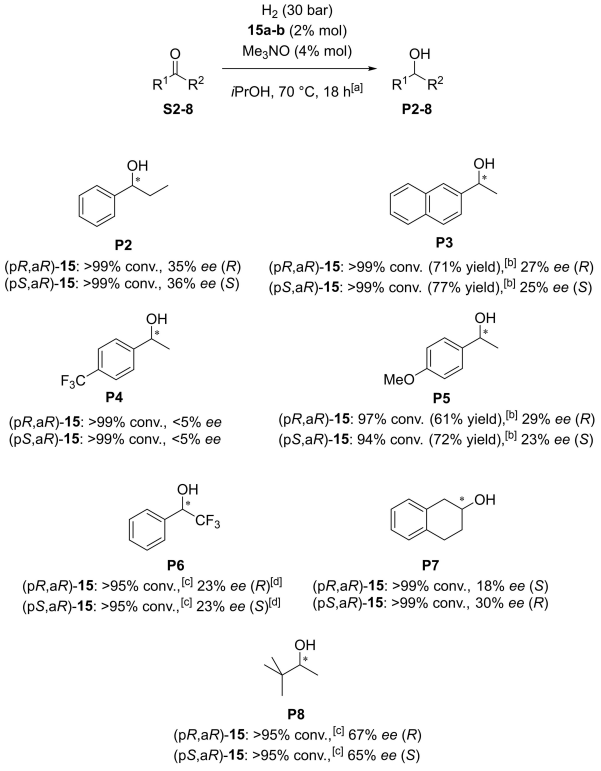
To test the stereochemical outcome was then evaluated by testing pre-catalyst (p*R*,a*R*)-**15** in the AH of acetophenone in isopropanol at 50 °C (Scheme 6).

Acetophenone was reduced to 1-phenylethanol in 90% conversion, but no improvement in terms of *ee* was observed compared to the test run at 70 °C.

With the optimized conditions in hands, we carried out a substrate scope investigation using CICs (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15** as pre-catalysts. Thus, the AH of several pro-chiral ketones was run in isopropanol at 70 °C under 30 bar H_2 pressure (Scheme 7). All substrates, including both alkyl aryl ketones and dialkyl ketones, were quantitatively converted to the corresponding alcohols. ^{1}H-NMR analysis of the crude mixtures recovered from the tests performed on substrates **S3** and **S5**



Scheme 6. Test of the AH of acetophenone (**S1**) promoted by complex (p*R*,a*R*)-**15** at 50 °C.



Scheme 7. Substrate screening for the AH of ketones catalyzed by CICs (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15**. [a] Reaction conditions: Substrate/Pre-cat./Me_3NO = 100:2:4, T = 70 °C, P_{H2} = 30 bar, $C_{0,S1}$ = 1.43 M. Conversions were determined by chiral GC analysis. [b] Yield determined by ^{1}H-NMR analysis. [c] Conversion determined by ^{1}H-NMR analysis. *ee*'s were determined by GC analysis with a chiral capillary column (see Supporting Information). [d] *ee* determined by chiral HPLC analysis.

revealed that, besides the alcohol products **P3** and **P5**, the corresponding symmetric ethers were obtained as byproducts. The mechanism responsible for this transformation is currently under investigation.

The AH of propiophenone (**S2**) occurred with a similar level of stereocontrol compared to acetophenone (35% *ee* towards (*R*)-1-phenylpropanol using pre-catalyst (p*R*,a*R*)-**15**, and 36% *ee* for (*S*)-1-phenylpropanol with (p*S*,a*R*)-**15**). Lower *ee*'s [29% (*R*) and 23% (*S*), respectively] were achieved in the reduction of 2-acetonaphthone (**S3**), with the expected stereochemical relationship between the configuration of the product and that of the pre-catalyst. The hydrogenation of electron-rich 4-methoxyacetophenone (**S5**) led to a similar stereochemical outcome, while negligible enantioselectivity was observed in the AH of 4′-(trifluoromethyl)acetophenone (**S4**). The reduction of 2,2,2-trifluoroacetophenone (**S6**) showed opposite stereochemical outcome compared to other ketones: product (*R*)-**P6** was preferentially formed in the reaction catalyzed by (p*R*,a*R*)-**15**, while (*S*)-**P6** was the major product when (p*S*,a*R*)-**15** was used.[20] The hydrogenation of β-tetralone (**S7**), in contrast with the other tests, showed a matched/mismatched effect: (p*R*,a*R*)-**15** afforded an excess of 18% in the formation of (*S*)-**P7**, while a higher *ee* of 30% towards (*R*)-**P7** was obtained with (p*S*,a*R*)-**15**. Finally, quite expectedly, *tert*-butyl methyl ketone (**S8**) was reduced with the best stereocontrol: 67% *ee* towards (*R*)-**P8** and 65% *ee* towards (*S*)-**P8**.

Conclusions

In this work we have described the synthesis and characterization of several chiral CICs possessing either two (*R*)-BINOL-derived stereogenic axes, or one stereogenic axis combined with a stereogenic plane. The formation of the stereogenic plane occurred upon cyclative complexation of chiral 1,7-diynes affording diastereomeric mixtures which could be separated in all cases by flash column chromatography. Notably, three of the new complexes could be characterized by XRD analysis, which allowed to unambiguously determine their absolute configuration and to propose an assignment of the other CICs of the series based on their elution order in chromatography. The CICs were found active in the hydrogenation of ketones, showing low to moderate enantioselectivity. The complexes possessing a stereogenic plane were found remarkably more stereoselective than those lacking it, and the stereoplane influenced the stereochemical course much more strongly than the stereoaxis. As a consequence, the two stereoaxis-epimers of each catalyst allow to synthesize the two enantiomers of each chiral alcohol with essentially the same *ee*. The two diastereomers of the most effective pre-catalyst were tested with several ketone substrates, showing good catalytic activity and moderate enantioselectivity.

Experimental Section

General information

All reactions were carried out in anhydrous solvents in flame-dried glassware with magnetic stirring under nitrogen or argon atmosphere, unless otherwise stated. Solvents were purchased from commercial suppliers (Sigma Aldrich: THF, DMF, toluene, 1,4-dioxane, CCl_4; Carlo Erba: DCM, THF, toluene) and stored under argon over molecular sieves. Commercially available reagents were purchased from commercial suppliers (TCI Chemicals, Fluorochem, Sigma Aldrich) and were used as received. Known compounds **2**,[11] **3**[12] and **5**[13] were prepared following modified literature procedures (see Supporting Information). The reactions were monitored by analytical thin-layer chromatography (TLC) using silica gel 60 F254 pre-coated glass or aluminum plates (0.25 mm thickness). Visualization was accomplished by irradiation with a UV lamp and/or by treatment with staining agents (potassium permanganate alkaline solution, vanillin/H_2SO_4 ethanolic solution, or phosphomolybdic acid ethanolic solution). Purifications through flash column chromatography were performed using silica gel (60 Å, particle size 40–64 μm) as stationary phase phase, following the procedure by Still and co-workers.[21] ^{1}H-NMR spectra were recorded on a Bruker spectrometer operating at 400 MHz. Proton chemical shifts are reported in ppm (δ) using solvent signal is used as reference ($CDCl_3$ $\delta = 7.26$ ppm; CD_2Cl_2 $\delta = 5.32$ ppm; $(CD_3)_2CO$ $\delta = 2.05$ ppm). The following abbreviations are used to describe spin multiplicity: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br s = broad signal, dd = doublet-doublet, td = triplet-doublet, ddd = doublet-doublet-doublet. Coupling constant values are reported in Hz. ^{13}C-NMR spectra were recorded on a Bruker spectrometer operating at 100 MHz, with complete proton decoupling. Carbon chemical shifts are reported in ppm (δ) using solvent signal is used as reference ($CDCl_3$ $\delta = 77.16$ ppm; CD_2Cl_2 $\delta = 54.00$ ppm; $(CD_3)_2CO$ $\delta = 29.84$ ppm, 206.26 ppm). Infrared spectra were recorded on standard FT/IR spectrometers. Wave numbers were reported in cm^{-1}. Optical rotation values were measured on an automatic polarimeter with a 1 dm cell at the sodium D line ($\lambda = 589$ nm). High resolution mass spectra (HRMS) were recorded on an ESI QTof SYNAPT G2 Si mass spectrometer (Waters), available at the UNITECH-COSPECT laboratories (Università degli Studi di Milano). Melting points were determined on a Büchi B-540 instrument. Single crystal X-ray diffraction (SC-XRD) data were collected with a Bruker Smart APEXII CCD area-detector diffractometer (Mo–Kα, $\lambda = 0.71073$ Å; generator settings: 50 kV, 30 mA). The data reduction was carried out with CrysAlis Pro[22] version 1.171.42.60a using an empirical absorption correction with spherical harmonics (SCALE3 ABSPACK). The structure was solved by dual space methods with SHELXT-2015[23] and refined with SHELXL-2018[24] using the WinGX program suite.[25] The pictures were generated with the program ORTEP-3.[25] Hydrogen atoms, solvent molecules and disorders are omitted for clarity in these representations. Additional crystallographic tables are reported in the Supporting Information.

Deposition Numbers 2280105 (for **1a**), 2280106 (for **15**), 2280107 (for **19**) contain the supplementary crystallographic data for this paper. These data are provided free of charge by the joint Cambridge Crystallographic Data Centre and Fachinformationszentrum Karlsruhe Access Structures service.

Synthesis of diyne 4

Iodide **3** (807 mg, 1.61 mmol, 1 eq) was dissolved in a 1:1 mixture of Et_3N (6.5 mL) and MeCN (6.5 mL). The solution was degassed with a stream of argon, then 1,7-octadiyne (107 μL, 86 mg, 0.81 mmol, 1 eq), CuI (15 mg, 0.08 mmol, 0.1 eq), and $Pd(PPh_3)_4$

(94 mg, 0.08 mmol, 0.1 eq) were added. The mixture was heated to 80 °C for 2 hours. The reaction was allowed to cool down to rt, and volatiles were removed in vacuo. The residue was purified through chromatographic column on silica gel (EtOAc/petroleum ether 1:9). **4** was isolated as a white crystalline solid. Yield: 556 mg (0.65 mmol, 81%). R_f = 0.42 (SiO_2, EtOAc/petroleum ether 1:4). M.p. = 147–149 °C. ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.08 (s, 2H), 7.94 (d, ^3J = 9.0 Hz, 2H), 7.85 (d, ^3J = 8.1 Hz, 2H), 7.78 (d, ^3J = 8.2 Hz, 2H), 7.56 (d, ^3J = 9.0 Hz, 2H), 7.38–7.32 (m, 4H), 7.26–7.13 (m, 8H), 5.13 (d, ^2J = 6.8 Hz, 2H), 4.97 (d, ^2J = 6.2 Hz, 4H), 4.87 (d, ^2J = 5.7 Hz, 2H), 3.14 (s, 6H), 2.61–2.54 (s, 10H), 1.89-1.84 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.9, 134.2, 133.9, 133.5, 130.6, 129.8, 129.8, 127.8, 127.6, 126.8, 126.6, 126.2, 126.1, 125.9, 125.4, 124.2, 120.8, 118.2, 116.8, 98.7, 95.2, 94.1, 78.2, 56.2, 56.0, 28.0, 19.5. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 1616.4, 1592.0, 1507.2, 1259.2, 1242.6, 1152.0, 1073.4, 1034.3, 1013.0, 983.7, 922.6, 896.7, 809.3, 763.5. HRMS (ESI+): *m/z* 873.3391 $[M+Na]^+$ (calculated for $C_{56}H_{50}O_8Na^+$ = 873.3398).

*Procedure for the synthesis of (cyclopentadienone)iron tricarbonyl complexes **1 a**, **15**, **16**, **17**, **18** (General procedure A).*

Diiron nonacarbonyl (2 eq) and the diyne precursor (1 eq) were charged in a flame-dried Schlenk under inert atmosphere. Toluene ($C_{0,diyne}$) = 0.1 M) was added and the mixture was heated to 110 °C for 18 h. The reaction was allowed to cool to room temperature and filtered through celite, rinsing with DCM. The corresponding products were purified through chromatographic column on silica gel.

Complex 1 a

Complex **1 a** was prepared according to General procedure A starting from diyne **4** (610 mg, 0.72 mmol). The product was purified through chromatographic column on silica gel (EtOAc/petroleum ether 1:4 to 3:7). **1 a** was isolated as a yellow crystalline solid. Yield: 466 mg (0.46 mmol, 64%). R_f = 0.39 (SiO_2, EtOAc/petroleum ether 3:7). M.p. = 245–250 °C (dec.). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.08–7.90 (m, 6H), 7.85 (t, ^3J = 9.1 Hz, 2H), 7.62 (d, ^3J = 9.1 Hz, 1H), 7.57 (d, ^3J = 9.0 Hz, 1H), 7.49–7.41 (m, 2H), 7.40–7.19 (m, 10H), 7.17 (d, ^3J = 8.4 Hz, 1H), 5.14–4.97 (m, 4H), 4.69 (d, ^2J = 4.8 Hz, 1H), 4.63 (d, ^2J = 5.0 Hz, 1H), 4.54 (d, ^2J = 4.8 Hz, 1H), 4.40 (d, ^2J = 4.2 Hz, 1H), 3.23 (s, 3H), 3.19 (s, 3H), 3.03–2.81 (m, 2H), 2.53–2.33 (m, 5H), 2.28 (s, 3H), 1.98–1.80 (m, 4H). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 209.2, 171.6, 153.6, 153.0, 152.3, 152.1, 136.2, 136.1, 134.4, 134.3, 134.2, 134.0, 131.2, 131.1, 129.9, 129.8, 129.8, 129.5, 128.4, 128.1, 127.7, 126.9, 126.7, 126.6, 126.6, 126.5, 126.3, 126.2, 126.1, 125.8, 125.4, 125.4, 125.2, 125.0, 124.9, 124.3, 123.9, 121.1, 120.0, 117.1, 115.9, 106.0, 105.2, 99.4, 99.4, 95.5, 94.6, 84.0, 83.8, 56.2, 56.1, 55.8, 22.5, 22.4, 22.3, 22.1. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2060 ($Fe(CO)_3$), 2013 ($Fe(CO)_3$), 1978 ($Fe(CO)_3$), 1731, 1639 (C=O), 1591, 1305.8, 1239.3, 1196.1, 1147.8, 1084.7, 1039.5, 1008.0, 924.1, 901.0, 811.4, 744.2, 722.0. HRMS (ESI+): *m/z* 1019.2739 $[M+H]^+$ (calculated for $C_{60}H_{51}FeO_{12}^+$ = 1019.2724).

Synthesis of complex 1 b

Complex **1 a** (156 mg, 0.15 mmol, 1 eq) was dissolved in THF (1.2 mL). Concentrated aqueous HCl (0.9 mL) was added, and the mixture was heated to 40 °C for 3 hours. The solution was diluted with water (5 mL) and extracted with Et_2O (2×5 mL). The organic phase was dried over Na_2SO_4, filtered, and concentrated in vacuo. The product was purified through chromatographic column on silica gel (EtOAc/petroleum ether 3:7). **1 b** was isolated as a yellow solid. Yield: 100 mg (0.12 mmol, 77%). R_f = 0.36 (SiO_2, EtOAc/petroleum ether 2:3). M.p. = 311–313 °C (dec.). $[\alpha]_D$ = +253.2 (*c* = 0.13 in CH_2Cl_2). ^{1}H-NMR (400 MHz, $(CD_3)_2CO$) δ [ppm] = 9.72 (s, 1H), 9.41 (s, 1H), 8.30 (d, ^3J = 10.9 Hz, 2H), 8.01–7.82 (m, 8H), 7.42–7.15 (m, 10H), 7.15–7.01 (m, 4H), 3.24–3.09 (m, 1H), 3.04–2.90 (m, 3H), 2.17–1.88 (m, 4H). ^{13}C-NMR (100 MHz, $(CD_3)_2CO$) δ [ppm] = 209.9, 166.9, 154.7, 154.3, 154.3, 153.7, 135.7, 135.7, 135.7, 135.6, 133.5, 132.6, 130.8, 130.5, 130.2, 130.1, 129.5, 129.5, 129.3, 129.1, 129.0, 127.9, 127.8, 127.3, 127.1, 125.7, 125.6, 125.5, 124.5, 124.5, 123.8, 123.7, 122.2, 121.6, 119.7, 119.6, 118.4, 117.9, 116.1, 115.5, 104.9, 102.4, 85.4, 83.9, 25.3, 24.2, 23.2, 23.1. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2853, 2074 ($Fe(CO)_3$), 2019 ($Fe(CO)_3$), 1620 (C=O), 1596, 1512, 1500, 1345, 1210, 1148, 817, 749, 722. MS (ESI+): *m/z* = 843.00 $[M+H]^+$, 864.95 $[M+Na]^+$ (calculated for $C_{52}H_{35}FeO_8^+$ = 843.17, $C_{52}H_{35}FeO_8Na^+$ = 865.15). HRMS (ESI−): *m/z* = 841.1522 $[M-H]^-$ (calculated for $C_{52}H_{33}FeO_8^-$ = 841.1530).

Synthesis of complex 1 c

Complex **1 b** (30 mg, 0.036 mmol, 1 eq) was dissolved in dry THF (0.7 mL). 4-dimethylaminopyridine (0.9 mg, 0.007 mmol, 0.2 eq), triethylamine (40 μL, 29 mg, 0.29 mmol, 8 eq), and acetyl chloride (15 μL, 17 mg, 0.21 mmol, 6 eq) were added. The mixture was stirred at room temperature for 4 hours. The reaction was quenched with water (5 mL) and extracted with Et_2O (2×5 mL). The organic phase was washed with a 0.5 M HCl solution (5 mL), water (5 mL), and brine, then dried over Na_2SO_4, filtered, and concentrated in vacuo. The product was purified through chromatographic column on silica gel (EtOAc/petroleum ether 3:7). **1 c** was isolated as a pale-yellow solid. Yield: 24.8 mg (0.024 mmol, 68%). R_f = 0.29 (SiO_2, EtOAc/petroleum ether 3:7). M.p. = 180 °C (dec.). $[\alpha]_D$ = +25.4 (*c* = 0.05 in CH_2Cl_2). ^{1}H-NMR (400 MHz, $(CD_3)_2CO$) δ [ppm] = 8.24 (s, 1H), 8.22–8.13 (m, 3H), 8.13–8.04 (m, 2H), 8.04–7.95 (m, 2H), 7.62–7.42 (m, 6H), 7.40–7.26 (m, 2H), 7.26–7.18 (m, 2H), 7.09 (d, ^3J = 8.4 Hz, 1H), 7.03 (d, ^3J = 8.4 Hz, 1H), 3.04–2.88 (m, 1H), 2.69–2.43 (m, 3H), 2.02–1.73 (m, 4H), 1.94 (s, 3H), 1.90 (s, 3H), 1.66 (s, 3H), 1.60 (s, 3H). ^{13}C-NMR (100 MHz, $(CD_3)_2CO$) δ [ppm] = 210.4, 171.2, 170.1, 169.5, 169.3, 168.3, 148.1, 148.0, 147.8, 147.5, 136.7, 136.0, 134.4, 134.2, 134.1, 132.7, 132.6, 132.6, 132.5, 130.7, 130.4, 129.4, 129.3, 129.1, 129.0, 128.2, 128.2, 127.8, 127.8, 127.6, 127.3, 127.3, 127.2, 126.9, 126.7, 126.6, 126.2, 125.5, 125.4, 124.2, 123.7, 123.7, 123.2, 105.2, 103.7, 84.3, 83.4, 24.0, 23.2, 23.2, 22.8, 21.1, 20.9, 20.8, 20.6. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2064 ($Fe(CO)_3$), 2007 ($Fe(CO)_3$), 1987 ($Fe(CO)_3$), 1762, 1654 (C=O), 1194.

Synthesis of complex 1 d

Complex **1 b** (39 mg, 0.046 mmol, 1 eq) was dissolved in dry THF (1.2 mL). 4-dimethylaminopyridine (1.1 mg, 0.009 mmol, 0.2 eq), triethylamine (52 μL, 38 mg, 0.37 mmol, 8 eq), and benzoyl chloride (32 μL, 39 mg, 0.28 mmol, 6 eq) were added. The mixture was stirred at room temperature for 4 hours. The reaction was quenched with water (5 mL) and extracted with Et_2O (2×5 mL). The organic phase was washed with a 0.5 M HCl solution (5 mL), water (5 mL), and brine, then dried over Na_2SO_4, filtered, and concentrated under reduced pressure. The product was purified through chromatographic column on silica gel (EtOAc/petroleum ether 1:3). **1 d** was isolated as a yellow solid. Yield: 24.8 mg (0.024 mmol, 68%). R_f = 0.51 (SiO_2, EtOAc/petroleum ether 3:7). M.p. = 176–182 °C (dec.). $[\alpha]_D$ = −32.8 (*c* = 0.21 in CH_2Cl_2). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.02–7.69 (m, 12H), 7.54–7.21 (m, 26H), 7.08 (dd, ^3J = 7.6 Hz, 2H), 6.99 (dd, ^3J = 7.1 Hz, 2H), 2.48 (ddd, ^3J = 17.1 Hz, ^3J = ^2J = 6.6 Hz, 1H), 2.39–2.25 (m, 2H), 2.03–1.89 (m, 1H), 1.75–1.60 (m, 1H), 1.54–1.39 (m, 2H), 1.39–1.29 (m, 1H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 209.3, 169.7, 165.4, 165.3, 165.1, 164.3, 147.7, 147.6, 147.1, 135.8 (br s), 134.6 (br s), 133.9, 133.8, 133.8, 133.7, 133.6, 133.6, 133.5, 132.1, 132.0, 131.8, 130.8, 130.4, 130.3, 130.1, 130.1, 130.1, 129.9, 129.6, 129.4, 129.3, 129.1, 129.0, 128.9, 128.8, 128.7, 128.6,

128.5, 128.5, 128.4, 128.3, 127.8, 127.7, 127.3, 127.2, 127.0, 126.7, 126.6, 126.4, 126.2, 126.1, 125.8, 125.8, 124.9, 124.5, 124.1, 124.0, 122.2, 122.1, 83.5, 83.2, 23.7, 22.8, 22.6, 22.0. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2066 ($Fe(CO)_3$), 2011 ($Fe(CO)_3$), 1991 ($Fe(CO)_3$), 1738, 1654 (C=O), 1600, 1263, 1212, 1177, 1079, 1063, 1022, 707. HRMS (ESI+): *m/z* = 1259.2717 $[M+H]^+$, *m/z* = 1281.2535 $[M+Na]^+$ (calculated for $C_{80}H_{51}FeO_{12}^+$ = 1259.2724, $C_{80}H_{50}FeO_{12}Na^+$ = 1281.2544).

Procedure for the synthesis of diynes 6, 7, 8 (General procedure B)

1,7-Octadiyne (3 eq) and the aryl iodide substrate (1 eq) were dissolved in dry 1,4-dioxane (C_0(iodide) = 0.075 M). Cs_2CO_3 (4 eq) was added, and the suspension was degassed with an argon stream. SPhos (0.1 eq), and $Pd(OAc)_2$ (0.05 eq) were added. The reaction mixture was heated to 100 °C for 4 hours. The reaction was allowed to cool to room temperature, and filtered through celite, rinsing with DCM. The corresponding products were purified through chromatographic column on silica gel.

Diyne 6

Diyne **6** was prepared according to General procedure B starting from iodomesitylene (150 mg, 0.61 mmol). The product was purified through chromatographic column (DCM/petroleum ether 1:9). **6** was isolated as a yellowish oil. Yield: 89 mg (0.397 mmol, 65%). R_f = 0.53 (SiO_2, DCM/petroleum ether 1:9). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 6.84 (s, 2H), 2.57–2.50 (m, 2H), 2.37 (s, 6H), 2.31–2.22 (m, 2H), 2.25 (s, 3H), 1.96 (t, ^4J = 2.6 Hz, 1H), 1.79–1.72 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 140.0, 136.9, 127.6, 120.8, 97.3, 84.3, 78.7, 68.6, 28.1, 27.7, 21.4, 21.2, 19.3, 18.1. HRMS (ESI+): *m/z* = 224.1573 $[M+H]^+$ (calculated for $C_{17}H_{21}^+$ = 224.1565).

Diyne 7

Diyne **7** was prepared according to General procedure B starting from iodopentafluorobenzene (133 μL, 294 mg, 1.00 mmol). The product was purified through chromatographic column (DCM/petroleum ether 1:15). **7** was isolated as a colorless liquid. Yield: 128 mg (0.47 mmol, 47%). R_f = 0.48 (SiO_2, DCM/petroleum ether 1:15). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 2.54 (t, ^3J = 6.6 Hz, 2H), 2.26 (td, ^3J = 6.5 Hz, ^4J = 2.3 Hz, 2H), 1.97 (t, ^4J = 2.4 Hz, 1H), 1.86-1.62 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 149.1–146.1, 142.7–139.5, 139.2–136.2, 103.6–103.3, 101.0–100.0, 84.0, 68.8, 65.4–65.0, 27.5, 27.2, 19.5, 18.1. ^{19}F-NMR (377 MHz, $CDCl_3$) δ [ppm] = −136.99–−137.26 (m, 2F), −154.20 (t, ^3J = 20.8 Hz, 1F), −162.33–−162.51 (m, 2F). IR (neat): $\tilde{\nu}$ [cm^{-1}] = 2949.4, 2868.0, 2666.2, 2438.1, 2247.9, 2119.2, 1737.3, 1649.4, 1626.7, 1518.6, 1496.9, 1459.7, 1430.5, 1374.2, 1320.7, 1273.9, 1176.6, 1148.5, 1048.7, 989.4, 923.1, 838.3, 816.9, 793.2.

Diyne 8

Diyne **8** was prepared according to General procedure B starting from 2-iodo-1,3-dimethoxybenzene (200 mg, 0.757 mmol). The product was purified through chromatographic column (DCM/petroleum ether 1:4 to 2:3). **8** was isolated as a yellowish oil. Yield: 101 mg (0.417 mmol, 55%). R_f = 0.15 (SiO_2, DCM/petroleum ether 1:4). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 7.17 (t, ^3J = 8.4 Hz, 1H), 6.51 (d, ^3J = 8.4 Hz, 2H), 3.87 (s, 6H), 2.60–2.54 (m, 2H), 2.33–2.21 (m, 2H), 1.95 (t, ^4J = 2.6 Hz, 1H), 1.86–1.69 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 161.6, 128.9, 103.6, 98.6, 84.6, 73.1, 68.4, 56.2, 27.9, 27.7, 19.8, 18.2. IR (neat): $\tilde{\nu}$ [cm^{-1}] = 3286.4, 3003.1, 2933.3, 2837.8, 2538.8, 2229.8, 2188.7, 2115.2, 1927.2, 1713.6, 1583.5, 1473.9, 1432.2, 1329.1, 1300.8, 1252.7, 1173.5, 1110.6, 1033.3, 958.4, 902.2, 776.9, 725.8. HRMS (ESI+): *m/z* 243.1358 $[M+H]^+$, 265.1205 $[M+Na]^+$ (calculated for $C_{16}H_{19}O_2^+$ = 243.1358, $C_{16}H_{18}O_2Na^+$ = 265.1204).

*Procedure for the coupling of iodide **3** with diynes **5**, **6**, **7**, **8** (General procedure C).*

Iodide **3** (1 eq) and the mono-substituted diyne substrate (1 eq) were dissolved in a 1:1 mixture of MeCN and triethylamine (C_0(3): 0.1 M). The solution was degassed with a stream of argon. CuI (0.1 eq) and $Pd(PPh_3)_4$ (0.05 eq) were added, and the reaction was heated to 80 °C for 2 hours. Volatiles were removed and the crude was suspended in a saturated solution of NH_4Cl. The residue was extracted with DCM. The collected organic layers were washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The corresponding products were purified through chromatographic column on silica gel.

Diyne 9

Diyne **9** was prepared according to General procedure C starting from mono-substituted diyne **5** (55 mg, 0.30 mmol). **9** was isolated through chromatographic column on silica gel (EtOAc/petroleum ether 1:9 to 1:4) as a thick yellow oil. Yield: 125 mg (0.23 mmol, 75%). R_f = 0.61 (SiO_2, EtOAc/ petroleum ether 1:4). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.09 (s, 1H), 7.95 (d, ^3J = 9.0 Hz, 1H), 7.85 (d, ^3J = 8.2 Hz, 1H), 7.81 (d, ^3J = 8.2 Hz, 1H), 7.57 (d, ^3J = 9.0 Hz, 1H), 7.43–7.31 (m, 4H), 7.31–7.23 (m, 4H), 7.23–7.13 (m, 3H), 5.14 (d, ^2J = 6.9 Hz, 1H), 4.99 (d, ^2J = 7.0 Hz, 1H), 4.99 (d, ^2J = 5.7 Hz, 1H), 4.88 (d, ^2J = 5.7 Hz, 1H), 3.16 (s, 3H), 2.57 (s, 3H), 2.62–2.53 (m, 2H), 2.53–2.46 (m, 2H), 1.94–1.75 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.9, 134.2, 133.9, 133.5, 131.7, 130.6, 129.8, 129.8, 128.3, 127.8, 127.7, 127.6, 126.8, 126.6, 126.2, 126.1, 126.0, 125.4, 124.2, 124.1, 120.8, 118.2, 116.9, 98.7, 95.2, 94.2, 89.9, 81.2, 78.2, 56.2, 56.0, 28.1, 28.0, 19.5, 19.2. HRMS (ESI+): *m/z* 577.2355 $[M+Na]^+$ (calcd. for $C_{38}H_{34}NaO_4^+$: 577.2355).

Diyne 10

Diyne **10** was prepared according to general procedure C starting from mono-substituted diyne **6** (80 mg, 0.36 mmol). 87 was isolated through chromatographic column on silica gel (EtOAc/petroleum ether 1:9) as a yellow oil. Yield: 139 mg (0.233 mmol, 65%). R_f = 0.71 (SiO_2, EtOAc/petroleum ether 1:4). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.07 (s, 1H), 7.94 (d, ^3J = 9.1 Hz, 1H), 7.85 (d, ^3J = 8.1 Hz, 1H), 7.80 (d, ^3J = 8.1 Hz, 1H), 7.57 (d, ^3J = 9.0 Hz, 1H), 7.41–7.31 (m, 2H), 7.30–7.12 (m, 4H), 6.83 (s, 2H), 5.14 (d, ^2J = 6.9 Hz, 1H), 5.02–4.93 (m, 2H), 4.87 (d, ^2J = 5.7 Hz, 1H), 3.15 (s, 3H), 2.63–2.50 (m, 7H), 2.37 (s, 6H), 2.25 (s, 3H), 1.93–1.77 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.9, 140.0, 136.9, 134.2, 133.9, 133.5, 130.6, 129.8, 129.8, 127.8, 127.6, 127.6, 126.2, 126.1, 126.0, 125.4, 124.2, 120.9, 120.8, 118.3, 116.9, 98.7, 97.4, 95.2, 94.3, 78.8, 78.1, 56.2, 56.0, 28.4, 28.0, 21.4, 21.2, 19.5, 19.4. HRMS (ESI+): *m/z* = 619.2817 $[M+Na]^+$ (calculated for $C_{41}H_{40}O_4Na^+$: 619.2819).

Diyne 11

Diyne **11** was prepared according to general procedure C starting from mono-substituted diyne **7** (56 mg, 0.21 mmol). was isolated through chromatographic column on silica gel (EtOAc/n-hexane 1:9) as a yellow oil. Yield: 102 mg (0.16 mmol, 77%). R_f = 0.26 (SiO_2, EtOAc/petroleum ether 1:9). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.08 (s, 1H), 7.94 (d, ^3J = 9.0 Hz, 1H), 7.85 (d, ^3J = 8.1 Hz, 1H), 7.81 (d, ^3J = 8.2 Hz, 1H), 7.57 (d, ^3J = 9.0 Hz, 1H), 7.42–7.30 (m, 2H), 7.30–7.11 (m, 4H), 5.14 (d, ^2J = 6.9 Hz, 1H), 5.03–4.93 (m, 2H), 4.86 (d, ^2J = 5.7 Hz, 1H), 3.15 (s, 3H), 2.65–2.50 (m, 4H), 2.57 (s, 3H), 1.94–1.74 (m,

4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.9, 149.0–146.2, 142.7–139.5, 139.2–136.2, 134.2, 133.9, 133.5, 130.6, 129.8, 129.8, 127.9, 127.6, 126.8, 126.6, 126.2, 126.1, 125.9, 125.4, 124.2, 120.8, 118.1, 116.9, 103.6–103.4, 100.9–100.4, 98.7, 95.2, 93.8, 78.3, 65.4–65.2, 56.2, 56.0, 27.8, 27.5, 19.5, 19.4. ^{19}F-NMR (377 MHz, $CDCl_3$) δ [ppm] = −136.95–137.13 (m, 2F), −154.18 (t, 3 J = 20.8 Hz, 1F), −162.27–162.51 (m, 2F). IR (neat): $\tilde{\nu}$ [cm^{-1}] = 1612.8, 1594.0, 1334.7, 1260.8, 1241.9, 1214.8, 1155.7, 1069.8, 1033.8, 1014.3, 976.5, 923.1, 809.1, 761.2, 691.1. HRMS (ESI+): m/z 667.1884 $[M+Na]^+$ (calculated for $C_{38}H_{29}O_4NaF_5^+$ = 667.1884).

Diyne 12

Diyne **12** was prepared according to General procedure C starting from mono-substituted diyne **8** (77 mg, 0.32 mmol). 89 was isolated through chromatographic column on silica gel (EtOAc/ petroleum ether 1:4 to 3:7) as a yellow solid. Yield: 152 mg (0.247 mmol, 78%). R_f = 0.39 (SiO_2, EtOAc/petroleum ether 1:4). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.07 (s, 1H), 7.94 (d, ^3J = 9.1 Hz, 1H), 7.85 (d, ^3J = 8.1 Hz, 1H), 7.80 (d, ^3J = 8.2 Hz, 1H), 7.57 (d, ^3J = 9.0 Hz, 1H), 7.41–7.30 (m, 2H), 7.30–7.10 (m, 5H), 6.51 (d, ^3J = 8.4 Hz, 2H), 5.14 (d, ^2J = 6.9 Hz, 1H), 5.01–4.94 (m, 2H), 4.87 (d, ^2J = 5.8 Hz, 1H), 3.86 (s, 6H), 3.16 (s, 3H), 2.68–2.51 (m, 4H), 2.56 (s, 3H), 1.97–1.79 (m, 4H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 161.6, 153.1, 153.0, 134.2, 133.9, 133.5, 130.6, 129.8, 128.9, 127.8, 127.6, 127.8, 127.6, 126.8, 126.6, 126.1, 126.0, 125.3, 124.2, 120.9, 118.3, 116.9, 103.6, 98.7, 98.6, 95.2, 94.6, 78.0, 73.2, 56.2, 56.2, 56.0, 28.2, 27.9, 19.9, 19.6. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 3058.4, 3007.4, 2934.7, 2836.7, 2227.0, 2191.1, 1711.5, 1622.1, 1529.6, 1584.1, 1473.4, 1432.3, 1393.1, 1357.7, 1334.5, 1301.7, 1253.8, 1217.2, 1199.4, 1155.8, 1112.6, 1071.3, 1033.9, 1014.3, 978.5, 923.5, 904.9, 810.9, 752.9, 725.3. HRMS (ESI+): m/z 637.2565 $[M+Na]^+$ (calculated for $C_{40}H_{38}O_6Na^+$ = 637.2566).

Synthesis of compound 13

Iodide **3** (500 mg, 1.00 mmol, 1 eq) was dissolved in a 1:1 mixture of MeCN (5 mL) and triethylamine (5 mL). The solution was degassed with a stream of argon. CuI (19 mg, 0.10 mmol, 0.1 eq), $Pd(PPh_3)_4$ (115 mg, 0.10 mmol, 0.1 eq), and propargyl alcohol (116 μL, 112 mg, 2.00 mmol, 2 eq) were added. The reaction was heated to 80 °C for 2 hours. Volatiles were removed in vacuo, and the residue was suspended in a saturated solution of NH_4Cl (15 mL). The residue was extracted with DCM (2×15 mL). The organic layer was washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The product was purified through chromatographic column on silica gel (EtOAc/petroleum ether 2:3). **13** was isolated as a pale-yellow solid. Yield: 355 mg (0.83 mmol, 83%). M.p. = 109–110 °C. R_f = 0.41 (SiO_2, EtOAc/ petroleum ether 2:3). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.12 (s, 1H), 7.96 (d, ^3J = 9.0 Hz, 1H), 7.89–7.80 (m, 2H), 7.58 (d, ^3J = 9.0 Hz, 1H), 7.44–7.32 (m, 2H), 7.30–7.22 (m, 2H), 7.20–7.13 (m, 2H), 5.14 (d, ^2J = 6.9 Hz, 1H), 5.00 (d, ^2J = 6.9 Hz, 1H), 4.90 (d, ^2J = 5.6 Hz, 1H), 4.82 (d, ^2J = 5.6 Hz, 1H), 4.55 (d, ^3J = 3.5 Hz, 2H), 3.16 (s, 3H), 2.71 (s, 3H), 1.91 (br s, 1H, OH). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.8, 134.2, 134.1, 134.0, 130.5, 130.0, 129.8, 127.9, 127.9, 127.3, 126.8, 126.4, 126.2, 125.7, 125.6, 124.3, 120.4, 117.0, 116.8, 99.0, 95.2, 91.5, 83.1, 56.5, 56.1, 52.0. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 3417.4, 2226.9, 1621.7, 1593.5, 1261.1, 1241.7, 1214.9, 1154.5, 1120.5, 1068.4, 1032.7, 1013.7, 974.0, 921.3, 864.4, 809.5, 761.4.

Synthesis of diyne 14

NaH (60% in mineral oil, 16.6 mg, 0.693 mmol, 1.5 eq) was suspended in THF (3 mL). **13** (198 mg, 0.462 mmol, 1 eq) was dissolved in THF (1.6 mL), and the solution was slowly added to the suspension of NaH under argon atmosphere at 0 °C. The mixture was left for 0.5 hours at rt. Propargyl bromide (80% in toluene, 77 μL, 82.5 mg, 0.693 mmol, 1.5 eq) was added at 0 °C. The mixture was left under stirring for 3 hours at rt. The reaction was quenched with sat. aq. NH_4Cl (10 mL). The crude was extracted with EtOAc (3×10 mL). The collected organic layers were washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The product was purified through chromatographic column on silica gel (EtOAc/ n-hexane 1:9 to 1:4). **14** was isolated as a thick yellow oil. Yield: 188 mg (0.40 mmol, 87%). R_f = 0.56 (SiO_2, EtOAc/petroleum ether 1:4). ^{1}H-NMR (400 MHz, $CDCl_3$) δ [ppm] = 8.14 (s, 1H), 7.96 (d, ^3J = 9.1 Hz, 1H), 7.89–7.80 (m, 2H), 7.58 (d, ^3J = 9.1 Hz, 1H), 7.48–7.31 (m, 2H), 7.31–7.20 (m, 2H), 7.20–7.13 (m, 2H), 5.14 (d, ^2J = 6.9 Hz, 1H), 5.00 (d, ^2J = 6.9 Hz, 1H), 4.93 (d, ^2J = 5.7 Hz, 1H), 4.82 (d, ^2J = 5.7 Hz, 1H), 4.57 (s, 2H), 4.37 (d, ^4J = 2.3 Hz, 2H), 3.16 (s, 3H), 2.66 (s, 3H), 2.47 (t, ^4J = 2.3 Hz, 1H). ^{13}C-NMR (100 MHz, $CDCl_3$) δ [ppm] = 153.1, 152.9, 134.5, 134.1, 134.1, 130.5, 130.0, 129.8, 127.9, 127.9, 127.3, 126.8, 126.4, 126.2, 125.8, 125.6, 124.3, 120.4, 116.9, 116.7, 99.0, 95.2, 88.2, 84.3, 79.1, 75.2, 57.6, 56.7, 56.4, 56.1. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 3286.5, 3058.6, 2945.5, 2853.1, 2225.1, 2116.7, 1738.6, 1621.9, 1594.1, 1508.8, 1469.9, 1428.0, 1393.3, 1357.2, 1242.5, 1156.1, 1077.6, 1033.6, 1014.0, 979.5, 923.0, 810.3, 751.6. HRMS (ESI+): m/z 489.1676 $[M+Na]^+$ (calculated for $C_{30}H_{26}O_5Na^+$ = 489.1672).

Complexes (pR,aR)-15 and (pS,aR)-15

Iron complexes (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15** were prepared according to General procedure A, starting from diyne **9** (125 mg, 0.225 mmol). (p*R*,a*R*)-**15** and (p*S*,a*R*)-**15** were isolated through chromatographic column on silica gel (Et_2O/*n*-hexane 1:1 to 3:2) as yellow solids.

(pR,aR)-**15**. Yield: 59 mg (0.082 mmol, 36%). M.p. = 112–114 °C. R_f = 0.34 (SiO_2, Et_2O/petroleum ether 3:2). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.03–7.97 (m, 2H), 7.94–7.87 (m, 2H), 7.77–7.72 (m, 2H), 7.63 (d, ^3J = 9.1 Hz, 1H), 7.50–7.44 (m, 1H), 7.44–7.31 (m, 4H), 7.31–7.22 (m, 2H), 7.19 (d, ^3J = 8.5 Hz, 1H), 7.13 (d, ^3J = 8.5 Hz, 1H), 5.14–5.08 (m, 2H), 4.50 (d, ^2J = 5.1 Hz, 1H), 4.34 (d, ^2J = 5.1 Hz, 1H), 3.24 (s, 3H), 2.95–2.78 (m, 2H), 2.78–2.65 (m, 1H), 2.72 (s, 3H), 2.39 (ddd, ^3J = 17.0 Hz, ^3J = ^2J = 5.3 Hz, 1H), 2.01–1.80 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 209.8, 171.4, 153.5, 153.1, 153.9, 134.7, 134.7, 132.3, 131.5, 130.5, 130.3, 130.2, 129.0, 128.7, 128.5, 128.5, 127.4, 127.3, 126.6, 126.4, 126.3, 125.9, 125.7, 124.7, 120.9, 117.4, 105.3, 101.8, 99.9, 95.9, 85.7, 81.2, 56.7, 56.2, 24.0, 23.2, 22.9, 22.6. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2059.7 ($Fe(CO)_3$), 1984.9 ($Fe(CO)_3$), 1639.7 (C=O), 1592.6, 1240.9, 1197.8, 1148.4, 1074.8, 1034.1, 1013.7, 965.6, 925.0, 749.7, 721.5. HRMS (ESI+): m/z 723.1678 $[M+H]^+$, 745.1500 $[M+Na]^+$ (calculated for $C_{42}H_{35}FeO_8^+$ = 723.1676, $C_{42}H_{34}FeO_8Na^+$ = 745.1495).

(*pS,aR*)-**15**. Yield: 56 mg (0.077 mmol, 34%). M.p. = 105–110 °C. R_f = 0.21 (SiO_2, Et_2O/petroleum ether 3:2). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.05–7.97 (m, 2H), 7.95–7.89 (m, 2H), 7.78–7.72 (m, 2H), 7.67 (d, ^3J = 9.1 Hz, 1H), 7.50–7.45 (m, 1H), 7.45–7.27 (m, 6H), 7.24 (d, ^3J = 8.5 Hz, 1H), 7.15 (d, ^3J = 8.5 Hz, 1H), 5.19 (d, ^2J = 7.1 Hz, 1H), 5.10 (d, ^2J = 7.1 Hz, 1H), 4.69 (d, ^2J = 5.1 Hz, 1H), 4.53 (d, ^2J = 5.1 Hz, 1H), 3.25 (s, 3H), 2.91–2.76 (m, 3H), 2.87 (s, 3H), 2.76–2.65 (m, 1H), 2.48–2.36 (m, 1H), 2.00–1.78 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 209.8, 171.6, 153.8, 152.8, 136.1, 134.6, 134.3, 132.3, 131.6, 130.6, 130.2, 130.2, 129.0, 128.8, 128.7, 128.5, 127.4, 127.2, 126.9, 126.0, 126.0, 125.7, 125.4, 124.6, 120.2, 116.4, 105.5, 101.9, 100.0, 95.2, 85.5 (s, 1 C), 81.2, 57.0, 56.6, 23.8, 23.2, 22.9, 22.6. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2059.5 ($Fe(CO)_3$), 1984.9 ($Fe(CO)_3$), 1640.5 (C=O), 1592.6, 1258.8, 1241.4, 1197.7, 1148.1, 1062.3, 1032.9, 1012.1, 964.8, 924.2, 749.7, 721.0. HRMS (ESI+): m/z 723.1677 $[M+H]^+$, 745.1500 $[M+Na]^+$ (calculated for $C_{42}H_{35}FeO_8^+$ = 723.1676, $C_{42}H_{34}FeO_8Na^+$ = 745.1495).

Complexes (pR,aR)-16 and (pS,aR)-16

Iron complexes (p*R*,a*R*)-**16** and (p*S*,a*R*)-**16** were prepared according to General procedure A, starting from diyne **10** (112 mg, 0.19 mmol). (p*R*,a*R*)-**16** and (p*S*,a*R*)-**16** were isolated through chromatographic column on silica gel (Et_2O/*n*-hexane 2:3 to 3:2) as yellow solids.

*(pR,aR)-**16***. Yield: 45 mg (0.058 mmol, 31 %). M.p. = 234–236 °C. $[\alpha]_D = +56.4$ ($c = 0.02$ in CH_2Cl_2). $R_f = 0.30$ (SiO_2, EtOAc/petroleum ether 1:4). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 7.99 (d, $^3J = 9.2$ Hz, 2H), 7.93 (s, 1H), 7.89 (d, $^3J = 8.2$ Hz, 1H), 7.62 (d, $^3J = 9.0$ Hz, 1H), 7.46 (t, $^3J = 7.4$ Hz, 1H), 7.37 (t, $^3J = 7.3$ Hz, 1H), 7.32–7.16 (m, 3H), 7.12 (d, $^3J = 8.5$ Hz, 1H), 6.98 (s, 1H), 6.94 (s, 1H), 5.10 (s, 2H), 4.59 (d, $^2J = 4.8$ Hz, 1H), 4.35 (d, $^2J = 4.7$ Hz, 1H), 3.23 (s, 3H), 3.04–2.91 (m, 1H), 2.62 (s, 3H), 2.47–2.35 (m, 4H), 2.34–2.21 (m, 5H), 2.11 (s, 3H), 2.00–1.73 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 210.2, 171.0, 153.7, 152.6, 138.6, 138.2, 137.2, 136.1, 131.4, 130.4, 130.3, 129.8, 128.7, 128.3, 127.3, 127.1, 126.8, 126.6, 126.5, 126.4, 125.9, 125.7, 124.7, 121.2, 117.5, 105.5, 103.0, 99.8, 96.1, 86.4, 85.6, 56.4, 56.2, 23.3, 23.2, 23.2, 23.1, 22.9, 21.4, 21.1. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2060.8 ($Fe(CO)_3$), 2008.4 ($Fe(CO)_3$), 1987.5 ($Fe(CO)_3$), 1644.0 (C=O), 1240.5, 1151.4, 1084.4, 1035.9, 1014.8, 969.9, 925.6, 721.5. HRMS (ESI$^+$): *m/z* 765.2145 $[M+H]^+$, 787.1967 $[M+Na]^+$ (calculated for $C_{45}H_{41}FeO_8^+ = 765.2145$, $C_{45}H_{40}FeO_8Na^+ = 787.1965$).

*(pS,aR)-**16***. Yield: 32 mg (0.041 mmol, 22 %). M.p. = 194–198 °C. $[\alpha]_D = +80.4$ ($c = 0.04$ in CH_2Cl_2). $R_f = 0.16$ (SiO_2, EtOAc/petroleum ether 1:4). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.01 (d, $^3J = 9.2$ Hz, 1H), 7.98 (d, $^3J = 8.4$ Hz, 1H), 7.93 (s, 1H), 7.91 (d, $^3J = 8.2$ Hz, 1H), 7.67 (d, $^3J = 9.1$ Hz, 1H), 7.52–7.43 (m, 1H), 7.38 (t, $^3J = 7.0$ Hz, 1H), 7.35–7.26 (m, 3H), 7.21 (d, $^3J = 8.4$ Hz, 1H), 6.98 (s, 1H), 6.95 (s, 1H), 5.16 (d, $^2J = 7.2$ Hz, 1H), 5.11 (d, $^2J = 7.2$ Hz, 1H), 4.70 (d, $^2J = 4.7$ Hz, 1H), 4.51 (d, $^2J = 4.7$ Hz, 1H), 3.26 (s, 3H), 2.97–2.84 (m, 1H), 2.63 (s, 3H), 2.54–2.41 (m, 4H), 2.35–2.21 (m, 5H), 2.11 (s, 3H), 2.05–1.84 (m, 2H), 1.84–1.65 (m, 2H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 210.2, 171.2, 154.1, 152.1, 138.5, 138.2, 137.3, 136.1, 134.5, 134.4, 131.5, 130.5, 130.3, 130.1, 129.8, 128.7, 128.6, 127.3, 127.1, 126.8, 126.5, 126.1, 126.0, 125.8, 125.4, 124.4, 120.1, 116.3, 105.9, 102.7, 99.9, 95.2, 86.2, 85.7, 56.7, 56.6, 23.3, 23.3, 23.1, 23.1, 22.9, 21.4, 21.1. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2060.6 ($Fe(CO)_3$), 2004.0 ($Fe(CO)_3$), 1989.5 ($Fe(CO)_3$), 1642.6 (C=O), 1241.6, 1148.3, 1032.7, 1012.2, 963.6, 925.6, 721.4. HRMS (ESI+): *m/z* 765.2144 $[M+H]^+$, 787.1966 $[M+Na]^+$ (calculated for $C_{45}H_{41}FeO_8^+ = 765.2145$, $C_{45}H_{40}FeO_8Na^+ = 787.1965$).

Complexes (pS,aR)-17 and (pR,aR)-17

Iron complexes (p*S*,a*R*)-**17** and (p*R*,a*R*)-**17** were prepared according to General procedure A, starting from diyne **11** (95 mg, 0.147 mmol). (p*S*,a*R*)-**17** and (p*R*,a*R*)-**17** were isolated through chromatographic column on silica gel (Et_2O/n-hexane 35:65) as yellow solids.

*(pS,aR)-**17***. Yield: 51 mg (0.063 mmol, 43 %). M.p. = 135–140 °C (dec.). $[\alpha]_D = 0.0$ ($c = 0.14$ in CH_2Cl_2). $R_f = 0.32$ (SiO_2, Et_2O/*n*-hexane 2:3). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.04–7.96 (m, 2H), 7.93–7.85 (m, 2H), 7.63 (d, $^3J = 9.1$ Hz, 1H), 7.51–7.43 (m, 1H), 7.40–7.33 (m, 1H), 7.33–7.21 (m, 2H), 7.20–7.10 (m, 2H), 5.17–5.07 (m, 2H), 4.41 (d, $^2J = 5.2$ Hz, 1H), 4.37 (d, $^2J = 5.2$ Hz, 1H), 3.25 (s, 3H), 2.97–2.87 (m, 1H), 2.84 (s, 3H), 2.72–2.59 (m, 1H), 2.50–2.34 (m, 2H), 2.08–1.73 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 208.7, 169.8, 153.5, 153.2, 144.0–140.0 (m), 140.0–136.5 (m), 135.5, 134.8, 134.6, 131.4, 130.6, 130.3, 128.7, 128.5, 127.5, 127.3, 126.6, 126.3, 126.2, 126.0, 125.0, 124.8, 120.6, 117.2, 107.7, 106.6 (m), 101.4, 100.0, 95.8, 86.7, 67.2, 56.9, 56.2, 23.3, 22.9, 22.7, 22.2. ^{19}F-NMR (377 MHz, CD_2Cl_2) δ [ppm] = −133.78 (br s, 1F), −137.62 (br s, 1F), −153.81 (t, ^3J = 20.7 Hz), −161.58 (br s, 1F), −162.72 (br s, 1F). IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2060.7 ($Fe(CO)_3$), 2010 ($Fe(CO)_3$), 1996.3 ($Fe(CO)_3$), 1648.2 (C=O), 1525.6, 1241.2, 1150.9, 1077.4, 1034.6, 1012.8, 988.7, 967.3, 721.2. HRMS (ESI+): *m/z* 813.1205 $[M+H]^+$, 835.1029 $[M+Na]^+$ (calculated for $C_{42}H_{30}F_5FeO_8^+ = 813.1205$, $C_{42}H_{29}F_5FeO_8Na^+ = 835.1024$).

(*pR,aR*)-***17***. Yield: 40.6 mg (0.050 mmol, 34 %). M.p. = 161-163 °C (dec.). $[\alpha]_D = 120.4$ ($c = 0.11$ in CH_2Cl_2). $R_f = 0.25$ (SiO_2, Et_2O/*n*-hexane 2:3). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.05–7.96 (m, 2H), 7.95–7.86 (m, 2H), 7.66 (d, $^3J = 9.1$ Hz, 1H), 7.52–7.43 (m, 1H), 7.43–7.36 (m, 1H), 7.36–7.27 (m, 2H), 7.22 (d, $^3J = 8.5$ Hz, 1H), 7.13 (d, $^3J = 8.5$ Hz, 1H), 5.17 (d, $^2J = 7.1$ Hz, 1H), 5.08 (d, $^2J = 7.1$ Hz, 1H), 4.61 (d, $^2J = 5.1$ Hz, 1H), 4.50 (d, $^2J = 5.1$ Hz, 1H), 3.23 (s, 3H), 3.00–2.79 (m, 1H), 2.95 (s, 3H), 2.69–2.57 (m, 1H), 2.52–2.32 (m, 2H), 2.05–1.77 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 208.7, 169.9, 153.8, 152.7, 143.6–140.3 (m), 140.3–136.7 (m), 135.8, 134.7, 134.2, 131.5, 130.7, 130.2, 128.8, 128.7, 127.6, 127.2, 126.9, 126.1, 126.0, 125.3, 125.0, 124.6, 120.0, 116.5, 108.0, 106.6 (m), 101.5, 100.1, 95.2, 86.3, 57.2, 56.6, 23.2, 22.9, 22.7, 22.2. ^{19}F-NMR (377 MHz, CD_2Cl_2) δ [ppm] = −133.70 (br s, 1F), −137.61 (br s, 1F), −153.80 (t, $^3J = 21.0$ Hz), −161.53 (br s, 1F), −162.63 (br s, 1F). IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2071.4 ($Fe(CO)_3$), 2021.1 ($Fe(CO)_3$), 1995.6 ($Fe(CO)_3$), 1651.4 (C=O), 1592.4, 1524.7, 1493.2, 1258.4, 1241.5, 1198.7, 1148.1, 1097.2, 1077.8, 1033.6, 1012.8, 989.1, 967.4, 921.6, 811.2, 802.1, 746.7, 721.8, 666.61. HRMS (ESI+): *m/z* 813.1204 $[M+H]^+$, 835.1028 $[M+Na]^+$ (calculated for $C_{42}H_{30}F_5FeO_8^+ = 813.1205$, $C_{42}H_{29}F_5FeO_8Na^+ = 835.1024$).

Complexes (pS,aR)-18 and (pR,aR)-18

Iron complexes (p*S*,a*R*)-**18** and (p*R*,a*R*)-**18** were prepared according to General procedure A, starting from diyne **12** (145 mg, 0.236 mmol). (p*S*,a*R*)-**18** and (p*R*,a*R*)-**18** were isolated through chromatographic column on silica gel (Et_2O/*n*-hexane 4:1 to 100 % Et_2O).

*(pS,aR)-**18***. Yield: 61 mg (0.076 mmol, 32 %). M.p. = 196-199 °C (dec.). $[\alpha]_D = 18.7$ ($c = 0.09$ in CH_2Cl_2). $R_f = 0.30$ (SiO_2, EtOAc/*n*-hexane 1:1). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.02–7.96 (m, 2H), 7.92 (s, 1H), 7.88 (d, $^3J = 8.1$ Hz, 1H), 7.63 (d, $^3J = 9.1$ Hz, 1H), 7.48–7.41 (m, 1H), 7.39–7.30 (m, 2H), 7.30–7.21 (m, 2H), 7.21–7.15 (m, 1H), 7.12 (d, $^3J = 8.2$ Hz, 1H), 6.69 (d, $^3J = 8.1$ Hz, 1H), 6.61 (d, $^3J = 8.1$ Hz, 1H), 5.11 (s, 2H), 4.58 (d, $^2J = 4.9$ Hz, 1H), 4.39 (d, $^2J = 4.9$ Hz, 1H), 3.94 (s, 3H), 3.68 (s, 3H), 3.25 (s, 3H), 2.98–2.84 (m, 1H), 2.59 (s, 3H), 2.52–2.42 (m, 1H), 2.37 (ddd, $^3J = 12.1$ Hz, $^3J = {}^2J = 5.8$ Hz, 1H), 2.27 (ddd, $^3J = 16.6$ Hz, $^3J = {}^2J = 5.2$ Hz, 1H), 1.92–1.73 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 210.4, 171.0, 159.7, 157.7, 153.6, 152.8, 136.1, 134.8, 134.6, 131.5, 130.4, 130.3, 130.3, 128.7, 128.3, 127.2, 127.1, 126.6, 126.5, 126.4, 126.3, 125.7, 124.7, 121.2, 117.5, 107.5, 104.8, 104.7, 104.1, 104.1, 99.7, 95.9, 86.3, 75.6, 56.6, 56.2, 56.2, 55.5, 23.2, 23.0, 22.5. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2059.7 ($Fe(CO)_3$), 2012.3 ($Fe(CO)_3$), 1988.7 ($Fe(CO)_3$), 1655.0 (C=O), 1593.0, 1251.0, 1149.4, 1109.2, 1030.5, 1005.5, 721.7. MS (ESI+): *m/z* = 783.1885 $[M+H]^+$, 805.1707 $[M+Na]^+$ (calculated for $C_{44}H_{39}FeO_{10}^+ = 783.1887$, $C_{44}H_{38}FeO_{10}Na^+ = 805.1707$).

*(pR,aR)-**18***. Yield: 46 mg (0.058 mmol, 25 %). M.p. = 239-241 °C (dec.). $[\alpha]_D = 95.9$ ($c = 0.09$ in CH_2Cl_2). $R_f = 0.12$ (SiO_2, EtOAc/*n*-hexane 1:1). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.04–7.96 (m, 2H), 7.93 (s, 1H), 7.91 (d, $^3J = 8.2$ Hz, 1H), 7.66 (d, $^3J = 9.1$ Hz, 1H), 7.50–7.42 (m, 1H), 7.42–7.27 (m, 4H), 7.24 (d, $^3J = 8.3$ Hz, 1H), 7.19 (d, $^3J = 8.4$ Hz, 1H), 6.70 (d, $^3J = 8.4$ Hz, 1H), 6.62 (d, $^3J = 8.3$ Hz, 1H), 5.17 (d, $^2J = 7.2$ Hz, 1H), 5.09 (d, $^2J = 7.2$ Hz, 1H), 4.68 (d, $^2J = 4.7$ Hz, 1H), 4.58 (d, $^2J = 4.7$ Hz, 1H), 3.95 (s, 3H), 3.70 (s, 3H), 3.25 (s, 3H), 2.86 (ddd, $^3J = 17.4$ Hz, $^3J = {}^2J = 6.3$ Hz, 1H), 2.79 (s, 3H), 2.54–2.35 (m, 2H), 2.26 (ddd, $^3J = 17.2$ Hz, $^3J = {}^2J = 6.3$ Hz, 1H), 1.95–1.74 (m, 4H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 210.4, 171.1, 159.6, 157.7, 153.9, 152.3, 136.3, 134.4, 134.4, 131.6, 130.4, 130.1, 128.7, 128.6, 127.1, 127.1, 126.8, 126.4, 126.0, 125.8, 125.5, 124.4, 120.3, 116.4, 107.4, 105.3,

104.8, 104.0, 103.9, 99.9, 95.2, 86.0, 75.6, 57.0, 56.6, 56.2, 55.5, 23.1, 23.1, 23.0, 22.6. IR (nujol): $\tilde{\nu}$ [cm^{-1}] = 2060.7 ($Fe(CO)_3$), 2000.4 ($Fe(CO)_3$), 1991.4 ($Fe(CO)_3$), 1733.1, 1636.0 (C=O), 1253.8, 1244.9, 1162.0, 1150.3, 1106.2, 1058.6, 1031.8, 1012.9, 989.8, 964.9, 932.7, 721.0. HRMS (ESI+): *m/z* 783.1885 $[M+H]^+$, 805.1708 $[M+Na]^+$ (calculated for $C_{44}H_{39}FeO_{10}^+$ = 783.1887, $C_{44}H_{38}FeO_{10}Na^+$ = 805.1707).

Complexes (pR,aR)-19 and (pS,aR)-19

Iron complexes (p*R*,a*R*)-**19** and (p*S*,a*R*)-**19** were prepared according to General procedure A, starting from diyne **14** (168 mg, 0.360 mmol). The reaction was conducted at 85 °C. (p*R*,a*R*)-**19** and (p*S*,a*R*)-**19** were isolated through chromatographic column on silica gel (EtOAc/*n*-hexane 7 : 3 to 4 : 1) as yellow solids.

*(pR,aR)-**19***. Yield: 59 mg (0.093 mmol, 26 %). M.p. = 190–193 °C (dec.). $[\alpha]_D$ = −20.2 (*c* = 0.20 in CH_2Cl_2). R_f = 0.37 (SiO_2, EtOAc/*n*-hexane 7 : 3). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.39 (s, 1H), 8.03–7.94 (m, 2H), 7.90 (d, ^3J = 8.1 Hz, 1H), 7.61 (d, ^3J = 9.1 Hz, 1H), 7.44 (t, ^3J = 7.5 Hz, 1H), 7.37 (t, ^3J = 7.4 Hz, 1H), 7.29–7.22 (m, 2H), 7.13 (d, ^3J = 8.4 Hz, 1H), 7.09 (d, ^3J = 8.5 Hz, 1H), 5.10–5.02 (m, 3H), 4.80 (d, ^2J = 13.4 Hz, 1H), 4.76 (s, 2H), 4.47 (d, ^2J = 4.9 Hz, 1H), 4.35 (s, 1H), 4.23 (d, ^2J = 4.9 Hz, 1H), 3.21 (s, 3H), 2.59 (s, 3H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 208.5, 173.1, 153.8, 151.3, 134.9, 134.7, 134.6, 134.3 131.3, 130.6, 130.3, 128.9, 128.6, 127.6, 127.3, 126.3, 126.2, 126.1, 124.7, 124.5, 120.6, 117.6, 107.4, 103.9, 99.8, 95.9, 80.1, 69.9, 67.8, 57.4, 57.2, 56.2. HRMS (ESI+): *m/z* 635.0999 $[M+H]^+$, 657.0823 $[M+Na]^+$ (calculated for $C_{34}H_{27}FeO_9^+$ = 635.0999, $C_{34}H_{26}FeO_9Na^+$ = 657.0818).

*(pS,aR)-**19***. Yield: 42 mg (0.066 mmol, 18 %). M.p. = 130–132 °C (dec.). $[\alpha]_D$ = 119.6 (*c* = 0.13 in CH_2Cl_2). R_f = 0.24 (SiO_2, EtOAc/*n*-hexane 7 : 3). ^{1}H-NMR (400 MHz, CD_2Cl_2) δ [ppm] = 8.41 (s, 1H), 8.01 (d, ^3J = 8.7 Hz, 1H), 7.97 (d, ^3J = 8.2 Hz, 1H), 7.90 (d, ^3J = 8.1 Hz, 1H), 7.65 (d, ^3J = 8.6 Hz, 1H), 7.45 (t, ^3J = 7.3 Hz, 1H), 7.38 (t, ^3J = 7.1 Hz, 1H), 7.34–7.21 (m, 3H), 7.13 (d, ^3J = 8.5 Hz, 1H), 5.20–5.08 (m, 2H), 4.97 (d, ^2J = 13.6 Hz, 1H), 4.76 (d, ^2J = 13.7 Hz, 1H), 4.74 (s, 2H), 4.67 (d, ^2J = 4.9 Hz, 1H), 4.42 (d, ^2J = 4.9 Hz, 1H), 4.36 (s, 1H), 3.24 (s, 3H), 2.73 (s, 3H). ^{13}C-NMR (100 MHz, CD_2Cl_2) δ [ppm] = 208.6, 173.1, 153.7, 151.1 134.9, 134.2, 134.1, 130.8, 130.2, 128.9, 128.6, 127.5, 127.3, 126.4, 126.2, 126.0, 125.2, 124.7, 124.5, 119.8, 116.1, 107.7, 103.9, 100.1, 95.2, 79.9, 69.9, 67.8, 57.5, 57.4, 56.7. HRMS (ESI+): *m/z* 635.1002 $[M+H]^+$, 657.0824 $[M+Na]^+$ (calculated for $C_{34}H_{27}FeO_9^+$ = 635.0999, $C_{34}H_{26}FeO_9Na^+$ = 657.0818).

General procedure for the AH of ketones

The pre-catalyst (0.010 mmol, 0.02 eq) was weighted in a 3 mL glass vial. A magnetic stirring bar was added, and the vial was charged in an autoclave. After purging the system with argon, the solvent (0.35 mL) was added. Me_3NO (1.5 mg, 0.020 mmol, 0.04 eq) was added and the mixture was stirred for 5 minutes under argon. The ketone (0.500 mmol, 1 eq) was then added. The autoclave was sealed and, after purging 2 times with hydrogen, it was charged with H_2 (30 bar). The reaction was heated to 70 °C. After 18 h the reaction was allowed to cool to rt. Hydrogen was removed, and the reaction mixture was filtered through celite, rinsing with AcOEt/petroleum ether 1 : 1. Conversion was evaluated through ^{1}H-NMR analysis and chiral GC analysis. Enantiomeric excesses were evaluated through GC analysis with a chiral column or through chiral HPLC analysis. The absolute configurations of the alcohol products were determined by comparison with literature data.

1-Phenylethanol (P1)

Conversion and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 95 °C for 20 min. $t_{substrate}$ = 4.9 min; t_R = 8.8 min; t_S = 11.0 min.[26]

1-Phenylpropan-1-ol (P2)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen programmed flow: 42 mL/min; oven temperature: 95 °C for 20 min. $t_{substrate}$ = 7.8 min; t_R = 11.5 min; t_S = 12.6 min.[26]

1-(Naphthalen-2-yl)ethan-1-ol (P3)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 150 °C for 20 min. $t_{substrate}$ = 8.3 min; t_R = 12.4 min; t_S = 13.3 min.[26]

1-(4-(Trifluoromethyl)phenyl)ethan-1-ol (P4)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 90 °C; 1 °C/min gradient; 100 °C; 0.5 °C/min gradient; 110 °C for 5 min. $t_{substrate}$ = 8.4 min; t_R = 19.0 min; t_S = 20.6 min.[26]

1-(4-Methoxyphenyl)ethan-1-ol (P5)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 110 °C for 10 min; 30 °C/min gradient; 120 °C for 10 min; 30 °C/min gradient; 130 °C for 10 min. $t_{substrate}$ = 16.6 min; t_R = 16.3 min; t_S = 18.7 min.[26]

2,2,2-Trifluoro-1-phenylethan-1-ol (P6)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 100 °C for 20 min. $t_{substrate}$ = 1.8 min; t_S = 7.8 min; t_R = 8.5 min.[7]

1,2,3,4-Tetrahydronaphtalen-2-ol (P7)

Conversions and *ee*'s were determined via chiral GC analysis. Column: MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length: 25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 120 °C for 40 min. t_R = 17.7 min; t_S = 18.1 min; $t_{substrate}$ = 44 min.[26]

3,3-Dimethylbutan-2-ol (P8)

Conversion was determined via ^{1}H-NMR analysis. *ee*'s were determined via chiral GC analysis. MEGA-DEX DAC Beta, diacetyl-*tert*-butylsilyl-β-cyclodextrin, 0.25 mm; diameter: 0.25 mm; length:

25 m; carrier: hydrogen; programmed flow: 42 mL/min; oven temperature: 40 °C; 2 °C/min gradient; 100 °C. t_S = 6.8 min; t_R = 8.0 min; $t_{substrate}$ = 8.9 min.[26] Absolute configurations were assigned by comparing the sign of optical rotation with literature data ($[\alpha_D{}^{20}] = +0.0496 \pm 0.0048$, $c = 0.25$ in $CHCl_3$ at $T = 27.8$ °C).[27]

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: iron catalysis · asymmetric hydrogenation · (cyclopentadienone)iron complexes · ketone reduction · stereogenic plane

[1] a) G. M. Fusi, S. Gazzola, U. Piarulli, *Adv. Synth. Catal.* **2022**, *364*, 696–714; b) H. Brunner, *Angew. Chem.* **1999**, *111*, 1248–1390; *Angew. Chem. Int. Ed.* **1999**, *38*, 1194–1208; c) M. Fontecave, O. Hamelin, S. Ménage, *Top. Organomet. Chem.* **2005**, *15*, 271–288; d) D. F. Toste, S.-L. You, *Organometallics* **2019**, *38*, 3899–3901; e) S. Shaaban, C. Davies, H. Waldmann, *Eur. J. Org. Chem.* **2020**, 6512–6524; f) I. Ojima, N. Clòs, C. Bastos, *Tetrahedron* **1989**, *45*, 6901–6939.
[2] B. Testa, *Helv. Chim. Acta* **2013**, *96*, 351–374.
[3] a) Y. Blum, D. Czarkle, Y. Rahamin, Y. Shvo, *Organometallics* **1986**, *4*, 1459–1461; b) R. T. Weberg, J. R. Norton, *J. Am. Chem. Soc.* **1990**, *112*, 1105–1108; c) B. L. Conley, M. K. Pennington-Boggio, E. Boz, T. J. Williams, *Chem. Rev.* **2010**, *110*, 2294–2312.
[4] X. Dou, T. Hayashi, *Adv. Synth. Catal.* **2016**, *358*, 1054–1058.
[5] a) W. Reppe, H. Vetter, *Justus Liebigs Ann. Chem.* **1953**, *582*, 133–161; b) G. N. Schrauzer, *J. Am. Chem. Soc.* **1959**, *81*, 5307–5310; c) H. J. Knölker, J. Heber, *Synlett* **1993**, 924–926; d) H. J. Knölker, E. Baum, J. Heber, *Tetrahedron Lett.* **1995**, *36*, 7647–7650; e) H.-J. Knölker, J. Heber, C. H. Mahler, *Synlett* **1992**, 1002–1004; f) A. J. Pearson, R. J. Shivley Jr., R. A. Dubbert, *Organometallics* **1992**, *11*, 4096–4104; g) A. J. Pearson, R. J. Shively, *Organometallics* **1994**, *13*, 578–584; h) A. J. Pearson, A. Perosa, *Organometallics* **1995**, *14*, 5178–5183; i) A. J. Pearson, X. Yao, *Synlett* **1997**, 1281–1282; j) A. J. Pearson, R. A. Dubbert, *J. Chem. Soc. Chem. Commun.* **1991**, *4*, 202–203.
[6] For reviews about the use of CICs in enantioselective catalysis see: a) L. Pignataro, C. Gennari, *Eur. J. Org. Chem.* **2020**, 3192–3205; b) U. Piarulli, S. V. Fachini, L. Pignataro, *Chimia* **2017**, *71*, 580–585; c) A. Quintard, J. Rodriguez, *Angew. Chem.* **2014**, *126*, 4124–4136; *Angew. Chem. Int. Ed.* **2014**, *53*, 4044–4055.
[7] X. Bai, M. Cettolin, G. Mazzoccanti, M. Pierini, U. Piarulli, V. Colombo, A. Dal Corso, L. Pignataro, C. Gennari, *Tetrahedron* **2019**, *75*, 1415–1424.
[8] a) J. P. Hopewell, J. E. D. Martins, T. C. Johnson, J. Godfrey, M. Wills, *Org. Biomol. Chem.* **2012**, *10*, 134–145; b) T. C. Johnson, G. J. Clarkson, M. Wills, *Organometallics* **2011**, *30*, 1859–1868; c) A. Del Grosso, A. E. Chamberlain, G. J. Clarkson, M. Wills, *Dalton Trans.* **2018**, *47*, 1451–1470.
[9] For a similar approach that involves the use of carbon stereocenters, see: C. A. M. R. Van Slagmaat, K. C. Chou, L. Morick, D. Hadavi, B. Blom, S. M. A. De Wildeman, *Catalysts* **2019**, *9*, 790.
[10] P. Gajewski, M. Renom-Carrasco, S. Vailati Facchini, L. Pignataro, L. Lefort, J. G. de Vries, R. Ferraccioli, U. Piarulli, C. Gennari, *Eur. J. Org. Chem.* **2015**, 5526–5536.
[11] N. Li, H. Feng, Q. Gong, C. Wu, H. Zhou, Z. Huang, J. Yang, X. Chen, N. Zhao, *J. Mater. Chem.* **2015**, *3*, 11458–11463.
[12] F. Yang, S. Wei, C. A. Chen, P. Xi, L. Yang, J. Lan, H. M. Gau, J. You, *Chem. Eur. J.* **2008**, *14*, 2223–2231.
[13] H. T. Chang, M. Jeganmohan, C. H. Cheng, *Org. Lett.* **2007**, *9*, 505–508.
[14] The *R* and *S* descriptors are preceded by the letter p when associated with the configuration of the plane, by the letter a when related to the configuration of the axis. The stereochemical descriptor of the stereogenic plane was assigned, as in Ref. 7, following the extended CIP rules: Nummerierung? a) J.-P. Djukic, A. Hijazi, H. D. Flack, G. Bernardinelli, *Chem. Soc. Rev.* **2008**, *37*, 406–425; b) T. E. Sloan, *Top. Stereochem.* **1981**, *12*, 1–36; c) K. Schlögl, *Top. Stereochem.* **1967**, *1*, 39–91; d) R. S. Cahn, C. Ingold, V. Prelog, *Angew. Chem.* **1966**, *78*, 413–447; *Angew. Chem. Int. Ed. Engl.* **1966**, *5*, 385–415.
[15] It must be noted that in the case of the pentafluorophenyl- and (2,6)-dimethoxyphenyl-substituted complexes (**17** nad **18**) the descriptors of the configuration of the stereogenic plane are opposite than in the other cases due to the different priority of the groups in the sequence rule. However, the geometry of each isomer is the same than in the other cases.
[16] a) L. Pignataro, C. Gennari, *Eur. J. Org. Chem.* **2020**, 3192–3205; b) M. Akter, P. Anbarasan, *Chem. Asian J.* **2021**, *16*, 1703–1724.
[17] a) R. Hodgkinson, A. Del Grosso, G. Clarkson, M. Wills, *Dalton Trans.* **2016**, *45*, 3992–4005; b) C. A. M. R. Van Slagmaat, K. C. Chou, L. Morick, D. Hadavi, B. Blom, S. M. A. De Wildeman, *Catalysts* **2019**, *9*, 790.
[18] a) A. Tlili, J. Schranck, H. Neumann, M. Beller, *Chem. Eur. J.* **2012**, *18*, 15935–15939; b) T. Y. Luh, *Coord. Chem. Rev.* **1984**, *60*, 255–276; c) A. Berkessel, S. Reichau, A. Von Der Höh, N. Leconte, J. M. Neudörfl, *Organometallics* **2011**, *30*, 3880–3887.
[19] C. P. Casey, H. Guan, *J. Am. Chem. Soc.* **2009**, *131*, 2499–2507.
[20] The descriptor of the configuration of the major enantiomer of **P6**, obtained with pre-catalyst (p*R*,a*R*)-**15**, is *R* like in the case of the reduction of acetophenone with the same catalyst. This is due to the higher priority of the CF_3 group according to the CIP rules.
[21] W. C. Still, M. Kahn, A. Mitra, *J. Org. Chem.* **1978**, *43*, 2923–2925.
[22] Agilent, CrysAlis PRO, Agilent Technologies Ltd, Yarnton, Oxfordshire, England **2019**.
[23] G. M. Sheldrick, *Acta Crystallogr.* **2015** *A71*, 3–8.
[24] G. M. Sheldrick, *Acta Crystallogr.* **2015** *C71*, 3–8.
[25] L. J. Farrugia, *J. Appl. Crystallogr.* **2012**, *45*, 849–854.
[26] P. Gajewski, M. Renom-Carrasco, S. Vailati Facchini, L. Pignataro, L. Lefort, J. G. de Vries, R. Ferraccioli, A. Forni, U. Piarulli, C. Gennari, *Eur. J. Org. Chem.* **2015**, 1887–1893.
[27] C. A. Swamy, P. A. Varenikov, G. de Ruiter, *Organometallics* **2020**, *39*, 247–257.

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