Chapter 4

Nickel-Catalyzed Asymmetric Reductive Cross-Coupling Between Vinyl and Benzyl Electrophiles[†]

4.1 INTRODUCTION

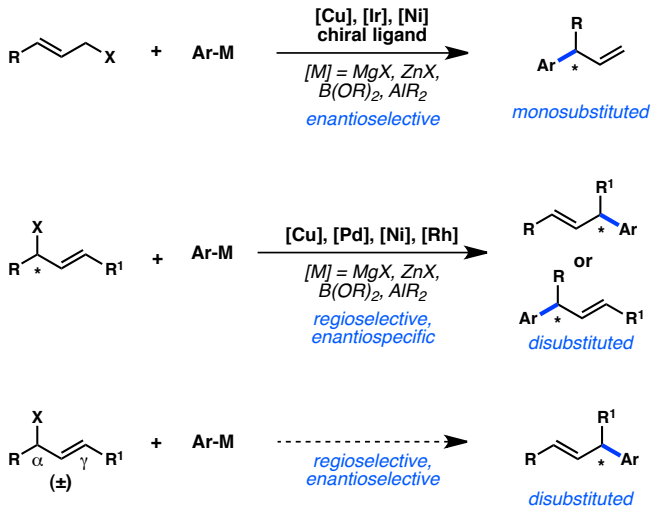
Ni-catalyzed reductive cross-coupling reactions have recently emerged as direct methods for carbon–carbon bond formation between two organic electrophiles.[1] In these reactions, Mn^0 or Zn^0 are typically employed as stoichiometric reductants to turn over a Ni catalyst. Improvements in ligand structure and mechanistic understanding have enabled the cross-coupling between a range of $C(sp^3)$ and $C(sp^2)$ electrophiles bearing a variety of functional groups.[2, 3, 4] The ability to employ bench stable and readily available organic halides, without the need to pre-generate a reactive organometallic reagent, endows these reductive cross-coupling reactions with a practical advantage over many conventional cross-coupling procedures. In addition, several studies have demonstrated

[†] Portions of this chapter have been reproduced from published studies (see reference 15) and the supporting information found therein.

that *sec*-alkyl electrophiles are competent reaction partners, providing racemic products bearing stereogenic centers.[2a,b,d,e,h,3a,5] The utility of such transformations would be greatly improved if rendered enantioselective, providing direct access to enantioenriched chiral products from racemic starting materials.

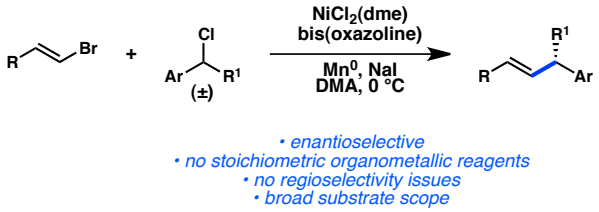
Alkenes bearing stereogenic, aryl-substituted tertiary allylic centers are synthetically useful compounds that can be challenging to prepare using conventional asymmetric allylic substitution reactions (Scheme 4.1).[6,7] Significant progress toward the catalytic enantioselective arylation of allylic electrophiles has been made to selectively form branched over linear *mono*substituted products.[8] Stereospecific and regioselective arylation of allylic electrophiles to form *di*substituted products has also been disclosed for a series of organometallic reagents.[9] However, catalysts that simultaneously induce high regio- and enantioselection in the arylation of acyclic, unsymmetrical α,γ-disubstituted allylic electrophiles have not been developed.[10]

Scheme 4.1. *Enantiocontrolled allylic arylation.*



We envisioned that a Ni-catalyzed asymmetric reductive cross-coupling could provide a mild and selective alternative approach to such products.[11] We realized that a complementary disconnection involving a vinyl halide starting material would avoid the regioselectivity issues that often complicate reactions of α,γ-disubstituted allylic electrophiles. Indeed, the reactivity of vinyl halides in Ni-catalyzed reductive cross-coupling reactions is well-precedented, with Semmelhack and coworkers reporting the first Ni-catalyzed homocoupling of such species in 1972.[12] Despite subsequent disclosures of electrochemical Ni-catalyzed couplings,[13] the first reductive *cross*-coupling of a vinyl halide that employed a chemical reductant such as Mn^0 or Zn^0 was developed by Weix and coworkers in 2012.[2d] Furthermore, our recent report on asymmetric reductive cross-coupling for the preparation of ketones suggested that secondary benzylic chlorides could be used to promote enantioinduction in the presence of a chiral catalyst.[14] In this chapter, we report a highly enantioselective Ni-catalyzed reductive cross-coupling between vinyl bromides and benzyl chlorides (Figure 4.1).[15,16] A variety of alkenyl products bearing allylic stereogenic centers are prepared in good yields with high enantiomeric excess under mild conditions.

Figure 4.1. *This work: Asymmetric reductive vinyl cross-coupling.*



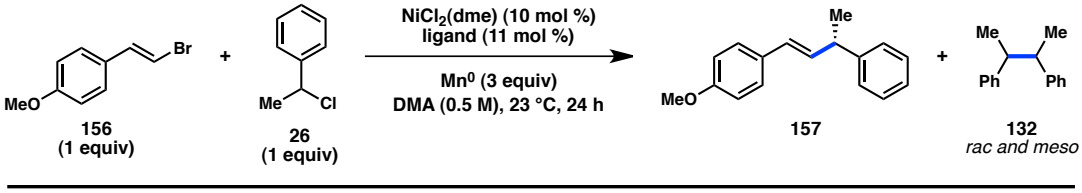
4.2 DEVELOPMENT OF AN ASYMMETRIC REDUCTIVE VINYL CROSS-COUPLING

4.2.1 Identification of a Chiral Catalyst System

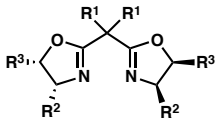
Our investigations commenced with the coupling of an equimolar mixture of vinyl bromide **156** and benzyl chloride **26** using $NiCl_2$(dme) (10 mol %), a chiral ligand (11 mol %), Mn^0 as the stoichiometric reductant, and DMA as solvent. A series of bis(oxazoline) ligands delivered a mixture of product **157** and butane-2,3-diyldibenzene (**132**), arising from homocoupling of **26** (Figure 4.2).[17] In all cases, **132** was observed as a 1:1 mixture of the *meso* and *rac* diastereomers. Formation of unreactive chlorostyrene side products, resulting from Ni-catalyzed halide exchange of **156**, was also observed.[18] Among simple isopropylidene-linked Box ligands, **L100** (R = Bn) delivered **157** in 71% ee while the bulky **L66** (R = ^{t}Bu) provided a nearly racemic product (entries 1–4). Tuning the ligand bite angle by investigating other linkers on the Box scaffold revealed that **L112**, bearing a cyclopropyl bridge, induced formation of **157** in 81% ee (entry 9). We next hypothesized that rigidifying the ligand framework would result in greater enantioinduction. In the event, indanyl-substituted ligands demonstrated that **L104**, also containing a cyclopropyl bridge, furnished the desired product in 89% ee (entry 11).

In addition to Box ligands, several other ligand families were also studied. Bi(oxazoline) ligands bearing less steric bulk delivered promising levels of enantioinduction (entries 12–15). Moderate enantioselectivity could also be achieved with cyanoBox **L106**. On the other hand, the PyOx, PHOX, and PyBox ligands that were tested all resulted in poor levels of asymmetric induction.

Figure 4.2. *Evaluation of chiral ligand frameworks.*

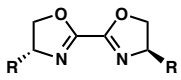


156 (1 equiv) + 26 (1 equiv) → 157 + 132 (*rac and meso*)



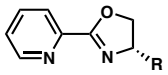
Bis(oxazoline) Ligand Scaffold

Entry	R^1	R^2	R^3	Ligand	ee (%)
1	Me	^{i}Pr	H	L99	47
2	Me	^{t}Bu	H	L66	2
3	Me	Bn	H	L100	71
4	Me	Ph	H	L36	45
5	Me	Ph	Ph	L109	41
6	Me	^{i}Bu	H	L110	32
7	H	Ph	H	L101	9
8	H	^{t}Bu	H	L111	1
9	$-CH_2CH_2-$	Bn	H	L112	81
10	Me	indanyl		L51	46
11	$-CH_2CH_2-$	indanyl		L104	89



Bi(oxazoline) Ligand Scaffold

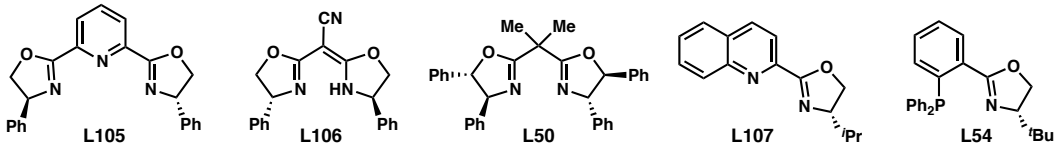
Entry	R	Ligand	ee (%)
12	^{i}Pr	L113	33
13	^{t}Bu	L114	5
14	Bn	L34	31
15	Ph	L115	1



Pyridine-oxazoline Ligand Scaffold

Entry	R	Ligand	ee (%)
16	^{t}Bu	L98	9
17	Bn	L116	16

Other Ligand Scaffolds

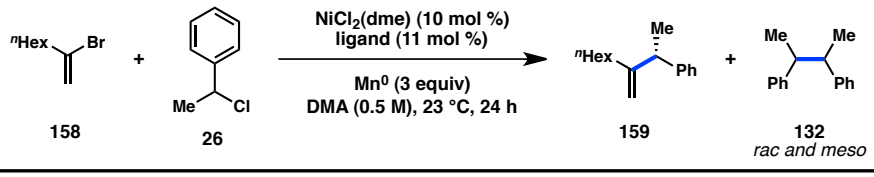


L105, 25% ee | L106, 53% ee | L50, 6% ee | L107, 1% ee | L54, 4% ee

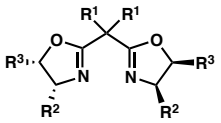
Having discovered a ligand that furnishes enantioenriched 1,2-disubstituted alkenes, we next pondered whether asymmetric generation of 1,1-disubstituted alkenes could also be achieved. Employing the coupling of vinyl bromide **158** and benzyl chloride **26** as a model system, we screened a variety of chiral ligands (Figure 4.3). In contrast to the reaction with styrenyl bromide **156**, bis(oxazoline) ligands resulted in poor enantioinduction (entries 1–8). On the other hand, bi(oxazoline) **L34** (R = Bn) provided a promising 35% ee of **159** (entry 11). The lower level of asymmetric induction for the

coupling of bromide **158** compared to styrenyl bromide **156** may be due to the increased steric congestion around the nickel center following oxidative addition.

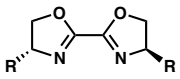
Figure 4.3. *Preparation of 1,1-disubstituted alkenes.*



158 26 159 132 *rac and meso*



Bis(oxazoline) Ligand Scaffold

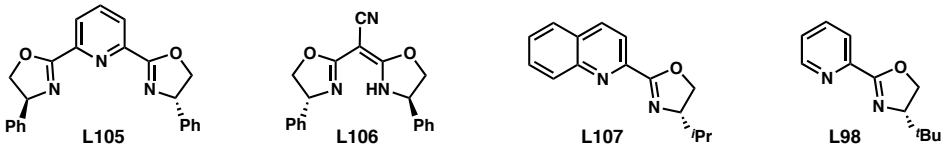


Bi(oxazoline) Ligand Scaffold

Entry	R^1	R^2	R^3	Ligand	ee (%)
1	Me	^{i}Pr	H	L99	7
2	Me	^{t}Bu	H	L66	12
3	Me	Bn	H	L100	4
4	Me	Ph	H	L36	3
5	H	Ph	Ph	L43	2
6	–CH_2CH_2–	Ph	Ph	L102	4
7	H	indanyl		L103	10
8	Me	indanyl		L51	5

Entry	R	Ligand	ee (%)
9	^{i}Pr	L113	7
10	^{t}Bu	L114	4
11	Bn	L34	35
12	Ph	L115	2

Other Ligand Scaffolds



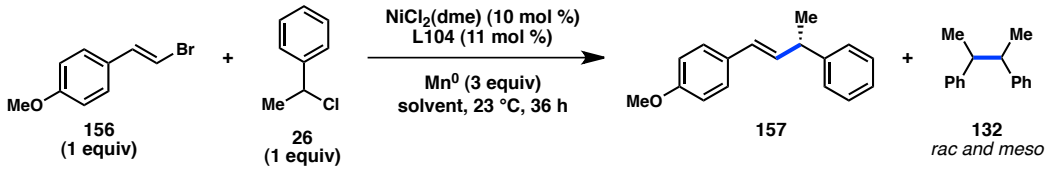
L105 no product; L106 no product; L107 17% ee; L98 4% ee

4.2.2 Optimization of Reactivity for an Enantioselective Reaction

With indanyl-substituted ligand **L104** in hand, we next investigated other reaction parameters to increase the yield of our desired transformation. Polar solvents with high dielectric constants provided the greatest yields of product **157** (Table 4.1, entries 1–4). In contrast to our previous acyl coupling, THF delivered reduced enantioinduction

compared to DMA. Overall, the enantioselectivity of the cross-coupling was not very sensitive to the choice of solvent as long as highly polar solvents were chosen. Under the best conditions, product **157** could be obtained in a 3:1 ratio with homocoupled product **132**.

Table 4.1. *Evaluation of solvents.*

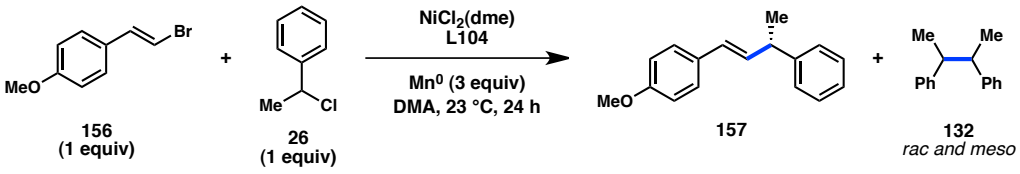


Entry	Solvent	Conversion (%)	Yield (%)	157:132	ee (%)
1	DMA	100	62	3:1	87
2	DMF	100	48	2:1	86
3	DMPU	100	57	2.5:1	89
4	NMP	100	51	2.5:1	91
5	DME	18	trace	--	45
6	dioxane	16	trace	--	3
7	THF	100	38	1.5:1	75
8	MeCN	39	10	1:1	2
9	EtOAc	100	33	1:1	15
10	CH_2Cl_2	21	trace	--	3

We next studied the effects of concentration, catalyst loading, and additives. Increasing the reaction concentration to 1.0 M raised the product yield to 69% with a concomitant improvement in the ratio of product to homocoupling (Table 4.2, entries 1–3). We next observed that lowering the catalyst loading below 10% led to a reduction in the selectivity for product formation over homocoupling without significantly altering the enantioinduction (entries 2, 4, and 5). With respect to additives, treatment with 2,6-dimethylbenzoic acid (DMBA), which was employed in our previous acyl coupling, led to a significant drop in yield and favored homodimer formation (entry 6).[14] On the other

hand, exposure to 0.5 equiv NaI improved the yield of product **157** and the selectivity for heterocoupling (entry 7). Several potential factors might be attributed to the beneficial role of NaI, which has previously found use in reductive cross-couplings.[2d] The iodide ion may be able to facilitate electron transfer between Ni and Mn by acting as a bridge between the two metals.[19] Improved reactivity may also be the result of ligand exchange on Ni[20] or the formation of a more reactive nickelate species.[21]

Table 4.2. *Evaluation of other reaction parameters.*



156 (1 equiv) + 26 (1 equiv) → 157 + 132 (*rac and meso*)

Entry	Concentration (M)	Cat. Loading (%)	Additive	Yield (%)	157:132	ee (%)
1	0.25	10	--	58	3:1	89
2	0.5	10	--	61	3:1	89
3	1.0	10	--	69	4.5:1	87
4	0.5	5	--	50	2:1	91
5	0.5	2.5	--	46	1.5:1	88
6	0.5	5	DMBA	16	1:2.5	76
7	0.5	5	NaI	75	5.5:1	93

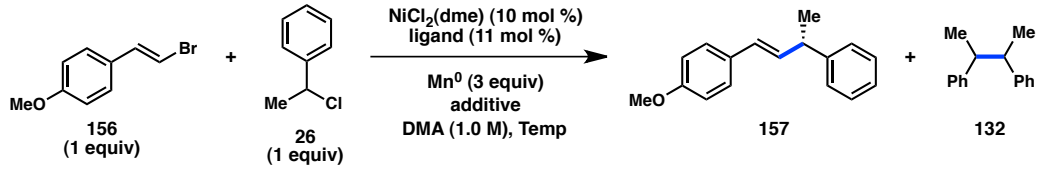
Alternatively, excess iodide may lead to in situ formation of organoiodide electrophiles. Generation of benzyl iodide in situ should lead to increased formation of homocoupling and is therefore unlikely. In contrast, crude reaction mixtures that did not proceed with complete conversion often revealed the presence of vinyl bromide **156** with competing amounts of the corresponding vinyl chloride and vinyl iodide. We rationalized that oxidative addition of Ni to bromide **156** is a reversible process; ligand exchange with a chloride followed by irreversible reductive elimination delivers a vinyl chloride side product, reducing the yield of desired product **157**.[22] Chloride ion, derived from benzyl

chloride **26**, increases over the course of the reaction. Addition of excess iodide could produce Ni-iodide complexes instead of Ni-chloride complexes. Importantly, reductive elimination from the vinyl-Ni-iodide complex would be reversible and not lead to a reduction in yield.

A summary of our optimization efforts for the coupling of vinyl bromide **156** and benzyl chloride **26** is shown in Table 4.3. Several isopropylidene-linked bis(oxazoline) ligands delivered product **157** in moderate yield and enantioselectivity, but favored formation of butane-2,3-diyldibenzene (**132**), arising from homocoupling of **26** (entries 1–3). Formation of unreactive chlorostyrene side products, resulting from Ni-catalyzed halide exchange of **156**, was also observed. Indanyl-substituted ligand **L51** slightly improved the selectivity, permitting formation of **157** in 26% yield and 70% ee (entry 4). Tuning the bite angle of the ligand by changing the central linker revealed that cyclopropyl-linked ligand **L104** produced **157** in 56% yield and 87% ee, favoring heterocoupling over homocoupling (entry 6).

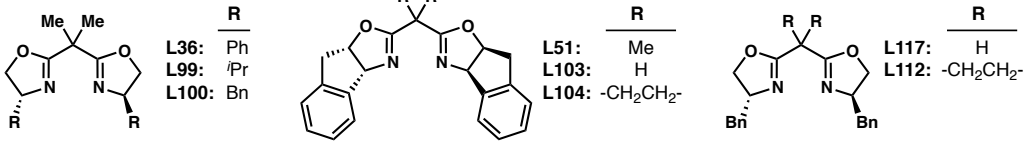
The reaction was further optimized through systematic study of several parameters. Trifluoroacetic acid (TFA) and trimethylsilyl chloride (TMSCl), additives known to activate the Mn^0 surface, failed to increase reaction efficiency (entries 9 and 10). In contrast, iodide sources, such as NaI or TBAI, improved the yield of **157** and decreased the yield of **132** (entries 11 and 12). Significantly, lowering the reaction temperature to 0 °C produced **157** in 93% yield and 93% ee (entry 13). A series of control experiments confirmed that product was not formed in the absence of Mn^0, Ni^{II} precatalyst, or ligand; significant decomposition of vinyl bromide **156** was also detected in the absence of ligand (entries 15–17).

Table 4.3. *Optimization of Ni-catalyzed asymmetric reductive coupling.*



Entry[a]	Ligand	Additive	Temp (°C)	Yield 132 (%)[b]	Yield 157 (%)[b]	ee 157 (%)[c]
1	L36	--	20	48	50	40
2	L99	--	20	33	21	57
3	L100	--	20	38	25	68
4	L51	--	20	35	26	70
5	L103	--	20	21	33	49
6	L104	--	20	20	56	87
7	L117	--	20	26	20	27
8	L112	--	20	21	56	78
9	L104	TFA	20	30	39	86
10	L104	TMSCl	20	26	33	73
11	L104	NaI[d]	20	17	67	87
12	L104	TBAI[d]	20	13	64	91
13	L104	NaI[d]	0	8	93	93
14[e]	L104	NaI[d]	0	8	69	89
15[f]	L104	NaI[d]	0	0	0	--
16[g]	L104	NaI[d]	0	0	0	--
17	--	NaI[d]	0	0	0	--

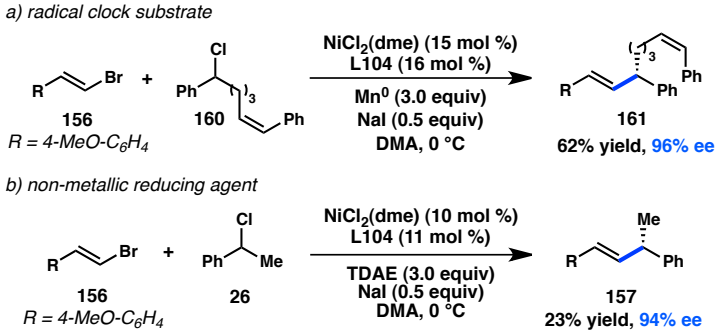
[a] Reactions conducted under N_2 on 0.2 mmol scale for 6 h. [b] Determined by GC versus an internal standard. [c] Determined by SFC using a chiral stationary phase. [d] 0.5 equiv. [e] Zn^0 used instead of Mn^0. [f] No Mn^0. [g] No $NiCl_2$(dme).



A series of experiments were conducted to provide insight into the reaction mechanism.[23] The reaction proceeds cleanly in the presence of the radical inhibitor 2,6-bis(1,1-dimethylethyl)-4-methylphenol (BHT, as high as 50 mol %).[24] In addition, radical clock substrate **160** was found to couple in good yield, without detection of any cyclized product or isomerization of the olefin geometry (Scheme 4.2, a). Taken together, these

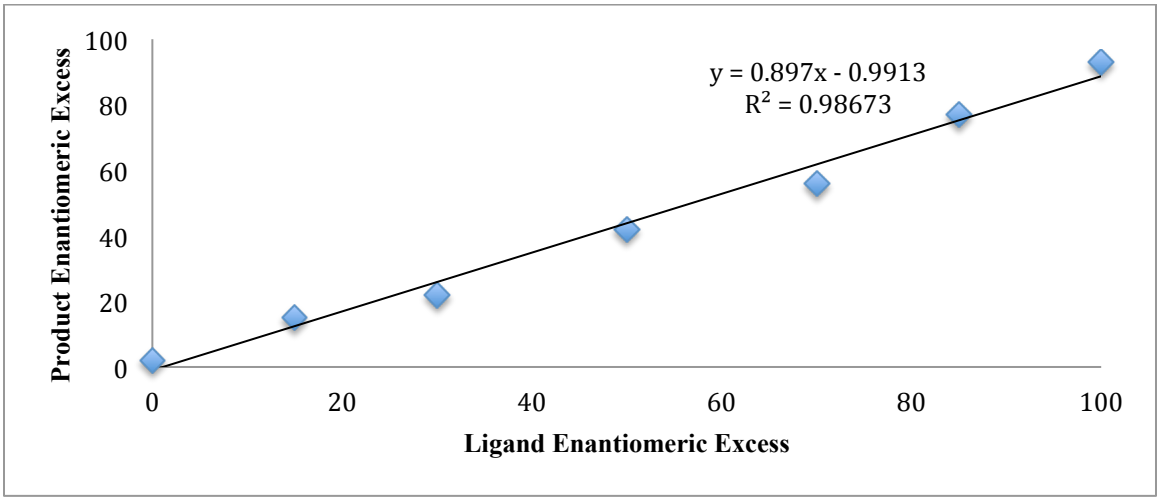
two results appear inconsistent with a radical chain reaction mechanism and suggest that if oxidative addition of **160** occurs by a step-wise mechanism, radical recombination is rapid and precludes cyclization.[25] The reaction proceeds with the same enantioselectivity when tetrakis(*N*,*N*-dimethylamino)ethylene (TDAE) is employed as the stoichiometric reductant, although the yield is reduced (Scheme 4.2, b).[26] This finding indicates that cross-coupling of an in situ-generated organomanganese reagent is unlikely. Lastly, use of enantioenriched benzyl chloride **26**, in either the presence or absence of NaI under otherwise optimized conditions, still delivers product **157** in 94% ee, illustrating the stereoconvergent nature of the transformation. Additional work is required to fully elucidate the reaction mechanism and the origin of enantioinduction.

Scheme 4.2. *Mechanistic investigations.*



Previous mechanistic studies by Amatore and Jutand have suggested that various reactive intermediates of Ni may aggregate under the reaction conditions.[23a] To assess the role of a reservoir effect in our system, we studied whether our enantioinduction exhibited any non-linear effects. As we increased the ee of scalemic ligand, we observed a linear increase in the ee of cross-coupled product **157** (Figure 4.4). This result suggests that a monomeric Ni complex is responsible for carrying out the cross-coupling reaction and that the active catalyst does not undergo reversible aggregation during the reaction.

Figure 4.4. *Examination of non-linear effects.*

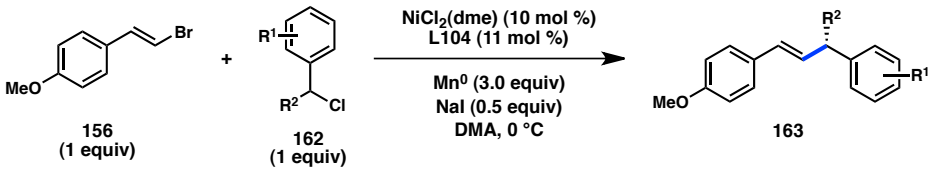


4.2.3 Substrate Scope and Further Studies

With optimized conditions in hand, we investigated the scope of the C(sp^3) coupling partner. A variety of benzyl chlorides can be coupled in high yield and high enantioselectivity (Table 4.4). Whereas *meta* and *para* substitution is well-tolerated, *ortho* substituents result in lower yield and ee (entries 2–4). Functional groups such as methoxide, fluoride, chloride, bromide, and trifluoromethoxide are tolerated (entries 5–9); however, in some cases increased levels of the butane-2,3-diyldiarene product is observed. We recalled that decreasing the catalyst loading was previously found to erode the selectivity for heterocoupling over homocoupling (see Table 4.2). We reasoned that increasing the catalyst loading might therefore decrease the level of homocoupling. Indeed, for these substrates, improved results are achieved with 15 mol % catalyst loading. For example, the yield of chloride **163g** rises from 54% to 76% when the catalyst loading increases from 10% to 15%. We were pleased to find that β-substituted

benzyl chlorides react with no erosion of ee as compared to the parent substrate **162a** (entries 10–14). Alkenyl substrate **162l**, potentially capable of cyclization under radical conditions, exclusively produced uncyclized product **163l** (entry 12). A substrate bearing a free alcohol can also be coupled in high yield and ee (entry 13).

Table 4.4. *Substrate scope of benzyl chlorides.*



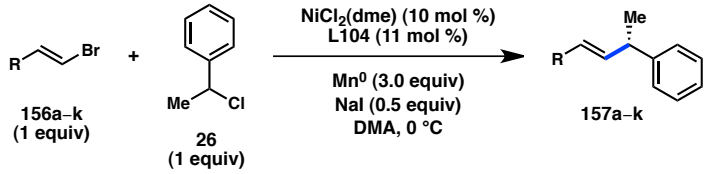
Entry	R^1	R^2	Pdt	Yield (%)[a]	ee (%)[b]
1	H	Me	163a	91	93
2	4-Me	Me	163b	82	94
3	3-Me	Me	163c	88	93
4[c]	2-Me	Me	163d	44	85
5	4-OMe	Me	163e	64	93
6	4-F	Me	163f	81	89
7[c]	4-Cl	Me	163g	75	88
8	4-Br	Me	163h	59	90
9[c]	4-OCF_3	Me	163i	84	88
10	H	Et	163j	80	97
11	H	Bn	163k	82	93
12	H	4-pentenyl	163l	68	94
13	H	2-hydroxyethyl	163m	81	96
14[c]	H	2-chloroethyl	163n	60	94

[a] Isolated yield, reactions conducted under N_2 on 0.2 mmol scale for 6 h. [b] Determined by SFC using a chiral stationary phase. [c] Run with 15 mol % $NiCl_2$(dme) and 16 mol % **L104**.

A broad scope of styrenyl bromides undergoes the cross-coupling to furnish products in good yields and enantioselectivities (Table 4.5). Regardless of the substitution pattern on the aryl ring of the styrene, a tight window of ee's (93–96%) is achieved. Higher catalyst loadings are sometimes necessary to mitigate formation of **132**. Notably, the dimethylamino (**157g**) and pinacol boronate (**157j**) functional groups are

compatible with the reaction. Both protected and free phenols also deliver the desired product in high yield (entries 6 and 11).

Table 4.5. *Substrate scope of styrenyl bromides.*



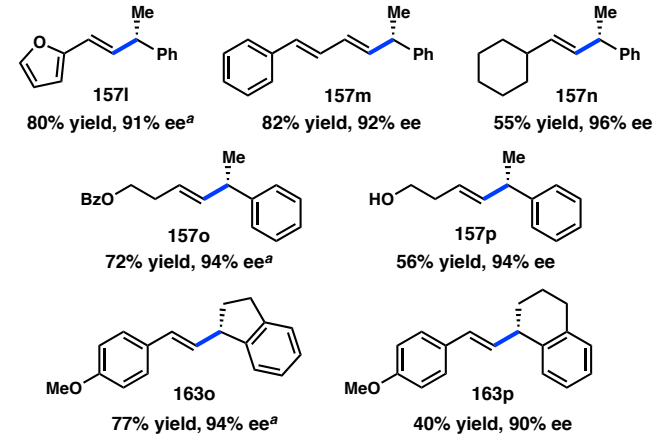
Entry	R	Pdt	Yield (%)[a]	ee (%)[b]
1	4-Me-C_6H_4	157a	83	96
2	4-F-C_6H_4	157b	74	94
3[c]	4-Cl-C_6H_4	157c	66	95
4[c]	4-CF_3-C_6H_4	157d	49	94
5[c]	4-OCF_3-C_6H_4	157e	81	94
6[c]	4-OTBS-C_6H_4	157f	82	96
7[c]	4-NMe_2-C_6H_4	157g	55	95
8[c]	2,3-diMe-C_6H_3	157h	76	96
9[c]	3,4-diMeO-C_6H_3	157i	73	95
10[c]	4-Bpin-C_6H_4	157j	59	94
11	4-OH-C_6H_4	157k	86	93

[a] Isolated yield, reactions conducted under N_2 on 0.2 mmol scale for 6 h. [b] Determined by SFC using a chiral stationary phase. [c] Run with 15 mol % $NiCl_2$(dme) and 16 mol % **L104**.

At this point, it was unclear whether either the reactivity or selectivity profile was dependent on our choice of an activated styrenyl halide. Studies on an asymmetric Kumada–Corriu cross-coupling by Knochel and coworkers demonstrated a significant drop in enantioselectivity as styrenyl halides were replaced with simple alkyl-substituted vinyl halides.[27] In contrast, we were delighted to observe that the reductive cross-coupling can be extended beyond styrenyl systems; for example, furan **157l** and diene **157m** are prepared in good yield and high ee (Figure 4.5). Non-conjugated vinyl bromides are also suitable reaction partners (**157n**–**p**), allowing for the preparation of products bearing either a free or protected alcohol. Cyclic benzylic halides (**162o** and

162p) can be cross-coupled with minimal erosion of enantioselectivity, exemplifying the wide scope of the enantioselective transformation.

Figure 4.5. *Beyond styrenyl halides.*

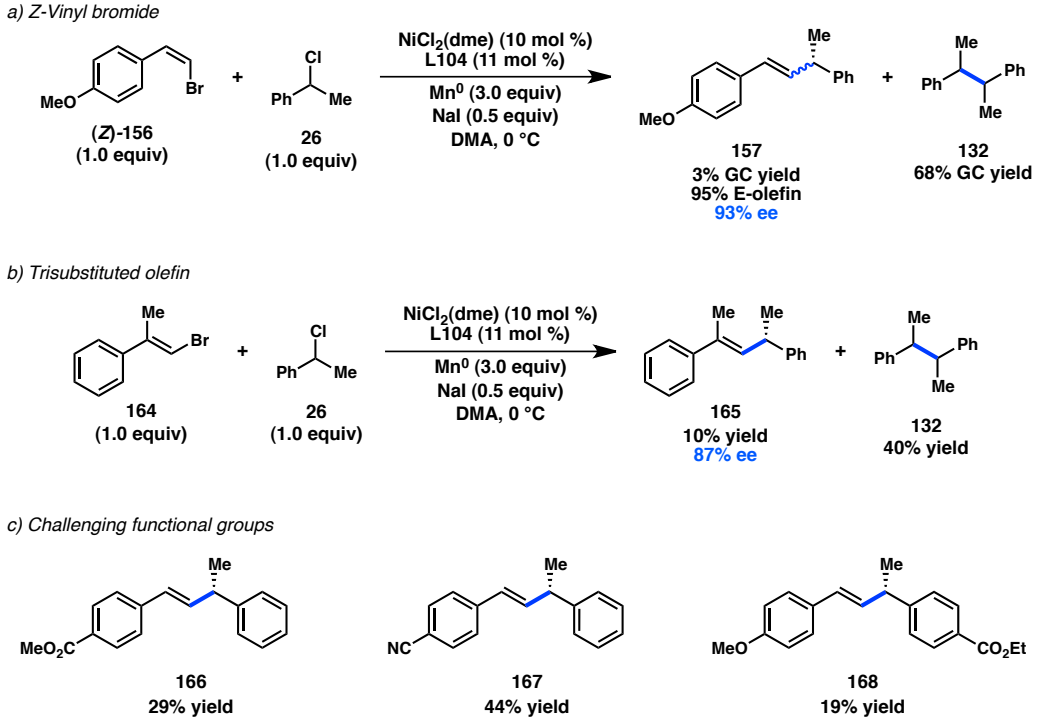


[a] Run with 15 mol % $NiCl_2$(dme) and 16 mol % **L104**.

Several key limitations to the established substrate scope still exist. The transformation remains sensitive to increased steric hindrance on either reaction partner, as evidenced by a decreased yield in the coupling of *o*-substituted benzyl chloride **162d**. Similarly, (*Z*)-**156** fails to couple with retention of olefin geometry, instead delivering trace quantities of (*E*)-**157** (Scheme 4.3, a). The poor result may be due to increased steric congestion intrinsic to oxidative addition of a *Z*-olefin compared to an *E*-olefin; sluggish oxidative addition would explain the high yield of homocoupling product **132**. In a similar fashion, trisubstituted olefin **164** delivered high yields of homodimer **132** and only a 10% yield of **165**, albeit with 87% ee (Scheme 4.3, b). This result can also be attributed to an increase in steric congestion on the vinyl bromide coupling partner. Several functional groups still maintain poor compatibility with the optimized reaction conditions, including aryl esters and aryl nitriles (Scheme 4.3, c). In general, substrates

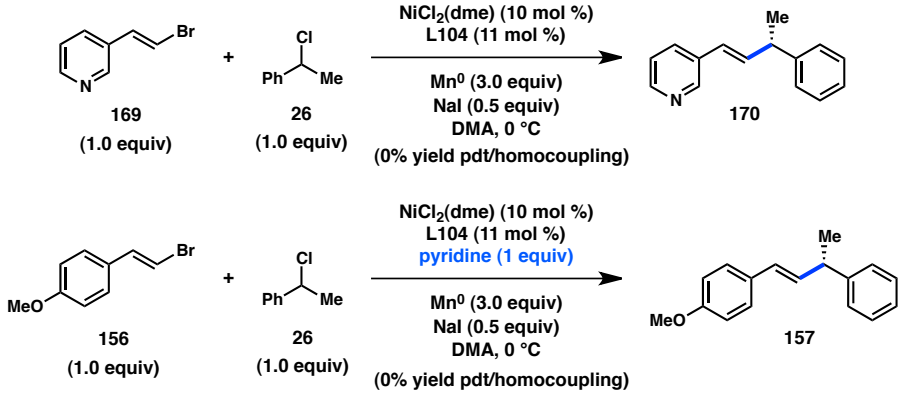
bearing aryl carbonyl groups provide reduced yields of the desired product and increased levels of homocoupling.

Scheme 4.3. *Limitations of substrate scope.*



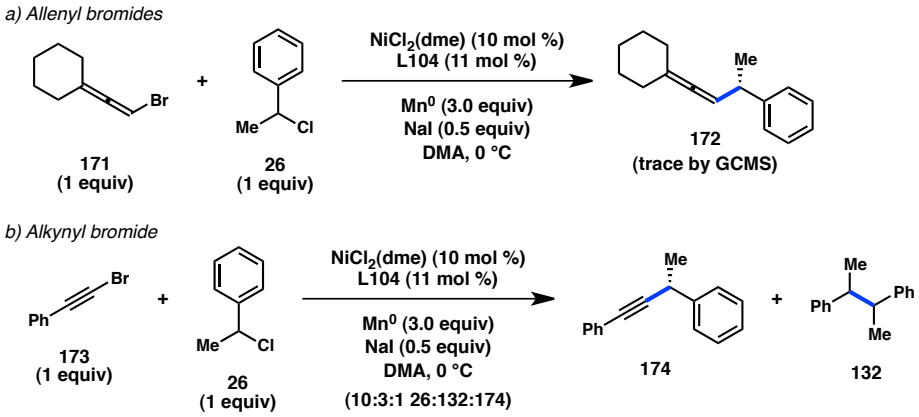
Encouraged by positive results in the preparation of furan **157l**, we tested whether a pyridine substituent can be tolerated. Exposure of pyridyl substrate **169** and benzyl chloride **26** to the optimized reaction conditions failed to deliver any cross-coupling or homocoupling products (Scheme 4.4). Reasoning that substrate **169** might inhibit the activity of Ni through coordination, we examined the coupling of styrenyl bromide **156** in the presence of 1 equiv pyridine as an additive. As before, no desired cross-coupling or homocoupling was observed. These studies confirm the inhibitory effect of certain nitrogen heterocycles and highlight the need to develop reaction conditions that are tolerant of such motifs.

Scheme 4.4. *Tolerance of pyridines.*



We hypothesized that unhindered allenyl bromides may react similarly to vinyl bromides. Under our optimized reaction conditions, allene **171** only formed trace amounts of product **172** (Scheme 4.5, a) The main side products were homocoupling of both bromide **171** and chloride **26**. Reexamining racemic coupling conditions with different solvents (DMA, DMPU, NMP, THF) and ligands (dtbpy, terpy, phen) revealed that product **172** was still not detected. Alkynyl bromide **173** was also tested under the optimized conditions, delivering a 10:3:1 ratio of starting material **26** to homodimer **132** to cross-coupled product **174** (Scheme 4.5, b). Further studies on increasing the yield of the of the C(sp) coupling have not been initiated.

Scheme 4.5. *Coupling of allenyl and alkynyl bromides.*



4.3 CONCLUDING REMARKS

In conclusion, a highly enantioselective reductive cross-coupling between vinyl bromides and benzyl chlorides has been developed. The reaction occurs under mild conditions and is tolerant of a variety of functional groups, providing products in good yields and high enantioselectivities. Preliminary mechanistic studies do not support the existence of a long-lived free radical, although further experiments are necessary. This work provides further evidence of the feasibility of developing a broad range of asymmetric reductive cross-coupling reactions, an endeavor that is currently ongoing in our laboratory.

4.4 EXPERIMENTAL SECTION

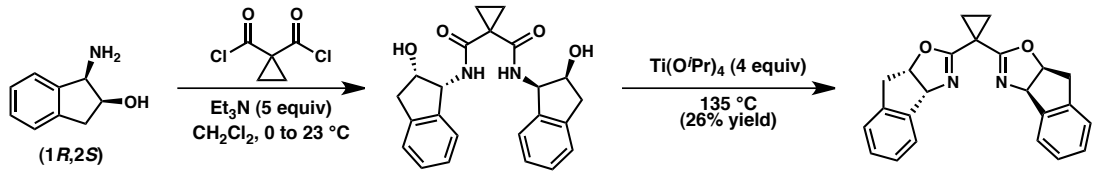
4.4.1 Materials and Methods

Unless otherwise stated, reactions were performed under a nitrogen atmosphere using freshly dried solvents. Tetrahydrofuran (THF), methylene chloride (CH_2Cl_2), and diethyl ether (Et_2O) were dried by passing through activated alumina columns. Anhydrous dimethylacetamide (DMA) was purchased from Aldrich and stored under inert atmosphere. Manganese powder (– 325 mesh, 99.3%) was purchased from Alfa Aesar. $NiCl_2$(dme) was purchased from Strem and stored in a glovebox under N_2 when not in use. Unless otherwise stated, chemicals and reagents were used as received. Triethylamine (Et_3N) was distilled over calcium hydride prior to use. All reactions were monitored by thin-layer chromatography using EMD/Merck silica gel 60 F254 pre-coated plates (0.25 mm) and were visualized by UV, CAM, or $KMnO_4$ staining. Flash column

chromatography was performed as described by Still et al.[28] using silica gel (particle size 0.032-0.063) purchased from Silicycle. Optical rotations were measured on a Jasco P-2000 polarimeter using a 100 mm path-length cell at 589 nm. ^{1}H and ^{13}C NMR spectra were recorded on a Varian Inova 500 (at 500 MHz and 126 MHz, respectively), and are reported relative to internal $CHCl_3$ (^{1}H, δ = 7.26) and $CDCl_3$ (^{13}C, δ = 77.0). Data for ^{1}H NMR spectra are reported as follows: chemical shift (δ ppm) (multiplicity, coupling constant (Hz), integration). Multiplicity and qualifier abbreviations are as follows: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad, app = apparent. IR spectra were recorded on a Perkin Elmer Paragon 1000 spectrometer and are reported in frequency of absorption (cm^{-1}). HRMS were acquired using an Agilent 6200 Series TOF with an Agilent G1978A Multimode source in electrospray ionization (ESI), atmospheric pressure chemical ionization (APCI), or mixed (MM) ionization mode. Analytical SFC was performed with a Mettler SFC supercritical CO_2 analytical chromatography system with Chiralcel AD-H, OD-H, AS-H, OB-H, and OJ-H columns (4.6 mm x 25 cm) with visualization at 254 nm. Analytical achiral GC-MS was performed with an Agilent 7890A GC and an Agilent 5975C VL MSD with triple axis detector utilizing an Agilent HP-5MS (30.0 m x 0.25 mm) column (0.4 mL/min He carrier gas flow). Analytical chiral HPLC was performed with an Agilent 1100 Series HPLC utilizing Chiralpak AD or Chiralcel OD-H columns (4.6 mm x 25 cm) obtained from Daicel Chemical Industries, Ltd with visualization at 254 nm.

4.4.2 Ligand and Substrate Synthesis

Ligand Preparation (L104)



To a flame-dried flask was added (1*R*,2*S*)-(+)-*cis*-1-amino-2-indanol (38 mmol, 2.1 equiv) and CH_2Cl_2 (70 mL). The reaction was cooled to 0 °C and freshly-distilled Et_3N (90 mmol, 5 equiv) was added dropwise. Cyclopropane-1,1-dicarbonyl dichloride[29] (18 mmol) was added dropwise and the solution was warmed to room temperature and stirred at 23 °C under N_2 for 6 h. A white precipitate slowly formed over the course of the reaction. The mixture was quenched with 1 M HCl and a white precipitate formed. The mixture was filtered and the white solid was collected and washed several times with an excess of water. The bis-amide product was dried under vacuum and used in the next step without any further purification.

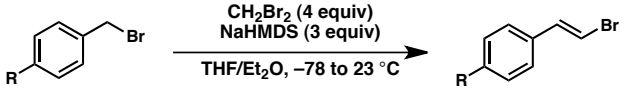
According to procedure by Kurosu and coworkers,[30] to a flame-dried flask was added crude bis-amide (3.6 mmol, 1 equiv) and anhydrous $Ti(O^iPr)_4$ (14.4 mmol, 4 equiv). The mixture was equipped with a distillation head and stirred at 135 °C under N_2 for 10 h. The reaction became a brown solution at high temperatures and isopropanol was observed to have been distilled from the solution. The reaction was cooled to 23 °C and 3-(dimethylamino)-1,2-propanediol (4.8 equiv) was added. The reaction was heated with a heat gun until the solution became homogeneous and was then stirred for 30 min. EtOAc (8 mL) and water (8 mL) were added and the reaction was stirred for 1 h. The

organic layer was separated and the aqueous layer was extracted with EtOAc. The combined organic layers were dried (Na_2SO_4), filtered, and concentrated. The crude residue was purified by flash chromatography (2% methanol/dichloromethane) to isolate a light brown solid. The material was recrystallized from isopropanol to provide a white solid (1.15 g, 26% yield). $[\alpha]_D^{25}$ = + 274.5° (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 – 7.42 (m, 2H), 7.30 – 7.20 (m, 6H), 5.53 (dd, *J* = 7.9, 0.8 Hz, 2H), 5.34 (ddd, *J* = 7.9, 7.0, 1.9 Hz, 2H), 3.44 – 3.35 (m, 2H), 3.20 (dd, *J* = 17.9, 1.8 Hz, 2H), 1.41 – 1.23 (m, 4H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 165.8, 141.8, 139.7, 128.3, 127.3, 125.6, 125.1, 83.3, 76.4, 39.6, 18.3, 15.7; FTIR (NaCl, thin film): 3246, 3023, 2917, 1654, 1534, 1479, 1459, 1426, 1364, 1302, 1247, 1159, 1115, 1001, 754, 733 cm^{-1}; HRMS (MM) calc'd for $C_{23}H_{20}N_2O_2$ $[M+Na]^+$ 379.1417, found 379.1438.

Substrate Preparation

Vinyl bromides **156**[31] and **156g**[32] and benzyl chlorides **162m**[33] and **162n**[34] were prepared according to literature precedent.

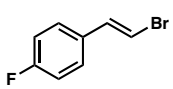
General Procedure 1: Vinyl Bromide Synthesis from Benzyl Bromides



According to a protocol by Charette and coworkers,[35] to a flame-dried flask under N_2 was added NaHMDS (9 mmol, 3 equiv, 1 M in THF) and Et_2O (6 mL). The flask was cooled to –78 °C and wrapped in aluminum foil. To the solution was added freshly-distilled dibromomethane (12 mmol, 4 equiv) dropwise. The solution was stirred at –78 °C for 20

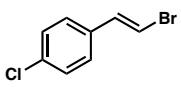
min and then benzyl bromide in 2 mL THF was added dropwise. The solution was stirred at –78 °C for an additional 3 h and then slowly warmed to room temperature and stirred in the dark at 23 °C for 21 h. The mixture was filtered through a pad of celite and silica and concentrated. The crude material was purified by flash chromatography.

(*E*)-1-(2-bromovinyl)-4-fluorobenzene (156b)



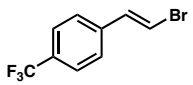
Prepared from 1-(bromomethyl)-4-(fluoromethyl)benzene (3.0 mmol) according to General Procedure 1. The crude residue was purified by silica gel chromatography (hexanes) to yield **156b** (419.2 mg, 70% yield) as a white solid. Spectral data matched those reported in the literature.

(*E*)-1-(2-bromovinyl)-4-chlorobenzene (156c)



Prepared from 1-(bromomethyl)-4-(chloromethyl)benzene (3.0 mmol) according to General Procedure 1. The crude residue was purified by silica gel chromatography (hexanes) to yield **156c** (496.2 mg, 76% yield) as a white solid. Spectral data matched those reported in the literature.

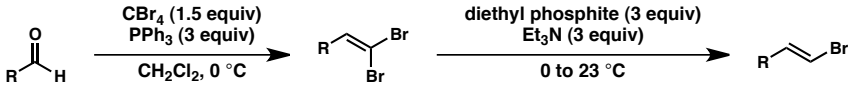
(*E*)-1-(2-bromovinyl)-4-(trifluoromethyl)benzene (156d)



Prepared from 1-(bromomethyl)-4-(trifluoromethyl)benzene (3.0 mmol) according to General Procedure 1. The crude residue was purified by silica gel chromatography (1 to 2% ethyl acetate/hexanes) to yield **156d** (138.4 mg, 18% yield) as a clear oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.60 (d, J = 7.7 Hz, 2H), 7.41 (d, J = 8.1 Hz, 2H), 7.15 (d, J = 14.1 Hz, 1H), 6.92 (d, J = 14.0 Hz, 1H); ^{13}C NMR (126 MHz,

$CDCl_3$) δ 139.2, 135.9, 130.1 (q, *J* = 33 Hz), 126.3, 125.8 (q, *J* = 4 Hz), 124.0 (q, *J* = 276 Hz), 109.4; FTIR (NaCl, thin film): 3074, 1617, 1604, 1574, 1411, 1326, 1166, 1127, 1068, 1017, 935, 848, 785, 739, 724 cm^{-1}; HRMS (MM) calc'd for $C_9H_6BrF_3$ $[M]^+$ 249.9605, found 249.9569.

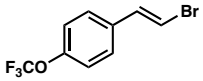
General Procedure 2: Vinyl Bromide Synthesis from Aldehydes



According to a modified synthetic sequence by Alexakis and coworkers,[36] to a flame-dried flask under N_2 was added aldehyde (10 mmol, 1 equiv), CBr_4 (15 mmol, 1.5 equiv), and CH_2Cl_2 (80 mL). The flask was cooled to 0 °C. A solution of PPh_3 (30 mmol, 3 equiv), in CH_2Cl_2 (70 mL) was added to the reaction dropwise via addition funnel over 30 min. The solution was stirred at 0 °C under N_2 for 1 h. The solution was concentrated to remove CH_2Cl_2 and $CHCl_3$ was added. The resulting mixture was filtered and washed with $CHCl_3$ (2 x 20 mL). The filtrate was concentrated to give a thick orange oil. The crude material was purified by flash chromatography to isolate the dibromoalkene.

To a vial containing dibromoalkene was added diethyl phosphite (3 equiv). Additional DMF was added to dissolve solid substrates. The solution was cooled to 0 °C and Et_3N (3 equiv) was added dropwise. The reaction was warmed to 23 °C and stirred overnight. The mixture was diluted with water. The aqueous layer was extracted with CH_2Cl_2 and the combined organic layers were washed with brine and dried (Na_2SO_4), filtered, and concentrated. The crude material was purified by flash chromatography.

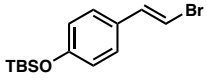
(*E*)-1-(2-bromovinyl)-4-(trifluoromethoxy)benzene (156e)



Prepared from 4-(trifluoromethoxy)benzaldehyde (10.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (hexanes) to yield **156e** (2.07 g, 72% yield, 94% E olefin) as a pale yellow oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.38 – 7.24 (m, 2H), 7.24 – 7.16 (m, 2H), 7.10 (d, *J* = 14.0 Hz, 1H), 6.79 (d, *J* = 14.0 Hz, 1H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.9 (q, *J* = 2 Hz), 135.7, 134.6, 127.4, 121.2, 120.40 (q, *J* = 257 Hz), 107.5; FTIR (NaCl, thin film): 3073, 2430, 1895, 1607, 1507, 1411, 1261, 1215, 1162, 1104, 1017, 948, 931, 841, 778, 745, 713 cm^{-1}; HRMS (MM) calc'd for $C_9H_6BrF_3O$ $[M+H_3O]^+$ 284.9733, found 284.9819.

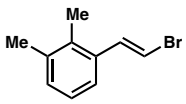
According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156e** (6 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 2 h. The reaction was cooled to room temperature and diluted with pentane and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (1.44 g, 82% yield).

(*E*)-(4-(2-bromovinyl)phenoxy)(*tert*-butyl)dimethylsilane (156f)



Prepared from 4-((*tert*-butyldimethylsilyl)oxy)benzaldehyde (18.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (hexanes) to yield **156f** (3.66 g, 66% yield, 88% E olefin) as a pale yellow oil. Spectral data matched those reported in the literature.

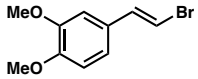
(*E*)-1-(2-bromovinyl)-2,3-dimethylbenzene (156h)



Prepared from 2,3-dimethylbenzaldehyde (10.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (hexanes) to yield **156h** (1.73 g, 82% yield, 88% E olefin) as a clear oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.47 – 7.37 (m, 1H), 7.23 – 7.05 (m, 3H), 6.64 – 6.57 (m, 1H), 2.35 (s, 3H), 2.28 (s, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 137.1, 136.5, 135.5, 133.8, 130.0, 125.8, 124.3, 107.2, 20.6, 15.6; FTIR (NaCl, thin film): 3068, 2942, 2864, 1725, 1607, 1587, 1456, 1383, 1248, 1203, 1181, 1168, 1092, 938, 784, 757, 707, 668 cm^{-1}; HRMS (MM) calc'd for $C_{10}H_{11}Br$ $[M]^+$ 210.0044, found 209.9930.

According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156h** (6 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 2 h. The reaction was cooled to room temperature and diluted with pentane and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (1.03 g, 81% yield).

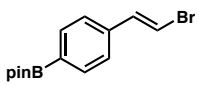
(*E*)-4-(2-bromovinyl)-1,2-dimethoxybenzene (156i)



Prepared from 3,4-dimethoxybenzaldehyde (10.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (0 to 5% ethyl acetate/hexanes) to yield **156i** (2.02 g, 83% yield, 93% E olefin) as a white solid. Spectral data matched those reported in the literature.

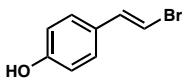
According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156i** (6 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 2 h. The reaction was cooled to room temperature and diluted with Et_2O and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (1.35 g, 92% yield).

(*E*)-2-(4-(2-bromovinyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (156j)



Prepared from 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde (12.5 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (10 to 20% ethyl acetate/hexanes) to yield **156j** (2.55 g, 68% yield) as a low melting solid. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.78 (d, *J* = 7.7 Hz, 2H), 7.31 (d, *J* = 8.1 Hz, 2H), 7.12 (d, *J* = 14.5 Hz, 1H), 6.86 (d, *J* = 14.4 Hz, 1H), 1.36 (s, 12H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 138.4, 137.2, 135.2, 125.4, 107.7, 83.9, 24.9; FTIR (NaCl, thin film): 3073, 2978, 2931, 1729, 1607, 1516, 1468, 1401, 1361, 1324, 1269, 1214, 1144, 1090, 1019, 962, 937, 860, 782, 745, 727, 653 cm^{-1}; HRMS (MM) calc'd for $C_{14}H_{18}BBrO_2$ $[M+H]^+$ 334.2213, found 334.2030.

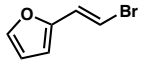
(*E*)-4-(2-bromovinyl)phenol (156k)



To a vial containing vinyl bromide **156f** (6 mmol, obtained from General Procedure 2) was added NaOH (0.85 equiv) and ^{i}PrOH. The mixture was stirred at 75 °C for 2 h. The reaction was cooled to room temperature and

diluted with Et_2O and water. The organic layer was washed with water (2x) and 1 M HCl (2x). The organic layer was then dried ($MgSO_4$), filtered, and concentrated. The crude residue was purified by flash chromatography (10 to 20% ethyl acetate/hexanes) to yield **156k** (750.0 mg, 63% yield, 92% E olefin) as a white solid. Spectral data for **156k** matched that reported in the literature.

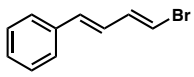
(*E*)-2-(2-bromovinyl)furan (156l)



Prepared from furfural (10.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel chromatography (hexanes) to yield **156l** (745 mg, 49% yield, 71% E olefin) as a yellow oil. Spectral data matched those reported in the literature.

According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156l** (6 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 1 h. The reaction was cooled to room temperature and diluted with pentane and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (54 mg, 8% yield).

((1*E*,3*E*)-4-bromobuta-1,3-dien-1-yl)benzene (156m)

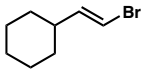


Prepared from cinnamaldehyde (10.0 mmol) according to General Procedure 2. The crude residue was purified by silica gel

chromatography (hexanes) to yield **156m** (910 mg, 44% yield, 73% E olefin) as a white solid. Spectral data matched those reported in the literature.

According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156m** (4.3 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 1 h. The reaction was cooled to room temperature and diluted with pentane and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (584 mg, 66% yield).

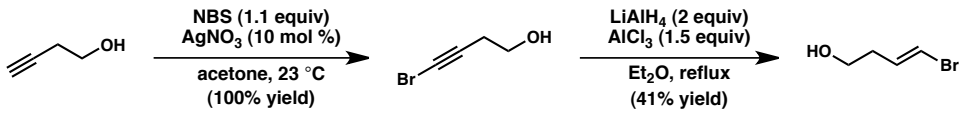
(*E*)-(2-bromovinyl)cyclohexane (156n)



Prepared from cyclohexanecarboxaldehyde (10.0 mmol) according to General Procedure 2, except the debromination was performed at 80 °C for 12 h. The crude residue was purified by silica gel chromatography (hexanes) to yield **156n** (800 mg, 43% yield, 72% E olefin) as a clear oil. Spectral data matched those reported in the literature.

According to Alexakis and coworkers,[36] to a vial containing vinyl bromide **156n** (3.7 mmol) was added NaOH (0.85 equiv) and IPA (0.5 M). The mixture was stirred at 75 °C for 1 h. The reaction was cooled to room temperature and diluted with pentane and water. The organic layer was washed with water and 1 M HCl. The organic layer was then dried (Na_2SO_4), filtered, and concentrated to isolate geometrically pure product (480 mg, 61% yield).

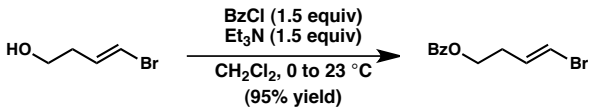
(*E*)-4-bromobut-3-en-1-ol (156p)



According to a procedure by Hofmeister and coworkers,[37] 3-butyn-1-ol (1 equiv, 15 mmol) was dissolved in acetone (50 mL). To the solution was added NBS (16.5 mmol, 1.1 equiv) and $AgNO_3$ (1.5 mmol, 10 mol %). The reaction was stirred at 23 °C for 2 h. The reaction was concentrated and diluted with Et_2O and water. The aqueous layer was extracted with Et_2O and the combined organic layers were dried ($MgSO_4$), filtered, and concentrated to give a clear oil (2.22 g, 100% yield).

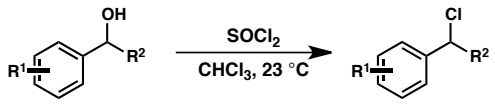
To a flame-dried flask was added $LiAlH_4$ (30 mmol, 2 equiv) and Et_2O (90 mL). The flask was equipped with a reflux condenser and cooled to –5 °C. $AlCl_3$ (22.5 mmol, 1.5 equiv) was carefully added to the reaction. The reaction was stirred for 10 min at –5 °C under N_2. Bromoalkyne (15 mmol, 1 equiv) was added dropwise and the reaction was stirred at reflux under N_2 for 2.5 h. The reaction was cooled to 0 °C and Et_2O (60 mL) was added, followed by 2 M HCl (60 mL) dropwise to quench the reaction. The aqueous layer was extracted with Et_2O (3 x 40 mL) and the combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. The crude material was purified by flash chromatography (15 to 30% ethyl acetate/hexanes) to isolate a clear oil (917.6 mg, 41% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.28 – 6.04 (m, 2H), 3.75 – 3.52 (m, 2H), 2.44 (s, 1H), 2.36 – 2.18 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 134.3, 106.6, 61.1, 36.1; FTIR (NaCl, thin film): 3338, 3065, 2935, 2880, 1622, 1427, 1227, 1168, 1046, 1002, 937, 710 cm^{-1}; HRMS (MM) calc'd for C_4H_7BrO $[M+OH]^+$ 166.9702, found 166.9662.

(*E*)-4-bromobut-3-en-1-yl benzoate (156o)



To a flame-dried flask was added alcohol **156p** (1.5 mmol, 1 equiv,) and CH_2Cl_2 (5 mL). The solution was cooled to 0 °C and Et_3N (2.25 mmol, 1.5 equiv) and BzCl (2.25 mmol, 1.5 equiv) were added. The solution was stirred at 23 °C under N_2 for 3 h. The reaction was quenched with sat. aqueous NH_4Cl and the aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated. The crude oil was purified by flash chromatography (1% ethyl acetate/hexanes) to isolate a clear oil (363.8 mg, 95% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 – 8.01 (m, 2H), 7.61 – 7.53 (m, 1H), 7.45 (td, *J* = 7.7, 1.6 Hz, 2H), 6.32 – 6.18 (m, 2H), 4.36 (td, *J* = 6.6, 1.8 Hz, 2H), 2.52 (qd, *J* = 6.6, 2.2 Hz, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 166.3, 133.4, 133.1, 130.0, 129.6, 128.4, 107.1, 63.1, 32.4; FTIR (NaCl, thin film): 3064, 2957, 2898, 1717, 1622, 1602, 1492, 1451, 1382, 1314, 1273, 1176, 1116, 1070, 1026, 937, 710 cm^{-1}; HRMS (ESI) calc'd for $C_{11}H_{11}BrO_2$ $[M+H]^+$ 255.0015, found 254.9994.

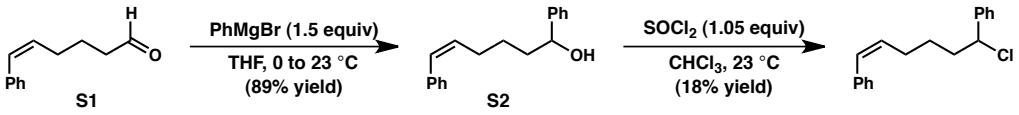
General Procedure 3: Benzyl Chloride Synthesis



A flask was charged with the appropriate benzyl alcohol (1.0 equiv) and $CHCl_3$ (1.5 M). Thionyl chloride (1.05 equiv) was added dropwise. Evolved gas was quenched via cannula by aqueous $NaHCO_3$. The solution was stirred at 23 °C for 12 h and then

concentrated to afford a yellow oil. The crude residue was purified by Kugelrohr distillation to isolate **162a–l**, **162o**, and **162p** as clear oils. Spectral data for all compounds matched those reported in the literature.

Preparation of Radical Clock Substrate 160



Aldehyde **S1** was prepared according to a known procedure from 5-hexyn-1-ol.[38] To a flame-dried flask was added PhMgBr (16 mmol, 1.5 equiv, 3 M in Et_2O) and THF (33 mL). The solution was cooled to 0 °C and aldehyde **S1** was added dropwise. The solution was slowly warmed to 23 °C and stirred under N_2 overnight. The reaction was quenched with sat. aqueous NH_4Cl and H_2O. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine and dried ($MgSO_4$), filtered, and concentrated. The crude residue was purified by flash chromatography (10% ethyl acetate/hexanes) to isolate **S2** as a pale yellow oil (2.37 g, 89% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 – 7.11 (m, 10H), 6.46 (d, *J* = 11.4 Hz, 1H), 5.67 (dt, *J* = 11.7, 7.2 Hz, 1H), 4.66 (dd, *J* = 7.5, 5.8 Hz, 1H), 2.52 – 2.28 (m, 2H), 2.12 – 1.93 (m, 1H), 1.93 – 1.68 (m, 2H), 1.68 – 1.36 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 144.7, 137.7, 132.6, 129.2, 128.8, 128.5, 128.2, 127.6, 126.5, 125.9, 74.5, 38.6, 28.4, 26.1; FTIR (NaCl, thin film): 3546, 3350, 3058, 3024, 2935, 2856, 1948, 1880, 1807, 1757, 1599, 1574, 1493, 1453, 1406, 1319, 1269, 1200, 1156, 1069, 1028, 1001, 914, 764, 699; HRMS (MM) calc'd for $C_{18}H_{20}O$ $[M]^+$ 252.1514, found 252.1520.

A flask was charged with **S2** (5.2 mmol, 1.0 equiv) and $CHCl_3$ (1.5 M). Thionyl chloride (5.5 mmol, 1.05 equiv) was added dropwise. Evolved gas was quenched via cannula by aqueous $NaHCO_3$. The solution was stirred at 23 °C for 12 h and then concentrated to afford a yellow oil. The crude residue was purified by flash chromatography (hexanes) to isolate **160** as a clear oil (250.9 mg, 18% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.48 – 7.09 (m, 10H), 6.46 (d, *J* = 11.8 Hz, 1H), 5.63 (dt, *J* = 11.6, 7.2 Hz, 1H), 4.83 (dd, *J* = 8.2, 6.4 Hz, 1H), 2.39 (qd, *J* = 7.4, 1.9 Hz, 2H), 2.25 – 1.97 (m, 2H), 1.80 – 1.34 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 141.7, 137.5, 132.0, 129.5, 128.7, 128.6, 128.24, 128.17, 126.9, 126.6, 63.5, 39.4, 27.8, 27.3; FTIR (NaCl, thin film): 3057, 3024, 2943, 2860, 1599, 1493, 1454, 1235, 1075, 1028, 914, 766, 752, 697 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{19}Cl$ $[M+H_3O]^+$ 289.1354, found 289.1340.

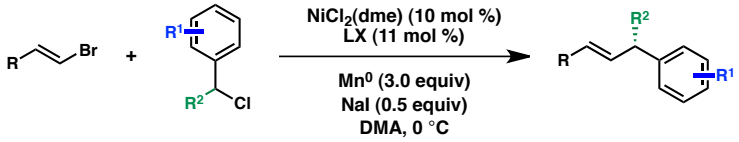
4.4.3 Enantioselective Reductive Cross-Coupling

General Procedure 4 (Table 4.3): Optimization of Reaction Conditions

On a bench-top, to a 1/2 dram vial was added the appropriate ligand (0.022 mmol, 11 mol %), reductant (0.6 mmol, 3 equiv), $NiCl_2$(dme) (0.02 mmol, 10 mol %), vinyl bromide (0.2 mmol, 1.0 equiv), and NaI (0.1 mmol, 0.5 equiv) if necessary. The vial was transferred into an N_2-filled glovebox and charged with the appropriate solvent (0.2 mL, 1.0 M) followed by benzyl chloride (0.2 mmol, 1.0 equiv) and dodecane (internal standard). The vial was sealed and removed from the glovebox. The mixture was stirred vigorously, ensuring that the reductant was uniformly suspended, at 20 °C for 6 h. The dark mixture was diluted with 10% ethyl acetate/hexane and passed through a plug of

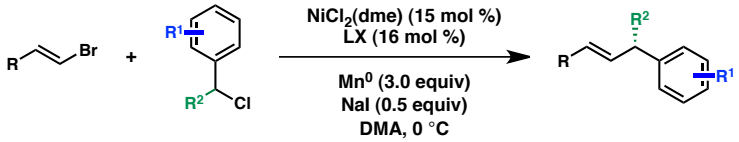
silica, using 10% ethyl acetate/hexane eluent. The solution was concentrated to afford a clear oil. The crude residue was analyzed by GC-MS. Dodecane was used as an internal standard. GC samples were analyzed by flame ionization detection and yields calculated based on a calibrated response factor.

General Procedure 5: Enantioselective Reductive Coupling of Benzyl Chlorides and Vinyl Bromides



On a bench-top, to a 10 mL round-bottom flask was added **L104** (0.022 mmol, 11 mol), Mn^0 (0.6 mmol, 3 equiv), $NiCl_2$(dme) (0.02 mmol, 10 mol %), vinyl bromide **156** (if a solid, 0.2 mmol, 1 equiv), and NaI (0.1 mmol, 0.5 equiv). The flask was covered with a rubber septum, purged with N_2, and cooled to 0 °C. To the mixture was added DMA (0.2 mL), vinyl bromide **156** (if an oil, 0.2 mmol, 1 equiv), and benzyl chloride **26** (0.2 mmol, 1 equiv). The mixture was stirred vigorously, ensuring that the manganese powder was uniformly suspended. After 6 h, the mixture was allowed to warm to room temperature and was quenched with 1 M HCl (0.5 mL). The mixture was transferred to a separatory funnel using water (5 mL) and Et_2O (10 mL), and the aqueous and organic layers were separated. The aqueous layer was extracted with Et_2O (2 x 10 mL) and the combined organic layers were washed with brine (1 x 5 mL) and dried ($MgSO_4$), filtered, and concentrated. The crude residue was purified by flash chromatography.

General Procedure 6: Enantioselective Reductive Coupling of Benzyl Chlorides and Vinyl Bromides – 15% Catalyst Loading



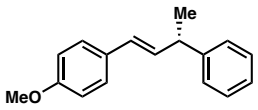
On a bench-top, to a 10 mL round-bottom flask was added **L104** (0.032 mmol, 16 mol %), Mn^0 (0.6 mmol, 3 equiv), $NiCl_2$(dme) (0.03 mmol, 15 mol %), vinyl bromide **156** (if a solid, 0.2 mmol, 1 equiv), and NaI (0.1 mmol, 0.5 equiv). The flask was covered with a rubber septum, purged with N_2, and cooled to 0 °C. To the mixture was added DMA (0.2 mL), vinyl bromide **156** (if an oil, 0.2 mmol, 1 equiv), and benzyl chloride **26** (0.2 mmol, 1 equiv). The mixture was stirred vigorously, ensuring that the manganese powder was uniformly suspended. After 6 h, the mixture was allowed to warm to room temperature and was quenched with 1 M HCl (0.5 mL). The mixture was transferred to a separatory funnel using water (5 mL) and Et_2O (10 mL), and the aqueous and organic layers were separated. The aqueous layer was extracted with Et_2O (2 x 10 mL) and the combined organic layers were washed with brine (1 x 5 mL) and dried ($MgSO_4$), filtered, and concentrated. The crude residue was purified by flash chromatography.

General Procedure 7: Racemic Reductive Cross-Coupling

On a bench-top, to a 1/2 dram vial was added neocuproine (0.022 mmol, 11 mol %), Mn^0 (0.6 mmol, 3 equiv), $NiCl_2$(dme) (0.02 mmol, 10 mol %), and vinyl bromide (0.2 mmol, 1.0 equiv). The vial was transferred into an N_2-filled glovebox and charged with DMPU (0.2 mL, 1.0 M) followed by benzyl chloride (0.2 mmol, 1.0 equiv). The vial was sealed

and removed from the glovebox. The mixture was stirred vigorously, ensuring that the reductant was uniformly suspended, at 20 °C for 6 h. The mixture was quenched with 1 M HCl (0.5 mL) and transferred to a separatory funnel using water (5 mL) and Et_2O (10 mL). The aqueous and organic layers were separated. The aqueous layer was extracted with Et_2O (2 x 10 mL) and the combined organic layers were washed with brine (1 x 5 mL) and dried ($MgSO_4$), filtered, and concentrated. The crude residue was purified by flash chromatography.

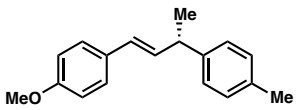
(*S*,*E*)-1-methoxy-4-(3-phenylbut-1-en-1-yl)benzene (163a)



Prepared from (1-chloroethyl)benzene (**162a**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163a** (43.4 mg, 91% yield) in 93% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 20% IPA in CO_2, λ = 254 nm): t_R (major) = 7.6 min, t_R (minor) = 9.2 min. $[\alpha]_D^{25} = -41.9°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.20 (m, 7H), 6.90 – 6.83 (m, 2H), 6.40 (d, *J* = 16.2 Hz, 1H), 6.28 (dd, *J* = 15.9, 6.7 Hz, 1H), 3.82 (s, 3H), 3.70 – 3.60 (m, 1H), 1.49 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 145.9, 133.2, 130.5, 128.4, 128.0, 127.3, 127.2, 126.1, 114.0, 55.3, 42.5, 21.3; FTIR (NaCl, thin film): 3026, 2962, 2834, 1607, 1577, 1511, 1492, 1452, 1298, 1251, 1174, 1034, 967, 818, 760 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{18}O$ $[M]^+$ 238.1358, found 238.1346.

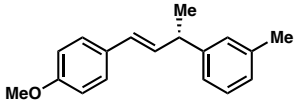
The optical rotation of the product generated in the presence of (*R*,*R*,*S*,*S*)-**L104** was measured as $[\alpha]_D^{25} = -41.9°$ (c = 1.0, $CHCl_3$). Lit: $[\alpha]_D^{20} = -16°$ (c = 1.28, $CHCl_3$, *S* enantiomer, 94% ee).[39] Based on the literature precedent, we assign our product as the *S* enantiomer.

(*S*,*E*)-1-methoxy-4-(3-(*p*-tolyl)but-1-en-1-yl)benzene (163b)



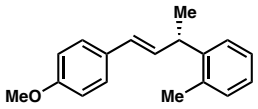
Prepared from 1-(1-chloroethyl)-4-methylbenzene (**162b**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163b** (41.4 mg, 82% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 11.4 min, t_R (minor) = 13.0 min. $[\alpha]_D^{25} = -41.1°$ (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 – 7.28 (m, 2H), 7.23 – 7.13 (m, 4H), 6.90 – 6.83 (m, 2H), 6.39 (d, *J* = 16.2 Hz, 1H), 6.27 (dd, *J* = 15.9, 6.7 Hz, 1H), 3.82 (s, 3H), 3.66 – 3.58 (m, 1H), 2.37 (s, 3H), 1.47 (d, *J* = 7.0 Hz, 3H).; ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 142.9, 135.6, 133.4, 130.5, 129.2, 127.7, 127.23, 127.18, 113.9, 55.3, 42.1, 21.4, 21.0.; FTIR (NaCl, thin film): 3019, 2961, 2929, 2834, 1607, 1577, 1511, 1454, 1298, 1273, 1250, 1174, 1036, 967, 814 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O$ $[M]^+$ 252.1514, found 252.1477.

(*S*,*E*)-1-(4-(4-methoxyphenyl)but-3-en-2-yl)-3-methylbenzene (163c)



Prepared from 1-(1-chloroethyl)-3-methylbenzene (**162c**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (0 to 2% Et_2O/hexanes) to yield **163c** (44.6 mg, 88% yield) in 93% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 7.1 min, t_R (minor) = 8.9 min. $[\alpha]_D^{25}$ = –40.5° (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 2H), 7.29 – 7.19 (m, 1H), 7.15 – 7.01 (m, 3H), 6.88 – 6.83 (m, 2H), 6.40 (d, *J* = 16.0 Hz, 1H), 6.28 (dd, *J* = 15.9, 6.8 Hz, 1H), 3.83 (s, 3H), 3.66 – 3.57 (m, 1H), 2.38 (s, 3H), 1.48 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 145.9, 138.0, 133.3, 130.5, 128.3, 128.1, 127.8, 127.2, 126.9, 124.3, 113.9, 55.3, 42.5, 21.5, 21.4; FTIR (NaCl, thin film): 3029, 2962, 2834, 1607, 1577, 1511, 1488, 1463, 1371, 1299, 1251, 1175, 1107, 1036, 967, 848, 817, 785, 767 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O$ $[M]^+$ 252.1514, found 252.1443.

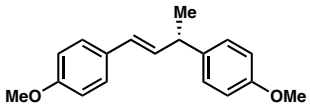
(*S*,*E*)-1-(4-(4-methoxyphenyl)but-3-en-2-yl)-2-methylbenzene (163d)



Prepared from 1-(1-chloroethyl)-2-methylbenzene (**162d**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163d** (22.3 mg, 44% yield) in 85% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 8.7 min, t_R (minor) = 10.4 min.

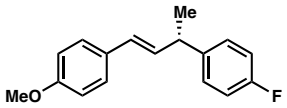
$[\alpha]_D^{25} = -40.3°$ (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.33 – 7.09 (m, 6H), 6.87 – 6.80 (m, 2H), 6.32 (d, *J* = 15.7 Hz, 1H), 6.23 (dd, *J* = 16.0, 6.2 Hz, 1H), 3.89 – 3.82 (m, 1H), 3.81 (s, 3H), 2.39 (s, 3H), 1.45 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 143.8, 135.6, 132.7, 130.42, 130.36, 127.8, 127.2, 126.3, 126.2, 126.0, 113.9, 55.3, 38.0, 20.6, 19.5; FTIR (NaCl, thin film): 3017, 2962, 2929, 2834, 1607, 1576, 1511, 1488, 1462, 1297, 1250, 1174, 1106, 1035, 968, 818, 758, 729 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O$ $[M]^+$ 252.1514, found 252.1673.

(*S*,*E*)-4,4'-(but-1-ene-1,3-diyl)bis(methoxybenzene) (163e)



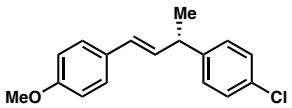
Prepared from 1-(1-chloroethyl)-4-methoxybenzene (**162e**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (0 to 2% Et_2O/hexanes) to yield **163e** (34.5 mg, 64% yield) in 93% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (AD-H, 2.5 mL/min, 20% IPA in CO_2, λ = 254 nm): t_R (major) = 7.3 min, t_R (minor) = 8.9 min. $[\alpha]_D^{25} = -32.1°$ (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 – 7.28 (m, 2H), 7.27 – 7.15 (m, 2H), 6.91 – 6.82 (m, 4H), 6.36 (d, *J* = 16.2 Hz, 1H), 6.25 (dd, *J* = 15.9, 6.7 Hz, 1H), 3.83 – 3.80 (m, 6H), 3.65 – 3.55 (m, 1H), 1.45 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 158.0, 138.0, 133.6, 130.5, 128.2, 127.7, 127.2, 113.94, 113.88, 55.3 (2C), 41.7, 21.4.; FTIR (NaCl, thin film): 2999, 2960, 2834, 1608, 1582, 1511, 1463, 1441, 1419, 1300, 1248, 1175, 1107, 1036, 968, 830, 818, 767 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O_2$ $[M]^+$ 268.1463, found 268.1394.

(*S*,*E*)-1-fluoro-4-(4-(4-methoxyphenyl)but-3-en-2-yl)benzene (163f)



Prepared from 1-(1-chloroethyl)-4-fluorobenzene (**162f**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (0 to 2% Et_2O/hexanes) to yield **163f** (41.4 mg, 81% yield) in 89% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 5.6 min, t_R (minor) = 8.0 min. $[\alpha]_D^{25} = -35.1°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.34 – 7.28 (m, 2H), 7.28 – 7.20 (m, 2H), 7.07 – 6.96 (m, 2H), 6.91 – 6.83 (m, 2H), 6.36 (d, *J* = 16.1 Hz, 1H), 6.23 (dd, *J* = 15.9, 6.7 Hz, 1H), 3.82 (s, 3H), 3.68 – 3.58 (m, 1H), 1.46 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 161.4 (d, *J* = 244 Hz), 159.0, 141.5, 132.9, 130.3, 128.6 (d, *J* = 8 Hz), 128.1, 127.2, 115.1 (d, *J* = 21 Hz), 114.0, 55.3, 41.8, 21.4; FTIR (NaCl, thin film): 3032, 2963, 2835, 1607, 1577, 1510, 1464, 1419, 1298, 1251, 1223, 1175, 1159, 1107, 1035, 968, 835, 821, 769 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{17}FO$ $[M]^+$ 265.1263, found 265.1223.

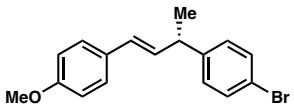
(*S*,*E*)-1-chloro-4-(4-(4-methoxyphenyl)but-3-en-2-yl)benzene (163g)



Prepared from 1-(1-chloroethyl)-4-chlorobenzene (**162g**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (0 to 2% Et_2O/hexanes) to yield **163g** (40.9 mg, 75% yield) in 88% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 25% IPA in CO_2, λ = 254 nm): t_R (major) = 6.6 min, t_R (minor) = 9.4 min.

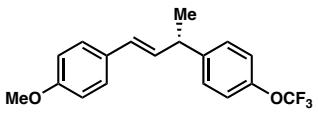
$[\alpha]_D^{25} = -27.9°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 – 7.26 (m, 4H), 7.25 – 7.18 (m, 2H), 6.91 – 6.82 (m, 2H), 6.36 (d, *J* = 16.0 Hz, 1H), 6.21 (dd, *J* = 15.9, 6.8 Hz, 1H), 3.82 (s, 3H), 3.66 – 3.56 (m, 1H), 1.45 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.0, 144.4, 132.5, 131.8, 130.2, 128.6, 128.5, 128.4, 127.3, 114.0, 55.3, 41.9, 21.3; FTIR (NaCl, thin film): 3030, 2963, 2834, 1607, 1576, 1511, 1491, 1463, 1408, 1297, 1251, 1174, 1091, 1035, 1012, 967, 828, 817 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{17}ClO$ $[M]^+$ 272.0968, found 272.0904.

(*S*,*E*)-1-bromo-4-(4-(4-methoxyphenyl)but-3-en-2-yl)benzene (163h)



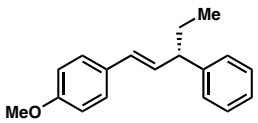
Prepared from 1-(1-chloroethyl)-4-bromobenzene (**162h**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163h** (37.6 mg, 59% yield) in 90% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 35% IPA in CO_2, λ = 254 nm): t_R (major) = 5.4 min, t_R (minor) = 9.0 min. $[\alpha]_D^{25} = -30.1°$ (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.51 – 7.38 (m, 2H), 7.38 – 7.22 (m, 2H), 7.22 – 7.08 (m, 2H), 6.91 – 6.78 (m, 2H), 6.36 (d, *J* = 15.8 Hz, 1H), 6.20 (dd, *J* = 15.9, 6.8 Hz, 1H), 3.82 (s, 3H), 3.71 – 3.47 (m, 1H), 1.45 (d, *J* = 6.9 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.0, 144.9, 132.4, 131.5, 130.2, 129.1, 128.4, 127.3, 119.8, 114.0, 55.3, 42.0, 21.2; FTIR (NaCl, thin film): 2962, 2930, 2834, 1607, 1577, 1511, 1487, 1297, 1250, 1174, 1073, 1035, 1008, 967, 816 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{17}BrO$ $[M+H]^+$ 317.0536, found 317.0449.

(*S*,*E*)-1-methoxy-4-(3-(4-(trifluoromethoxy)phenyl)but-1-en-1-yl)benzene (163i)



Prepared from 1-(1-chloroethyl)-4-(trifluoromethoxy)benzene (**162i**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163i** (54.2 mg, 84% yield) in 88% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (AD-H, 2.5 mL/min, 7% IPA in CO_2, λ = 254 nm): t_R (major) = 7.7 min, t_R (minor) = 8.8 min. $[\alpha]_D^{25} = -27.2°$ (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.37 – 7.23 (m, 4H), 7.23 – 7.13 (m, 2H), 6.90 – 6.83 (m, 2H), 6.38 (d, *J* = 16.0 Hz, 1H), 6.22 (dd, *J* = 15.9, 6.8 Hz, 1H), 3.82 (s, 3H), 3.70 – 3.61 (m, 1H), 1.47 (d, *J* = 7.1 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.0, 147.6, 144.6, 132.4, 130.2, 128.5, 128.4, 127.3, 120.9, 114.0, 55.3, 41.9, 21.3; FTIR (NaCl, thin film): 3033, 2965, 2836, 1607, 1577, 1511, 1465, 1420, 1374, 1255, 1223, 1174, 1106, 1036, 1015, 968, 849, 819 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{17}F_3O_2$ $[M]^+$ 322.1181, found 322.1105.

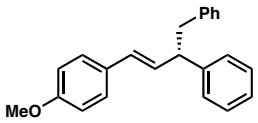
(*S*,*E*)-1-methoxy-4-(3-phenylpent-1-en-1-yl)benzene (163j)



Prepared from (1-chloropropyl)benzene (**162j**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163j** (40.3 mg, 80% yield) in 97% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (minor) = 7.7 min, t_R (major) = 9.3 min. $[\alpha]_D^{25} = -47.8°$ (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.19 (m, 5H), 6.90 – 6.83 (m, 2H),

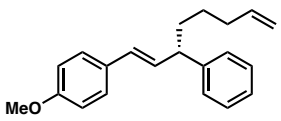
6.38 (d, *J* = 14.8 Hz, 1H), 6.23 (dd, *J* = 15.8, 7.9 Hz, 1H), 3.82 (s, 3H), 3.32 (q, *J* = 7.3 Hz, 1H), 1.86 (pd, *J* = 7.4, 2.4 Hz, 2H), 0.95 (t, *J* = 7.4 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 144.8, 132.2, 130.6, 128.9, 128.4, 127.7, 127.2, 126.1, 113.9, 55.3, 51.0, 28.9, 12.2; FTIR (NaCl, thin film): 3025, 2958, 2929, 2834, 1607, 1510, 1451, 1300, 1247, 1174, 1107, 1034, 964, 830, 757 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O$ $[M]^+$ 252.1514, found 252.1466.

(*S*,*E*)-(4-(4-methoxyphenyl)but-3-ene-1,2-diyl)dibenzene (163k)



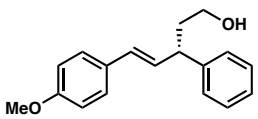
Prepared from (1-chloroethane-1,2-diyl)dibenzene (**162k**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (0 to 2% Et_2O/hexanes) to yield **163k** (51.3 mg, 82% yield) in 93% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (AS-H, 2.5 mL/min, 10% IPA in CO_2, λ = 254 nm): t_R (minor) = 5.8 min, t_R (major) = 6.4 min. $[\alpha]_D^{25}$ = +18.9° (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.45 – 7.02 (m, 10H), 6.94 – 6.78 (m, 2H), 6.40 – 6.24 (m, 2H), 3.82 (s, 3H), 3.76 (q, *J* = 7.2 Hz, 1H), 3.22 – 3.09 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 144.1, 140.1, 131.3, 130.4, 129.4, 129.3, 128.4, 128.1, 127.9, 127.3, 126.3, 125.9, 113.9, 55.3, 50.9, 42.8; FTIR (NaCl, thin film): 3060, 3026, 2932, 2834, 1607, 1577, 1511, 1494, 1452, 1299, 1249, 1174, 1109, 1033, 965, 820, 756 cm^{-1}; HRMS (MM) calc'd for $C_{23}H_{22}O$ $[M+H]^+$ 315.1743, found 315.1699.

(*S*,*E*)-1-methoxy-4-(3-phenylocta-1,7-dien-1-yl)benzene (163l)



Prepared from (1-chlorohex-5-en-1-yl)benzene (**162l**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163l** (39.6 mg, 68% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (AS-H, 2.5 mL/min, 10% IPA in CO_2, λ = 254 nm): t_R (minor) = 3.1 min, t_R (major) = 3.7 min. $[\alpha]_D^{25} = -22.7°$ (c = 1.2, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.19 (m, 7H), 6.89 – 6.81 (m, 2H), 6.36 (d, *J* = 15.8 Hz, 1H), 6.21 (dd, *J* = 15.8, 7.9 Hz, 1H), 5.81 (ddt, *J* = 17.0, 10.2, 6.7 Hz, 1H), 5.06 – 4.93 (m, 2H), 3.81 (s, 3H), 3.41 (q, *J* = 7.6 Hz, 1H), 2.15 – 2.04 (m, 2H), 1.87 – 1.77 (m, 2H), 1.53 – 1.32 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 144.8, 138.7, 132.2, 130.4, 128.8, 128.5, 127.6, 127.2, 126.1, 114.5, 113.9, 55.3, 49.1, 35.5, 33.7, 27.0; FTIR (NaCl, thin film): 3060, 3026, 2931, 2856, 2834, 1639, 1607, 1577, 1511, 1493, 1464, 1452, 1441, 1418, 1299, 1250, 1174, 1108, 1036, 965, 910, 828, 759 cm^{-1}; HRMS (MM) calc'd for $C_{21}H_{24}O$ $[M+H]^+$ 293.1900, found 293.1867.

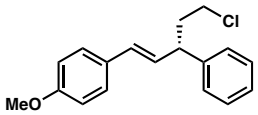
(*S*,*E*)-5-(4-methoxyphenyl)-3-phenylpent-4-en-1-ol (163m)



Prepared from 3-chloro-3-phenylpropan-1-ol (**162m**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (10 to 20% ethyl acetate/hexanes) to yield **163m** (43.3 mg, 81% yield) in 96% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 30% IPA in CO_2, λ = 254 nm): t_R (minor) = 5.5 min, t_R

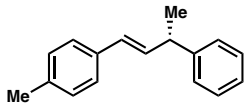
(major) = 6.9 min. $[\alpha]_D^{25} = -27.5°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.38 – 7.20 (m, 7H), 6.90 – 6.81 (m, 2H), 6.41 (d, *J* = 15.5 Hz, 1H), 6.22 (dd, *J* = 15.8, 8.0 Hz, 1H), 3.81 (s, 3H), 3.74 – 3.60 (m, 3H), 2.18 – 2.01 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 144.1, 131.4, 130.1, 129.1, 128.6, 127.6, 127.3, 126.4, 113.9, 61.0, 55.3, 45.5, 38.5; FTIR (NaCl, thin film): 3350, 3026, 2933, 2835, 1607, 1577, 1511, 1492, 1452, 1300, 1249, 1175, 1033, 967, 809, 760 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O_2$ $[M+H]^+$ 269.1536, found 269.1470.

(*S*,*E*)- 1-(5-chloro-3-phenylpent-1-en-1-yl)-4-methoxybenzene (163n)



Prepared from (1,3-dichloropropyl)benzene (**162n**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (5 to 20% toluene/hexanes) to yield **163n** (34.3 mg, 60% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (AS-H, 2.5 mL/min, 3% ACN in CO_2, λ = 254 nm): t_R (major) = 15.5 min, t_R (minor) = 22.0 min. $[\alpha]_D^{25} = -10.9°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41 – 7.15 (m, 7H), 6.91 – 6.82 (m, 2H), 6.44 (d, *J* = 16.1 Hz, 3H), 6.18 (dd, *J* = 15.8, 8.0 Hz, 1H), 3.81 (s, 3H), 3.76 – 3.68 (m, 1H), 3.61 – 3.45 (m, 2H), 2.34 – 2.19 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 159.0, 143.1, 130.1, 129.9, 129.8, 128.7, 127.6, 127.3, 126.6, 113.9, 55.3, 45.9, 43.1, 38.4; FTIR (NaCl, thin film): 3027, 2956, 2835, 1607, 1576, 1511, 1492, 1452, 1291, 1250, 1175, 1034, 967, 760, 701 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{19}ClO$ $[M]^+$ 286.1119, found 286.1119.

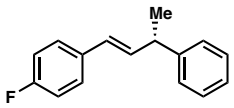
(*S*,*E*)-1-methyl-4-(3-phenylbut-1-en-1-yl)benzene (157a)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methylbenzene (**156a**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (hexanes, 6% $AgNO_3$-adsorbed silica gel) to yield **157a** (36.9 mg, 83% yield) in 96% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 7% IPA in CO_2, λ = 254 nm): t_R (minor) = 7.5 min, t_R (major) = 9.3 min. $[\alpha]_D^{25}$ = –47.3° (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 – 7.18 (m, 7H), 7.17 – 7.08 (m, 2H), 6.53 – 6.23 (m, 2H), 3.73 – 3.59 (m, 1H), 2.35 (s, 3H), 1.54 – 1.42 (m, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.8, 136.8, 134.8, 134.2, 129.2, 128.5, 128.4, 127.3, 126.2, 126.0, 42.6, 21.3, 21.2; FTIR (NaCl, thin film): 3083, 3024, 2964, 2924, 2870, 1602, 1512, 1492, 1451, 1371, 1154, 1017, 967, 803, 759 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{18}$ $[M+H_2O]^+$ 240.1509, found 240.1517.

The optical rotation of the product generated in the presence of (*R*,*R*,*S*,*S*)-**L104** was measured as $[\alpha]_D^{25}$ = –47.3° (c = 1.1, $CHCl_3$). Lit: $[\alpha]_D^{20}$ = +38.4° (c = 0.98, $CHCl_3$, *R* enantiomer, 91% ee). Based on the literature precedent, we assign our product as the *S* enantiomer.[40]

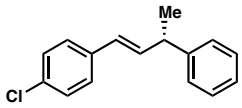
(*S*,*E*)-1-fluoro-4-(3-phenylbut-1-en-1-yl)benzene (157b)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-fluorobenzene (**156b**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (hexanes, 6%

$AgNO_3$-adsorbed silica gel) to yield **157b** (33.7 mg, 74% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 7% IPA in CO_2, λ = 254 nm): t_R (minor) = 5.9 min, t_R (major) = 7.1 min. $[\alpha]_D^{25}$ = –34.6° (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.48 – 7.12 (m, 7H), 7.10 – 6.88 (m, 2H), 6.47 – 6.21 (m, 2H), 3.81 – 3.53 (m, 1H), 1.49 (d, *J* = 7.2 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 162.0 (d, *J* = 246 Hz), 145.5, 135.0, 133.7, 128.5, 127.6 (d, *J* = 8 Hz), 127.35, 127.28, 126.3, 115.3 (d, *J* = 22 Hz), 42.6, 21.2; FTIR (NaCl, thin film): 3025, 2965, 2927, 2871, 1602, 1508, 1492, 1451, 1226, 1157, 1094, 1011, 965, 855, 818, 761 cm^{-1}; HRMS (MM) calc'd for $C_{16}H_{15}F$ $[M+Li]^+$ 232.1304, found 232.1321.

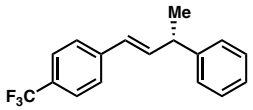
(*S*,*E*)-1-chloro-4-(3-phenylbut-1-en-1-yl)benzene (157c)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-chlorobenzene (**156c**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes, 6% $AgNO_3$-adsorbed silica gel) to yield **157c** (32.1 mg, 66% yield) in 95% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 10% IPA in CO_2, λ = 254 nm): t_R (minor) = 6.4 min, t_R (major) = 7.9 min. $[\alpha]_D^{25}$ = –42.2° (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.53 – 7.09 (m, 9H), 6.45 – 6.32 (m, 2H), 3.70 – 3.60 (m, 1H), 1.49 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.3, 136.1, 136.0, 132.6, 128.6, 127.6, 127.4, 127.3, 126.3, 42.6, 21.1; FTIR (NaCl, thin film): 3082, 3060, 3026, 2965, 2927, 2871, 1646, 1602, 1491, 1451, 1404, 1372, 1062, 1012, 966, 858, 810, 761 cm^{-1}; HRMS (ESI) calc'd for $C_{16}H_{15}Cl$ $[M+H]^+$ 243.0935, found 243.0985.

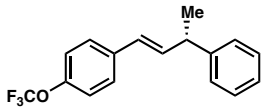
The optical rotation of the product generated in the presence of (*R*,*R*,*S*,*S*)-**L104** was measured as $[\alpha]_D^{25} = -42.2°$ (c = 1.0, $CHCl_3$). Lit: $[\alpha]_D^{20} = +33°$ (c = 1.0, $CHCl_3$, *R* enantiomer, 91% ee).[41] Based on the literature precedent, we assign our product as the *S* enantiomer.

(*S*,*E*)-1-(3-phenylbut-1-en-1-yl)-4-(trifluoromethyl)benzene (157d)



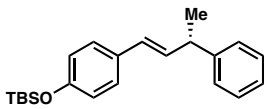
Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-(trifluoromethyl)benzene (**156d**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes) to yield **157d** (27.0 mg, 49% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 3% IPA in CO_2, λ = 254 nm): t_R (minor) = 5.4 min, t_R (major) = 6.3 min. $[\alpha]_D^{25} = -33.1°$ (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 – 7.52 (m, 2H), 7.49 – 7.41 (m, 2H), 7.40 – 7.21 (m, 4H), 6.52 (dd, *J* = 15.9, 6.3 Hz, 1H), 6.45 (d, *J* = 16.0 Hz, 1H), 3.73 – 3.63 (m, 1H), 1.50 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.0, 138.0, 128.6, 127.6, 127.33, 127.29, 126.4, 126.3, 125.4 (q, *J* = 4 Hz), 124.3 (q, *J* = 272 Hz) 42.6, 21.0; FTIR (NaCl, thin film): 3027, 2967, 1614, 1493, 1452, 1413, 1326, 1164, 1122, 1067, 1016, 967, 864, 820, 760 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{15}F_3$ $[M+H]^+$ 227.1199, found 227.1490.

(*S*,*E*)-1-(3-phenylbut-1-en-1-yl)-4-(trifluoromethoxy)benzene (157e)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-(trifluoromethoxy)benzene (**156e**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes, 6% $AgNO_3$-adsorbed silica gel) to yield **157e** (47.1 mg, 81% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 10% IPA in CO_2, λ = 254 nm): t_R (minor) = 2.3 min, t_R (major) = 2.5 min. $[\alpha]_D^{25} = -27.9°$ (c = 1.0, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 – 7.20 (m, 5H), 7.20 – 7.08 (m, 2H), 6.57 – 6.24 (m, 2H), 3.83 – 3.53 (m, 1H), 1.49 (d, *J* = 7.2 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 148.1, 145.3, 136.4, 128.6, 128.3, 127.31, 127.28, 127.1, 126.4, 121.1, 42.6, 21.1; FTIR (NaCl, thin film): 3083, 3061, 3027, 2967, 2930, 2873, 1602, 1587, 1507, 1493, 1452, 1260, 1220, 1164, 1017, 965, 864, 762 cm^{-1}; HRMS (MM) calc'd for $C_{17}H_{15}F_3O$ $[M+H]^+$ 293.1148, found 293.1237.

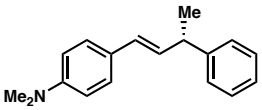
(*S*,*E*)-*tert*-butyldimethyl(4-(3-phenylbut-1-en-1-yl)phenoxy)silane (157f)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-(4-(2-bromovinyl)phenoxy)(*tert*-butyl)dimethylsilane (**156f**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes, 6% $AgNO_3$-adsorbed silica gel) to yield **157f** (55.4 mg, 82% yield) in 96% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 5% IPA in CO_2, λ = 254 nm): t_R (major) = 8.6 min, t_R (minor) = 13.2 min. $[\alpha]_D^{25} = -31.1°$ (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.45 – 7.10 (m, 7H), 6.87 – 6.68 (m, 2H), 6.38 (d, *J* = 17.3 Hz, 1H), 6.27 (dd, *J* = 15.9, 6.8 Hz,

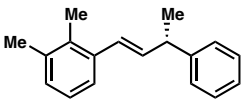
1H), 3.69 – 3.58 (m, 1H), 1.48 (d, J = 7.0 Hz, 3H), 1.00 (s, 9H), 0.21 (s, 6H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 154.9, 145.9, 133.2, 130.9, 128.5, 128.0, 127.3, 127.2, 126.1, 120.2, 42.6, 25.7, 21.3, 18.3, –4.4; FTIR (NaCl, thin film): 3060, 3027, 2958, 2929, 2884, 2857, 1604, 1508, 1472, 1462 1451, 1362, 1264, 1168, 1099, 1009, 967, 914, 839, 822, 802, 781 cm^{-1}; HRMS (MM) calc'd for $C_{22}H_{30}OSi$ $[M+H]^+$ 339.2139, found 339.2118.

(*S*,*E*)-*N*,*N*-dimethyl-4-(3-phenylbut-1-en-1-yl)aniline (157g)



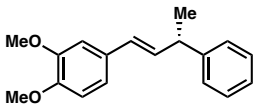
Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-4-(2-bromovinyl)-*N*,*N*-dimethylaniline (**156g**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (20 to 40% toluene/hexanes) to yield **157g** (27.5 mg, 55% yield) in 95% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 35% IPA in CO_2, λ = 254 nm): t_R (major) = 5.7 min, t_R (major) = 9.0 min. $[\alpha]_D^{25}$ = –67.3° (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.38 – 7.17 (m, 7H), 6.70 (d, J = 8.3 Hz, 2H), 6.37 (d, J = 15.9 Hz, 1H), 6.21 (dd, J = 15.9, 6.8 Hz, 1H), 3.69 – 3.59 (m, 1H), 2.96 (s, 6H), 1.48 (d, J = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.8, 146.3, 131.2, 128.4, 128.2, 127.3, 127.0, 126.0, 112.6, 42.5, 40.7, 21.5; FTIR (NaCl, thin film): 3009, 2955, 2870, 2808, 1611, 1525, 1490, 1446, 1359, 1231, 1186, 1168, 1063, 1020, 958, 802, 754 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{21}N$ $[M+H]^+$ 252.1747, found 252.1789.

(*S*,*E*)-1,2-dimethyl-3-(3-phenylbut-1-en-1-yl)benzene (157h)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-2,3-dimethylbenzene (**156h**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes, 6% $AgNO_3$-adsorbed silica gel) to yield **157h** (35.9 mg, 76% yield) in 96% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 4% EtOH in CO_2, λ = 254 nm): t_R (minor) = 4.4 min, t_R (major) = 5.6 min. $[\alpha]_D^{25} = -19.4°$ (c = 1.2, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 – 7.16 (m, 7H), 7.08 (d, *J* = 4.7 Hz, 2H), 6.73 (dd, *J* = 15.6, 1.4 Hz, 1H), 6.23 (dd, *J* = 15.7, 6.9 Hz, 1H), 3.75 – 3.66 (m, 1H), 2.33 (s, 3H), 2.28 (s, 3H), 1.52 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.8, 137.2, 137.0, 136.6, 133.8, 128.7, 128.5, 127.4, 127.3, 126.2, 125.5, 124.1, 42.8, 21.5, 20.7, 15.4; FTIR (NaCl, thin film): 3060, 3025, 2963, 2927, 2869, 1600, 1582, 1491, 1451, 1371, 1015, 971, 781, 759 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}$ $[M]^+$ 236.1565, found 236.1477.

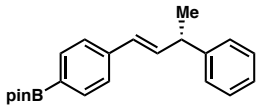
(*S*,*E*)-1,2-dimethoxy-4-(3-phenylbut-1-en-1-yl)benzene (157i)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-4-(2-bromovinyl)-1,2-dimethoxybenzene (**156i**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (20 to 40% toluene/hexanes) to yield **157i** (39.3 mg, 73% yield) in 95% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 25% IPA in CO_2, λ = 254 nm): t_R (minor) = 5.6 min, t_R (major) = 7.8 min. $[\alpha]_D^{25} = -36.4°$ (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.19 (m, 5H), 6.96 – 6.88 (m, 2H),

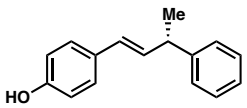
6.82 (d, J = 8.2 Hz, 1H), 6.38 (d, J = 15.9 Hz, 1H), 6.28 (dd, J = 15.8, 6.6 Hz, 1H), 3.90 (s, 3H), 3.89 (s, 3H), 3.70 – 3.61 (m, 1H), 1.49 (d, J = 7.1 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 149.0, 148.4, 145.8, 133.4, 130.7, 128.5, 128.1, 127.3, 126.2, 119.1, 111.1, 108.5, 55.9, 55.8, 42.5, 21.3; FTIR (NaCl, thin film): 3058, 3024, 2961, 2931, 2833, 1601, 1583, 1513, 1492, 1463 1451, 1417, 1264, 1158, 1139, 1027, 966, 803, 763 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{20}O_2$ $[M+H]^+$ 269.1536, found 269.1534.

(*S*,*E*)-4,4,5,5-tetramethyl-2-(4-(3-phenylbut-1-en-1-yl)phenyl)-1,3,2-dioxaborolane (157j)



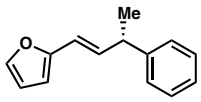
Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-2-(4-(2-bromovinyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (**156j**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (20 to 40% hexanes) to yield **157j** (39.4 mg, 59% yield) in 94% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 3.9 min, t_R (minor) = 7.5 min. $[\alpha]_D^{25}$ = –33.5° (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.80 – 7.72 (m, 2H), 7.40 – 7.19 (m, 7H), 6.53 – 6.39 (m, 2H), 3.71 – 3.62 (m, 1H), 1.49 (d, J = 7.2 Hz, 3H), 1.36 (s, 12H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.5, 140.3, 136.4, 135.0, 128.6, 128.5, 127.3, 126.3, 125.5, 83.7, 42.7, 24.9, 21.2; FTIR (NaCl, thin film): 3025, 2975, 2929, 1607, 1602, 1492, 1452, 1397, 1360, 1321, 1270, 1144, 1090, 1017, 962, 860 cm^{-1}; HRMS (MM) calc'd for $C_{22}H_{27}BO_2$ $[M]^+$ 333.2140, found 333.1960.

(*S*,*E*)-4-(3-phenylbut-1-en-1-yl)phenol (157k)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-4-(2-bromovinyl)phenol (**156k**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (10 to 20% ethyl acetate/hexanes) to yield **157k** (38.6 mg, 86% yield) in 93% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 30% IPA in CO_2, λ = 254 nm): t_R (major) = 3.0 min, t_R (minor) = 3.4 min. $[\alpha]_D^{25} = -39.1°$ (c = 0.8, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.38 – 7.16 (m, 7H), 6.84 – 6.74 (m, 2H), 6.37 (d, *J* = 16.0 Hz, 1H), 6.26 (dd, *J* = 15.9, 6.7 Hz, 1H), 4.89 (s, 1H), 3.69 – 3.60 (m, 1H), 1.48 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 154.6, 145.9, 133.2, 130.6, 128.5, 127.8, 127.5, 127.3, 126.2, 115.4, 42.5, 21.3; FTIR (NaCl, thin film): 3368, 3025, 2963, 2927, 2871, 1633, 1608, 1512, 1492, 1451, 1371, 1227, 1170, 1010, 966, 819, 762 cm^{-1}; HRMS (MM) calc'd for $C_{16}H_{16}O$ $[M]^+$ 224.1201, found 224.1164.

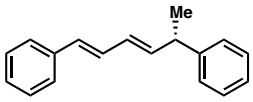
(*S*,*E*)-2-(3-phenylbut-1-en-1-yl)furan (157l)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-2-(2-bromovinyl)furan (**156l**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes) to yield **157l** (31.7 mg, 80% yield) in 91% ee as a yellow oil. The enantiomeric excess was determined by chiral SFC analysis (AD-H, 2.5 mL/min, 3% IPA in CO_2, λ = 254 nm): t_R (miajor) = 3.2 min, t_R (minor) = 3.5 min. $[\alpha]_D^{25} = -48.3°$ (c = 0.9, $CHCl_3$), lit:[39] $[\alpha]_D^{20} = -48°$ (c = 1.0, $CHCl_3$, *S* enantiomer, 95% ee); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41 – 7.18 (m, 6H), 6.43 – 6.35 (m, 2H), 6.26 – 6.16 (m, 2H), 3.69 – 3.58 (m, 1H), 1.48 (d, *J* = 7.1 Hz, 3H); ^{13}C

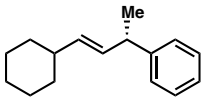
NMR (126 MHz, $CDCl_3$) δ 153.1, 145.3, 141.4, 134.2, 128.5, 127.3, 126.3, 117.4, 111.2, 106.7, 42.3, 21.1; FTIR (NaCl, thin film): 3060, 3026, 2965, 2928, 2871, 1602, 1491, 1452, 1371, 1255, 1151, 1012, 961, 928, 884, 760, 732 cm^{-1}; HRMS (MM) calc'd for $C_{14}H_{14}O$ $[M+H]^+$ 199.1117, found 199.1067.

(*S*,1*E*,3*E*)-hexa-1,3-diene-1,5-diyldibenzene (157m)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and ((1*E*,3*E*)-4-bromobuta-1,3-dien-1-yl)benzene (**156m**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by flash chromatography (hexanes, florisil) to yield **157m** (38.5 mg, 82% yield) in 92% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 15% IPA in CO_2, λ = 254 nm): t_R (major) = 6.9 min, t_R (minor) = 9.4 min. $[\alpha]_D^{25} = -34.1°$ (c = 1.0, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$) δ 7.43 – 7.16 (m, 9H), 6.80 (dd, *J* = 15.7, 10.4 Hz, 1H), 6.52 (d, *J* = 15.7 Hz, 1H), 6.26 (dd, *J* = 15.2, 10.4 Hz, 1H), 6.03 (dd, *J* = 15.3, 6.8 Hz, 1H), 3.66 – 3.56 (m, 1H), 1.46 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.6, 139.9, 137.5, 131.0, 129.20, 129.18, 128.6, 128.5, 127.3, 127.2, 126.23, 126.19, 42.5, 21.2; FTIR (NaCl, thin film): 3059, 3023, 2964, 2927, 2870, 1638, 1596, 1492, 1448, 1371, 1259, 1154, 1117, 1072, 988, 909, 760, 745 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{18}$ $[M]^+$ 234.1409, found 234.1342.

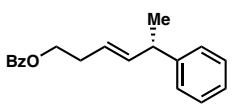
(*S*,*E*)-(4-cyclohexylbut-3-en-2-yl)benzene (157n)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-(2-bromovinyl)cyclohexane (**156n**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by flash chromatography (hexanes) to yield **157n** (23.6 mg, 55% yield) in 96% ee as a clear oil. The enantiomeric excess was determined by chiral HPLC analysis (OJ-H, 1 mL/min, 1% IPA in hexanes, λ = 220 nm): t_R (minor) = 5.1 min, t_R (major) = 5.8 min. $[\alpha]_D^{25} = -5.5°$ (c = 0.8, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$) δ 7.35 – 7.26 (m, 2H), 7.26 – 7.16 (m, 3H), 5.57 (ddd, *J* = 15.5, 6.7, 1.2 Hz, 1H), 5.44 (ddd, *J* = 15.4, 6.7, 1.2 Hz, 1H), 3.47 – 3.37 (m, 1H), 2.01 – 1.89 (m, 1H), 1.78 – 1.61 (m, 4H), 1.35 (d, *J* = 7.0 Hz, 3H), 1.32 – 1.01 (m, 6H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 146.7, 135.2, 132.3, 128.3, 127.2, 125.8, 42.2, 40.6, 33.20, 33.18, 26.2, 26.1, 21.7; FTIR (NaCl, thin film): 3024, 2962, 2922, 2850, 1601, 1492, 1448, 1371, 1009, 965, 759, 698 cm^{-1}; HRMS (MM) calc'd for $C_{16}H_{22}$ $[M]^+$ 214.1722, found 214.1689.

The optical rotation of the product generated in the presence of (*R*,*R*,*S*,*S*)-**L104** was measured as $[\alpha]_D^{25} = -5.5°$ (c = 0.8, $CHCl_3$). Lit: $[\alpha]_D^{20} = +10.1°$ (c = 0.45, $CHCl_3$, *R* enantiomer, 95% ee).[42] Based on the literature precedent, we assign our product as the *S* enantiomer.

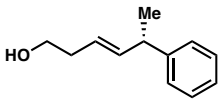
(*S*,*E*)-5-phenylhex-3-en-1-yl benzoate (157o)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-4-bromobut-3-en-1-yl benzoate (**156o**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (2%

Et_2O/hexanes) to yield **157o** (40.5 mg, 72% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 10% IPA in CO_2, λ = 210 nm): t_R (major) = 5.0 min, t_R (minor) = 5.8 min. $[\alpha]_D^{25}$ = 2.8° (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 – 7.99 (m, 2H), 7.63 – 7.54 (m, 1H), 7.51 – 7.40 (m, 2H), 7.31 – 7.14 (m, 5H), 5.78 (ddt, *J* = 15.4, 6.8, 1.4 Hz, 1H), 5.54 (dtd, *J* = 15.2, 6.8, 1.3 Hz, 1H), 4.37 (td, *J* = 6.7, 2.2 Hz, 2H), 3.52 – 3.43 (m, 1H), 2.51 (qt, *J* = 6.7, 1.1 Hz, 2H), 1.36 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 166.6, 145.9, 138.2, 132.8, 130.4, 129.6, 128.4, 128.3, 127.1, 126.0, 124.1, 64.3, 42.3, 32.1, 21.3; FTIR (NaCl, thin film): 3061, 3027, 2963, 2929, 2898, 2872, 1720, 1602, 1584, 1492, 1451, 1380, 1314, 1274, 1176, 1116, 1070, 1026, 968, 760, 712 cm^{-1}; HRMS (MM) calc'd for $C_{19}H_{20}O_2$ $[M+H]^+$ 281.1536, found 281.1522.

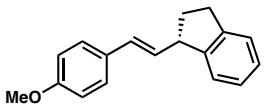
(*S*,*E*)-5-phenylhex-3-en-1-ol (157p)



Prepared from (1-chloroethyl)benzene (**26**, 0.2 mmol) and (*E*)-4-bromobut-3-en-1-ol (**156p**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (10 to 20% ethyl acetate/hexanes) to yield **157p** (19.7 mg, 56% yield) in 94% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 2% MeOH in CO_2, λ = 210 nm): t_R (major) = 9.6 min, t_R (minor) = 10.5 min. $[\alpha]_D^{25}$ = +13.1° (c = 0.6, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 – 7.27 (m, 2H), 7.25 – 7.15 (m, 3H), 5.77 (ddt, *J* = 15.4, 6.8, 1.4 Hz, 1H), 5.46 (dtd, *J* = 15.4, 7.0, 1.4 Hz, 1H), 3.66 (t, *J* = 6.2 Hz, 2H), 3.52 – 3.43 (m, 1H), 2.37 – 2.27 (m, 2H), 1.37 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 145.9, 138.7, 128.4, 127.1, 126.1, 124.7, 62.1, 42.4, 35.9,

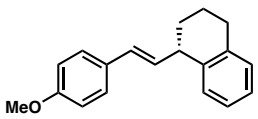
21.4; FTIR (NaCl, thin film): 3337, 3025, 2963, 2928, 1653, 1636, 1491, 1451, 1371, 1258, 1150, 1048, 968, 759 cm^{-1}; HRMS (MM) calc'd for $C_{12}H_{16}O$ $[M+H]^+$ 177.1274, found 177.1248.

(*S*,*E*)-1-(4-methoxystyryl)-2,3-dihydro-1*H*-indene (163o)



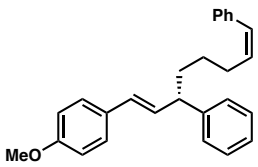
Prepared from 1-chloro-2,3-dihydro-1*H*-indene (**162o**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163o** (38.8 mg, 77% yield) in 94% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 20% IPA in CO_2, λ = 254 nm): t_R (major) = 5.1 min, t_R (minor) = 8.7 min. $[\alpha]_D^{25}$ = –6.5° (c = 1.1, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.32 (m, 2H), 7.32 – 7.16 (m, 4H), 6.91 – 6.85 (m, 2H), 6.51 (d, *J* = 15.7 Hz, 1H), 6.14 (dd, *J* = 15.9, 8.6 Hz, 1H), 3.97 – 3.88 (m, 1H), 3.83 (s, 3H), 3.06 – 2.89 (m, 2H), 2.49 – 2.38 (m, 1H), 2.01 – 1.89 (m, 1H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.9, 146.1, 144.0, 130.9, 130.3, 129.7, 127.3, 126.6, 126.2, 124.53, 124.50, 114.0, 55.3, 49.2, 33.7, 31.7; FTIR (NaCl, thin film): 3065, 3018, 2952, 2835, 1606, 1576, 1511, 1476, 1457, 1440, 1292, 1250, 1174, 1036, 965, 844, 811, 754, 740 cm^{-1}; HRMS (MM) calc'd for $C_{18}H_{18}O$ $[M+H]^+$ 251.1430, found 251.1371.

(*S*,*E*)-1-(4-methoxystyryl)-1,2,3,4-tetrahydronaphthalene (163p)



Prepared from 1-chloro-1,2,3,4-tetrahydronaphthalene (**162p**, 0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 5. The crude residue was purified by silica gel chromatography (5 to 15% toluene/hexanes) to yield **163p** (21.2 mg, 40% yield) in 90% ee as a white solid. The enantiomeric excess was determined by chiral SFC analysis (OB-H, 2.5 mL/min, 20% IPA in CO_2, λ = 254 nm): t_R (major) = 5.4 min, t_R (minor) = 8.3 min. $[\alpha]_D^{25}$ = +9.1° (c = 0.9, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 2H), 7.25 – 7.19 (m, 1H), 7.20 – 7.09 (m, 3H), 6.91 – 6.81 (m, 2H), 6.38 (d, *J* = 15.7 Hz, 1H), 6.16 (dd, *J* = 15.7, 8.5 Hz, 1H), 3.82 (s, 3H), 3.66 – 3.58 (m, 1H), 2.91 – 2.77 (m, 2H), 2.10 – 1.91 (m, 2H), 1.86 – 1.72 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 138.6, 137.0, 132.9, 130.4, 129.7, 129.6, 129.2, 127.2, 126.0, 125.6, 113.9, 55.3, 42.9, 30.5, 29.7, 21.0; FTIR (NaCl, thin film): 3014, 2930, 2856, 2834, 1607, 1577, 1511, 1489, 1463, 1450, 1297, 1249, 1174, 1035, 965, 843, 814, 755, 735 cm^{-1}; HRMS (MM) calc'd for $C_{19}H_{20}O$ $[M+H]^+$ 265.1587, found 265.1483.

((*S*,1*Z*,7*E*)-8-(4-methoxyphenyl)octa-1,7-diene-1,6-diyl)dibenzene (161)

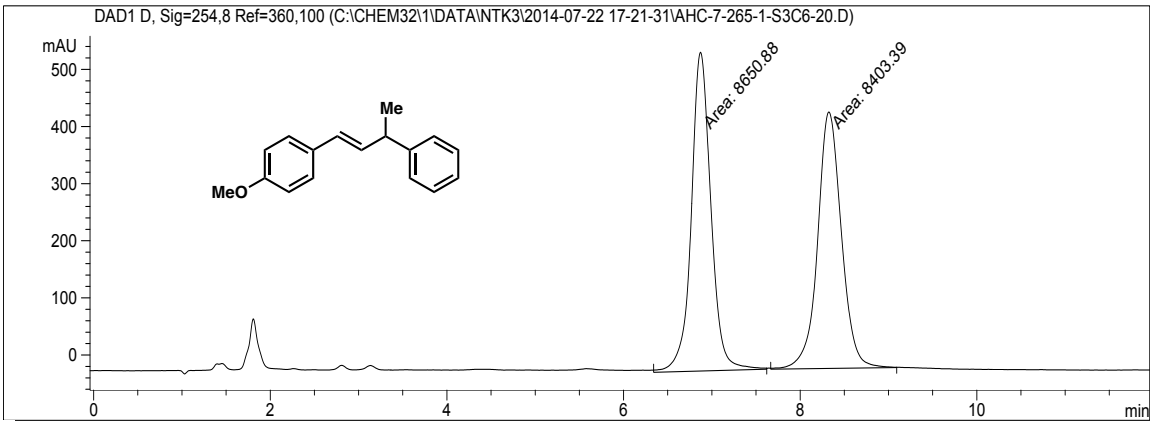


Prepared from **160** (0.2 mmol) and (*E*)-1-(2-bromovinyl)-4-methoxybenzene (**156**, 0.2 mmol) according to General Procedure 6. The crude residue was purified by silica gel chromatography (hexanes) to yield **161** (45.8 mg, 62% yield) in 96% ee as a clear oil. The enantiomeric excess was determined by chiral SFC analysis (OJ-H, 2.5 mL/min, 10% IPA in CO_2, λ = 254 nm): t_R (minor) = 7.2 min, t_R (major) = 7.9 min. $[\alpha]_D^{25}$ = –2.0° (c = 1.1, $CHCl_3$); ^{1}H

NMR (500 MHz, $CDCl_3$) δ 7.43 – 7.13 (m, 12H), 6.94 – 6.75 (m, 2H), 6.43 (dt, *J* = 11.7, 1.9 Hz, 1H), 6.34 (d, *J* = 16.4 Hz, 1H), 6.20 (dd, *J* = 15.8, 7.9 Hz, 1H), 5.65 (dt, *J* = 11.7, 7.2 Hz, 1H), 3.81 (s, 3H), 3.50 – 3.30 (m, 1H), 2.39 (qd, *J* = 7.4, 1.8 Hz, 2H), 1.94 – 1.74 (m, 2H), 1.64 – 1.35 (m, 2H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 158.8, 144.7, 137.7, 132.8, 132.1, 130.4, 129.0, 128.8, 128.7, 128.5, 128.1, 127.6, 127.2, 126.5, 126.2, 113.9, 55.3, 49.0, 35.5, 28.5, 27.9; FTIR (NaCl, thin film): 3057, 3024, 2931, 2856, 2834, 1607, 1576, 1511, 1492, 1452, 1300, 1249, 1174, 1035, 965, 914, 829, 804, 760, 699 cm^{-1}; HRMS (MM) calc'd for $C_{27}H_{28}O$ $[M+H]^+$ 369.2213, found 369.2219.

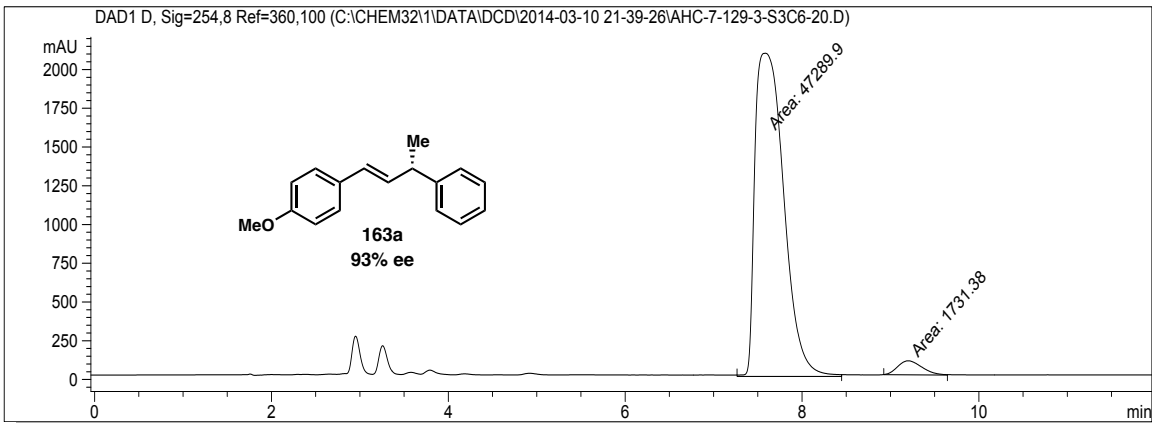
4.4.4 SFC Traces of Racemic and Enantioenriched Products

163a (Table 4.4, entry 1): racemic



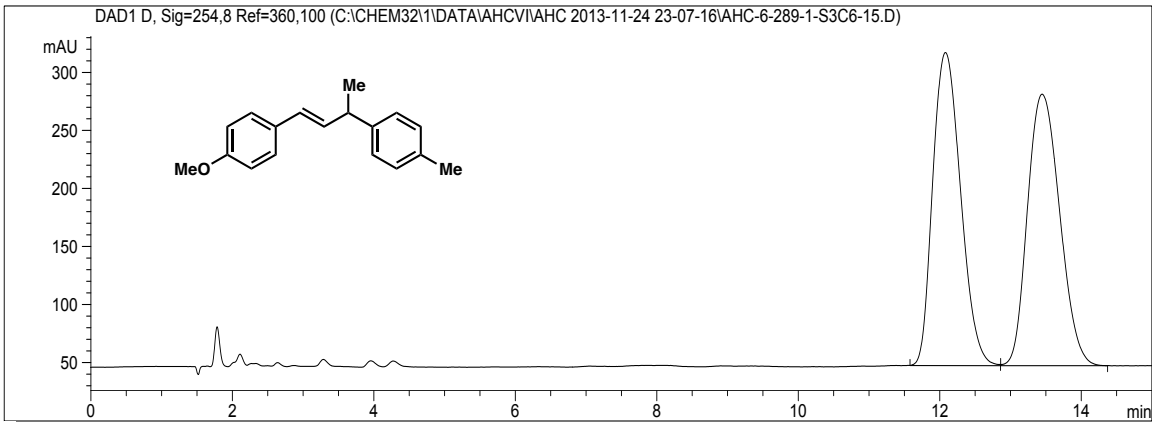
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.871	MM	0.2583	8650.88281	558.20911	50.7256
2	8.325	MM	0.3119	8403.38672	449.10953	49.2744

163a (Table 4.4, entry 1): enantioenriched, 93% ee



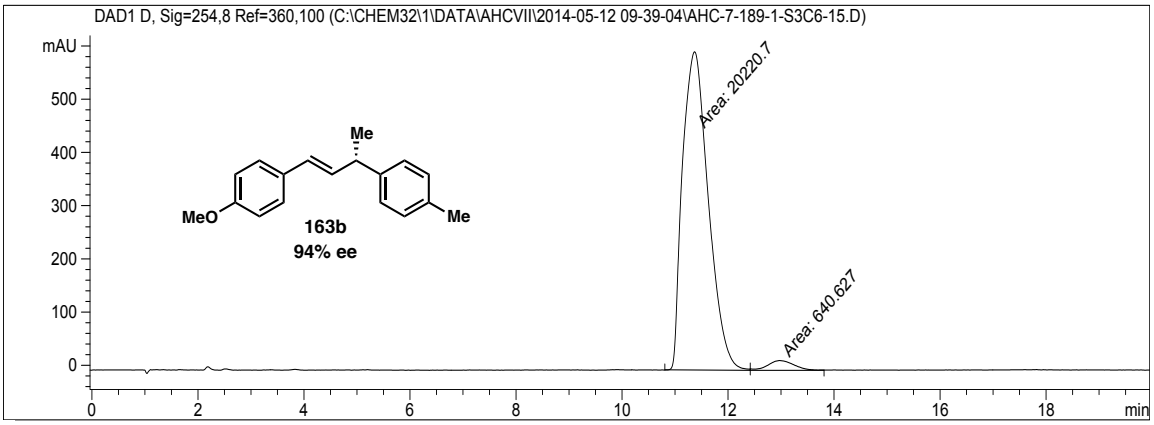
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.587	MM	0.3780	4.72899e4	2085.26416	96.4681
2	9.201	MM	0.3190	1731.38208	90.45088	3.5319

163b (Table 4.4, entry 2): racemic



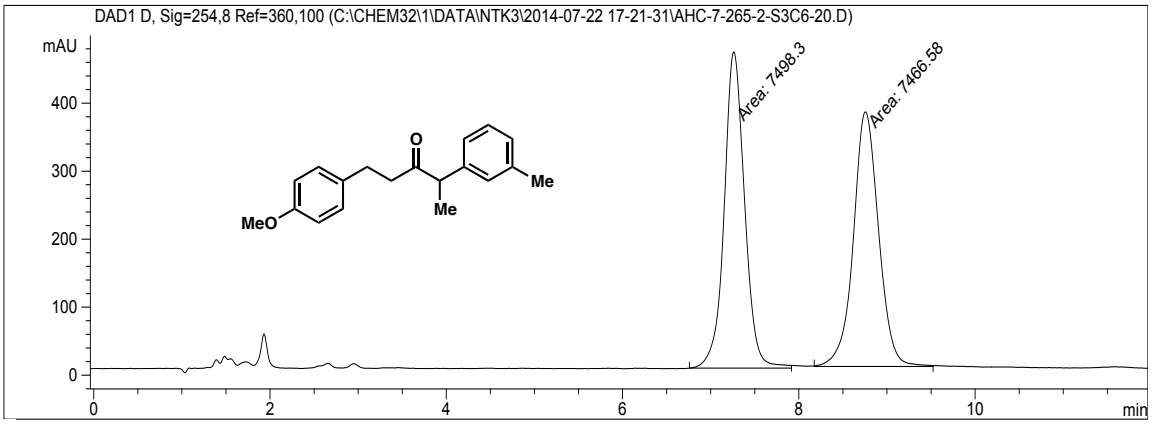
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	12.081	BB	0.4356	7393.43018	269.87115	49.9809
2	13.448	BB	0.5069	7399.08838	233.99118	50.0191

163b (Table 4.4, entry 2): enantioenriched, 94% ee



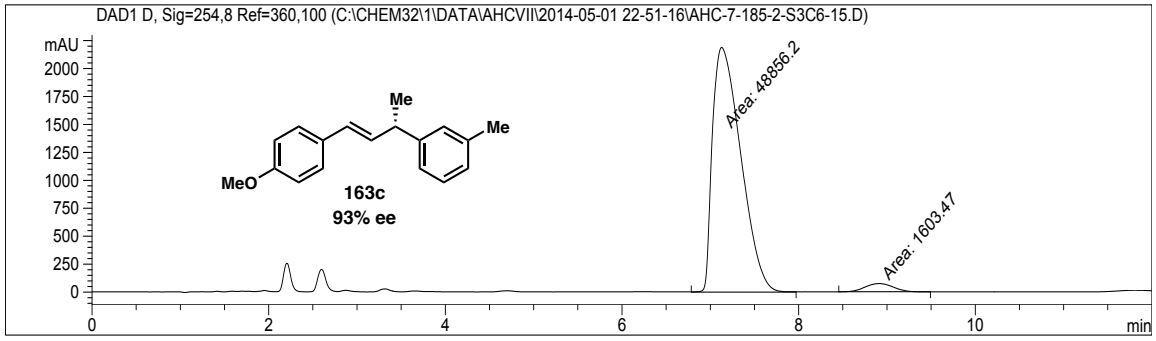
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	11.369	MM	0.5638	2.02207e4	597.78845	96.9291
2	12.970	MM	0.5781	640.62689	18.46935	3.0709

163c (Table 4.4, entry 3): racemic



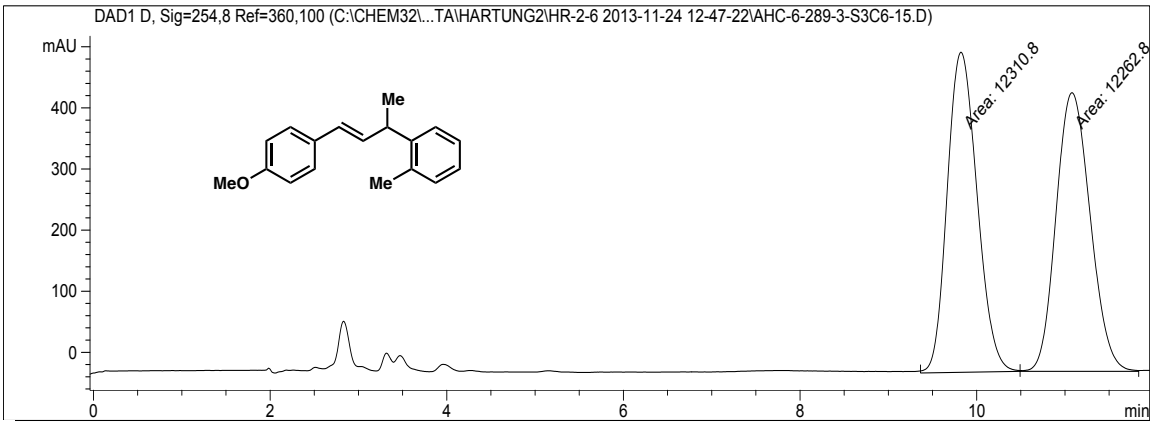
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.261	MM	0.2686	7498.30225	465.33981	50.1060
2	8.755	MM	0.3322	7466.58496	374.60574	49.8940

163c (Table 4.4, entry 3): enantioenriched, 93% ee



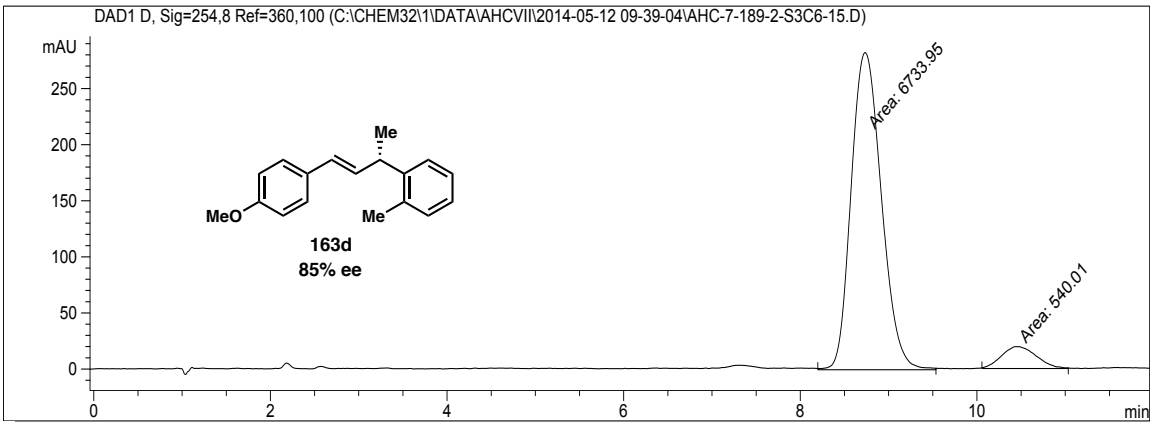
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.129	MM	0.3720	4.88562e4	2189.11938	96.8223
2	8.913	MM	0.3645	1603.46533	73.32549	3.1777

163d (Table 4.4, entry 4): racemic



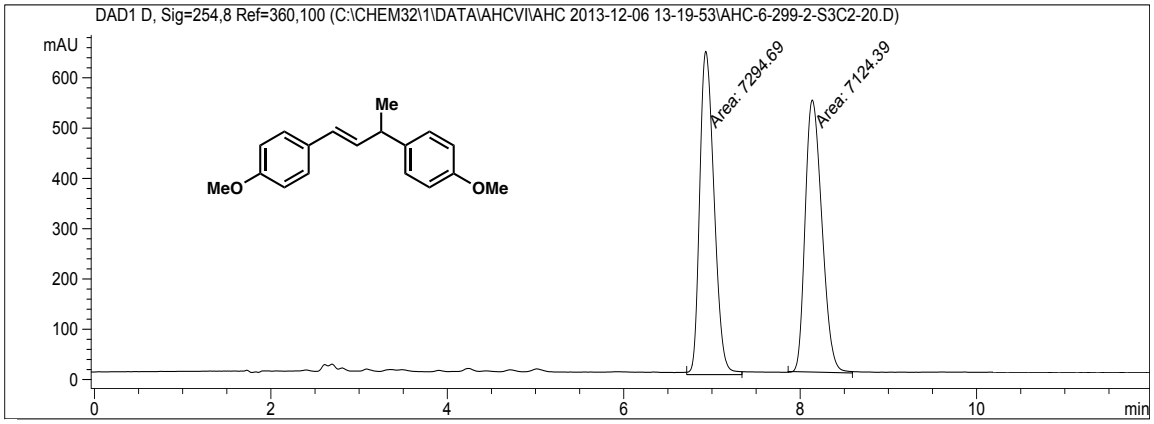
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	9.822	MM	0.3917	1.23108e4	523.83447	50.0978
2	11.079	MM	0.4482	1.22628e4	456.04102	49.9022

163d (Table 4.4, entry 4): enantioenriched, 85% ee



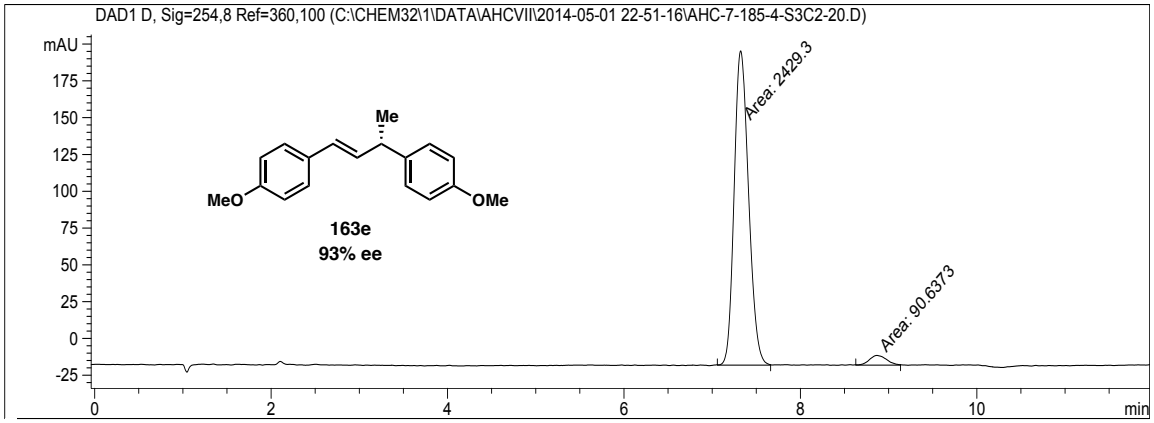
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	8.734	MM	0.3969	6733.94727	282.75232	92.5761
2	10.444	MM	0.4602	540.01031	19.55776	7.4239

163e (Table 4.4, entry 5): racemic



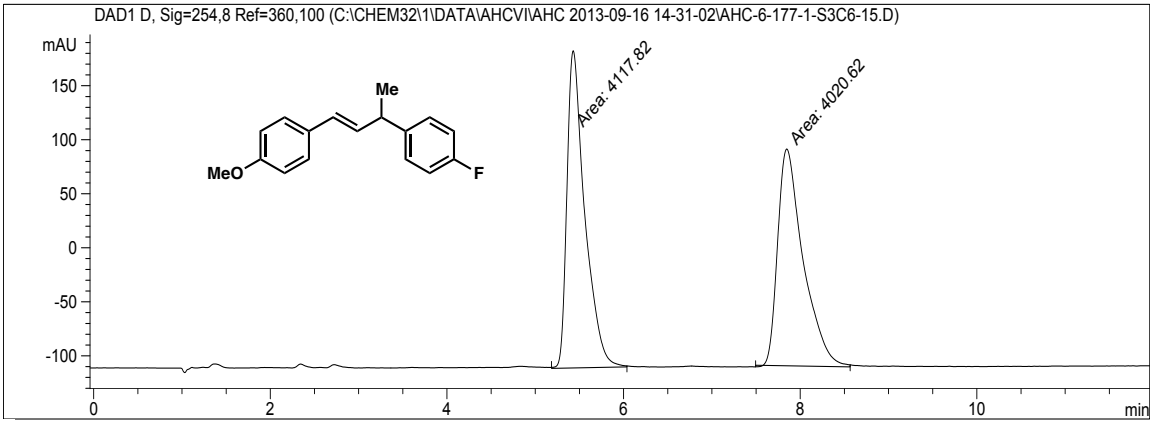
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.930	MM	0.1890	7294.69238	643.23810	50.5906
2	8.137	MM	0.2193	7124.38721	541.33319	49.4094

163e (Table 4.4, entry 5): enantioenriched, 93% ee



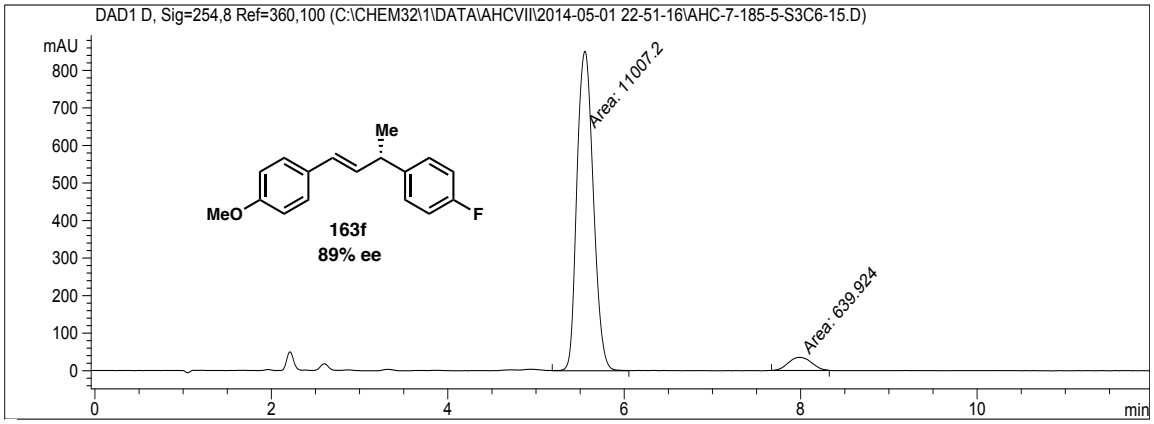
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.323	MM	0.1893	2429.29541	213.84731	96.4032
2	8.864	MM	0.2287	90.63728	6.60611	3.5968

163f (Table 4.4, entry 6): racemic



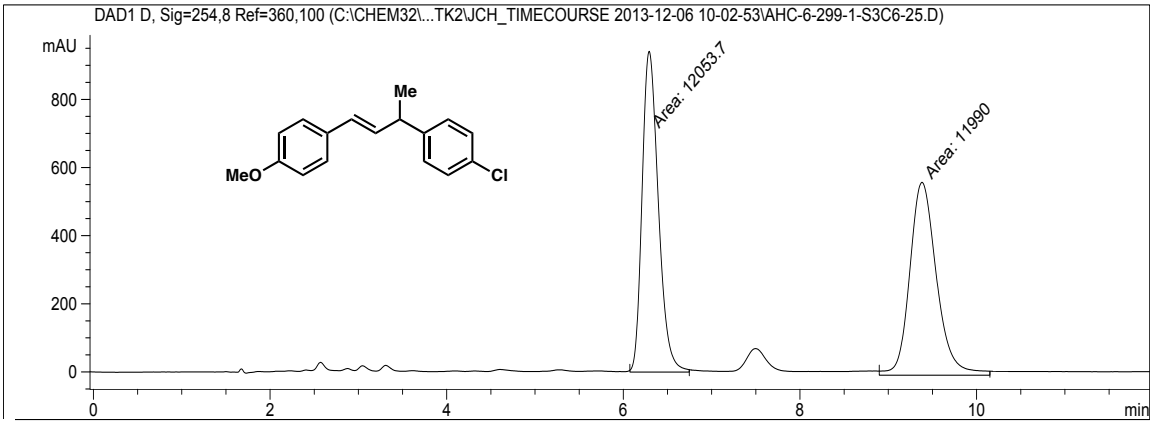
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.429	MM	0.2337	4117.82129	293.71591	50.5972
2	7.848	MM	0.3339	4020.61816	200.69434	49.4028

163f (Table 4.4, entry 6): enantioenriched, 89% ee



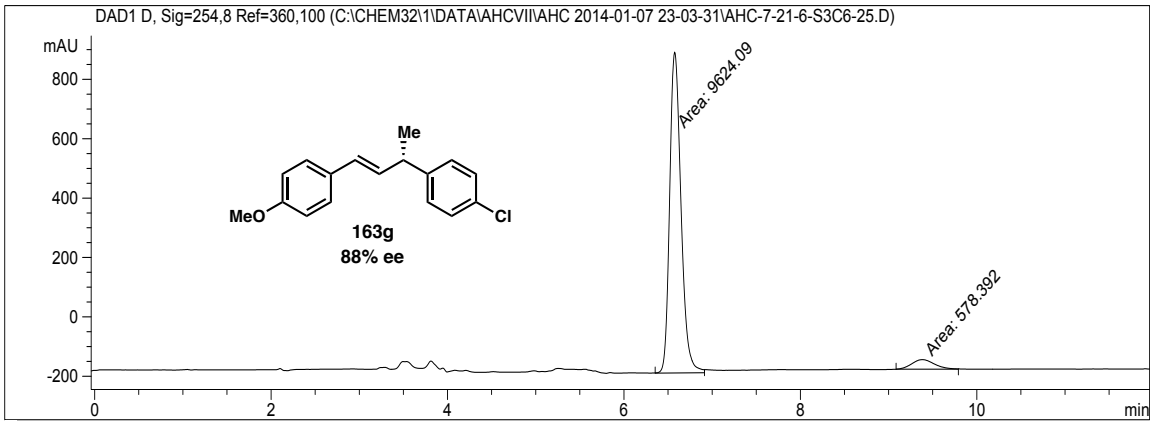
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.554	MM	0.2155	1.10072e4	851.35431	94.5057
2	7.988	MM	0.3047	639.92358	34.99786	5.4943

163g (Table 4.4, entry 7): racemic



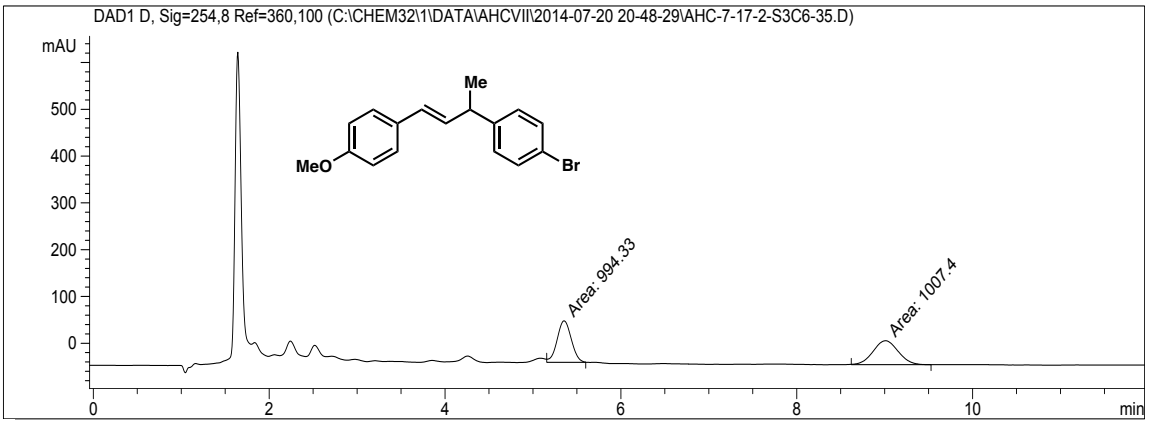
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.292	MM	0.2133	1.20537e4	941.72620	50.1325
2	9.381	MM	0.3530	1.19900e4	566.09015	49.8675

163g (Table 4.4, entry 7): enantioenriched, 88% ee



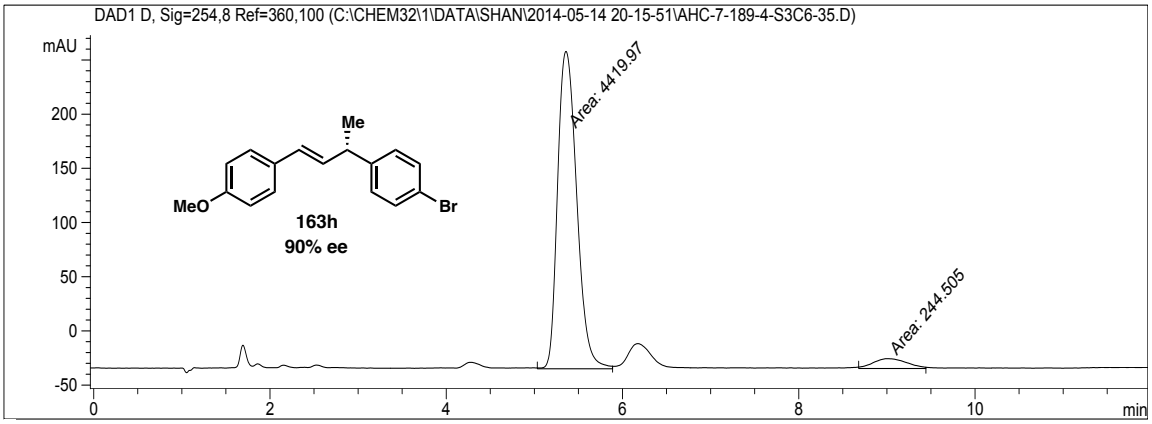
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.575	MM	0.1483	9624.08691	1081.90076	94.3309
2	9.384	MM	0.2997	578.39185	32.16311	5.6691

163h (Table 4.4, entry 8): racemic



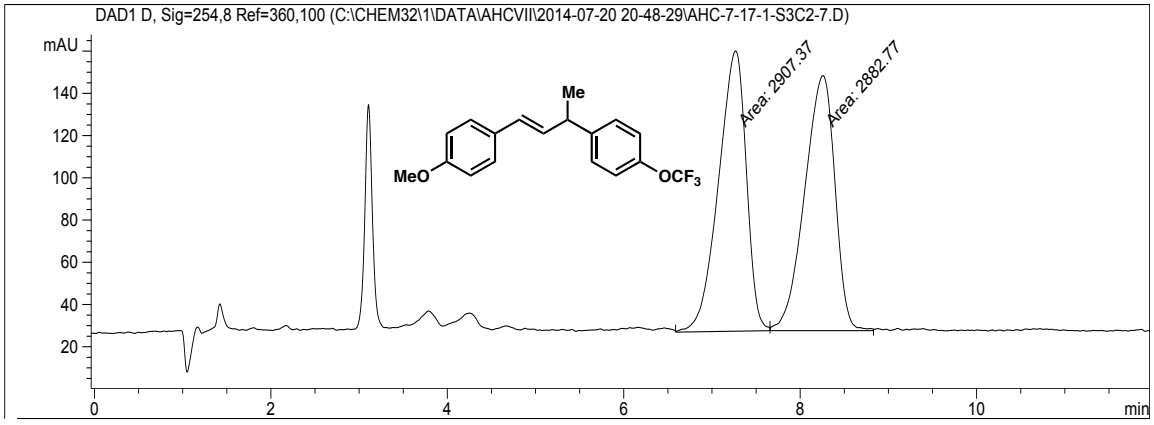
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.354	MM	0.1867	994.32965	88.77684	49.6736
2	9.010	MM	0.3286	1007.39520	51.08786	50.3264

163h (Table 4.4, entry 8): enantioenriched, 90% ee



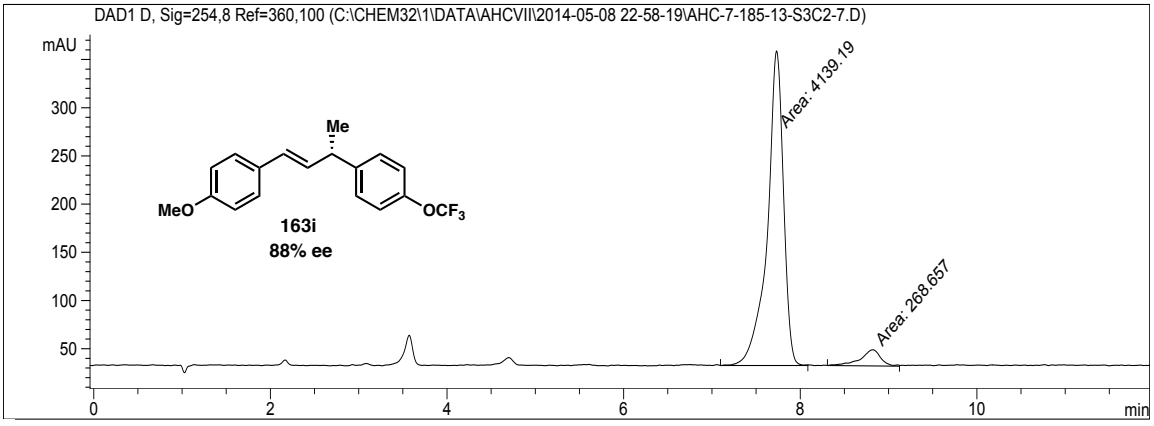
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.359	MM	0.2515	4419.97461	292.93845	94.7581
2	9.000	MM	0.4463	244.50519	9.13001	5.2419

163i (Table 4.4, entry 9): racemic



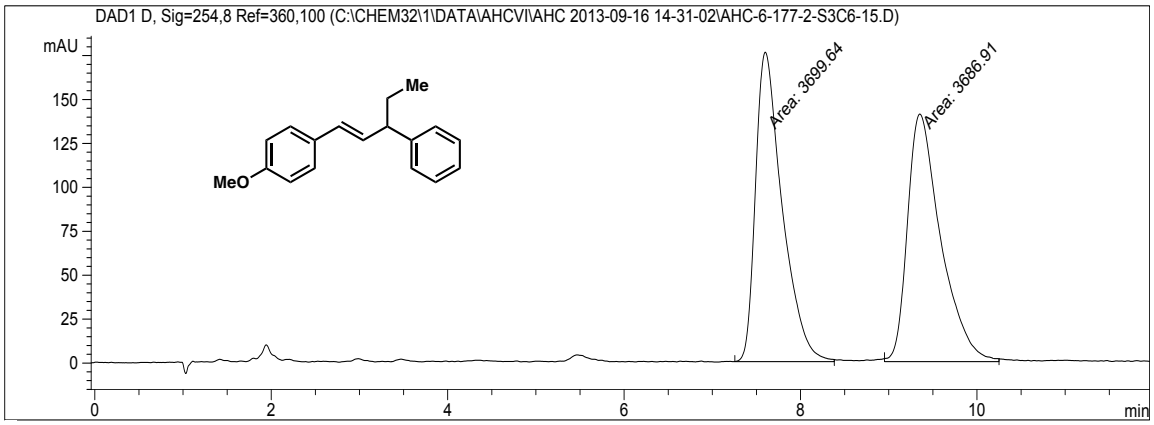
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.268	MM	0.3649	2907.36719	132.79340	50.2124
2	8.258	MM	0.3976	2882.76611	120.83252	49.7876

163i (Table 4.4, entry 9): enantioenriched, 88% ee



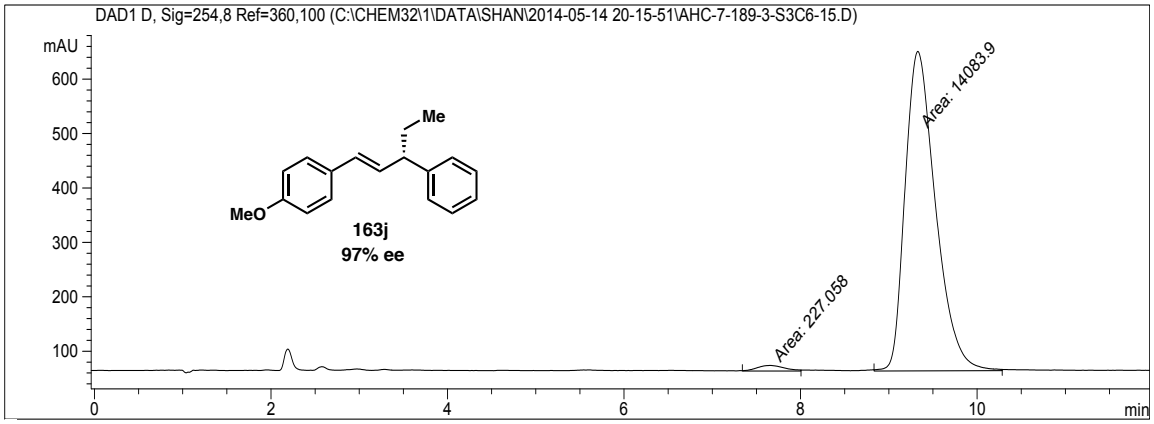
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.733	MM	0.2112	4139.18750	326.62589	93.9050
2	8.821	MM	0.2665	268.65671	16.80058	6.0950

163j (Table 4.4, entry 10): racemic



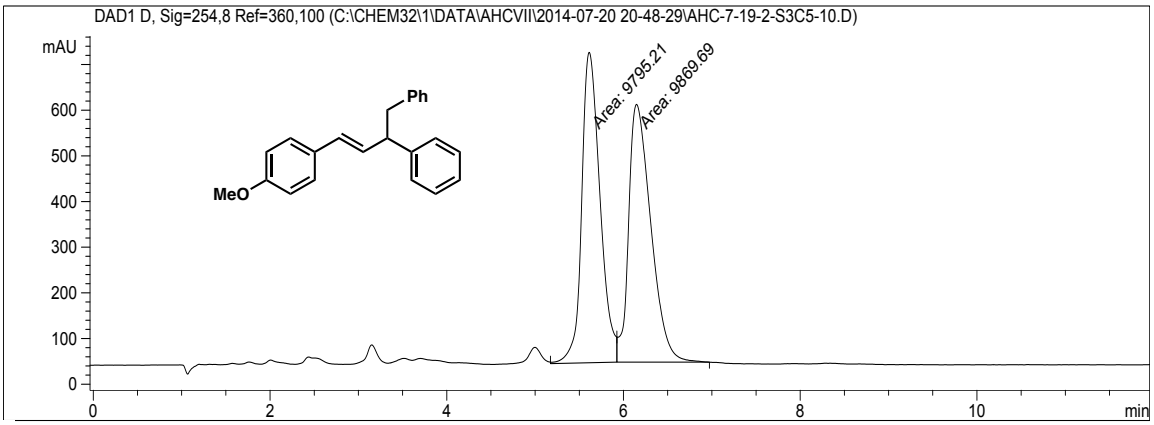
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.600	MM	0.3500	3699.64233	176.16603	50.0862
2	9.352	MM	0.4361	3686.90503	140.91353	49.9138

163j (Table 4.4, entry 10): enantioenriched, 97% ee



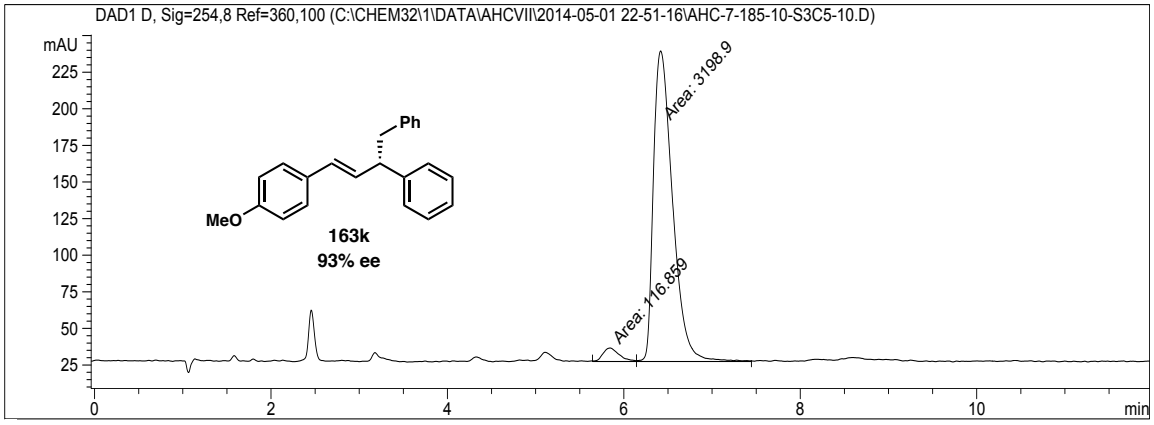
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.659	MM	0.3658	227.05769	10.34652	1.5866
2	9.329	MM	0.3998	1.40839e4	587.16370	98.4134

163k (Table 4.4, entry 11): racemic



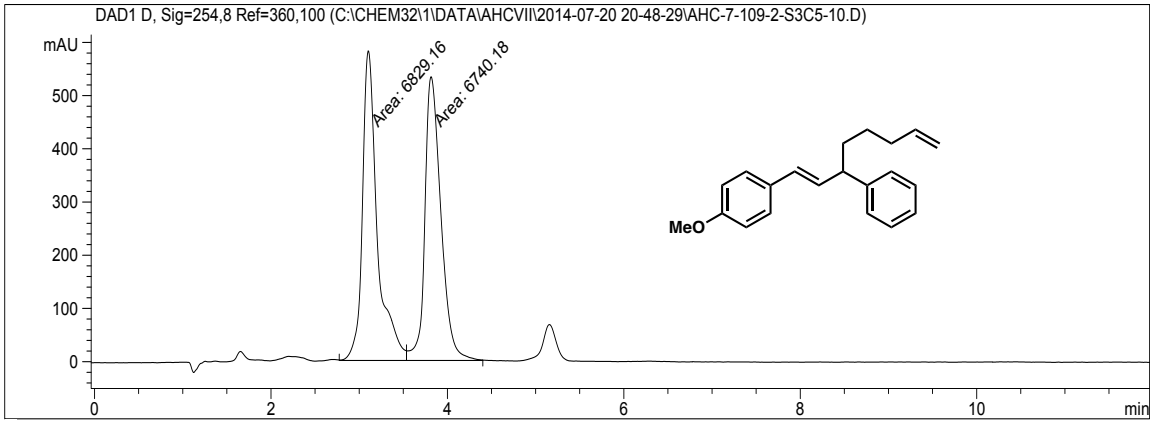
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.612	MM	0.2400	9795.21289	680.30035	49.8106
2	6.148	MM	0.2913	9869.69043	564.75275	50.1894

163k (Table 4.4, entry 11): enantioenriched, 93% ee



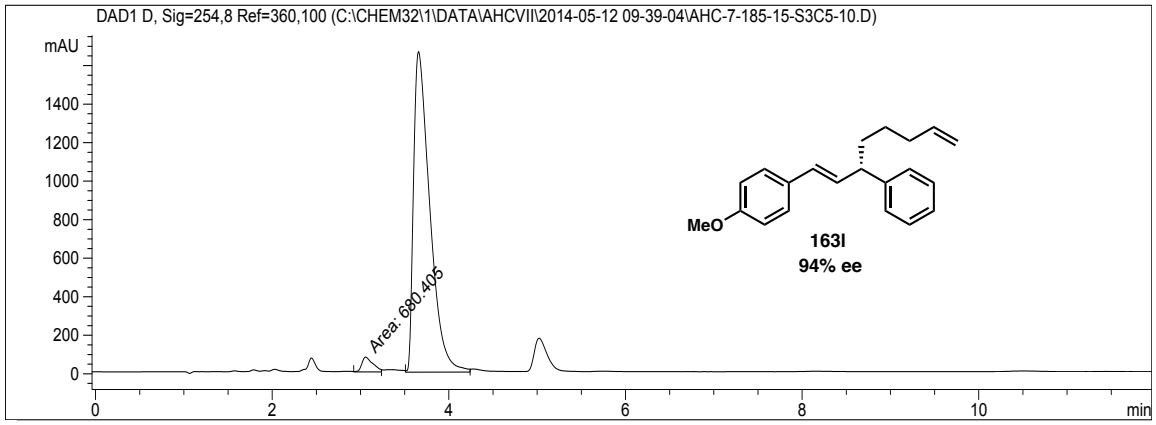
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.843	MM	0.2131	116.85924	9.14146	3.5244
2	6.416	MM	0.2513	3198.90405	212.16275	96.4756

163l (Table 4.4, entry 12): racemic



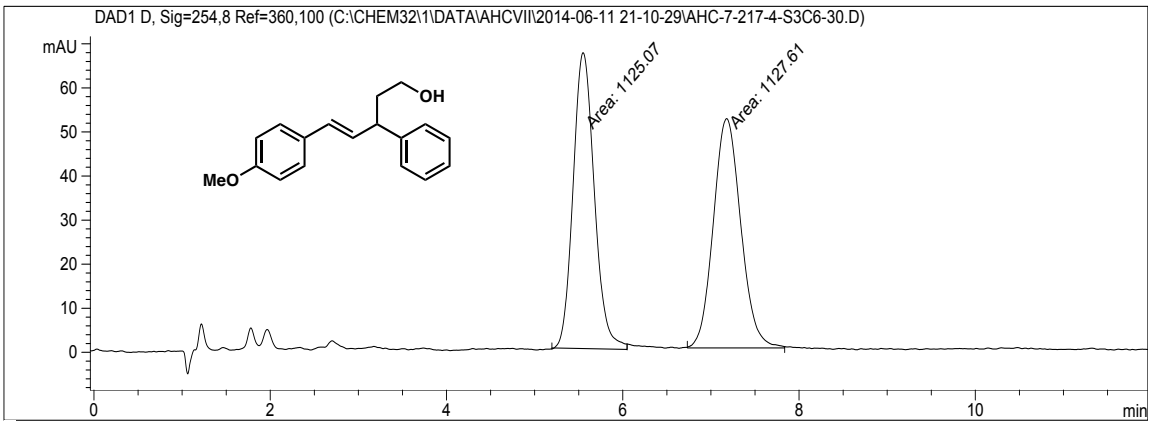
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.104	MM	0.1953	6829.15918	582.89142	50.3279
2	3.815	MM	0.2105	6740.18213	533.69666	49.6721

163l (Table 4.4, entry 12): enantioenriched, 94% ee



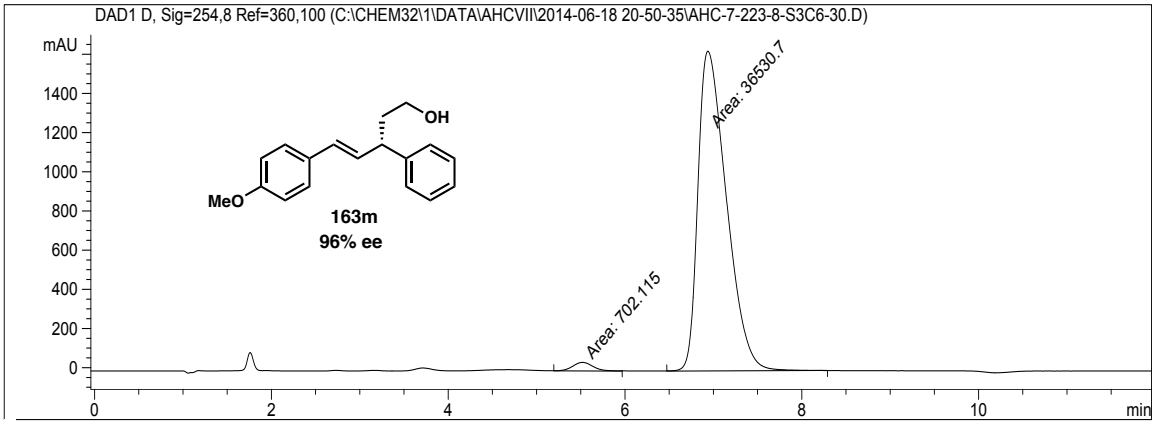
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.058	MM	0.1470	680.40527	77.13821	3.0921
2	3.659	VV	0.1956	2.13239e4	1663.29028	96.9079

163m (Table 4.4, entry 13): racemic



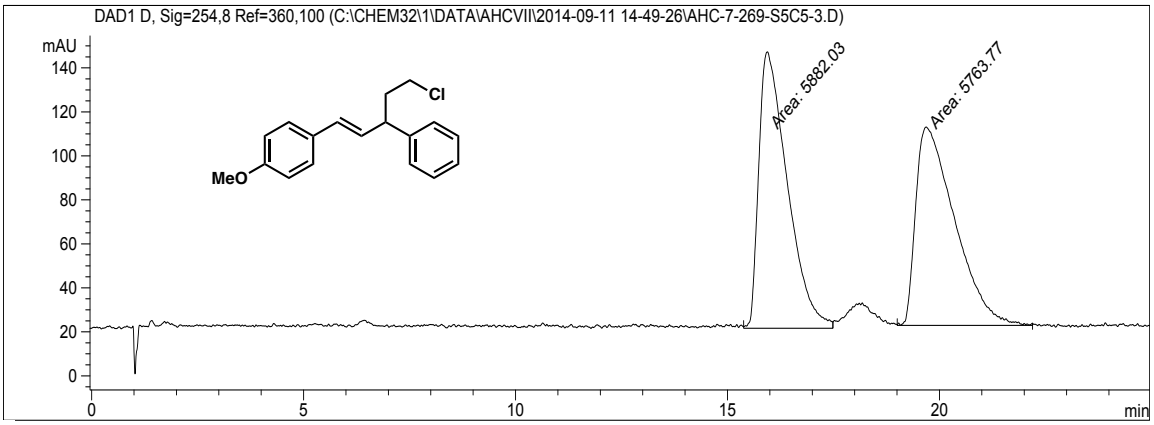
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.549	MM	0.2793	1125.06787	67.14302	49.9435
2	7.178	MM	0.3612	1127.61450	52.03247	50.0565

163m (Table 4.4, entry 13): enantioenriched, 96% ee



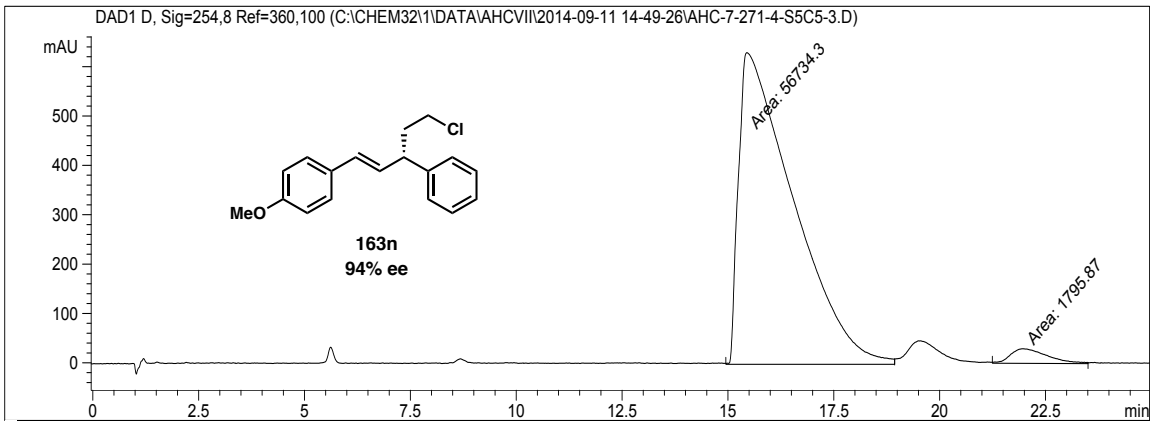
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.519	MM	0.2665	702.11481	43.90331	1.8857
2	6.938	MM	0.3729	3.65307e4	1632.66406	98.1143

163n (Table 4.4, entry 14): racemic



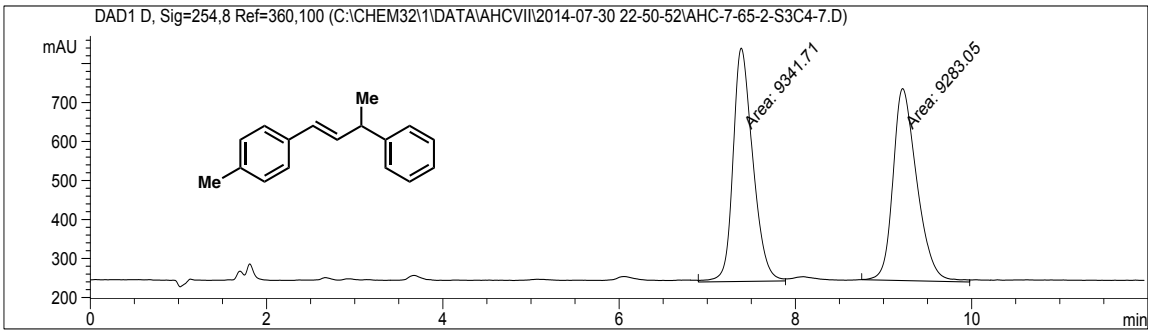
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	15.941	MM	0.7802	5882.02979	125.65482	50.5077
2	19.687	MM	1.0651	5763.77490	90.19390	49.4923

163n (Table 4.4, entry 14): enantioenriched, 94% ee



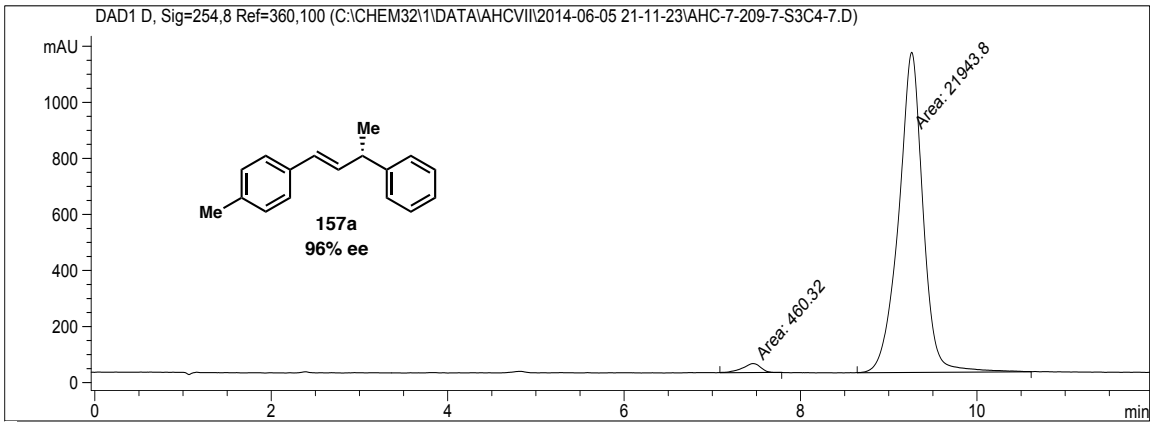
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	15.449	MM	1.4976	5.67343e4	631.38782	96.9317
2	21.994	MM	1.0162	1795.87158	29.45459	3.0683

157a (Table 4.5, entry 1): racemic



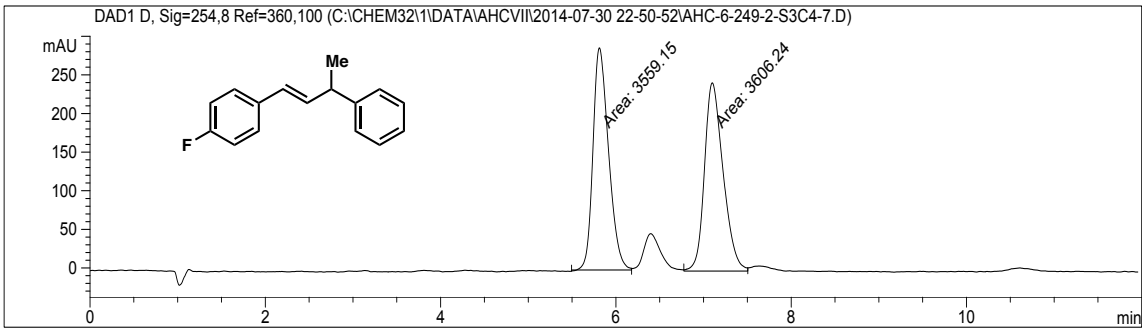
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.386	MM	0.2600	9341.71094	598.85675	50.1575
2	9.217	MM	0.3140	9283.04590	492.80606	49.8425

157a (Table 4.5, entry 1): enantioenriched, 96% ee



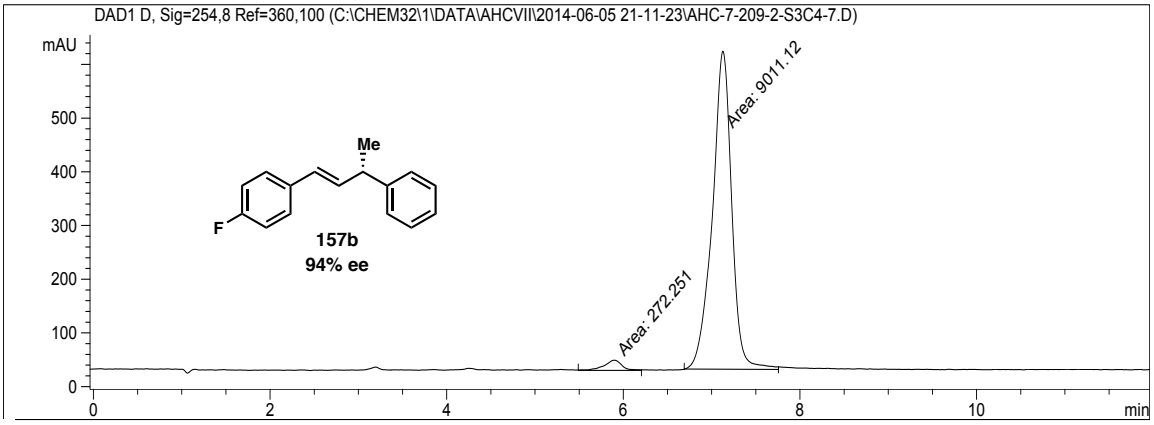
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.461	MM	0.2411	460.31961	31.82347	2.0546
2	9.260	MM	0.3201	2.19438e4	1142.71289	97.9454

157b (Table 4.5, entry 2): racemic



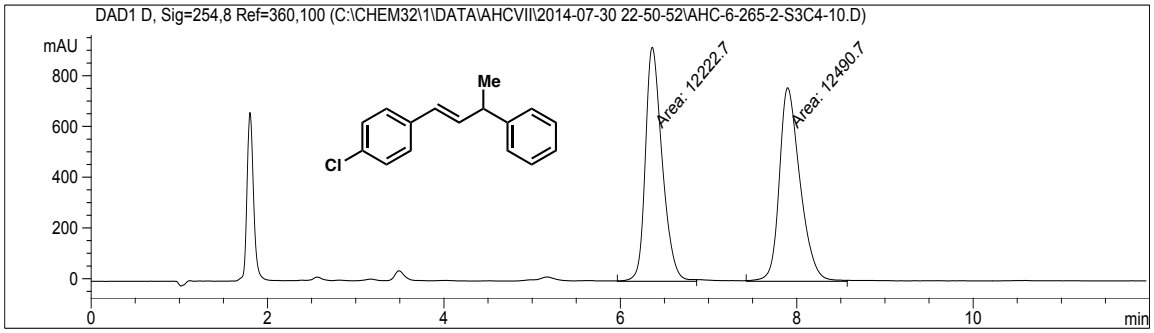
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.812	MM	0.2061	3559.15161	287.79590	49.6714
2	7.099	MM	0.2464	3606.24365	243.90446	50.3286

157b (Table 4.5, entry 2): enantioenriched, 94% ee



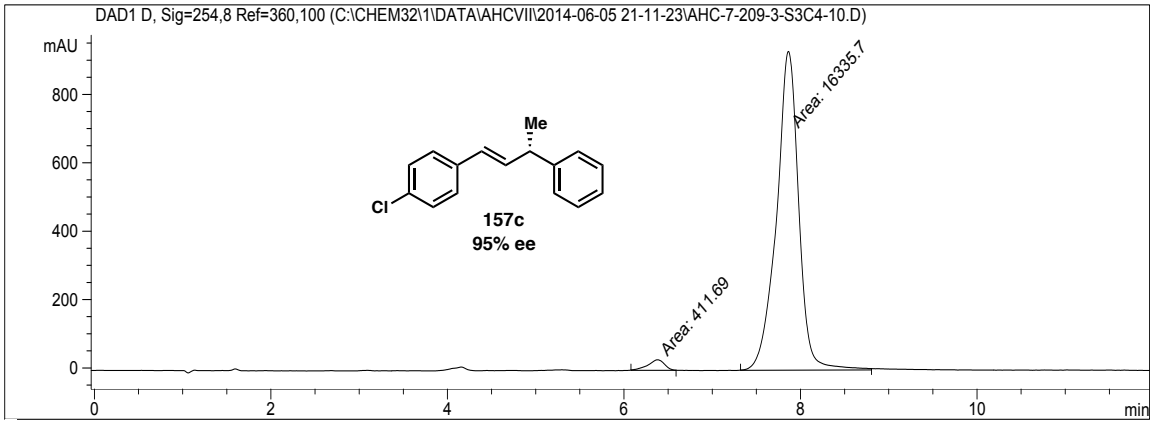
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.899	MM	0.2386	272.25067	19.01509	2.9327
2	7.128	MM	0.2536	9011.11523	592.32813	97.0673

157c (Table 4.5, entry 3): racemic



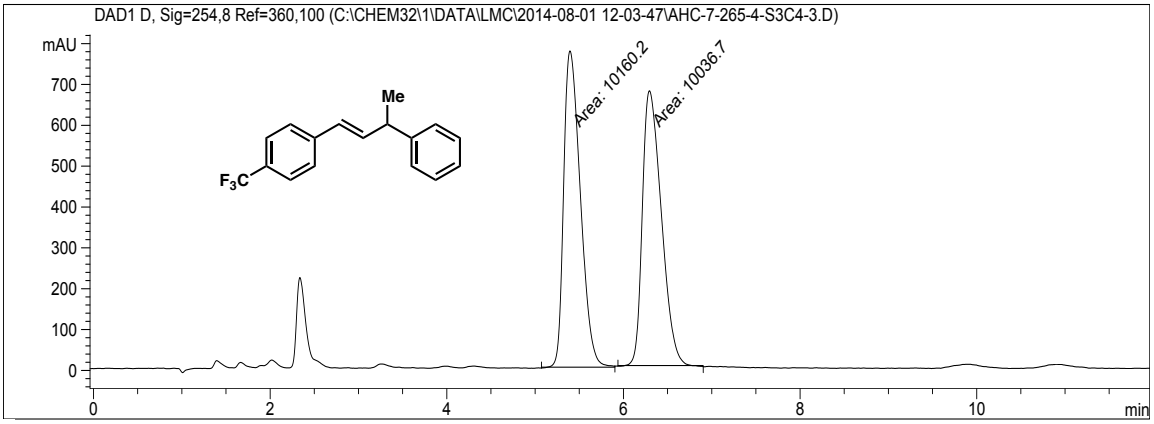
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.362	MM	0.2207	1.22227e4	922.92114	49.4580
2	7.898	MM	0.2727	1.24907e4	763.51147	50.5420

157c (Table 4.5, entry 3): enantioenriched, 95% ee



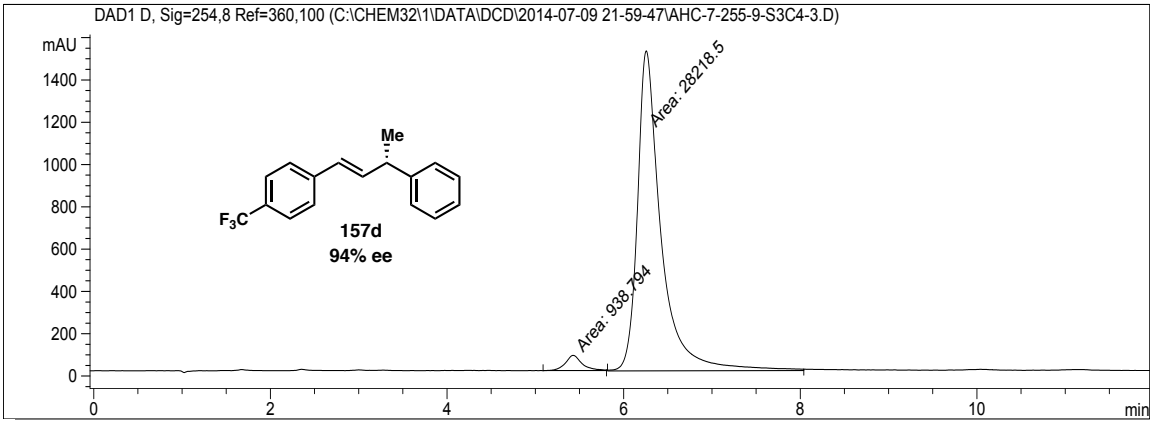
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.381	MM	0.2204	411.68973	31.13871	2.4582
2	7.864	MM	0.2918	1.63357e4	932.91962	97.5418

157d (Table 4.5, entry 4): racemic



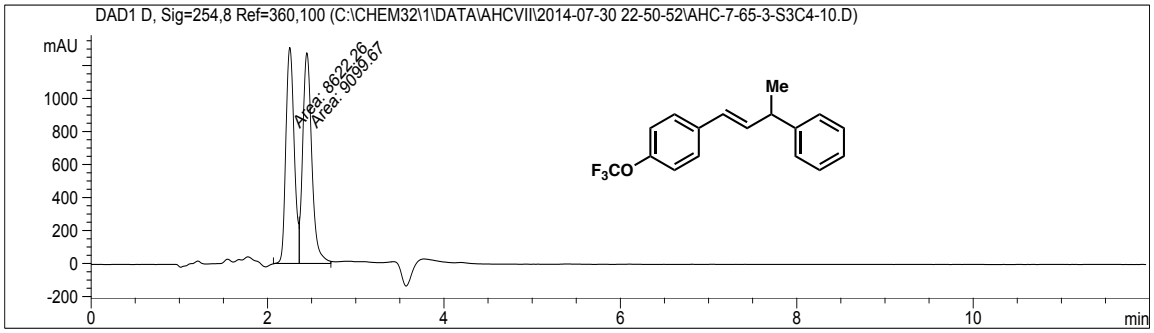
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.395	MM	0.2185	1.01602e4	774.91656	50.3057
2	6.295	MM	0.2484	1.00367e4	673.30627	49.6943

157d (Table 4.5, entry 4): enantioenriched, 94% ee



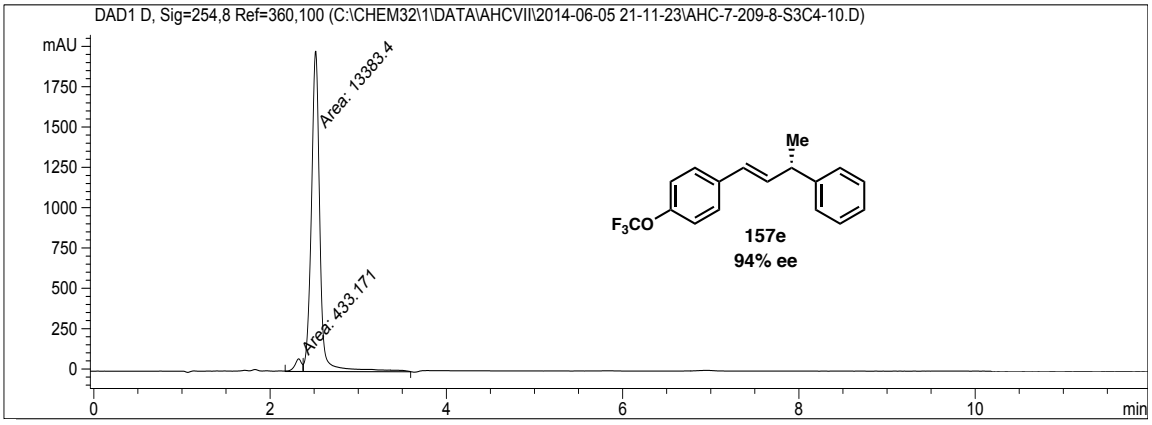
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.428	MM	0.2175	938.79395	71.92260	3.2198
2	6.256	MM	0.3107	2.82185e4	1513.67834	96.7802

157e (Table 4.5, entry 5): racemic



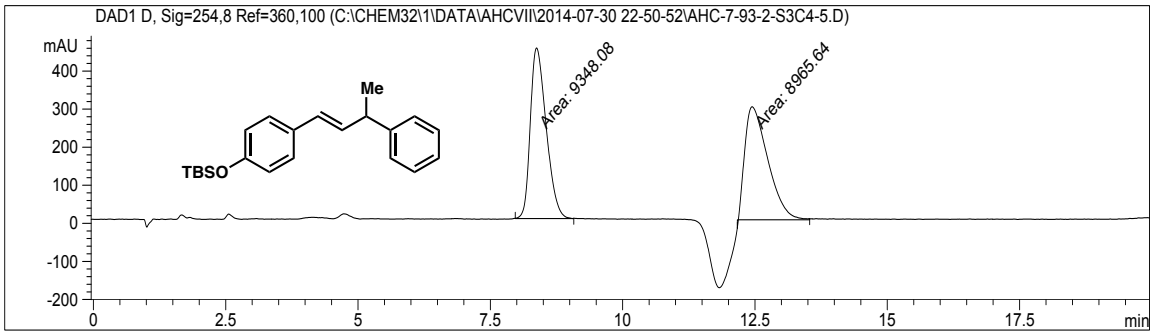
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	2.252	MM	0.1095	8622.25586	1312.58875	48.6531
2	2.446	MM	0.1185	9099.66504	1279.80774	51.3469

157e (Table 4.5, entry 5): enantioenriched, 94% ee



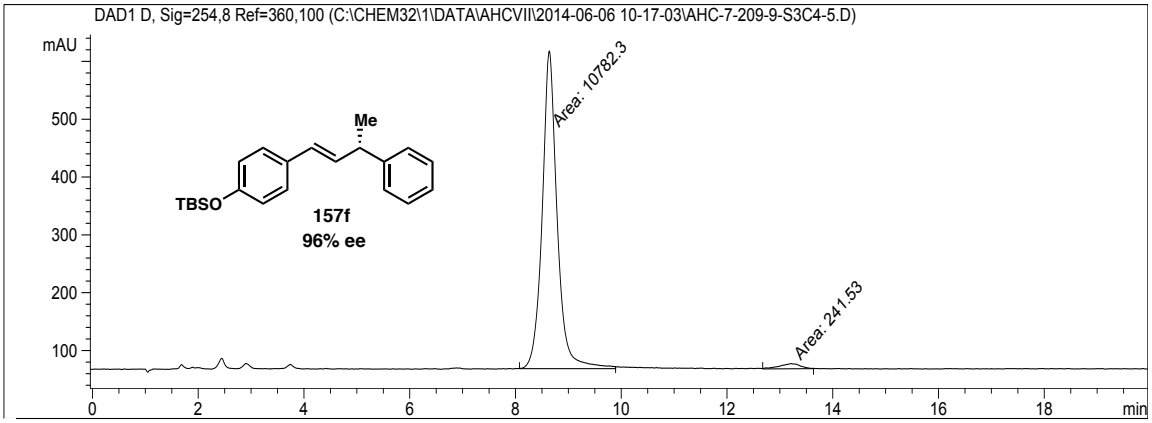
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	2.324	MM	0.0917	433.17111	78.69621	3.1352
2	2.517	MM	0.1119	1.33834e4	1993.22083	96.8648

157f (Table 4.5, entry 6): racemic



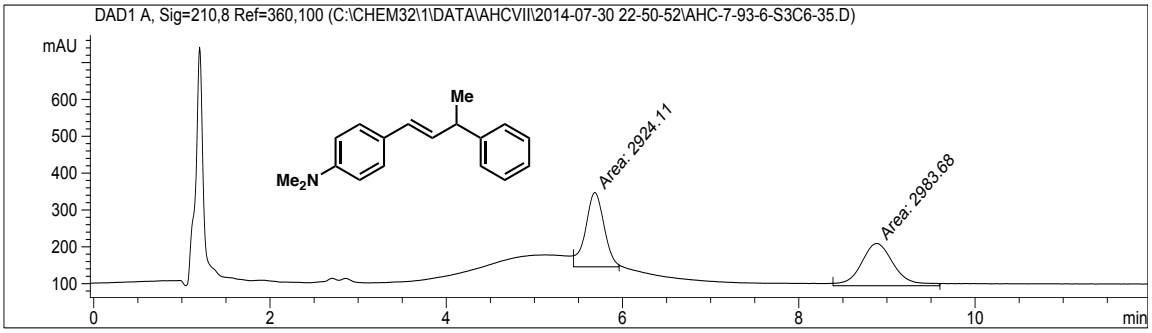
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	8.373	MM	0.3477	9348.08398	448.07748	51.0442
2	12.445	MM	0.5034	8965.63672	296.82007	48.9558

157f (Table 4.5, entry 6): enantioenriched, 96% ee



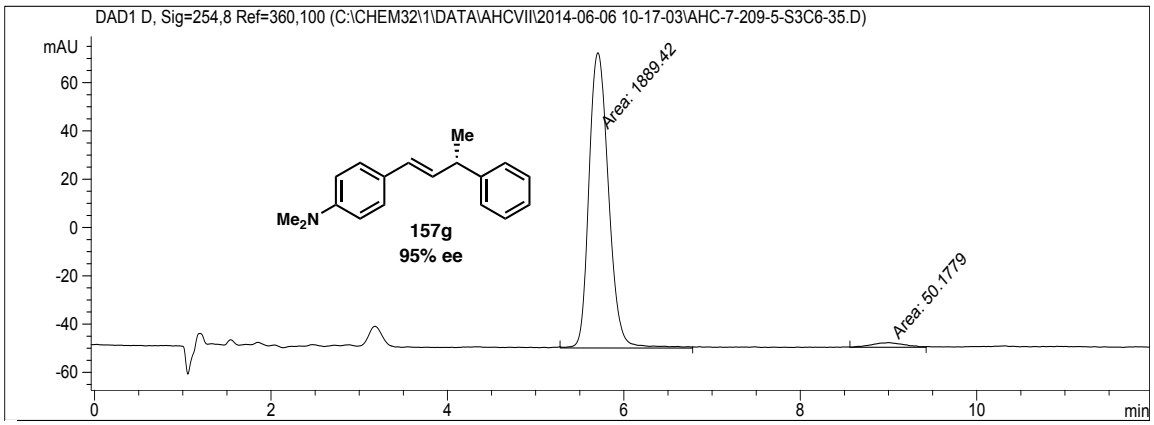
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	8.638	MM	0.3270	1.07823e4	549.47449	97.8090
2	13.210	MM	0.4557	241.52989	8.83361	2.1910

157g (Table 4.5, entry 7): racemic



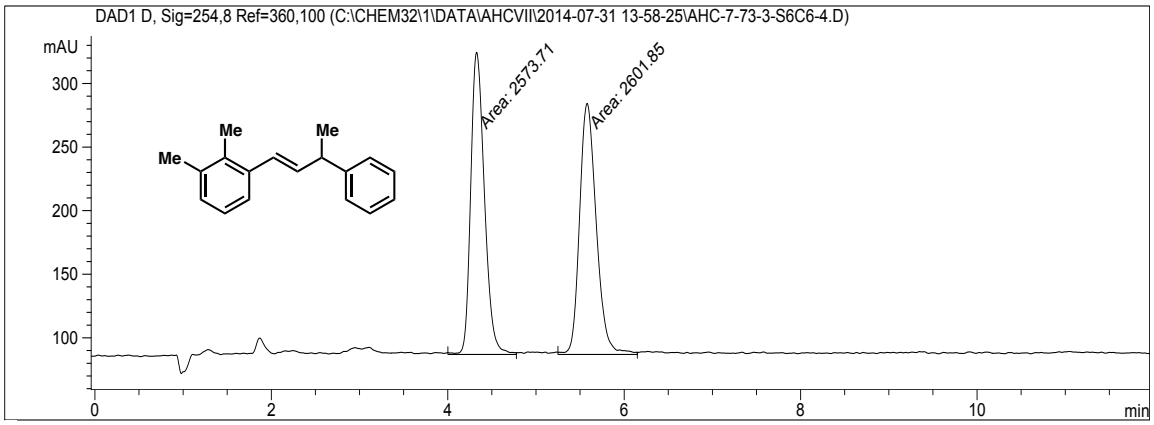
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.686	MM	0.2419	2924.10986	201.49109	49.4958
2	8.884	MM	0.4337	2983.68335	114.67265	50.5042

157g (Table 4.5, entry 7): enantioenriched, 95% ee



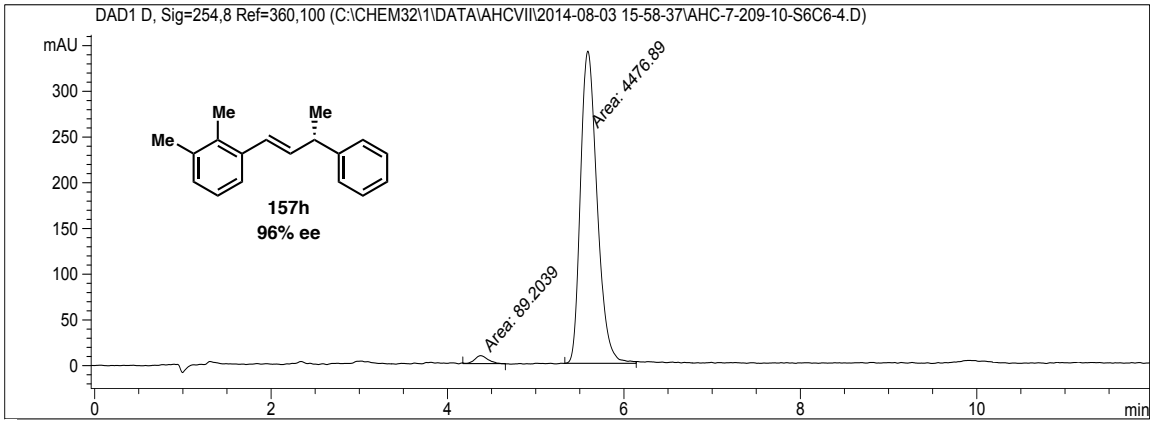
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.706	MM	0.2574	1889.41882	122.31673	97.4130
2	9.005	MM	0.4300	50.17793	1.94500	2.5870

157h (Table 4.5, entry 8): racemic



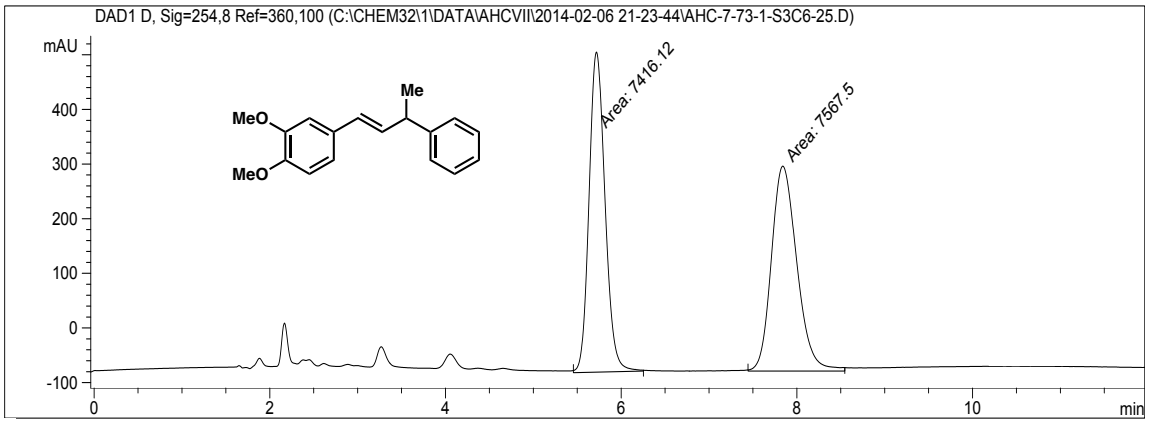
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	4.327	MM	0.1803	2573.70605	237.87602	49.7281
2	5.579	MM	0.2195	2601.85254	197.58577	50.2719

157h (Table 4.5, entry 8): enantioenriched, 96% ee



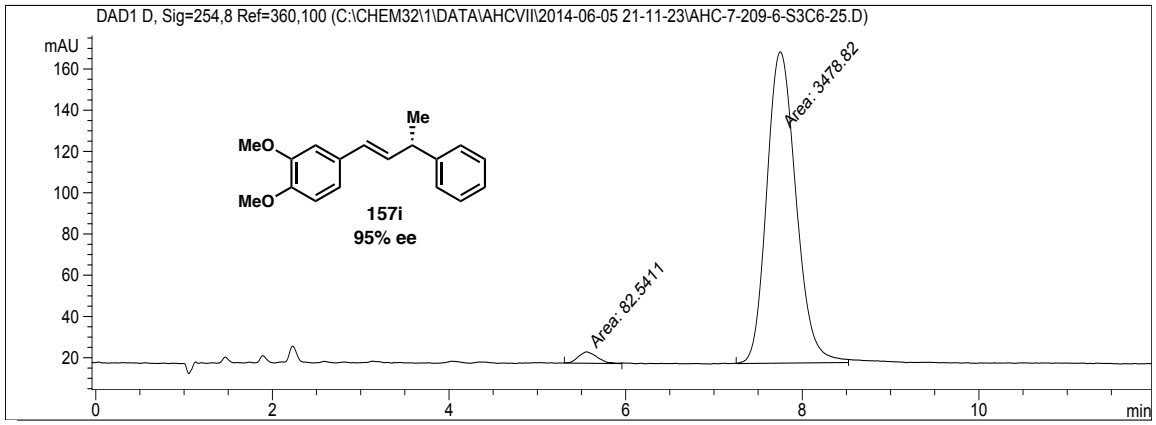
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	4.374	MM	0.1704	89.20393	8.72473	1.9536
2	5.590	MM	0.2184	4476.88916	341.59937	98.0464

157i (Table 4.5, entry 9): racemic



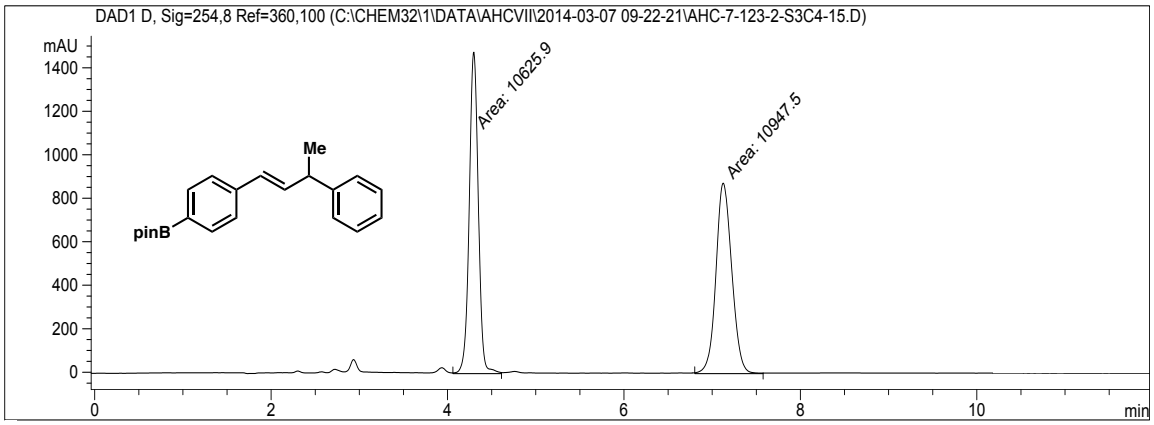
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.719	MM	0.2109	7416.11523	586.16187	49.4948
2	7.839	MM	0.3362	7567.49658	375.18320	50.5052

157i (Table 4.5, entry 9): enantioenriched, 95% ee



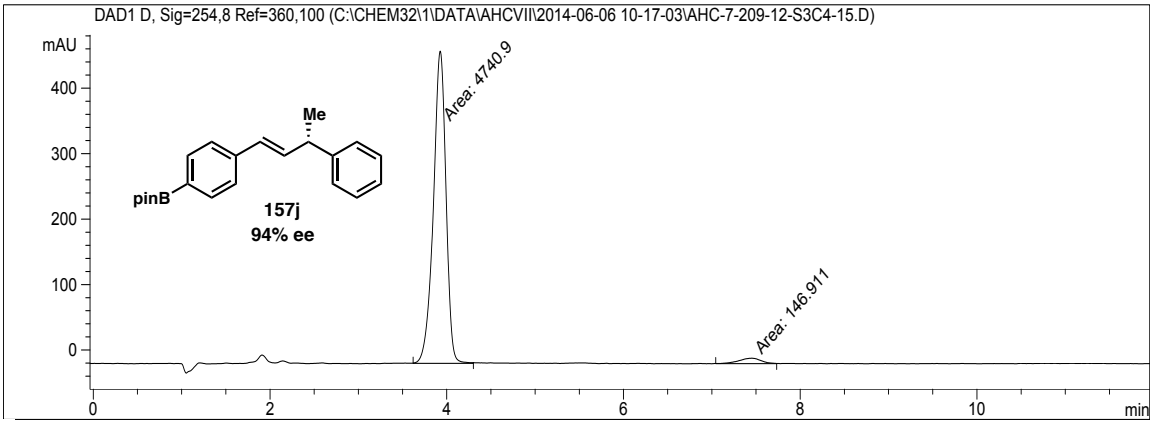
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.558	MM	0.2489	82.54113	5.52799	2.3177
2	7.751	MM	0.3840	3478.81641	150.97183	97.6823

157j (Table 4.5, entry 10): racemic



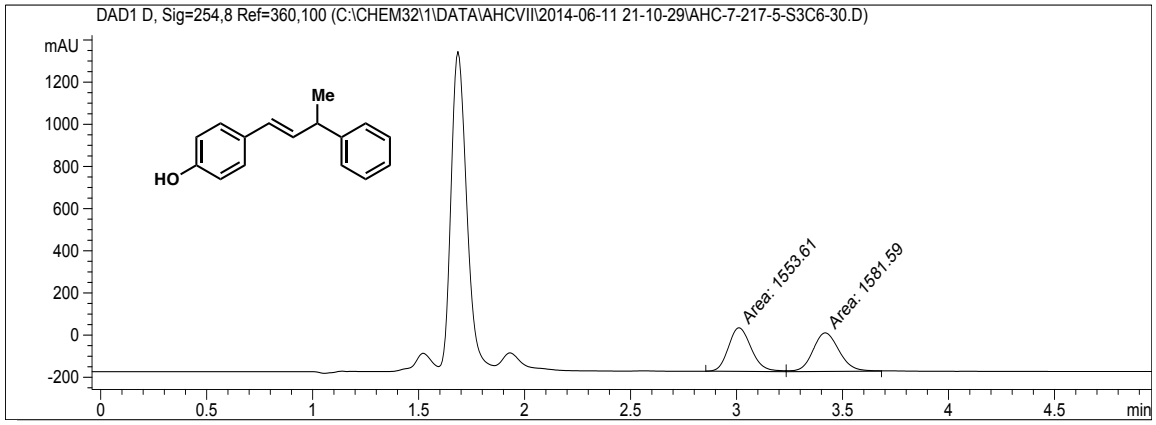
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	4.297	MM	0.1195	1.06259e4	1481.47107	49.2547
2	7.125	MM	0.2081	1.09475e4	876.78436	50.7453

157j (Table 4.5, entry 10): enantioenriched, 94% ee



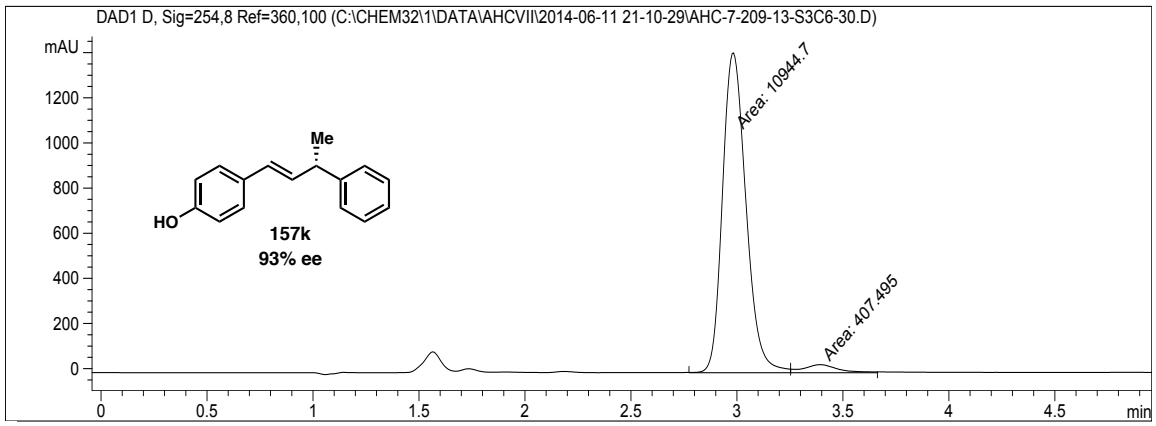
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.926	MM	0.1654	4740.90332	477.81689	96.9943
2	7.451	MM	0.2946	146.91095	8.30996	3.0057

157k (Table 4.5, entry 11): racemic



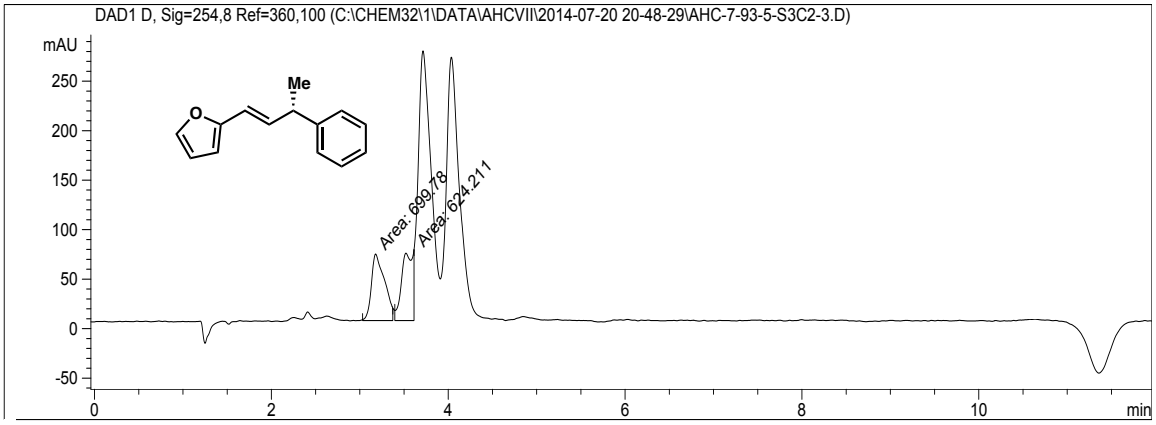
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.011	MM	0.1249	1553.60925	207.25208	49.5538
2	3.418	MM	0.1438	1581.58533	183.37068	50.4462

157k (Table 4.5, entry 11): enantioenriched, 93% ee



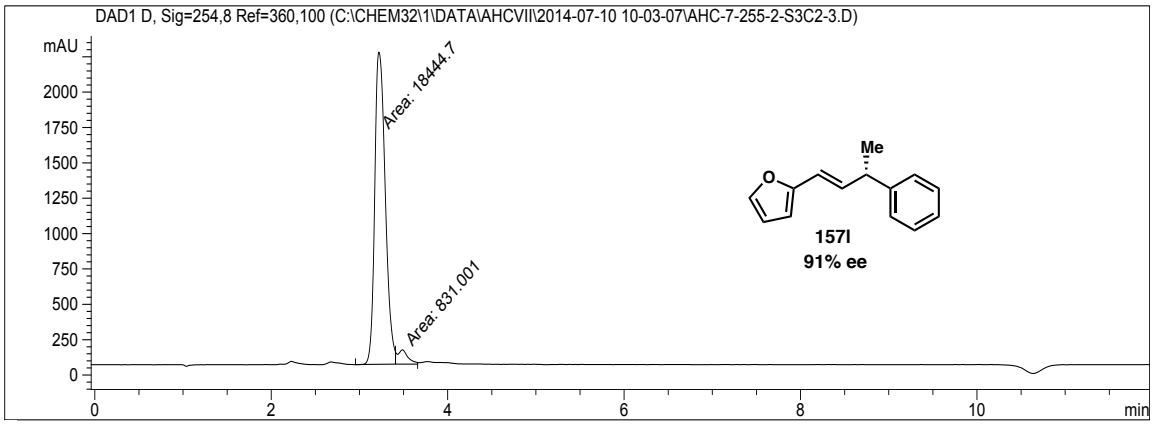
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	2.982	MM	0.1285	1.09447e4	1419.67334	96.4104
2	3.392	MM	0.1893	407.49545	35.88238	3.5896

157l (Figure 4.5): racemic



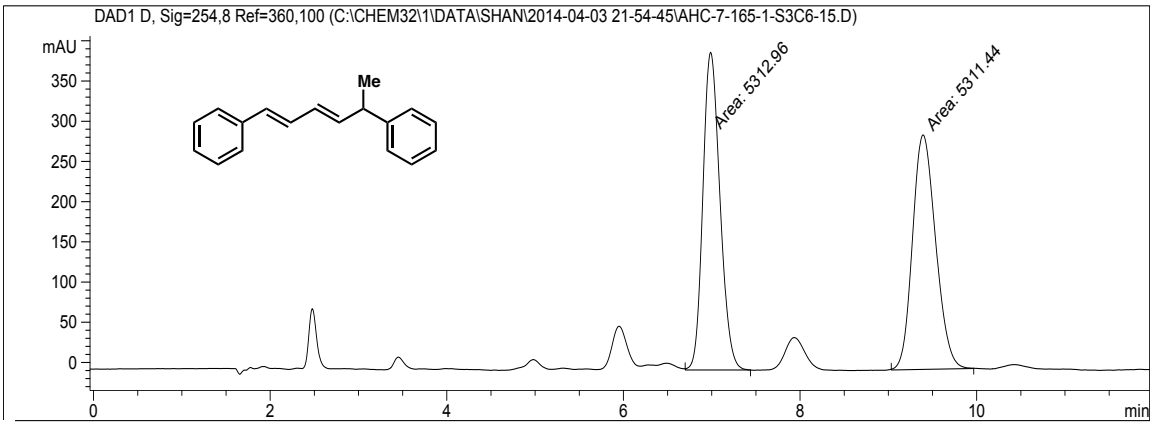
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.178	MM	0.1734	699.77979	67.27696	52.8538
2	3.611	MM	0.1474	624.21143	70.55936	47.1462

157l (Figure 4.5): enantioenriched, 91% ee



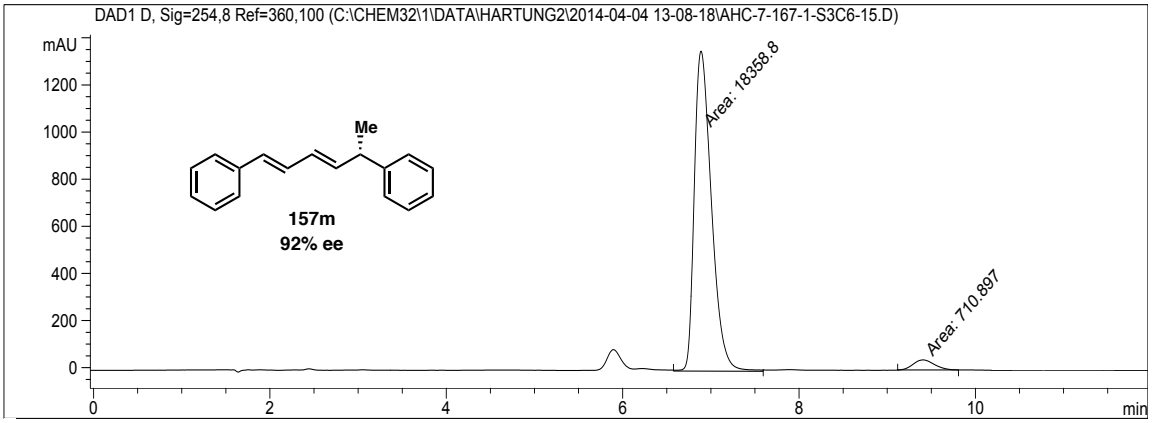
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	3.220	MM	0.1391	1.84447e4	2209.27100	95.6889
2	3.487	MM	0.1366	831.00092	101.37794	4.3111

157m (Figure 4.5): racemic



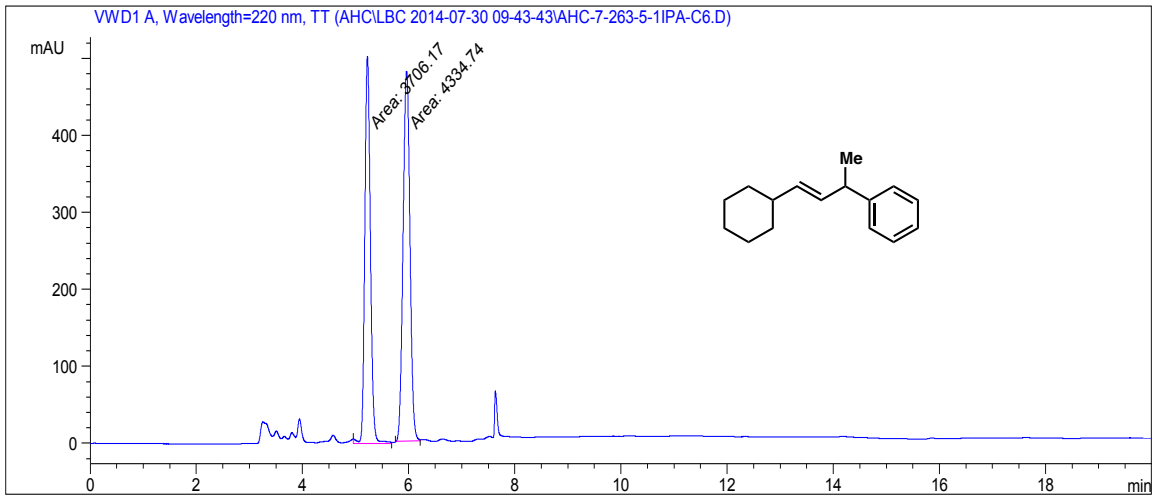
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.987	MM	0.2241	5312.95996	395.21527	50.0072
2	9.393	MM	0.3035	5311.43506	291.66327	49.9928

157m (Figure 4.5): enantioenriched, 92% ee



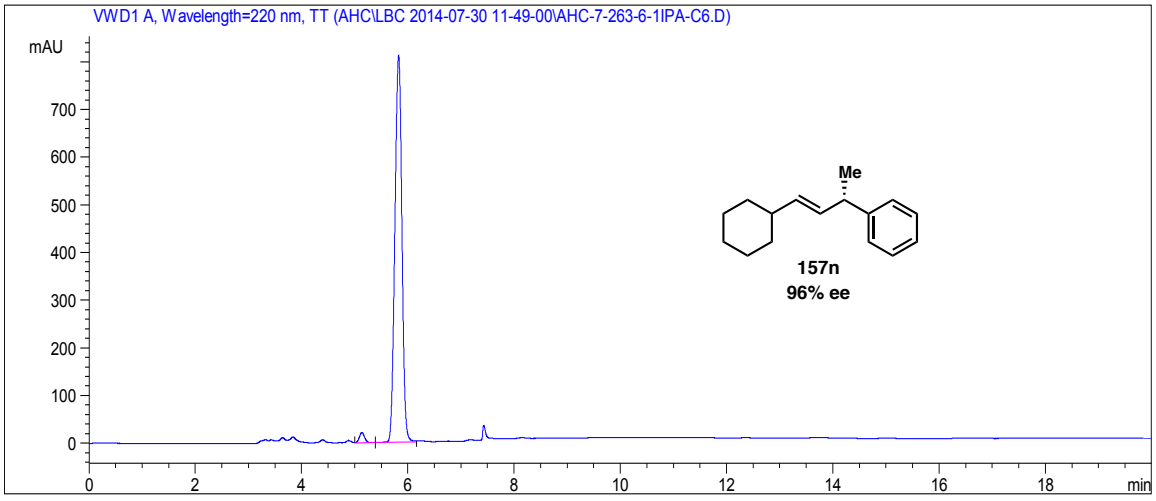
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	6.889	MM	0.2251	1.83588e4	1359.02136	96.2721
2	9.404	MM	0.2780	710.89673	42.61983	3.7279

157n (Figure 4.5): racemic



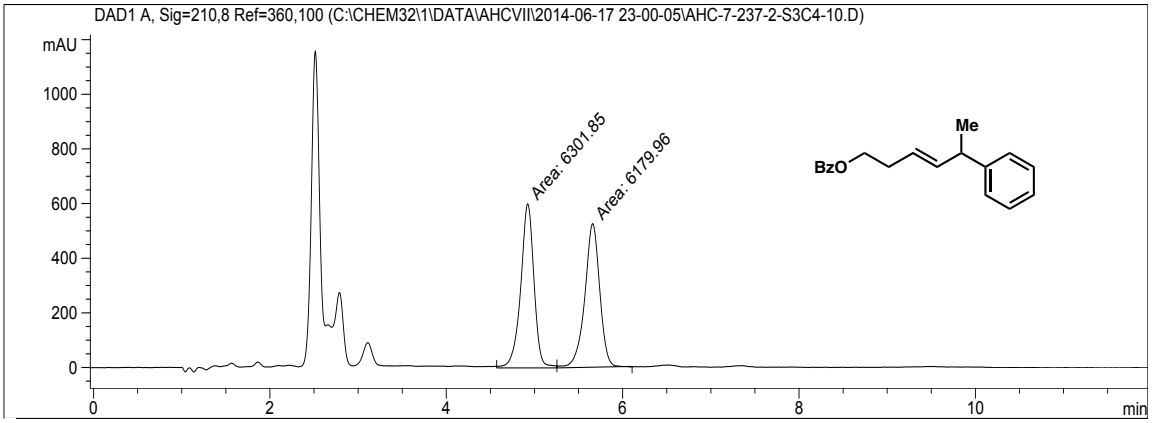
Peak #	RetTime [min]	Type	Width [min]	Area mAU *s	Height [mAU]	Area %
1	5.224	MM	0.1228	3706.16968	503.21298	46.0914
2	5.962	MM	0.1500	4334.74365	481.51410	53.9086

157n (Figure 4.5): enantioenriched, 96% ee



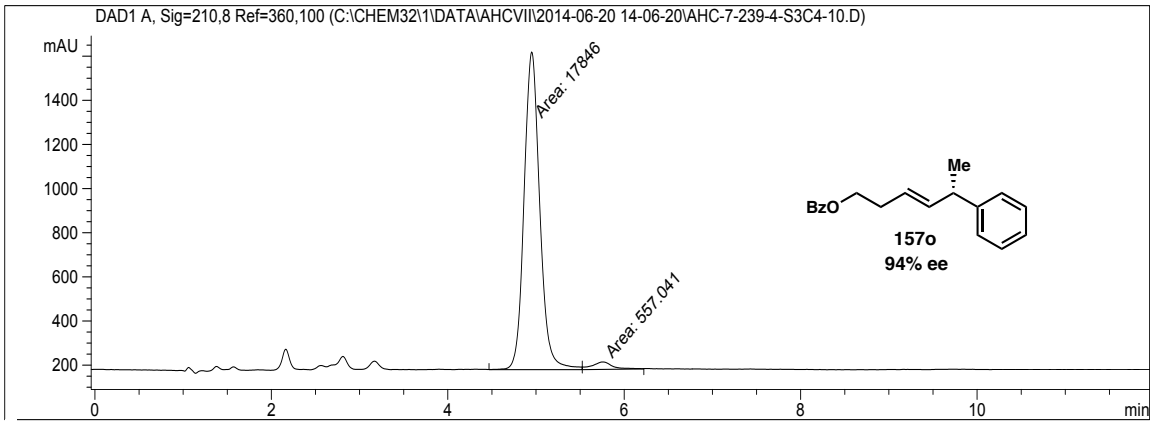
Peak #	RetTime [min]	Type	Width [min]	Area mAU *s	Height [mAU]	Area %
1	5.135	VV	0.1050	148.14879	21.73537	1.9461
2	5.828	VV	0.1459	7464.48193	811.72534	98.0539

157o (Figure 4.5): racemic



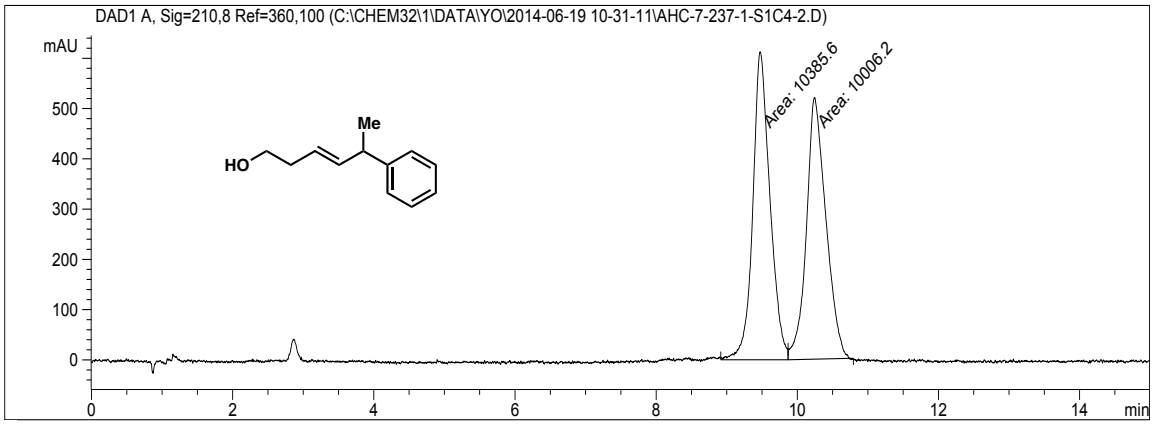
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	4.924	MM	0.1744	6301.85156	602.20233	50.4883
2	5.660	MM	0.1955	6179.95850	526.80280	49.5117

157o (Figure 4.5): enantioenriched, 94% ee



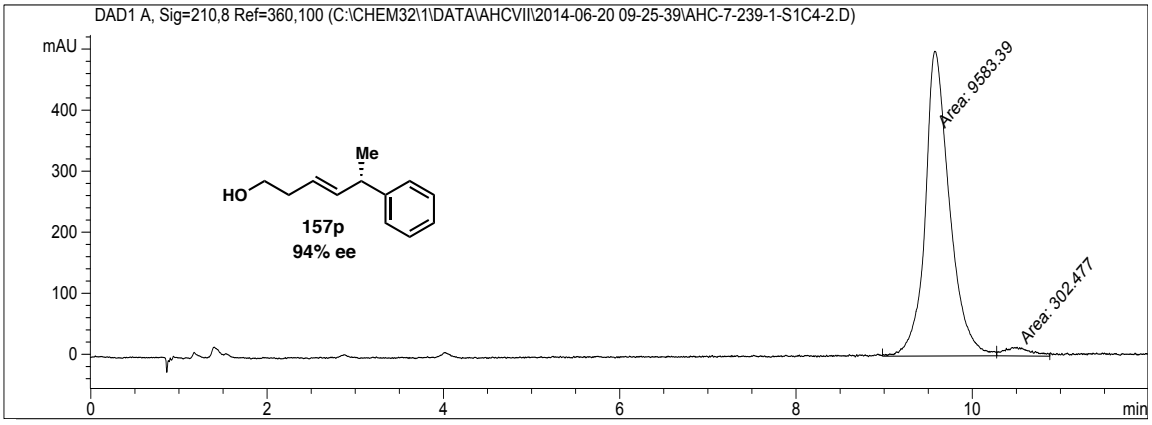
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	4.951	MM	0.2063	1.78460e4	1441.90649	96.9731
2	5.755	MM	0.2719	557.04138	34.14230	3.0269

157p (Figure 4.5): racemic



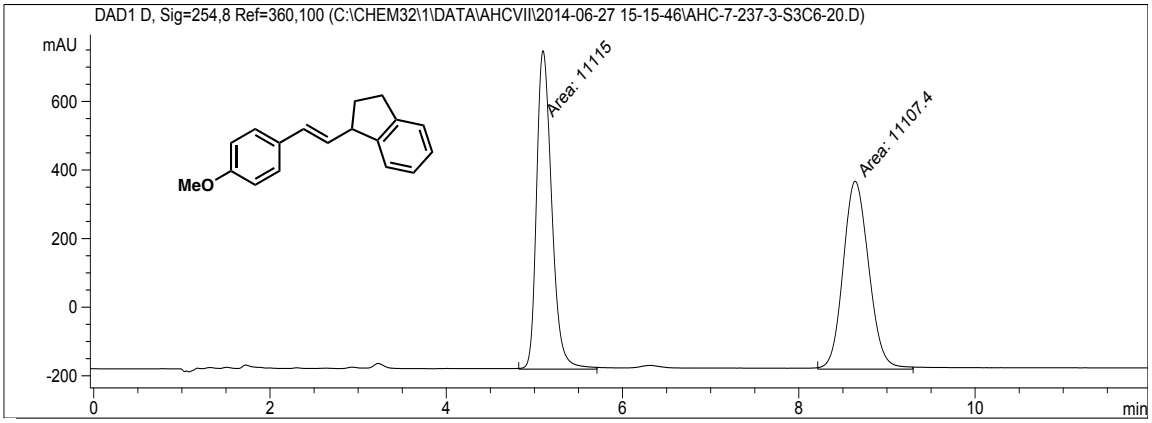
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	9.474	MM	0.2823	1.03856e4	613.19647	50.9302
2	10.244	MM	0.3204	1.00062e4	520.49475	49.0698

157p (Figure 4.5): enantioenriched, 94% ee



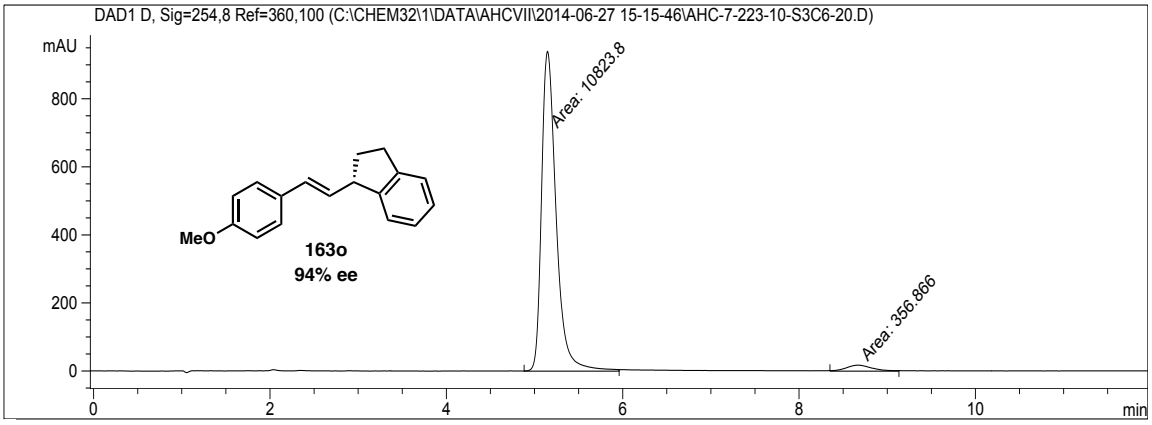
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	9.577	MM	0.3197	9583.38965	499.54858	96.9403
2	10.504	MM	0.3286	302.47656	13.89878	3.0597

163o (Figure 4.5): racemic



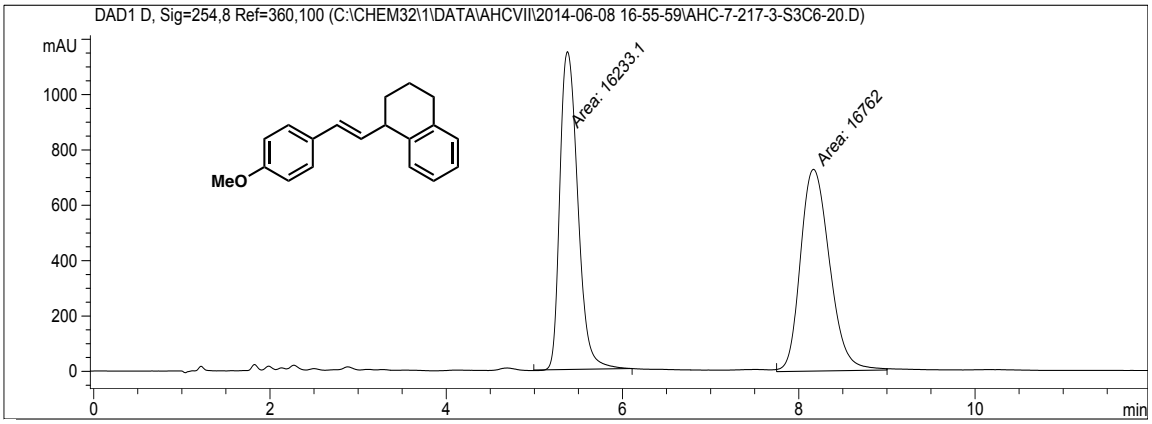
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.098	MM	0.1994	1.11150e4	929.12982	50.0170
2	8.639	MM	0.3377	1.11074e4	548.26196	49.9830

163o (Figure 4.5): enantioenriched, 94% ee



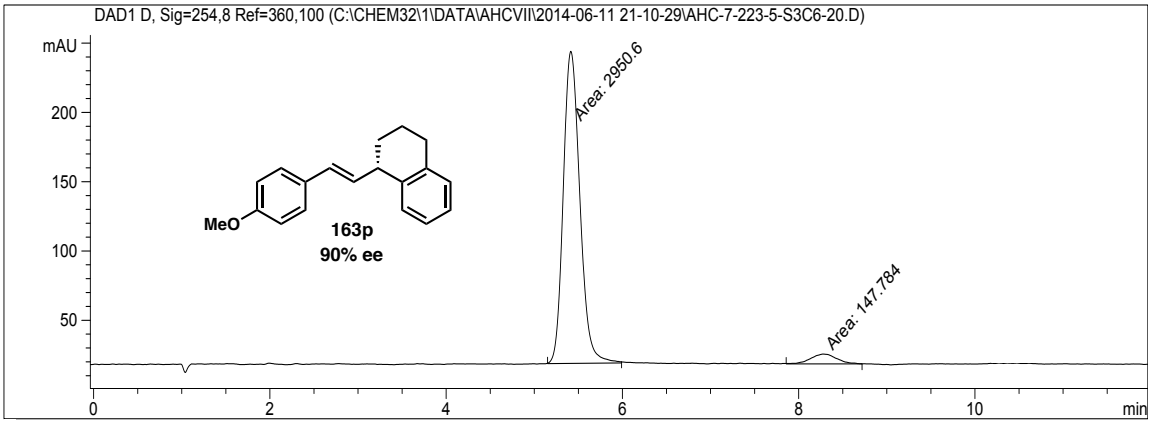
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.147	MM	0.1918	1.08238e4	940.38129	96.8082
2	8.669	MM	0.3406	356.86603	17.46182	3.1918

163p (Figure 4.5): racemic



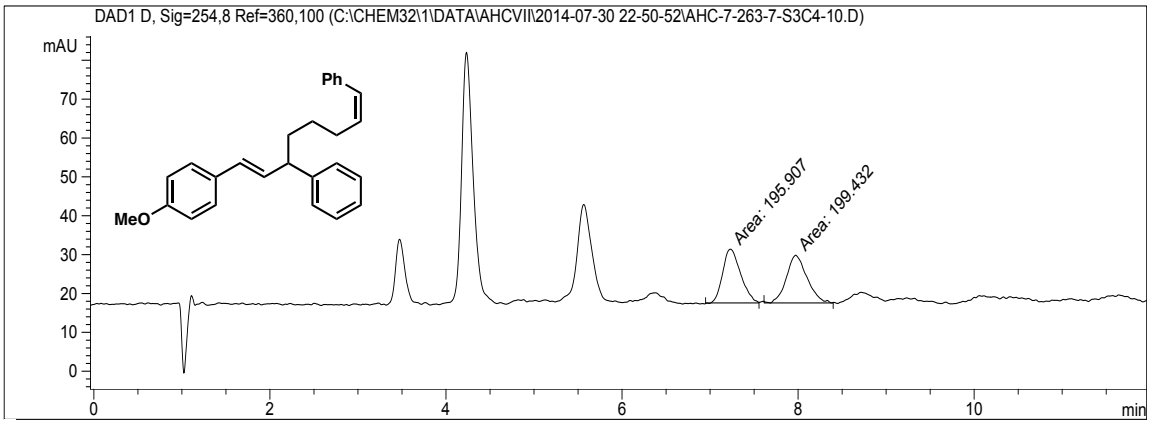
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.375	MM	0.2355	1.62331e4	1148.88831	49.1985
2	8.167	MM	0.3832	1.67620e4	728.97369	50.8015

163p (Figure 4.5): enantioenriched, 90% ee



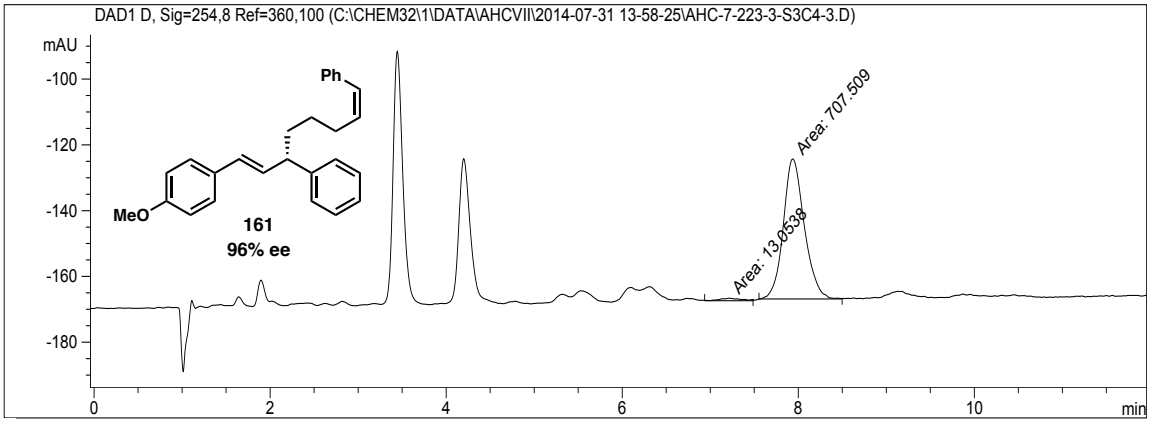
Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	5.414	MM	0.2183	2950.59619	225.29623	95.2303
2	8.276	MM	0.3454	147.78352	7.13138	4.7697

161 (Scheme 4.2): racemic



Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.230	MM	0.2362	195.90703	13.82199	49.5542
2	7.972	MM	0.2706	199.43159	12.28512	50.4458

161 (Scheme 4.2): enantioenriched, 96% ee



Peak #	RetTime [min]	Type	Width [min]	Area [mAU*s]	Height [mAU]	Area %
1	7.215	MM	0.2808	13.05381	7.74711e-1	1.8116
2	7.938	MM	0.2768	707.50922	42.60372	98.1884

4.5 NOTES AND REFERENCES

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