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A New Approach to Diastereoselective and Enantioselective Cyclopropane Syntheses Using the Chiral Iron Carbene Complexes *S*- and *R*-[(η^5-C_5H_5)$(CO)_2$Fe=CH[(η^6-*o*-$CH_3OC_6H_4$)$Cr(CO)_3$]]$^+$

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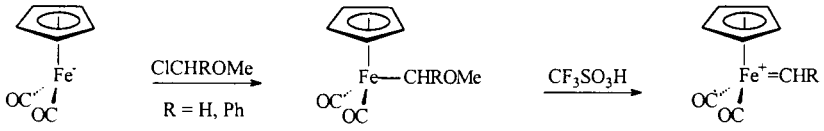
Abstract—Different methods for the synthesis of iron carbene complexes or their precursors have been summarized. New diastereomerically pure carbene precursors *RR*-(+)- and *SS*-(−)-(η^5-C_5H_5)$(CO)_2$FeCH$(OSiMe_3)$[η^6-*o*-$CH_3OC_6H_4Cr(CO)_3$] have been prepared by the reaction of the Fp anion with enantiomerically pure *S*-(+) or *R*-(−)-*o*-anisaldehyde(tricarbonyl)chromium complexes. They were then converted to the corresponding iron carbene complexes *S*- and *R*-[(η^5-C_5H_5)$(CO)_2$Fe=CH[(η^6-*o*-$CH_3OC_6H_4$)$Cr(CO)_3$]]$^+$. Enantioselective carbene transfers from these complexes to 2-methylpropene, 1,1-diphenylethylene, styrene, *p*-methylstyrene, *p*-chlorostyrene, and *p*-trifluoromethylstyrene gave *o*-methoxyphenylcyclopropanes with high diastereoselectivities and moderate to excellent enantioselectivities. © 2000 Published by Elsevier Science Ltd.

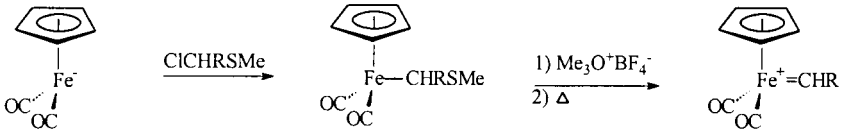
Introduction

Metal carbenes (L_nM=CRR′) are reactive intermediates in a variety of important catalytic processes such as olefin metathesis,[1] Fischer–Tropsch processes[2] and metal-catalyzed carbene transfers using diazo compounds.[3] With the discovery of carbene complexes by Fischer in 1964,[4] the possibility of using these compounds as cyclopropanation reagents has become a reality. Iron carbene complexes, $Cp(CO)(L)Fe^+$=CRR′ (L=CO, PR_3), have been found to be effective in transferring their carbene ligands to alkenes to form a wide variety of cyclopropanes.[5] Due to lability of most of these electrophilic iron carbenes, it is often necessary to generate them in situ from their precursors.

Although several routes are known for synthesizing these iron carbene precursors, the most widely used technique is to synthesize these carbenes from the Fp anion, [Fp=$CpFe(CO)_2$] **1** and α-chloroalkylmethylethers or α-chloroalkylmethylthioethers (Schemes 1 and 2).[6]



Scheme 1. Carbene complex from α-chloroalkyl ethers.



Scheme 2. Carbene complex from α-chloroalkyl thioether.

Keywords: alkene; bimetallics; carbenes; cyclopropanation; enantioselection.

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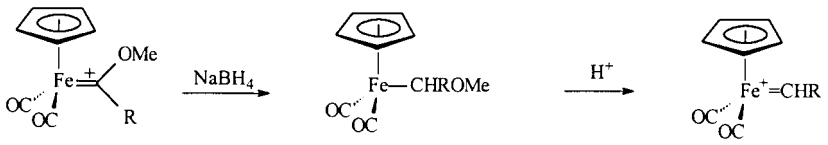
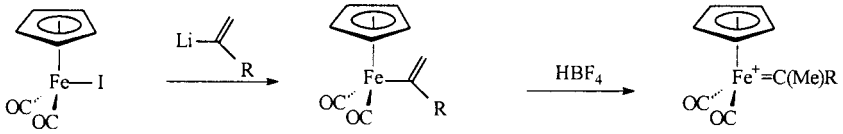


Scheme 3. Carbene complex via Fischer carbene complex.

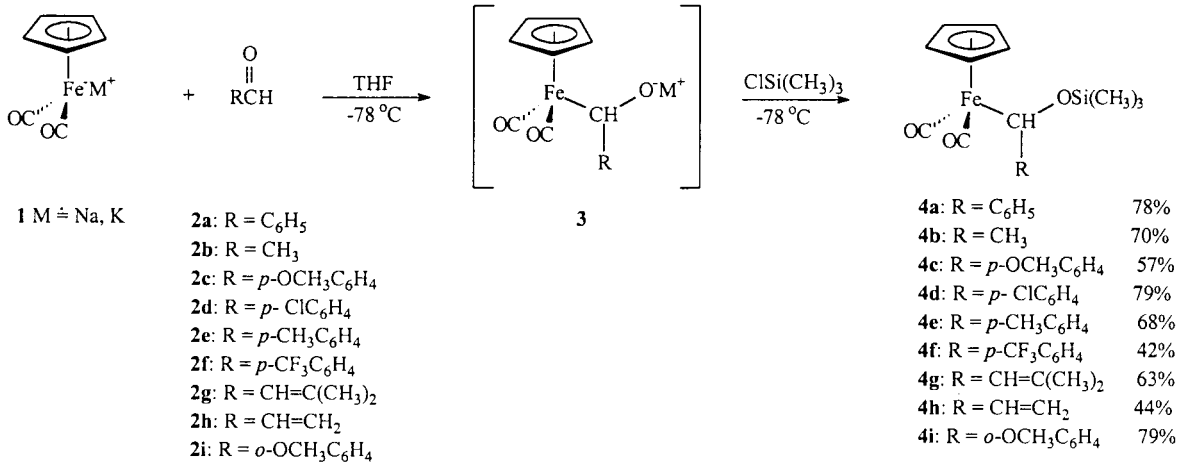


Scheme 4. Carbene complex via η^1-vinyl complex.

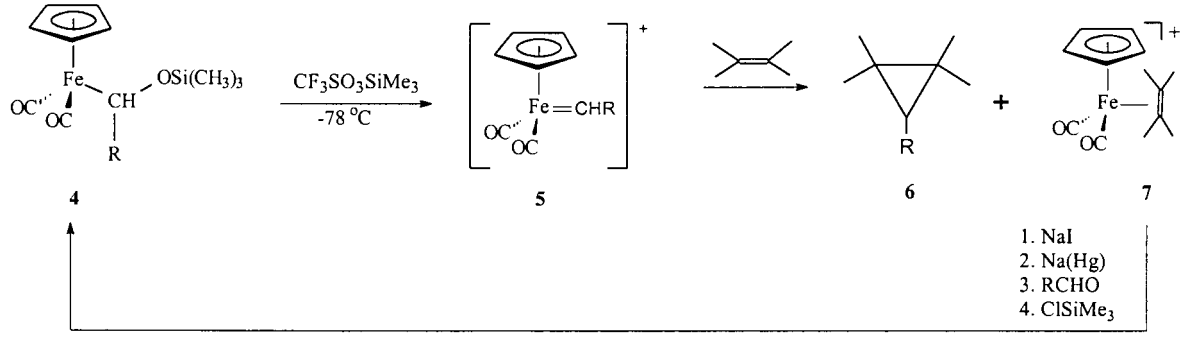
Due to the toxicity of the starting chloro compounds and difficulties in their preparation, an alternative route has been devised involving hydride reduction of Fischer carbenes (Scheme 3).[7] Another, less frequently used approach utilized η^1-vinyl complexes as carbene precursors, generating the carbene via protonation (Scheme 4).[8]

In 1992, it was discovered that the Fp anion acts as a nucleophile in reactions with aldehydes to form the alkoxides, FpCH(O^-)R, which were then trapped with chlorotrimethylsilane to provide the relatively stable α-siloxyalkyliron complexes, FpCH($OSiMe_3$)R (Scheme 5).[9] The reaction depicted in Scheme 5 represents the first successful nucleophilic addition of a transition metal anion complex to an aldehyde.

The precursors **4** were converted to electrophilic iron carbenes **5** by treatment with trimethylsilyltriflate. Cyclopropanes were obtained from the carbenes prepared in situ by treatment with alkenes (Scheme 6).[9] Thus, a simple, efficient method to generate electrophilic iron carbenes from diversely substituted, inexpensive and readily



Scheme 5. Synthesis of α-siloxyalkyliron complexes.



Scheme 6.

Table 1. Selected results of diastereoselectivities observed for iron carbene transfers (R^*=*S*-2-methylbutyl)

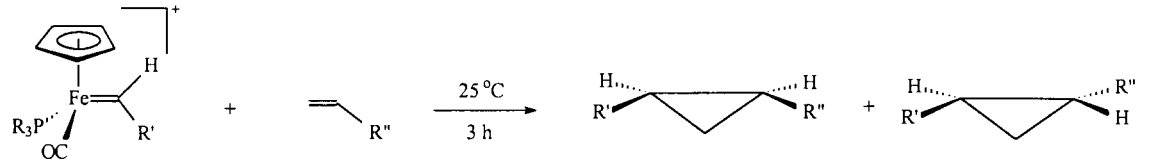
$Cp(CO)(L)Fe{=}CHR^+$		Substrate	Product ratio (*cis–trans*)	Reference
L	R			
CO	Ph	Styrene	>100:1	6b,9b
CO	Ph	$CH_2{=}CHCH_3$	7.8:1	6b
CO	CH_3	Styrene	6:1	11a
CO	CH_3	$CH_3CH{=}C(CH_3)_2$	>50:1	5
PPh_2R^*	Ph	$CH_2{=}CHOAc$	4:1	12b
PPh_2R^*	Ph	$CH_2{=}CHCH_3$	2:3	12b
PPh_2R^*	CH_3	Styrene	1:4	5
PPh_3	CH_3	(*Z*)-DCH=CHC_6H_4(*p*-OCH_3)	1:1.5 (Ar, D all *cis*)	5

available aldehydes was developed. In addition, making structurally elaborate carbene complexes is much easier using this method vs. those in Schemes 1–4.

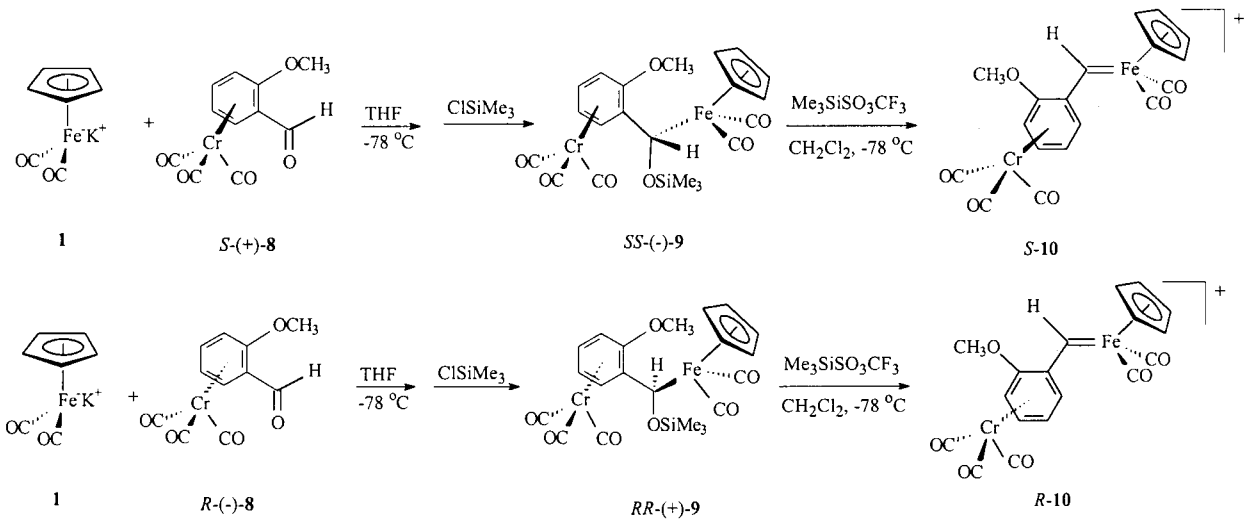
Variations of $Cp(CO)(L)Fe{=}CHR^+$ have been widely used for carbene transfers (R=–H,[6a,10] $-CH_3$,[6c,7a,c,8a,11] $-C_6H_5$,[6b,9b,12] c-C_3H_5[13] $-CH{=}C(CH_3)_2$,[8c]) in addition to the carbenes derived from the precursors in Scheme 6. Representative results for iron carbene transfers to simple alkyl- and aryl-substituted alkenes are summarized in Table 1. An interesting feature to note from the large number of carbene transfer reactions is that the highly reactive dicarbonyl complex $Cp(CO)_2Fe{=}CHR^+$ generally exhibits *cis* (or *syn*) selectivity, while the less reactive phosphine-substituted systems, $Cp(CO)(PR'_3)Fe{=}CHR^+$ tend to show *trans* selectivity.[11b]

Asymmetric cyclopropanation has also been studied using chiral iron carbene complexes. Phosphine-substituted derivatives, $Cp(CO)(PR'_3)Fe{=}CHR^+$, which possess a chiral metal center, provide the possibility of enantioselective carbene transfer reactions. Davison[10c] and Flood[10e] reported the first enantioselective carbene transfer reactions, most likely occurring through $Cp(CO)(PPh_3)Fe{=}CH_2^+$, with low to moderate (10–38%) enantioselectivities. Brookhart was able to improve this methodology by changing the carbene moiety to one containing a prochiral face, such as R_{Fe}- and S_{Fe}-$Cp(CO)(PR_3)Fe{=}CHR'^+$ (R=Me, Et, Ph; R′=CH_3, Ph) (Scheme 7).[11b,12b] Enantioselective transfer of ethylidene to alkenes generally gave good to excellent enantiomeric excesses (64–95%).[11b] Benzylidene transfers provided moderate to excellent optical yields (41–92% ee).[12b] Brookhart's studies also revealed valuable information on the mechanism of transfer and the origin of enantioselectivity.

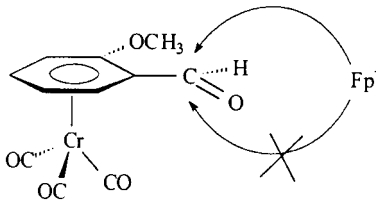
While the phosphine-substituted derivatives ($L{=}PR_3$) possessing a chiral metal center can be used in carbene transfer reactions with high enantioselectivities, they exhibited a lower *cis–trans* selectivity than their carbon



Scheme 7. Cyclopropanation via iron carbenes having chirality at the metal center.



Scheme 8.



Scheme 9.

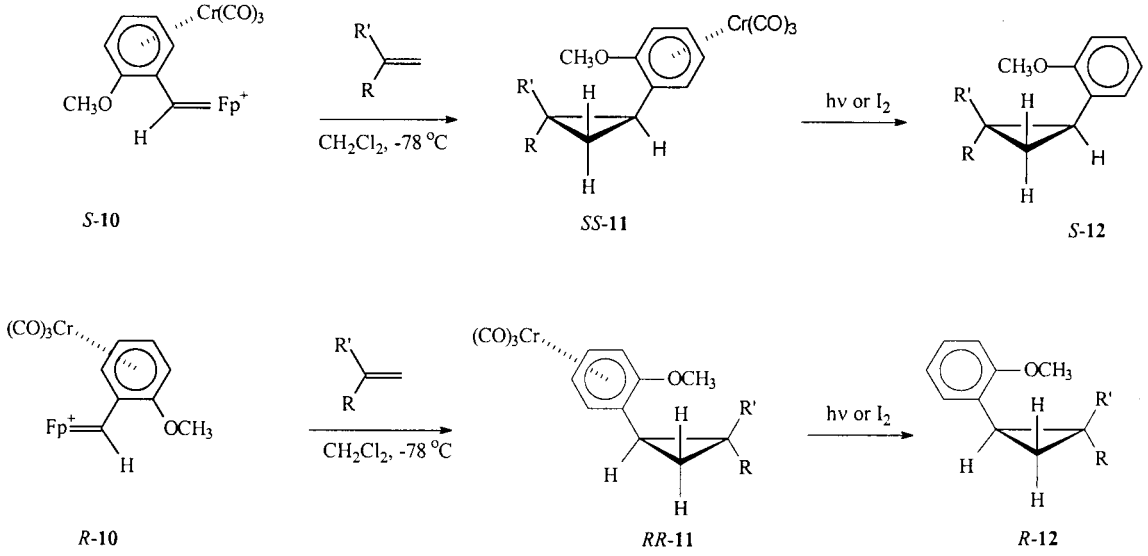
monoxide anologs.[11b] Another approach utilizes an iron carbene complex possessing a chiral carbene ligand. Chiral-at-carbene-ligand iron complexes allow the possibility of dicarbonyl ligation to iron and, thus, higher *cis–trans* selectivity. Recently, we developed a new method for the syntheses of chiral iron carbene complexes by reacting the Fp anion with chiral aldehydes **8**. This is the first study of iron carbene complexes having chirality at the *carbene* ligand in enantioselective transfer reactions. Preliminary accounts of this work have been previously reported.[14,15] Herein, we report our latest results of this new approach as a means of evaluating the role of chirality at the carbene ligand in asymmetric cyclopropanation.

Results and Discussion

Syntheses of *SS*-(−) and *RR*-(+)-(η^5-C_5H_5)-$(CO)_2FeCH(OSiMe_3)(\eta^6$-*o*-$CH_3OC_6H_4)Cr(CO)_3$ 9 and conversion to carbene complexes *S*- and *R*-$[(\eta^5$-$C_5H_5)(CO)_2Fe{=}CH[(\eta^6$-*o*-$CH_3OC_6H_4)Cr(CO)_3]]^+$ 10

Initially, the reaction of the Fp anion 1 with *S*-(+)-8[14,15] and *R*-(−)-**8**[15] was studied. Subsequently, bimetallic complexes *RR*-(+) and *SS*-(−)-**9** were prepared with over 90% yields and with optical rotations of $[\alpha]_D^{25}=+335$ (*c*, 0.832, $CHCl_3$) and $[\alpha]_D^{25}=-335$ (*c*, 0.226, $CHCl_3$), respectively (Scheme 8).

In the formation of the bimetallic complex *RR*-(+)-**9**, a new chiral center at C_α is generated and two diastereomers are expected, however, only one of the diastereomers, *RR*-**9** (not *RS*-**9**), is detected by NMR. This can be ascribed to the fact that the $Cr(CO)_3$ moiety blocks one face of the aldehyde carbonyl group. Nucleophiles such as the Fp anion attack the aldehydes only *anti* to the $Cr(CO)_3$ group (Scheme 9).[16] In the *o*-anisaldehyde complex the carbonyl group and methoxy group exist in an *anti* isomer and, thus, very high



Scheme 10.

Table 2. Enantioselective carbene transfer reactions from $[Cp(CO)_2Fe{=}CH[(o\text{-}CH_3OC_6H_4)Cr(CO)_3]]^+$ to alkenes

	Carbene complexes	$CH_2{=}CRR'$	Product	% Yield total cyclopropanes	*cis–trans* ratio	% ee product *cis*, *trans*
1	*R*-**10**	**a** R=CH_3, R′=CH_3	*R*-**12a**	90	–	>95, –
2	*S*-**10**	**a** R=CH_3, R′=CH_3	*S*-**12a**[a]	89	–	>95, –
3	*R*-**10**	**b** R=Ph, R′=Ph	*R*-**12b**	85	–	92, –
4	*S*-**10**	**b** R=Ph, R′=Ph	*S*-**12b**	86	–	92, –
5	*R*-**10**	**c** R=H, R′=Ph	*R*-**12c**[b,c]	93	10:1	60,[d]
6	*S*-**10**	**c** R=H, R′=Ph	*S*-**12c**[b,c]	89	10:1	60,[d]
7	*R*-**10**	**d** R=H, R′=*p*-CH_3Ph	*R*-**12d**[c]	90	7:1	55,[d]
8	*R*-**10**	**e** R=H, R′=*p*-ClPh	*R*-**12e**[c]	60	6:1	46, 53
9	*R*-**10**	**f** R=H, R′=*p*-CF_3Ph	*R*-**12f**[c]	45	3:1	30, 72

[a] Ref. 14.
[b] Ref. 15.
[c] The absolute configuration shown here is the chiral center of the cyclopropane α to the *o*-methoxyphenyl ring.
[d] Measurement was not obtained for the *trans* isomer of cyclopropanes.

asymmetric induction is achieved.[17] The configuration at C_α shown in Scheme 8 is assigned based on Scheme 9. Similarly, only *SS*-**9**, not *SR*-**9**, was produced from *S*-**8**. The carbene complex *S*- and *R*-**10** was generated by abstraction of OTMS from the complex *SS*- and *RR*-**9** with TMSOTf. However, when the carbene complex was generated, the chiral center at C_α was eliminated. This method provides an inexpensive and efficient route to chiral-at-carbene-ligand iron complexes.

Enantioselective carbene transfer reactions

Treatment of *SS*- or *RR*-**9** with TMSOTf generated the chiral iron carbene complexes, in situ, which subsequently reacted with olefins to provide the complexed cyclopropanes **11**. Photolysis of **11** gave the final product of cyclopropanes **12** (Scheme 10). Results including yields, *cis–trans* ratios and enantiomeric excesses are listed in Table 2.

These new chiral iron carbene complexes can be used to produce cyclopropanes with excellent ee (92–95%) when reacted with *gem*-disubstituted olefins. The reaction proceeds with high *cis–trans* selectivities and moderate % ee when using styrene and substituted styrene derivatives.

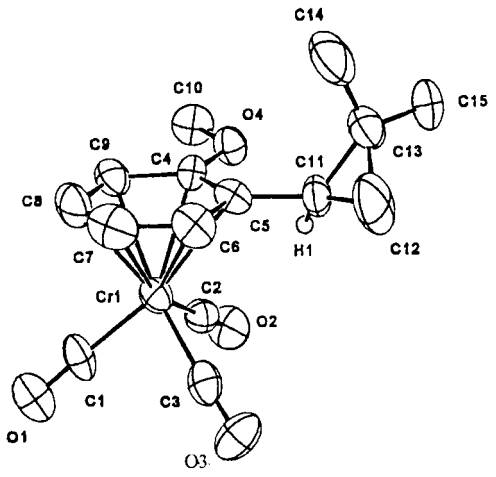


Figure 1. ORTEP drawing of *RR*-(+)-**11a**. Ellipsoids are drawn at the 35% probability level.

Table 4. Bond distances (Å) of *RR*-(+)-**11a**

Cr1–C1	1.820 (12)	C1–O1	1.164 (15)	C7–C8	1.411 (19)
Cr1–C2	1.835 (11)	C2–O2	1.160 (13)	C8–C9	1.384 (18)
Cr1–C3	1.864 (12)	C3–O3	1.142 (15)	C10–O4	1.429 (12)
Cr1–C4	2.258 (10)	C4–C5	1.366 (13)	C11–C12	1.478 (17)
Cr1–C5	2.251 (10)	C4–C9	1.431 (14)	C11–C13	1.499 (17)
Cr1–C6	2.213 (13)	C4–O4	1.368 (12)	C12–C13	1.440 (24)
Cr1–C7	2.216 (12)	C5–C6	1.447 (15)	C13–C14	1.473 (22)
Cr1–C8	2.188 (13)	C5–C11	1.490 (13)	C13–C15	1.513 (18)
Cr1–C9	2.254 (12)	C6–C7	1.397 (20)		

The absolute configuration of *RR*-**11a** (R=R′=CH_3) was established by an X-ray diffraction study as *RR*-(+)-1-*o*-methoxyphenyl(tricarbonyl chromium)-2,2-dimethylcyclopropane (Fig. 1) (Table 3). Selected bond distances and bond angles are listed in Tables 4 and 5, respectively.

It is rationalized that two factors could control the diastereoselectivity of the cyclopropanation reaction using the chiral-at-carbene-ligand iron complexes. First, the bulky $Cr(CO)_3$ group completely shields the bottom face from the alkene attack (Scheme 11). This expectation was based upon the demonstrated capacity of chiral chromium-tricarbonyl-complexed aldehydes to undergo stereospecific addition reactions with organic nucleophiles, *anti* to the metal moiety.[16]

A second factor could be the orientation of the methoxy group with respect to the Fp moiety. In the *o*-anisaldehyde complex the carbonyl group and methoxy group exist solely in an *anti* relationship, as we have discussed before. However, it may be possible for the carbene complexes to exist as both *syn* and *anti* isomers (Scheme 12 for *R*-**10**). Due to steric interactions, the *ortho*-methoxy substituent would be *anti* to the Fp group. Alternatively, a lone pair of electrons on the oxygen of the methoxy group may electrostatically interact with the positive charge density of the iron center to stabilize the *syn* isomer.

The diastereoselectivity of the cyclopropanation may originate from a faster rate of reaction for the *anti* isomer over the *syn* isomer. This is the key to the second factor. The transfer results reported (Scheme 10) show that when carbene *R*-**10** reacted with 2-methylpropene, cyclopropane *RR*-**11a** was predominantly formed (Fig. 1). It has been previously proposed that when alkenes attack iron carbenes,

Table 3. Crystallographic data for *RR*-(+)-**11a**

Formula	$C_{15}H_{16}O_4Cr$	Radiation	Ni-filtered Cu Kα, λ=1.54178 Å
Molar mass	312.28	2θ rang, deg	4–100
Cryst syst	Orthorhombic	Index ranges	$0\le h\le 6$; $0\le k\le 9$; $0\le l\le 22$
Space group	$P2_12_12_1$	Scan type	θ/2θ
a, Å	6.5903(22)	No. of data collected	948
b, Å	9.8189(17)	No. of unique data	898 ($I>2.5\sigma$ (I))
c, Å	23.0750(25)	No. of parameters	182
V, Å^3	1493.3(6)	GOF[a]	2.20
Z	4	R, R_w[b]	0.062, 0.062
d_{calc}, g cm^{-3}	1.389	$(\Delta\rho)_{max}$, eÅ^3	−0.62, +0.36
μ, mm^{-1}	6.49	Flack *x* parameter	0.034 (0.043)
T, °C	22(2)		

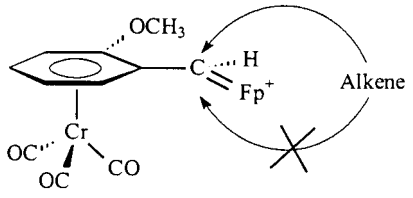
[a] GOF=$[\sum[w(F_o^2-F_c^2)^2]/(M-N)]^{1/2}$, where M is the number of reflections and N is the number of parameters refined.
[b] $R=\sum|F_c|/|F_o|$; $R_w=\sum[w^{1/2}|(F_o-F_c)|]/\sum[w^{1/2}|F_o|]$.

Table 5. Bond angles (°) of *RR*-(+)-**11a**

C1–Cr1–C2	90.3 (5)	Cr1–C2–O2	179.1 (9)	C4–C9–C8	117.2 (10)
C1–Cr1–C3	90.7 (5)	Cr1–C3–O3	178.3 (10)	C5–O4–C10	118.6 (8)
C1–Cr1–C4	135.9 (5)	Cr1–C4–C5	72.1 (6)	C5–C11–C12	123.6 (10)
C1–Cr1–C5	167.3 (5)	Cr1–C4–C9	71.4 (6)	C5–C11–C13	122.1 (11)
C1–Cr1–C6	137.9 (5)	Cr1–C4–O4	131.9 (7)	C12–C11–C13	57.8 (10)
C1–Cr1–C7	104.5 (6)	Cr1–C4–C9	123.8 (9)	C11–C12–C13	61.8 (9)
C1–Cr1–C8	88.5 (6)	5–4-O4	114.5 (8)	C11–C13–C12	60.4 (9)
C1–Cr1–C9	102.0 (5)	C9–C4–O4	121.7 (9)	C11–C13–C14	119.4 (10)
C2–Cr1–C3	90.1 (5)	Cr1–C5–C4	72.6 (6)	C11–C13–C15	116.3 (11)
C2–Cr1–C4	84.7 (4)	Cr1–C5–C6	69.7 (6)	C12–C13–C14	117.8 (15)
C2–Cr1–C5	96.6 (4)	Cr1–C5–C11	127.2 (8)	C11–C13–C15	118.2 (12)
C2–Cr1–C6	131.4 (5)	4–C5–C6	117.7 (9)	C14–C13–C15	114.4 (13)
C2–Cr1–C7	161.1 (5)	4–C5–C11	120.4 (8)	C5–Cr1–C6	37.8 (4)
C2–Cr1–C8	134.0 (5)	6–C5–C11	121.8 (9)	C5–Cr1–C7	66.8 (5)
C2–Cr1–C9	99.9 (5)	Cr1–C6–C5	72.5 (6)	C5–Cr1–C8	79.0 (4)
C3–Cr1–C4	133.0 (4)	Cr1–C6–C7	71.7 (7)	C5–Cr1–C9	66.4 (4)
C3–Cr1–C5	99.9 (4)	C5–C6–C7	119.6 (10)	C6–Cr1–C7	36.8 (5)
C3–Cr1–C6	85.0 (5)	Cr1–C7–C6	71.5 (7)	C6–Cr1–C8	67.2 (5)
C3–Cr1–C7	101.2 (5)	Cr1–C7–C8	70.2 (7)	C6–Cr1–C9	78.8 (4)
C3–Cr1–C8	135.9 (5)	C6–C7–C8	120.3 (11)	C7–Cr1–C8	37.4 (5)
C3–Cr1–C9	163.7 (5)	Cr1–C8–C7	72.4 (7)	C7–Cr1–C9	66.0 (4)
C4–Cr1–C5	35.3 (3)	Cr1–C8–C9	74.5 (8)	C8–Cr1–C9	36.3 (5)
C4–Cr1–C6	65.1 (4)	C7–C8–C9	121.2 (12)	Cr1–C1–O1	176.3 (12)
C4–Cr1–C7	76.5 (4)	Cr1–C9–C4	71.7 (6)	C4–Cr1–C9	37.0 (4)

the resulting cyclopropanes would form through backside ring closure.[11b] If this mechanism also applies here, the chiral cyclopropane *RR*-**11a** would be formed from the *anti* isomer. Should the *syn* isomer react with 2-methylpropene and backside ring closure occur, the cyclopropane *RS*-**11a** would form (Scheme 12).

The transfer results (Table 2) illustrate higher ee (92–95%) for the final cyclopropanes from the disubstituted alkenes. Lower enantiomeric excesses were observed for the cyclopropanes resulting from styrene and the styrene derivatives. Experimentally it was observed that the characteristic purple color of the reaction mixture, assumed to be the carbene, disappeared at low temperature in the presence of the disubstituted alkenes such as 2-methylpropene and 1,1-diphenylethylene. At lower temperature, the *anti* isomer may react faster than the *syn* isomer and, thus, enhance the asymmetric induction. In contrast, the purple color persisted at low temperature in the presence of mono-substituted alkenes, such as styrene. It faded only when the reaction temperature was slowly increased to room temperature. At higher temperature, both *syn* and *anti* may react at appreciable rates and, thus, result in lower diastereoselectivity. Kinetic studies are currently underway in order to substantiate this mechanism of the carbene transfer and rationale of selectivity.



Scheme 11.

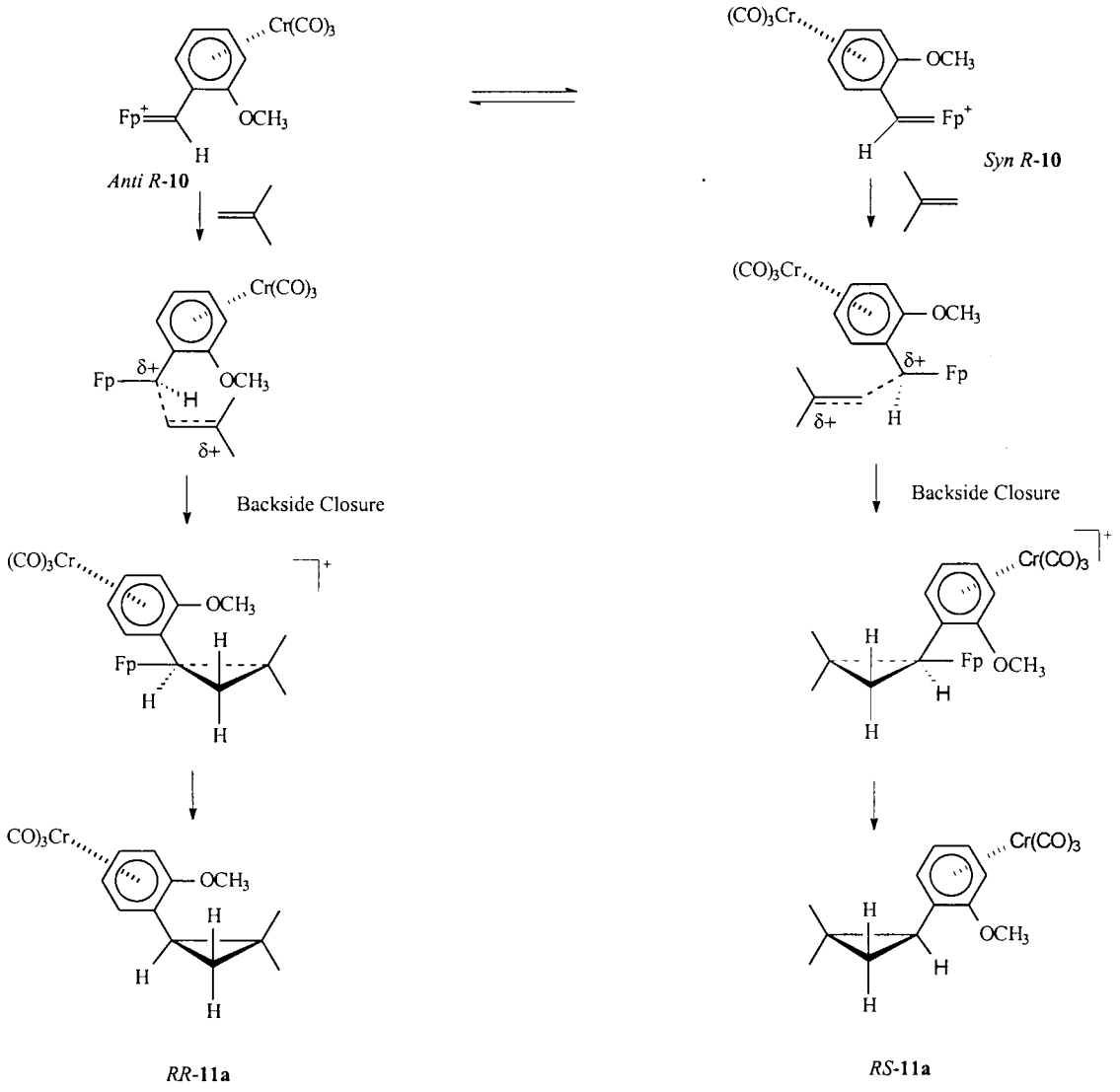
Determination of *cis* or *trans* configuration and the *cis*–*trans* ratio of the cyclopropanes

The *cis* or *trans* configuration of the cyclopropanes can be established unambiguously by ^{1}H NMR and 2D NOESY spectroscopy. Proton NMR spectra of cyclopropanes **12d**, **12e** and *cis* **12f** in $CDCl_3$ show overlapping peaks for the two protons α to the arene groups. Well-resolved ^{1}H NMR spectra were obtained for these cyclopropanes in C_6D_6. These spectra allow the chemical shifts and coupling constants to be determined. The *cis* isomer of **12f** produces a doublet of triplets with two *cis* vicinal couplings, each being J_{HH}=8.8 Hz, and a *trans* vicinal coupling, J_{HH}=6.3 Hz. The *trans* isomer of **12f** shows a doublet of doublets, with J_{HH}=9.0 Hz for the *cis* vicinal coupling and two small *trans* vicinal couplings, J_{HH}=6.2 and 5.1 Hz. In order to further verify the *cis* or *trans* configuration, 2D NOESY NMR spectra were studied for the *cis* and *trans* 1-*p*-trifluoromethylphenyl-2-*o*-methoxyphenylcyclopropanes **12f**. The 2D NOESY study clearly shows that the *cis* isomer exhibits a strong interaction between H_a and H_b (Fig. 2), while the *trans* isomer has no such interaction (Fig. 3). Similarly, the configurations of *cis* **12d** and *cis* **12e** were also established by ^{1}H NMR and 2D NOESY NMR studies.

The *cis*–*trans* ratios of the cyclopropanes were determined by ^{1}H NMR. The methoxy protons of the *cis* and *trans* cyclopropanes **12c**–**f** have different chemical shifts. The ratios were easily determined by integration of the ^{1}H NMR singlets.

Determination of enantiomeric excess

Due to the complexity of the ^{1}H NMR spectra for most of the complexed cyclopropanes **11**, the diastereomeric excesses (de) can not be simply determined. The



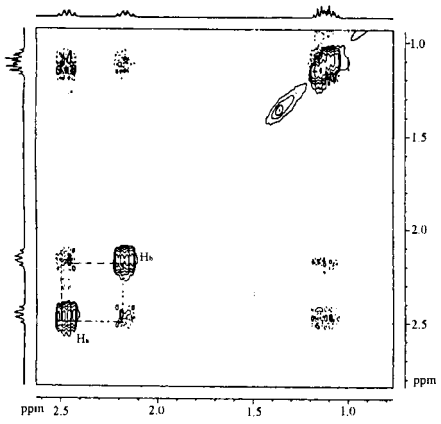
Scheme 12.

enantiomeric excess of each cyclopropane was determined by a shift experiment utilizing either a lanthanide shift reagent[18] (for *R*- and *S*-**12a**, *RS*- and *SR*-**12c**) or the combination of a lanthanide shift reagent and silver-fod[19] (*R*- and *S*-**12b**, *RS*-**12d**, *RS*-**12e**, *RR*-**12e** *RS*-**12f** and *RR*-**12f**). The ^{1}H NMR signal for the methoxy protons of the cyclopropanes exhibited baseline separation for the two enantiomers after 1–3 equiv. of shift reagents were added. Integration of the two peaks allowed for the determination of the enantiomeric excess. The ee's for the cyclopropanes are listed in Table 2.

The absolute configuration of *R*-(+)-1-*o*-methoxyphenyl-2,2-dimethylcyclopropane, *R*-**12a**, was based upon the X-ray structure of it's precursor, the corresponding complexed cyclopropane *RR*-**11a**. *S*-**12a** was also determined by X-ray structure analysis of the analogous chromium complex.[14] Scheme 10 shows the absolute configuration of the major cyclopropane enantiomer formed via carbene transfer from *S* or *R* carbene complexes to the *different* olefins.

Summary

An efficient route has been developed for the synthesis of diastereomerically pure carbene precursors (η^5-C_5H_5)-$(CO)_2FeCH(OSiMe_3)[\eta^6$-(*o*-$CH_3OC_6H_4)Cr(CO)_3]$ in a two step, one-pot reaction. The reaction of the Fp anion with optically pure *S*- or *R*-*o*-anisaldehyde(tricarbonyl)chromium complex followed by chlorotrimethylsilane trapping conveniently produced the carbene precursors. These were easily converted into chiral carbene complexes by treatment with triflate. There are several conceivable advantages of this route. First, it maintains dicarbonyl ligation to iron and, thus, maintains higher reactivity. This also provides better *cis–trans* selectivity than its chiral-at-metal analogs. Second, it is possible to separate the diastereomers of the cyclopropanes before the elimination of the chiral chromium auxiliary and, thus, could facilitate high ee. Finally, this route is potentially applicable to any chiral aldehyde, reactive towards the Fp anion.



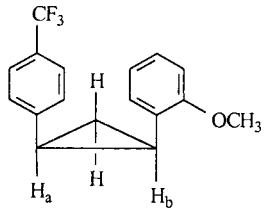
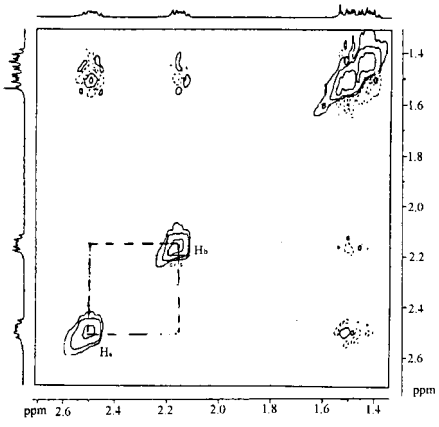


Figure 2. {^{1}H, ^{1}H} NOESY 2D NMR spectrum of *cis* **12f**.



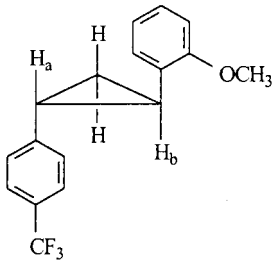


Figure 3. {^{1}H, ^{1}H} NOESY 2D NMR spectrum of *trans* **12f**.

Experimental

General methods

All reactions and manipulations of transition metal complexes were performed under a dry nitrogen atmosphere using standard Schlenk line and/or dry box techniques. All glassware required for the above was either flamed under vacuum or dried in an oven prior to use.

Tetrahydrofuran (Baker, reagent grade) and diethyl ether (EM Science, reagent grade) were freshly distilled under a nitrogen atmosphere from sodium benzophenone ketyl. Dichloromethane (Baker, HPLC grade) was distilled under nitrogen from phosphorus pentoxide. Pentane (technical grade) was purified by stirring overnight with concentrated sulfuric acid, washing with $NaHCO_3$ and water, drying over anhydrous Na_2SO_4, distilling, and redistilling prior to use from sodium under nitrogen.

Potassium cyclopentadienyldicarbonylferrate[20] and enantiomerically pure *S*- and *R*-*o*-anisaldehyde (tricarbonyl) chromium complexes[21] were prepared according to the literature procedure. *o*-Anisaldehyde (Aldrich), chlorotrimethylsilane (Lancaster) and trimethylsilyl triflate (Lancaster) were used without purification. All of the olefins, 2-methylpropene (Aldrich), 1,1-diphenylethylene (Aldrich), styrene (Aldrich), *p*-methylstyrene (Aldrich), *p*-chlorostyrene (Acros), and *p*-trifluoromethylstyrene (Aldrich) were used without purification unless stated otherwise. Deuterated chloroform (Isotec) was refluxed over phosphorous pentoxide, degassed using several freeze–pump–thaw cycles, distilled under vacuum from P_2O_5 using a Schlenk flask and stored under nitrogen. Benzene-d_6 was obtained from Aldrich and used without purification. Shift reagents, (+)-Eu(hfc)$_3$, D-Yb(hfc)$_3$ and Ag-fod were obtained from Lancaster and used without purification.

^{1}H and ^{13}C NMR spectra were obtained in $CDCl_3$ or C_6D_6 on a 250 or 300 MHz spectrometer. Chemical shifts for the ^{1}H NMR spectra were referenced to residual $CHCl_3$ (δ 7.24) or C_6H_6 (δ 7.15). ^{13}C NMR resonances were measured from $CDCl_3$ (77.0 ppm). Infrared spectra were recorded using a standard FTIR spectrometer. Optical rotations were determined on a digital polarimeter at 25°C. The CHN analyses were carried out with a standard element analyzer. Mass spectra were obtained on a GC/MS system, operated with DIP (direct insertion probe) and EI-70 eV. X-Ray diffraction analysis was performed on a 4-circle autodiffractomer at 22(2)°C.

Synthesis of *SS*-(−)- and *RR*-(+)-(η^5-C_5H_5)-(CO)$_2$FeCH(OSiMe$_3$)[η^6-*o*-$CH_3OC_6H_4Cr(CO)_3$] 9

The synthesis of *SS*-(−)-**9** has been previously described.[14] Using the same procedure, *RR*-(+)-**9** was obtained as a golden–yellow solid in 92% yield. ^{1}H NMR and ^{13}C NMR are identical with its *SS*-(−) isomer. Anal. calcd for $C_{21}H_{22}O_7FeCrSi$: C, 48.29; H, 4.24. Found: C, 48.12; H, 4.21. $[\alpha]_D^{25}=+335$ (*c*, 0.832, $CHCl_3$).

Synthesis of complexed cyclopropane of *SS*-(−)- and *RR*-(+)-1-*o*-methoxyphenyl (tricarbonyl chromium)-2,2-dimethylcyclopropane 11a

The synthesis of *SS*-**11a** has been previously described.[14] Using the same procedure, a bright yellow solid of *RR*-11a was isolated with 92% yield. ^{1}H NMR and ^{13}C NMR

are identical with its *SS*-(−) isomer. Anal. calcd for $C_{15}H_{16}O_4Cr$: C, 57.69; H, 5.16. Found: C, 57.73; H, 5.24. $[\alpha]_D^{25}=+191$ (*c*, 0.136, $CHCl_3$).

X-Ray diffraction study on the structure of *RR*-11a

The procedure for data collection was exactly the same as described for *SS*-**11a**.[14] The crystallographic data are listed in Table 3.

General procedure for transfer of carbene ligands to olefins to form cyclopropanes

The chiral isomers of **12a**–**f**, were synthesized according to the following procedure. A 2.5–3.0 mmol (1 equiv.) sample of the diastereomerically pure precursor *SS*- or *RR*-**9** was dissolved in 25 ml of CH_2Cl_2 and then cooled to −78°C. 5.0–6.0 mmol (2 equiv.) (an excess of 2-methylpropene was used[14]) of the olefin was added. After adding 2.7–3.3 mmol (1.1 equiv.) of TMSOTf, the color of the reaction mixture changed to purple. The solution was stirred for 4 h at −78°C and warmed to room temperature over 0.5 h. During this period, the purple color changed at a different rate, depending upon which olefin was used, indicating the consumption of the carbene. Passing the reaction mixture through a short column of neutral alumina (activity 4) followed by removal of the solvent under reduced pressure gave a yellow–brown residue. To decomplex the $Cr(CO)_3$ moiety, the crude product was dissolved in pentane and ether (1:1) and stirred under a sun lamp or natural sunlight for 3 days with the solution open to the air. When the solution became colorless, it was subjected to gravity filtration. The solvent was removed under reduced pressure and a colorless liquid of cyclopropane mixture was obtained with a good yield. This mixture was directly analyzed by ^{1}H NMR to determine the *cis*–*trans* ratio. Otherwise, the mixture was separated by column chromatography on silica or alumina (activity III) and all cyclopropanes were collected to determine the *cis*–*trans* ratio and ee by ^{1}H NMR. Further purification by column chromatography or preparative TLC provided the *cis* or *trans* cyclopropanes. The yields and isomeric ratios are listed in Table 2.

Specific procedure for the decomplexation of $Cr(CO)_3$ moiety

An alternative procedure for the decomplexation of the $Cr(CO)_3$ moiety has been employed for preparing *S*- and *R*-**12c**. To a diethyl ether solution of crude cyclopropane complex, 4 equiv. of iodine were added. After 4 h of stirring at room temperature, the mixture was added to an aqueous solution of sodium thiosulfate. The organic layer was washed with tap water. The organic layer was then passed through a short neutral alumina (activity 4) column and dried over anhydrous magnesium sulfate. The solvent was removed by simple distillation. The oily residue was separated using neutral alumina (activity 1) with a solution of ether in pentane followed by removal of solvents under reduced pressure.

Cyclopropane *R*-12a. The cyclopropane *R*-**12a** was isolated as a colorless liquid. ^{1}H and ^{13}C NMR spectra are identical with the *S* enantiomer.[14] Anal. calcd for $C_{12}H_{16}O$: C, 81.77; H, 9.15. Found: C, 81.80; H, 9.46. MS *m*/*z*: 176 (46%, M+). $[\alpha]_D^{25}=+52$ (*c*, 0.214, $CHCl_3$), >95% ee.

Cyclopropanes *S*-12b and *R*-12b. The complexed cyclopropanes *RR*-**11b** and *SS*-**11b** were not separated and purified. However, the cyclopropanes *S*-**12b** and *R*-**12b** were isolated as white solids. ^{1}H NMR, ^{13}C NMR and CHN analyses are identical with the racemic cyclopropane **12b** reported.[9b] *S*-**12b**: $[\alpha]_D^{25}=-81$ (*c*, 0.100, $CHCl_3$), 92% ee. *R*-**12b**: $[\alpha]_D^{25}=+80$ (*c*, 0.100, $CHCl_3$), 92% ee.

Cyclopropanes *RS*-12c and *SR*-12c. The complexed cyclopropanes **11c** were not separated and purified. Following the procedure stated above, only *cis* cyclopropanes *RS*-**12c** and *SR*-**12c** were isolated. Analytic data are identical with the racemic *cis* cyclopropane **12c** reported.[9b] *RS*-**12c**: $[\alpha]_D^{25}=+21$ (*c*, 1.7, $CHCl_3$), 60% ee. *SR*-**12c**: $[\alpha]_D^{25}=-21$ (*c*, 1.7, $CHCl_3$), 60% ee.

Cyclopropane *RRS*-11d and *RS*-12d. The crude product of complexed cyclopropane *RRS*-**11d** was isolated by alumina (activity IV) column separation. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.04–6.70 (m, 4H, Ph), 5.23 (t, *J*=6.42 Hz, 1H, Ph), 5.04 (d, *J*=5.85 Hz, 1H, Ph), 4.94 (d, *J*=6.84 Hz, 1H, Ph), 4.65 (t, *J*=6.26 Hz, 1H, Ph), 3.71 (s, 3H, OCH_3), 2.50 (m, 2H, CH), 2.21 (s, 3H, CH_3), 1.37 (m, 1H, CH_2), 1.27 (m, 1H, CH_2). Using the procedure described above, only *cis* cyclopropane, *RS*-**12d**, was isolated as a colorless liquid. ^{1}H NMR (C_6D_6, 300 MHz) δ: 7.06–6.78 (m, 6H, Ph), 6.70 (t, *J*=7.5 Hz, 1H, Ph), 6.40 (d, *J*=8.1 Hz, 1H, Ph), 3.29 (s, 3H, OCH_3), 2.58 (d of t, *J*=8.7 Hz, *J*=6.9 Hz, 1H, CH), 2.39 (d of t, *J*=8.7 Hz, *J*=6.3 Hz, 1H, CH), 1.96 (s, 3H CH_3), 1.32 (q, *J*=6.0 Hz, 1H, one of CH_2), 1.16 (m, 1H, one of CH_2). ^{13}C NMR ($CDCl_3$, 75.4 MHz) δ: 159.4, 157.8, 136.2, 134.9, 129.7, 128.5 (2C), 128.4 (2C), 127.3, 120.1, 110.3, 55.7 (OCH_3), 23.5 (CH), 21.3 (CH_3), 20.4 (CH), 10.4 (CH_2). Anal. calcd for $C_{17}H_{18}O$: C, 85.67; H, 7.61. Found: C, 85.63; H, 7.69. MS *m*/*z*: 238 (100%, M^+). $[\alpha]_D^{25}=+66$ (*c*, 0.89, $CHCl_3$), 55% ee.

Cyclopropane *RRS*-11e and *RS*-12e. The crude product of complexed cyclopropane *RRS*-**11e** was isolated by alumina (activity IV) column separation. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.00 (d, *J*=8.60 Hz, 2H, Ph), 6.88 (d, *J*=8.22 Hz, 2H, Ph), 5.19 (t, *J*=6.81 Hz, 1H, Ph), 5.00 (d, *J*=6.08 Hz, 1H, Ph), 4.86 (d, *J*=6.60 Hz, 1H, Ph), 4.61 (t, *J*=6.87 Hz, 1H, Ph), 3.63 (s, 3H, OCH_3), 2.44 (m, 2H, CH), 1.35 (m, 2H, CH_2). Using the procedure described above, only *cis* cyclopropane *RS*-**12e** was isolated as a colorless liquid. ^{1}H NMR (C_6D_6, 300 MHz) δ: 6.92–6.87 (m, 4H, Ph), 6.69–6.63 (m, 3H, Ph), 6.33 (d, *J*=8.1 Hz, 1H, Ph), 3.17 (s, 3H, OCH_3), 2.47 (m 1H, CH), 2.17 (d of t, *J*=9.0 Hz, *J*=6.0 Hz, 1H, CH), 1.10 (m, 2H, CH_2). ^{13}C NMR ($CDCl_3$, 75.4 MHz) δ: 159.3, 138.2, 131.2, 129.9, 129.8 (2C), 128.1, 127.8 (2C), 126.6, 120.3, 110.3, 55.6 (OCH_3), 23.2 (CH), 21.1 (CH), 10.6 (CH_2). Anal. calcd for $C_{16}H_{15}OCl$: C, 74.27; H, 5.84. Found: C, 74.33; H, 5.85. MS *m*/*z*: 258 (93%, M^+). $[\alpha]_D^{25}=+109$ (*c*, 1.62, $CHCl_3$), 46% ee. The *trans* cyclopropane *RR*-**12e** was detected by ^{1}H NMR and the ee was determined as 53% by chiral shift reagent from the crude product, however, it was not isolated and characterized.

Cyclopropane *RS*-12f. The complexed cyclopropane was not separated and purified. After preparative TLC, *cis* **12f** was obtained as a colorless liquid. ^{1}H NMR (C_6D_6, 300 MHz) δ: 7.09–6.68 (m, 7H, Ph), 6.26 (d, J=8.1 Hz, 1H, Ph), 3.09 (s, 3H, OCH_3), 2.45 (d of t, J=8.7 Hz, J=7.1 Hz, 1H, CH), 2.15 (d of t, J=8.7 Hz, J=6.3 Hz, 1H, CH), 1.10 (m, 2H, CH_2). ^{13}C NMR ($CDCl_3$, 75.4 MHz) δ: 158.7, 143.7, 129.7, 127.8 (2C), 127.5, [129.7, 126.1, 122.5, 118.9, q, ^1J (C,F)=271 Hz, CF_3], [127.8, 127.4, 127.0, 126.6, q, ^2J (C,F)=30 Hz], 125.7, 123.9, 123.8, 119.8, 109.8, 55.0 (OCH_3), 23.0 (CH), 21.3 (CH), 10.7 (CH_2). ^{19}F NMR ($CDCl_3$, 282.2 MHz) δ: −62.67 (s). Anal. calcd for $C_{17}H_{15}OF_3$: C, 69.85; H, 5.17. Found: C, 69.88; H, 5.15. MS *m/z*: 292 (100%, M^+). $[\alpha]_D^{25}$=+31 (*c*, 0.33, $CHCl_3$), 30% ee.

Cyclopropane *RR*-12f. The complexed cyclopropane was not separated and purified. After preparative TLC, *trans* **12f** was obtained as a white solid. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 751 (d, J=8.2 Hz, 2H, Ph), 7.27–7.23 (m, 2H, Ph), 7.17 (t, J=9.0 Hz, 1H, Ph), 6.98–6.84 (m, 3H, Ph), 3.81 (s, 3H, OCH_3), 2.45 (d of d of d, J=8.7 Hz, J=6.0 Hz, J=5.1 Hz, 1H, CH), 2.12 (d of d of d, J=8.7 Hz, J=5.4 Hz, J=5.4 Hz, 1H, CH), 1.43 (m, 2H, CH_2). ^{13}C NMR[22] ($CDCl_3$, 75.4 MHz) δ: 158.1, 147.3, 130.0, [128.3, 127.9, 127.5, 127.1, q, ^2J (C,F)=30 Hz], 126.9, 126.1 (2C), 125.1(2C), 125.0, 120.4, 110.2, 55.4 (OCH_3), 26.2 (CH), 22.5 (CH), 17.1 (CH_2). ^{19}F NMR ($CDCl_3$, 282.2 MHz) δ: −62.65 (s). Anal. calcd for $C_{17}H_{15}OF_3$: C, 69.85; H, 5.17. Found: C, 69.79; H, 5.19. MS *m/z*: 292 (100%, M^+). $[\alpha]_D^{25}$=−115 (*c*, 0.25, $CHCl_3$), 72% ee.

^{1}H NMR shift experiments on the cyclopropanes

Method I. The enantiomeric excess of the cyclopropane *R*-**12a** was determined as before.[14]

Method II. To determine the enantiomeric excess of *SR*- and *RS*-**12c**, (+)-Eu(hfc)$_3$ was employed. 7.1 mg (0.036 mmol) of sample was dissolved in 0.5 ml of $CDCl_3$ in a NMR tube. After adding 0.5 ml solution of 43 mg (0.0036 mmol) (+)-Eu(hfc)$_3$ to the sample in two portions, ^{1}H NMR spectra were recorded. The methoxy peak of the cyclopropane shifted downfield and split into two peaks. After allowing this shift reagent/cyclopropane mixture to sit overnight, a very clear resolution was observed. 1:1 peak integrations for racemic **12c** and 1:4 or 4:1 peak integrations for *SR*- or *RS*-**12c** were obtained.

Method III. For the determination of the enantiomeric excess for *R*- and *S*-**12b**, *RS*-**12d**, **e**, **f**, both D-Yb(hfc)$_3$ and Ag-fod were employed. Typically, 2 mg of sample were dissolved in 0.5 ml of $CDCl_3$. Yb(hfc)$_3$ and Ag-fod were added as needed in increasing quantities of 0.5–3 equiv. Each time the shift reagent was added, the ^{1}H NMR spectrum was recorded. The resonance of the methoxy signal shifted downfield and split upon addition of the appropriate amount shift reagents. Clear separation of sharp signals for the methoxy peaks was achieved upon addition of a total of 2 equiv. of Yb(hfc)$_3$ and 1 equiv. of Ag-fod for most cases. All of the %ee are listed in Table 2.

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