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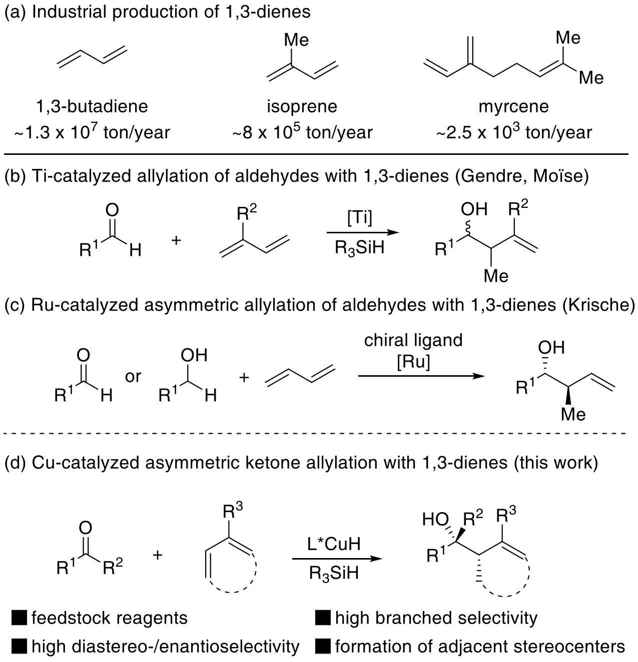
ABSTRACT: Chiral tertiary alcohols are important building blocks for the synthesis of pharmaceutical agents and biologically active natural products. The addition of carbon nucleophiles to ketones is the most common approach to tertiary alcohol synthesis, but traditionally relies on stoichiometric organometallic reagents that are difficult to prepare, sensitive, and uneconomical. We describe a mild and efficient method for the copper-catalyzed allylation of ketones, using widely available 1,3-dienes as allylmetal surrogates. Homoallylic alcohols bearing a wide range of functional groups are obtained in high yield and with good regio-, diastereo-, and enantioselectivity. Mechanistic investigations using density functional theory (DFT) implicate the *in situ* formation of a rapidly equilibrating mixture of isomeric copper(I) allyl complexes, from which Curtin-Hammett kinetics determine the major isomer of product. A stereochemical model is provided to explain the high diastereo- and enantioselectivity of this process. Finally, this method was applied toward the preparation of an important drug, (*R*)-Procyclidine, and a key intermediate in the synthesis of several pharmaceuticals.

INTRODUCTION

Enantiomerically enriched tertiary alcohols and their derivatives feature prominently in a variety of important pharmaceutical agents and complex natural products.[1] Consequently, their efficient synthesis has attracted great attention from synthetic chemists.[2] Traditionally, the addition of organomagnesium (Grignard) reagents to ketones has been a popular method to obtain tertiary alcohols in racemic form.[3] However, the harsh methods required to prepare these organometallic reagents, as well as their instability and Brønsted basicity, have limited the tolerance of these reagents toward polar functional groups. Furthermore, the necessity to use stoichiometric organometallic reagents, and often, chiral auxiliaries for enantioselective transformations, is intrinsically inefficient and operationally complicating. Thus, the development of highly efficient catalytic, asymmetric strategies for constructing tertiary alcohols remains a goal of high priority in organic synthesis.[4]

1,3-ienes are important industrial raw materials that are produced on an enormous scale annually (Figure 1a). These chemicals include butadiene[5] (about 13 × 10^6 ton/year production), isoprene[6] (about 8 × 10^5 ton/year) and myrcene[7] (about 2500 ton/year). Recently, a number of groups have proposed that these inexpensive and stable compounds could serve as ideal surrogates for stoichiometric organometallic reagents in carbonyl addition reactions. In 2005, a pioneering report by Gendre and Moïse[8] demonstrated the first titanium-catalyzed aldehyde allylation using conjugated dienes as reagents (Figure 1b), although due to the highly reactive nature of the titanium-allyl species, the functional group tolerance was limited. Subsequently, Krische[5b] has developed ruthenium-catalyzed stereoselective aldehyde (or alcohol) allylations with 1,3-butadiene (Figure 1c). Unfortunately, the same method cannot be generally applied to ketones for the synthesis of tertiary alcohols. Despite reports of a number of other transition-metal-catalyzed reductive couplings (Ni,[9] Ru,[10] Rh[11] and Ir[12]) with conjugated dienes, reactions involving ketones, rather than aldehydes, remain challenging, even in a non-stereoselective manner.


(a) Industrial production of 1,3-dienes

(b) Ti-catalyzed allylation of aldehydes with 1,3-dienes (Gendre, Moïse)

(c) Ru-catalyzed asymmetric allylation of aldehydes with 1,3-dienes (Krische)

(d) Cu-catalyzed asymmetric ketone allylation with 1,3-dienes (this work)

Figure 1. Overview of 1,3-dienes in industry and in catalytic allylation processes.

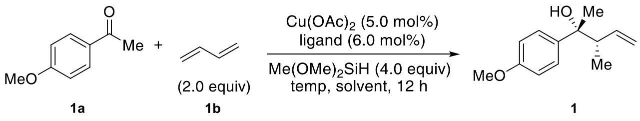
Over the past several years, a number of research groups, including ours, have reported approaches for the copper-catalyzed hydroamination of unsaturated substrates through the *in situ* generation of alkylcopper nucleophiles.[13] Using this strategy, activated pronucleophiles such as enynes and allenes were successfully engaged in nucleophilic addition reactions with ketones.[14] This reactivity pattern has since also been extended to the reductive coupling of olefin pronucleophiles with imines.[2e,15]

Following this general concept, herein we describe a highly regio- and enantioselective copper-catalyzed method for the allylation of ketones using readily available 1,3-dienes (Figure 1d). Previously, we had reported a single, unoptimized example of this transformation.[14a] In addition, we report a computational study of the mechanism of this class of transformations, revealing a complex kinetic basis for diastereo- and enantioselectivity resulting from an equilibrating mixture of allylcopper intermediates of similar energy. Furthermore, we propose a stereochemical model for these allylation processes using non-C_2-symmetric JOSIPHOS-derived chiral ligands. Finally, we apply our method toward an efficient and concise synthesis of the pharmaceutical agent (*R*)-procyclidine and key intermediates in the synthesis of (*R*)-Oxyphencyclimine, (*R*)-Oxybutynin and (*R*)-Oxyphenonium bromide.

RESULTS AND DISCUSSION

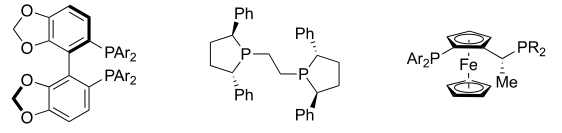
We began by studying the reaction between 4-methoxyacetophenone (**1a**) and 1,3-butadiene (**1b**) under conditions previously reported for Cu-catalyzed reductive coupling reactions (Table 1, entry 1).[14] With (*R*)-DTBM-SEGPHOS (**L1**) as the ligand, homoallylic alcohol **1** was obtained with 44% yield, 1.2:1 dr and 83.5:16.5 er for the major diastereomer (65.5:34.5 er for the minor). Based on ^{1}H NMR analysis of the crude reaction mixture, the remainder of the ketone underwent direct reduction by copper hydride. When the ligand was exchanged for (*S*,*S*)-Ph-BPE (**L2**), this reduction pathway was suppressed,[14a] and a 96% yield of **1** was obtained with moderate dr and ee (Table 1, entry 2). Further ligand screening revealed that use of the commercially available JOSIPHOS[16] derivative SL-J011-1 further improved the stereoselectivity to 4:1 dr and 97:3 er (96:4 er for the minor diastereomer, Table 1, entry 3).

Table 1. Evaluation of Reaction Conditions for the CuH-Catalyzed Allylation of 4-Methoxyacetophenone.[a]



1a **1b** **1**

Entry	Ligand	Solvent	Temp (°C)	Yield[b] 1 (%)	dr	er[c] major (minor)
1	**L1**	PhMe	25	44	1.2:1	83.5:16.5 (65.5:34.5)
2	**L2**	PhMe	25	96	3.1:1	86.5:13.5 (84:16)
3	**L3**	PhMe	25	90	4:1	97:3 (96:4)
4	**L3**	CyH	25	71	3:1	96.5:3.5 (94:6)
5	**L3**	THF	25	88	4:1	96.5:3.5 (94:6)
6	**L3**	MTBE	25	83	3.4:1	97:3 (94.5:5.5)
7	**L3**	Dioxane	25	55	3.9:1	96.5:3.5 (94:6)
8	**L3**	PhMe	40	75	3.6:1	95:5 (93:7)
9	**L3**	PhMe	0	94	4:1	98:2 (97:3)
10	**L3**	PhMe	-20	89	1.8:1	98:2 (97:3)



Ar = 3,5-(*t*Bu)$_2$-4-MeO-C$_6$H$_2$
(*R*)-DTBM-SEGPHOS (**L1**)

(*S*,*S*)-Ph-BPE (**L2**)

R = *t*Bu, Ar = 4-CF$_3$-C$_6$H$_4$
SL-J011-1(**L3**)

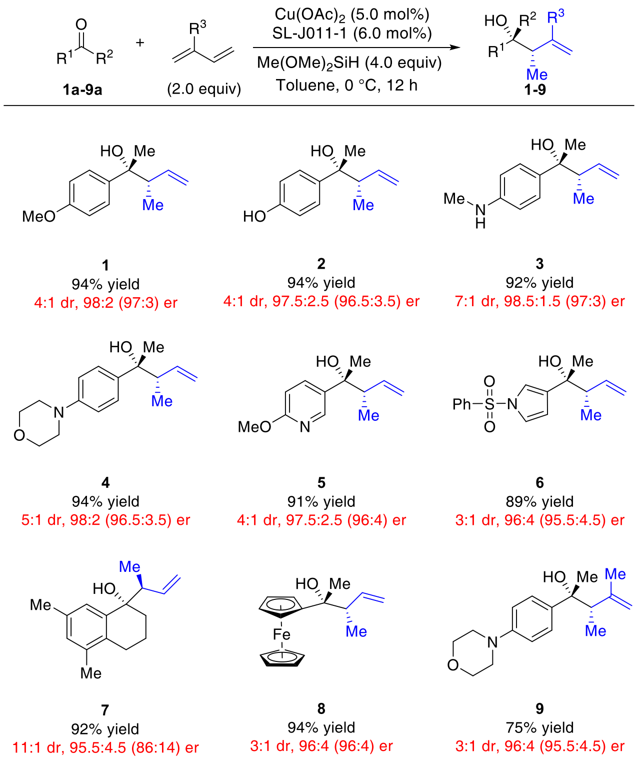
[a]Conditions: 0.2 mmol ketone (1 equiv), 1,3-butadiene (2 equiv), copper(II) acetate (0.05 equiv), ligand (0.06 equiv), dimethoxy(methyl)silane (4 equiv) in solvent (0.2 mL), ketone was added slowly by syringe pump; see the Supporting Information for details. [b]Yield and diastereomeric ratio were determined by ^{1}H NMR spectroscopy of the crude mixture, using dibromomethane as an internal standard. [c]Enantiomeric ratio was determined by HPLC or SFC analysis on commercial chiral columns, and the relative configuration of **1** was determined by comparing its NMR data with reported data.[17]

Evaluation of the reaction solvent (Table 1, entry 4-7) indicated that toluene was optimal for this transformation. The results were very sensitive to the reaction temperature: the yield, dr, and er were all diminished at slightly elevated temperatures (40 °C, Table 1, entry 8). However, excellent yield (94%), dr (4:1), and er (98:2 and 97:3 respectively for the major and minor diastereomers) were achieved when the reaction was performed at 0 °C (Table 1, entry 9). Further lowering of the reaction temperature (-20 °C) significantly decreased the dr again (Table 1, entry 10).

Next, the substrate scope of the asymmetric reductive coupling of diverse ketones with acyclic 1,3-dienes was examined (Table 2). A range of chiral homoallylic tertiary alcohols were prepared with excellent yields and enantiomeric purity (>94:6 er). The reaction was compatible with ether (**1**), alcohol (**2**), secondary (**3**) and tertiary amine (**4**) groups, as well as aromatic heterocycles (**5**, **6**). Cyclic ketones such as **7a** reacted with particularly good diastereoselectivity, as well as excellent yield and enantioselectivity. Using acetylferrocene, we obtained enantiomerically enriched ferrocene **8**. In addition to butadiene, isoprene was also found to react with good yield and excellent enantioselectivity (**9**).

We also surveyed the scope of ketone allylation using cyclic 1,3-dienes. However, under the conditions used for acyclic dienes, the yield of the desired product was unsatisfactory, and direct reduction of the ketone was instead the major reaction that was observed (see Supporting Information for details). We hypothesized that in the case of cyclic dienes, the **L3**-ligated CuH is unable to react with the diene at a rate competitive with direct ketone reduction. Revisiting our initial ligand evaluation data, we noticed that the use of (*S*,*S*)-Ph-BPE (**L2)** provided less ketone reduction byproduct than with **L3** (Table 1, entries 2 and 3).[14a] Accordingly, we hypothesized that substituting **L2** for **L3** might be useful in these cases where ketone reduction is a problem: indeed, the catalyst derived from **L2** provided greatly improved yields with cyclic diene substrates.

Table 2. Evaluation of the Scope of the Ketone Allylation with Acyclic Dienes.[a]

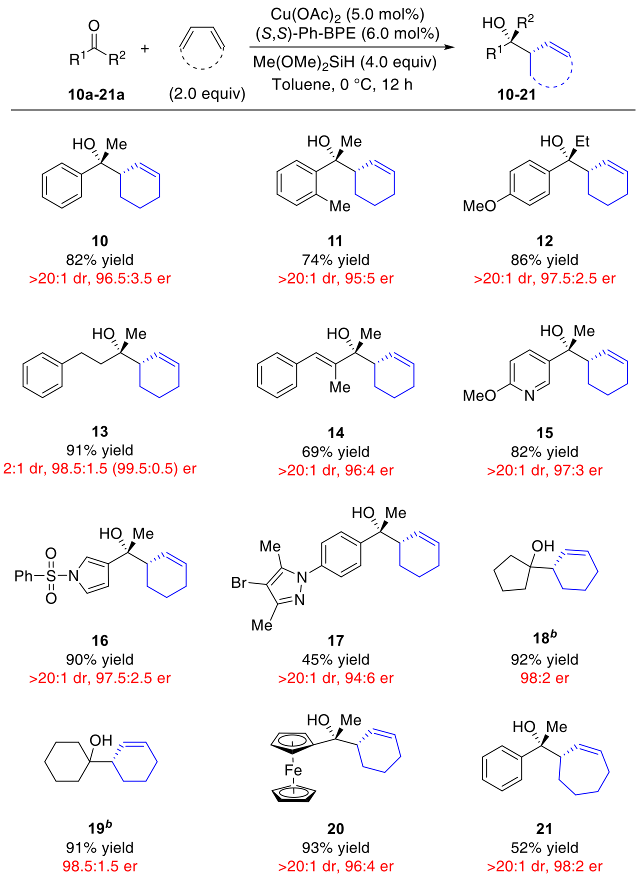


Product	Yield	dr, er
1	94% yield	4:1 dr, 98:2 (97:3) er
2	94% yield	4:1 dr, 97.5:2.5 (96.5:3.5) er
3	92% yield	7:1 dr, 98.5:1.5 (97:3) er
4	94% yield	5:1 dr, 98:2 (96.5:3.5) er
5	91% yield	4:1 dr, 97.5:2.5 (96:4) er
6	89% yield	3:1 dr, 96:4 (95.5:4.5) er
7	92% yield	11:1 dr, 95.5:4.5 (86:14) er
8	94% yield	3:1 dr, 96:4 (96:4) er
9	75% yield	3:1 dr, 96:4 (95.5:4.5) er

[a] Yields indicate the isolated yield of product as a mixture of two diastereomers on a 1.0 mmol scale. Diastereomeric ratios were determined by ^{1}H NMR spectroscopy for both the crude and purified products; enantiomeric ratios were determined by HPLC or SFC analysis on commercial chiral columns; enantiomeric ratios of minor diastereomers are indicated in parentheses after those of the major diastereomers. Yields, diastereomeric ratios, and enantiomeric ratios are the averages for two identical runs. See Supporting Information for full details.

Using **L2**, several classes of ketones were coupled with cyclic 1,3-dienes in high regio- and enantioselectivity (Table 3). The reaction is most efficient for aryl methyl ketones. A broad range of aromatic carbonyl substituents, including an ortho-substituted arene (**11**), a pyridine (**15**), a pyrrole (**16**), a bromopyrazole (**17**), and a ferrocene (**20**) were evaluated, all providing good results. Several additional types of ketones were converted with high yield and stereoselectivity under the same conditions. For instance, a dialkyl ketone (**13**) and a vinyl methyl ketone (**14**) underwent allylation with high enantioselectivity. We proposed that the low diastereoselectivity observed in the case of **13** may be due to the minimal steric differentiation between the methyl and methylene groups attached to the carbonyl. Accordingly, we found that our method can be particularly useful on symmetric dialkyl ketones, which react to form homoallylic alcohol products with exceptionally high yield and enantioselectivity (**18**, **19**). Finally, a larger ring diene, 1,3-cycloheptadiene, is also an effective reagent, providing **21** with moderate yield and excellent stereoselectivity.

Table 3. Scope Evaluation of Ketone Allylation with Cyclic Dienes.[a]



Product	Yield	dr, er
10	82% yield	>20:1 dr, 96.5:3.5 er
11	74% yield	>20:1 dr, 95:5 er
12	86% yield	>20:1 dr, 97.5:2.5 er
13	91% yield	2:1 dr, 98.5:1.5 (99.5:0.5) er
14	69% yield	>20:1 dr, 96:4 er
15	82% yield	>20:1 dr, 97:3 er
16	90% yield	>20:1 dr, 97.5:2.5 er
17	45% yield	>20:1 dr, 94:6 er
18[b]	92% yield	98:2 er
19[b]	91% yield	98.5:1.5 er
20	93% yield	>20:1 dr, 96:4 er
21	52% yield	>20:1 dr, 98:2 er

[a] Yields indicate the isolated yield of product as a mixture of two diastereomers on a 1.0 mmol scale. Diastereomeric ratios were determined by ^{1}H NMR spectroscopy for both the crude and purified products; enantiomeric ratios were determined by HPLC or SFC analysis on commercial chiral columns; enantiomeric ratios of minor diastereomers are indicated in parentheses after those of the major diastereomers. Yields, diastereomeric ratios, and enantiomeric ratios are the averages for two identical runs. See Supporting Information for full details. [b] The yield was determined by ^{1}H NMR versus an internal standard due to the volatility of the product.

■ MECHANISTIC STUDIES

The proposed catalytic cycle of this CuH-catalyzed allylation reaction is summarized in Figure 2. We envisioned that a primary allylic copper intermediate (**III**) might be formed by hydrocupration of a diene. Selectivity-determining nucleophilic addition of **III** to the ketone would provide copper alkoxide **V**. Subsequently, σ-bond metathesis with a hydrosilane **VI** should rapidly regenerate the copper hydride catalyst **I**, with concomitant formation of the silylated homoallylic alcohol (**VII**) in a process that is well precedented.[14a]

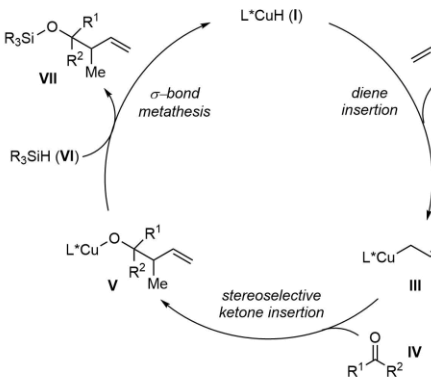


Figure 2. Proposed catalytic cycle.

We performed density functional theory (DFT) calculations to investigate several aspects of this proposed reaction mechanism. First, a comparison of the candidate hydrocupration mechanisms was performed to understand the mechanism of generation of the key allylcopper intermediate. Next, the energies and interconversion barriers of several possible allylic complexes were evaluated. From here, a thorough consideration of possible insertion transition states for the addition of the allylcopper intermediate to ketones was undertaken to reveal the origin the observed diastereoselectivity. Finally, we sought to explain the π-facial selectivity with respect to the ketone. While the mechanism of chiral induction in enantioselective reactions utilizing C_2-symmetric ligands such as Ph-BPE has been frequently rationalized using quadrant-diagrams,[18a-c] analogous intuitive models for less symmetric ligands such as JOSIPHOS derivatives are rare.[18d] Therefore, we focused on developing an understanding of the high enantioselectivity observed with **L3**-supported copper catalysts.

We started our computational investigation with a conformational search on the **L3**-supported CuH catalyst. Two lowest-energy conformers with almost identical energies (**22a** and **22b**, Figure 3) were located. These conformers differ in the arrangement of the six-membered chelate ring. In **22a**, the chiral carbon center is puckered out-of-plane, while the two phosphorus atoms and the Cu are nearly co-planar with one of the Cp rings of the ferrocene. In contrast, in **22b**, the Cu is puckered out-of-plane, while the two phosphorus atoms and the chiral carbon are nearly co-planar with the ferrocene Cp ring. As a result, the *P*-*t*Bu and *P*-Ar substituents in **22a** and **22b** adopt different orientations, and thus create distinct steric environments around the Cu center. In **22a**, the *P*-*t*Bu group in quadrant **IV** and the *P*-aryl group in quadrant **II** are placed in closer proximity to the Cu center, while the *P*-*t*Bu and *P*-aryl groups in quadrants **I** and **III** are more distal from the Cu. Therefore, the steric environment of this conformer resembles those of C_2-symmetric ligands. In contrast, conformer **22b** is pseudo-C_S symmetric. The *P*-*t*Bu and *P*-aryl groups in quadrants **IV** and **III** are placed closer to the Cu center, while quadrants **I** and **II** are relatively unoccupied by the ligand as the *P*-substituents in these quadrants are placed further away from the Cu. Considering the similar stability of **22a** and **22b**, both ligand conformations were considered when locating the transition states in the proposed catalytic cycle. Our calculations indicated the hydrocupration, 1,3-migration, and ketone addition transition states all are lower in energy when the ligand adopts the conformation in **22a**, which has a pseudo-C_2-symmetric steric environment (see below). This is consistent with the high efficiency of CuH catalysts with C_2-symmetric ligands such as Ph-BPE in promoting similar transformations.

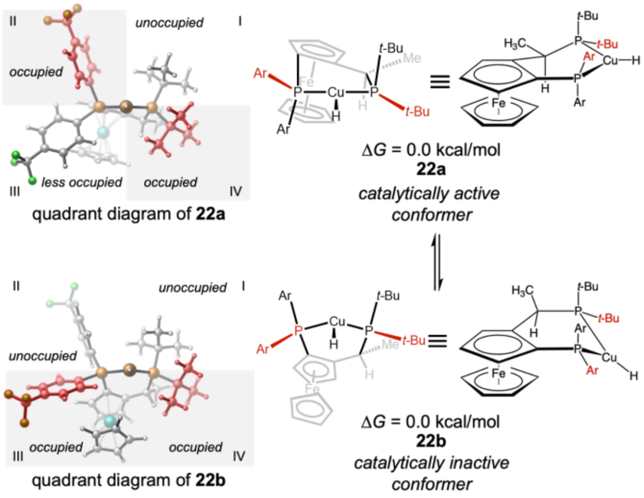
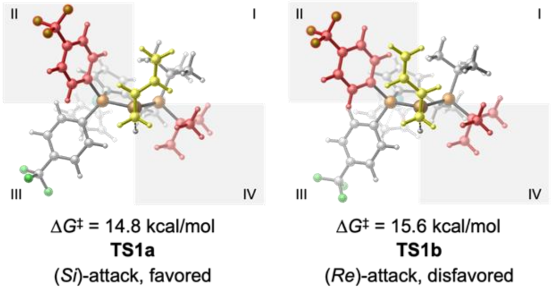


Figure 3. Conformers of the CuH catalyst supported by the SL-J011-1 ligand (**L3**). The *P*-Ar and *P*-*t*Bu groups proximal to the Cu center are highlighted in red.

(a) Quadrant diagrams of the 1,2-hydrocupration transition states



(b) Most favorable 1,2- and 1,4-hydrocupration transition states

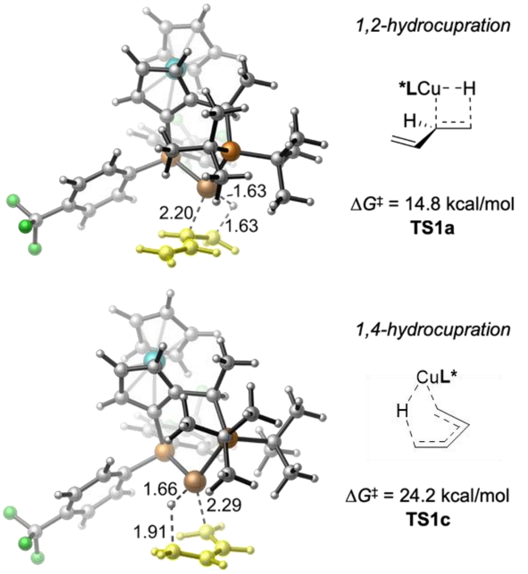


Figure 4. Optimized geometries of the 1,2- and 1,4-hydrocupration transition states. The diene is highlighted in yellow. The *P*-aryl and *P*-*t*Bu groups "proximal" to the Cu center are highlighted in red in Figure 4a.

We selected 2-acetonaphthone and 1,3-butadiene as the model substrates for our computational investigation of the catalytic cycle. Experimentally, this pair of substrates react with 95% yield, 2.5:1 dr, and 93:7 er (for the major diastereomer, 90.5:9.5 er for the minor diastereomer) under the standard reaction conditions (see Supporting Information for details). We hypothesized that, initially, the hydrocupration of 1,3-butadiene might proceed via either direct 1,4-hydrocupration of the diene or via 1,2-hydrocupration followed by a 1,3-migration. Our calculations suggest that this process strongly prefers to occur through the 1,2-addition pathway (**TS1a**, Figure 4) to form a secondary allylcopper intermediate (**23**, Figure 5). In comparison, the 1,4-hydrocupration of the diene requires 9.6 kcal/mol higher activation energy (**TS1c**, Figure 4b). The 1,2-hydrocupration proceeds with moderate π-facial selectivity ($\Delta\Delta G^{\ddagger}$ = 0.8 kcal/mol, Figure 4a) leading initially to an (*S*)-allylcopper intermediate. However, this stereocenter is rapidly ablated: the secondary allyl complex **23** undergoes facile 1,3-migration via either **TS2-cis** or **TS2-trans** to form primary allylcopper intermediates **24-cis** and **24-trans**, which are similar in energy to each other, and both more stable than **23** (Figure 5). This 1,3-migration step requires a very low barrier and is reversible. Therefore, the *cis*/*trans* isomers of the primary allylcopper intermediates exist in equilibrium with each other, and with the branched isomers, prior to the nucleophilic addition to the ketone.

The enantio- and diastereoselectivity are both determined in the subsequent ketone addition step. We found that the ketone addition occurs through a six-membered Zimmerman-Traxler-type transition state.[19] After exhaustive computational investigation of possible transition state isomers, **TS3a** and **TS3b** were identified as the most favorable pathways for the ketone additions (see SI for other less favorable TS structures). In both **TS3a** and **TS3b**, the bulkier aryl group on the ketone is placed in a pseudo-equatorial orientation, and the methyl substituent is pseudo-axial. Counterintuitively, the preferred pathway for reaction with the ketone takes place from the *cis*-allylcopper species **24-cis** via **TS3a**, which places the terminal methyl substituent of the allyl group pseudo-axial.[19b] In comparison, the ketone addition process from **24-trans,** which involves a pseudo-equatorial methyl substituent, requires an additional 1.3 kcal/mol of activation energy (**TS3b**). An examination of **TS3b** reveals the origin of this destabilization: the methyl substituent on the C=C double bond is placed between the aryl and methyl groups of the ketone, and thus induces greater steric repulsions at the forming C–C bond. On the other hand, the 1,3-diaxial repulsions with the same methyl substituent in **TS3a** are relatively weak because only one H…Me interaction is expected to contribute. The most favorable ketone addition transition state **TS3a** leads to the alkoxycopper intermediate **26a**, from which rapid σ-bond metathesis with a silane generates the observed major product in silyl-protected form (**27a**). This step is known to be very rapid for copper alkoxides, which renders the ketone addition step effectively irreversible.[14a]

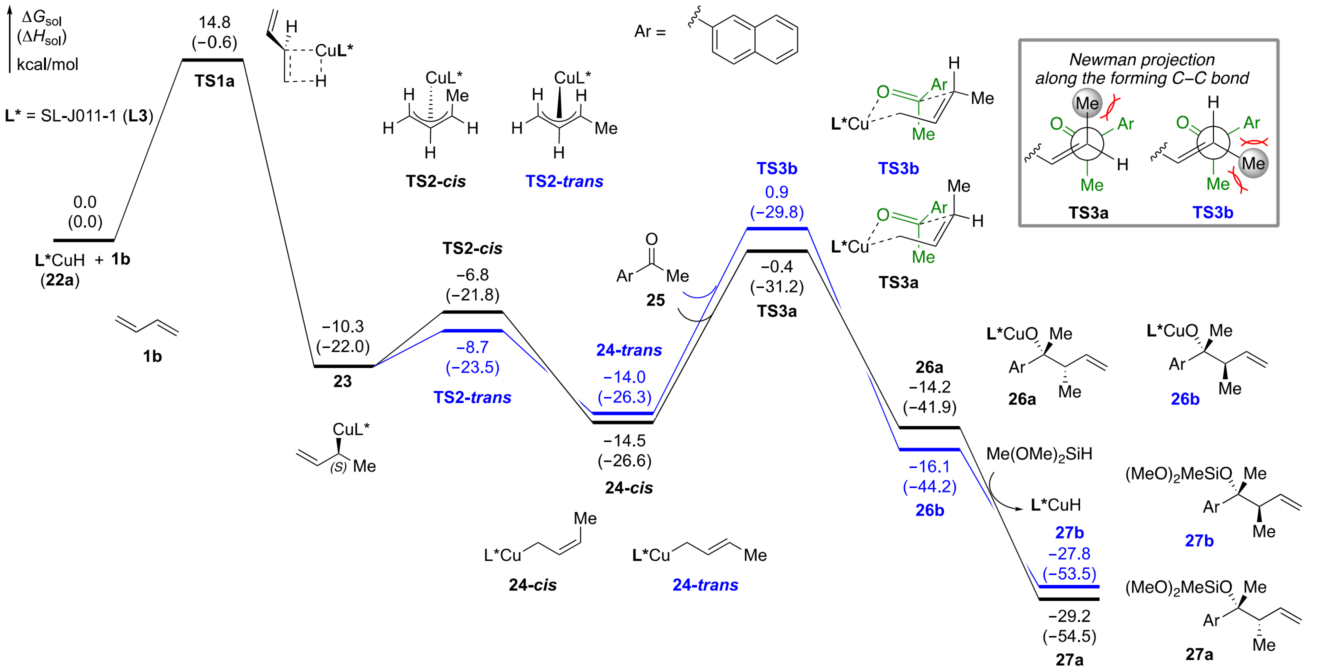


Figure 5. Computed energy profiles of the CuH-catalyzed allylation of 2-acetonaphthone **25**. The calculations were performed at the M06-2X/SDD–6-311+G(d,p)/SMD(toluene)//B3LYP/SDD–6-31G(d) level of theory. All energies are with respect to the separate **L***CuH catalyst (**22a**) and reactants (**1b** and **25**).

We next turned our attention to the enantioselectivity of this process, which is determined by the π-facial selectivity of the ketone addition step as dictated by the ligand. Relative to favored transition state structure **TS3a**, disfavored structure **TS3c** involves the addition to the opposite face of the ketone (Figure 6). In **TS3c**, the α-methylene group and the pseudo-axial methyl group of the ketone are both placed in the two quadrants occupied by the "proximal" *P*-aryl and *P*-*t*-Bu groups (highlighted in red in Figure 6). As such, **TS3c** is destabilized by the steric repulsions with the ligand. In contrast, in the more stable transition state **TS3a**, the α-methylene group and the pseudo-axial methyl group are both placed in the "unoccupied" quadrants, in which the *P*-substituents are further away ("distal") from the Cu center and the substrate. Due to the diminished ligand-substrate steric repulsions, **TS3a** is 4.0 kcal/mol more stable than **TS3c**, which is in qualitative agreement with the high levels of enantioselectivity observed in the experiment.

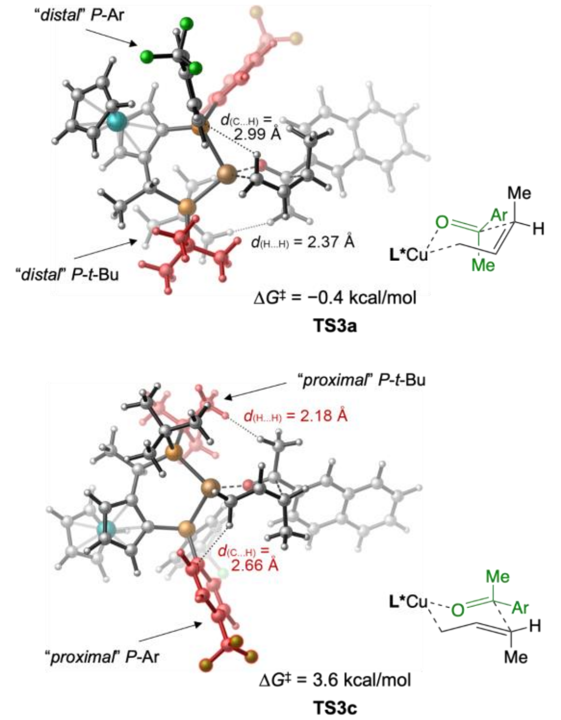


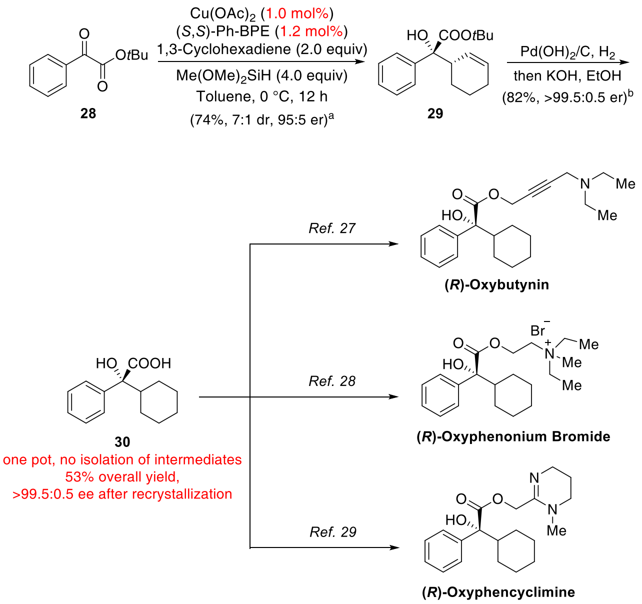
Figure 6. Origin of enantioselectivity.

APPLICATIONS

To demonstrate the synthetic utility of this asymmetric transformation, we sought to prepare chiral tertiary alcohol **30**, a key intermediate in the synthesis of anticholinergic agents (*R*)-Oxybutynin,[20] (*R*)-Oxyphenonium bromide[21] and (*R*)-Oxyphencyclimine.[22] Currently, these drugs are typically administered in their racemic form, which is synthesized through the addition of a cyclohexyl Grignard reagent to a ketone.[23] However, motivated by the decreased side effects[24] and higher efficiency[22,25] associated with the single enantiomer forms, several groups have developed synthetic routes to enantioenriched key chiral intermediate **30** using chiral auxiliaries,[26] chiral pool synthesis,[20c] an organocatalytic aldol-elimination-hydrogenation-deprotection sequence,[20b] or palladium-catalyzed asymmetric allylic alkylation followed by functional group interconversions.[20d] Using our method, we devised an alternative, catalytic, enantioselective synthetic route to this key chiral intermediate (Scheme 1) that yields enantiopure product and does not require the purification of intermediates. From commercially available starting material **28**, after CuH-catalyzed coupling with cyclohexadiene, reduction, hydrolysis, and recrystallization, **30** was obtained in 53% overall yield and with over 99.5:0.5 er in a one-pot sequence without the need for chromatography.

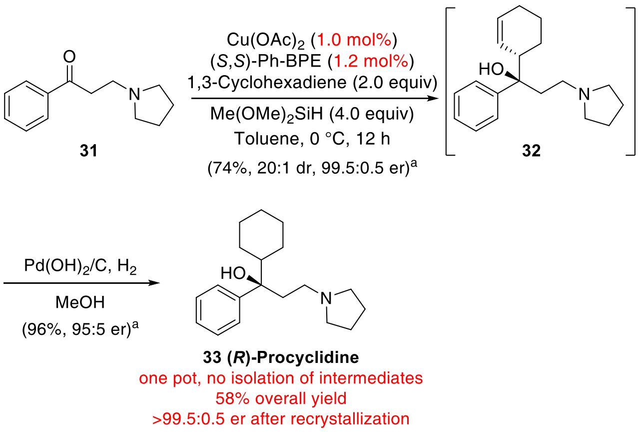
We also applied our method toward a new synthetic route to (*R*)-Procyclidine, a treatment for Parkinson's disease.[30] Biological testing suggests that (*R*)-Procyclidine has a higher affinity for the relevant muscarinic receptor both in humans and in animal models.[22b,30] Thus, an efficient asymmetric synthesis of (*R*)-Procyclidine would be valuable. We studied the copper-catalyzed allylation of commercially available ketone **31**, which provided chiral tertiary alcohol **32**. Again, without requiring chromatographic purification, the mixture containing **32** was subjected to simple hydrogenation and direct crystallization to yield (*R*)-Procyclidine (**33**) in 58% overall yield and over 99.5:0.5 er.

Scheme 1. Synthesis of a Key Tertiary α-Hydroxy Acid Intermediate.



[a] Parenthetical data reflect results of an independent run for which intermediates were isolated, purified, and characterized. See the Supporting Information for details. [b] After recrystallization. See the Supporting Information for details.

Scheme 2. Synthesis of (*R*)-Procyclidine.



[a] Parenthetical data reflect results of an independent run for which intermediates were isolated, purified, and characterized. See the Supporting Information for details.

CONCLUSION

In summary, we have developed a highly efficient copper-catalyzed allylation of ketones with feedstock linear and cyclic conjugated dienes. A large variety of chiral tertiary alcohols were prepared in excellent yield, regio-, and enantioselectivity, and with a high level of functional group compatibility. Guided by DFT calculations, a rationale explaining the factors responsible for the enantio- and diastereoselectivity of this transformation was derived. From a mixture of rapidly equilibrating allylcopper intermediates of similar energy, selective reaction of the *cis*-allyl complex generates the observed diastereomer. Furthermore, a model for the enantioselectivity of the addition of the allylcopper intermediates to ketones was proposed for catalysts bearing the non-C_2-symmetric JOSIPHOS ligands. Our method also enabled a new, concise, and enantioselective synthesis of pharmaceutically important drug (*R*)-Procyclidine and a key intermediate for anticholinergic drugs (*R*)-Oxyphencyclimine, (*R*)-Oxybutynin and (*R*)-Oxyphenonium bromide.

ASSOCIATED CONTENT

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.

Experimental procedures and characterization data for all compounds (PDF)
NMR spectra (PDF)
SFC and HPLC traces (PDF)
Computational details and Cartesian coordinates of optimized geometries (PDF)

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Notes

The authors declare no competing financial interest.

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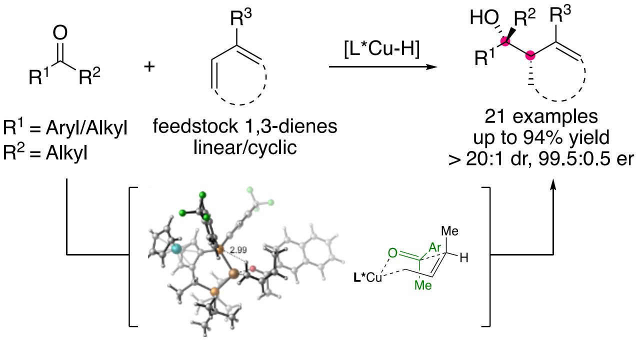
Table of Contents Graphic:



CuH-Catalyzed Enantioselective Ketone Allylation with 1,3-Dienes: Scope, Mechanism, and Applications

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Contents

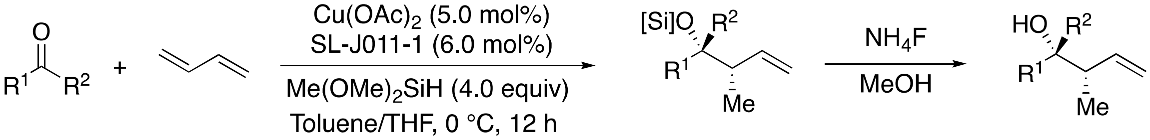
I. General Information.

General reagent information. All reactions were performed under a nitrogen atmosphere using the indicated method in the general procedures. Toluene and tetrahydrofuran (THF) were purchased from J.T. Baker in CYCLE-TAINER® solvent delivery kegs and purified by passage under argon pressure through two packed columns of neutral alumina and copper(II) oxide. Copper(II) acetate was purchased from Strem and was used as received. 1,2-Bis((2*S*,5*S*)2,5-diphenylphospholano)ethane, 1,2-Bis((2*R*,5*R*)2,5-diphenylphosphol-ano)ethane (Ph-BPE) ligands were purchased from Namena Corp. and stored in a nitrogen-filled glove box. Josiphos ligand (*R*)-1-{(S_P)-2-[Bis[4-(trifluoromethyl)-phenyl]phosphino]ferrocenyl}ethyldi-tert-butylphosphine (Josiphos SL-J011-1) was donated by Solvias and stored in a nitrogen-filled glove box. Dimethoxy(methyl)silane (DMMS) was purchased from Tokyo Chemical Industry Co. (TCI) and stored in a nitrogen-filled glove box at −20 °C for long term storage. (***Caution****: Dimethoxy(methyl)silane (DMMS, CAS: 16881-77-9) is listed by several vendors (TCI, Alfa Aesar) SDS or MSDS as a H318, a category 1 Causes Serious Eye Damage Other vendors (Sigma-Aldrich, Gelest) list DMMS as a H319, a category II Eye Irritant. DMMS should be handled in a well-ventilated fumehood using proper precaution as outlined for the handling of hazardous materials in prudent practices in the laboratory*[1]*. At the end of the reaction ammonium fluoride in methanol should be carefully added to the reaction mixture. This should be allowed to stir for at least 30 min or the time indicated in the detailed reaction procedure.)* All other solvents and commercial reagents were used as received from Sigma Aldrich, Alfa Aesar, Acros Organics, TCI and Combi-Blocks, unless otherwise noted. Flash column chromatography was performed using 40-63 µm silica gel (SiliaFlash® F60 from Silicycle), or with the aid of a Biotage Isolera Automated Flash Chromatography System using prepacked SNAP silica cartridges (10-100 g). Organic solutions were concentrated in vacuo using a Buchi rotary evaporator.

General analytical information. All new compounds were characterized by NMR spectroscopy, IR spectroscopy, elemental analysis or high resolution mass spectrometry, optical rotation (if applicable), and melting point analysis (if solids). ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ on a Bruker AMX-400 spectrometer. Chemical shifts for ^{1}H NMR are reported as follows: chemical shift in reference to residual $CHCl_3$ at 7.26 ppm (δ ppm), multiplicity (s = singlet, br s = broad singlet, d = doublet, t = triplet, q = quartet, sex = sextet, sep = septet, ddd = doublet of double of doublets, td = triplet of doublets, m = multiplet), coupling constant (Hz), and integration. Chemical shifts for ^{13}C NMR are reported in terms of chemical shift in reference to the $CDCl_3$ solvent signal (77.16 ppm). IR spectra were recorded on a Thermo Scientific Nicolet iS5 spectrometer (iD5 ATR, diamond) and are reported in terms of frequency of absorption (cm^{-1}). Melting points were measured on a Mel-Temp capillary melting point apparatus. Optical rotations were measured using a Jasco P-1010 digital polarimeter. Elemental analyses were performed by Atlantic Microlabs Inc., Norcross, GA. High-resolution mass spectra were recorded on a JEOL AccuTOF LC-Plus 46 DART system and on an Agilent Technologies 6545 Q-TOF LC/MS system. Achiral gas chromatography (GC) analyses were performed on an Agilent 7890A gas chromatograph with an FID detector using a J & W DB-1 column (10 m, 0.1 mm I.D.). Enantiomeric ratios (er's) were determined by chiral SFC analysis using a Waters Acquity UPC2 instrument or HPLC (high performance liquid chromatography) analysis using a chiral stationary phase. Specific columns and analytical methods are provided in the experimental details for individual compounds; the wavelengths of light used for chiral analyses are provided with the associated chromatograms. Thin-layer chromatography (TLC) was performed on silica gel 60Å F_{254} plates (SiliaPlate from Silicycle) and visualized with UV light or potassium permanganate stain. Preparatory thin-layer chromatography (Prep-TLC) was performed on silica gel GF with UV 254 (20 x 20 cm, 1000 microns, catalog # TLG-R10011B-341 from Silicycle) and visualized with UV light. The syringe pumps (PHD 2000 and PHD Ultra) were purchased from Harvard Apparatus. Isolated yields reported in Tables 2 and 3 of the manuscript reflect the average values from two independent runs.

II. General Procedures for CuH-Catalyzed Ketone Allylation Reactions.

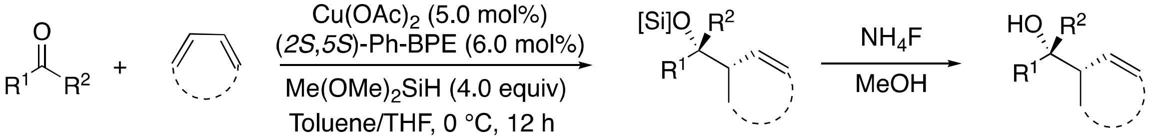
General procedure A for 1 mmol scale reaction with acyclic dienes.



In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube (Fisherbrand, 20 x 125 mm, catalog no. 1495937A) equipped with a stir bar was charged with $Cu(OAc)_2$ (9.2

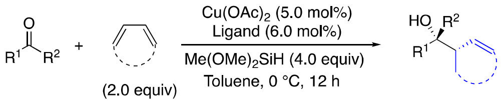
mg, 0.05 mmol, 5.0 mol %) and SL-J011-1 (40.7 mg, 0.06 mmol, 6.0 mol %), followed by the addition of toluene (0.3 mL) via syringe. The mixture was stirred at room temperature for 1 min before the addition of dimethoxymethylsilane (DMMS) (490 µL, 4.0 mmol, 4.0 equiv) via syringe. The reaction vessel was then capped (Cap: Kimble Chase Open Top S/T Closure catalog no. 73804-15425; Septum: Thermo Scientific 1.3 mm silicone/PTFE catalog no. B7995-18) and removed from the glove box. The acyclic diene (2.0 mmol, 2.0 equiv) was added directly into the reaction tube via syringe. The cap was wrapped in parafilm and the reaction tube was submerged into an ice bath. The ketone (1.0 mmol, 1.0 equiv) dissolved in toluene (1.0 mL) was added slowly via a syringe pump (1.0 mol/L, 7.5 uL/min). The reaction tube was stirred at 0 °C for 12 h. After the reaction was complete, as judged by GC-MS, a saturated solution of NH_4F in MeOH (ca. 10 mL) was carefully added to quench the reaction (Caution: gas evolution was observed). The reaction mixture was allowed to stir for 30 min at room temperature, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at room temperature and then filtered through a short plug of Celite (2.0 cm) eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. At this point, the combined yield (of the diastereomers) and the diasteromeric ratio (dr) were determined by ^{1}H NMR spectroscopic analysis using dibromomethane as an internal standard. The crude reaction mixture was then purified by flash column chromatography with the aid of a Biotage Isolera instrument to afford the desired product. Enantiomeric ratios (er's) were determined by chiral SFC analysis using a Waters Acquity UPC2 instrument or HPLC analysis using a chiral stationary phase.

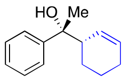
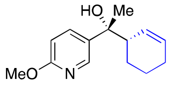
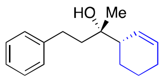
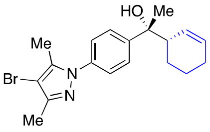
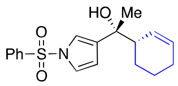
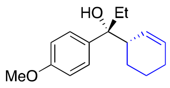
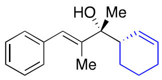
General procedure B for 1 mmol scale reaction with cyclic dienes.



In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube (Fisherbrand, 20 x 125 mm, catalog no. 1495937A) equipped with a stir bar was charged with $Cu(OAc)_2$ (9.2 mg, 0.05 mmol, 5.0 mol %) and (*S,S*)-Ph-BPE (30.4 mg, 0.06 mmol, 6.0 mol %), followed the addition of by toluene (0.3 mL) via syringe. The reaction mixture was stirred at room temperature for 1 min before the addition of DMMS (490 µL, 4.0 mmol, 4.0 equiv) and a cyclic diene (2.0 mmol, 2.0 equiv) via syringe. The reaction vessel was then capped (Cap: Kimble Chase Open Top S/T Closure catalog no. 73804-15425; Septum: Thermo Scientific 1.3 mm silicone/PTFE catalog no. B7995-18) and removed from the glove box. The cap was wrapped in parafilm and the reaction tube was inserted into an ice bath. The ketone (1.0 mmol, 1.0 equiv) dissolved in toluene (1.0 mL) was added slowly via syringe pump (1.0 mol/L, 7.5 uL/min). The reaction tube was stirred at 0 °C for 12 h. After the reaction was complete as judged by GC-MS, a saturated solution of NH_4F in MeOH (ca. 10 mL) was carefully added to quench the reaction (Caution: gas evolution was observed). The reaction mixture was allowed to stir for 30 min at room temperature, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at room temperature and then filtered through a short plug of Celite (2.0 cm) eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. At this point, the combined yield (of the diastereomers) and the diasteromeric ratio (dr) were determined by ^{1}H-NMR spectroscopic analysis using dibromomethane as an internal standard. The crude reaction mixture was purified by flash column chromatography with the aid of a Biotage Isolera instrument to afford the desired product. Enantiomeric ratios (er's) were determined by chiral SFC analysis using a Waters Acquity UPC2 instrument or HPLC analysis using a chiral stationary phase.

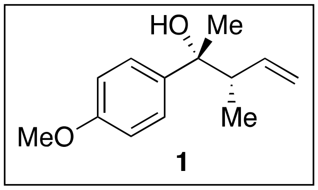
III. Study of Ligand Effect for Cyclic Diene Substrates.



Entry	Substrate	Ligand	Yield of product (%)	dr	er	Yield of reduced byproduct (%)
1		(*S*,*S*)-Ph-BPE	82	>20:1	96.5:3.5	~18%
		SL-J011-1	55	>20:1	97.5:2.5	~45%
2		(*S*,*S*)-Ph-BPE	82	>20:1	97:3	~18%
		SL-J011-1	63	>20:1	97:3	~35%
3		(*S*,*S*)-Ph-BPE	91	2:1	98.5:1.5 (major)/99.5:0.5 (minor)	~8%
		SL-J011-1	63	2:1	97:3 (major)/88:12 (minor)	~36%
4		(*S*,*S*)-Ph-BPE	45	>20:1	94:6	~50%
		SL-J011-1	trace	— —	— —	— —
5		(*S*,*S*)-Ph-BPE	90	>20:1	97.5:2.5	~10%
		SL-J011-1	trace	— —	— —	— —
6		(*S*,*S*)-Ph-BPE	86	>20:1	97.5:2.5	~12%
		SL-J011-1	35	>20:1	93:7	~60%
7		(*S*,*S*)-Ph-BPE	69	>20:1	96:4	~30%
		SL-J011-1	10	>20:1	95:5	~90%

Yields indicate the isolated yield of product as a mixture of two diastereomers on a 1.0 mmol scale. The yields of reduced byproducts were detected by GC-MS. Diastereomeric ratios were determined by ^{1}H NMR spectroscopy for both the crude and purified products; enantiomeric ratios (er's) were determined by HPLC or SFC analysis on commercial chiral columns; enantiomeric ratios of minor diastereomers are indicated in parentheses.

IV. Characterization Data for Tertiary Homoallylic Alcohol Products.



1

(2*R*,3*S*)-2-(4-methoxyphenyl)-3-methylpent-4-en-2-ol (1): General procedure **A** was followed using 1-(4-methoxyphenyl)ethan-1-one (150 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 column volumes (CV), then 2-15% EtOAc/hexanes for 15 CV, then 15-20% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: 3.5:1) as a clear oil (194 mg, 94%).

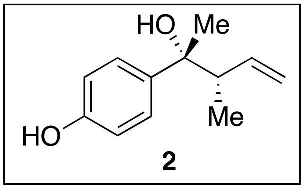
Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.31 (d, *J* = 8.8 Hz, 2H), 6.87 (d, *J* = 8.8 Hz, 2H), 5.79 (ddd, *J* = 16.7, 10.7, 8.2 Hz, 1H), 5.06~5.13 (m, 2H), 3.81 (s, 3H), 2.51 (p, *J* = 6.9 Hz, 1H), 1.89 (br s, 1H), 1.51 (s, 3H), 0.88 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 158.2, 140.1, 139.2, 126.5, 116.3, 113.3, 75.6, 55.3, 49.2, 28.4, 14.9 ppm. **SFC** analysis (AD-H column, $scCO_2$/*i*PrOH = 98/2 to 93/7, 2.5 mL/min) indicated a 98:2 er: t_R (major)= 7.83 min, 8.11 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.35 (d, *J* = 8.8 Hz, 2H), 6.88 (d, *J* = 8.9 Hz, 2H), 5.69~5.76 (m, 1H), 5.06~5.13 (m, 2H), 3.81 (s, 3H), 2.56 (p, *J* = 7.4 Hz, 1H), 1.98 (br s, 1H), 1.51 (s, 3H), 0.94 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 158.4, 140.3, 139.3, 126.8, 116.7, 113.3, 75.6, 55.3, 49.2, 25.9, 14.4 ppm. **SFC** analysis (AD-H column, $scCO_2$/*i*PrOH = 98/2 to 93/7, 2.5 mL/min) indicated a 97:3 er: t_R (major) = 7.56 min, 8.35 min.

Properties for mixture of diastereomers:
IR: 3495 (-OH, broad), 2977, 2932, 2832, 1608, 1511, 1459, 1369, 1295, 1250, 1182, 1030, 914, 829, 739 cm^{-1}. **$[\alpha]_D^{24}$** = +20.7, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{13}H_{18}O_2$:

C, 75.69; H, 8.80. Found: C, 75.43; H, 8.68. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 3.5:1 dr.

Duplicate experiment: Yield: 93%, 192 mg; dr: 4:1; er: 98:2 (major), 96.5:3.5 (minor). Average yield: 93.5%.



2

4-((2*R*,3*S*)-2-hydroxy-3-methylpent-4-en-2-yl)phenol (2): General procedure **A** was followed using 1-(4-hydroxyphenyl)ethan-1-one (136 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 20 CV) to afford the title compound (as a mixture of diastereomers, dr: 4:1) as a white solid (180 mg, 94%).

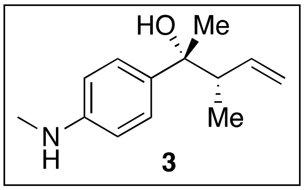
Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.23 (d, *J* = 8.7 Hz, 2H), 6.92 (br s, 1H), 6.80 (d, *J* = 8.4 Hz, 2H), 5.70~5.80 (m, 1H), 5.07~5.17 (m, 2H), 2.50~2.63 (m, 2H), 1.54 (s, 3H), 0.93 (d, *J* = 7.1 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 154.5, 139.8, 138.4, 126.7, 116.5, 114.9, 76.4, 49.1, 27.8, 14.9 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 99/1(initial) to 98/2 (0 ~10 min) to 97/3 (10 ~20 min) to 96/4 (20 ~30 min) to 95/5 (30 ~40 min) to 96/4 (40 ~50 min) to 97/3 (50 ~60 min) 2.5 mL/min, add 0.1% diethylamine) indicated a 97.5:2.5 er: t_R (major)= 39.83 min, 45.33 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.27 (d, *J* = 8.8 Hz, 2H), 6.92 (br s, 1H), 6.80 (d, *J* = 8.4 Hz, 2H), 5.70~5.80 (m, 1H), 5.07~5.17 (m, 2H), 2.50~2.63 (m, 2H), 1.53 (s, 3H), 0.92 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 154.6, 139.9, 138.4, 127.0, 117.1, 115.0, 76.3, 49.1, 25.3, 14.5 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 99/1(initial) to 98/2 (0 ~10 min) to 97/3 (10 ~20 min) to 96/4 (20 ~30 min) to 95/5 (30 ~40 min) to 96/4 (40 ~50 min) to 97/3 (50 ~60 min) 2.5 mL/min, add 0.1% diethylamine) indicated a 96:4 er: t_R (major)= 40.66 min, 43.10 min.

Properties for mixture of diastereomers:
IR: 3341 (-OH, broad), 2974, 2929, 1613, 1601, 1511, 1447, 1371, 1217, 1175, 1073, 1014, 912, 834, 744, 637 cm^{-1}. **$[\alpha]_D^{24}$** = +18.3, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{12}H_{16}O_2$: C, 74.97; H, 8.39. Found: C, 75.04; H, 8.43. ^{1}H NMR spectroscopic analysis of

the unpurified reaction mixture indicated 4:1 dr. Melting point was not obtained for the inseparable mixture of diastereomers.

Duplicate experiment: Yield: 94%, 180 mg; dr: 4:1; er: 97.5:2.5 (major), 96.5:3.5 (minor). Average yield: 94%.



3

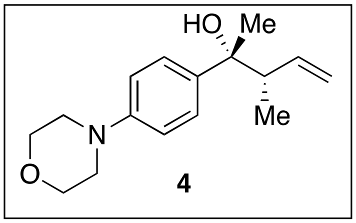
(2*R*,3*S*)-3-methyl-2-(4-(methylamino)phenyl)pent-4-en-2-ol (3): General procedure **A** was followed using 1-(4-(methylamino)phenyl)ethan-1-one (149 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-15% EtOAc/hexanes for 20 CV, then 15-25% EtOAc/hexanes for 10 CV) to afford the title compound (as a mixture of diastereomers, dr: 7:1) as a brown oil (187 mg, 91%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.05 (d, *J* = 8.6 Hz, 2H), 6.42 (d, *J* = 8.6 Hz, 2H), 5.58~5.67 (m, 1H), 4.88~4.97 (m, 2H), 2.67 (s, 3H), 2.35 (p, *J* = 7.4 Hz, 1H), 1.33 (br s, 3H), 0.74 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 147.9, 140.5, 135.8, 126.3, 115.9, 112.0, 75.6, 49.2, 30.9, 28.2, 15.0 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 98.5:1.5 er: t_R (major) = 5.86 min, 6.61 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.06~7.10 (m, 2H), 6.70 (d, *J* = 8.7 Hz, 2H), 5.56~5.64 (m, 1H), 4.88~4.95 (m, 2H), 2.67 (s, 3H), 2.39 (p, *J* = 7.1 Hz, 1H), 1.32 (s, 3H), 0.76 (d, *J* = 7.6 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 148.1, 140.6, 135.8, 126.6, 116.3, 112.0, 75.6, 49.1, 30.9, 25.6, 14.5 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 97:3 er: t_R (major) = 6.09 min, 6.24 min.

Properties for mixture of diastereomers:
IR: 3412 (-OH, broad), 3067, 2972, 2879, 2808, 1613, 1516, 1374, 1317, 1184, 1153, 1080, 914, 817, 734 cm^{-1}. **$[\alpha]_D^{24}$** = +25.1, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{13}H_{19}NO$: C, 76.06; H, 9.33. Found: C, 75.80; H, 9.12. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 7:1 dr.

Duplicate experiment: Yield: 93%, 191 mg; dr: 7:1; er: 99:1 (major), 97:3 (minor). Average yield: 92%.



4

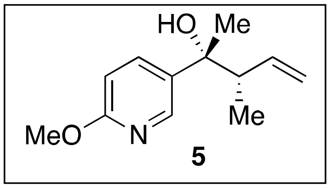
(2*R*,3*S*)-3-methyl-2-(4-morpholinophenyl)pent-4-en-2-ol (4): General procedure **A** was followed using 1-(4-morpholinophenyl)ethan-1-one (205 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-20% EtOAc/hexanes for 20 CV, then 20-30% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: 5:1) as a clear oil (250 mg, 95%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.30 (d, *J* = 8.9 Hz, 2H), 6.88 (d, *J* = 8.9 Hz, 2H), 5.78 (ddd, *J* = 16.6, 11.2, 8.5 Hz, 1H), 5.06~5.13 (m, 2H), 3.86 (t, *J* = 4.8 Hz, 4H), 3.16 (t, *J* = 4.9 Hz, 4H), 2.51 (p, *J* = 7.2 Hz, 1H), 1.87 (br s, 1H), 1.50 (s, 3H), 0.88 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 149.8, 140.2, 138.6, 126.3, 116.2, 115.1, 75.6, 67.1, 49.5, 49.2, 28.3, 15.0 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 94/6, 2.5 mL/min, add 0.1% diethylamine) indicated a 98:2 er: t_R (major) = 26.83 min, 38.55 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.33 (d, *J* = 9.1 Hz, 2H), 6.88 (d, *J* = 8.9 Hz, 2H), 5.69~5.80 (m, 1H), 5.06~5.13 (m, 2H), 3.86 (t, *J* = 4.8 Hz, 4H), 3.16 (t, *J* = 4.9 Hz, 4H), 2.56 (p, *J* = 7.2 Hz, 1H), 1.95 (br s, 1H), 1.50 (s, 3H), 0.93 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 149.8, 140.3, 138.6, 126.6, 116.6, 115.1, 75.5, 67.1, 49.4, 49.1, 25.8, 14.4 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5, 2.5 mL/min, add 0.1% diethylamine) indicated a 96:4 er: t_R (major) = 31.53 min, 34.71 min.

Properties for mixture of diastereomers:
IR: 3460 (-OH, broad), 2965, 2856, 2818, 1611, 1511, 1447, 1367, 1258, 1220, 1115, 924, 819, 661 cm^{-1}. **$[\alpha]_D^{24}$** = +14.4, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{16}H_{23}NO_2+H]^+$: 262.1807. Found: 262.1810. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 5:1 dr.

Duplicate experiment: Yield: 93%, 243 mg; dr: 5:1; er: 98:2 (major), 96.5:3.5 (minor). Average yield: 94%.



5

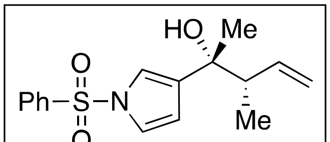
(2*R*,3*S*)-2-(6-methoxypyridin-3-yl)-3-methylpent-4-en-2-ol (5): General procedure **A** was followed using 1-(6-methoxypyridin-3-yl)ethan-1-one (151 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-15% EtOAc/hexanes for 15 CV, then 15-20% EtOAc/hexanes for 10 CV) to afford the title compound (as a mixture of diastereomers, dr: 4:1) as a light brown oil (188 mg, 91%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 8.17 (br s, 1H), 7.60 (d, *J* = 8.4 Hz, 1H), 6.70 (d, *J* = 8.8 Hz, 1H), 5.74 (ddd, *J* = 16.7, 10.3, 8.2 Hz, 1H), 5.05~5.12 (m, 2H), 3.92 (s, 3H), 2.46 (p, *J* = 6.5 Hz, 1H), 2.01 (s, 1H), 1.51 (s, 3H), 0.89 (d, *J* = 6.7 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 163.1, 144.0, 139.5, 136.6, 135.0, 116.9, 110.0, 74.6, 53.5, 49.2, 28.1, 14.8 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5, 2.5 mL/min) indicated a 97.5:2.5 er: t_R (major) = 8.51 min, 9.29 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 8.17 (br s, 1H), 7.65 (d, *J* = 8.8 Hz, 1H), 6.70 (d, *J* = 8.8 Hz, 1H), 5.70 (ddd, *J* = 17.9, 10.4, 8.0 Hz, 1H), 5.05~5.12 (m, 2H), 3.92 (s, 3H), 2.50 (p, *J* = 7.1 Hz, 1H), 2.08 (s, 1H), 1.50 (s, 3H), 0.93 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 163.2, 144.3, 139.7, 136.8, 134.8, 117.3, 110.0, 74.6, 53.5, 49.3, 25.7, 14.5 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5, 2.5 mL/min) indicated a 96:4 er: t_R (minor) = 7.51 min, 8.73 min.

Properties for mixture of diastereomers:
IR: 3434 (-OH, broad), 3076, 2977, 2936, 1603, 1570, 1490, 1378, 1281, 1123, 1021, 909, 829, 760, 654 cm^{-1}. **$[\alpha]_D^{23}$** = +22.2, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{12}H_{17}NO_2+H]^+$: 208.1338. Found: 208.1336. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 4:1 dr.

Duplicate experiment: Yield: 90%, 187 mg; dr: 4:1; er: 97.5:2.5 (major), 96:4 (minor). Average yield: 90.5%.



6

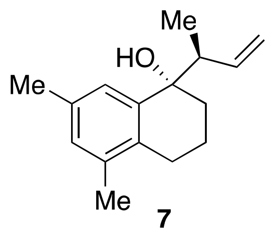
(2*R*,3*S*)-3-methyl-2-(1-(phenylsulfonyl)-1H-pyrrol-3-yl)pent-4-en-2-ol (6): General procedure **A** was followed using 1-(1-(phenylsulfonyl)-1H-pyrrol-3-yl)ethan-1-one (249 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve ketone at slow addition step. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-15% EtOAc/hexanes for 15 CV, then 15-20% EtOAc/hexanes for 10 CV) to afford the title compound (as a mixture of diastereomers, dr: 3:1) as a brown oil (280 mg, 92%).

Major diastereomer: ^{1}**H NMR** (400 MHz, $CDCl_3$) δ: 7.80~7.83 (m, 2H), 7.56~7.60 (m, 1H), 7.45~7.49 (m, 2H), 7.09 (dd, *J* = 3.3, 2.3 Hz, 1H), 7.02 (dd, *J* = 2.3, 1.7 Hz, 1H), 6.20 (dd, *J* = 3.3, 1.7 Hz, 1H), 5.58~5.68 (m, 1H), 4.97~5.03 (m, 2H), 2.31~2.34 (m, 1H), 1.99 (br s, 1H), 1.39 (s, 3H), 0.88 (d, *J* = 6.9 Hz, 3H) ppm. ^{13}**C NMR** (101 MHz, $CDCl_3$) δ: 139.7, 136.1, 133.9, 129.4, 126.8, 121.0, 117.1, 116.6, 112.8, 73.1, 48.9, 27.2, 15.0 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 95.5:4.5 er: t_R (major) = 4.64 min, 5.02 min.

Minor diastereomer: ^{1}**H NMR** (400 MHz, $CDCl_3$) δ: 7.80~7.84 (m, 2H), 7.56~7.60 (m, 1H), 7.45~7.49 (m, 2H), 7.10 (dd, *J* = 3.1, 2.3 Hz, 1H), 7.04 (dd, *J* = 2.3, 1.7 Hz, 1H), 6.26 (dd, *J* = 3.3, 1.7 Hz, 1H), 5.65~5.73 (m, 1H), 4.99~5.08 (m, 2H), 2.36~2.44 (m, 1H), 1.98 (br s, 1H), 1.38 (s, 3H), 0.86 (d, *J* = 6.9 Hz, 3H) ppm. ^{13}**C NMR** (101 MHz, $CDCl_3$) δ: 139.7, 139.1, 136.1, 129.4, 126.8, 121.1, 117.3, 116.9, 112.7, 73.0, 48.7, 25.4, 14.7 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 95:5 er: t_R (minor)= 4.76 min, 4.96 min.

Properties for mixture of diastereomers:
IR: 3552 (-OH, broad), 3138, 3069, 2972, 2932, 1447, 1369, 1170, 1063, 912, 784, 727, 682, 618, 585 cm^{-1}. $[\alpha]_D^{23}$ = +10.7, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{16}H_{19}NO_3S\text{-}OH]^+$: 288.1058. Found: 288.1055. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 3:1 dr.

Duplicate experiment: Yield: 87%, 265 mg; dr: 3:1. er: 96.5:3.5 (major), 96:4 (minor). Average yield: 89.5%.



7

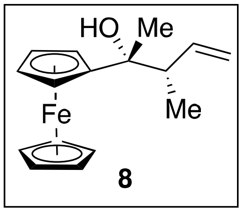
(*S*)-1-((*S*)-but-3-en-2-yl)-5,7-dimethyl-1,2,3,4-tetrahydronaphthalen-1-ol (7): General procedure **A** was followed using 5,7-dimethyl-3,4-dihydronaphthalen-1(2H)-one (174 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-10% EtOAc/hexanes for 10 CV, then 10-10% EtOAc/hexanes for 10 CV, then 10-16% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: 11:1) as a clear oil (210 mg, 91%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.33 (s, 1H), 6.96 (s, 1H), 5.61 (ddd, *J* = 17.1, 10.6, 6.3 Hz, 1H), 4.96~5.06 (m, 2H), 2.92~2.99 (m, 1H), 2.72 (dt, *J* = 15.9, 4.9 Hz, 1H), 2.42~2.52 (m, 1H), 2.36 (s, 3H), 2.26 (s, 3H), 1.76~1.99 (m, 5H), 1.24 (d, *J* = 6.8 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 141.2, 140.5, 136.0, 134.8, 133.1, 129.7, 124.7, 114.8, 73.8, 46.3, 32.2, 26.4, 21.2, 20.0, 18.7, 13.0 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 80/20, 2.5 mL/min) indicated a 95.5:4.5 er: t_R (major) = 3.92 min, 4.10 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.28 (s, 1H), 6.96 (s, 1H), 6.11 (ddd, *J* = 17.7, 10.4, 7.7 Hz, 1H), 5.25~5.31 (m, 2H), 2.97~3.04 (m, 1H), 2.74 (dt, *J* = 11.8, 3.5 Hz, 1H), 2.42~2.52 (m, 1H), 2.36 (s, 3H), 2.26 (s, 3H), 1.78~1.99 (m, 5H), 0.82 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 140.3, 139.9, 135.9, 135.1, 133.8, 129.7, 124.6, 116.7, 74.1, 48.1, 31.9, 26.8, 21.2, 20.0, 18.8, 15.6 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 80/20, 2.5 mL/min) indicated a 86:14 er: t_R (minor) = 3.49 min, 4.32 min.

Properties for mixture of diastereomers:
IR: 3446 (-OH, broad), 2929, 2865, 1634, 1610, 1475, 1449, 1366, 1336, 1253, 1137, 1078, 995, 959, 905, 855, 744 cm^{-1}. **$[\alpha]_D^{24}$** = -71.0, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{16}H_{22}O$: C, 83.43; H, 9.63. Found: C, 83.22; H, 9.73. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 11:1 dr.

Duplicate experiment: Yield: 94%, 216 mg; dr: 11:1. er: 95.5:4.5 (major), 86:14 (minor). Average yield: 92.5%.



8

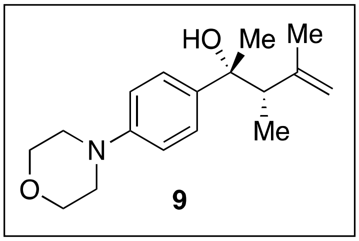
(2*R*,3*S*)-3-methyl-2-ferrocenepent-4-en-2-ol (8): General procedure **A** was followed using acetylferrocene (228 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-10% EtOAc/hexanes for 15 CV, then 10-15% EtOAc/hexanes for 10 CV) to afford the title compound (as a mixture of diastereomers, dr: 3:1) as a brown oil (268 mg, 94%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 5.61 (ddd, *J* = 17.2, 10.5, 7.7 Hz, 1H), 4.87~5.01 (m, 2H), 4.21~4.23 (m, 1H), 4.22 (s, 5H), 4.14~4.17 (m, 2H), 4.01~4.03 (m, 1H), 2.28~2.34 (m, 1H), 2.26 (s, 1H), 1.48 (s, 3H), 0.97 (d, *J* = 7.0 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 140.5, 115.2, 98.4, 72.8, 68.4 (5C), 68.4, 67.8, 67.6, 65.7, 49.2, 25.6, 15.0 ppm. **SFC** analysis (CEL-2 column, $scCO_2$/IPA = 99/1 to 95/5, 1.75 mL/min) indicated a 96:4 er: t_R (major) = 4.23 min, 5.33 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 5.74~5.83 (m, 1H), 4.91~5.05 (m, 2H), 4.27~4.28 (m, 1H), 4.22 (s, 5H), 4.14~4.17 (m, 2H), 4.03~4.05 (m, 1H), 2.28~2.35 (m, 1H), 2.29 (s, 1H), 1.46 (s, 3H), 0.80 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 140.8, 115.3, 98.5, 73.0, 68.6, 68.4 (5C), 68.0, 67.6, 65.5, 49.3, 25.1, 15.3 ppm. **SFC** analysis (CEL-2 column, $scCO_2$/IPA = 99/1 to 95/5, 1.75 mL/min) indicated a 96:4 er: t_R (minor) = 4.52 min, 5.44 min.

Properties for mixture of diastereomers:
IR: 3562 (-OH, broad), 3093, 2972, 2937, 2879, 1637, 1449, 1409, 1371, 1324, 1104, 1002, 914, 817, 751 cm^{-1}. **$[\alpha]_D^{26}$** = -53.4, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{16}H_{20}FeO$: C, 67.57; H, 7.15. Found: C, 67.62; H, 7.09. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 3:1 dr.

Duplicate experiment: Yield: 94%, 268 mg; dr: 3:1. er: 96.5:3.5 (major), 96:4 (minor). Average yield: 94%.



9

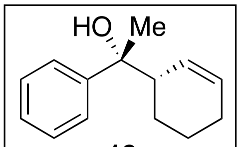
(2*R*,3*S*)-3,4-dimethyl-2-(4-morpholinophenyl)pent-4-en-2-ol (9): General procedure **A** was followed using 1-(4-morpholinophenyl)ethan-1-one (205 mg, 1.0 mmol, 1.0 equiv) and isoprene (0.2 mL, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-20% EtOAc/hexanes for 20 CV, then 20-30% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: 3:1) as a white solid (200 mg, 73%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.32 (d, *J* = 8.9 Hz, 2H), 6.88 (d, *J* = 9.0 Hz, 2H), 4.92 (br s, 1H), 4.84 (br s, 1H), 3.86 (t, *J* = 4.7 Hz, 4H), 3.16 (t, *J* = 4.3 Hz, 4H), 2.53 (q, *J* = 7.1 Hz, 1H), 1.98 (br s, 1H), 1.69 (s, 3H), 1.49 (s, 3H), 0.89 (d, *J* = 7.1 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 149.7, 148.3, 139.2, 126.0, 115.2, 113.4, 75.6, 67.1, 51.7, 49.5, 29.5, 22.7, 14.7 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 96:4 er: t_R (major) = 7.78 min, 8.46 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.32 (d, *J* = 8.7 Hz, 2H), 6.88 (d, *J* = 8.3 Hz, 2H), 4.88 (br s, 1H), 4.77 (br s, 1H), 3.86 (t, *J* = 4.7 Hz, 4H), 3.16 (t, *J* = 4.3 Hz, 4H), 2.58 (q, *J* = 7.4 Hz, 1H), 2.24 (br s, 1H), 1.51 (s, 3H), 1.45 (s, 3H), 1.05 (d, *J* = 7.1 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 149.8, 148.6, 139.7, 126.3, 115.1, 113.5, 75.0, 67.1, 51.5, 49.5, 26.6, 23.7, 15.1 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 95.5:4.5 er: t_R (minor) = 7.10 min, 7.55 min.

Properties for mixture of diastereomers:
IR: 3460 (-OH, broad), 2965, 2856, 2821, 1608, 1511, 1450, 1372, 1258, 1116, 922, 820 cm^{-1}. **$[\alpha]_D^{24}$** = +13.5, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{17}H_{25}NO_2+H]^+$: 276.1963. Found: 276.1960. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 3:1 dr. Melting point was not obtained for the inseparable mixture of diastereomers.

Duplicate experiment: Yield: 77%, 213 mg; dr: 3:1; er: 96.5:3.5 (major), 96:4 (minor). Average yield: 75%.



10

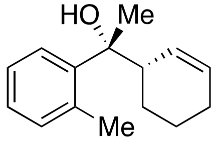
(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-phenylethan-1-ol (10): General procedure **B** was followed using acetophenone (120 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a clear oil (170 mg, 83%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.32~7.35 (m, 2H), 7.24 (t, *J* = 7.7 Hz, 2H), 7.11~7.16 (m, 1H), 5.82 (dq, *J* = 10.2, 3.4 Hz, 1H), 5.68 (dp, *J* = 10.5, 2.1 Hz, 1H), 2.42~2.49 (m, 1H), 1.83~1.87 (m, 2H), 1.75 (s, 1H), 1.58~1.66 (m, 1H), 1.50 (s, 3H), 1.27~1.38 (m, 2H), 1.13~1.22 (m, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 147.3, 131.6, 128.0, 126.5, 126.5, 125.3, 76.1, 46.6, 27.9, 25.3, 24.4, 22.0 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 96.5:3.5 er: t_R (major) = 5.25 min, 6.34 min; t_R (minor)= 4.55 min, 4.85 min.

Properties for mixture of diastereomers:

IR: 3443 (-OH, broad), 3028, 2928, 2856, 1445, 1107, 1062, 699, 659 cm^{-1}. **$[\alpha]_D^{23}$** = +48.2, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{14}H_{18}O\text{-}OH]^+$: 185.1330. Found: 185.1342. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 80%, 160 mg; dr: >20:1; er: 97:3. Average yield: 81.5%.



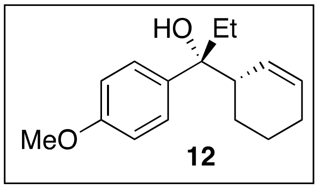
11

(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-(*o*-tolyl)ethan-1-ol (11): General procedure **B** was followed using 1-(o-tolyl)ethan-1-one (134 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system(25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a clear oil (162 mg, 75%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.52~7.57 (m, 1H), 7.13~7.20 (m, 3H), 5.90 ~ 5.95 (m, 1H), 5.64 ~ 5.69 (m, 1H), 2.87~2.93 (m, 1H), 2.52 (s, 3H), 1.96~2.02 (m, 2H), 1.81 (br s, 1H), 1.73~1.80 (m, 1H), 1.65 (s, 3H), 1.30~1.53 (m, 3H) ppm. **^{13}C NMR** (101 MHz, CDCl$_3$) δ: 144.9, 134.8, 132.6, 131.5, 126.9, 126.8, 126.7, 125.6, 77.3, 43.9, 27.2, 25.3, 24.4, 22.8, 22.2 ppm. **SFC** analysis (AD-H column, scCO$_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 95:5 er: t$_R$ (major)= 3.26 min, 3.57 min; t$_R$ (minor) = 3.16 min, 3.74 min.

Properties for mixture of diastereomers:
IR: 3516 (-OH, broad), 3022, 2932, 2839, 1449, 1371, 1267, 1096, 1056, 760, 727, 647 cm^{-1}. **[α]$_D^{23}$** = +26.2, (c = 1.00, CHCl$_3$). **HRMS** Calcd. m/z for [C$_{15}$H$_{20}$O-OH]$^+$: 199.1487. Found: 199.1484. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 73%, 158 mg; dr: >20:1; er: 95:5. Average yield: 74%.



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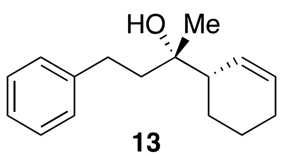
(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-(4-methoxyphenyl)propan-1-ol (12): General procedure **B** was followed using 1-(4-methoxyphenyl)propan-1-one (164 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a clear oil (210 mg, 84%).

Major diastereomer: **^{1}H NMR** (400 MHz, CDCl$_3$) δ: 7.28~7.32 (m, 2H), 6.87~6.91 (m, 2H), 5.89~5.97 (m, 2H), 3.82 (s, 3H), 2.53~2.59 (m, 1H), 1.86~2.07 (m, 4H), 1.69~1.74 (m, 1H), 1.67 (s, 1H), 1.34~1.46 (m, 2H), 1.20~1.30 (m, 1H), 0.74 (t, *J* = 7.4 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, CDCl$_3$) δ: 157.9, 136.6, 131.8, 127.0, 126.6, 113.1, 78.5, 55.2, 46.0, 32.6, 25.3, 24.5, 22.1, 7.9 ppm. **SFC** analysis (AD-H column, scCO$_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 97:3 er: t$_R$ (major) = 6.55 min, 7.92 min; t$_R$ (minor)= 5.73 min, 10.86 min.

Properties for mixture of diastereomers:
IR: 3538 (-OH, broad), 3026, 2929, 2835, 1613, 1511, 1456, 1298, 1246, 1170, 1035, 962, 832, 813, 728, 645 cm^{-1}. **[α]$_D^{24}$** = +36.8, (c = 1.00, CHCl$_3$). **HRMS** Calcd. m/z for [C$_{16}$H$_{22}$O$_2$-OH]$^+$: 229.1592. Found: 229.1591. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 88%, 216 mg; dr: >20:1; er: 98:2. Average yield: 86%.



13

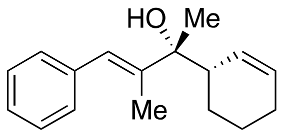
(*S*)-2-((*S*)-cyclohex-2-en-1-yl)-4-phenylbutan-2-ol (13): General procedure **B** was followed using 4-phenylbutan-2-one (148 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: 2:1) as a clear oil (212 mg, 92%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.10 (t, *J* = 7.4 Hz, 2H), 6.98~7.04 (m, 3H), 5.53~5.69 (m, 2H), 2.44~2.60 (m, 2H), 2.11 (m, 1H), 1.79 (m, 2H), 1.55~1.69 (m, 4H), 1.10~1.39 (m, 3H), 1.05 (s, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 142.8, 129.9, 128.5, 128.4, 127.3, 125.8, 74.4, 45.8, 41.0, 30.1, 25.2, 24.9, 24.0, 22.4 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 98.5:1.5 er: t_R (major) = 5.51 min, 6.30 min.

Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.10 (t, *J* = 7.4 Hz, 2H), 6.98~7.04 (m, 3H), 5.53~5.69 (m, 2H), 2.44~2.60 (m, 2H), 2.11 (m, 1H), 1.79 (m, 2H), 1.55~1.69 (m, 4H), 1.10~1.39 (m, 3H), 0.99 (s, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 142.8, 129.7, 128.5, 128.4, 127.4, 125.8, 74.5, 45.2, 42.5, 30.0, 25.2, 24.6, 23.4, 22.4 ppm. SFC analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 99.5:0.5 er: t_R (minor) = 5.38 min, 8.23 min.

Properties for mixture of diastereomers:
IR: 3422 (-OH, broad), 3024, 2934, 2856, 1656, 1452, 1374, 1054, 917, 744, 697, 673 cm^{-1}. **$[\alpha]_D^{24}$** = -6.9, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{16}H_{22}O\text{-}OH]^+$: 213.1643. Found: 213.1637. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 2:1 dr.

Duplicate experiment: Yield: 91%, 210 mg; dr: 2:1. er: 99:1 (major), 99.5:0.5 (minor). Average yield: 91.5%.



14

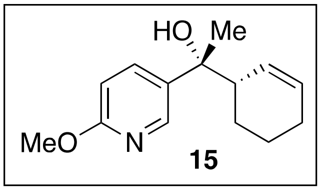
(*R*,*E*)-2-((*S*)-cyclohex-2-en-1-yl)-3-methyl-4-phenylbut-3-en-2-ol (14): General procedure **B** was followed using (*E*)-3-methyl-4-phenylbut-3-en-2-one (160 mg, 1.0

mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a clear oil (160 mg, 67%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.25 (t, *J* = 7.6 Hz, 2H), 7.18 (d, *J* = 7.0 Hz, 2H), 7.10~7.14 (m, 1H), 6.62 (s, 1H), 5.89 (dq, *J* = 10.2, 3.4 Hz, 1H), 5.69~5.73 (m, 1H), 2.41 (ddt, *J* = 8.4, 5.5, 2.7 Hz, 1H), 1.93 (dt, *J* = 7.2, 3.4 Hz, 2H), 1.76 (br s, 1H), 1.72~1.78 (m, 3H), 1.53~1.59 (m, 2H), 1.37 (s, 3H), 1.31~1.48 (m, 2H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 142.2, 138.7, 131.8, 129.2, 128.1, 126.5, 126.2, 124.0, 77.2, 42.5, 25.8, 25.3, 24.1, 22.2, 14.8 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 96:4 er: t_R (major) = 5.36 min, 5.54 min; t_R (minor) = 4.45 min, 6.11 min.

Properties for mixture of diastereomers:
IR: 3472 (-OH, broad), 3017, 2929, 2865, 2837, 1445, 1366, 1094, 917, 876, 772, 741, 722, 696 cm^{-1}. **$[\alpha]_D^{23}$** = +29.8, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{17}H_{22}O\text{-}OH]^+$: 225.1643. Found: 225.1633. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 72%, 175 mg; dr: >20:1; er: 96:4. Average yield: 69.5%.



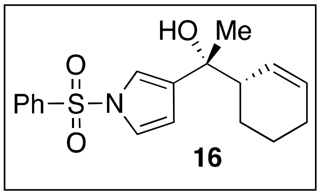
15

(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-(6-methoxypyridin-3-yl)ethan-1-ol (15): General procedure **B** was followed using 1-(6-methoxypyridin-3-yl)ethan-1-one (151 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-16% EtOAc/hexanes for 16 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a white solid (190 mg, 82%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 8.11 (d, *J* = 2.0 Hz, 1H), 7.60 (dd, *J* = 8.6, 2.6 Hz, 1H), 6.64 (d, *J* = 8.9 Hz, 1H), 5.79~5.84 (m, 1H), 5.67 (dt, *J* = 10.2, 1.9 Hz, 1H), 3.86 (s, 3H), 2.38~2.45 (m, 1H), 2.19 (s, 1H), 1.83~1.90 (m, 2H), 1.62~1.69 (m, 1H), 1.52 (s, 3H), 1.32~1.52 (m, 2H), 1.15~1.24 (m, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 162.9, 144.0, 136.6, 135.1, 131.4, 126.2, 109.8, 74.8, 53.4, 46.8, 27.4, 25.1, 24.4, 21.9 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 97:3 er: t_R (major) = 5.28 min, 7.36 min.

Properties for mixture of diastereomers:
IR: 3408 (-OH, broad), 3022, 2934, 2830, 1601, 1499, 1376, 1282, 1125, 1026, 825, 758, 652, 609 cm^{-1}. **$[\alpha]_D^{24}$** = +38.9, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{14}H_{19}NO_2+H]^+$: 234.1494. Found: 234.1482. ^1H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr. Melting point was not obtained for the inseparable mixture of diastereomers.

Duplicate experiment: Yield: 81%, 189 mg; dr: >20:1; er: 97:3. Average yield: 81.5%.



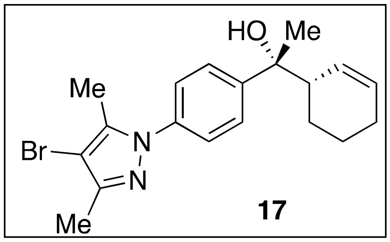
16

(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-(1-(phenylsulfonyl)-1H-pyrrol-3-yl)ethan-1-ol (16): General procedure **B** was followed using 1-(1-(phenylsulfonyl)-1H-pyrrol-3-yl)ethan-1-one (249 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-20% EtOAc/hexanes for 20 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a white solid (300 mg, 90%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.66 (d, *J* = 7.1 Hz, 2H), 7.41 (t, *J* = 7.4 Hz, 1H), 7.30 (t, *J* = 7.7 Hz, 2H), 6.90~6.93 (m, 2H), 6.09 (dd, *J* = 3.3, 1.7 Hz, 1H), 5.58 (dq, *J* = 7.7, 2.4 Hz, 1H), 5.42~5.45 (m, 1H), 2.17~2.24 (m, 1H), 1.85 (s, 1H), 1.60~1.77 (m, 2H), 1.42~1.55 (m, 2H), 1.26 (s, 3H), 1.19~1.30 (m, 1H), 0.97~1.10 (m, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 138.9, 136.1, 133.7, 130.2, 129.3, 126.8, 126.6, 120.9, 117.2, 112.8, 73.4, 46.2, 26.4, 25.0, 24.2, 21.9 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 97.5:2.5 er: t_R (major) = 5.44 min, 6.70 min; t_R (minor) = 6.00 min, 6.09 min.

Properties for mixture of diastereomers:
IR: 3559 (-OH, broad), 3135, 3022, 2927, 2861, 1473, 1445, 1369, 1175, 1096, 1056, 791, 720, 682, 625 cm^{-1}. **$[\alpha]_D^{23}$** = +7.0, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{18}H_{21}NO_3S\text{-}OH]^+$: 314.1215. Found: 314.1216. ^1H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr. Melting point was not obtained for the inseparable mixture of diastereomers.

Duplicate experiment: Yield: 91%, 301 mg; dr: >20:1; er: 97:3. Average yield: 90.5%.



17

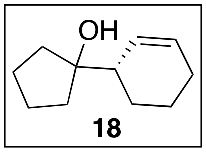
(*R*)-1-(4-(4-bromo-3,5-dimethyl-1H-pyrazol-1-yl)phenyl)-1-((*S*)-cyclohex-2-en-1-yl)ethan-1-ol (17): General procedure **B** was followed using 1-(4-(4-bromo-3,5-dimethyl-1H-pyrazol-1-yl)phenyl)ethan-1-one (293 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-25% EtOAc/hexanes for 20 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a white solid (180 mg, 48%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.49~7.52 (m, 2H), 7.33~7.37 (m, 2H), 5.91~5.96 (m, 1H), 5.76~5.81 (m, 1H), 2.51~2.58 (m, 1H), 2.30 (s, 3H), 2.29 (s, 3H), 1.92~1.97 (m, 2H), 1.66~1.84 (m, 2H), 1.61 (s, 3H), 1.36~1.47 (m, 2H), 1.20~1.30 (m, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 147.5, 146.9, 138.1, 137.5, 132.2, 126.1, 125.9, 124.1, 96.2, 75.9, 46.6, 28.1, 25.1, 24.3, 21.8, 12.4, 11.8 ppm. **SFC** analysis (CEL-2 column, $scCO_2$/MeOH = 96/4, 2.5 mL/min, add 0.1% diethylamine) indicated a 94.5:5.5 er: t_R = 8.13 min, 8.91 min.

Properties for mixture of diastereomers:

IR: 3396 (-OH, broad), 3033, 2922, 2861, 1544, 1516, 1407, 1359, 1262, 1087, 1014, 841, 722 cm^{-1}. **$[\alpha]_D^{23}$** = +33.2, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{19}H_{23}BrN_2O+H]^+$: 375.1072. Found: 375.1057. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr. Melting point was not obtained for the inseparable mixture of diastereomers.

Duplicate experiment: Yield: 43%, 161 mg; dr: >20:1; er: 93.5:6.5; Average yield: 45%.



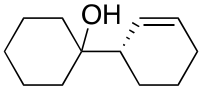
18

(*S*)-1-(cyclohex-2-en-1-yl)cyclopentan-1-ol (18): General procedure **B** was followed using cyclopentanone (84.1 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-10%

EtOAc/hexanes for 15 CV) to afford the title compound as a clear oil (90% yield determined by ^{1}H NMR using dibromomethane as an internal standard due to low boiling point of product).

^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.89 (dq, *J* = 10.3, 3.4 Hz, 1H), 5.66~5.69 (m, 1H), 2.18~2.24 (m, 1H), 1.98 (m, 2H), 1.77~1.85 (m, 4H), 1.46~1.68 (m, 8H), 1.22 (br s, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 131.1, 128.0, 84.5, 45.7, 38.9, 37.6, 25.3, 24.7, 24.0 (2C), 22.2 ppm. **IR**: 3429 (-OH, broad), 3026, 3022, 2932, 2861, 2835, 1447, 1269, 1099, 992, 888, 767, 720 cm^{-1}. **$[\alpha]_D^{21}$** = -19.7, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{11}H_{18}O\text{-}OH]^+$: 149.1330. Found: 149.1326. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 97:3 er: t_R = 4.12 min, 4.46 min.

Duplicate experiment: NMR yield: 94%; er: 98.5:1.5. Average NMR yield: 92%.

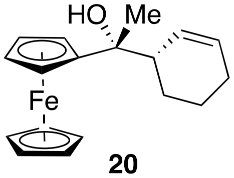


19

(*S*)-[1,1'-bi(cyclohexan)]-2'-en-1-ol (19): General procedure **B** was followed using cyclohexanone (98.2 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-10% EtOAc/hexanes for 15 CV) to afford the title compound as a clear oil (89% yield determined by ^{1}H NMR with dibromomethane as an internal standard due to low boiling point of product).

^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.85 (dq, *J* = 10.3, 3.4 Hz, 1H), 5.73~5.75 (m, 1H), 2.13~2.19 (m, 1H), 1.94~1.99 (m, 2H), 1.76~1.85 (m, 2H), 1.34~1.64 (m, 11H), 1.13~1.27 (m, 2H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 130.3, 127.1, 73.2, 45.7, 35.3, 33.9, 26.0, 25.3, 23.5, 22.4, 22.1 ppm. **IR**: 3445 (-OH, broad), 3026, 2931, 2858, 1443, 1347, 1267, 1147, 961, 886, 765, 743, 720, 680 cm^{-1}. **$[\alpha]_D^{23}$** = -16.4, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{12}H_{20}O\text{-}OH]^+$: 163.1487. Found: 163.1485. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 99:1 er: t_R = 5.50 min, 6.37 min.

Duplicate experiment: NMR yield: 92%; er: 98:2. Average NMR yield: 91%.



20

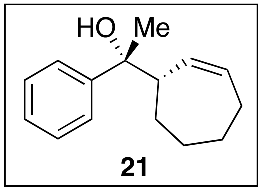
(*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-ferroceneethan-1-ol (20): The general procedure **B** was followed using acetylferrocene (228 mg, 1.0 mmol, 1.0 equiv) and cyclohexa-1,3-diene (160 mg, 2.0 mmol, 2.0 equiv) but THF (1 mL) was used to dissolve the ketone instead of toluene. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-10% EtOAc/hexanes for 15 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a brown oil (293 mg, 94%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 5.65 (dddd, *J* = 10.1, 5.4, 3.0, 0.9 Hz, 1H), 5.49 (dp, *J* = 10.4, 2.1 Hz, 1H), 4.27 (dt, *J* = 2.5, 1.2 Hz, 1H), 4.21~4.24 (m, 2H), 4.23 (s, 3H), 4.18 (td, *J* = 2.4, 1.2 Hz, 1H), 4.15 (td, *J* = 2.4, 1.1 Hz, 1H), 4.08 (dt, *J* = 2.5, 1.3 Hz, 1H), 2.27~2.33 (m, 1H), 2.25 (br s, 1H), 1.79~1.90 (m, 3H), 1.67~1.75 (m, 1H), 1.48 (s, 3H), 1.39~1.50 (m, 1H), 1.23~1.33 (m, 1H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 128.7, 128.0, 99.1, 73.2, 68.6, 68.4, 68.0, 67.6, 65.7, 47.2, 25.4, 25.2, 24.8, 22.2 ppm. **HPLC** analysis (IC column, Hexane/IPA = 98.5/1.5, 0.8 mL/min) indicated a 96:4 er: t_R = 8.52 min, 9.52 min.

Properties for mixture of diastereomers:

IR: 3561 (-OH, broad), 3088, 3024, 2927, 2858, 1449, 1364, 1314, 1106, 1023, 999, 919, 812, 727, 668 cm^{-1}. **$[\alpha]_D^{23}$** = -96.4, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{18}H_{22}FeO-OH]^+$: 293.0987. Found: 293.0989. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 93%, 288 mg; dr: >20:1; er: 96:4. Average yield: 93.5%.



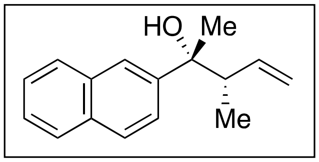
21

(*R*)-1-((*S*)-cyclohept-2-en-1-yl)-1-phenylethan-1-ol (21): General procedure **B** was followed using acetophenone (120 mg, 1.0 mmol, 1.0 equiv) and cyclohepta-1,3-diene (188 mg, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-15% EtOAc/hexanes for 15 CV, then 15-20% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: >20:1) as a clear oil (110 mg, 51%).

Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.29 (d, *J* = 7.5 Hz, 2H), 7.17 (d, *J* = 7.7 Hz, 2H), 7.05~7.09 (m, 1H), 5.59~5.69 (m, 2H), 2.55~2.58 (m, 1H), 1.89~2.02 (m, 2H), 1.74~1.82 (m, 1H), 1.65 (br s, 1H), 1.45~1.55 (m, 2H), 1.37 (s, 3H), 1.27~1.39 (m, 1H), 0.94~1.13 (m, 2H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 147.9, 133.5, 132.2, 128.2, 126.7, 125.4, 77.0, 50.5, 31.1, 28.3, 28.2, 27.1, 26.4 ppm. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 98:2 er: t_R = 4.99 min, 6.52 min.

Properties for mixture of diastereomers:
IR: 3455 (-OH, broad), 3022, 2920, 2849, 1495, 1447, 1374, 1113, 1057, 1024, 884, 768, 697, 647 cm^{-1}. **[α]$_D$^{24}** = +21.9, (c = 1.00, $CHCl_3$). **Anal. Calcd.** For $C_{15}H_{20}O$: C, 83.28; H, 9.32. Found: C, 83.52; H, 9.24. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated >20:1 dr.

Duplicate experiment: Yield: 53%, 114 mg; dr: >20:1; er: 98:2. Average yield: 52%.



(2*R*,3*S*)-3-methyl-2-(naphthalen-2-yl)pent-4-en-2-ol: General procedure **A** was followed using 1-(naphthalen-2-yl)ethan-1-one (170 mg, 1.0 mmol, 1.0 equiv) and buta-1,3-diene (1.2 mL, 15% in hexane, 2.0 mmol, 2.0 equiv). The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 column volumes (CV), then 2-5% EtOAc/hexanes for 15 CV, then 5-10% EtOAc/hexanes for 5 CV) to afford the title compound (as a mixture of diastereomers, dr: 2.5:1) as a clear oil (216 mg, 95%).

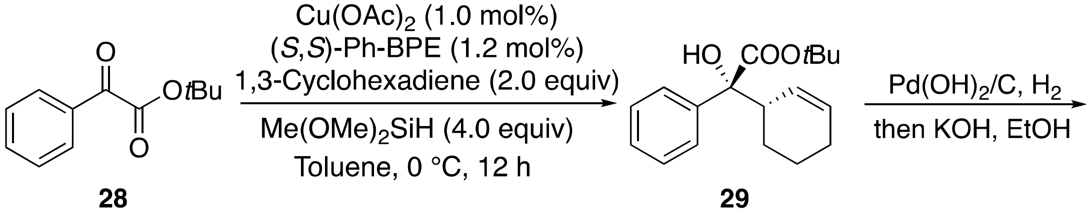
Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.82~7.88 (m, 4H), 7.45~7.52 (m, 3H), 5.86~5.95 (m, 1H), 5.10~5.18 (m, 2H), 2.69 (m, 1H), 2.02 (br s, 1H), 1.64 (s, 3H), 0.91 (d, *J* = 6.9 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 144.6, 139.9, 133.2, 132.3, 128.3, 127.7, 127.6, 126.1, 125.8, 124.0, 123.9, 116.6, 76.1, 48.8, 28.8, 14.9 ppm. **HPLC** analysis (IC column, Hexane/IPA = 98.5/1.5, 0.8 mL/min) indicated a 93:7 er: t_R (major)= 8.23 min, 10.17 min.

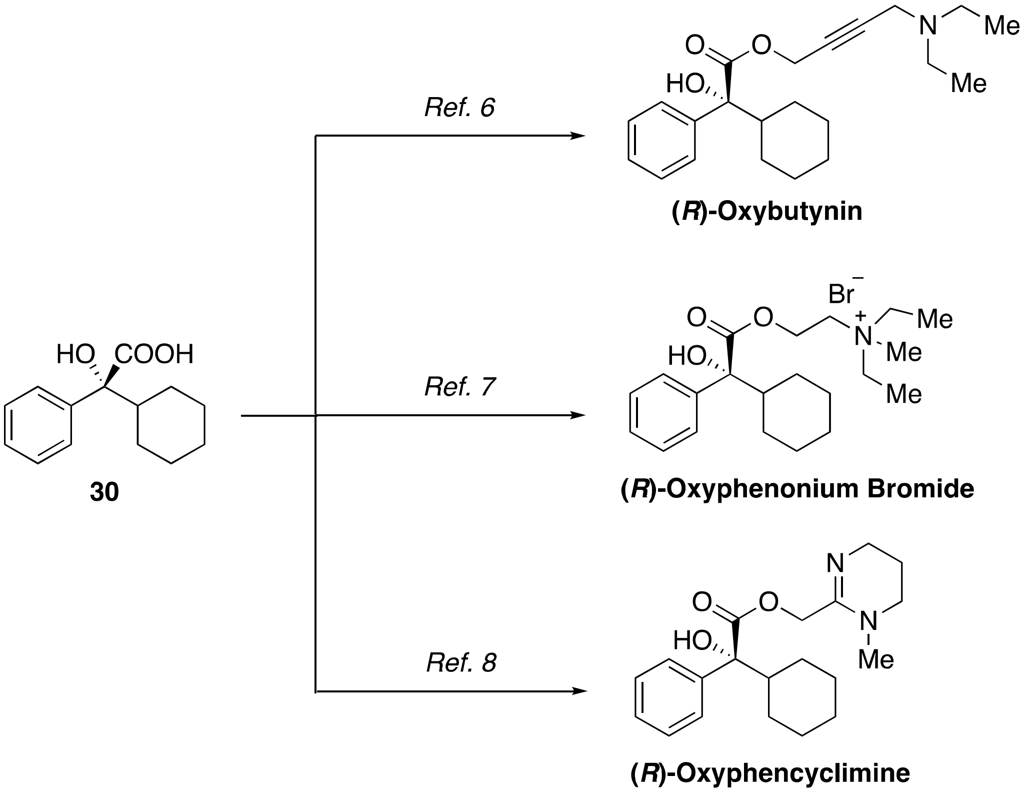
Minor diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.87~7.92 (m, 4H), 7.51~7.60 (m, 3H), 5.71~5.81 (m, 1H), 5.05~5.15 (m, 2H), 2.75 (m, 1H), 2.02 (br s, 1H), 1.65 (s, 3H), 1.04 (d, *J* = 6.8 Hz, 3H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 144.7, 140.0, 133.2, 132.4, 128.3, 127.7, 127.6, 126.1, 125.8, 124.2, 124.1, 116.9, 76.0, 48.6, 26.1, 14.2 ppm. HPLC analysis (IC column, Hexane/IPA = 98.5/1.5, 0.8 mL/min) indicated a 90.5:9.5 er: t_R (major)= 9.87 min, 12.01 min.

Properties for mixture of diastereomers:
IR: 3481 (-OH, broad), 3062, 2974, 1634, 1601, 1501, 1449, 1369, 1272, 1125, 907, 855, 817, 744 cm^{-1}. **[α]$_D$^{23}** = +22.6, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{16}H_{18}O\text{-}OH]^+$: 206.1325. Found: 206.1327. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 2.5:1 dr.

Duplicate experiment: Yield: 95%, 216 mg; dr: 2.5:1; er: 93:7 (major), 90.5:9.5 (minor). Average yield: 95%.

V. Synthesis of (*R*)-Procyclidine and a Key Tertiary α-Hydroxy Acid Intermediate





Procedure A (Stepwise synthesis): *tert*-Butyl (*R*)-2-((*S*)-cyclohex-2-en-1-yl)-2-hydroxy-2-phenylacetate (29): In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube equipped with a stir bar was charged with Cu(OAc)$_2$ (1.8 mg, 0.01 mmol, 1.0 mol %) and (*S*,*S*)-Ph-BPE (6.2 mg, 0.012 mmol, 1.2 mol %), followed by the addition of toluene (0.3 mL) via syringe. The reaction mixture was stirred at room temperature for 1 min before the addition of DMMS (490 µL, 4.0 mmol, 4.0 equiv) and cyclohexa-1,3-diene (190 µL, 2.0 mmol, 2.0 equiv) via syringe. The reaction vessel was then capped and removed from the glove box. The sides and top of the cap were sealed using Parafilm. The reaction tube partially submerged in an ice bath, and tert-butyl 2-oxo-2-phenylacetate[2] (206 mg, 1.0 mmol, 1.0 equiv) dissolved in toluene (1.0 mL) was slowly added via syringe pump (1.0 mol/L, 7.5 uL/min). Then, the reaction mixture was stirred at 0 °C for an additional 12 h. After the reaction was complete as judged by GC-MS, the cap was removed and a saturated solution of NH_4F in MeOH (ca. 5.0 mL) was carefully added to quench the reaction (Caution: hydrogen gas evolution was observed). The reaction mixture was allowed to stir for 30 min at room temperature, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at room temperature, and then filtered through a short plug of Celite (2.0 cm), eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 7:1 dr and a 74% combined yield for the two diastereomers. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% EtOAc/hexanes for 3 CV, then 2-9% EtOAc/hexanes for 30 CV) to afford the title compound **29** as a clear oil (180 mg, 62% yield for the major diastereomer). **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.62~7.66 (m, 2H), 7.32~7.36 (m, 2H), 7.27 (tt, *J* = 6.4, 1.3 Hz, 1H), 5.92 (dddt, *J* = 10.0, 5.5, 2.6, 1.4 Hz, 1H), 5.49 (dqd, *J* = 10.2, 2.1, 1.1 Hz, 1H), 3.65 (s, 1H), 3.11 (ddt, *J* = 8.7, 5.9, 3.0 Hz, 1H), 1.97~2.03 (m, 2H), 1.68~1.77 (m, 1H), 1.47 (s, 9H), 1.40~1.46 (m, 1H), 1.24~1.36 (m, 2H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 174.4, 140.8, 131.2, 128.1, 127.4, 126.9, 126.1, 83.5, 80.3, 43.9, 28.0, 25.2, 23.1, 22.0 ppm. **IR**: 3512 (-OH, broad), 3019, 2977, 2934, 1714, 1449, 1371, 1267, 1158, 1127, 1073, 841, 748, 694 cm^{-1}. **$[\alpha]_D^{26}$** = -25.3, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{18}H_{24}O_3\text{-O}t\text{Bu}]^+$: 215.1072. Found: 215.1072. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min) indicated a 95:5 er: t_R = 2.35 min, 2.54 min.

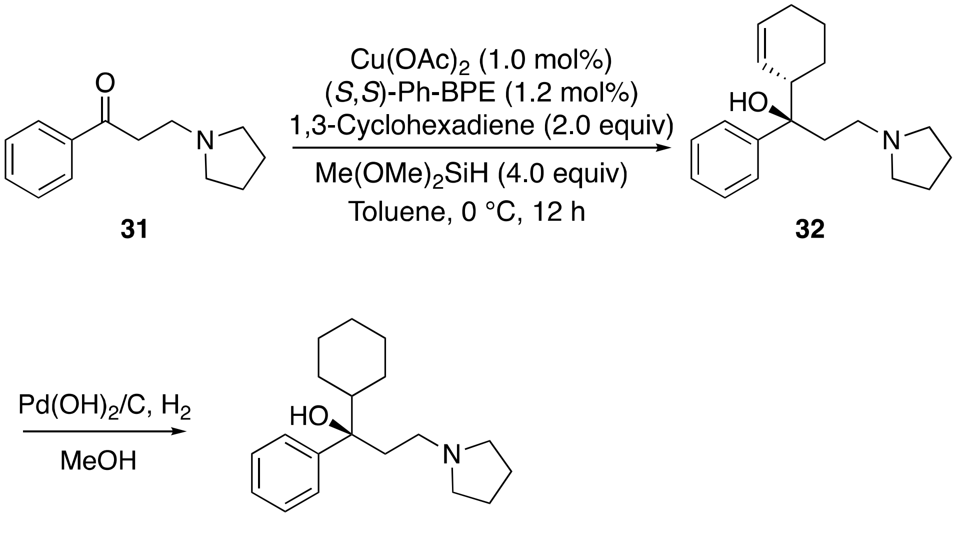
(*R*)-2-cyclohexyl-2-hydroxy-2-phenylacetic acid (30)[3]**:** A 50 mL round bottom flask, which was equipped with a magnetic stir bar, was charged with compound **29** (180 mg, 0.62 mmol) by first transferring a solution of this compound in methanol (ca. 5 mL), then removing the solvent in vacuo with the aid of a rotary evaporator. The reaction vessel was then evacuated and backfilled with dry nitrogen for a total of three times by using a needle connected to a Schlenk line. Next, 20% $Pd(OH)_2/C$ (62 mg, 15 mol %) was transferred into the reaction flask by temporarily removing the septum (Caution: dry $Pd(OH)_2/C$ can cause fires in a laboratory environment).[4] Methanol (2.0 mL) was added carefully down the side of the flask wall using a plastic syringe. While the reaction mixture was stirring, the flask was briefly evacuated by using a needle connected to a Schlenk line until the solvent began to bubble. The Schlenk line was closed to vacuum, and the flask was then carefully backfilled with hydrogen using a needle connected to a hydrogen-filled balloon. This evacuation-refill cycle was repeated a total of three times. The reaction mixture was stirred for 4 h at 40 °C by partially submerging the flask into a heated oil bath. Then, the reaction mixture was cooled to rt, and the septum was removed slowly and carefully. Using a gentle stream of nitrogen directed into the flask, the hydrogen in the headspace was displaced. (Caution: as detailed in ref. 4b, ensure that hydrogen is fully removed by carefully bubbling nitrogen through the solution. This will reduce the risk of fire during the subsequent filtration). After 5 min, the mixture was poured onto a plug of Celite and filtered to remove $Pd(OH)_2/C$. The Celite pad was washed with additional EtOAc (ca. 20 mL). (Caution: during the filtration, solvent should be continuously added so that the Celite and other solids do not fully dry. The $Pd(OH)_2/C$ at the top of the filter cake may ignite if not continuously covered with solvent. After the filtration is complete, the wet filter cake should be carefully transferred to a labelled waste bottle containing water).[4] In a 50 mL round bottom flask, equipped with a magnetic stir bar, this crude material was dissolved in ethanol (10 mL), followed by the addition of KOH (186 mg). The flask was fitted with a reflux condenser, and the reaction mixture was heated to vigorous reflux by partially submerging the vial in a heated oil bath and stirred for 12 h. After cooling to room temperature, the solvent was removed in vacuo with the aid of a rotary evaporator. Water (20 mL) was added to dissolve the solid. The mixture was acidified to pH = 1 by addition of 1 M HCl and extracted with ethyl acetate (20 mL, five times). The combined organic layers were dried over Na_2SO_4 and concentrated in vacuo to give the crude product. The obtained crude product was recrystallized from hexane/CH_2Cl_2 (95/5) to give 2-cyclohexyl-2-hydroxy-2-phenylacetic acid **30** as a white solid (120 mg, 82%). **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.63 (d, J = 7.7 Hz, 2H), 7.34(t, J = 7.5 Hz, 2H), 7.25~7.29 (m, 1H), 2.24~2.29 (m, 1H), 1.81 (d, J = 11.8 Hz, 1H), 1.59~1.67 (m, 3H), 0.99~1.48 (m, 6H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 180.3, 140.1, 128.4, 127.9, 126.1, 81.3, 45.9, 27.6, 26.4 (2C), 26.3, 25.6 ppm. **IR**: 3510 (-OH, broad), 2930, 2851, 1703, 1447, 1338, 1265, 1234, 1168, 1113, 900, 729, 697 cm^{-1}. **$[\alpha]_D^{27}$** = -22.7, (c = 1.00, EtOH) (lit.[5] $[\alpha]_D^{28}$ = -23.6, (c = 1.40, EtOH)). **M.P.** = 136-138 °C. **HRMS** Calcd. m/z for $[C_{14}H_{18}O_3\text{-}OH]^+$: 217.1229. Found: 217.1230. **SFC** analysis (AD-H column, $scCO_2$/Isopropanol = 95/5 to 60/40, 2.5 mL/min) indicated a >99.5:0.5 er: t_R = 5,84 min, 6.12 min.

Procedure B (One pot synthesis): (*R*)-2-cyclohexyl-2-hydroxy-2-phenylacetic acid (30): In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube equipped with a stir bar was charged with $Cu(OAc)_2$ (1.8 mg, 0.01 mmol, 1.0 mol %) and (*S*,*S*)-Ph-BPE (6.2 mg, 0.012 mmol, 1.2 mol %), followed by the addition of toluene (0.3 mL) via syringe. The reaction mixture was stirred at room temperature for 1 min before the addition of DMMS (490 μL, 4.0 mmol, 4.0 equiv) and cyclohexa-1,3-diene (190 μL, 2.0 mmol, 2.0 equiv) via syringe. The reaction vessel was then capped and removed from the glove box. The sides and top of the cap were sealed using Parafilm. The reaction tube was partially submerged in an ice bath, and *tert*-butyl 2-oxo-2-phenylacetate (206 mg, 1.0 mmol, 1.0 equiv), dissolved in toluene (1.0 mL), was slowly added via syringe pump (1.0 mol/L, 4.0 uL/min). Then, the reaction mixture was stirred at 0 °C for an additional 12 h. After removing the cap, a saturated solution of NH_4F in MeOH (ca. 5.0 mL) was carefully added to quench the reaction (Caution: hydrogen gas evolution was observed). The reaction mixture was allowed to stir for 30 min at room temperature, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at room temperature, and then filtered through a short plug of Celite (2.0 cm), eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 7:1 dr and 86% combined yield (of the diastereomers). NaOH solution (6M, 5 mL) was added and the mixture was stirred at rt for 1 h. Next, the resulting mixture was extracted with ethyl acetate (20 mL, three times). The organic layer was washed with brine, dried over Na_2SO_4 and concentrated in vacuo. The crude compound **29** was obtained as a clear oil.

A 50 mL round bottom flask, which was equipped with a magnetic stir bar, was charged with compound **29** by transferring a solution of this compound in methanol (ca. 5 mL), then removing the solvent in vacuo with the aid of a rotary evaporator. The reaction vessel was then evacuated and backfilled with dry nitrogen for a total of three times by using a needle connected to a Schlenk line. Next, 20% $Pd(OH)_2/C$ (100 mg, 15 mol %) was transferred into the reaction flask by temporarily removing the septum (Caution: dry $Pd(OH)_2/C$ can cause fires in a laboratory environment).[4] Methanol (2.0 mL) was added carefully down the side of the flask wall using a plastic syringe. While the reaction mixture was stirring, the flask was briefly evacuated by using a needle connected to a Schlenk line until the solvent began to bubble. The Schlenk line was closed to vacuum, and the flask was then carefully backfilled with hydrogen using a needle connected to a hydrogen-filled balloon. This evacuation-refill cycle was repeated a total of three times. The reaction mixture was stirred for 4 h at 40 °C by partially submerging the flask into a heated oil bath. Then, the reaction mixture was cooled to rt, and the septum was removed slowly and carefully. Using a gentle stream of nitrogen directed into the flask, the hydrogen in the headspace was displaced. (Caution: as detailed in ref. 4b, ensure that hydrogen is fully removed by carefully bubbling nitrogen through the solution. This will reduce the risk of fire during the subsequent filtration). After 5 min, the mixture was poured onto a plug of Celite and filtered to remove $Pd(OH)_2/C$. The Celite pad was washed with additional EtOAc (ca. 20 mL). (Caution: during the filtration, solvent should be continuously added so that the Celite and other solids do not fully dry. The $Pd(OH)_2/C$ at the top of the filter cake may ignite if not continuously covered with solvent. After the filtration is complete, the wet filter cake should be carefully transferred to a labelled waste bottle containing water).[4] This material was used in the next step with no further purification.

In a 50 mL round bottom flask, equipped with a magnetic stir bar, this crude mixture was dissolved in ethanol (10 mL), and KOH was added (300 mg). The flask was fitted with a reflux condenser, and the reaction mixture was heated to vigorous reflux by partial submersion in a heated oil bath and stirred for 12 h. After cooling to rt, the solvent was removed in vacuo. water (20 mL) was added to dissolve the solid, and the resulting mixture was extracted with diethyl ether (20 mL, three times). The combined organic layers were then extracted with water (20 mL, three times), and all aqueous phases were combined. The aqueous mixture was acidified to pH = 1 by addition of 1 M HCl and extracted with ethyl acetate (20 mL, five times). The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated in vacuo. The crude product obtained in this manner was recrystallized from hexane/CH_2Cl_2 (95/5) to give 2-cyclohexyl-2-hydroxy-2-phenylacetic acid **30** as a white solid (121 mg, 52%). **SFC** analysis (AD-H column, $scCO_2$/Isopropanol = 95/5 to 60/40, 2.5 mL/min) indicated an er of (90:10)[9] (before recrystallization) and 99:1 (after recrystallization) er: t_R = 5.84 min, 6.12 min. **M.P.** = 136-138 ºC.

Duplicate experiment: Overall yield: 54%, 126 mg; er: >99.5:0.5. Average yield: 53%.



33 (*R*)-Procyclidine

Procedure A (Stepwise synthesis): (*R*)-1-((*S*)-cyclohex-2-en-1-yl)-1-phenyl-3-(pyrrolidin-1-yl)propan-1-ol (32): In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube equipped with a stir bar was charged with $Cu(OAc)_2$ (1.8 mg, 0.01 mmol, 1.0 mol %) and (*S*,*S*)-Ph-BPE (6.1 mg, 0.012 mmol, 1.2 mol %), followed by the addition of toluene (0.3 mL) via syringe. The reaction mixture was stirred at rt for 1 min before the addition of DMMS (490 µL, 4.0 mmol, 4.0 equiv) and cyclohexa-1,3-diene (190 µL, 2.0 mmol, 2.0 equiv) via syringe. The reaction vessel was then capped and removed from the glove box. The sides and top of the cap were sealed using Parafilm. The reaction tube partially submerged in an ice bath, and 1-phenyl-3-(pyrrolidin-1-yl)propan-1-one[10] (203 mg, 1.0 mmol, 1.0 equiv) dissolved in toluene (1.0 mL) was added slowly via syringe pump (1.0 mol/L, 7.5 uL/min). The reaction tube was stirred at 0 °C for an additional 12 h. After the reaction was complete as judged by GC-MS, the cap was removed and a saturated solution of NH_4F in MeOH (ca. 5.0 mL) was carefully added to quench the reaction (Caution: hydrogen gas evolution was observed). The reaction mixture was allowed to stir for 30 min at rt, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at rt, and then filtered through a short plug of Celite (2.0 cm) eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated product with a 20:1 dr had been formed. The crude reaction mixture was purified with the aid of a Biotage Isolera system (25 g SNAP cartridge, 2% MeOH/EtOAc for 3 CV, then 2-10% MeOH/EtOAc for 20 CV, then 10-20% MeOH/EtOAc 20 CV, then 20-50% MeOH/EtOAc 10 CV) to afford the title compound **32** (as a mixture of diastereomers, dr: 20:1) as a clear oil (210 mg, 74%). Major diastereomer: **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.42 (d, *J* = 7.6 Hz, 2H), 7.32 (t, *J* = 7.6 Hz, 2H), 7.21 (t, *J* = 7.3 Hz, 1H), 5.98~6.01 (m, 1H), 5.80~5.84 (m, 1H), 2.59~2.66 (m, 3H), 2.38~2.46 (m, 2H), 2.27~2.34 (m, 3H), 1.83~1,96 (m, 3H), 1.64~1.76 (m, 5H), 1.34~1.43 (m, 1H), 1.19~1.30 (m, 2H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 146.6, 129.5, 127.9, 127.8, 126.2, 126.0, 79.7, 54.0, 52.6, 46.8, 34.8, 25.4, 24.4, 23.6, 22.6 ppm. Properties for mixture of diastereomers: **IR**: 3209 (-OH, broad), 3024, 2934, 2808, 1442, 1267, 1134, 1061, 917, 886, 755, 725, 696, 613 cm^{-1}. **$[\alpha]_D^{23}$** = -31.4, (c = 1.00, $CHCl_3$). **HRMS** Calcd. m/z for $[C_{19}H_{27}NO+H]^+$: 286.2171. Found: 286.2158. **SFC** analysis (AD-H column, $scCO_2$/MeOH = 95/5, 2.5 mL/min, add 0.1% diethylamine) indicated a >99.5:0.5 er: t_R = 18.42 min, 20.20 min.

(*R*)-Procyclidine (33): A 50 mL round bottom flask, which was equipped with a magnetic stir bar, was charged with compound **32** (210 mg, 0.74 mmol, as a mixture of diastereomers, dr: 20:1) by transferring a solution of this compound in methanol (ca. 5 mL), then removing the solvent in vacuo with the aid of a rotary evaporator. The reaction vessel was then capped with a septum, evacuated, and backfilled with dry nitrogen for a total of three times by using a needle connected to a Schlenk line. Next, 20% $Pd(OH)_2/C$ (74 mg, 15 mol %) was transferred into the reaction flask by temporarily removing the septum (Caution: dry $Pd(OH)_2/C$ can cause fires in a laboratory environment).[4] Methanol (2.0 mL) was added carefully down the side of the flask wall using a plastic syringe. While the reaction mixture was stirring, the flask was briefly evacuated by using a needle connected to a Schlenk line until the solvent began to bubble. The Schlenk line was closed to vacuum, and the flask was then carefully backfilled with hydrogen using a needle connected to a hydrogen-filled balloon. This evacuation-refill cycle was repeated a total of three times. The reaction mixture was stirred for 4 h at 40 °C by partially submerging the flask into a heated oil bath. Then, the reaction mixture was cooled to rt, and the septum was removed slowly and carefully. Using a gentle stream of nitrogen directed into the flask, the hydrogen in the headspace was displaced. (Caution: as detailed in ref. 4b, ensure that hydrogen is fully removed by carefully bubbling nitrogen through the solution. This will reduce the risk of fire during the subsequent filtration). After 5 min, the mixture was poured onto a plug of Celite and filtered to remove $Pd(OH)_2/C$. The Celite pad was washed with additional EtOAc (ca. 20 mL). (Caution: during the filtration, solvent should be continuously added so that the Celite and other solids do not fully dry. The $Pd(OH)_2/C$ at the top of the filter cake may ignite if not continuously covered with solvent. After the filtration is complete, the wet filter cake should be carefully transferred to a labelled waste bottle containing water).[4] The title compound **33** was obtained as a white solid (203 mg, 96%). **^{1}H NMR** (400 MHz, $CDCl_3$) δ: 7.40 (d, *J* = 7.7 Hz, 2H), 7.31 (t, *J* = 7.6 Hz, 2H), 7.20 (t, *J* = 7.3 Hz, 1H), 2.53~2.62 (m, 3H), 2.19~2.30 (m, 4H), 1.95~1.99 (m, 1H), 1.72~1.83 (m, 6H), 1.52~1.65 (m, 3H), 1.17~1.33 (m, 3H), 0.95~1.14 (m, 4H) ppm. **^{13}C NMR** (101 MHz, $CDCl_3$) δ: 147.2, 127.7, 126.4, 125.9, 80.2, 53.9, 52.7, 49.2, 34.7, 27.3, 27.0, 26.9, 26.9, 26.7, 23.6 ppm. **IR**: 3209 (-OH, broad), 2932, 2844, 2804, 1490, 1447, 1132, 1059, 760, 699 cm^{-1}. **$[\alpha]_D^{23}$** = -37.8, (c = 0.30, CH_3Cl). **M.P.** = 105-107 ºC. **HRMS** Calcd. m/z for $[C_{19}H_{29}NO+H]^+$: 288.2327. Found: 288.2333. **SFC** analysis (CEL-2 column, $scCO_2$/MeOH = 95/5 to 65/35 (0 to 6 min), then 65/35 (6 to 7 min), 2.5 mL/min, add 0.1% diethylamine) indicated a 95:5 er:[9] t_R = 2.74 min, 2.99 min.

Procedure B (One pot synthesis): (*R*)-Procyclidine (33): In a nitrogen-filled glove box, an oven-dried screw-cap reaction tube equipped with a stir bar was charged with $Cu(OAc)_2$ (1.8 mg, 0.01 mmol, 1.0 mol %) and (*S*,*S*)-Ph-BPE (6.1 mg, 0.012 mmol, 1.2 mol %), followed by the addition of toluene (0.3 mL) *via* syringe. The reaction mixture was stirred at rt for 1 min before the addition of DMMS (490 μL, 4.0 mmol, 4.0 equiv) and cyclohexa-1,3-diene (190 μL, 2.0 mmol, 2.0 equiv). The reaction vessel was then capped and removed from the glove box. The sides and top of the cap were sealed using Parafilm. The reaction tube partially submerged in an ice bath, and 1-phenyl-3-(pyrrolidin-1-yl)propan-1-one (203 mg, 1.0 mmol, 1.0 equiv) dissolved in toluene (1.0 mL) was added slowly via syringe pump (1.0 mol/L, 4.0 uL/min). The reaction tube was stirred at 0 °C for an additional 12 h. The cap was removed, and a saturated solution of NH_4F in MeOH (ca. 5.0 mL) was carefully added to quench the reaction (Caution: hydrogen gas evolution was observed). The reaction mixture was allowed to stir for 30 min at rt, diluted with EtOAc (ca. 10 mL), stirred for an additional 20 min at rt. and then filtered through a short plug of Celite (2.0 cm) eluting with additional EtOAc (ca. 20 mL). The solvent was removed in vacuo with the aid of a rotary evaporator. ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture indicated 20:1 dr and 76% combined yield (of the diastereomers). Aqueous NaOH solution (6 M, 5 mL) was added, and the mixture was stirred at rt for 1 h. The resulting mixture was extracted with ethyl acetate (20 mL, three times). The organic layer was washed with brine, dried over Na_2SO_4 and concentrated in vacuo. The crude compound **32** was obtained as a clear oil and was used without purification for the next step.

A 50 mL round bottom flask, which was equipped with a magnetic stir bar, was charged with compound **32** (as a mixture of diastereomers, dr: 20:1) by transferring a solution of this compound in methanol (ca. 5 mL), then removing the solvent in vacuo with the aid of a rotary evaporator. The reaction vessel was then capped with a septum, evacuated, and backfilled with dry nitrogen for a total of three times by using a needle connected to a Schlenk line. Next, 20% $Pd(OH)_2/C$ (100 mg, 15 mol %) was transferred into the reaction flask by temporarily removing the septum (Caution: dry $Pd(OH)_2/C$ can cause fires in a laboratory environment).[4] Methanol (2.0 mL) was added carefully down the side of the flask wall using a plastic syringe. While the reaction mixture was stirring, the flask was briefly evacuated by using a needle connected to a Schlenk line until the solvent began to bubble. The Schlenk line was closed to vacuum, and the flask was then carefully backfilled with hydrogen using a needle connected to a hydrogen-filled balloon. This evacuation-refill cycle was repeated a total of three times. The reaction mixture was stirred for 4 h at 40 °C by partially submerging the flask into a heated oil bath. Then, the reaction mixture was cooled to rt, and the septum was removed slowly and carefully. Using a gentle stream of nitrogen directed into the flask, the hydrogen in the headspace was displaced. (Caution: as detailed in ref. 4b, ensure that hydrogen is fully removed by carefully bubbling nitrogen through the solution. This will reduce the risk of fire during the subsequent filtration). After 5 min, the mixture was poured onto a plug of Celite and filtered to remove $Pd(OH)_2/C$. The Celite pad was washed with additional EtOAc (ca. 20 mL). (Caution: during the filtration, solvent should be continuously added so that the Celite and other solids do not fully dry. The $Pd(OH)_2/C$ at the top of the filter cake may ignite if not continuously covered with solvent. After the filtration is complete, the wet filter cake should be carefully transferred to a labelled waste bottle containing water).[4] After filtration, the solution was concentrated with the aid of a rotary evaporator. The crude product so obtained was recrystallized from hexane/CH_2Cl_2 (95/5) to give **(*R*)-Procyclidine 33** as a white solid (175 mg, 61%). $[\alpha]_D^{23}$ = -41.0, (c = 1.00, CH_3Cl). **SFC** analysis (OD-H column, $scCO_2$/MeOH = 95/5 to 60/40, 2.5 mL/min, add 0.1% diethylamine) indicated a >99.5:0.5 er: t_R = 3.58 min, 3.71 min. **M.P.** = 106-108 ºC.

Duplicate experiment: Overall yield: 55%, 158 mg; er: 99:1. Average yield: 58%.

VI. References

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VII. Computational Studies

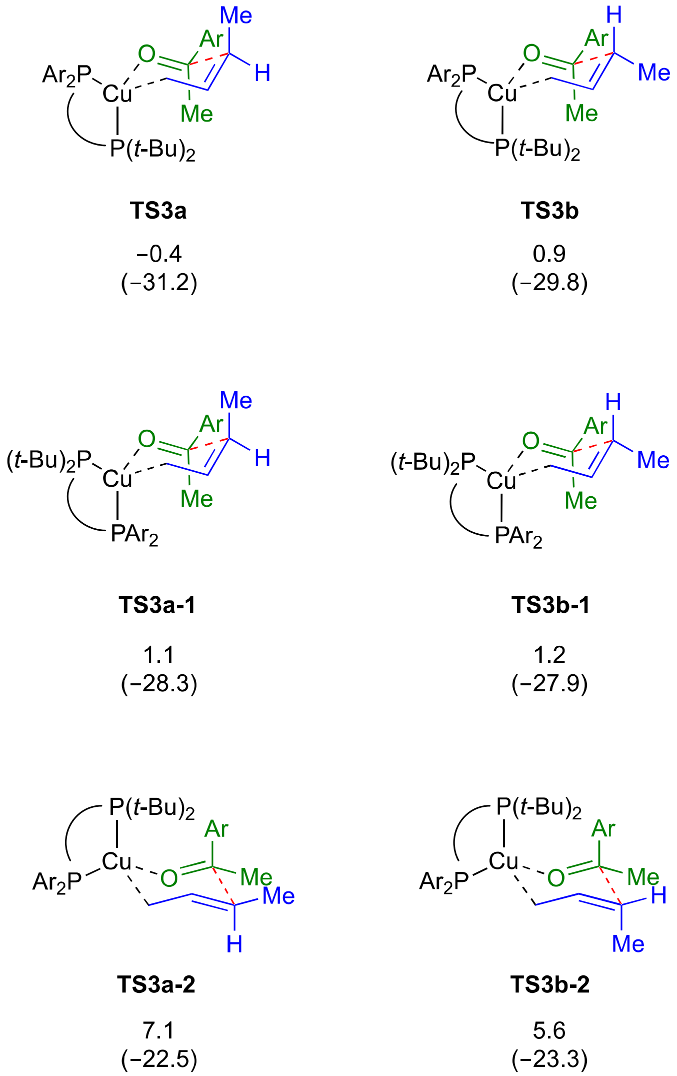
Computational Details

All DFT calculations were performed with Gaussian 09.[11] The DFT calculations were performed at a level of theory similar to that in our recent computational study on the CuH- catalyzed reductive coupling of enynes and ketones.[12] A benchmark study in our previous publication indicated the predicted enantio- and diastereoselectivities using this level of theory are consistent with those from a few other popular modern density functionals and solvation models.[12]

Here, geometry optimizations were performed in the gas phase with the B3LYP functional and a mixed basis set of SDD for Cu and Fe and 6-31G(d) for other atoms. Single point energies were calculated with the M06 functional[13,14] and a mixed basis set of SDD for Cu and Fe and 6-311+G(d,p) for other atoms. Solvation energy corrections were calculated using the implicit SMD solvation model[15] with toluene as the solvent.

Isomers of the Ketone Addition Transition State

We systematically considered the possible isomers of the six-membered Zimmerman-Traxler- type transition state that involves the nucleophilic attack of the allylic Cu species (**24-cis** and **24-trans**) on the 2-acetonaphthone (**25**). The computed Gibbs free energies and enthalpies of these transition state isomers with respect to the separate CuH catalyst, 1,3-butadiene, and the ketone are shown in Figure S1. As discussed in the main manuscript, the most favorable transition states involve the bulky aryl substituents at the equatorial position of the chair transition state (*i.e.* **TS3a** and **TS3b**). Placing the Ar group at the axial position (**TS3a-2** and **TS3b-2**) leads to much higher transition state energies. In addition, the di-*tert*-butyl substituted phosphorus atom on the ligand prefers to be *syn* to the methyl on the ketone (see **TS3a** and **TS3b**). Placing the di-aryl substituted phosphorus atom *syn* to the methyl on the ketone (**TS3a-1** and **TS3b-1**) is slightly less favorable.



TS3a
−0.4
(−31.2)

TS3b
0.9
(−29.8)

TS3a-1
1.1
(−28.3)

TS3b-1
1.2
(−27.9)

TS3a-2
7.1
(−22.5)

TS3b-2
5.6
(−23.3)

Figure S1. Isomers of the ketone addition transition states. Gibbs free energies and enthalpies (in parenthesis) are in kcal/mol with respect to the separated reactants (**1b** and **25**) and the CuH catalyst (**22a**).

In addition, we evaluated ketone addition transition states with the two different ligand conformations as in **22a** and **22b**. As discussed in the main manuscript, in **22a**, the chiral carbon center is puckered out-of-plane, while the two phosphorus atoms and the Cu are nearly co-planar with one of the Cp rings of the ferrocene. In contrast, in **22b**, the Cu is puckered out-of-plane, while the two phosphorus atoms and the chiral carbon are nearly co-planar with the ferrocene Cp ring. We considered both ligand conformations in the ketone addition transition state isomers that lead to the experimentally observed diastereomeric product (Figure S2). It was observed that the ligand conformation as in **22a** is more favored in the ketone addition transition state.

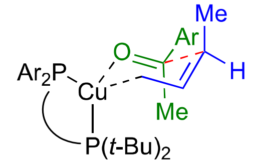
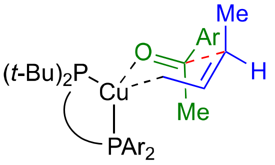
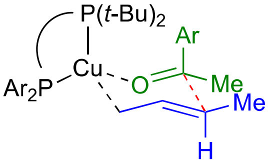
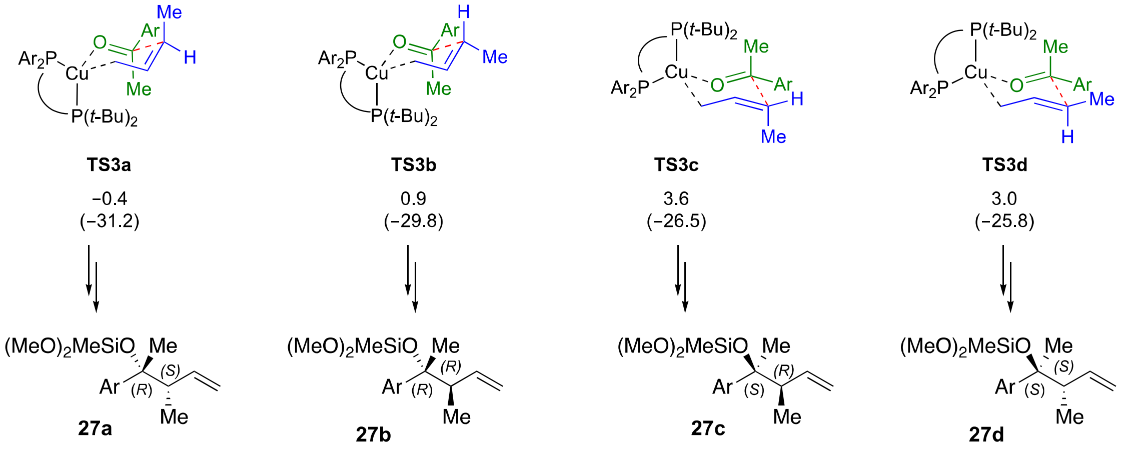
	ligand conformation **a** (as in **22a**)	ligand conformation **b** (as in **22b**)
	**TS3a** −0.4 (−31.2)	**TS3a-3** 7.6 (−23.0)
	**TS3a-1** 1.1 (−28.3)	**TS3a-4** 9.1 (−19.8)
	**TS3a-2** 7.1 (−22.5)	**TS3a-5** 7.3 (−21.5)

Figure S2. Effects of ligand conformation on the stability of the ketone addition transition state. Gibbs free energies and enthalpies (in parenthesis) are in kcal/mol with respect to the separated reactants (**1b** and **25**) and the CuH catalyst (**22a**).

Using these insights into the most favorable orientations of the substrates and the conformation of the ligand, we computed the four isomeric transition states leading to the four possible stereoisomeric products (Figure S3). The calculations indicate the most favorable transition state is **TS3a**.



TS3a	**TS3b**	**TS3c**	**TS3d**
−0.4	0.9	3.6	3.0
(−31.2)	(−29.8)	(−26.5)	(−25.8)
27a	**27b**	**27c**	**27d**

Figure S3. Transition state isomers leading to the four possible stereoisomeric products.

Cartesian Coordinates

1b

B3LYP electronic energy: -155.98888551 a.u.
B3LYP enthalpy: -155.897788 a.u.
B3LYP free energy: -155.929822 a.u.
M06 SCF energy in solution: -155.90276055 a.u.
M06 enthalpy in solution: -155.811663 a.u.
M06 free energy in solution: -155.843697 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-0.608790	0.400681	0.000274
C	-1.849247	-0.109061	-0.000411
H	-2.023172	-1.183012	0.000529
H	-0.473844	1.482772	0.000213
C	0.608959	-0.400834	0.000100
C	1.849101	0.109174	-0.000109
H	-2.729614	0.526583	0.000336
H	0.474217	-1.482936	0.000120
H	2.729552	-0.526327	-0.000045
H	2.022724	1.183163	-0.000278

22a

B3LYP electronic energy: -2922.12935731 a.u.
B3LYP enthalpy: -2921.427664 a.u.
B3LYP free energy: -2921.557670 a.u.
M06 SCF energy in solution: -2921.54835136 a.u.
M06 enthalpy in solution: -2920.846658 a.u.
M06 free energy in solution: -2920.976664 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.138822	-2.275799	2.134890
P	0.293484	0.318222	-0.356420
C	-0.244445	-0.444425	1.219395
C	-1.500472	-1.141718	1.482519
C	-1.553836	-1.343404	2.903093
H	-2.336060	-1.859763	3.439241
C	-0.382603	-0.809078	3.511215
H	-0.138294	-0.851901	4.564958
C	0.425863	-0.265141	2.481889
H	1.388248	0.209730	2.614761
C	-0.047083	-4.232457	1.438490
H	-0.916830	-4.627316	0.928855
C	0.166812	-4.228642	2.850260
C	1.980635	-3.205443	1.850184
H	2.912813	-2.676472	1.704021
C	1.072903	-3.601053	0.821347

H	1.205350	-3.427179	-0.237724
C	0.531420	2.100588	0.080503
C	0.000973	2.702680	1.231062
H	-0.510718	2.102681	1.975164
C	0.125551	4.077437	1.438738
H	-0.291386	4.530819	2.332110
C	0.780328	4.870961	0.496448
C	1.303288	4.286480	-0.662197
H	1.795685	4.904076	-1.406321
C	1.170595	2.917729	-0.871523
H	1.554446	2.481052	-1.788753
C	2.031732	-0.251624	-0.643893
C	3.127493	0.147467	0.138299
H	2.988116	0.845435	0.958225
C	4.407976	-0.326196	-0.138195
H	5.248810	-0.017042	0.474814
C	4.611178	-1.204471	-1.208487
C	3.534695	-1.593313	-2.007705
H	3.695568	-2.262777	-2.846200
C	2.254419	-1.113192	-1.727981
H	1.421817	-1.391199	-2.368929
C	1.421135	-3.596683	3.103053
H	1.854495	-3.413746	4.078084
C	-2.579719	-1.685865	0.529251
C	-3.715956	-2.344587	1.339844
H	-4.504469	-2.729450	0.697236
H	-3.326263	-3.188359	1.922391
H	-4.175068	-1.643061	2.042206
H	-2.106666	-2.481267	-0.058627
P	-3.109970	-0.528349	-0.907956
C	-3.896290	-1.721790	-2.216591
C	-4.501172	-0.842705	-3.333866
C	-2.713258	-2.506904	-2.829953
C	-4.959049	-2.740348	-1.758019
H	-5.426560	-0.351413	-3.016689
H	-3.792496	-0.083136	-3.678388
H	-4.751298	-1.483263	-4.189860
H	-2.222461	-3.163389	-2.100993
H	-3.089941	-3.148722	-3.637708
H	-1.963393	-1.831828	-3.258381
H	-5.388242	-3.221902	-2.647140
H	-4.529812	-3.540289	-1.146985
H	-5.785249	-2.285468	-1.205536
C	-4.387763	0.732635	-0.228492
C	-5.810361	0.194340	0.015410
C	-3.821064	1.288371	1.096376
C	-4.456748	1.909091	-1.229644
H	-6.289522	-0.135703	-0.910944
H	-5.830179	-0.635891	0.726558
H	-6.432598	0.998358	0.431955
H	-2.814517	1.700017	0.967952
H	-4.467271	2.104822	1.444786
H	-3.781969	0.536729	1.889439
H	-5.091783	2.700499	-0.809098

H	-3.465613	2.331875	-1.423389
H	-4.884093	1.617683	-2.191622
H	-0.514482	-4.611983	3.599129
C	6.005490	-1.670724	-1.534697
C	0.971859	6.341879	0.746149
F	6.001480	-2.849950	-2.192454
F	6.656659	-0.781576	-2.318370
F	6.751637	-1.829370	-0.418235
F	0.009310	6.848097	1.548804
F	0.961276	7.053316	-0.402125
F	2.158001	6.593193	1.350601
Cu	-1.258341	0.345893	-2.044566
H	-1.080719	0.787748	-3.525371

22b

B3LYP electronic energy: -2922.12770145 a.u.
B3LYP enthalpy: -2921.425848 a.u.
B3LYP free energy: -2921.555867 a.u.
M06 SCF energy in solution: -2921.54847371 a.u.
M06 enthalpy in solution: -2920.846620 a.u.
M06 free energy in solution: -2920.976639 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.273812	-2.472191	1.792845
P	0.353534	0.246575	-0.308985
C	-0.217991	-0.449615	1.285869
C	-1.573617	-0.815898	1.691334
C	-1.463251	-1.316736	3.033830
H	-2.280616	-1.711297	3.622189
C	-0.109649	-1.256878	3.466366
H	0.270632	-1.598789	4.420529
C	0.657218	-0.733060	2.396070
H	1.729975	-0.602031	2.391369
C	-1.157928	-4.186155	0.995088
H	-2.204826	-4.287717	0.743606
C	-0.574439	-4.477652	2.263994
C	1.100991	-3.734676	0.859329
H	2.065323	-3.417046	0.487443
C	-0.124569	-3.724669	0.125920
H	-0.253558	-3.397172	-0.898016
C	0.731227	2.017821	0.080978
C	0.586938	2.593483	1.351524
H	0.263726	1.985228	2.190130
C	0.850610	3.949126	1.552713
H	0.730057	4.385695	2.538876
C	1.263108	4.747829	0.484756
C	1.410164	4.187388	-0.788823
H	1.720447	4.809670	-1.622138
C	1.140436	2.836795	-0.987586
H	1.244899	2.414094	-1.983849

C	2.077591	-0.406435	-0.539591
C	3.178648	0.025030	0.217693
H	3.052467	0.786985	0.981285
C	4.449852	-0.496602	-0.014323
H	5.295996	-0.155764	0.573340
C	4.638310	-1.447915	-1.021481
C	3.557382	-1.860595	-1.804658
H	3.710626	-2.574225	-2.608014
C	2.285541	-1.337769	-1.568066
H	1.448184	-1.627626	-2.199204
C	0.822581	-4.199955	2.178079
H	1.539598	-4.291930	2.983997
C	-2.973645	-0.749072	1.041663
P	-3.120311	-0.168844	-0.780953
C	-4.467506	-1.376272	-1.460777
C	-4.884864	-0.923527	-2.875162
C	-3.771099	-2.747536	-1.613490
C	-5.723772	-1.560109	-0.587208
H	-5.495858	-0.016406	-2.864220
H	-4.012321	-0.755993	-3.515384
H	-5.490107	-1.715043	-3.336263
H	-3.460864	-3.167106	-0.650807
H	-4.476442	-3.459294	-2.062622
H	-2.890594	-2.678793	-2.260484
H	-6.401400	-2.268611	-1.082652
H	-5.488821	-1.981441	0.395809
H	-6.279911	-0.631301	-0.436472
C	-3.752714	1.655441	-0.870749
C	-5.238734	1.907189	-0.549972
C	-2.884326	2.519637	0.065312
C	-3.471799	2.141637	-2.314766
H	-5.909925	1.376191	-1.230050
H	-5.502675	1.636944	0.475090
H	-5.446967	2.979630	-0.666076
H	-1.822901	2.431392	-0.172320
H	-3.160777	3.573988	-0.067387
H	-3.018948	2.278737	1.121986
H	-3.707027	3.212584	-2.381515
H	-2.419630	2.009544	-2.589585
H	-4.076349	1.624154	-3.062131
H	-1.102675	-4.821428	3.144289
C	5.996422	-2.061166	-1.235996
C	1.602237	6.196555	0.709585
F	6.992481	-1.237080	-0.842928
F	6.135247	-3.209541	-0.531021
F	6.210427	-2.369922	-2.532938
F	2.920665	6.365004	0.965809
F	0.928950	6.715294	1.760373
F	1.314819	6.953619	-0.372303
Cu	-1.142761	-0.417252	-1.958708
C	-3.985887	-0.127179	2.035351
H	-4.053933	-0.733588	2.944089
H	-3.696663	0.880089	2.343229
H	-4.989144	-0.082445	1.609515

H	-3.278203	-1.794482	0.927775
H	-0.754043	-1.091205	-3.307465

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B3LYP electronic energy: -3078.14712403 a.u.
B3LYP enthalpy: -3077.348291 a.u.
B3LYP free energy: -3077.491686 a.u.
M06 SCF energy in solution: -3077.49217094 a.u.
M06 enthalpy in solution: -3076.693338 a.u.
M06 free energy in solution: -3076.836733 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.626149	-2.267124	-2.456801
P	-0.321414	0.342798	0.067558
C	0.032690	-0.520564	-1.510823
C	1.161050	-1.404793	-1.770503
C	1.196666	-1.607498	-3.191218
H	1.889087	-2.244137	-3.722345
C	0.133657	-0.884759	-3.804748
H	-0.102600	-0.877174	-4.861136
C	-0.589418	-0.227491	-2.776909
H	-1.452195	0.409930	-2.915292
C	-0.830673	-4.154864	-1.596279
H	-0.124258	-4.595374	-0.903808
C	-0.789391	-4.261867	-3.019627
C	-2.599641	-2.943814	-2.453242
H	-3.471001	-2.306718	-2.524577
C	-1.949755	-3.342112	-1.247089
H	-2.239496	-3.055459	-0.245728
C	-0.712443	2.062165	-0.480615
C	0.004480	2.670487	-1.525170
H	0.715733	2.093081	-2.106783
C	-0.192084	4.013328	-1.839595
H	0.359651	4.465251	-2.657384
C	-1.106251	4.776953	-1.109936
C	-1.815109	4.190444	-0.058487
H	-2.526564	4.780120	0.510457
C	-1.615509	2.848325	0.255798
H	-2.172825	2.413276	1.079170
C	-1.953803	-0.280903	0.673954
C	-3.153709	-0.151719	-0.045870
H	-3.160508	0.353946	-1.006317
C	-4.344141	-0.663639	0.461488
H	-5.266153	-0.566129	-0.103367
C	-4.352404	-1.314737	1.701486
C	-3.171592	-1.440077	2.433304
H	-3.180510	-1.937714	3.397175
C	-1.980074	-0.920421	1.920536
H	-1.063131	-1.002795	2.497674
C	-1.882430	-3.512593	-3.548815

H	-2.109707	-3.376076	-4.598314
C	2.112827	-2.103102	-0.793811
P	2.995745	-0.954838	0.478021
C	3.540415	-2.157923	1.897427
C	4.437176	-1.358529	2.867280
C	2.241649	-2.527196	2.650678
C	4.265865	-3.467760	1.530384
H	5.433724	-1.179819	2.452367
H	3.991670	-0.396246	3.136322
H	4.568273	-1.938495	3.790411
H	1.541719	-3.094144	2.025031
H	2.490904	-3.160474	3.512591
H	1.728656	-1.634126	3.024860
H	4.612824	-3.946452	2.456095
H	3.602051	-4.184245	1.037721
H	5.143485	-3.312935	0.897470
C	4.505187	-0.144438	-0.392983
C	5.713140	-1.064027	-0.655949
C	3.990938	0.424915	-1.733473
C	4.969736	1.054794	0.464895
H	6.166902	-1.420543	0.273625
H	5.462370	-1.933003	-1.269540
H	6.484826	-0.494602	-1.191941
H	3.137288	1.095782	-1.585731
H	4.792519	1.011219	-2.201390
H	3.692997	-0.353089	-2.441118
H	5.753069	1.596285	-0.082964
H	4.156251	1.755733	0.675929
H	5.396455	0.744814	1.421685
H	-0.043859	-4.792157	-3.598299
C	-5.656392	-1.824034	2.257658
C	-1.285598	6.239093	-1.414205
F	-6.429391	-2.365672	1.289499
F	-5.469632	-2.766655	3.205233
F	-6.376382	-0.827992	2.821511
F	-0.460235	7.010697	-0.671503
F	-2.546760	6.653651	-1.156363
F	-1.023772	6.519233	-2.711220
Cu	1.505645	0.493331	1.531230
C	1.379788	1.748028	3.104386
C	2.529780	2.659880	2.920761
H	3.479936	2.285476	3.319373
C	2.559959	3.860685	2.305943
H	3.483647	4.422896	2.194115
H	1.659637	4.314247	1.893806
H	0.446471	2.310954	2.949073
C	1.340529	1.099481	4.498822
H	0.507666	0.389901	4.594924
H	2.262031	0.540235	4.714949
H	1.225651	1.839995	5.309328
C	3.002919	-3.107115	-1.555054
H	2.379118	-3.850058	-2.066064
H	3.614660	-2.612797	-2.314421
H	3.677266	-3.643248	-0.891966

H	1.484831	-2.680878	-0.105000

24_cis

B3LYP electronic energy: -3078.15576284 a.u.
B3LYP enthalpy: -3077.356675 a.u.
B3LYP free energy: -3077.499465 a.u.
M06 SCF energy in solution: -3077.49974737 a.u.
M06 enthalpy in solution: -3076.700660 a.u.
M06 free energy in solution: -3076.843450 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.099745	-1.916258	-2.787161
P	-0.364793	0.353727	0.026714
C	0.248304	-0.187371	-1.618461
C	1.577477	-0.703694	-1.924605
C	1.689657	-0.711777	-3.355248
H	2.536502	-1.073647	-3.920102
C	0.481669	-0.226572	-3.932513
H	0.268055	-0.151646	-4.991103
C	-0.406091	0.087065	-2.872256
H	-1.404286	0.489169	-2.980246
C	0.423023	-3.892849	-2.205883
H	1.236981	-4.230119	-1.576888
C	0.452677	-3.783088	-3.629353
C	-1.623461	-3.081908	-2.900269
H	-2.632009	-2.691887	-2.888339
C	-0.859327	-3.460516	-1.755990
H	-1.187827	-3.403720	-0.727360
C	-1.162364	1.977145	-0.359124
C	-0.563983	2.878531	-1.256854
H	0.307018	2.578490	-1.830677
C	-1.083160	4.158488	-1.437676
H	-0.618553	4.837238	-2.145800
C	-2.209367	4.565701	-0.717903
C	-2.808279	3.685317	0.186315
H	-3.685216	3.996177	0.744660
C	-2.286761	2.405959	0.366018
H	-2.764082	1.738895	1.076658
C	-1.807885	-0.715792	0.468346
C	-2.927350	-0.889144	-0.363886
H	-2.984896	-0.369472	-1.314977
C	-3.978085	-1.715621	0.022413
H	-4.843722	-1.838836	-0.620937
C	-3.924946	-2.381144	1.253413
C	-2.831656	-2.199611	2.099876
H	-2.804521	-2.692734	3.065765
C	-1.779795	-1.365280	1.710879
H	-0.953621	-1.194160	2.396013
C	-0.813053	-3.282533	-4.058097
H	-1.096708	-3.063248	-5.079488

C	2.675462	-1.227435	-0.991586
P	3.175680	-0.035768	0.432363
C	3.980334	-1.199736	1.753626
C	4.602430	-0.309673	2.851903
C	2.809120	-1.983863	2.390898
C	5.040036	-2.220035	1.291505
H	5.526308	0.173263	2.518213
H	3.905477	0.460335	3.195319
H	4.858748	-0.939193	3.714002
H	2.307101	-2.643805	1.673245
H	3.200177	-2.621650	3.194761
H	2.061764	-1.315155	2.831229
H	5.481122	-2.693311	2.179222
H	4.605004	-3.025370	0.692025
H	5.858098	-1.767192	0.725143
C	4.431768	1.242867	-0.254500
C	5.859460	0.725960	-0.515344
C	3.839516	1.795257	-1.569804
C	4.497831	2.419476	0.746643
H	6.354165	0.404148	0.405829
H	5.884856	-0.104762	-1.225258
H	6.464821	1.538959	-0.939298
H	2.823536	2.179544	-1.426372
H	4.461482	2.630196	-1.918197
H	3.808838	1.049827	-2.368328
H	5.113946	3.220546	0.316345
H	3.503017	2.825724	0.955659
H	4.946073	2.135030	1.701120
H	1.296184	-4.009954	-4.268912
C	-5.031746	-3.330171	1.631102
C	-2.736071	5.965684	-0.875092
F	-4.833537	-4.554520	1.088282
F	-5.122761	-3.499477	2.966530
F	-6.233878	-2.897562	1.190045
F	-4.059141	6.039347	-0.609395
F	-2.546900	6.435030	-2.129590
F	-2.117963	6.830373	-0.037974
Cu	1.333446	0.835986	1.559306
H	2.142174	0.055339	5.409356
C	0.006645	0.010357	5.042808
C	1.244891	-0.469289	5.753062
H	1.417966	-1.547183	5.609018
C	-0.049709	0.935644	4.058205
C	1.033548	1.663846	3.357793
H	1.169677	-0.313622	6.839691
H	0.728928	2.701122	3.157384
H	-0.932381	-0.418723	5.395956
H	-1.054283	1.167847	3.691224
H	1.966311	1.694751	3.934567
C	3.819230	-1.853786	-1.815518
H	3.431420	-2.671278	-2.435111
H	4.286044	-1.127180	-2.486268
H	4.603094	-2.263694	-1.182187
H	2.228275	-2.032520	-0.396534

24_trans

B3LYP electronic energy: -3078.15734356 a.u.
B3LYP enthalpy: -3077.358489 a.u.
B3LYP free energy: -3077.500981 a.u.
M06 SCF energy in solution: -3077.49903598 a.u.
M06 enthalpy in solution: -3076.700181 a.u.
M06 free energy in solution: -3076.842673 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.147103	-1.878797	-2.803999
P	-0.294548	0.384471	0.013035
C	0.377964	-0.185812	-1.597318
C	1.671452	-0.819268	-1.823567
C	1.877062	-0.822190	-3.243837
H	2.723804	-1.251059	-3.759440
C	0.760637	-0.219775	-3.891004
H	0.627348	-0.112452	-4.959918
C	-0.164577	0.161397	-2.886209
H	-1.112973	0.654109	-3.051878
C	0.233247	-3.877350	-2.215507
H	0.959943	-4.285549	-1.524180
C	0.388764	-3.770198	-3.631029
C	-1.664826	-2.876384	-3.067171
H	-2.630321	-2.393387	-3.134327
C	-1.035690	-3.326413	-1.867988
H	-1.439416	-3.239307	-0.868679
C	-0.880117	2.093565	-0.380604
C	-0.144156	2.931588	-1.236208
H	0.708604	2.539458	-1.780572
C	-0.503806	4.265640	-1.413334
H	0.065567	4.895914	-2.089160
C	-1.604743	4.790883	-0.731915
C	-2.340072	3.973348	0.129583
H	-3.197653	4.376452	0.657999
C	-1.977965	2.639555	0.305609
H	-2.559874	2.021881	0.982262
C	-1.872297	-0.532848	0.313617
C	-2.956919	-0.523089	-0.580125
H	-2.900064	0.050946	-1.499484
C	-4.118613	-1.234250	-0.294877
H	-4.956806	-1.212818	-0.984335
C	-4.212883	-1.967693	0.894232
C	-3.150589	-1.974038	1.798018
H	-3.233555	-2.521058	2.731085
C	-1.987194	-1.254619	1.510452
H	-1.179964	-1.232165	2.237603
C	-0.784610	-3.151477	-4.156858
H	-0.961748	-2.906516	-5.196231
C	2.647287	-1.458185	-0.829962

P	3.160434	-0.331974	0.644310
C	3.797477	-1.563803	1.992388
C	4.422453	-0.729655	3.131711
C	2.536219	-2.259921	2.557796
C	4.800809	-2.659854	1.579741
H	5.396544	-0.316085	2.853309
H	3.766510	0.088374	3.442901
H	4.582690	-1.381398	4.000641
H	2.010429	-2.852983	1.799799
H	2.838672	-2.953039	3.354237
H	1.829664	-1.542812	2.990026
H	5.156482	-3.167009	2.486888
H	4.337978	-3.428613	0.953793
H	5.679790	-2.269800	1.060247
C	4.551041	0.852381	0.048486
C	5.947756	0.227223	-0.130022
C	4.085252	1.457489	-1.293383
C	4.646129	2.014277	1.065048
H	6.359828	-0.133533	0.816914
H	5.952418	-0.602336	-0.841964
H	6.638343	0.991783	-0.511692
H	3.091005	1.909612	-1.208418
H	4.784259	2.250681	-1.589724
H	4.055004	0.724584	-2.103370
H	5.353304	2.763824	0.684693
H	3.676402	2.501088	1.211015
H	5.004571	1.689501	2.044453
H	1.256143	-4.075308	-4.202406
C	-5.449749	-2.782987	1.166502
C	-1.954680	6.245412	-0.886942
F	-5.382101	-3.995112	0.567472
F	-5.631748	-3.002900	2.485012
F	-6.561385	-2.175711	0.694998
F	-3.256756	6.484449	-0.616542
F	-1.712509	6.686865	-2.142746
F	-1.228803	7.026011	-0.053593
Cu	1.309418	0.650419	1.680436
C	-0.110222	-0.318155	5.056143
C	-0.146252	0.670566	4.138778
C	0.986705	1.389286	3.511284
H	0.750678	2.455283	3.384303
H	-1.139277	0.964851	3.779298
H	1.895773	1.316661	4.124309
C	3.779998	-2.180921	-1.586582
H	3.360439	-2.941549	-2.255709
H	4.366097	-1.491280	-2.200303
H	4.468402	-2.682217	-0.909691
H	2.081466	-2.221961	-0.283070
C	-1.318329	-1.015527	5.622207
H	-2.243021	-0.635742	5.168905
H	-1.292959	-2.105026	5.460434
H	-1.406850	-0.873050	6.710150
H	0.858166	-0.629426	5.456137

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B3LYP electronic energy: -538.52971863 a.u.
B3LYP enthalpy: -538.332978 a.u.
B3LYP free energy: -538.380576 a.u.
M06 SCF energy in solution: -538.28544153 a.u.
M06 enthalpy in solution: -538.088701 a.u.
M06 free energy in solution: -538.136299 a.u.

Cartesian coordinates

ATOM	X	Y	Z
O	-3.706531	0.823065	-0.000423
C	-2.906594	-0.101259	-0.000080
C	-3.394554	-1.542169	0.000348
H	-3.034178	-2.081442	0.884527
H	-3.033245	-2.082554	-0.882749
H	-4.485898	-1.539473	-0.000199
C	-1.433278	0.168729	0.000017
C	-0.487194	-0.841263	-0.000074
C	-1.004084	1.527161	0.000080
C	0.902135	-0.551589	-0.000051
H	-0.791182	-1.884428	-0.000203
C	0.331774	1.839287	0.000128
H	-1.766633	2.298538	0.000101
C	1.323917	0.818195	0.000068
C	1.887108	-1.576653	-0.000139
H	0.652657	2.878398	0.000197
C	2.713972	1.105876	0.000101
C	3.228236	-1.264618	-0.000103
H	1.562529	-2.614670	-0.000231
C	3.644607	0.089591	0.000019
H	3.033627	2.145194	0.000192
H	3.972676	-2.055933	-0.000167
H	4.705620	0.324107	0.000047

26a

B3LYP electronic energy: -3616.70803112 a.u.
B3LYP enthalpy: -3615.707832 a.u.
B3LYP free energy: -3615.873312 a.u.
M06 SCF energy in solution: -3615.81394221 a.u.
M06 enthalpy in solution: -3614.813743 a.u.
M06 free energy in solution: -3614.979223 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	4.247119	-0.616113	-1.555607
P	0.801360	-0.463202	-0.309970
C	2.202759	-0.138672	-1.456673
C	3.000889	1.076715	-1.456824
C	3.771150	1.070287	-2.665213

H	4.500338	1.814922	-2.953793
C	3.468429	-0.109614	-3.406588
H	3.919046	-0.403189	-4.346065
C	2.518432	-0.858872	-2.661419
H	2.089953	-1.808381	-2.951542
C	5.717371	-0.540942	-0.066920
H	5.849184	0.260741	0.648117
C	6.317531	-0.623040	-1.359901
C	4.999998	-2.496096	-1.060683
H	4.482856	-3.429280	-1.240025
C	4.905106	-1.696942	0.117435
H	4.307852	-1.920786	0.989648
C	-0.400310	-1.395828	-1.355670
C	-0.672306	-0.990586	-2.674739
H	-0.101229	-0.187368	-3.128205
C	-1.665589	-1.614423	-3.425330
H	-1.850887	-1.299827	-4.447232
C	-2.418238	-2.651300	-2.867480
C	-2.178359	-3.048001	-1.550317
H	-2.764950	-3.846702	-1.108483
C	-1.184215	-2.421640	-0.801488
H	-1.024291	-2.739484	0.222753
C	1.370476	-1.737195	0.904774
C	1.735535	-3.047921	0.550418
H	1.677216	-3.366824	-0.485704
C	2.164112	-3.950387	1.518231
H	2.435945	-4.964107	1.239770
C	2.241872	-3.552119	2.859430
C	1.873773	-2.259041	3.227709
H	1.916090	-1.958950	4.269140
C	1.431132	-1.360008	2.252707
H	1.112718	-0.363295	2.545642
C	5.875557	-1.833508	-1.972811
H	6.132704	-2.172208	-2.968232
C	3.072503	2.155731	-0.386135
P	1.434377	3.156347	-0.180045
C	1.814396	4.437012	1.214973
C	0.464475	4.937935	1.776649
C	2.505104	3.673789	2.369603
C	2.657452	5.662565	0.809742
H	-0.134781	5.472520	1.036932
H	-0.130667	4.108025	2.165305
H	0.662721	5.631377	2.605156
H	3.521113	3.347732	2.132674
H	2.574712	4.340341	3.238934
H	1.918740	2.800277	2.676549
H	2.859132	6.265460	1.705318
H	3.621342	5.402597	0.367618
H	2.125465	6.307977	0.104768
C	1.026917	4.028374	-1.845537
C	2.222528	4.677689	-2.568266
C	0.424709	2.944111	-2.769443
C	-0.067234	5.091189	-1.609894
H	2.742528	5.416396	-1.952852

H	2.946035	3.928524	-2.901435
H	1.857871	5.195566	-3.465575
H	-0.472751	2.495904	-2.329486
H	0.137556	3.407504	-3.723060
H	1.139226	2.146576	-2.989691
H	-0.430971	5.441254	-2.584734
H	-0.924313	4.683409	-1.063902
H	0.306068	5.966472	-1.070937
H	6.970669	0.114188	-1.809141
C	2.762888	-4.530056	3.879538
C	-3.519667	-3.296531	-3.661516
F	2.214670	-5.754302	3.715437
F	4.103098	-4.685863	3.767399
F	2.511109	-4.134763	5.143949
F	-3.260008	-3.280603	-4.988071
F	-4.705190	-2.658960	-3.491859
F	-3.715472	-4.583191	-3.299526
C	-0.646526	1.734969	4.347621
C	-1.751519	2.173433	3.733061
C	-2.837880	1.342227	3.099406
O	-1.865021	1.049680	0.880072
C	-2.957415	1.597185	1.527851
C	-3.105372	3.111354	1.228302
H	-3.930247	3.576644	1.782900
H	-3.301297	3.243995	0.158374
H	-2.179760	3.640479	1.470934
Cu	-0.176222	1.706487	0.392739
H	-0.420798	0.677034	4.449659
H	0.060673	2.426520	4.800097
C	-4.262895	0.919286	1.025741
C	-5.508744	1.220724	1.546843
C	-4.192769	-0.013632	-0.043449
C	-6.698627	0.623361	1.051647
H	-5.609322	1.936212	2.360775
C	-5.324059	-0.609257	-0.555053
H	-3.211878	-0.237274	-0.443801
C	-6.608540	-0.315390	-0.027105
C	-7.981179	0.925824	1.587488
H	-5.245072	-1.313294	-1.380444
C	-7.799860	-0.910554	-0.523853
C	-9.117504	0.331974	1.084974
H	-8.049641	1.638462	2.406957
C	-9.026676	-0.596646	0.017436
H	-7.724286	-1.622054	-1.343507
H	-10.090313	0.573246	1.506021
H	-9.930172	-1.059354	-0.371493
H	-1.914472	3.251462	3.702341
C	4.388197	2.953207	-0.494594
H	5.227943	2.255919	-0.575813
H	4.416512	3.610216	-1.365889
H	4.560668	3.568203	0.388678
H	3.089324	1.637590	0.579811
C	-2.704739	-0.153380	3.404305
H	-1.799127	-0.560511	2.945524

H	-2.663151	-0.332184	4.485094
H	-3.558979	-0.704161	3.000192
H	-3.781640	1.696680	3.541498

26b

B3LYP electronic energy: -3616.71246661 a.u.
B3LYP enthalpy: -3615.712509 a.u.
B3LYP free energy: -3615.877437 a.u.
M06 SCF energy in solution: -3615.81738425 a.u.
M06 enthalpy in solution: -3614.817427 a.u.
M06 free energy in solution: -3614.982355 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-2.133285	2.814091	2.125709
P	-0.623270	0.672505	-0.395911
C	-2.001567	1.497801	0.499968
C	-2.813720	0.913171	1.557156
C	-3.912765	1.805578	1.776033
H	-4.684281	1.681703	2.523321
C	-3.798932	2.920239	0.894726
H	-4.464868	3.772684	0.857546
C	-2.622768	2.740459	0.119143
H	-2.259362	3.414233	-0.644835
C	-1.113676	2.670217	3.939635
H	-0.943768	1.749347	4.482652
C	-2.247312	3.528495	4.073032
C	-0.854151	4.426795	2.464969
H	-0.454925	5.069092	1.691542
C	-0.253332	3.226817	2.948380
H	0.677952	2.799609	2.604672
C	-0.927926	1.138825	-2.163564
C	-2.226864	1.232165	-2.690203
H	-3.086799	1.133621	-2.038453
C	-2.433245	1.462507	-4.048887
H	-3.443429	1.531942	-4.439551
C	-1.342385	1.597134	-4.910630
C	-0.044481	1.496059	-4.404639
H	0.806171	1.589517	-5.071565
C	0.158879	1.264128	-3.046135
H	1.175080	1.184523	-2.674619
C	0.910239	1.632595	-0.009289
C	1.057326	2.988699	-0.349634
H	0.261800	3.509338	-0.873375
C	2.225370	3.675450	-0.034516
H	2.337340	4.719556	-0.309252
C	3.267425	3.012174	0.625699
C	3.140850	1.663646	0.957908
H	3.958312	1.139209	1.440622
C	1.965502	0.976826	0.637405
H	1.886982	-0.078999	0.878374

C	-2.086482	4.614140	3.160976
H	-2.791593	5.419897	3.001340
C	-2.573131	-0.366231	2.347037
P	-2.594227	-1.936258	1.237099
C	-2.223194	-3.414102	2.419684
C	-1.750567	-4.598997	1.541892
C	-1.017127	-2.996101	3.293429
C	-3.375800	-3.896243	3.322770
H	-2.564292	-5.030960	0.954530
H	-0.948231	-4.306008	0.855955
H	-1.375586	-5.392244	2.203503
H	-1.261741	-2.223091	4.028195
H	-0.664255	-3.872938	3.851150
H	-0.181367	-2.641997	2.679679
H	-3.007323	-4.709735	3.962508
H	-3.770589	-3.118207	3.981094
H	-4.209269	-4.302380	2.741926
C	-4.335334	-2.114888	0.441819
C	-5.527360	-1.856687	1.383360
C	-4.404171	-1.100444	-0.721213
C	-4.464082	-3.522345	-0.178286
H	-5.511646	-2.491522	2.272706
H	-5.567771	-0.811547	1.703854
H	-6.462382	-2.065045	0.845351
H	-3.615100	-1.282757	-1.458148
H	-5.371109	-1.206488	-1.231555
H	-4.325005	-0.067284	-0.373019
H	-5.365176	-3.549453	-0.805153
H	-3.607876	-3.767127	-0.815720
H	-4.569673	-4.306728	0.575353
H	-3.094305	3.370543	4.728473
C	4.504371	3.778124	1.016806
C	-1.570052	1.909200	-6.364633
F	4.802395	4.739654	0.113663
F	4.338241	4.400790	2.208465
F	5.582325	2.978657	1.134101
F	-1.685756	3.242656	-6.573764
F	-2.706650	1.342584	-6.826841
F	-0.552991	1.477097	-7.140329
C	2.963862	-6.363717	-0.129030
C	1.901498	-5.610959	-0.421516
C	1.748820	-4.758798	-1.655433
O	0.270994	-3.153036	-0.582429
C	1.460167	-3.236052	-1.308229
C	1.342845	-2.441599	-2.630915
H	2.163046	-2.637754	-3.333327
H	1.321977	-1.367297	-2.420363
H	0.403211	-2.703529	-3.123930
Cu	-0.713143	-1.587204	-0.142176
H	3.844748	-6.385742	-0.768489
H	3.000825	-6.982483	0.764687
C	2.647689	-2.703532	-0.470154
C	3.775823	-2.125637	-1.020699
C	2.584304	-2.812968	0.949490

C	4.837065	-1.618700	-0.219197
H	3.875798	-2.030785	-2.098665
C	3.595469	-2.348850	1.758698
H	1.703601	-3.275829	1.377786
C	4.748998	-1.727766	1.206251
C	5.979146	-0.988944	-0.784851
H	3.524276	-2.452621	2.840141
C	5.801398	-1.203911	2.005024
C	6.981518	-0.484974	0.014988
H	6.047040	-0.907291	-1.867636
C	6.892122	-0.592254	1.424943
H	5.731522	-1.294004	3.087223
H	7.846207	-0.002781	-0.433212
H	7.688954	-0.192789	2.046648
H	2.697510	-4.792497	-2.210051
C	0.639648	-5.364502	-2.540394
H	0.821469	-6.433798	-2.696614
H	-0.334745	-5.244266	-2.056336
H	0.593564	-4.886764	-3.524582
H	1.040556	-5.619989	0.246693
C	-3.376497	-0.380077	3.662430
H	-3.194409	0.548946	4.213958
H	-4.453272	-0.469618	3.505055
H	-3.068241	-1.206597	4.303668
H	-1.513048	-0.364473	2.627241

27a

B3LYP electronic energy: -1254.94465419 a.u.
B3LYP enthalpy: -1254.505124 a.u.
B3LYP free energy: -1254.589699 a.u.
M06 SCF energy in solution: -1254.54005731 a.u.
M06 enthalpy in solution: -1254.100527 a.u.
M06 free energy in solution: -1254.185102 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.475188	-3.609619	-0.167510
C	2.860764	-2.490771	-0.555620
C	1.366223	-2.283968	-0.584331
O	1.490534	0.101589	-0.275557
C	0.922419	-1.071652	0.312810
C	1.435099	-1.248888	1.754078
H	1.052197	-2.171532	2.200336
H	1.117783	-0.406903	2.375158
H	2.526941	-1.309780	1.763419
H	2.919762	-4.473349	0.194084
H	4.557119	-3.710490	-0.200164
C	-0.610107	-0.958638	0.311395
C	-1.261170	0.108148	-0.273865
C	-1.397590	-1.984219	0.911912
C	-2.679734	0.210915	-0.278568

H	-0.681816	0.890571	-0.752384
C	-2.771036	-1.918488	0.921965
H	-0.909548	-2.838378	1.372497
C	-3.457654	-0.823220	0.333050
C	-3.353698	1.310410	-0.876359
H	-3.350707	-2.712565	1.387319
C	-4.874115	-0.718573	0.326464
C	-4.729177	1.384498	-0.867878
H	-2.762337	2.095098	-1.342602
C	-5.497434	0.360574	-0.260351
H	-5.460004	-1.507085	0.793449
H	-5.231604	2.230979	-1.328396
H	-6.581866	0.430629	-0.260023
H	3.455726	-1.652030	-0.917628
C	0.892592	-2.133672	-2.042725
H	1.342075	-1.249619	-2.506168
H	1.189648	-3.012205	-2.624859
H	-0.195315	-2.031686	-2.102084
H	0.890744	-3.177144	-0.157781
Si	2.132213	1.525470	0.288786
C	3.961375	1.346797	0.619745
H	4.400441	2.318668	0.869611
H	4.149776	0.668154	1.458667
H	4.489055	0.949267	-0.254874
O	1.812212	2.636847	-0.898919
O	1.445665	2.099054	1.672011
C	2.035879	2.432795	-2.284567
H	1.682951	3.319409	-2.820759
H	3.104540	2.301034	-2.504721
H	1.490858	1.555244	-2.653277
C	0.223729	2.820541	1.784419
H	0.222143	3.326134	2.755013
H	0.130695	3.570448	0.991080
H	-0.636850	2.142811	1.737433

27b

B3LYP electronic energy: -1254.94219120 a.u.
B3LYP enthalpy: -1254.502492 a.u.
B3LYP free energy: -1254.586406 a.u.
M06 SCF energy in solution: -1254.53862962 a.u.
M06 enthalpy in solution: -1254.098930 a.u.
M06 free energy in solution: -1254.182844 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-3.597430	3.360218	-0.941222
C	-2.837970	2.265388	-1.022039
C	-1.353131	2.165292	-0.748543
O	-1.596540	-0.171710	-0.314310
C	-1.044362	1.014859	0.284677
C	-1.730175	1.281324	1.632321

H	-1.420046	2.236832	2.064941
H	-1.498480	0.488110	2.349697
H	-2.812271	1.325750	1.485008
H	-3.204652	4.330275	-0.649334
H	-4.658346	3.324586	-1.175619
C	0.478070	0.831101	0.410154
C	1.176323	0.217705	-0.614803
C	1.211484	1.300461	1.535159
C	2.584582	0.047635	-0.571944
H	0.635205	-0.164318	-1.475709
C	2.578951	1.150801	1.611155
H	0.691782	1.781595	2.356332
C	3.309123	0.525638	0.567796
C	3.303356	-0.584986	-1.624000
H	3.116831	1.513533	2.484187
C	4.719533	0.354484	0.611158
C	4.669916	-0.734542	-1.553673
H	2.752361	-0.949502	-2.487845
C	5.385602	-0.260288	-0.424953
H	5.264777	0.718801	1.478890
H	5.207241	-1.218925	-2.364585
H	6.464195	-0.385414	-0.381892
H	-3.301354	1.328182	-1.323643
Si	-1.991410	-1.664821	0.305507
C	-3.774149	-1.694414	0.862715
H	-4.073240	-2.712215	1.135478
H	-3.926653	-1.053490	1.737854
H	-4.445656	-1.342105	0.071199
O	-1.704902	-2.740383	-0.921736
O	-1.078602	-2.131574	1.593133
C	-2.045238	-2.533889	-2.282146
H	-1.624880	-3.357522	-2.868008
H	-3.134791	-2.529773	-2.427047
H	-1.639468	-1.586913	-2.659127
C	0.226821	-2.699349	1.554208
H	0.390832	-3.225470	2.499889
H	0.326374	-3.411618	0.727870
H	0.986072	-1.917510	1.445657
C	-0.705727	3.506635	-0.383143
H	-1.126583	3.931608	0.535314
H	0.373421	3.400990	-0.243461
H	-0.869946	4.233074	-1.185873
H	-0.886092	1.813818	-1.681219

TS1a

B3LYP electronic energy: -3078.10612418 a.u.
B3LYP enthalpy: -3077.312134 a.u.
B3LYP free energy: -3077.449597 a.u.
M06 SCF energy in solution: -3077.45328999 a.u.
M06 enthalpy in solution: -3076.659300 a.u.
M06 free energy in solution: -3076.796763 a.u.

Imaginary frequency: -841.9506 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.635457	-2.111760	2.435362
P	0.335145	0.361565	-0.232571
C	-0.070438	-0.441717	1.370620
C	-1.148038	-1.393148	1.584734
C	-1.280394	-1.557677	3.001665
H	-1.969844	-2.227905	3.496205
C	-0.316097	-0.740950	3.662116
H	-0.157951	-0.681308	4.731322
C	0.436669	-0.065662	2.664011
H	1.246682	0.628740	2.841327
C	1.038038	-4.034571	1.721597
H	0.421485	-4.580110	1.018775
C	0.908364	-4.048182	3.143711
C	2.648114	-2.631254	2.596903
H	3.460194	-1.920722	2.675313
C	2.113484	-3.162144	1.385468
H	2.450691	-2.928850	0.386102
C	0.824726	2.080375	0.251382
C	0.104493	2.788660	1.229319
H	-0.679845	2.294098	1.791817
C	0.377438	4.128953	1.489906
H	-0.187427	4.658756	2.250178
C	1.367584	4.797854	0.764523
C	2.074116	4.116937	-0.228393
H	2.832070	4.635149	-0.806779
C	1.801596	2.773873	-0.483722
H	2.361404	2.266559	-1.262815
C	1.948875	-0.364486	-0.791564
C	3.162037	-0.179782	-0.107699
H	3.195282	0.430933	0.789458
C	4.334966	-0.772650	-0.568286
H	5.267665	-0.629664	-0.032225
C	4.308889	-1.567944	-1.719902
C	3.111332	-1.755335	-2.412416
H	3.092330	-2.370466	-3.306453
C	1.939816	-1.150228	-1.951877
H	1.005606	-1.280496	-2.494570
C	1.904205	-3.180819	3.684391
H	2.047940	-2.954721	4.733211
C	-1.979059	-2.129829	0.543943
P	-3.054336	-0.946090	-0.530232
C	-3.992795	-2.102473	-1.761590
C	-4.478893	-1.221526	-2.937189
C	-2.965035	-3.095291	-2.353570
C	-5.199177	-2.880658	-1.199350
H	-5.221344	-0.479662	-2.635132
H	-3.640902	-0.699084	-3.407078
H	-4.945469	-1.865778	-3.694539
H	-2.630592	-3.849723	-1.635606
H	-3.433255	-3.631101	-3.189692

H	-2.087244	-2.566872	-2.741760
H	-5.611417	-3.518451	-1.993261
H	-4.938538	-3.533092	-0.362721
H	-6.004481	-2.217283	-0.872126
C	-4.296485	-0.036624	0.630888
C	-4.935909	-0.907793	1.729388
C	-3.508233	1.107973	1.308407
C	-5.410370	0.621140	-0.210502
H	-5.462869	-1.779548	1.332257
H	-4.193987	-1.250044	2.456296
H	-5.670021	-0.303874	2.280150
H	-3.107114	1.805534	0.567077
H	-4.190541	1.665632	1.964557
H	-2.688623	0.732134	1.926998
H	-6.010685	1.261382	0.449818
H	-5.000107	1.261768	-0.995967
H	-6.091502	-0.107403	-0.658570
H	0.166681	-4.594950	3.712058
C	5.584229	-2.172050	-2.246226
C	1.707388	6.225738	1.091891
F	6.474158	-2.406769	-1.256841
F	5.359479	-3.343743	-2.879575
F	6.190456	-1.353340	-3.136310
F	0.631915	6.909833	1.539957
F	2.196299	6.887332	0.020419
F	2.650339	6.301740	2.062394
Cu	-1.485844	0.310952	-1.629752
H	-1.099771	-0.200256	-3.133134
C	-1.767084	2.301424	-2.517959
C	-1.324406	1.367450	-3.508582
H	-2.028284	1.102898	-4.296161
H	-1.012290	2.910253	-2.024555
C	-3.136344	2.774178	-2.463647
C	-3.614777	3.828819	-1.767829
H	-0.303417	1.455278	-3.871448
H	-3.842228	2.220138	-3.089762
H	-4.658380	4.121700	-1.829101
H	-2.970338	4.437630	-1.136626
C	-2.641087	-3.385305	1.146508
H	-3.059252	-4.026313	0.369951
H	-1.885830	-3.971001	1.681632
H	-3.442738	-3.153418	1.850057
H	-1.280517	-2.477572	-0.225848

TS1b

B3LYP electronic energy: -3078.10425366 a.u.
B3LYP enthalpy: -3077.310245 a.u.
B3LYP free energy: -3077.447076 a.u.
M06 SCF energy in solution: -3077.45272553 a.u.
M06 enthalpy in solution: -3076.658717 a.u.
M06 free energy in solution: -3076.795548 a.u.

Imaginary frequency: -844.7746 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.075120	-2.069248	2.498294
P	0.387171	0.282519	-0.281775
C	-0.241676	-0.313888	1.344587
C	-1.554785	-0.882846	1.598585
C	-1.721921	-0.926722	3.021019
H	-2.579870	-1.327803	3.542610
C	-0.549132	-0.412950	3.647322
H	-0.370814	-0.352517	4.713298
C	0.365372	-0.050523	2.622455
H	1.349374	0.372116	2.771866
C	-0.308312	-4.063266	1.911913
H	-1.082261	-4.432085	1.251270
C	-0.397939	-3.945901	3.332258
C	1.680505	-3.179021	2.679752
H	2.675917	-2.756174	2.706160
C	0.973990	-3.590099	1.510096
H	1.338186	-3.533892	0.494744
C	1.442163	1.732926	0.177955
C	0.970644	2.689252	1.093119
H	0.033998	2.526584	1.614698
C	1.684922	3.858386	1.340674
H	1.304962	4.584639	2.051554
C	2.878706	4.108203	0.659110
C	3.344868	3.184119	-0.278759
H	4.261337	3.381896	-0.825357
C	2.631117	2.011692	-0.518786
H	3.010162	1.311193	-1.255468
C	1.647322	-0.965012	-0.833785
C	2.853006	-1.190577	-0.147730
H	3.094438	-0.606694	0.735203
C	3.755760	-2.151414	-0.594195
H	4.690436	-2.311300	-0.065888
C	3.460828	-2.909475	-1.734069
C	2.269811	-2.692064	-2.427724
H	2.049690	-3.268012	-3.320728
C	1.371931	-1.718840	-1.981404
H	0.451466	-1.528103	-2.529482
C	0.832785	-3.401021	3.806670
H	1.068320	-3.166268	4.836819
C	-2.583076	-1.381375	0.592787
P	-3.240312	0.018213	-0.549066
C	-4.500148	-0.849460	-1.730755
C	-4.695964	0.073470	-2.957343
C	-3.833121	-2.141963	-2.256798
C	-5.887676	-1.181936	-1.145900
H	-5.182372	1.018440	-2.705233
H	-3.740808	0.296059	-3.440680
H	-5.334819	-0.439802	-3.688738
H	-3.749844	-2.924045	-1.496715
H	-4.445033	-2.547984	-3.072707

H	-2.834291	-1.935185	-2.657404
H	-6.477951	-1.709570	-1.907624
H	-5.841222	-1.827688	-0.266064
H	-6.447119	-0.281933	-0.875546
C	-4.128408	1.331741	0.547932
C	-5.020091	0.769648	1.671807
C	-3.019360	2.197746	1.189654
C	-4.968368	2.265688	-0.349213
H	-5.789745	0.084555	1.306268
H	-4.427446	0.253886	2.432472
H	-5.531960	1.602412	2.173229
H	-2.392129	2.677561	0.431709
H	-3.491562	2.986850	1.790916
H	-2.378161	1.615368	1.857080
H	-5.305934	3.120865	0.251062
H	-4.380797	2.661554	-1.183152
H	-5.862249	1.779626	-0.749888
H	-1.257615	-4.196700	3.940615
C	4.408789	-3.994447	-2.171768
C	3.682752	5.340991	0.965832
F	5.695996	-3.664235	-1.926331
F	4.169316	-5.153415	-1.514185
F	4.299908	-4.259691	-3.490793
F	2.903127	6.362731	1.382348
F	4.377837	5.770236	-0.110603
F	4.588144	5.114072	1.949145
Cu	-1.375985	0.739979	-1.677136
H	-1.110771	0.113237	-3.161452
C	-1.523136	2.694359	-2.676923
C	-1.156500	1.674985	-3.612586
H	-1.873369	1.420016	-4.388981
H	-2.574651	2.973635	-2.637976
C	-0.578873	3.648659	-2.131139
C	-0.868493	4.810869	-1.506952
H	-0.129499	1.671232	-3.974906
H	0.475278	3.395752	-2.268559
H	-0.085502	5.473673	-1.153265
H	-1.895513	5.136919	-1.351755
C	-3.600765	-2.329723	1.256422
H	-4.215248	-2.837797	0.512460
H	-3.064583	-3.100869	1.819814
H	-4.274149	-1.821265	1.949030
H	-2.036589	-1.970850	-0.152366

TS1c

B3LYP electronic energy: -3078.09148035 a.u.
B3LYP enthalpy: -3077.298739 a.u.
B3LYP free energy: -3077.437837 a.u.
M06 SCF energy in solution: -3077.43543222 a.u.
M06 enthalpy in solution: -3076.642691 a.u.
M06 free energy in solution: -3076.781789 a.u.

Imaginary frequency: -544.2584 cm-1

Cartesian coordinates

ATOM	X	Y	Z
H	-1.926299	2.857720	-0.636857
C	-2.934303	3.833825	-2.767225
C	-2.328655	4.414053	-1.672075
H	-2.877237	5.110821	-1.042178
C	-2.325312	2.748116	-3.446044
C	-1.097475	2.198506	-3.097889
H	-1.251123	4.483593	-1.590598
H	-0.706733	1.374074	-3.693948
H	-3.991832	4.016968	-2.949278
H	-2.926146	2.221900	-4.189224
H	-0.339540	2.804434	-2.610939
Cu	-1.647003	1.283412	-1.069417
P	0.399852	0.359085	-0.213858
P	-3.198878	-0.320831	-0.357270
C	-0.072013	-0.314794	1.433873
C	1.405330	1.856385	0.207009
C	1.690082	-0.795943	-0.892478
C	-2.371401	-1.590091	0.832136
C	-4.687137	0.489472	0.551705
C	-3.789678	-1.408070	-1.845428
Fe	0.302338	-2.058880	2.549228
C	-1.321988	-0.983084	1.763998
C	0.595892	-0.015007	2.673123
C	0.923839	2.775799	1.156931
C	2.549025	2.202828	-0.530620
C	2.947257	-0.999396	-0.297226
C	1.384823	-1.498331	-2.066088
C	-3.308513	-2.528738	1.619289
H	-1.829024	-2.208236	0.105527
C	-5.920676	-0.400844	0.794255
C	-4.137944	1.006084	1.900308
C	-5.121255	1.730563	-0.262541
C	-4.700013	-0.551974	-2.750901
C	-2.514953	-1.745573	-2.651209
C	-4.515552	-2.728928	-1.524588
C	0.140827	-4.070250	2.002303
C	-1.385708	-1.049867	3.195023
C	-0.218075	-0.452411	3.750044
H	1.553005	0.480264	2.761361
H	0.014537	2.561200	1.707234
C	1.590414	3.974047	1.394789
C	3.213900	3.407401	-0.301209
H	2.931951	1.534360	-1.294266
H	3.214132	-0.455996	0.603671
C	3.864361	-1.887756	-0.851893
C	2.295854	-2.399514	-2.622744
H	0.427603	-1.338565	-2.552959
H	-4.024608	-3.032210	0.971798
H	-2.718784	-3.297929	2.130197
H	-3.878399	-1.993394	2.382732

H	-6.389607	-0.717187	-0.142766
H	-5.696821	-1.294239	1.381946
H	-6.672498	0.177046	1.349236
H	-3.265742	1.651880	1.751505
H	-4.915540	1.603357	2.394562
H	-3.856778	0.200819	2.583956
H	-5.856631	2.295839	0.326490
H	-4.272789	2.387203	-0.476024
H	-5.598209	1.465143	-1.208654
H	-5.692685	-0.405635	-2.315531
H	-4.264340	0.429872	-2.961818
H	-4.838634	-1.070645	-3.708979
H	-1.796547	-2.334072	-2.069099
H	-2.789036	-2.343712	-3.530819
H	-2.011969	-0.837896	-2.999310
H	-4.862422	-3.181699	-2.463669
H	-3.852630	-3.457909	-1.048438
H	-5.392928	-2.588600	-0.887749
H	-0.678827	-4.499828	1.440711
C	0.211685	-3.944607	3.422952
C	1.331977	-3.516066	1.450093
H	-2.170198	-1.518010	3.772161
H	0.023683	-0.386823	4.803169
H	1.205533	4.670080	2.133072
C	2.741986	4.293025	0.668487
H	4.095368	3.658414	-0.882231
H	4.835764	-2.031228	-0.389154
C	3.535728	-2.595461	-2.014380
H	2.047739	-2.935466	-3.532975
C	1.449033	-3.312450	3.746937
H	-0.550227	-4.248848	4.129269
C	2.141358	-3.046017	2.527748
H	1.571259	-3.447018	0.398549
C	3.496065	5.558900	0.967447
C	4.500460	-3.609837	-2.569402
H	1.787796	-3.051731	4.741484
H	3.102253	-2.557797	2.436239
F	2.677463	6.546449	1.392117
F	4.162146	6.018225	-0.114869
F	4.418794	5.370882	1.942765
F	4.330192	-3.796287	-3.895616
F	5.784905	-3.242788	-2.369303
F	4.339431	-4.816057	-1.976693

TS2_cis

B3LYP electronic energy: -3078.14233408 a.u.
B3LYP enthalpy: -3077.343631 a.u.
B3LYP free energy: -3077.481748 a.u.
M06 SCF energy in solution: -3077.49171900 a.u.
M06 enthalpy in solution: -3076.693016 a.u.
M06 free energy in solution: -3076.831133 a.u.

Imaginary frequency: -61.8711 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.459217	-1.763626	-2.775786
P	-0.495758	0.272369	0.138684
C	0.170170	-0.093502	-1.530129
C	1.575875	-0.228307	-1.873757
C	1.653299	-0.157211	-3.305560
H	2.550511	-0.259545	-3.898311
C	0.345832	0.007975	-3.845024
H	0.094100	0.060091	-4.896582
C	-0.567878	0.031337	-2.759820
H	-1.640179	0.148562	-2.833429
C	1.348973	-3.603079	-2.345387
H	2.261797	-3.730567	-1.777422
C	1.257027	-3.413759	-3.757782
C	-0.881310	-3.358667	-2.887459
H	-1.956422	-3.269342	-2.806396
C	0.029053	-3.569704	-1.808426
H	-0.235255	-3.664771	-0.764837
C	-1.950314	1.356215	-0.227400
C	-1.789010	2.460544	-1.084365
H	-0.846988	2.611500	-1.601430
C	-2.824687	3.367551	-1.286619
H	-2.689316	4.203442	-1.965284
C	-4.041936	3.202159	-0.617398
C	-4.209254	2.127725	0.256342
H	-5.150910	1.995550	0.779275
C	-3.171884	1.214524	0.449859
H	-3.327169	0.384796	1.130912
C	-1.295683	-1.278112	0.767397
C	-2.330818	-1.947489	0.091755
H	-2.700253	-1.560730	-0.853044
C	-2.889136	-3.107899	0.619148
H	-3.684544	-3.622981	0.089266
C	-2.413502	-3.621712	1.832648
C	-1.391648	-2.964789	2.517442
H	-1.027332	-3.362049	3.458949
C	-0.841157	-1.794384	1.987465
H	-0.058957	-1.267080	2.527406
C	-0.122018	-3.263638	-4.092209
H	-0.519161	-3.078382	-5.081991
C	2.777271	-0.495421	-0.965986
P	3.100129	0.802263	0.430674
C	4.185565	-0.187309	1.704889
C	4.763102	0.816343	2.724806
C	3.215114	-1.125951	2.457282
C	5.347567	-1.050801	1.171088
H	5.570073	1.418849	2.297789
H	3.997594	1.485679	3.122394
H	5.186931	0.258046	3.570030
H	2.752522	-1.864830	1.791378
H	3.775182	-1.683079	3.220637

H	2.415982	-0.562647	2.948682
H	5.912703	-1.437779	2.029924
H	4.992805	-1.921754	0.612139
H	6.050990	-0.494885	0.546080
C	4.105174	2.252465	-0.347752
C	5.578662	1.958602	-0.692029
C	3.347597	2.677720	-1.624219
C	4.056879	3.449518	0.627229
H	6.174820	1.742005	0.199419
H	5.699528	1.129556	-1.392740
H	6.016763	2.849982	-1.161494
H	2.290234	2.871829	-1.413724
H	3.787380	3.607738	-2.008091
H	3.404781	1.932292	-2.421209
H	4.541003	4.313412	0.151828
H	3.025221	3.723852	0.861608
H	4.582251	3.253906	1.565069
H	2.087358	-3.361511	-4.450379
C	-3.054652	-4.855445	2.411615
C	-5.140843	4.214656	-0.788981
F	-3.346896	-5.760057	1.449909
F	-2.258793	-5.464532	3.315644
F	-4.217242	-4.561968	3.037654
F	-5.036791	5.222542	0.107270
F	-6.364043	3.663894	-0.619123
F	-5.116994	4.779506	-2.017426
Cu	1.106755	1.338472	1.442956
C	0.638145	1.800622	3.505808
C	-0.096578	2.661915	2.620154
H	-1.131508	2.369135	2.429065
C	0.371476	3.726478	1.863248
H	-0.300891	4.262218	1.201276
H	1.328144	4.195641	2.070918
H	0.002617	1.097562	4.046358
C	1.769060	2.355401	4.355730
H	2.359505	1.554089	4.817358
H	2.463115	2.975779	3.776431
H	1.394632	2.990657	5.177771
C	3.993922	-0.887823	-1.830350
H	3.748348	-1.769831	-2.432447
H	4.275401	-0.089360	-2.520810
H	4.869704	-1.125782	-1.233614
H	2.517922	-1.365083	-0.349257

TS2_trans

B3LYP electronic energy: -3078.14624984 a.u.
B3LYP enthalpy: -3077.348314 a.u.
B3LYP free energy: -3077.486669 a.u.
M06 SCF energy in solution: -3077.49373086 a.u.
M06 enthalpy in solution: -3076.695795 a.u.
M06 free energy in solution: -3076.834150 a.u.

```
Imaginary frequency:             -53.0709 cm-1

Cartesian coordinates
ATOM       X           Y           Z
Fe       0.430714    1.847782    2.707640
P       -0.456917   -0.299058   -0.122704
C        0.217870    0.119025    1.533948
C        1.615984    0.318272    1.892114
C        1.670576    0.308450    3.327304
H        2.553850    0.465794    3.928373
C        0.361692    0.122328    3.855384
H        0.095946    0.106125    4.904641
C       -0.532865    0.021933    2.759691
H       -1.601632   -0.129063    2.824012
C        1.227080    3.692715    2.148608
H        2.116938    3.824758    1.546084
C        1.186157    3.580773    3.571638
C       -0.973494    3.389047    2.776147
H       -2.045080    3.249141    2.732253
C       -0.106774    3.574968    1.657871
H       -0.407180    3.594842    0.619781
C       -1.760733   -1.553160    0.260010
C       -1.537421   -2.558496    1.218996
H       -0.636461   -2.542029    1.823583
C       -2.463654   -3.577056    1.415060
H       -2.284701   -4.334087    2.172481
C       -3.629941   -3.624821    0.642932
C       -3.854985   -2.649755   -0.328591
H       -4.755870   -2.683467   -0.931841
C       -2.927805   -1.624497   -0.518035
H       -3.124952   -0.874921   -1.277408
C       -1.457060    1.162653   -0.670322
C       -2.588755    1.629927    0.019319
H       -2.930759    1.119285    0.914210
C       -3.287568    2.744346   -0.435817
H       -4.158998    3.102293    0.103566
C       -2.859519    3.413226   -1.589303
C       -1.742649    2.955420   -2.288812
H       -1.416303    3.470577   -3.186225
C       -1.050235    1.830805   -1.832654
H       -0.195087    1.452485   -2.387319
C       -0.174431    3.393318    3.958850
H       -0.532698    3.248033    4.969952
C        2.840719    0.592180    1.010429
P        3.144611   -0.643233   -0.433420
C        4.326072    0.320339   -1.636519
C        4.759276   -0.673486   -2.736744
C        3.457710    1.414018   -2.298469
C        5.591990    1.000658   -1.075066
H        5.496340   -1.394998   -2.371486
H        3.908038   -1.222211   -3.149796
H        5.228011   -0.115015   -3.557633
H        3.123199    2.170589   -1.578277
H        4.053642    1.934370   -3.060344
```

H	2.574862	0.984205	-2.781993
H	6.202816	1.348548	-1.919107
H	5.353878	1.885734	-0.478211
H	6.217456	0.333988	-0.476390
C	4.003892	-2.206853	0.291868
C	5.490862	-2.053316	0.664849
C	3.202291	-2.618700	1.545976
C	3.862806	-3.352056	-0.736114
H	6.116751	-1.863251	-0.212265
H	5.667862	-1.255693	1.390947
H	5.844579	-2.991024	1.114962
H	2.137491	-2.742082	1.321528
H	3.578558	-3.585134	1.906637
H	3.295893	-1.901278	2.365116
H	4.242472	-4.280051	-0.287381
H	2.817643	-3.511439	-1.017879
H	4.436891	-3.171172	-1.648309
H	2.039067	3.602773	4.238015
C	-3.649808	4.588240	-2.102108
C	-4.601847	-4.754047	0.845333
F	-4.148689	5.332732	-1.089753
F	-2.900715	5.402469	-2.875829
F	-4.703478	4.188177	-2.849997
F	-4.157711	-5.904535	0.288934
F	-5.809940	-4.490427	0.302287
F	-4.795359	-5.011310	2.160559
Cu	1.174026	-0.962763	-1.586205
C	0.530541	-1.292039	-3.519372
C	0.912891	-2.645606	-3.147769
H	1.902642	-2.961251	-3.494686
C	0.246636	-3.525917	-2.336498
H	0.675605	-4.490948	-2.083686
H	-0.763876	-3.330704	-1.986954
H	-0.553827	-1.135125	-3.495738
C	1.155090	-0.706571	-4.779658
H	1.001942	0.378660	-4.846293
H	2.239939	-0.874584	-4.812067
H	0.739812	-1.141176	-5.705837
C	4.059231	0.923557	1.896590
H	3.844412	1.803467	2.514135
H	4.307469	0.100672	2.572074
H	4.947101	1.142622	1.309532
H	2.609675	1.491005	0.426181

TS3a_1

B3LYP electronic energy: -3616.68484128 a.u.
B3LYP enthalpy: -3615.687531 a.u.
B3LYP free energy: -3615.850824 a.u.
M06 SCF energy in solution: -3615.78874008 a.u.
M06 enthalpy in solution: -3614.791430 a.u.
M06 free energy in solution: -3614.954723 a.u.

Imaginary frequency: -222.8559 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-4.464205	-1.086153	0.056417
P	-1.138190	0.462213	-0.233477
C	-2.664158	-0.398419	-0.796858
C	-2.813630	-1.827829	-1.018072
C	-4.034114	-2.003321	-1.750922
H	-4.460248	-2.949910	-2.051005
C	-4.639145	-0.734151	-1.977078
H	-5.583633	-0.559245	-2.476270
C	-3.811766	0.250597	-1.376685
H	-3.995334	1.315969	-1.370849
C	-4.790440	-2.265086	1.749952
H	-4.224971	-3.150152	2.011688
C	-5.962342	-2.226604	0.935231
C	-5.462813	-0.064319	1.574188
H	-5.497239	1.012242	1.674250
C	-4.482641	-0.931064	2.144746
H	-3.641516	-0.627614	2.751369
C	-1.243268	2.100368	-1.090134
C	-1.553225	2.159464	-2.461291
H	-1.842621	1.258310	-2.991981
C	-1.498714	3.362857	-3.159249
H	-1.743901	3.388428	-4.215994
C	-1.114564	4.536220	-2.504278
C	-0.777559	4.491770	-1.150302
H	-0.462714	5.396515	-0.640381
C	-0.837325	3.285720	-0.453476
H	-0.563751	3.276961	0.596058
C	-1.415876	0.915146	1.544212
C	-2.400986	1.821148	1.973471
H	-3.037355	2.317359	1.247359
C	-2.567922	2.102050	3.326557
H	-3.324007	2.811045	3.648962
C	-1.754837	1.471262	4.276072
C	-0.768089	0.574965	3.865161
H	-0.126032	0.100611	4.599948
C	-0.595992	0.307709	2.504625
H	0.190846	-0.368452	2.185358
C	-6.378374	-0.865862	0.828162
H	-7.220895	-0.502734	0.253618
C	-1.936680	-2.979439	-0.528494
P	-0.117545	-2.935756	-1.158129
C	0.838292	-4.008638	0.143970
C	2.283100	-4.185339	-0.371964
C	0.911721	-3.172831	1.442785
C	0.268722	-5.393725	0.513861
H	2.341138	-4.882544	-1.213372
H	2.723319	-3.227611	-0.662952
H	2.899029	-4.600959	0.436485
H	-0.079659	-2.964731	1.863719
H	1.465198	-3.747076	2.198343

H	1.439063	-2.230096	1.278418
H	1.003060	-5.912301	1.145150
H	-0.649502	-5.315213	1.103779
H	0.074744	-6.033306	-0.349782
C	-0.082031	-3.779999	-2.894995
C	-0.240427	-5.312630	-2.923966
C	-1.205324	-3.126629	-3.729523
C	1.255087	-3.422547	-3.582337
H	0.609624	-5.818342	-2.456461
H	-1.154784	-5.661629	-2.439408
H	-0.275921	-5.645936	-3.970372
H	-1.146874	-2.033027	-3.697467
H	-1.097829	-3.434669	-4.778018
H	-2.204854	-3.421110	-3.401082
H	1.260059	-3.858146	-4.590725
H	1.377203	-2.342679	-3.681431
H	2.125404	-3.813498	-3.050541
H	-6.436117	-3.075017	0.458102
C	-1.990271	1.725196	5.741864
C	-1.122045	5.849396	-3.237399
F	-2.379786	2.998374	5.971880
F	-2.965425	0.922487	6.228674
F	-0.883890	1.495899	6.479834
F	-2.322788	6.468643	-3.131373
F	-0.878677	5.692766	-4.556667
F	-0.197702	6.704914	-2.748960
C	1.582448	0.273602	-2.772800
C	2.280617	1.364584	-2.231856
C	3.605740	1.365648	-1.788918
O	2.512182	-0.686504	-0.032144
C	3.285359	0.300051	0.237256
C	2.701368	1.470741	1.014078
H	3.290527	2.386474	0.929982
H	2.633750	1.208621	2.081027
H	1.691278	1.671026	0.652006
Cu	0.729358	-0.721009	-1.043688
H	2.180012	-0.522651	-3.214566
H	0.655582	0.487594	-3.305479
C	4.737572	-0.008361	0.414479
C	5.586762	0.768776	1.187730
C	5.273692	-1.175872	-0.210094
C	6.958522	0.437094	1.360025
H	5.213947	1.650588	1.700123
C	6.594151	-1.518029	-0.071467
H	4.604253	-1.785390	-0.806673
C	7.481641	-0.729360	0.714976
C	7.832796	1.226392	2.155478
H	6.983265	-2.407911	-0.562251
C	8.851590	-1.055348	0.884635
C	9.159557	0.883927	2.302793
H	7.435955	2.111939	2.647247
C	9.675531	-0.267650	1.660631
H	9.243294	-1.941671	0.390159
H	9.815811	1.498726	2.913267

H	10.723567	-0.528193	1.782413
H	4.225759	0.537948	-2.130596
C	4.340757	2.659851	-1.542382
H	4.866467	3.005317	-2.445414
H	3.652212	3.461921	-1.246568
H	5.104404	2.560652	-0.759139
H	1.704471	2.275749	-2.048341
C	-2.693106	-4.317457	-0.659759
H	-3.639522	-4.264027	-0.110144
H	-2.933642	-4.554045	-1.698924
H	-2.120823	-5.151260	-0.258935
H	-1.762730	-2.810332	0.541301

TS3a_2

B3LYP electronic energy: -3616.67853770 a.u.
B3LYP enthalpy: -3615.681000 a.u.
B3LYP free energy: -3615.843446 a.u.
M06 SCF energy in solution: -3615.78046678 a.u.
M06 enthalpy in solution: -3614.782929 a.u.
M06 free energy in solution: -3614.945375 a.u.
Imaginary frequency: -240.1079 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-3.998216	-2.187643	-0.638810
P	-1.279952	0.337146	-0.222255
C	-2.387066	-0.882663	-1.042965
C	-2.033305	-2.249950	-1.394337
C	-2.985410	-2.681835	-2.376283
H	-3.033160	-3.665045	-2.821802
C	-3.913377	-1.632228	-2.631165
H	-4.762405	-1.681518	-3.300940
C	-3.560647	-0.535546	-1.802950
H	-4.070994	0.416288	-1.759935
C	-4.237662	-3.656250	0.832267
H	-3.477726	-4.368360	1.127151
C	-5.196383	-3.831939	-0.211270
C	-5.522502	-1.742067	0.715604
H	-5.915802	-0.751576	0.903711
C	-4.438349	-2.366948	1.403807
H	-3.856829	-1.932239	2.204085
C	-1.880259	1.953733	-0.898272
C	-1.943679	2.132926	-2.293779
H	-1.739441	1.298308	-2.957296
C	-2.268870	3.368015	-2.845599
H	-2.313069	3.486299	-3.923427
C	-2.518253	4.463456	-2.012662
C	-2.435988	4.310353	-0.628363
H	-2.616141	5.159838	0.022418
C	-2.118238	3.068180	-0.077980
H	-2.059720	2.976057	1.000773

C	-1.720169	0.473508	1.569165
C	-3.034247	0.628498	2.040648
H	-3.861468	0.648330	1.338522
C	-3.287636	0.766644	3.402886
H	-4.304242	0.894697	3.761277
C	-2.224118	0.754349	4.313511
C	-0.912981	0.619173	3.856561
H	-0.089191	0.630803	4.562683
C	-0.661442	0.483664	2.488860
H	0.360478	0.408271	2.126586
C	-5.992054	-2.649480	-0.280717
H	-6.789967	-2.460953	-0.987523
C	-0.944120	-3.147687	-0.808304
P	0.866481	-2.515406	-1.027769
C	1.786575	-3.359855	0.454576
C	3.307500	-3.215427	0.246310
C	1.413388	-2.542388	1.712169
C	1.471198	-4.842245	0.737594
H	3.684443	-3.872964	-0.542768
H	3.588635	-2.184828	0.017553
H	3.820768	-3.495594	1.175470
H	0.334133	-2.535123	1.906033
H	1.894717	-2.999093	2.587732
H	1.759911	-1.509482	1.630656
H	2.128944	-5.189433	1.545827
H	0.443546	-4.987451	1.084115
H	1.645163	-5.492885	-0.123670
C	1.524854	-3.171463	-2.714934
C	1.784314	-4.686783	-2.828514
C	0.489275	-2.738558	-3.776718
C	2.846536	-2.432783	-3.032495
H	2.566260	-5.021536	-2.140122
H	0.892595	-5.290886	-2.650273
H	2.134349	-4.912070	-3.845398
H	0.284720	-1.663750	-3.723859
H	0.887255	-2.953733	-4.777177
H	-0.462665	-3.266594	-3.679751
H	3.138483	-2.657376	-4.067293
H	2.739288	-1.349503	-2.935287
H	3.667837	-2.750037	-2.385822
H	-5.283838	-4.695224	-0.858562
C	-2.508322	0.838280	5.790153
C	-2.924710	5.782555	-2.609662
F	-3.588173	1.608924	6.049133
F	-2.764551	-0.383648	6.313356
F	-1.466375	1.351504	6.477647
F	-4.264340	5.849036	-2.803786
F	-2.346828	5.988643	-3.813479
F	-2.592954	6.822094	-1.813575
C	1.553843	1.184452	-2.434654
C	2.790002	1.743437	-2.079165
C	2.996218	2.802964	-1.192204
O	2.228920	0.581647	0.591692
C	2.946733	1.627711	0.779633

C	2.297595	2.768935	1.557447
H	2.798100	3.732252	1.425438
H	2.300004	2.532362	2.632622
H	1.256593	2.869168	1.240127
Cu	0.963474	-0.165027	-0.843534
H	1.541193	0.507760	-3.289034
H	0.683613	1.838274	-2.377534
C	4.427617	1.429675	0.933443
C	5.057352	0.381111	0.280527
C	5.219759	2.269128	1.770180
C	6.444761	0.135357	0.412566
H	4.466633	-0.255921	-0.369646
C	6.569696	2.050514	1.931777
H	4.752512	3.089031	2.305641
C	7.226941	0.986141	1.262550
C	7.096754	-0.931837	-0.268786
H	7.151807	2.699398	2.582698
C	8.618552	0.734195	1.399826
C	8.447144	-1.148422	-0.116580
H	6.505089	-1.575885	-0.915731
C	9.217216	-0.307793	0.727586
H	9.205772	1.382407	2.046686
H	8.930751	-1.966662	-0.643936
H	10.282756	-0.489735	0.839911
H	2.103701	3.374434	-0.932388
C	4.276478	3.604948	-1.226048
H	5.140674	2.970334	-1.453542
H	4.234995	4.392617	-1.993802
H	4.483540	4.105870	-0.271935
H	3.689171	1.237519	-2.444012
C	-1.216441	-4.618125	-1.188362
H	-2.214700	-4.909129	-0.843856
H	-1.187818	-4.774008	-2.269368
H	-0.496587	-5.299559	-0.741080
H	-1.034540	-3.073702	0.282475

TS3a_3

B3LYP electronic energy: -3616.67597865 a.u.
B3LYP enthalpy: -3615.677497 a.u.
B3LYP free energy: -3615.838396 a.u.
M06 SCF energy in solution: -3615.78219078 a.u.
M06 enthalpy in solution: -3614.783709 a.u.
M06 free energy in solution: -3614.944608 a.u.
Imaginary frequency: -228.5659 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	4.296261	0.917379	-0.535379
P	0.903907	0.531268	0.431780
C	2.707033	0.444708	0.746569
C	3.606831	-0.695739	0.634575

C	4.893983	-0.227825	1.077318
H	5.803896	-0.810755	1.090028
C	4.809617	1.139702	1.458549
H	5.630522	1.758422	1.798208
C	3.472012	1.557949	1.248258
H	3.081209	2.553392	1.408939
C	4.828560	0.265832	-2.446170
H	4.865791	-0.767249	-2.765976
C	5.902105	0.997558	-1.856216
C	4.069500	2.397196	-1.986498
H	3.423624	3.257720	-1.878751
C	3.695882	1.129056	-2.526682
H	2.721614	0.856582	-2.908644
C	0.170587	0.422774	2.134277
C	0.891603	0.639110	3.318965
H	1.948585	0.881852	3.278481
C	0.263660	0.538831	4.560010
H	0.827515	0.711698	5.471302
C	-1.096502	0.226106	4.631645
C	-1.823898	0.002862	3.459483
H	-2.878698	-0.246574	3.513900
C	-1.192693	0.092654	2.219597
H	-1.746219	-0.134878	1.312432
C	0.629324	2.339386	0.072231
C	0.373458	3.293299	1.070728
H	0.342532	2.997156	2.113640
C	0.153119	4.631332	0.745020
H	-0.033291	5.357573	1.529574
C	0.179026	5.039771	-0.589896
C	0.418585	4.101975	-1.597702
H	0.431960	4.413580	-2.637256
C	0.637167	2.766231	-1.265322
H	0.812487	2.047274	-2.056230
C	5.432488	2.315289	-1.574160
H	5.999887	3.103050	-1.095339
C	3.458304	-2.169210	0.194674
P	1.734129	-2.870240	-0.307862
C	2.273052	-4.107314	-1.708396
C	1.080285	-5.011015	-2.082025
C	2.593867	-3.252233	-2.952853
C	3.500252	-4.997334	-1.421616
H	0.853388	-5.753847	-1.313209
H	0.175963	-4.426415	-2.276335
H	1.323004	-5.559645	-3.001860
H	3.370040	-2.502475	-2.766094
H	2.958161	-3.906124	-3.756147
H	1.705485	-2.733055	-3.314245
H	3.664323	-5.655204	-2.285933
H	4.416899	-4.414198	-1.289926
H	3.372039	-5.638892	-0.547678
C	1.000077	-3.884454	1.179200
C	1.640403	-5.249163	1.506184
C	1.059789	-2.998288	2.439263
C	-0.495516	-4.118800	0.863810

H	1.586578	-5.954726	0.673119
H	2.681450	-5.170367	1.825718
H	1.082969	-5.698931	2.339032
H	0.509963	-2.067268	2.301552
H	0.584837	-3.534869	3.271248
H	2.078564	-2.753943	2.748930
H	-0.975703	-4.562587	1.746572
H	-1.013241	-3.186059	0.624514
H	-0.644661	-4.810778	0.030945
H	6.889708	0.612763	-1.635630
C	-0.114556	6.472378	-0.946409
C	-1.754629	0.061949	5.975168
F	0.531682	6.851888	-2.071150
F	-1.434138	6.671409	-1.164927
F	0.253111	7.320366	0.040032
F	-1.612209	-1.199074	6.447933
F	-3.079788	0.315183	5.924305
F	-1.217019	0.887911	6.901303
C	0.053450	-0.539075	-3.153353
C	-1.075962	-1.243080	-3.603957
C	-2.402621	-0.812830	-3.510153
O	-1.839338	-1.246883	-0.701554
C	-2.802116	-1.679407	-1.428142
C	-2.797260	-3.154799	-1.816269
H	-1.772466	-3.472725	-2.010876
H	-3.403601	-3.376836	-2.697697
H	-3.185505	-3.752506	-0.978849
Cu	0.227489	-1.160950	-1.069092
H	1.027366	-0.860848	-3.516302
H	-0.047134	0.540392	-3.067814
C	-4.144385	-1.032112	-1.242898
C	-5.321583	-1.585896	-1.723687
C	-4.228530	0.184484	-0.501925
C	-6.583317	-0.974683	-1.504924
H	-5.304375	-2.512410	-2.289674
C	-5.433487	0.801887	-0.272578
H	-3.308906	0.617954	-0.127457
C	-6.648104	0.249236	-0.762558
C	-7.792248	-1.537877	-1.999924
H	-5.472552	1.730639	0.292883
C	-7.911939	0.858575	-0.546655
C	-9.003357	-0.922165	-1.775411
H	-7.743294	-2.467105	-2.563418
C	-9.064777	0.288568	-1.041382
H	-7.955016	1.787784	0.017298
H	-9.918566	-1.363242	-2.161488
H	-10.026141	0.765711	-0.870594
H	-0.913374	-2.267070	-3.948094
C	4.287747	-3.062704	1.152937
H	5.355603	-2.845400	1.049915
H	4.022406	-2.891729	2.199058
H	4.164171	-4.121465	0.937514
H	3.958307	-2.226131	-0.777542
C	-2.715875	0.657179	-3.360403

H	-2.271856	1.071204	-2.446016
H	-2.317875	1.240800	-4.204765
H	-3.793184	0.836250	-3.311891
H	-3.146218	-1.408554	-4.035126

TS3a_4

B3LYP electronic energy: -3616.67053840 a.u.
B3LYP enthalpy: -3615.672369 a.u.
B3LYP free energy: -3615.836013 a.u.
M06 SCF energy in solution: -3615.77674162 a.u.
M06 enthalpy in solution: -3614.778572 a.u.
M06 free energy in solution: -3614.942216 a.u.
Imaginary frequency: -183.6659 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.604695	0.756243	3.368033
P	-1.546059	0.321242	0.008420
C	-1.831624	0.076700	1.798198
C	-1.435588	-1.060041	2.606598
C	-1.874263	-0.774543	3.945179
H	-1.714459	-1.424514	4.797288
C	-2.559149	0.472117	3.971252
H	-2.975415	0.955055	4.846298
C	-2.524592	1.004741	2.655480
H	-2.913470	1.965320	2.347032
C	1.395211	0.643957	3.996242
H	1.962802	-0.262262	4.142860
C	0.599773	1.292884	4.984540
C	0.462007	2.517553	3.034651
H	0.171159	3.270947	2.316688
C	1.306728	1.393458	2.785264
H	1.769409	1.132448	1.840944
C	-3.131804	-0.279410	-0.745438
C	-4.200097	-0.786810	0.007902
H	-4.132251	-0.818617	1.090436
C	-5.360722	-1.244351	-0.618338
H	-6.184509	-1.627353	-0.024391
C	-5.469959	-1.195137	-2.009346
C	-4.415995	-0.683485	-2.773229
H	-4.503220	-0.635898	-3.853793
C	-3.258158	-0.234175	-2.144377
H	-2.445292	0.158655	-2.748466
C	-1.788163	2.155620	-0.193390
C	-3.046602	2.756194	-0.361124
H	-3.945368	2.148647	-0.365938
C	-3.161877	4.135162	-0.530956
H	-4.139526	4.586576	-0.666259
C	-2.017777	4.937217	-0.540163
C	-0.758528	4.354608	-0.380087
H	0.133107	4.972823	-0.402802

C	-0.650182	2.974499	-0.211229
H	0.329399	2.526358	-0.096445
C	0.023586	2.453838	4.389606
H	-0.658488	3.144150	4.869612
C	-0.972808	-2.489270	2.289247
P	0.083269	-2.809268	0.693507
C	1.708425	-3.481544	1.503963
C	2.781196	-3.751587	0.427762
C	2.247657	-2.334740	2.383863
C	1.537202	-4.744796	2.369211
H	2.592690	-4.661899	-0.142311
H	2.868415	-2.914909	-0.269970
H	3.753275	-3.878105	0.922723
H	1.590306	-2.109652	3.226435
H	3.219083	-2.633265	2.800415
H	2.391352	-1.419902	1.801308
H	2.478565	-4.950986	2.896822
H	0.757790	-4.642025	3.133453
H	1.308634	-5.627273	1.765381
C	-0.733786	-4.225893	-0.377978
C	-1.254524	-5.518926	0.292296
C	-1.908344	-3.570039	-1.132438
C	0.307914	-4.663987	-1.436140
H	-0.560041	-5.943024	1.020843
H	-2.222199	-5.383432	0.775620
H	-1.398680	-6.273227	-0.493075
H	-1.570637	-2.737795	-1.754516
H	-2.373238	-4.317587	-1.789482
H	-2.687212	-3.197506	-0.461512
H	-0.225352	-5.127324	-2.276439
H	0.891334	-3.831240	-1.833234
H	0.996658	-5.415039	-1.041134
H	0.439087	0.950587	5.999031
C	-2.151907	6.431168	-0.669522
C	-6.694326	-1.746097	-2.689115
F	-1.052581	6.991564	-1.217695
F	-3.211335	6.775151	-1.434310
F	-2.332973	7.017299	0.537602
F	-6.939920	-1.125910	-3.863731
F	-7.798474	-1.616289	-1.920479
F	-6.559212	-3.065083	-2.961725
C	0.558605	-1.099455	-2.873098
C	1.458652	-0.101102	-3.300936
C	2.846620	-0.179605	-3.309933
O	2.308524	-0.018847	-0.389022
C	3.091678	0.693961	-1.102577
C	2.665818	2.114729	-1.446604
H	3.227771	2.554066	-2.273167
H	2.817067	2.755893	-0.564137
H	1.608374	2.130092	-1.708339
Cu	0.398784	-0.842853	-0.719829
H	0.892342	-2.132549	-2.951192
H	-0.486688	-0.965177	-3.151570
C	4.564691	0.427816	-1.013889

C	5.519460	1.206450	-1.653693
C	5.018870	-0.648257	-0.195943
C	6.907658	0.948353	-1.526354
H	5.222052	2.035512	-2.288466
C	6.356448	-0.924005	-0.049456
H	4.274576	-1.239093	0.321199
C	7.344892	-0.143105	-0.706816
C	7.887298	1.740563	-2.188103
H	6.677947	-1.748947	0.583247
C	8.735981	-0.397168	-0.581377
C	9.229488	1.468221	-2.047688
H	7.555952	2.568879	-2.810517
C	9.659311	0.388575	-1.235909
H	9.061868	-1.226689	0.042369
H	9.966227	2.081454	-2.559818
H	10.721499	0.183289	-1.132730
H	1.024573	0.872432	-3.539334
C	3.556990	-1.506597	-3.231903
H	4.642549	-1.380981	-3.186868
H	3.252008	-2.070184	-2.340785
H	3.331055	-2.140680	-4.103574
H	3.386750	0.631509	-3.792821
C	-2.190346	-3.423327	2.492492
H	-2.704568	-3.159065	3.421897
H	-2.922145	-3.340762	1.684098
H	-1.878851	-4.465207	2.575884
H	-0.278868	-2.747097	3.094119

TS3a_5

B3LYP electronic energy: -3616.67360861 a.u.
B3LYP enthalpy: -3615.675880 a.u.
B3LYP free energy: -3615.839699 a.u.
M06 SCF energy in solution: -3615.77895028 a.u.
M06 enthalpy in solution: -3614.781222 a.u.
M06 free energy in solution: -3614.945041 a.u.
Imaginary frequency: -230.5396 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.870860	0.603407	3.422856
P	-1.627284	0.100708	0.034321
C	-1.900872	-0.233860	1.806348
C	-1.324265	-1.292473	2.620547
C	-1.876584	-1.124393	3.938275
H	-1.624352	-1.722701	4.803487
C	-2.775449	-0.021647	3.949664
H	-3.311607	0.355184	4.811426
C	-2.785939	0.533843	2.645568
H	-3.339136	1.407222	2.328767
C	1.117229	0.713637	4.049816
H	1.786949	-0.129650	4.149410

C	0.249282	1.209987	5.067572
C	-0.044703	2.503167	3.178921
H	-0.426250	3.246738	2.493305
C	0.936078	1.508216	2.878324
H	1.428011	1.355517	1.924469
C	-3.157507	-0.574470	-0.767544
C	-4.225631	-1.138379	-0.054987
H	-4.193701	-1.180127	1.028826
C	-5.336861	-1.652811	-0.724559
H	-6.154809	-2.092186	-0.162757
C	-5.395727	-1.609108	-2.118559
C	-4.337484	-1.050939	-2.843137
H	-4.376423	-1.026555	-3.927470
C	-3.227709	-0.544810	-2.172281
H	-2.404403	-0.131010	-2.747182
C	-1.948942	1.918592	-0.135108
C	-3.230271	2.481302	-0.247219
H	-4.110307	1.846048	-0.230404
C	-3.389775	3.858343	-0.394030
H	-4.383241	4.285576	-0.484786
C	-2.267537	4.690292	-0.438728
C	-0.986280	4.140656	-0.345208
H	-0.114636	4.785019	-0.401786
C	-0.830409	2.762208	-0.200222
H	0.162576	2.326178	-0.147427
C	-0.467800	2.319043	4.528133
H	-1.228062	2.894944	5.040455
C	-0.376723	-2.480443	2.362758
P	0.515883	-2.686301	0.660485
C	2.264084	-3.239450	1.284252
C	3.082816	-3.796205	0.101748
C	2.947776	-1.949955	1.793276
C	2.303521	-4.278740	2.424906
H	2.772548	-4.807963	-0.175638
H	3.013949	-3.162151	-0.785434
H	4.140062	-3.847753	0.391278
H	2.456374	-1.563585	2.692085
H	3.987369	-2.175060	2.064929
H	2.950954	-1.152184	1.047133
H	3.354113	-4.480621	2.674244
H	1.826980	-3.916869	3.341143
H	1.845774	-5.233476	2.154009
C	-0.300003	-4.149145	-0.327688
C	-0.136209	-5.579017	0.228281
C	-1.801850	-3.834809	-0.481656
C	0.300520	-4.135872	-1.754603
H	0.912589	-5.866957	0.336608
H	-0.636381	-5.731455	1.185705
H	-0.588331	-6.280877	-0.485700
H	-1.959869	-2.905715	-1.032246
H	-2.277538	-4.640261	-1.057002
H	-2.331004	-3.759176	0.471198
H	-0.281503	-4.820613	-2.385934
H	0.254983	-3.141267	-2.203926

H	1.338570	-4.473017	-1.780833
H	0.133545	0.799608	6.062787
C	-2.445147	6.182126	-0.534755
C	-6.616404	-2.111395	-2.841210
F	-2.555963	6.745737	0.691870
F	-1.399216	6.777630	-1.146862
F	-3.562082	6.512984	-1.219457
F	-7.507293	-1.116674	-3.063394
F	-7.262260	-3.066628	-2.136477
F	-6.305833	-2.634844	-4.047703
C	0.502723	-0.327979	-2.849155
C	1.820445	-0.078703	-3.260743
C	2.463978	1.161211	-3.252556
O	2.057398	0.695731	-0.366103
C	2.962426	1.341665	-1.007204
C	2.856787	2.863781	-1.000500
H	1.819325	3.162557	-1.157838
H	3.470498	3.341154	-1.768972
H	3.175301	3.251851	-0.021424
Cu	0.511280	-0.688505	-0.698829
H	-0.180882	0.522208	-2.871487
H	0.049118	-1.268329	-3.162241
C	4.344274	0.764613	-1.089068
C	5.484878	1.548456	-1.020386
C	4.508608	-0.644672	-1.221898
C	6.789535	0.984730	-1.075189
H	5.408896	2.625473	-0.905434
C	5.750794	-1.222106	-1.292097
H	3.614478	-1.250750	-1.289047
C	6.933266	-0.432485	-1.216988
C	7.961465	1.784340	-0.994090
H	5.848660	-2.299733	-1.408114
C	8.235502	-0.991415	-1.277721
C	9.214275	1.212911	-1.053798
H	7.853097	2.861228	-0.884989
C	9.353793	-0.188547	-1.198135
H	8.338332	-2.068819	-1.388471
H	10.101183	1.837959	-0.991205
H	10.346235	-0.628844	-1.245754
H	2.432227	-0.947691	-3.519242
C	3.731316	1.390486	-4.040968
H	4.366698	2.168217	-3.597595
H	4.335586	0.477747	-4.100627
H	3.511735	1.708624	-5.071381
H	1.806582	2.027568	-3.174993
C	-1.015312	-3.770182	2.933871
H	-1.251897	-3.640150	3.993896
H	-1.948141	-4.029716	2.427748
H	-0.335978	-4.619048	2.863405
H	0.492190	-2.277634	2.996110

TS3a

B3LYP electronic energy: -3616.68723567 a.u.
B3LYP enthalpy: -3615.689410 a.u.
B3LYP free energy: -3615.849963 a.u.
M06 SCF energy in solution: -3615.78992264 a.u.
M06 enthalpy in solution: -3614.792097 a.u.
M06 free energy in solution: -3614.952650 a.u.
Imaginary frequency: -232.7308 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	4.057680	-0.163292	-1.886638
P	0.865378	-0.427196	-0.097250
C	2.010505	0.075767	-1.449962
C	2.656157	1.372319	-1.551807
C	3.217177	1.457071	-2.867719
H	3.800750	2.281588	-3.253396
C	2.936862	0.251140	-3.574760
H	3.261794	0.012428	-4.579382
C	2.212070	-0.604794	-2.701912
H	1.856958	-1.597920	-2.939804
C	5.722048	0.074555	-0.640967
H	5.860697	0.875025	0.074183
C	6.117498	0.092966	-2.012861
C	5.107136	-1.939369	-1.585625
H	4.689796	-2.928699	-1.717553
C	5.100003	-1.180266	-0.377972
H	4.681944	-1.494172	0.567130
C	-0.361547	-1.509356	-0.957547
C	-0.861995	-1.171564	-2.225833
H	-0.471241	-0.309443	-2.754587
C	-1.863500	-1.930454	-2.828624
H	-2.232589	-1.658619	-3.811551
C	-2.401225	-3.033647	-2.163385
C	-1.943584	-3.360362	-0.883731
H	-2.376005	-4.201451	-0.350572
C	-0.940263	-2.601969	-0.286371
H	-0.605864	-2.871305	0.709942
C	1.824008	-1.635991	0.933023
C	2.166775	-2.928403	0.500955
H	1.841602	-3.279794	-0.473201
C	2.916124	-3.776322	1.312480
H	3.168221	-4.775910	0.972902
C	3.341600	-3.341180	2.572806
C	3.006509	-2.061826	3.018165
H	3.322156	-1.730136	4.001883
C	2.246707	-1.219632	2.203361
H	1.972744	-0.232765	2.562627
C	5.738363	-1.152981	-2.596050
H	5.875430	-1.437387	-3.631460
C	2.771797	2.449739	-0.483924
P	1.068420	3.223750	-0.004671
C	1.508197	4.583817	1.300009

C	0.209297	4.936203	2.061608
C	2.460794	3.939645	2.334649
C	2.125195	5.894033	0.769324
H	-0.536508	5.419759	1.426999
H	-0.244545	4.046370	2.505272
H	0.451735	5.635151	2.873515
H	3.464865	3.755322	1.943657
H	2.567019	4.617569	3.191463
H	2.058444	2.993181	2.710781
H	2.359136	6.548400	1.620444
H	3.052026	5.744374	0.211697
H	1.431263	6.443105	0.126762
C	0.313410	4.024491	-1.590663
C	1.309939	4.760910	-2.505683
C	-0.334647	2.869316	-2.389960
C	-0.818487	4.995548	-1.197993
H	1.850793	5.560045	-1.991289
H	2.037947	4.073964	-2.945378
H	0.758427	5.220030	-3.337717
H	-1.093461	2.348787	-1.797073
H	-0.820525	3.284926	-3.283648
H	0.406339	2.139152	-2.726841
H	-1.353741	5.294462	-2.108911
H	-1.546636	4.527326	-0.530239
H	-0.447792	5.910261	-0.727420
H	6.594149	0.916542	-2.529200
C	4.211491	-4.232435	3.419512
C	-3.445477	-3.897462	-2.813161
F	3.932637	-5.539344	3.223648
F	5.522170	-4.061682	3.126426
F	4.065619	-3.975278	4.736570
F	-2.935187	-5.090889	-3.198933
F	-3.983815	-3.321440	-3.907232
F	-4.462722	-4.177244	-1.959447
C	-0.454735	1.122602	3.075944
C	-1.752191	1.602168	3.325182
C	-2.948366	0.916186	3.093762
O	-2.157484	1.187250	0.356328
C	-3.221875	1.589763	0.943430
C	-3.383474	3.088281	1.182897
H	-4.088606	3.333823	1.981214
H	-3.745905	3.561754	0.258453
H	-2.413563	3.520020	1.432904
Cu	-0.196285	1.464118	0.926257
H	-0.305975	0.044024	3.101555
H	0.372792	1.693196	3.498543
C	-4.482194	0.811166	0.690456
C	-5.734473	1.244689	1.098700
C	-4.394047	-0.414621	-0.032031
C	-6.909585	0.497272	0.829476
H	-5.845356	2.173558	1.650751
C	-5.512023	-1.164168	-0.307480
H	-3.413612	-0.734827	-0.362554
C	-6.801928	-0.739049	0.112439

C	-8.196747	0.933197	1.250554
H	-5.420519	-2.098430	-0.855982
C	-7.979996	-1.486063	-0.152495
C	-9.320780	0.185508	0.979264
H	-8.278296	1.871610	1.794983
C	-9.212149	-1.037162	0.270514
H	-7.891803	-2.423222	-0.697600
H	-10.297364	0.530712	1.308757
H	-10.106092	-1.619213	0.062347
H	-1.841383	2.652739	3.608832
C	3.949629	3.398631	-0.787763
H	4.841219	2.806208	-1.018454
H	3.757136	4.056028	-1.637373
H	4.191062	4.028528	0.068458
H	3.008505	1.936740	0.455935
C	-2.949532	-0.588057	2.973476
H	-2.354689	-0.914100	2.109468
H	-2.515889	-1.066034	3.865412
H	-3.961701	-0.980464	2.843570
H	-3.854984	1.370857	3.486530

TS3b_1

B3LYP electronic energy: -3615.78874008 a.u.
B3LYP enthalpy: 0.000000 a.u.
B3LYP free energy: 0.000000 a.u.
M06 SCF energy in solution: -3616.68484128 a.u.
M06 enthalpy in solution: -0.896101 a.u.
M06 free energy in solution: -0.896101 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-4.464205	-1.086153	0.056417
P	-1.138190	0.462213	-0.233477
C	-2.664158	-0.398419	-0.796858
C	-2.813630	-1.827829	-1.018072
C	-4.034114	-2.003321	-1.750922
H	-4.460248	-2.949910	-2.051005
C	-4.639145	-0.734151	-1.977078
H	-5.583633	-0.559245	-2.476270
C	-3.811766	0.250597	-1.376685
H	-3.995334	1.315969	-1.370849
C	-4.790440	-2.265086	1.749952
H	-4.224971	-3.150152	2.011688
C	-5.962342	-2.226604	0.935231
C	-5.462813	-0.064319	1.574188
H	-5.497239	1.012242	1.674250
C	-4.482641	-0.931064	2.144746
H	-3.641516	-0.627614	2.751369
C	-1.243268	2.100368	-1.090134
C	-1.553225	2.159464	-2.461291
H	-1.842621	1.258310	-2.991981

C	-1.498714	3.362857	-3.159249
H	-1.743901	3.388428	-4.215994
C	-1.114564	4.536220	-2.504278
C	-0.777559	4.491770	-1.150302
H	-0.462714	5.396515	-0.640381
C	-0.837325	3.285720	-0.453476
H	-0.563751	3.276961	0.596058
C	-1.415876	0.915146	1.544212
C	-2.400986	1.821148	1.973471
H	-3.037355	2.317359	1.247359
C	-2.567922	2.102050	3.326557
H	-3.324007	2.811045	3.648962
C	-1.754837	1.471262	4.276072
C	-0.768089	0.574965	3.865161
H	-0.126032	0.100611	4.599948
C	-0.595992	0.307709	2.504625
H	0.190846	-0.368452	2.185358
C	-6.378374	-0.865862	0.828162
H	-7.220895	-0.502734	0.253618
C	-1.936680	-2.979439	-0.528494
P	-0.117545	-2.935756	-1.158129
C	0.838292	-4.008638	0.143970
C	2.283100	-4.185339	-0.371964
C	0.911721	-3.172831	1.442785
C	0.268722	-5.393725	0.513861
H	2.341138	-4.882544	-1.213372
H	2.723319	-3.227611	-0.662952
H	2.899029	-4.600959	0.436485
H	-0.079659	-2.964731	1.863719
H	1.465198	-3.747076	2.198343
H	1.439063	-2.230096	1.278418
H	1.003060	-5.912301	1.145150
H	-0.649502	-5.315213	1.103779
H	0.074744	-6.033306	-0.349782
C	-0.082031	-3.779999	-2.894995
C	-0.240427	-5.312630	-2.923966
C	-1.205324	-3.126629	-3.729523
C	1.255087	-3.422547	-3.582337
H	0.609624	-5.818342	-2.456461
H	-1.154784	-5.661629	-2.439408
H	-0.275921	-5.645936	-3.970372
H	-1.146874	-2.033027	-3.697467
H	-1.097829	-3.434669	-4.778018
H	-2.204854	-3.421110	-3.401082
H	1.260059	-3.858146	-4.590725
H	1.377203	-2.342679	-3.681431
H	2.125404	-3.813498	-3.050541
H	-6.436117	-3.075017	0.458102
C	-1.990271	1.725196	5.741864
C	-1.122045	5.849396	-3.237399
F	-2.379786	2.998374	5.971880
F	-2.965425	0.922487	6.228674
F	-0.883890	1.495899	6.479834
F	-2.322788	6.468643	-3.131373

F	-0.878677	5.692766	-4.556667
F	-0.197702	6.704914	-2.748960
C	1.582448	0.273602	-2.772800
C	2.280617	1.364584	-2.231856
C	3.605740	1.365648	-1.788918
O	2.512182	-0.686504	-0.032144
C	3.285359	0.300051	0.237256
C	2.701368	1.470741	1.014078
H	3.290527	2.386474	0.929982
H	2.633750	1.208621	2.081027
H	1.691278	1.671026	0.652006
Cu	0.729358	-0.721009	-1.043688
H	2.180012	-0.522651	-3.214566
H	0.655582	0.487594	-3.305479
C	4.737572	-0.008361	0.414479
C	5.586762	0.768776	1.187730
C	5.273692	-1.175872	-0.210094
C	6.958522	0.437094	1.360025
H	5.213947	1.650588	1.700123
C	6.594151	-1.518029	-0.071467
H	4.604253	-1.785390	-0.806673
C	7.481641	-0.729360	0.714976
C	7.832796	1.226392	2.155478
H	6.983265	-2.407911	-0.562251
C	8.851590	-1.055348	0.884635
C	9.159557	0.883927	2.302793
H	7.435955	2.111939	2.647247
C	9.675531	-0.267650	1.660631
H	9.243294	-1.941671	0.390159
H	9.815811	1.498726	2.913267
H	10.723567	-0.528193	1.782413
H	4.225759	0.537948	-2.130596
C	4.340757	2.659851	-1.542382
H	4.866467	3.005317	-2.445414
H	3.652212	3.461921	-1.246568
H	5.104404	2.560652	-0.759139
H	1.704471	2.275749	-2.048341
C	-2.693106	-4.317457	-0.659759
H	-3.639522	-4.264027	-0.110144
H	-2.933642	-4.554045	-1.698924
H	-2.120823	-5.151260	-0.258935
H	-1.762730	-2.810332	0.541301

TS3b_2

B3LYP electronic energy: -3616.67759599 a.u.

B3LYP enthalpy: -3615.679928 a.u.

B3LYP free energy: -3615.843501 a.u.

M06 SCF energy in solution: -3615.78184542 a.u.

M06 enthalpy in solution: -3614.784177 a.u.

M06 free energy in solution: -3614.947750 a.u.

Imaginary frequency: -240.9560 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-4.249613	-1.870418	-0.503098
P	-1.262038	0.373390	-0.212818
C	-2.504060	-0.764583	-0.958106
C	-2.303736	-2.175563	-1.256419
C	-3.302053	-2.538532	-2.220241
H	-3.456304	-3.526910	-2.628889
C	-4.111837	-1.405293	-2.515199
H	-4.964995	-1.388218	-3.181127
C	-3.638194	-0.323122	-1.729853
H	-4.043087	0.678777	-1.722915
C	-4.661252	-3.259519	1.006355
H	-4.000514	-4.056685	1.321085
C	-5.644360	-3.338409	-0.025823
C	-5.693831	-1.201381	0.847372
H	-5.956809	-0.164342	1.011681
C	-4.691437	-1.941605	1.545288
H	-4.051540	-1.563958	2.330088
C	-1.737455	2.009757	-0.941223
C	-1.787550	2.142195	-2.342464
H	-1.649020	1.270839	-2.974923
C	-2.023858	3.376268	-2.939778
H	-2.072082	3.455799	-4.020908
C	-2.199785	4.515099	-2.147613
C	-2.136178	4.405768	-0.758217
H	-2.275754	5.285775	-0.138699
C	-1.906112	3.165345	-0.162130
H	-1.864013	3.107247	0.919561
C	-1.625921	0.622578	1.582422
C	-2.908950	0.880925	2.092653
H	-3.760394	0.910356	1.420792
C	-3.098133	1.105814	3.453408
H	-4.092623	1.298195	3.844373
C	-2.000713	1.079728	4.323136
C	-0.719773	0.838918	3.827102
H	0.129420	0.824049	4.502088
C	-0.532788	0.611717	2.460723
H	0.466247	0.437391	2.069013
C	-6.283096	-2.066282	-0.122628
H	-7.056523	-1.795722	-0.830013
C	-1.315200	-3.164586	-0.641211
P	0.551515	-2.729459	-0.877245
C	1.360797	-3.591110	0.660329
C	2.890555	-3.628408	0.476410
C	1.066237	-2.672535	1.867609
C	0.878080	-5.012730	1.009206
H	3.202556	-4.346993	-0.287299
H	3.293700	-2.644326	0.229160
H	3.352127	-3.940810	1.422483
H	-0.007218	-2.542907	2.050121
H	1.492805	-3.127477	2.771989
H	1.519265	-1.687652	1.732034

H	1.476150	-5.384651	1.852109
H	-0.166487	-5.028669	1.334388
H	1.000907	-5.723634	0.187461
C	1.151972	-3.534880	-2.522190
C	1.258751	-5.072142	-2.556701
C	0.176709	-3.053106	-3.619398
C	2.544195	-2.949993	-2.855533
H	1.996759	-5.447415	-1.841326
H	0.309163	-5.573263	-2.361270
H	1.593431	-5.383340	-3.555921
H	0.088240	-1.961286	-3.626296
H	0.558136	-3.363013	-4.601335
H	-0.827029	-3.471032	-3.508608
H	2.834137	-3.276181	-3.863604
H	2.539111	-1.857229	-2.841180
H	3.318072	-3.293988	-2.165524
H	-5.853101	-4.202387	-0.643718
C	-2.215797	1.373874	5.784514
C	-2.392188	5.859511	-2.794172
F	-2.317555	2.704017	6.010891
F	-3.358846	0.812700	6.240268
F	-1.203763	0.916216	6.550469
F	-3.118363	6.693331	-2.016328
F	-3.026635	5.758042	-3.984005
F	-1.210519	6.473625	-3.031570
C	1.570186	0.821082	-2.543142
C	2.853683	1.244113	-2.176244
C	3.174612	2.321720	-1.341344
O	2.362061	0.186738	0.521349
C	3.261202	1.099822	0.605076
C	2.965686	2.249229	1.560192
H	3.590606	3.130958	1.400108
H	3.127827	1.902202	2.591703
H	1.918413	2.543038	1.466219
Cu	0.901955	-0.384787	-0.836694
H	1.493659	0.083427	-3.341750
H	0.769604	1.558383	-2.542805
C	4.701031	0.688146	0.458965
C	5.747576	1.379410	1.049112
C	5.014013	-0.486585	-0.287238
C	7.097258	0.954564	0.921695
H	5.557382	2.272948	1.636027
C	6.307107	-0.922539	-0.435849
H	4.197303	-1.026027	-0.750323
C	7.391871	-0.223038	0.161561
C	8.172234	1.660459	1.528318
H	6.519526	-1.818256	-1.016330
C	8.741005	-0.644104	0.035157
C	9.472490	1.227112	1.388323
H	7.949855	2.554280	2.107119
C	9.761176	0.063334	0.634065
H	8.957628	-1.538562	-0.545013
H	10.283456	1.778550	1.856884
H	10.790629	-0.269015	0.529853

H	4.221293	2.614716	-1.315329
C	2.174133	3.433479	-1.121784
H	1.926265	3.942567	-2.065736
H	1.228033	3.059432	-0.710914
H	2.555577	4.196415	-0.435944
H	3.683420	0.594577	-2.458106
C	-1.739625	-4.609678	-0.976897
H	-2.766153	-4.780696	-0.634768
H	-1.718895	-4.803175	-2.051908
H	-1.101775	-5.349814	-0.498874
H	-1.392730	-3.048318	0.446797

TS3b

B3LYP electronic energy: -3616.68764955 a.u.
B3LYP enthalpy: -3615.690086 a.u.
B3LYP free energy: -3615.850761 a.u.
M06 SCF energy in solution: -3615.78874008 a.u.
M06 enthalpy in solution: -3614.791177 a.u.
M06 free energy in solution: -3614.951852 a.u.
Imaginary frequency: -260.1530 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	4.028166	-0.180323	-1.978752
P	0.900677	-0.450811	-0.079251
C	1.992809	0.039845	-1.477593
C	2.618858	1.342442	-1.614722
C	3.137336	1.418468	-2.948141
H	3.699209	2.245109	-3.360815
C	2.847078	0.201541	-3.632704
H	3.141357	-0.045049	-4.644816
C	2.159537	-0.652226	-2.727749
H	1.807643	-1.651971	-2.941787
C	5.737831	0.098901	-0.802905
H	5.895565	0.915192	-0.110052
C	6.079139	0.092597	-2.189377
C	5.107346	-1.939924	-1.681356
H	4.695728	-2.935797	-1.777101
C	5.139547	-1.155759	-0.490066
H	4.761158	-1.453802	0.476566
C	-0.316510	-1.604711	-0.854094
C	-0.899829	-1.310530	-2.097785
H	-0.572825	-0.444090	-2.662178
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C	-0.812703	-2.705470	-0.132698
H	-0.412886	-2.942737	0.847432
C	1.920830	-1.587778	0.973704

C	2.312529	-2.876517	0.572515
H	1.999028	-3.264098	-0.391645
C	3.096063	-3.674368	1.401770
H	3.384753	-4.672130	1.086951
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C	3.128571	-1.913960	3.062347
H	3.435251	-1.545068	4.035624
C	2.332439	-1.123196	2.230450
H	2.019585	-0.139710	2.566418
C	5.691118	-1.169030	-2.731468
H	5.791867	-1.474100	-3.765190
C	2.744463	2.432674	-0.561712
P	1.040996	3.204649	-0.077643
C	1.477653	4.572974	1.217488
C	0.177552	4.928318	1.975731
C	2.428812	3.933674	2.256124
C	2.095592	5.879595	0.679462
H	-0.563585	5.417836	1.340217
H	-0.282594	4.038361	2.413434
H	0.420167	5.623013	2.791250
H	3.428837	3.732906	1.862371
H	2.546650	4.622072	3.102999
H	2.017071	2.996937	2.647248
H	2.319563	6.543349	1.525947
H	3.028285	5.727148	0.132415
H	1.406264	6.419810	0.024632
C	0.273642	3.988659	-1.666362
C	1.264034	4.711664	-2.598681
C	-0.385039	2.824223	-2.443638
C	-0.850403	4.970581	-1.278372
H	1.810635	5.515610	-2.097692
H	1.986758	4.019002	-3.037618
H	0.705692	5.162686	-3.430526
H	-1.139552	2.314382	-1.836027
H	-0.877810	3.228293	-3.338809
H	0.350182	2.086283	-2.776244
H	-1.389696	5.260471	-2.189842
H	-1.577032	4.516080	-0.600227
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C	4.414526	-4.028826	3.512991
C	-3.412150	-4.134856	-2.487654
F	4.175032	-5.348853	3.356686
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F	4.270753	-3.738635	4.823333
F	-2.864748	-5.268612	-2.987946
F	-4.104383	-3.554176	-3.488060
F	-4.306604	-4.527348	-1.545847
C	-0.523718	1.040475	2.994770
C	-1.763715	1.610481	3.306227
C	-3.031044	1.060056	3.064288
O	-2.151504	1.130374	0.357666
C	-3.239752	1.549563	0.898125
C	-3.441312	3.056727	1.005511

H	-4.209749	3.346228	1.726497
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H	-2.497764	3.521146	1.297896
Cu	-0.216171	1.463795	0.863679
H	-0.473022	-0.045963	2.927196
H	0.361478	1.504959	3.430300
C	-4.460526	0.706665	0.671991
C	-5.750935	1.209793	0.729211
C	-4.286828	-0.669830	0.337145
C	-6.886654	0.391596	0.480615
H	-5.926437	2.257860	0.952330
C	-5.361466	-1.487310	0.092953
H	-3.274049	-1.049486	0.270115
C	-6.693798	-0.989789	0.157603
C	-8.212403	0.900812	0.538774
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H	-9.964081	-1.916106	-0.216161
H	-3.049547	-0.008840	2.851255
C	-4.231615	1.582190	3.819416
H	-4.366339	1.056091	4.776325
H	-4.122838	2.648991	4.054912
H	-5.163798	1.451308	3.256171
H	-1.752496	2.636926	3.686055
C	3.914079	3.384457	-0.886513
H	4.803281	2.794980	-1.132454
H	3.705795	4.041439	-1.732578
H	4.167579	4.014857	-0.033716
H	2.992401	1.931244	0.381456

TS3c

B3LYP electronic energy: -3616.68228290 a.u.
B3LYP enthalpy: -3615.684669 a.u.
B3LYP free energy: -3615.846373 a.u.
M06 SCF energy in solution: -3615.78688993 a.u.
M06 enthalpy in solution: -3614.789276 a.u.
M06 free energy in solution: -3614.950980 a.u.
Imaginary frequency: -190.7029 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-4.504230	0.955221	0.418793
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C	-2.676893	0.497886	-0.543158
C	-3.506510	-0.692841	-0.439972
C	-4.730663	-0.403396	-1.128989

H	-5.583077	-1.062199	-1.211082
C	-4.683466	0.923802	-1.642334
H	-5.477813	1.428191	-2.177560
C	-3.434527	1.484481	-1.269429
H	-3.090421	2.480812	-1.507782
C	-5.223018	0.455191	2.319408
H	-5.133675	-0.517242	2.786065
C	-6.291659	0.891360	1.479119
C	-4.767631	2.617767	1.653329
H	-4.278292	3.573935	1.519893
C	-4.282938	1.519830	2.427078
H	-3.354767	1.490948	2.979436
C	-0.348879	1.940769	-1.430444
C	-0.705146	1.876000	-2.791597
H	-1.338233	1.069805	-3.148614
C	-0.261117	2.834454	-3.696622
H	-0.547682	2.768171	-4.741344
C	0.570659	3.872928	-3.265083
C	0.955594	3.937262	-1.926141
H	1.612854	4.731915	-1.588859
C	0.501581	2.978463	-1.019278
H	0.817726	3.049903	0.015195
C	-0.465820	1.262896	1.364557
C	-1.076244	2.415983	1.885290
H	-1.843884	2.926604	1.313011
C	-0.702931	2.916940	3.129927
H	-1.183319	3.804772	3.529371
C	0.292878	2.269613	3.871317
C	0.918265	1.132829	3.359085
H	1.696071	0.637043	3.930458
C	0.541440	0.632338	2.109846
H	1.046580	-0.237297	1.698857
C	-6.010360	2.228812	1.069198
H	-6.616684	2.830726	0.404556
C	-3.237018	-1.994105	0.314005
P	-1.708880	-3.005449	-0.290946
C	-1.220405	-3.993995	1.307528
C	-0.235182	-5.118374	0.930058
C	-0.463022	-2.993577	2.210629
C	-2.362648	-4.610713	2.139721
H	-0.723698	-5.943444	0.403237
H	0.589333	-4.749200	0.316326
H	0.198686	-5.533384	1.849734
H	-1.080425	-2.132731	2.493748
H	-0.172930	-3.501685	3.140505
H	0.442188	-2.619711	1.725590
H	-1.920753	-5.186966	2.963837
H	-2.999865	-3.847034	2.595659
H	-2.993047	-5.295939	1.566426
C	-2.300133	-4.197589	-1.685771
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C	-1.044716	-4.784862	-2.371309
H	-2.713265	-6.053755	-0.581835

H	-4.148548	-5.043770	-0.812376
H	-3.474048	-5.948387	-2.167912
H	-2.404911	-2.466170	-3.036240
H	-3.238280	-3.915673	-3.621096
H	-3.975074	-2.921421	-2.359214
H	-1.354707	-5.334748	-3.270133
H	-0.347860	-4.000229	-2.675722
H	-0.507045	-5.485818	-1.728503
H	-7.149811	0.302810	1.180824
C	0.728799	2.847277	5.192112
C	0.996640	4.941063	-4.234073
F	1.659403	3.815524	5.026072
F	-0.305574	3.409712	5.857144
F	1.271312	1.911135	5.999008
F	0.056615	5.911250	-4.346906
F	1.192174	4.444809	-5.475791
F	2.140821	5.547438	-3.851201
C	0.749563	-1.403815	-3.009045
C	1.996025	-2.063662	-3.006315
C	3.221396	-1.525495	-2.621116
O	1.888125	-1.604749	-0.004799
C	3.001063	-2.127430	-0.351176
C	3.053251	-3.636307	-0.552229
H	3.888269	-3.967778	-1.173968
H	2.124568	-3.968025	-1.018294
H	3.144457	-4.129379	0.427092
Cu	0.032576	-1.559643	-0.974035
H	-0.059118	-1.888831	-3.556934
H	0.762496	-0.321007	-3.122034
C	4.257190	-1.445325	0.094435
C	5.508870	-2.038959	0.014344
C	4.166089	-0.144826	0.675870
C	6.679366	-1.387866	0.480829
H	5.623305	-3.028480	-0.417759
C	5.280131	0.512283	1.136770
H	3.187408	0.314818	0.743469
C	6.570091	-0.080175	1.056874
C	7.964618	-1.992264	0.397504
H	5.187528	1.503710	1.575549
C	7.743609	0.567642	1.523722
C	9.085067	-1.337789	0.858303
H	8.047614	-2.984780	-0.039953
C	8.974453	-0.044540	1.427401
H	7.654563	1.560215	1.959828
H	10.060650	-1.811417	0.786699
H	9.865752	0.462547	1.787226
H	4.106407	-2.130953	-2.803679
C	3.428667	-0.033500	-2.553276
H	3.270976	0.442260	-3.533320
H	2.724474	0.437232	-1.854683
H	4.440139	0.217174	-2.221819
H	1.981680	-3.135119	-3.218284
C	-4.555999	-2.772705	0.501586
H	-5.287539	-2.138096	1.012973

H	-4.995395	-3.069878	-0.453261
H	-4.423457	-3.674034	1.095239
H	-2.882393	-1.708806	1.312018

TS3d

B3LYP electronic energy: -3616.68424237 a.u.
B3LYP enthalpy: -3615.686950 a.u.
B3LYP free energy: -3615.850587 a.u.
M06 SCF energy in solution: -3615.78550296 a.u.
M06 enthalpy in solution: -3614.788211 a.u.
M06 free energy in solution: -3614.951848 a.u.
Imaginary frequency: -220.5033 cm-1

Cartesian coordinates

ATOM	X	Y	Z
Fe	-4.409878	-1.266120	-0.327188
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C	-3.549162	0.523991	0.372046
C	-4.760919	0.214652	1.074756
H	-5.660584	0.813121	1.079186
C	-4.626067	-1.047838	1.719414
H	-5.390660	-1.553872	2.294866
C	-3.333334	-1.548787	1.417276
H	-2.921785	-2.487827	1.759606
C	-5.107131	-1.002971	-2.282186
H	-5.060880	-0.076553	-2.839937
C	-6.170441	-1.417892	-1.424049
C	-4.543588	-3.056148	-1.390281
H	-4.002523	-3.961932	-1.149617
C	-4.103887	-2.014228	-2.262285
H	-3.164555	-1.985405	-2.795468
C	-0.218891	-1.726249	1.665780
C	-0.600331	-1.520054	3.005821
H	-1.301321	-0.729293	3.254443
C	-0.095803	-2.317787	4.027382
H	-0.403141	-2.144394	5.053758
C	0.822890	-3.331528	3.735552
C	1.232519	-3.532565	2.417650
H	1.954741	-4.308936	2.187513
C	0.717893	-2.735407	1.393996
H	1.053081	-2.911957	0.378085
C	-0.364293	-1.425209	-1.193054
C	-0.890384	-2.678376	-1.551250
H	-1.616823	-3.163327	-0.907373
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H	-0.886682	-4.282509	-2.989351
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H	1.759342	-1.000473	-3.830051
C	0.599714	-0.830471	-2.019917

H	1.052456	0.112214	-1.723775
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H	-6.409375	-3.255722	-0.164358
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P	-1.912813	2.933283	-0.001296
C	-1.487316	3.816552	-1.673259
C	-0.581015	5.029449	-1.379811
C	-0.661017	2.800173	-2.494667
C	-2.661098	4.296500	-2.550028
H	-1.133453	5.863207	-0.936120
H	0.250685	4.769363	-0.721013
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H	-1.224807	1.887575	-2.722435
H	-0.387805	3.257583	-3.455484
H	0.257341	2.513211	-1.975397
H	-2.252217	4.841919	-3.411448
H	-3.244789	3.463721	-2.953654
H	-3.337104	4.978099	-2.026482
C	-2.590776	4.187386	1.296625
C	-3.595405	5.245107	0.797787
C	-3.239884	3.337455	2.411736
C	-1.387271	4.928230	1.924829
H	-3.149484	5.915910	0.057467
H	-4.498388	4.811891	0.363692
H	-3.907179	5.867727	1.647757
H	-2.551624	2.571726	2.785921
H	-3.503584	3.989798	3.254701
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H	-1.743157	5.517873	2.780459
H	-0.624450	4.232667	2.283859
H	-0.912139	5.620937	1.226520
H	-7.069849	-0.856664	-1.204829
C	0.847831	-3.367968	-4.843721
C	1.316235	-4.230752	4.835275
F	1.011153	-4.700687	-4.680746
F	-0.111529	-3.206763	-5.785787
F	1.994484	-2.876453	-5.355654
F	0.449312	-5.245492	5.072020
F	1.460474	-3.564247	6.002008
F	2.506505	-4.794198	4.536092
C	0.759203	1.786204	2.762083
C	1.909486	2.588858	2.691088
C	3.187975	2.182695	2.301612
O	1.754026	1.673330	-0.188262
C	2.878790	2.254140	0.014285
C	2.937306	3.764472	-0.157989
H	3.824230	4.221524	0.286158
H	2.052099	4.209004	0.300967
H	2.927775	4.013820	-1.229703
Cu	-0.070901	1.706949	0.766611
H	-0.095857	2.190330	3.305142
H	0.911055	0.717790	2.909691
C	4.108530	1.456428	-0.282070
C	5.320451	2.031623	-0.633044

C	4.023164	0.030571	-0.247258
C	6.462003	1.243904	-0.945931
H	5.420421	3.110932	-0.696960
C	5.108024	-0.756951	-0.535637
H	3.071236	-0.415129	0.019218
C	6.360882	-0.183517	-0.895188
C	7.705259	1.826980	-1.312693
H	5.023352	-1.841125	-0.497011
C	7.501350	-0.967293	-1.206504
C	8.796292	1.039481	-1.610500
H	7.782537	2.911348	-1.352661
C	8.694688	-0.371756	-1.556582
H	7.418510	-2.051178	-1.164683
H	9.740750	1.500269	-1.887882
H	9.561313	-0.983524	-1.792686
H	3.358371	1.106980	2.267674
C	4.402124	3.014095	2.636563
H	4.155284	4.082200	2.692831
H	4.826373	2.731405	3.611734
H	5.206681	2.888401	1.899975
H	1.776937	3.660920	2.869458
C	-4.730477	2.428059	-0.765794
H	-5.409786	1.705508	-1.230884
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H	-4.651043	3.287441	-1.427096
H	-2.986385	1.406555	-1.472328

Compiled SFC and HPLC Traces for

CuH-Catalyzed Enantioselective Ketone Allylation with 1,3-Dienes: Scope, Mechanism, and Applications

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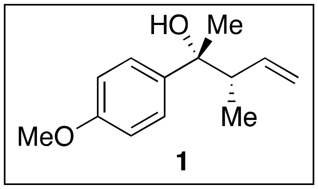

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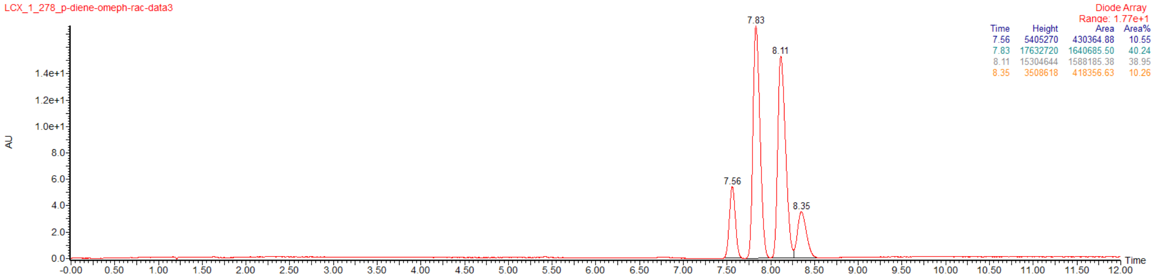

LCX_1_278_p-diene-omeph-rac-data3

Diode Array
Range: 1.77e+1

Time	Height	Area	Area%
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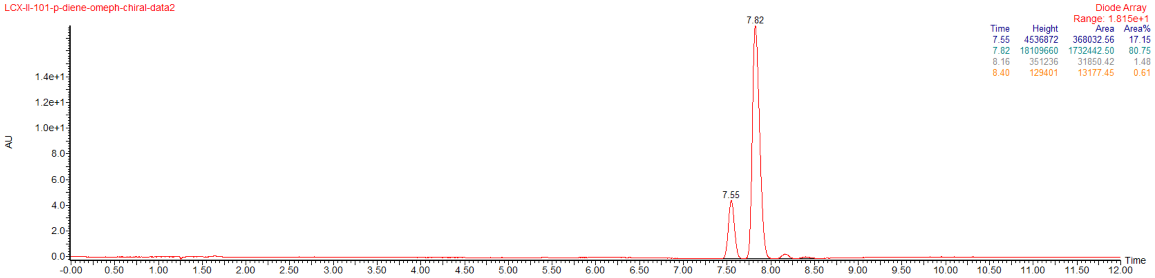
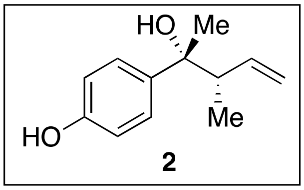
8.11	15304644	1588185.38	38.95
8.35	3508618	418356.63	10.26



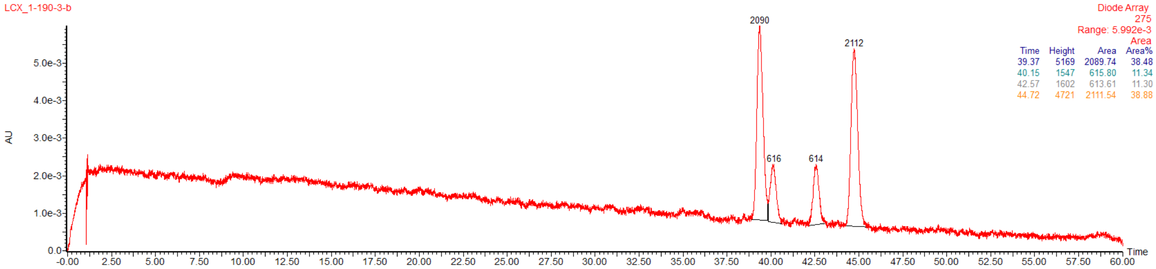
LCX-II-101-p-diene-omeph-chiral-data2

Diode Array
Range: 1.815e+1

Time	Height	Area	Area%
7.55	4536872	368032.56	17.15
7.82	18109660	1732442.50	80.75
8.16	351236	31850.42	1.48
8.40	129401	13177.45	0.61



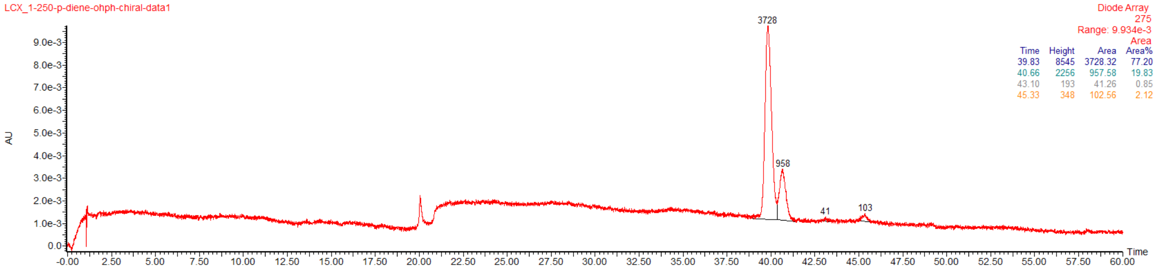
2



LCX_1-190-3-b

Diode Array
275
Range: 5.992e-3
Area

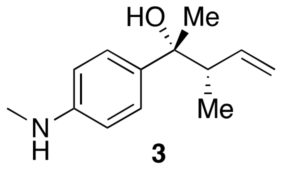
Time	Height	Area	Area%
39.37	5169	2089.74	38.48
40.15	1547	615.80	11.34
42.57	1602	613.61	11.30
44.72	4721	2111.54	38.88



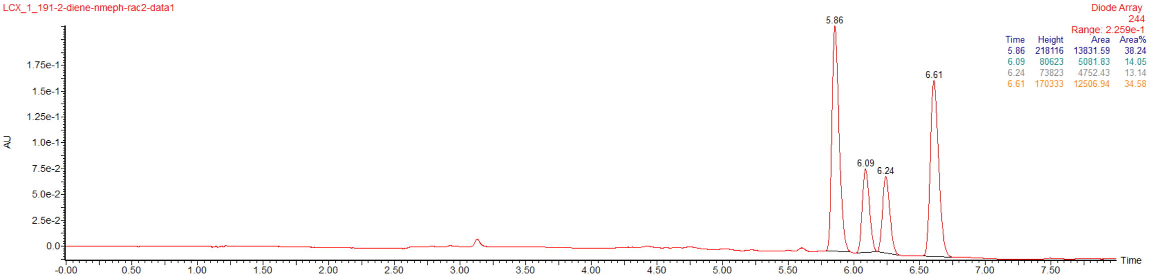
LCX_1-250-p-diene-ohph-chiral-data1

Diode Array
275
Range: 9.934e-3
Area

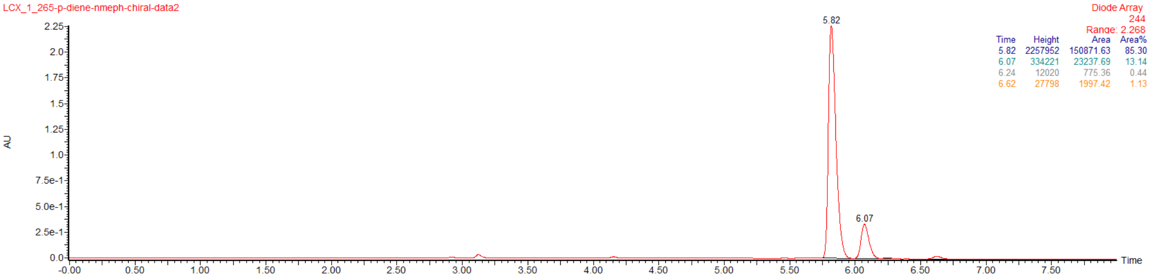
Time	Height	Area	Area%
39.83	8545	3728.32	77.20
40.66	2256	957.58	19.83
43.10	193	41.26	0.85
45.33	348	102.56	2.12



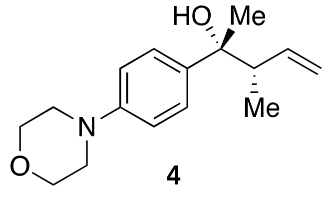
3


LCX_1_191-2-diene-nmeph-rac2-data1

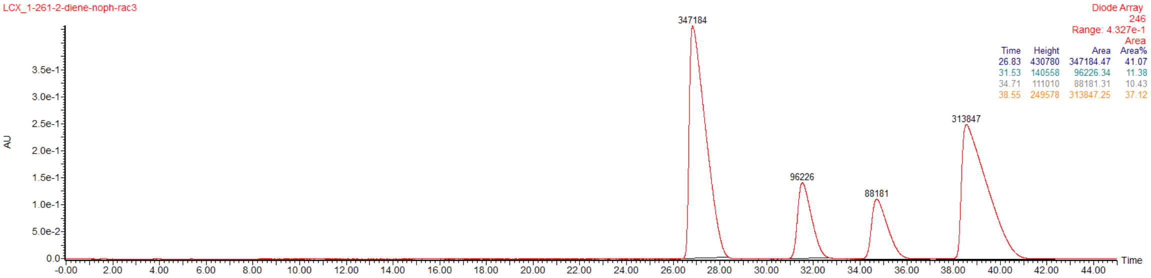
Time	Height	Area	Area%
5.86	218116	13831.59	38.24
6.09	80623	5081.83	14.05
6.24	73823	4752.43	13.14
6.61	170333	12506.94	34.58


LCX_1_265-p-diene-nmeph-chiral-data2

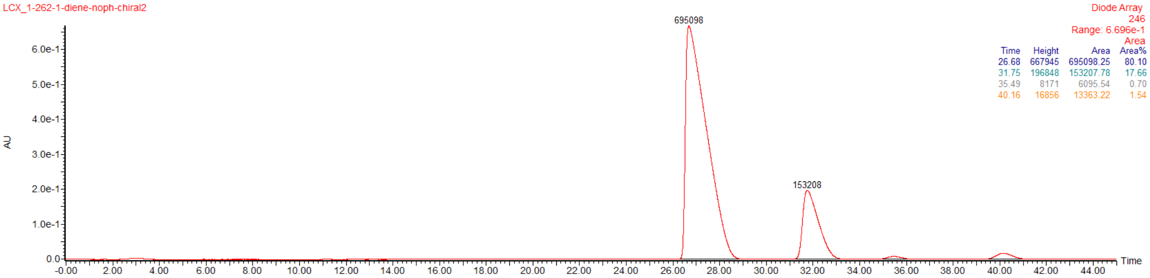
Time	Height	Area	Area%
5.82	2257952	150871.63	85.30
6.07	334221	23237.69	13.14
6.24	12020	775.36	0.44
6.62	27798	1997.42	1.13



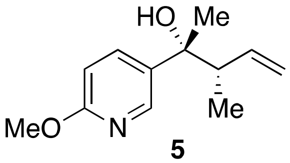
4


LCX_1-261-2-diene-noph-rac3

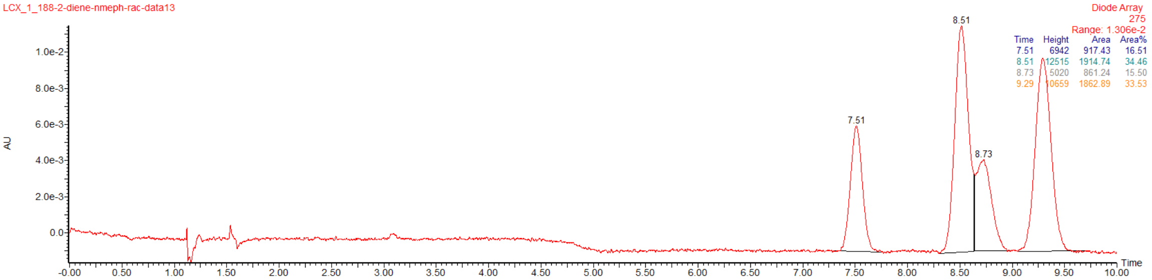
			Area
Time	Height	Area	Area%
26.83	430780	347184.47	41.07
31.53	140558	96226.34	11.38
34.71	111010	88181.31	10.43
38.55	249578	313847.25	37.12


LCX_1-262-1-diene-noph-chiral2

			Area
Time	Height	Area	Area%
26.68	667945	695098.25	80.10
31.75	196848	153207.78	17.66
35.49	8171	6095.54	0.70
40.16	16856	13363.22	1.54

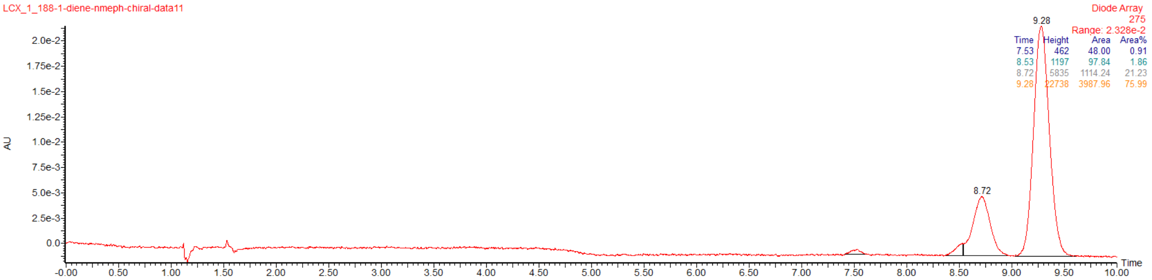


5



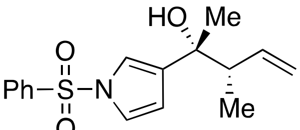
LCX_1_188-2-diene-nmeph-rac-data13

Time	Height	Area	Area%
7.51	6942	917.43	16.51
8.51	12515	1914.74	34.46
8.73	5020	861.24	15.50
9.29	10659	1862.89	33.53

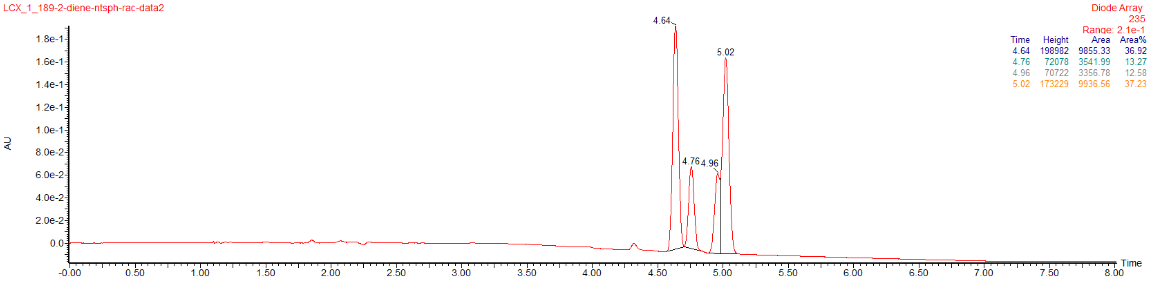


LCX_1_188-1-diene-nmeph-chiral-data11

Time	Height	Area	Area%
7.53	462	48.00	0.91
8.53	1197	97.84	1.86
8.72	5835	1114.24	21.23
9.28	22738	3987.96	75.99

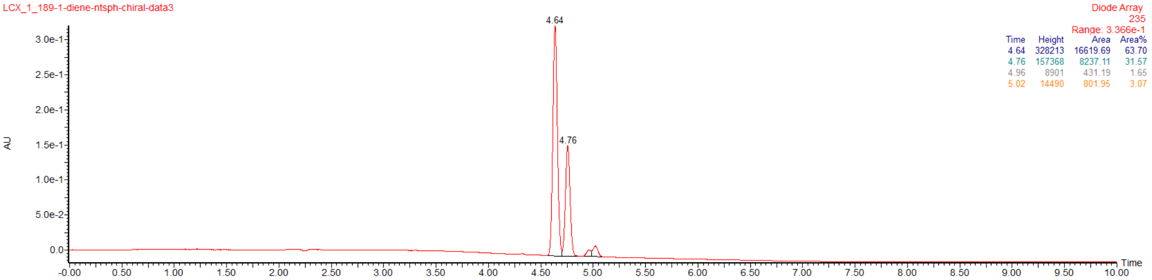


6



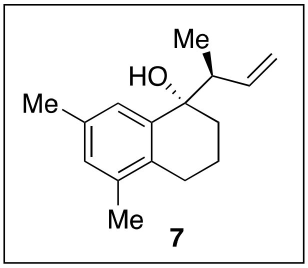
LCX_1_189-2-diene-ntsph-rac-data2

Time	Height	Area	Area%
4.64	198982	9855.33	36.92
4.76	72078	3541.99	13.27
4.96	70722	3356.78	12.58
5.02	173229	9936.56	37.23

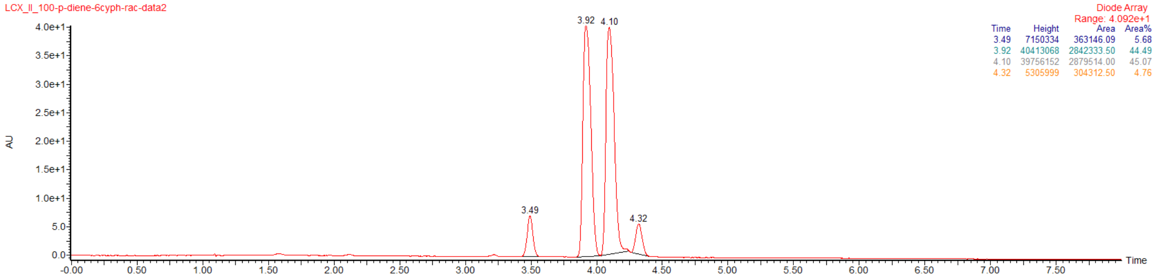


LCX_1_189-1-diene-ntsph-chiral-data3

Time	Height	Area	Area%
4.64	328213	16619.69	63.70
4.76	157368	8237.11	31.57
4.96	8901	431.19	1.65
5.02	14490	801.95	3.07

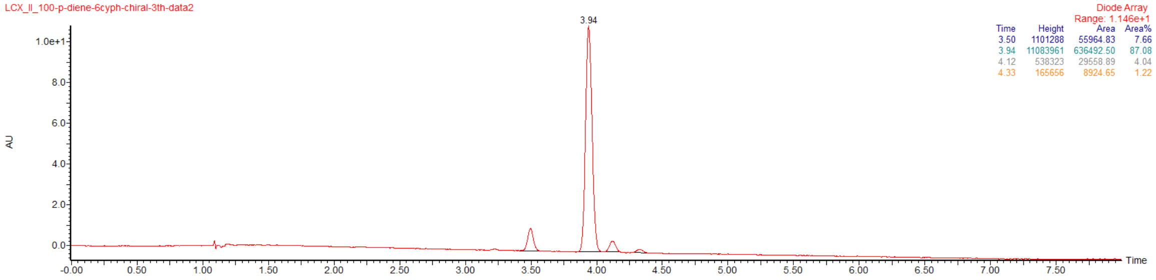


7



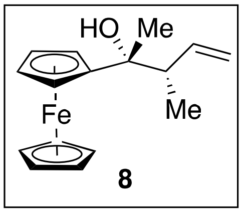
Diode Array
Range: 4.092e+1

Time	Height	Area	Area%
3.49	7150334	363146.09	5.68
3.92	40413068	2842333.50	44.49
4.10	39756152	2879514.00	45.07
4.32	5305999	304312.50	4.76

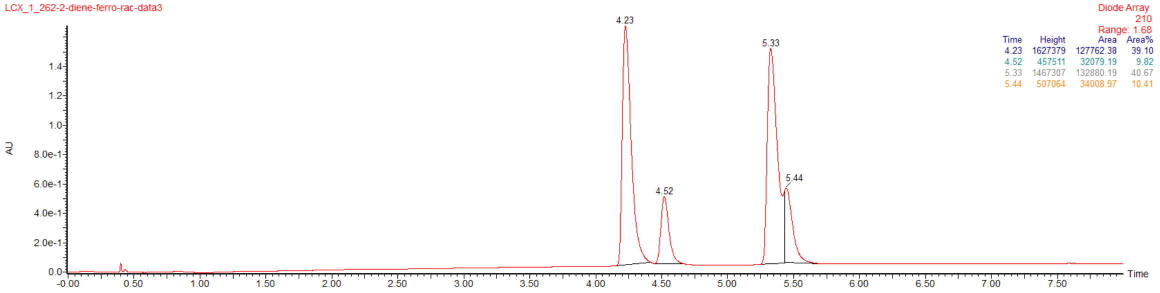


Diode Array
Range: 1.146e+1

Time	Height	Area	Area%
3.50	1101288	55964.83	7.66
3.94	11083961	636492.50	87.08
4.12	538323	29558.89	4.04
4.33	165656	8924.65	1.22



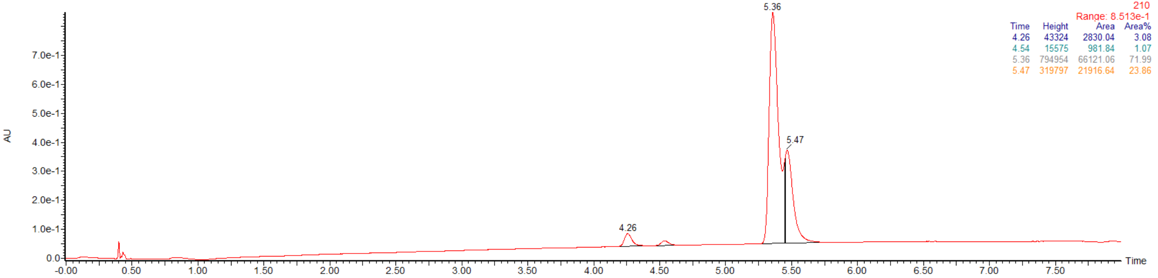
8



Diode Array
210
Range: 1.68

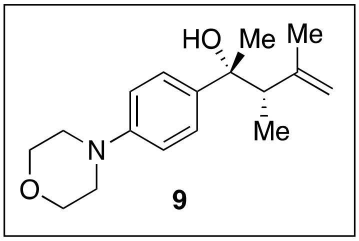
Time	Height	Area	Area%
4.23	1627379	127762.38	39.10
4.52	457511	32079.19	9.82
5.33	1467307	132880.19	40.67
5.44	507064	34008.97	10.41

LCX_1_262-1-diene-ferro-chiral-data6



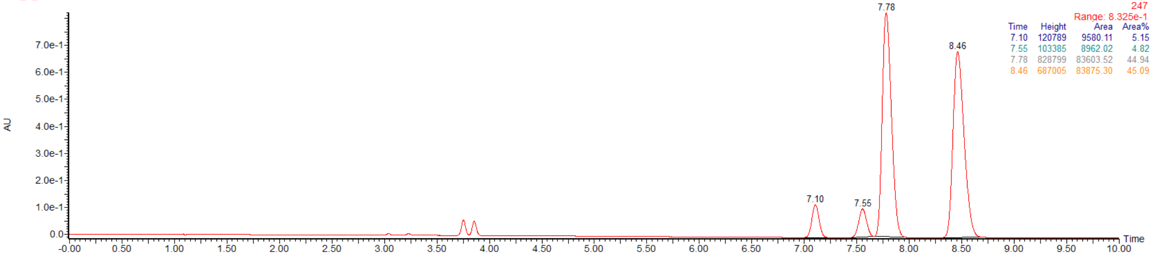
Diode Array
210
Range: 8.513e-1

Time	Height	Area	Area%
4.26	43324	2830.04	3.08
4.54	15575	981.84	1.07
5.36	794954	66121.06	71.99
5.47	319797	21916.64	23.86



9

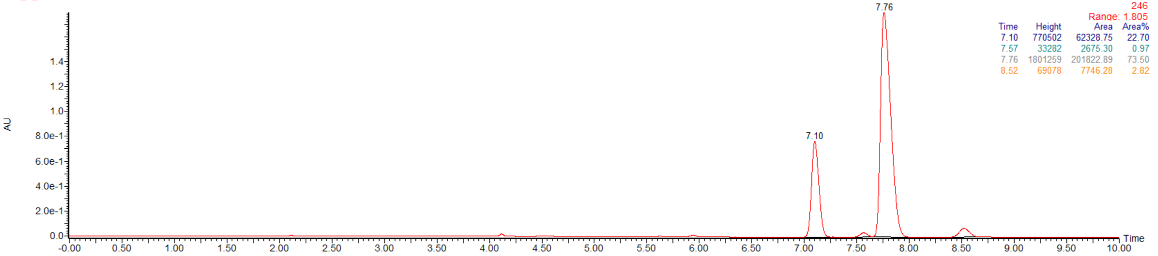
LCX_1_268-2-isoprene-noph-rac-data3



Diode Array
247
Range: 8.325e-1

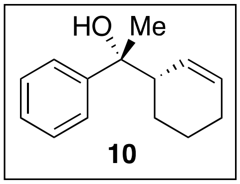
Time	Height	Area	Area%
7.10	120789	9580.11	5.15
7.55	103385	8962.02	4.82
7.78	828799	83603.52	44.94
8.46	687005	83875.30	45.09

LCX_1_268-2-isoprene-noph-chiral-data1

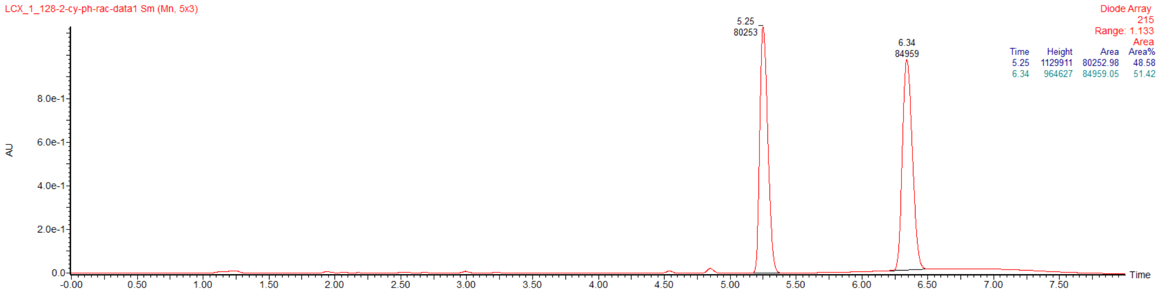


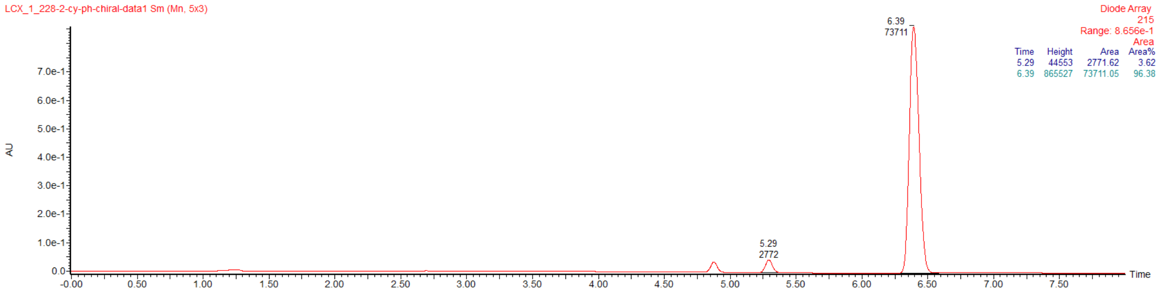
Diode Array
246
Range: 1.805

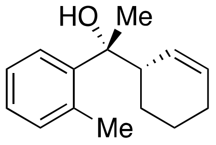
Time	Height	Area	Area%
7.10	770502	62328.75	22.70
7.57	33282	2675.30	0.97
7.76	1801259	201822.89	73.50
8.52	69078	7746.28	2.82



10


LCX_1_128-2-cy-ph-rac-data1 Sm (Mn, 5x3)
Diode Array
215
Range: 1.133
Area
Time Height Area Area%
5.25 1129911 80252.98 48.58
6.34 964627 84959.05 51.42
5.25
80253
6.34
84959
AU
8.0e-1
6.0e-1
4.0e-1
2.0e-1
0.0
-0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00 7.50
Time


LCX_1_228-2-cy-ph-chiral-data1 Sm (Mn, 5x3)
Diode Array
215
Range: 8.656e-1
Area
Time Height Area Area%
5.29 44553 2771.62 3.62
6.39 865527 73711.05 96.38
6.39
73711
5.29
2772
AU
7.0e-1
6.0e-1
5.0e-1
4.0e-1
3.0e-1
2.0e-1
1.0e-1
0.0
-0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00 7.50
Time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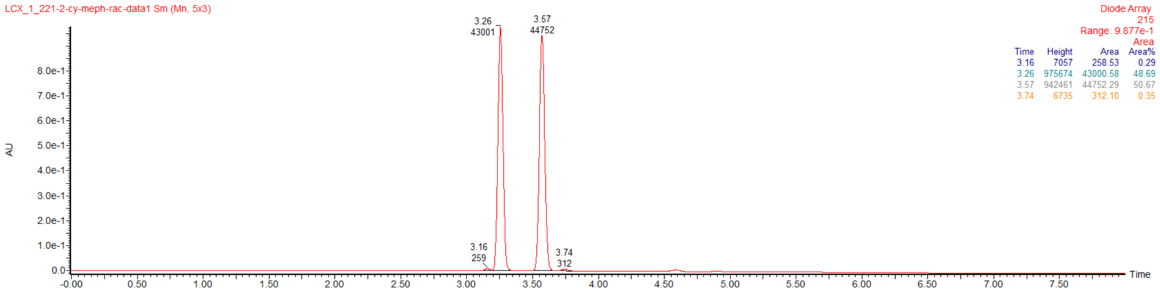
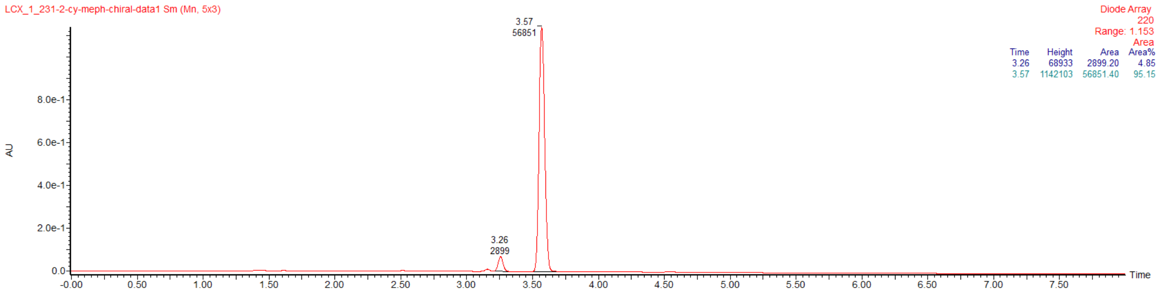
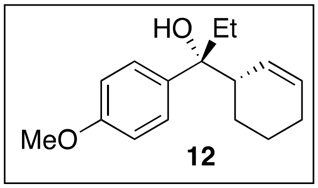

LCX_1_221-2-cy-meph-rac-data1 Sm (Mn, 5x3)
Diode Array
215
Range: 9.877e-1
Area
Time Height Area Area%
3.16 7057 258.53 0.29
3.26 975674 43000.58 48.69
3.57 942461 44752.29 50.67
3.74 6735 312.10 0.35
3.26
43001
3.57
44752
3.16
259
3.74
312
AU
8.0e-1
7.0e-1
6.0e-1
5.0e-1
4.0e-1
3.0e-1
2.0e-1
1.0e-1
0.0
-0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00 7.50
Time


LCX_1_231-2-cy-meph-chiral-data1 Sm (Mn, 5x3)
Diode Array
220
Range: 1.153
Area
Time Height Area Area%
3.26 68933 2899.20 4.85
3.57 1142103 56851.40 95.15
3.57
56851
3.26
2899
AU
8.0e-1
6.0e-1
4.0e-1
2.0e-1
0.0
-0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.00 6.50 7.00 7.50
Time



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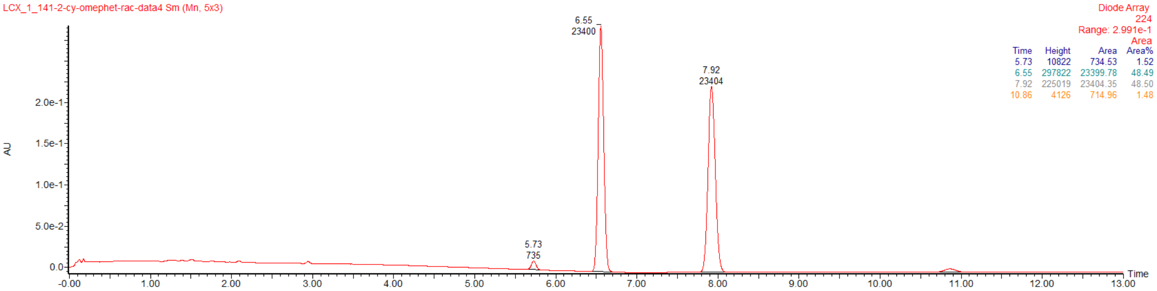
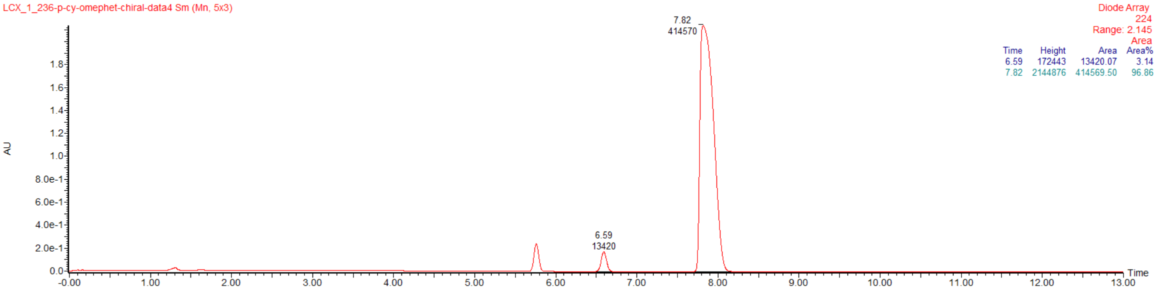
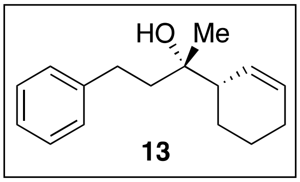

LCX_1_141-2-cy-omephet-rac-data4 Sm (Mn, 5x3)

			Area
Time	Height	Area	Area%
5.73	10822	734.53	1.52
6.55	297822	23399.78	48.49
7.92	225019	23404.35	48.50
10.86	4126	714.96	1.48


LCX_1_236-p-cy-omephet-chiral-data4 Sm (Mn, 5x3)

			Area
Time	Height	Area	Area%
6.59	172443	13420.07	3.14
7.82	2144876	414569.50	96.86



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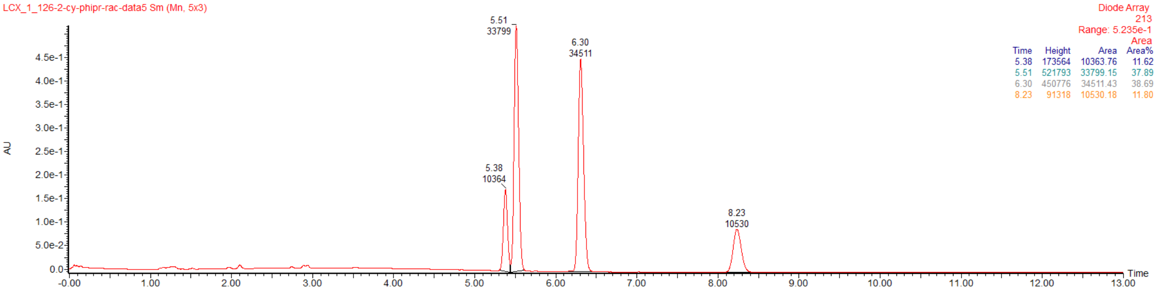
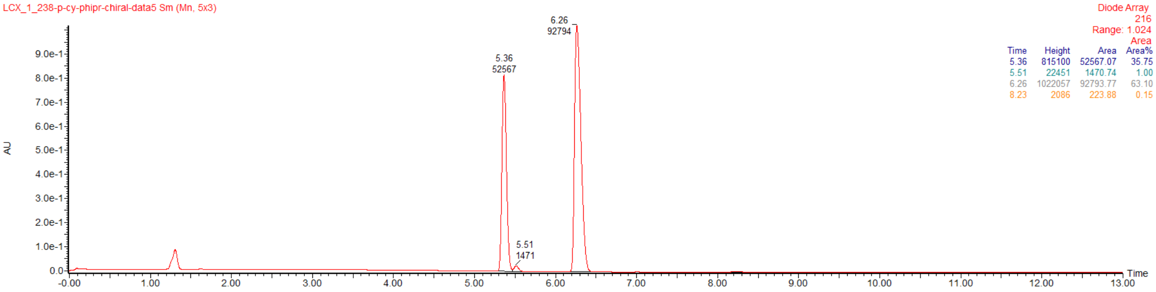
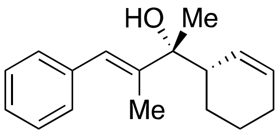

LCX_1_126-2-cy-phipr-rac-data5 Sm (Mn, 5x3)

			Area
Time	Height	Area	Area%
5.38	173564	10363.76	11.62
5.51	521793	33799.15	37.89
6.30	450776	34511.43	38.69
8.23	91318	10530.18	11.80


LCX_1_238-p-cy-phipr-chiral-data5 Sm (Mn, 5x3)

			Area
Time	Height	Area	Area%
5.36	815100	52567.07	35.75
5.51	22451	1470.74	1.00
6.26	1022057	92793.77	63.10
8.23	2086	223.88	0.15



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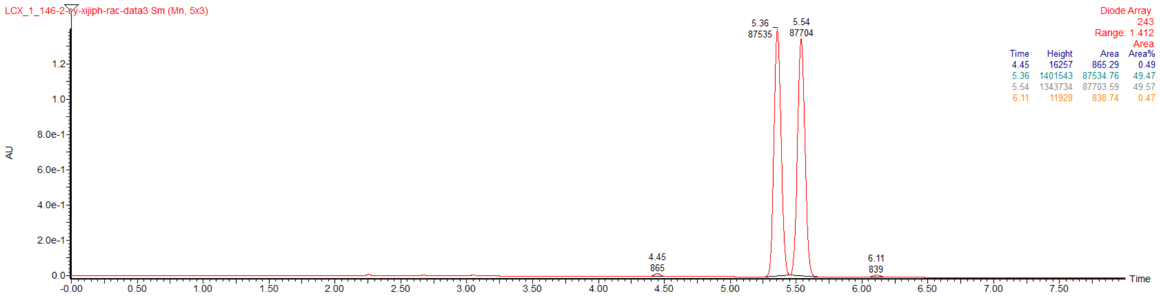
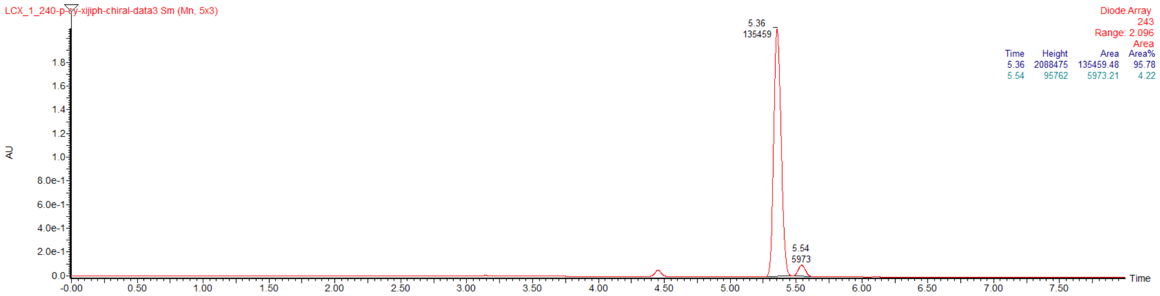
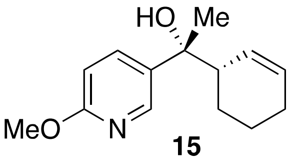


Time	Height	Area	Area Area%
4.45	16257	865.29	0.49
5.36	1401543	87534.76	49.47
5.54	1343734	87703.59	49.57
6.11	11928	838.74	0.47



Time	Height	Area	Area Area%
5.36	2088475	135459.48	95.78
5.54	95762	5973.21	4.22



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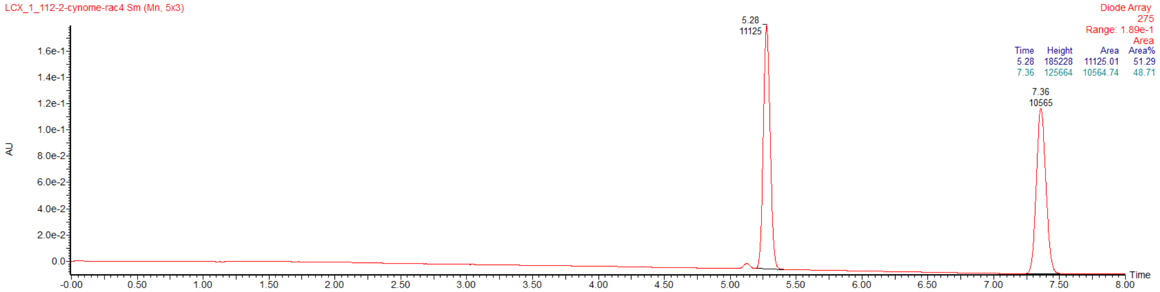
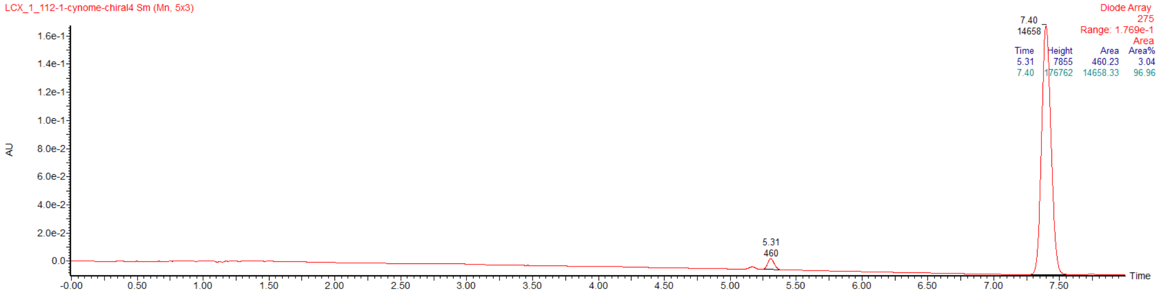
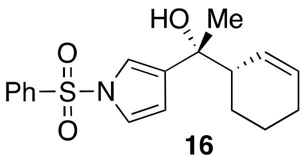


Time	Height	Area	Area Area%
5.28	185228	11125.01	51.29
7.36	125664	10564.74	48.71



Time	Height	Area	Area Area%
5.31	7855	460.23	3.04
7.40	176762	14658.33	96.96



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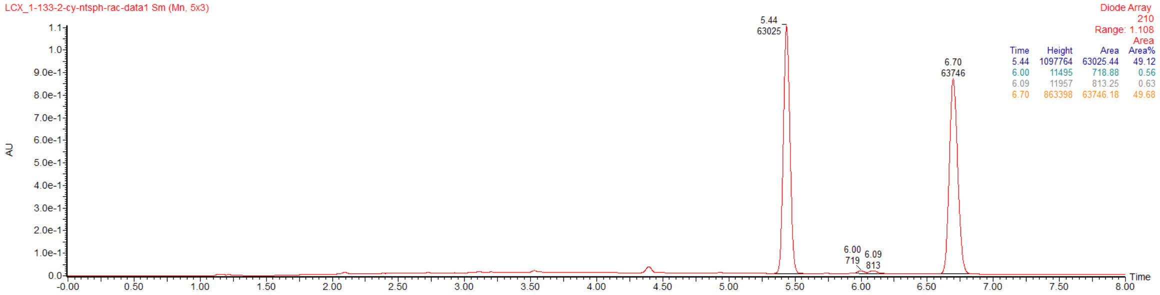
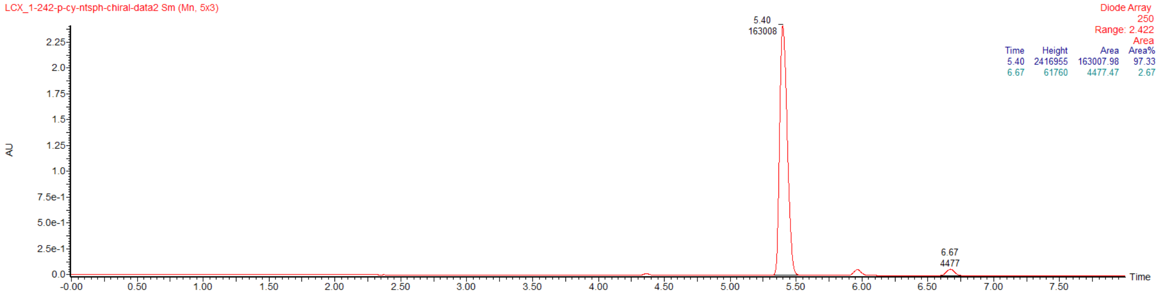
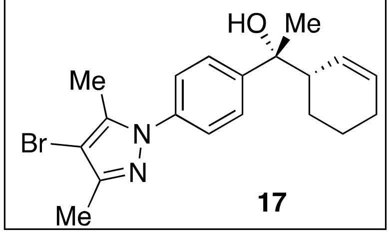


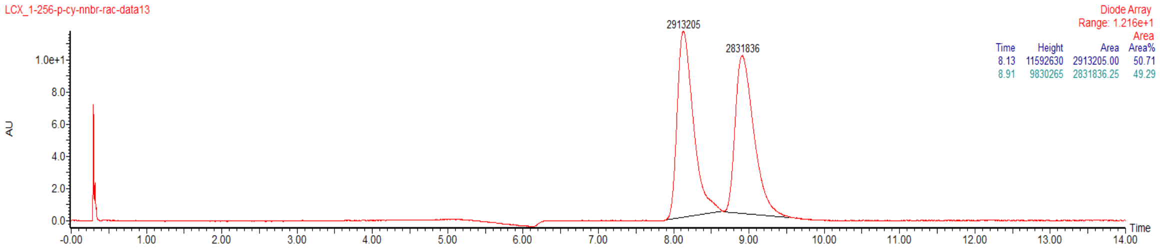
Time	Height	Area	Area%
5.44	1097764	63025.44	49.12
6.00	11495	718.88	0.56
6.09	11957	813.25	0.63
6.70	863398	63746.18	49.68



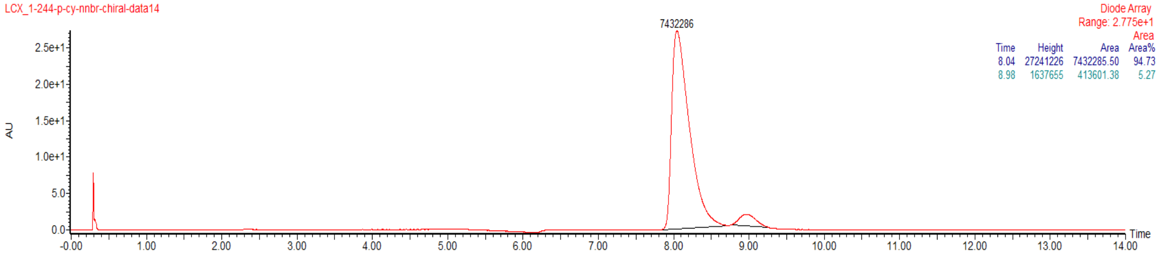
Time	Height	Area	Area%
5.40	2416955	163007.98	97.33
6.67	61760	4477.47	2.67



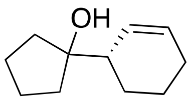
17



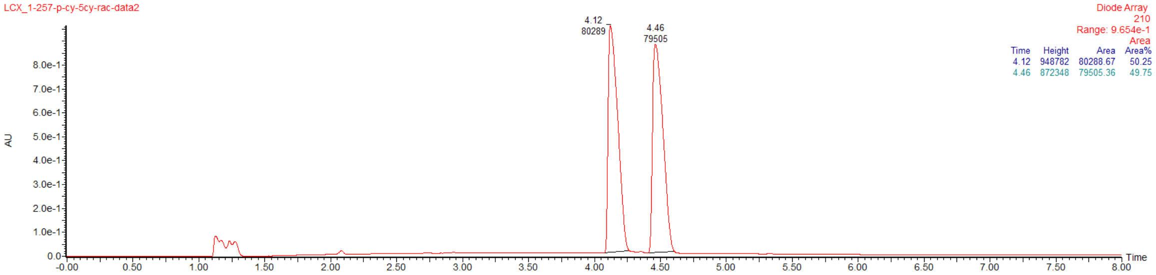
Time	Height	Area	Area%
8.13	11592630	2913205.00	50.71
8.91	9830265	2831836.25	49.29



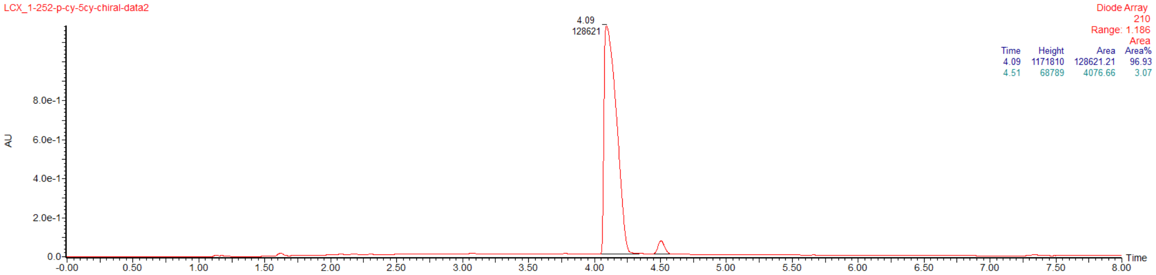
Time	Height	Area	Area%
8.04	27241226	7432285.50	94.73
8.98	1637655	413601.38	5.27



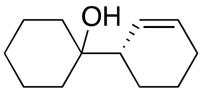
18



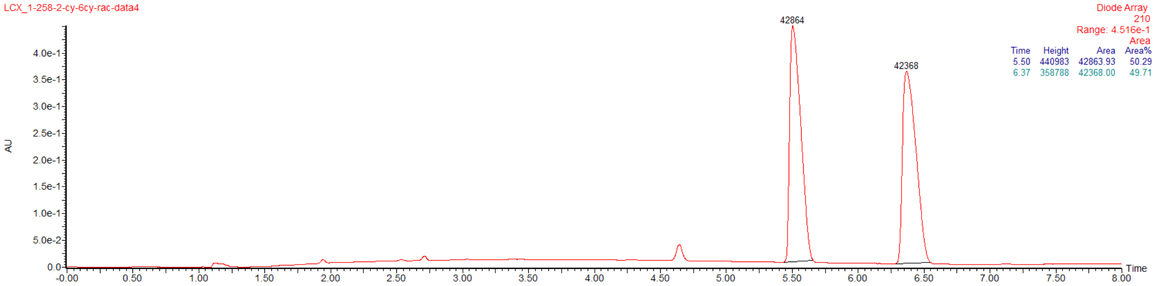
Time	Height	Area	Area Area%
4.12	948782	80288.67	50.25
4.46	872348	79505.36	49.75



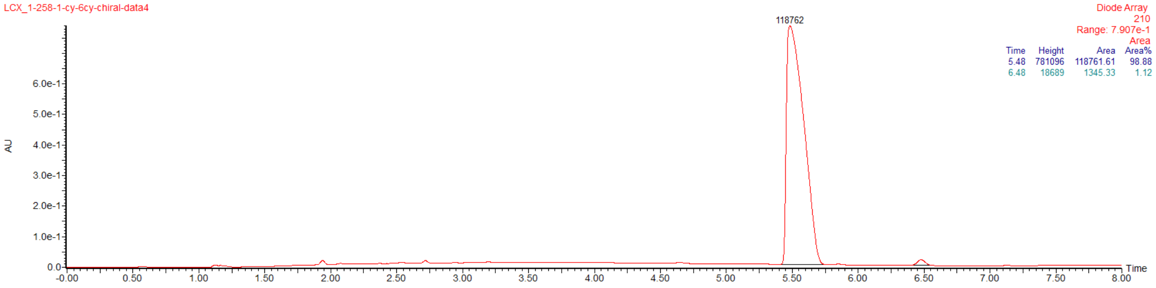
Time	Height	Area	Area Area%
4.09	1171810	128621.21	96.93
4.51	68789	4076.66	3.07



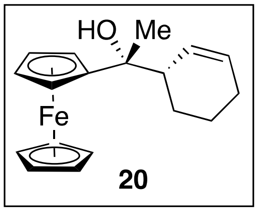
19



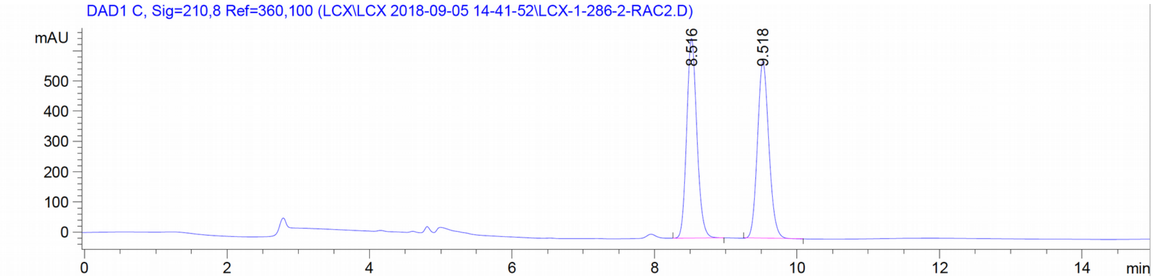
Time	Height	Area	Area Area%
5.50	440983	42863.93	50.29
6.37	358788	42368.00	49.71



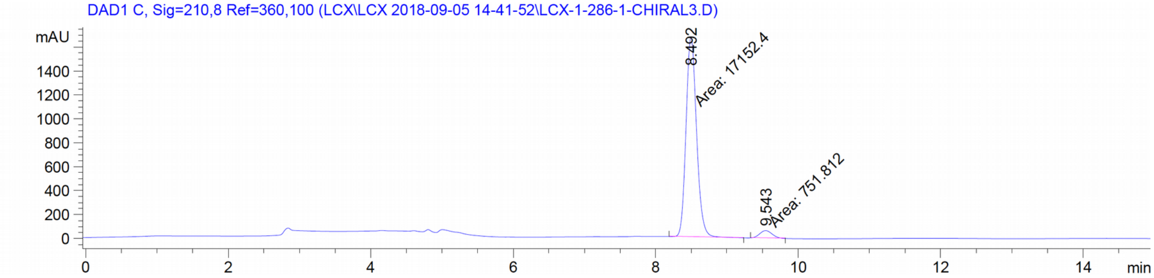
Time	Height	Area	Area Area%
5.48	781096	118761.61	98.88
6.48	18689	1345.33	1.12



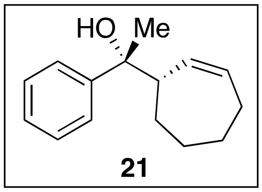
20



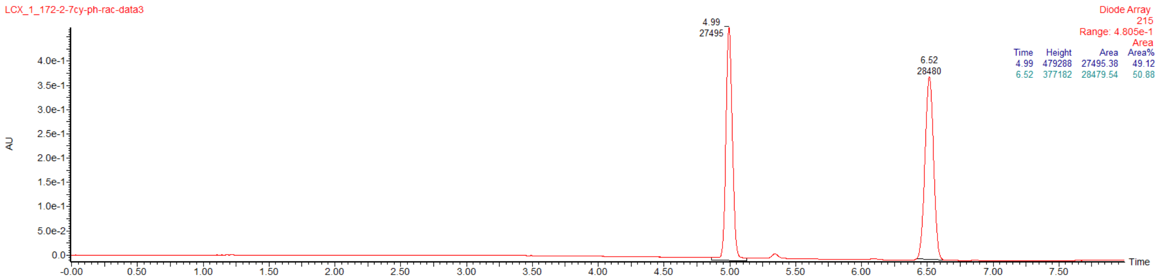
```
Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [mAU*s]     [mAU]        %
----|-------|----|-------|----------|----------|--------|
   1   8.516 BB    0.1542 6585.54395  661.06000  50.2750
   2   9.518 BB    0.1740 6513.50635  584.43677  49.7250
```



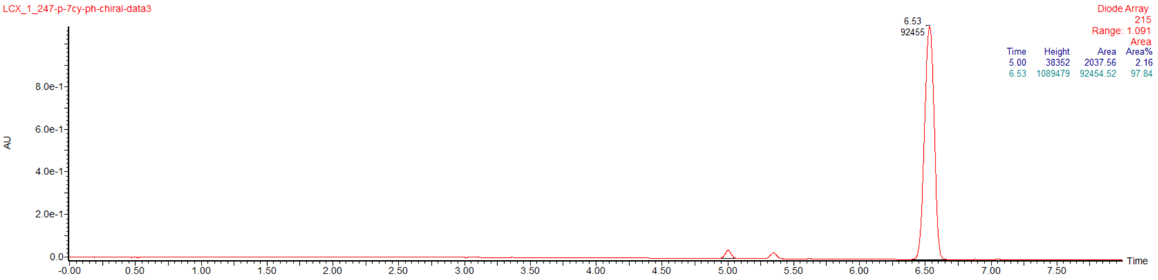
```
Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [mAU*s]     [mAU]        %
----|-------|----|-------|----------|----------|--------|
   1   8.492 MM    0.1713 1.71524e4  1668.59265  95.8009
   2   9.543 MM    0.2004  751.81238   62.51367   4.1991
```



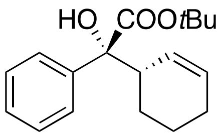
21



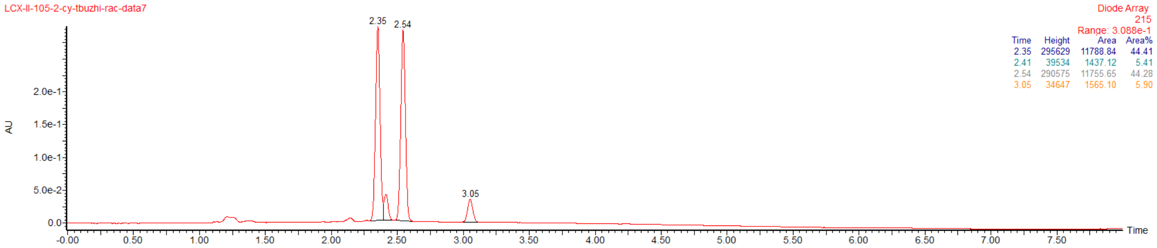
Time	Height	Area	Area%
4.99	479288	27495.38	49.12
6.52	377182	28479.54	50.88



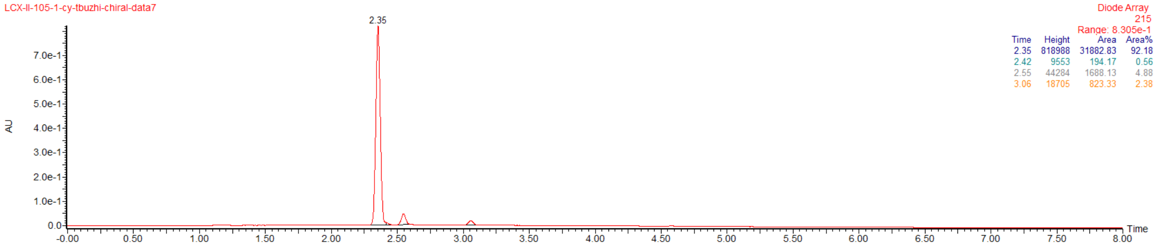
Time	Height	Area	Area Area%
5.00	38352	2037.56	2.16
6.53	1089479	92454.52	97.84



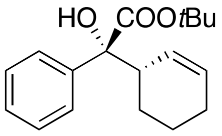
29 (stepwise)



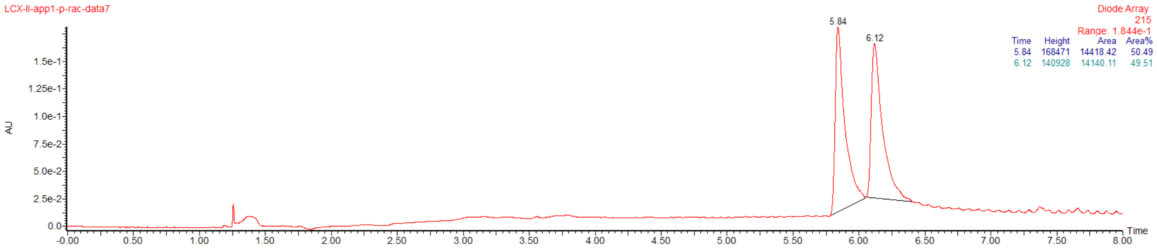
Time	Height	Area	Area%
2.35	295629	11788.84	44.41
2.41	39534	1437.12	5.41
2.54	290575	11755.65	44.28
3.05	34647	1565.10	5.90



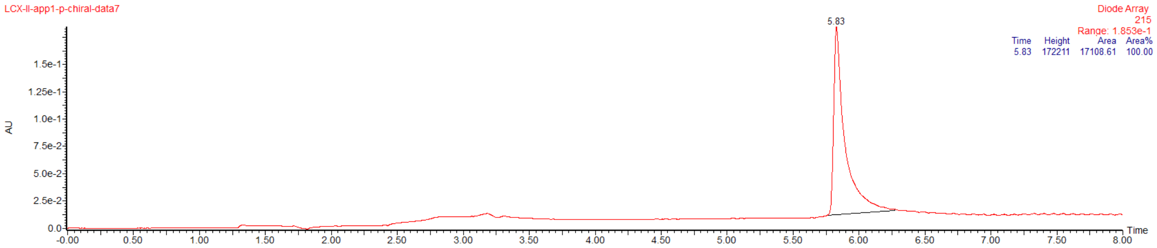
Time	Height	Area	Area%
2.35	818988	31882.83	92.18
2.42	9553	194.17	0.56
2.55	44284	1688.13	4.88
3.06	18705	823.33	2.38



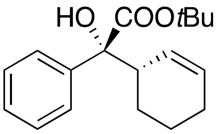
30 (stepwise)



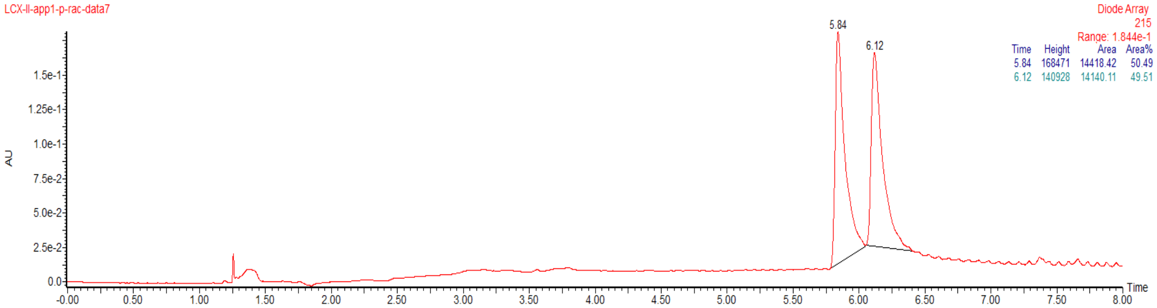
Time	Height	Area	Area%
5.84	168471	14418.42	50.49
6.12	140928	14140.11	49.51



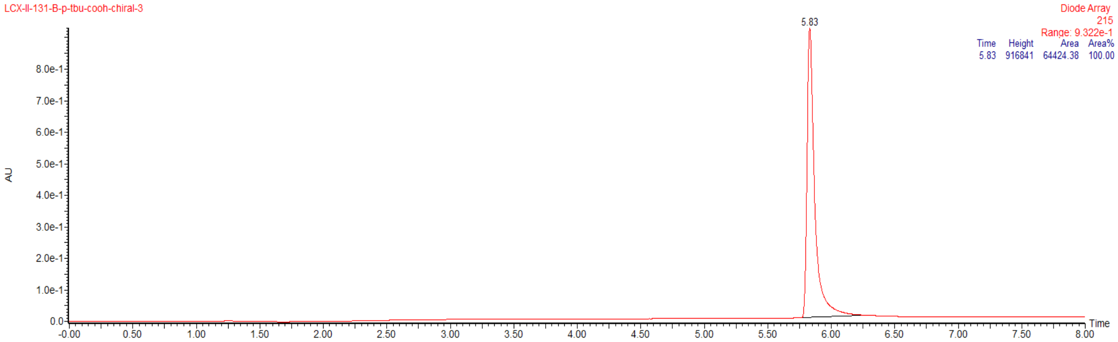
Time	Height	Area	Area%
5.83	172211	17108.61	100.00



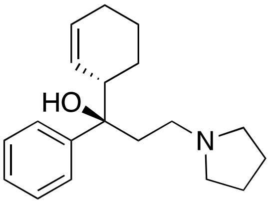
30 (one pot)



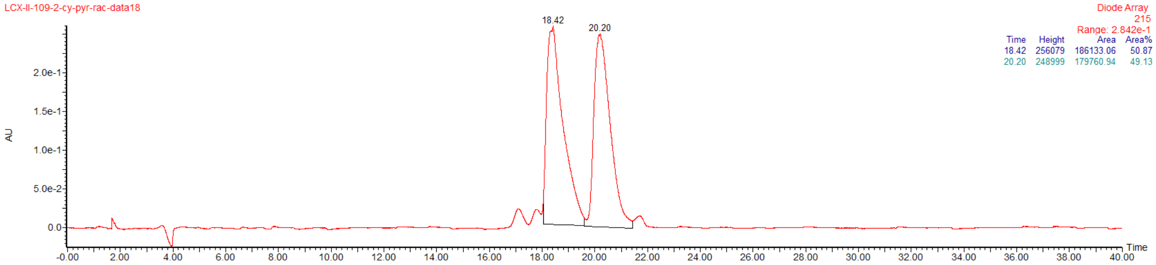
Time	Height	Area	Area%
5.84	168471	14418.42	50.49
6.12	140928	14140.11	49.51



Time	Height	Area	Area%
5.83	916841	64424.38	100.00

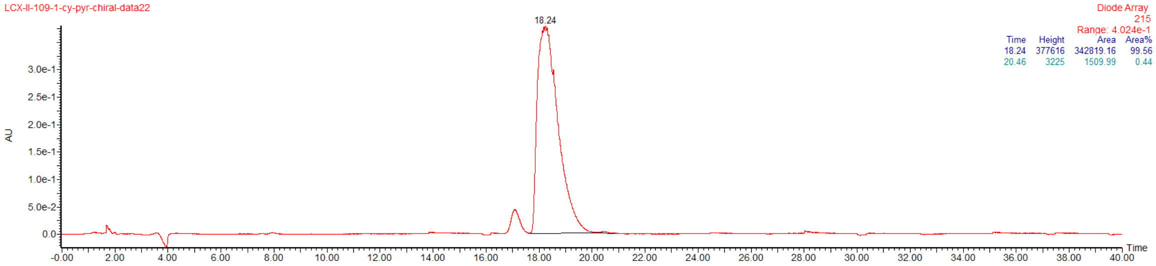


32 (stepwise)


LCX-II-109-2-cy-pyr-rac-data18

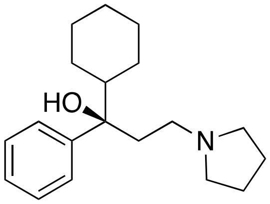
Diode Array
215
Range: 2.842e-1

Time	Height	Area	Area%
18.42	256079	186133.06	50.87
20.20	248999	179760.94	49.13

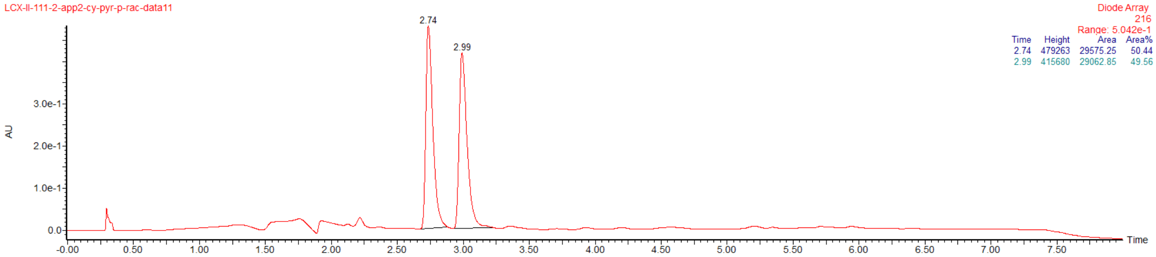

LCX-II-109-1-cy-pyr-chiral-data22

Diode Array
215
Range: 4.024e-1

Time	Height	Area	Area%
18.24	377616	342819.16	99.56
20.46	3225	1509.99	0.44

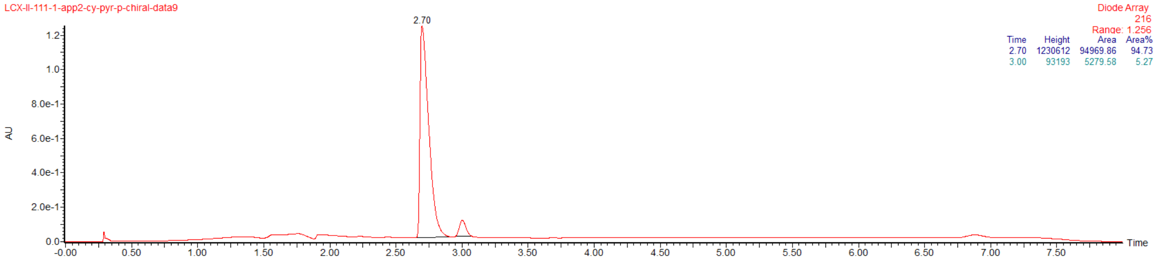


33 (*R*)-Procyclidine (stepwise)


LCX-II-111-2-app2-cy-pyr-p-rac-data11

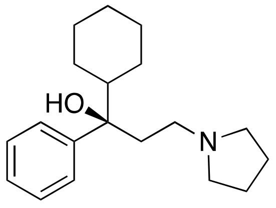
Diode Array
216
Range: 5.042e-1

Time	Height	Area	Area%
2.74	479263	29575.25	50.44
2.99	415680	29062.85	49.56

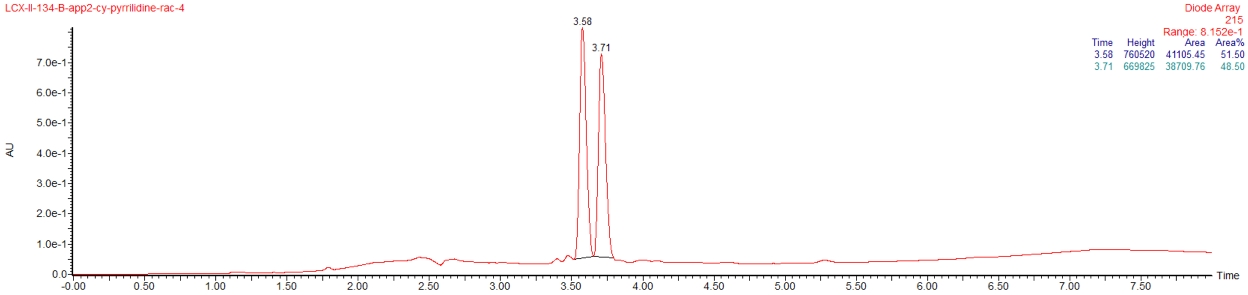

LCX-II-111-1-app2-cy-pyr-p-chiral-data9

Diode Array
216
Range: 1.256

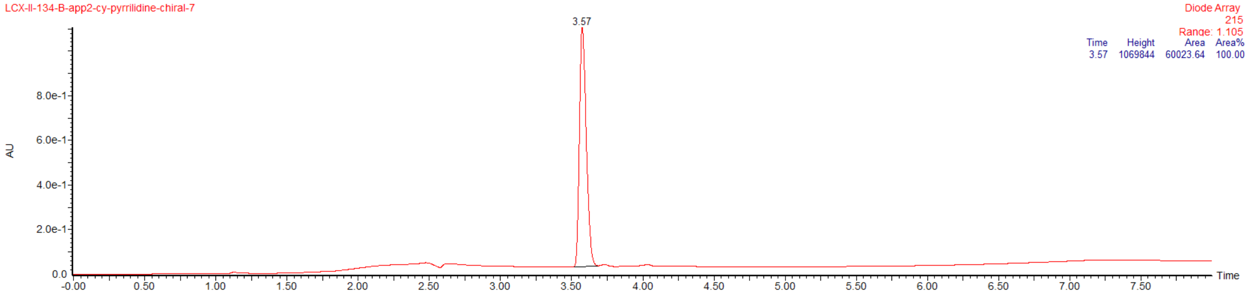
Time	Height	Area	Area%
2.70	1230612	94969.86	94.73
3.00	93193	5279.58	5.27



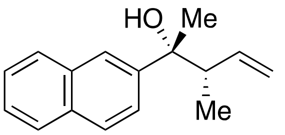
33 (*R*)-Procyclidine (one pot)

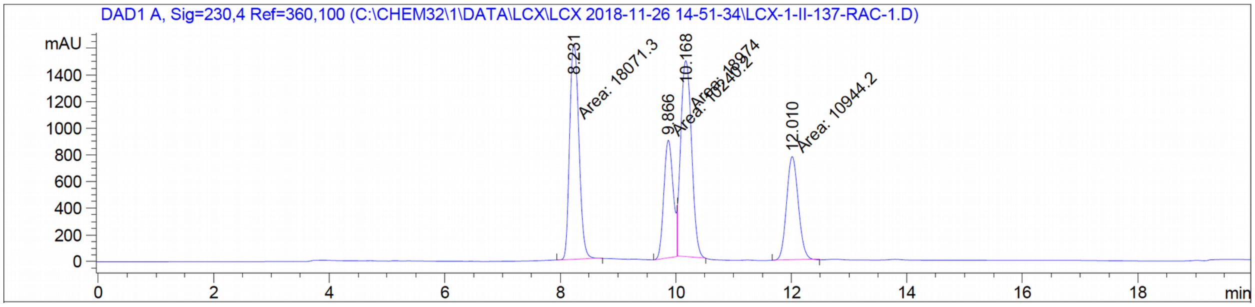


Time	Height	Area	Area%
3.58	760520	41105.45	51.50
3.71	669825	38709.76	48.50



Time	Height	Area	Area%
3.57	1069844	60023.64	100.00





```
Signal 1: DAD1 A, Sig=230,4 Ref=360,100

Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [mAU*s]     [mAU]       %
----|-------|----|-------|----------|----------|--------|
   1   8.231 MM    0.1865 1.80713e4 1614.86646  31.0345
   2   9.866 MM    0.1932 1.02402e4  883.41339  17.5858
   3  10.168 MM    0.2150 1.89740e4 1470.73889  32.5847
   4  12.010 MM    0.2353 1.09442e4  775.32892  18.7949

Totals :                  5.82297e4 4744.34766
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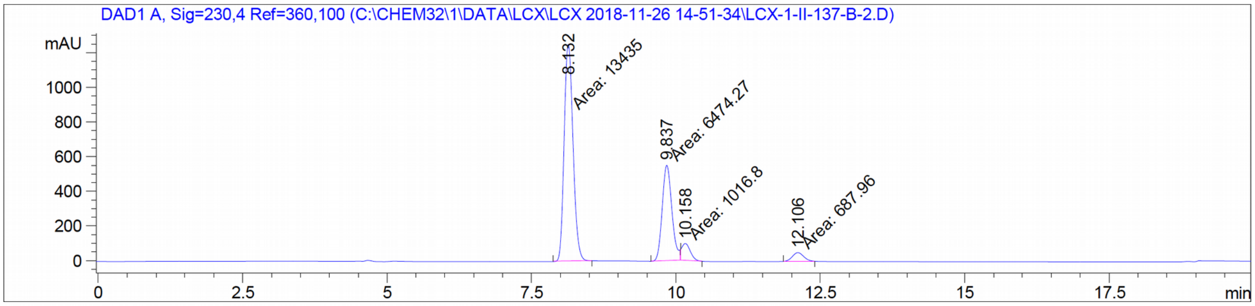

```
Signal 1: DAD1 A, Sig=230,4 Ref=360,100

Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [mAU*s]     [mAU]       %
----|-------|----|-------|----------|----------|--------|
   1   8.132 MM    0.1783 1.34350e4 1255.86975  62.1587
   2   9.837 MM    0.1953 6474.26709  552.61267  29.9540
   3  10.158 MM    0.1708 1016.79987   99.19756   4.7043
   4  12.106 MM    0.2267  687.95978   50.57132   3.1829

Totals :                  2.16140e4 1958.25130
```

Compiled NMR Spectra for

CuH-Catalyzed Enantioselective Ketone Allylation with 1,3-Dienes: Scope, Mechanism, and Applications

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