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I. General methods

General. Unless otherwise noted, all chemicals and reagents were obtained from commercial suppliers (Sigma-Aldrich, VWR, Alfa Aesar, Combi-Blocks and Enamine) and used without further purification. Silica gel chromatography was carried out using AMD Silica Gel 60, 230-400 mesh. ^{1}H, and ^{13}C NMR spectra were recorded on a Varian Inova 300 MHz or Bruker Prodigy 400 MHz instrument in $CDCl_3$ and are referenced to residual protio solvent signals. ^{19}F NMR spectra (where applicable) were recorded on a Varian Inova 300 MHz and are referenced to $CFCl_3$ as the external standard. Data for ^{1}H NMR are reported as follows: chemical shift (δ ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, sext = sextet, m = multiplet, dd = doublet of doublets, dt = doublet of triplets, ddd = doublet of doublet of doublets), coupling constant (Hz), integration. Sonication was performed using a Qsonica Q500 sonicator. All IR spectra were taken on a Thermo Scientific Nicolet iS5 spectrometer (iD5 ATR, diamond). High-resolution mass spectrometry data were obtained at the California Institute of Technology Mass Spectral Facility. Samples were analyzed by liquid chromatography mass spectrometry (LCMS-ESI) or fast atom bombardment (FAB) mass spectrometry. LC-MS samples were run on a Waters Acquity BEH C4 column with a fast 5 min gradient of water (0.1% formic acid) and acetonitrile (0.1% formic acid). The LC was interfaced to a Waters LCT Premier XE time-of-flight mass spectrometer with an electrospray ion source operated in the positive ion mode. FAB samples were analyzed by a JEOL JMS-60H double focussing magnetic sector mass spectrometer using FAB ionization in the positive ion mode. Synthetic reactions were monitored by thin layer chromatography (TLC, Merck 60 gel plates) using a UV-lamp or an appropriate TLC stain for visualization.

E. coli cells were grown using Luria-Bertani medium (LB) or Hyperbroth (AthenaES) (HB) with 0.1 mg/mL ampicillin (LB_{amp} or HB_{amp}). Primer sequences are available upon request. T5 exonuclease, Phusion polymerase, and Taq ligase were purchased from New England Biolabs (NEB, Ipswich, MA). M9-N minimal medium (abbreviated as M9-N buffer; pH 7.4) was used as a buffering system for whole cells and lysates, unless otherwise specified. M9-N buffer was used without a nitrogen source; it contains 47.7 mM Na_2HPO_4, 22.0 mM KH_2PO_4, 8.6 mM NaCl, 2.0 mM $MgSO_4$, and 0.1 mM $CaCl_2$.

Chromatography. Analytical reversed-phase high-performance liquid chromatography (HPLC) was carried out using an Agilent 1200 series instrument and a Kromasil 100-5-C18 column (4.6 × 50 mm, 5 μm) or an Eclipse XDB C18 column (4.6 × 150 mm, 3 μm) with water and acetonitrile as the mobile phase. Analytical chiral HPLC was conducted using either an Agilent 1200 series instrument with hexanes and isopropanol as the mobile phase or JACSO 2000 series supercritical fluid chromatography (SFC) system with supercritical CO_2 and isopropanol as the mobile phase. Enantiomers were separated using one of the following chiral columns: Chiralpak AD-H, Chiralpak IC (4.6 mm × 25 cm), Chiralcel OD-H (4.6 mm × 25 cm). Gas chromatography (GC) analysis was carried out using an Agilent 7820A or Shimadzu GC-17A GC system, both equipped with an FID detector and with a J&W HP-5 column (30 m × 0.32 mm, 0.25 μm film). Chiral GC was conducted using an Agilent 7820A instrument (FID) and an Agilent CycloSil-B column (30 m × 0.32 mm, 0.25 μm film). Gas chromatography-mass spectrometry (GC-MS) analyses were carried out using a Shimadzu GCMS-QP2010SE system and J&W HP-5ms column (30 m × 0.25 mm, 0.25 μm film).

Cloning and site-saturation mutagenesis. pET22b(+) was used as a cloning and expression vector for all enzymes described in this study. All enzymes described in this study were expressed with a C-terminal 6 × His-tag. Site-saturation mutagenesis was performed using the "22c-trick" method.[1] The PCR products were digested with DpnI, gel purified, and ligated using Gibson Mix™.[2] The ligation mixture was used to directly transform electrocompetent *E. coli* strain *E. cloni* BL21(DE3) cells (Lucigen).

Expression of P450 and P411 variants in 96-well plates. Single colonies from LB_{amp} agar plates were picked using sterile toothpicks and cultured in deep-well 96-well plates containing LB_{amp} (400 μL/well) at 37 °C, 220 rpm shaking, and 80% relative humidity overnight. After, HB_{amp} (900 μL/well) in a deep-well 96-well plate was inoculated with an aliquot (100 μL/ well) of these overnight cultures and allowed to shake for 2.5 h at 37 °C, 220 rpm, and 80% relative humidity. The plates were cooled on ice for 20 min and the cultures were induced with 0.5 mM isopropyl β-D-1-thiogalactopyranoside (IPTG) and 1.0 mM 5-aminolevulinic acid (final concentrations). Expression was conducted at 20 ºC, 230 rpm for 16–18 h.

Reaction screening in 96-well plate format. *E. coli* (*E. cloni* BL21(DE3)) cells in deep-well 96-well plates were pelleted (3,000 g, 3 min, 4 °C) and resuspended in M9-N buffer (20 μL/well) by gentle shaking for 3 min. A GOx oxygen depletion system was added (20 μL/well of a stock solution containing 14,000 U/mL catalase and 1,000 U/mL glucose oxidase in M9-N buffer, pH 7.4), and the 96-well plate was then transferred into an anaerobic chamber. In the anaerobic chamber, reaction buffer (50 mM glucose in M9-N, 320 μL/well) was added, followed by the sulfamoyl azide substrate (20 μL/well, 400 mM in EtOH). The plate was sealed with an aluminum foil and shaken at room temperature and 500 rpm in the anaerobic chamber. After 12–20 h, the seal was removed and the reactions were worked up following the appropriate method below.

(A) Product formation screening and enantioselectivity screening using GC or GC-MS. After 12–20 h, a solution of 1 mM 1,2,3- trimethoxybenzene (internal standard) in a mixed solvent system (hexanes/ EtOAc = 1:1, 400 μL – 1 mL) was added. The plate was tightly sealed with a reusable silicone mat, shaken vigorously, and centrifuged (4500 g, 3 min) to completely separate the organic and aqueous layers. The organic layers (200 μL/well) were transferred to 500 μL vial inserts, which were then placed in 2 mL vials and analyzed by GC or GC-MS.

(B) Product formation screening using HPLC-MS. After 12–20 h, the reaction mixtures were quenched by the addition of EtOH or MeCN (800 μL/well). The plate containing the resulting mixture was tightly sealed with a reusable silicone mat, shaken vigorously and centrifuged (4500 g, 5 min) to pellet the cells. The supernatant (300 μL/well) was filtered through an AcroPrep 96-well filter plate (0.2 μm) into a shallow-well plate and analyzed by reverse-phase LCMS.

Expression of P411 variants. *E. coli* (*E. cloni* BL21(DE3)) cells carrying plasmid encoding the appropriate P411 variant were grown overnight in 4 mL LB_{amp}. Preculture (3 mL) was used to inoculate 27 mL of HB_{amp} in a 125 mL Erlenmeyer flask. This culture was incubated at 37 °C,

230 rpm for 2.5 h. The culture was then cooled on ice for 20 min and induced with 0.5 mM IPTG and 1.0 mM 5-aminolevulinic acid (final concentrations). Expression was conducted at 20 °C, 130 rpm, for 16–18 h. *E. coli* cells were then pelleted by centrifugation (4500 g, 3 min, 4 °C). Media was removed and the resulting cell pellet was resuspended in M9-N buffer to OD_{600} = 30–40. An aliquot of this cell suspension (2 mL) was taken to determine P411 concentration using the hemochrome assay after lysis by sonication. When applicable, the remaining cell suspension was further diluted with M9-N buffer to the OD_{600} used for the biotransformation and the concentration of P411 protein in the biotransformation was calculated accordingly.

Hemochrome assay for the determination of heme protein concentration.[3] *E. coli* cells expressing heme protein resuspended in M9-N buffer were lysed by sonication using a Qsonica Q500 sonicator equipped with a microtip (5 min in total, 1 sec on, 1 sec off, 30% amplitude); samples were kept on wet ice for this process. The resulting lysed solution was centrifuged (14000 rpm, 10 min, 4 °C) to remove cell debris. The supernatant (clarified lysate) was separated from the pellet and kept on ice until use.

In a Falcon tube, a solution of 0.2 M NaOH, 40% (v/v) pyridine, 0.5 mM $K_3Fe(CN)_6$ was prepared (pyridine-NaOH-$K_3Fe(CN)_6$ solution). In another Eppendorf tube, a solution of 0.5 M $Na_2S_2O_4$ (sodium dithionite) was prepared in 0.1 M NaOH. To an Eppendorf tube containing 500 µL of clarified lysate in M9-N buffer was added 500 µL of the pyridine-NaOH-$K_3Fe(CN)_6$ solution, mixed, and transferred to a cuvette; the UV-Vis spectrum of the oxidized Fe^{III} state was recorded immediately. To the cuvette was then added 10 µL of the sodium dithionite solution. The cuvette was sealed with parafilm and the UV-Vis spectrum of the reduced Fe^{II} state was recorded immediately. A cuvette containing 500 µL of M9-N, 100 µL 1 M NaOH, 200 µL pyridine, and 200 µL water (complete mixture without protein and $K_3Fe(CN)_6$) was used as a reference for all absorbance measurements. Concentrations of cytochromes P450, cytochromes P411, and globins were determined using a published extinction coefficient for heme *b*, $\varepsilon_{556(reduced)-540(oxidized)} = 23.98\ mM^{-1}cm^{-1}$.

Biotransformations using whole *E. coli* cells. Suspensions of *E. coli* (*E. cloni* BL21(DE3)) cells expressing the appropriate heme protein variant in M9-N buffer (typically OD_{600} = 30) were

kept on ice. In another falcon tube, a solution of D-glucose (250 mM in M9-N) was prepared. All solutions were then transferred into an anaerobic chamber for reaction set up. To a 2 mL vial were added a GOx oxygen depletion solution (20 μL of stock solution containing 14,000 U/mL catalase and 1,000 U/mL glucose oxidase in M9-N buffer), D-glucose (40 μL of 250 mM stock solution in M9-N buffer), the suspension of *E. coli* expressing P411 (typically OD_{600} = 30, 320 μL) and the sulfamoyl azide substrate (20 μL of 400 mM stock solution in EtOH) in succession. Final reaction volume was 400 μL; final concentrations were 10 mM sulfamoyl azide and 25 mM D-glucose. (Note: reaction performed with *E. coli* cells resuspended to OD_{600} = 30 indicates that 320 μL of OD_{600} = 30 cells were added, and likewise for other reaction OD_{600} descriptions.) The vials were sealed and shaken at room temperature and 500 rpm for 12-20 h.

Preparative scale biotransformations using whole *E. coli* cells. HB_{amp} (480 mL) in a 1 L flask was inoculated with an overnight culture (20 mL, LB_{amp}) of *E. coli* (*E. cloni* BL21(DE3)) cells containing a pET22b(+) plasmid encoding the desired $P411_{Diane}$ variant. The cell culture was shaken at 37 °C and 220 rpm for 2.5 h. The culture was placed on ice for 30 min, and 5-aminolevulinic acid (1.0 mM final concentration) and IPTG (0.5 mM final concentration) were added. The culture was allowed to shake for 16–18 hours at 20 °C and 130 rpm. Cells were pelleted by centrifugation (4,000 g, 3 min, 4 °C), resuspended in M9-N buffer and adjusted to OD_{600} = 30–40. An aliquot of cells (2 mL) was taken for the hemochrome assay to determine the concentration of P411 enzyme. Cell suspensions in M9-N buffer were kept on ice until use (Note: leaving the cell suspension at room temperature for a long period of time (e.g., several hours) leads to significantly reduced enzyme activity).

To an Erlenmeyer flask equipped with a screw cap were added a suspension of *E. coli* cells in M9-N buffer expressing $P411_{Diane}$ and a GOx oxygen depletion solution (stock solution containing 14,000 U/mL catalase and 1,000 U/mL glucose oxidase in M9-N buffer). The flask was transferred to an anaerobic chamber, where D-glucose and a stock solution of the substrate (200 –400 mM in EtOH) were added. The flask was capped, sealed with parafilm, taken out of the anaerobic chamber and allowed to shake at room temperature at 200 rpm for 12–24 h. If needed, a second batch of cell suspensions in M9-N buffer was added 1–3 h later in the anaerobic chamber.

The reaction mixture was extracted with EtOAc (3 times). If needed, the mixture was transferred to a 50 mL Falcon tube and centrifuged (5000 g, 3 min) to separate the organic layer from the aqueous layer. Combined organic layers were dried over $MgSO_4$, concentrated in vacuo with the aid of a rotary evaporator and purified by column chromatography with the aid of Biotage Isolera.

GC/GC-MS calibration curve development. Stock solutions of products (100 mM in EtOAc) were prepared (at least 20 mg of sample was weighed to make a 100 mM stock solution in EtOAc). To a microcentrifuge tube were added 380 μL M9-N buffer, 5–80 μL product stock solution, 5 μL internal standard (200 mM 1,2,3-trimethoxybenzene in toluene), and 1 mL mixed solvent system (hexanes:EtOAc = 1:1). The mixture was vortexed (20 s for 3 times) and centrifuged (20,000 g, 5 min) to completely separate the organic and aqueous layers. The organic layer was removed for GC analysis. The calibration curves plot product concentration in mM (y-axis) against the ratio of the peak area of product to the peak area of internal standard from GC/GC-MS analysis (x-axis).

Protein purification. *E. coli* (*E. cloni* BL21(DE3)) cells carrying plasmid encoding a P411 variant were grown overnight in 19 mL LB_{amp} (37 ºC, 250 rpm). HB_{amp} (450 mL) media in a 1 L flask was inoculated with 19 mL of the preculture and shaken for 2.5 h at 37 °C and 220 rpm. Cultures were cooled on ice (30 min) and induced with 0.5 mM IPTG and 1.0 mM 5-aminolevulinic acid (final concentrations). Expression was conducted at 22 °C, 130 rpm, for 16–20 h. Cultures were then centrifuged (5,000 g, 10 min, 4 °C) and the cell pellets were frozen at -20 °C. For purification, frozen cells from two such cultures were resuspended in His-trap buffer A (25 mM Tris, 100 mM NaCl, 20 mM imidazole, pH 7.5, 4 mL/g of cell wet weight), loaded with hemin (1 mg/g wet cell weight) and powdered DNase I, and lysed by sonication. To pellet cell debris, lysates were centrifuged (20,000 g, 20 min, 4 °C). The protein containing a C-terminal 6×His-tag was purified with a nickel NTA column (1 mL HisTrap HP, GE Healthcare, Piscataway, NJ) using an AKTA purified FPLC system (GE healthcare). Proteins were eluted on a linear gradient from His-trap buffer A to His-trap buffer B (25 mM Tris, 500 mM imidazole, 100 mM NaCl, pH 7.5) over 10 column volumes. Fractions containing the desired heme protein

were combined, concentrated, and subjected to three exchanges of phosphate buffer (0.1 M potassium phosphate, pH 8.0) using centrifugal filters (10 kDa molecular weight cut-off, Amicon Ultra, Merck Millipore) to remove excess salt and imidazole. Concentrated proteins were aliquoted, flash-frozen on powdered dry ice, and stored at -80 °C.

II. Supplementary figures

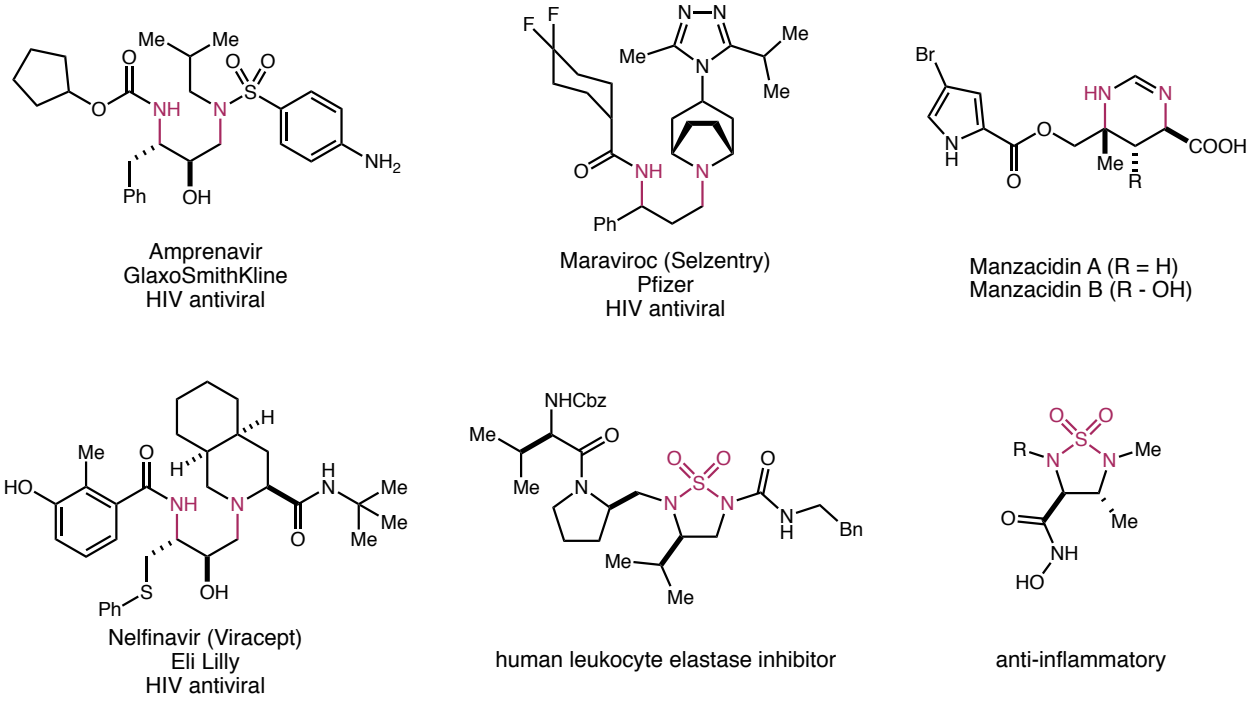
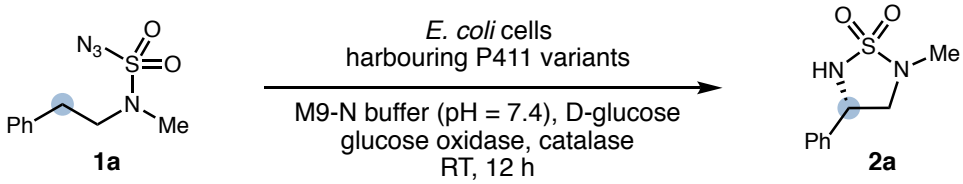


Fig. 1. Selected examples of bioactive 1,2- and 1,3-diamine derivatives

III. Screening of enzymes for C–H amination activity and directed evolution of P411$_{Diane}$

Table 1. Initial evaluation of P411$_{BM3}$ variants for the enantioselective synthesis of 1,2-diamines



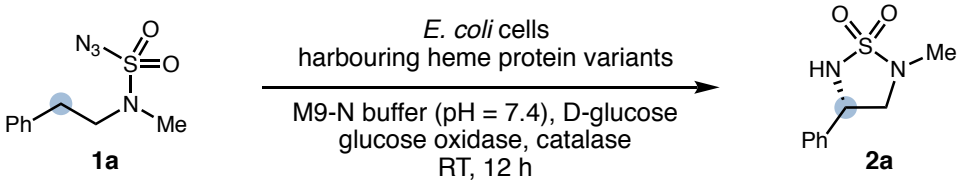
P411$_{BM3}$ variant	mutations relative to the wild type P450$_{BM3}$	yield
pET22b(+) vector	not expressing any heme protein	N.D.
P411$_{BM3}$ T268A	T268A C400S	5% (>99% ee)
P411$_{BM3}$ T268A F87A	F87A T268A C400S	N.D.
P411$_{BM3}$-CIS T438S	V78A, F87V, P142S, T175I, A184V, S226R, H236Q, E252G, T268A, A290V, L353V, I366V, C400S, T438S, E442K	N.D.
P411$_{BM3}$-CIS T438S I263F ("P-I263F")	V78A, F87V, P142S, T175I, A184V, S226R, H236Q, E252G, I263F, T268A, A290V, L353V, I366V, C400S, T438S, E442K	N.D.
P-I263M	V78A, F87V, P142S, T175I, A184V, S226R, H236Q, E252G, I263M, T268A, A290V, L353V, I366V, C400S, T438S, E442K	N.D.
P-I263Y	V78A, F87V, P142S, T175I, A184V, S226R, H236Q, E252G, I263Y, T268A, A290V, L353V, I366V, C400S, T438S, E442K	N.D.
P-I263F V87A A328V (P-3)	V78A, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263F, T268A, A290V, A328V, L353V, I366V, C400S, T438S, E442K	N.D.
P-I263F V87A A328V A268G A82L ("P-4 A82L")	V78A, A82L, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263F, T268G, A290V, A328V, L353V, I366V, C400S, T438S, E442K	1.5%

P-I263F V87A A328V A268G A82I (“P-5”)	V78A, A82I, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263F, T268G, A290V, A328V, L353V, I366V, C400S, T438S, E442K	N.D.
P-4 A82L F263Y A78L T327I (“T327I”)	V78L, A82L, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263Y, T268G, A290V, T327I, A328V, L353V, I366V, C400S, T438S, E442K	N.D.
P-4 A82L F263Y A78L T327I A74G L437Q ΔFAD (“L437Q”)	A74G, V78L, A82L, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263Y, T268G, A290V, T327I, A328V, L353V, I366V, C400S, L437Q, T438S, E442K, ΔFAD domain	3%
“T436L” FMN665	A74G, V78L, A82L, F87A, P142S, T175I, A184V, S226R, H236Q, E252G, I263Y, T268G, A290V, T327I, A328V, L353V, I366V, C400S, T436L, L437Q, E442K	8%
"M177L" FMN665 ($P411_{Diane1}$)	A74G, V78L, A82L, F87A, P142S, T175I, M177L, A184V, S226R, H236Q, E252G, I263Y, T268G, A290V, T327I, A328V, L353V, I366V, C400S, T436L, L437Q, E442K	10%
"M177L" H266V FMN665	A74G, V78L, A82L, F87A, P142S, T175I, M177L, A184V, S226R, H236Q, E252G, I263Y, H266V, T268G, A290V, T327I, A328V, L353V, I366V, C400S, T436L, L437Q, E442K, ΔFAD domain	8%
"M177L" H266V N70E A330Y FMN665	N70E, A74G, V78L, A82L, F87A, P142S, T175I, M177L, A184V, S226R, H236Q, E252G, I263Y, H266V, T268G, A290V, T327I, A328V, A330Y, L353V, I366V, C400S, T436L, L437Q, E442K, ΔFAD domain	8%
"I327T" G74P Q437L FMN665 (P411-CHF)	N70E, A74P, V78L, A82L, F87A, P142S, T175I, M177L, A184V, S226R, H236Q, E252G, I263Y, H266V, T268G, A290V, A328V, A330Y, L353V,	4%

	I366V, C400S, T436L, E442K, ΔFAD domain	

N.D. = not detected.

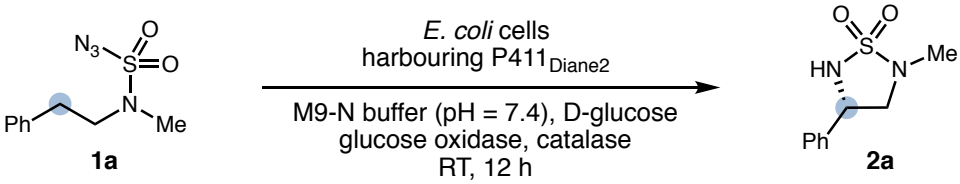
Table 2. Initial evaluation of other heme protein variants for the enantioselective synthesis of 1,2-diamines



heme protein variant	UniProt ID	mutations relative to the wild type protein	yield
WT *Rma* cyt *c*	B3FQS5		N.D.
Rma cyt *c* M100D V75G		M100D V75G	0.4%
Rma cyt *c* M100D V75G M89F		M100D V75G M89F	0.4%
WT *Rma* NOD	D0MGT2		N.D.
Rma NOD Y32C F46F L56N V97L		Y32C F46F L56N V97L	0.3%
WT ApePgb	Q9YFF4		<1%
Hth cyt *c*	P15452		N.D.

N.D. = not detected.

Table 3. Effect of reductase domain truncation on the enantioselective synthesis of 1,2-diamines



variant	TTN	ee
$P411_{Diane2}$ (heme domain + FMN domain)	3490	>99%
$P411_{Diane2}$ (heme domain)	1810	>99%

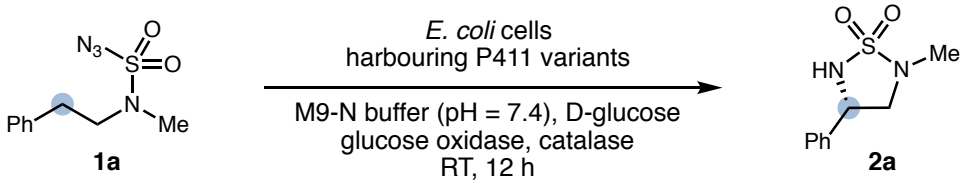
$P411_{Diane2}$ (heme domain + FMN domain + FAD domain)	3480	>99%

Domain structure of $P450_{BM3}$:

heme domain	FMN domain	FAD domain
1	463 664	1048

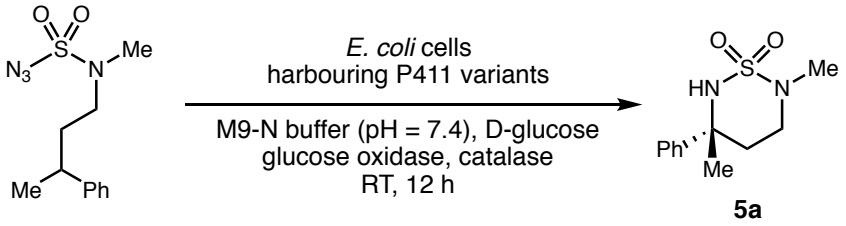
For its native monooxygenase activity, the FMN and FAD domains of $P450_{BM3}$, collectively called the reductase domain, are responsible for delivering the reducing equivalents from NADPH to the heme domain. The end of the FMN domain and the fragment of the polypeptide chain included in the ΔFAD complex were chosen based on a report by S. Govindaraj and T. L. Poulos.[4] In the current study, the FAD domain was found to be unnecessary for the C–H amination, but the heme domain only construct provided a lower TTN. The enantioselectivity of the 1,2-diamine product remained the same for the three variants tested (>99% ee).

Table 4. Directed evolution of $P411_{Diane}$ for the enantioselective synthesis of 1,2-diamines



variant	evolution strategy	TTN	ee
$P411_{Diane1}$	screening of lineage plate	450	94%
$P411_{Diane1}$ I327P	site saturation mutagenesis (75X, 268X, 327X, 438X)	1140	98.6%
$P411_{Diane1}$ I327P Y263W	site saturation mutagenesis (87X, 263X, 437X)	2540	99.4%
$P411_{Diane1}$ I327P Y263W Q437F	site saturation mutagenesis (437X)	3490	99.9%

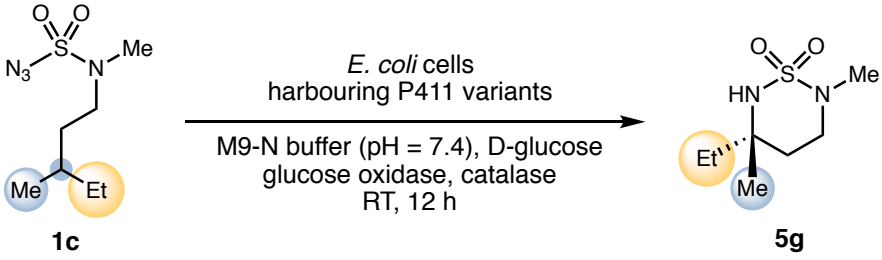
Table 5. Directed evolution of $P411_{Diane}$ for the enantioselective synthesis of 1,3-diamines via tertiary C(sp^3)-H amination



variant	evolution strategy	TTN	ee
$P411_{Diane1}$	-	1320	96%
$P411_{Diane1}$ L78A A87G	site-saturation mutagenesis (75X, 268X, 327X and 438X) and double-site saturation mutagenesis (78X87X)	3230	99%
$P411_{Diane1}$ L78A A87G Q437G	site saturation mutagenesis (181X, 263X, 437X and 438X)	4040	99%
$P411_{Diane1}$ L78A A87G Q437G I327V	site saturation mutagenesis (72X, 327X, 328X and 439X)	4450	99%

Note: directed evolution was performed using *E. coli* cell suspension in M9-N buffer (OD_{600} = 30).

Table 6. Directed evolution of $P411_{Diane}$ for the enantioselective synthesis of 1,3-diamine **5g** bearing a "methyl-ethyl" stereocenter



variant	evolution strategy	TTN	ee
$P411_{Diane1}$	-	1530	47%
$P411_{Diane1}$ I327T	site saturation mutagenesis (327X)	2200	69%

$P411_{Diane1}$ I327T L181V	site saturation mutagenesis (181X, 263X, 437X, 438X)	1710	78%
$P411_{Diane1}$ I327T L181V L82C	site saturation mutagenesis (82X, 437X, 401X)	1900	80%
$P411_{Diane1}$ I327T L181V L82C Q437G	site saturation mutagenesis (437X)	2160	83%
$P411_{Diane1}$ I327T L181V L82C Q437G A330M	double-site saturation mutagenesis (329X330X)	2120	87%

IV. Nucleotide and amino acid sequences

DNA and amino acid sequence of $P411_{Diane1}$:

ATGACAATTAAAGAAATGCCTCAGCCAAAAACGTTTGGAGAGCTTAAAAATTTACCGTTATTAA
ACACAGATAAACCGGTTCAAGCTTTGATGAAAATTGCGGATGAATTAGGAGAAATCTTTAAATT
CGAGGCGCCTGGTCGTGTAACGCGCTACTTATCAAGTCAGCGTCTAATTAAAGAAGCATGCGAT
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DNA and amino acid sequence of $P411_{Diane3}$ ($P411_{Diane1}$ L78A A87G I327V Q437G):

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DNA and amino acid sequence of P411$_{Diane4}$ (P411$_{Diane1}$ L82C L181V I327T A330M Q437G):

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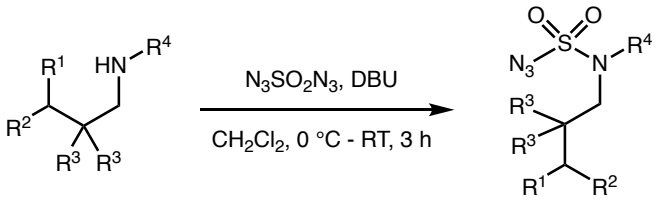
V. Synthesis and characterization of substrates

General procedure for the synthesis of sulfamoyl azide substrates



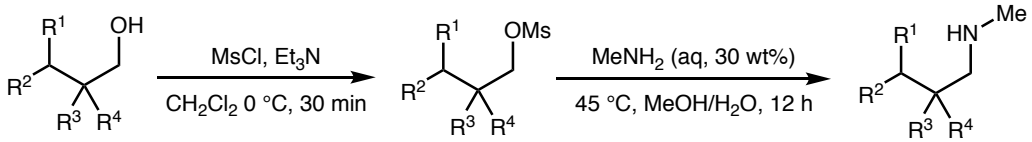
This procedure is modified from a published procedure.[5,6]

Preparation of sulfuryl azide ($N_3SO_2N_3$): To a suspension of NaN_3 (5.2 g, 80 mmol) in MeCN (80 mL) were added pyridine (3.23 mL, 40 mmol), and sulfuryl chloride (SO_2Cl_2, 1.62 mL, 20 mmol) at room temperature. (Note: sodium azide is potentially explosive and the reaction should be carried out behind a shield.) The reaction mixture was allowed to stir at room temperature for 4 h, carefully quenched with ice and extracted with CH_2Cl_2 (40 mL × 2). The combined organic layers were washed with 1M HCl (aq.), 1M KOH (aq.), 1 M HCl (aq.), and water. After drying over $MgSO_4$, the sulfuryl azide solution was used directly without further

purification. (Note: due to the low solubility of sodium azide in MeCN, this reaction is not homogeneous. As a result, vigorous stirring is important to ensure a good yield.)

Preparation of sulfamoyl azide: At 0 °C, the amine (10–15 mmol, 1 eq) and DBU (1.2 eq) were added to a solution of sulfuryl azide (ca. 0.25 M in CH_2Cl_2, 2 eq). The reaction mixture was allowed to warm to room temperature and stirred for 1–3 h when TLC analysis indicated full conversion. The reaction mixture was then concentrated *in vacuo* with the aid of rotary evaporator and purified by column chromatography with the aid of Biotage Isolera as detailed below (75 – 95% yield).

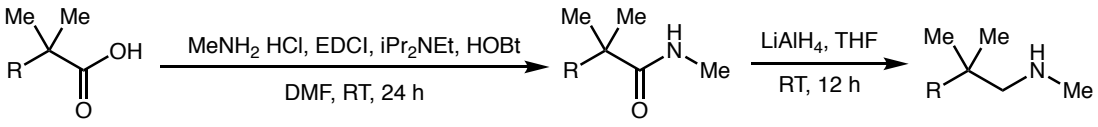
General procedure for the synthesis of amines



At 0 °C, Et_3N (1.6 eq) and MsCl (1.12 eq) were slowly added to a solution of the alcohol (0.25 M in CH_2Cl_2). The reaction mixture was allowed to stir at 0 °C until TLC indicated complete conversion of the alcohol and white precipitation formed (30 min to 1 h). The reaction mixture was carefully quenched with ice and extracted with CH_2Cl_2. The combined organic layers were then washed with 1M HCl, sat. $NaHCO_3$ (aq.) and water and dried over $MgSO_4$. The crude reaction mixture was concentrated *in vacuo* with the aid of rotary evaporator and directly used for the next step without purification.

To the crude mesylate were added MeOH and $MeNH_2$ (30 wt%, aq.), and the reaction mixture was allowed to stir at 45 °C for 12 h. Solvent was removed *in vacuo* with the aid of rotary evaporator, and the residue was taken up with EtOAc and washed with brine (3×). The organic layer was dried over $MgSO_4$ and concentrated *in vacuo*. The crude amine was directly used for the next step without further purification (ca. 85% yield over 2 steps).

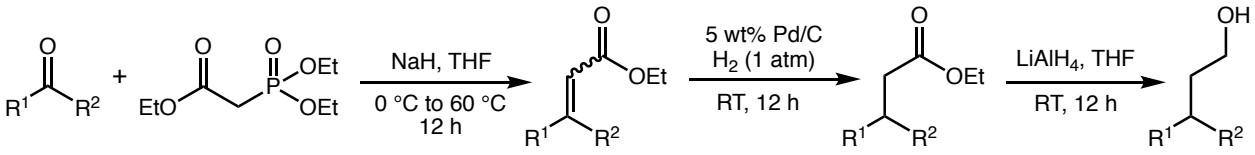
General procedure for the synthesis of geminal dimethyl substituted amines



The α,α-dimethylcarboxylic acid (1 eq, 15 mmol), methylamine HCl salt (1 eq, 1.02 g, 15 mmol), EDCI (1.2 eq, 3.456 g, 18 mmol), *i*-Pr_2NEt (3.5 eq, 9.1 mL, 52.5 mmol) and HOBt (1.2 eq, 2.43 g, 18 mmol) were added to DMF (45 mL). The reaction mixture was allowed to stir at room temperature for 24 h and quenched with water. EtOAc was added, and the organic layer was washed with water (3×). The combined organic layers were dried over $MgSO_4$ and concentrated *in vacuo* to afford the amide (>95% purity), which was directly used for the next step without further purification.

The amide was dissolved in anhydrous THF (45 mL) and the solution was cooled to 0 °C. $LiAlH_4$ (3 eq, 1.71 g, 45 mmol) was carefully added in small portions, and the reaction mixture was allowed to warm to room temperature and stirred for 12 h. The reaction mixture was then cooled to 0 °C, diluted with Et_2O, quenched with water and 10% NaOH (aq.), and dried over $MgSO_4$. The mixture was filtered through a plug of celite and concentrated *in vacuo* to afford the crude amine (ca. 60% yield over 2 steps), which was directly used for the next step without further purification.

General procedure for the synthesis of (*rac*)-3,3,-disubstituted alcohols



At 0 °C, NaH (60% dispersion in mineral oil, 1.2 g, 30 mmol, 1.5 eq) was slowly added to a solution of triethyl phosphonoacetate (6.34 mL, 32 mmol, 1.6 eq) and the reaction mixture was allowed to stirt at 0 °C for 20 min. When H_2 evolution stopped, the ketone (20 mmol) was added. The reaction mixture was heated to 60 °C for 12 h and then cooled to room temperature. The reaction was quenched with brine and extracted with Et_2O (3×). The combined organic layers were washed with brine, dried over $MgSO_4$, and purified by column chromatography with the aid of Biotage Isolera (100 g SNAP cartridge, 0-13% EtOAc/hexanes for 8 CV and 13% EtOAc/hexanes for 5 CV). The α,β-unsaturated ester was obtained as a mixture of *trans*- and *cis*-isomers and was used for the next step without the need to separate the two isomers.

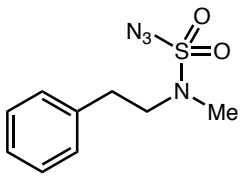
Under N_2, Pd/C (5 wt %) was added to a MeOH solution of the α,β-unsaturated ester. The reaction mixture was then stirred at room temperature under a balloon pressure of H_2 for 2-12 h

until TLC analysis indicated no starting material was left. The reaction mixture was diluted with CH_2Cl_2 and filtered through a plug of celite eluting with CH_2Cl_2. The product was found to be of >95% purity and was directly used for the next step without further purification.

The ester was dissolved in anhydrous THF (45 mL) and the solution was cooled to 0 °C. $LiAlH_4$ (3 eq) was carefully added in small portions, and the reaction mixture was allowed to warm to room temperature and stirred for 12 h. The reaction mixture was then cooled to 0 °C, diluted with Et_2O, and quenched with water and 10% NaOH (aq.) and dried over $MgSO_4$. The mixture was filtered through a plug of celite and concentrated *in vacuo* to afford the alcohol product (ca. 70% yield over 3 steps).

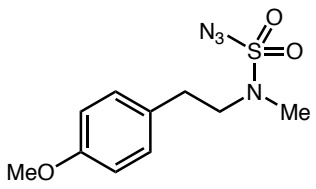
Characterization data for sulfamoyl azide substrates

(2-((Azidosulfonyl)(methyl)amino)ethyl)benzene (1a)

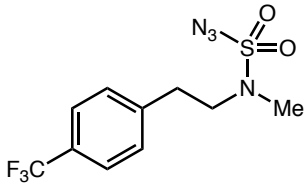


Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.37 – 7.18 (m, 5H), 3.53 – 3.43 (m, 2H), 3.02 – 2.83 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 137.6, 128.9, 127.0, 53.2, 36.5, 34.3 ppm. Spectral data match those previously reported.[5]

1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-4-methoxybenzene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.13 (d, J = 7.1 Hz, 2H), 6.86 (d, J = 7.2 Hz, 2H), 3.79 (s, 3H), 3.56 – 3.33 (m, 2H), 3.08 – 2.79 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 158.6, 129.9, 129.5, 114.3, 55.4, 53.4, 36.5, 33.4 ppm. IR: 2937, 2122, 1513, 1378, 1202, 1178, 965, 823, 728 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_4O_3S$ requires 271.0865, observed 271.0863.

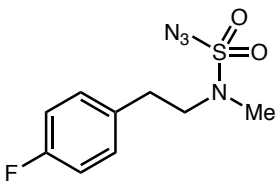


1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-4-(trifluoromethyl)benzene

Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6

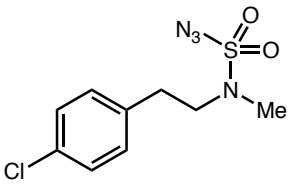
CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.59 (d, *J* = 7.9 Hz, 2H), 7.38 – 7.30 (m, 2H), 3.53 – 3.45 (m, 2H), 3.04 – 2.96 (m, 2H), 2.93 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.65 (q, *J* = 1 Hz), 129.4 (q, *J* = 33 Hz), 129.3, 125.8 (q, *J* = 4 Hz), 124.2 (q, *J* = 273 Hz), 52.7, 36.6, 34.1 ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ: -62.5 (s) ppm. IR: 2123, 1382, 1323, 1161, 1118, 967, 826, 733, 636 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{11}F_3N_4O_2S$ requires 309.0633, observed 309.0631.

1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-4-fluorobenzene



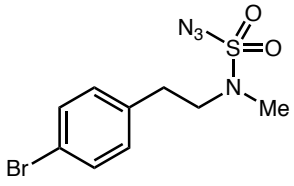
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.21 – 7.14 (m, 2H), 7.05 – 6.97 (m, 2H), 3.48 – 3.41 (m, 2H), 2.95 – 2.87 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.0 (d, *J* = 246 Hz), 133.2 (d, *J* = 3 Hz), 130.4 (d, *J* = 8.1 Hz), 115.8 (d, *J* = 21 Hz), 53.2 (d, *J* = 2 Hz), 36.6, 33.5 ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ: -115.89 – -115.95 (m, 1F) ppm. IR: 2937, 2122, 1510, 1459, 1196, 1158, 965, 825, 730 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}FN_4O_2S$ requires 259.0665, observed 259.0657.

1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-4-chlorobenzene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.19 (d, *J* = 8.4 Hz, 2H), 7.05 (d, *J* = 8.4 Hz, 2H), 3.39 – 3.31 (m, 2H), 2.85 – 2.77 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 136.0, 132.9, 130.3, 129.0, 53.0, 36.6, 33.7 ppm. IR: 2122, 1492, 1381, 1196, 1162, 966, 847, 811 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}ClN_4O_2S$ requires 275.0370, observed 275.0369.

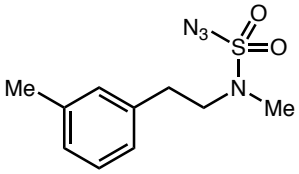
1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-4-bromobenzene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.44 (d, *J* = 8.4 Hz, 2H),

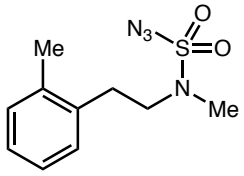
7.14 – 7.05 (m, 2H), 3.48 – 3.40 (m, 2H), 2.96 – 2.83 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 136.5, 132.0, 130.6, 121.0, 52.9, 36.6, 33.7 ppm. IR: 2937, 2872, 2122, 1488, 1380, 1198, 1162, 966, 752, 639 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}BrN_4O_2S$ requires 318.9864, observed 318.9878.

1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-3-methylbenzene



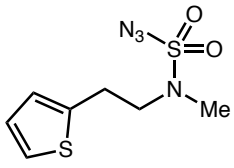
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.21 (t, *J* = 7.5 Hz, 1H), 7.11 – 7.05 (m, 1H), 7.05 – 6.99 (m, 2H), 3.51 – 3.43 (m, 2H), 2.94 (s, 3H), 2.93 – 2.87 (m, 2H), 2.34 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 138.6, 137.5, 129.7, 128.8, 127.8, 125.9, 53.2, 36.5, 34.2, 21.5 ppm. IR: 2940, 2122, 1381, 1201, 1162, 963, 728, 698 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_4O_2S$ requires 255.0916, observed 255.0923.

1-(2-((Azidosulfonyl)(methyl)amino)ethyl)-2-methylbenzene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.21 – 7.12 (m, 4H), 3.45 – 3.38 (m, 2H), 3.01 – 2.90 (m, 5H), 2.36 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 136.3, 135.6, 130.7, 129.6, 127.2, 126.5, 52.1, 36.5, 31.7, 19.3 ppm. IR: 2951, 2121, 1460, 1378, 1202, 1162, 1097, 963, 731 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_4O_2S$ requires 255.0916, observed 255.0902.

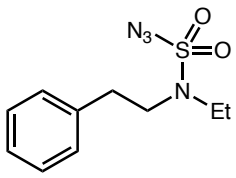
2-(2-((Azidosulfonyl)(methyl)amino)ethyl)thiophene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.19 (dd, *J* = 5.1, 1.2 Hz, 1H), 6.96 (dd, *J* = 5.1, 3.4 Hz, 1H), 6.89 (dd, *J* = 3.4, 1.2 Hz, 1H), 3.56 – 3.47 (m, 2H), 3.20

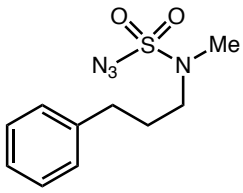
– 3.13 (m, 2H), 2.94 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.5, 127.3, 126.0, 124.5, 53.2, 36.7, 28.5 ppm. IR: 2123, 1455, 1378, 1202, 1164, 962, 828, 738, 700 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{10}N_4O_2S_2$ requires 247.0323, observed 247.0326.

(2-((Azidosulfonyl)(ethyl)amino)ethyl)benzene



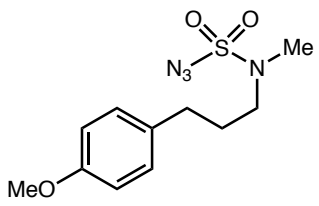
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.36 – 7.29 (m, 2H), 7.28 – 7.20 (m, 3H), 3.52 – 3.44 (m, 2H), 3.33 (q, J = 7.2 Hz, 2H), 3.00 – 2.91 (m, 2H), 1.21 (t, J = 7.2 Hz, 3H) ppm. Spectral data match those previously reported.[7]

(3-((Azidosulfonyl)(methyl)amino)propyl)benzene



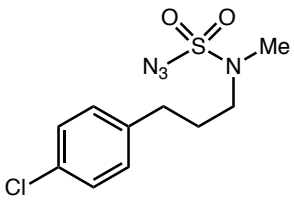
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.33 – 7.28 (m, 2H), 7.25 – 7.16 (m, 3H), 3.34 – 3.21 (m, 2H), 2.93 (s, 3H), 2.74 – 2.60 (m, 2H), 1.95 (p, J = 7.5 Hz, 2H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.8, 128.7, 128.4, 126.4, 51.2, 35.9, 32.7, 28.9 ppm. Spectral data match those previously reported.[5]

1-(3-((Azidosulfonyl)(methyl)amino)propyl)-4-methoxybenzene



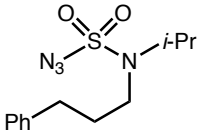
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.10 (d, J = 8.8 Hz, 2H), 6.84 (d, J = 8.6 Hz, 2H), 3.79 (s, 3H), 3.30 – 3.19 (m, 2H), 2.93 (s, 3H), 2.66 – 2.54 (m, 2H), 1.91 (tt, J = 8.8, 6.7 Hz, 2H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 158.2, 132.8, 129.4, 114.1, 55.4, 51.1, 35.9, 31.8, 29.1 ppm. IR: 2938, 2836, 2121, 1612, 1512, 1379, 1244, 1162, 1033, 969, 733 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{11}H_{16}N_4O_3S$ requires 285.1021, observed 285.1006.

1-(3-((Azidosulfonyl)(methyl)amino)propyl)-4-chlorobenzene



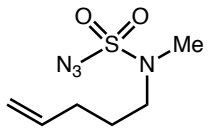
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.27 (d, J = 8.4 Hz, 2H), 7.12 (d, J = 8.6 Hz, 2H), 3.31 – 3.20 (m, 2H), 2.93 (s, 3H), 2.71 – 2.57 (m, 2H), 2.00 – 1.84 (m, 2H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.2, 132.1, 129.8, 128.8, 51.0, 36.0, 32.0, 28.8 ppm. IR: 2937, 2869, 2122, 1492, 1373, 1203, 1161, 1091, 969, 732, 658 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{13}ClN_4O_2S$ requires 289.0526, observed 289.0512.

(3-((Azidosulfonyl)(isopropyl)amino)propyl)benzene

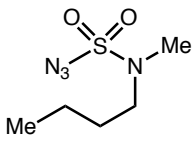


Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.31 (t, J = 7.2 Hz, 2H), 7.24 – 7.17 (m, 3H), 4.07 (hept, J = 6.8 Hz, 1H), 3.22 – 3.11 (m, 2H), 2.65 (t, J = 7.7 Hz, 2H), 2.09 – 1.96 (m, 2H), 1.21 (d, J = 6.8 Hz, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 140.8, 128.7, 128.4, 126.3, 52.2, 44.5, 33.2, 32.1, 20.8 ppm. IR: 2981, 2944, 2118, 1454, 1367, 1202, 1147, 982, 732, 699 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_2S$ requires 283.1229, observed 283.1228.

5-((Azidosulfonyl)(methyl)amino)pent-1-ene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.79 (ddt, J = 16.9, 10.2, 6.6 Hz, 1H), 5.13 – 4.96 (m, 2H), 3.32 – 3.17 (m, 2H), 2.94 (s, 3H), 2.18 – 2.05 (m, 2H), 1.72 (tt, J = 8.9, 6.6 Hz, 2H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 137.0, 116.0, 51.1, 35.9, 30.5, 26.5 ppm. IR: 2937, 2873, 2121, 1641, 1459, 1373, 1200, 1162 cm^{-1}. IR: cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_6H_{12}N_4O_2S$ requires 205.0759, observed 205.0752.

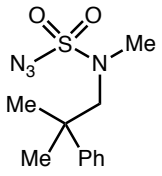


1-((Azidosulfonyl)(methyl)amino)butane

Purified by Biotage (50 g SNAP cartridge, 0-12% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 8 CV) to afford the product as a colorless oil. ^{1}H

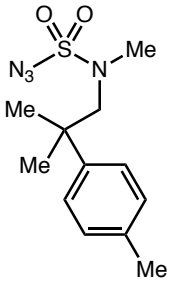
NMR (400 MHz, $CDCl_3$) δ: 3.30 – 3.18 (m, 2H), 2.94 (s, 3H), 1.65 – 1.55 (m, 3H), 1.37 (dq, *J* = 14.7, 7.3 Hz, 2H), 0.95 (t, *J* = 7.3 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 51.3, 35.8, 29.3, 19.7, 13.7 ppm. The spectral data match those previously reported.[5]

(1-((Azidosulfonyl)(methyl)amino)-2-methylpropan-2-yl)benzene



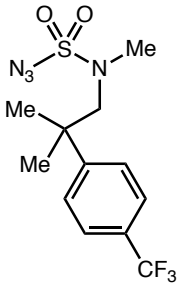
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ: 7.42 – 7.32 (m, 4H), 7.26 – 7.22 (m, 1H), 3.32 (s, 2H), 2.39 (s, 3H), 1.42 (s, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.3, 128.7, 126.8, 126.2, 64.0, 39.3, 38.6, 26.5 ppm. Spectral data match those previously reported.[5]

1-(1-((Azidosulfonyl)(methyl)amino)-2-methylpropan-2-yl)-4-methylbenzene



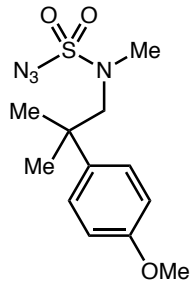
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ: 7.30 – 7.24 (m, 2H), 7.18 – 7.12 (m, 2H), 3.30 (s, 2H), 2.41 (s, 3H), 2.33 (s, 3H), 1.40 (s, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 143.3, 136.3, 129.3, 126.1, 64.0, 38.9, 38.7, 26.7, 21.0 ppm. IR: 2970, 2927, 2121, 1377, 1201, 1164, 985, 817, 760, 731 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_2S$ requires 283.1229, observed 283.1212.

1-(1-((Azidosulfonyl)(methyl)amino)-2-methylpropan-2-yl)-4-(trifluoromethyl)benzene



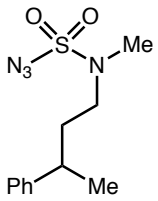
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^1H NMR (400 MHz, $CDCl_3$) δ: 7.61 (d, *J* = 8.2 Hz, 2H), 7.52 (d, *J* = 8.2 Hz, 2H), 3.34 (s, 2H), 2.46 (s, 3H), 1.45 (s, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 150.5 (q, *J* = 2.0 Hz), 128.8 (q, *J* = 33 Hz), 126.7, 125.6 (q, *J* = 4.0 Hz), 124.2 (q, *J* = 274 Hz), 63.7, 39.6, 38.9, 26.6 ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ: -62.5 (s) ppm. IR: 2976, 2123, 1380, 1325, 1154, 1098, 986, 840, 762, 732 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{15}F_3N_4O_2S$ requires 337.0946, observed 337.0958.

1-(1-((Azidosulfonyl)(methyl)amino)-2-methylpropan-2-yl)-4-methoxybenzene



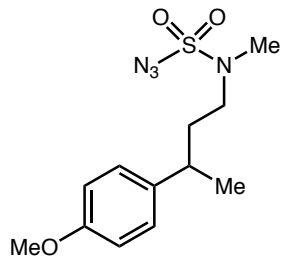
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.29 (d, J = 8.9 Hz, 2H), 6.88 (d, J = 8.9 Hz, 2H), 3.80 (s, 3H), 3.28 (s, 2H), 2.41 (s, 3H), 1.39 (s, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 158.3, 138.3, 127.3, 113.9, 64.0, 55.4, 38.69, 38.64, 26.7 ppm. IR: 2969, 2837, 2122, 1514, 1378, 1164, 1033, 985, 959, 830, 761 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_3S$ requires 299.1178, observed 299.1170.

(4-((Azidosulfonyl)(methyl)amino)butan-2-yl)benzene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.34 – 7.31 (m, 2H), 7.25 – 7.16 (m, 3H), 3.20 (ddd, J = 13.8, 8.6, 6.4 Hz, 1H), 3.07 (ddd, J = 13.8, 8.6, 6.4 Hz, 1H), 2.87 (s, 3H), 2.76 (h, J = 7.0 Hz, 1H), 1.98 – 1.83 (m, 2H), 1.29 (d, J = 7.0 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 145.9, 128.8, 126.9, 126.6, 50.2, 37.4, 36.0, 35.4, 22.5 ppm. Spectral data match those previously reported.[5]

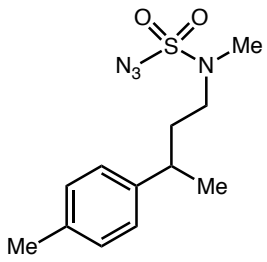
1-(4-((Azidosulfonyl)(methyl)amino)butan-2-yl)-4-methoxybenzene



(*rac*)-

Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.11 (d, J = 8.6 Hz, 2H), 6.86 (d, J = 8.6 Hz, 2H), 3.80 (s, 3H), 3.24 – 3.13 (m, 1H), 3.11 – 2.99 (m, 1H), 2.87 (s, 3H), 2.71 (p, J = 7.1 Hz, 1H), 1.87 (q, J = 7.5 Hz, 2H), 1.26 (d, J = 7.0 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 158.2, 137.9, 127.8, 114.1, 55.4, 50.2, 36.6, 36.0, 35.6, 22.8 ppm. IR: 2958, 2838, 2121, 1611, 1512, 1376, 1245, 1164, 1033, 942, 731 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_3S$ requires 299.1178, observed 299.1171.

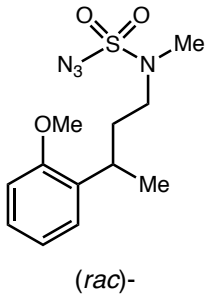
1-(4-((Azidosulfonyl)(methyl)amino)butan-2-yl)-4-methylbenzene



(*rac*)-

Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.13 (d, *J* = 8.0 Hz, 2H), 7.08 (d, *J* = 8.0 Hz, 2H), 3.19 (ddd, *J* = 13.8, 8.4, 6.9 Hz, 1H), 3.06 (ddd, *J* = 13.8, 8.4, 6.9 Hz, 1H), 2.88 (s, 3H), 2.73 (h, *J* = 7.0 Hz, 1H), 2.33 (s, 3H), 1.95 – 1.84 (m, 2H), 1.27 (d, *J* = 6.9 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.8, 136.1, 129.5, 126.8, 50.3, 37.0, 36.0, 35.5, 22.7, 21.1 ppm. IR: 2960, 2926, 2871, 2120, 1515, 1376, 1164, 955, 818, 757, 731 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_2S$ requires 283.1229, observed 283.1239.

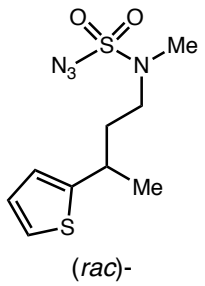
1-(4-((Azidosulfonyl)(methyl)amino)butan-2-yl)-2-methoxybenzene



(*rac*)-

Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.23 – 7.14 (m, 2H), 6.94 (td, *J* = 7.5, 1.2 Hz, 1H), 6.87 (dd, *J* = 8.2, 1.2 Hz, 1H), 3.82 (s, 3H), 3.31 – 3.10 (m, 3H), 2.89 (s, 3H), 1.98 (dddd, *J* = 12.8, 9.1, 7.8, 6.5 Hz, 1H), 1.82 (dddd, *J* = 12.8, 9.1, 6.9, 6.0 Hz, 1H), 1.26 (d, *J* = 7.0 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.0, 133.9, 127.3, 126.8, 120.9, 110.6, 55.4, 50.2, 35.7, 34.3, 29.7, 20.6 ppm. IR: 2961, 2937, 2120, 1491, 1463, 1377, 1239, 1164, 1027, 942, 753 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_3S$ requires 299.1178, observed299.1168.

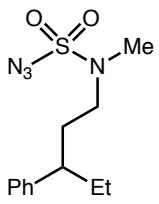
2-(4-((Azidosulfonyl)(methyl)amino)butan-2-yl)thiophene



(*rac*)-

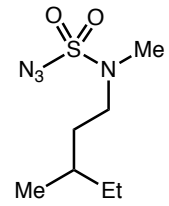
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.16 (dd, *J* = 5.1, 1.2 Hz, 1H), 6.93 (dd, *J* = 5.1, 3.5 Hz, 1H), 6.83 (ddd, *J* = 3.5, 1.2, 0.7 Hz, 1H), 3.30 – 3.06 (m, 3H), 2.90 (s, 3H), 1.99 – 1.90 (m, 2H), 1.37 (d, *J* = 6.9 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 149.9, 126.8, 123.4, 123.2, 49.9, 36.5, 36.1, 32.9, 23.5 ppm. IR: 2965, 2871, 2121, 1456, 1374, 1202, 1163, 942, 849, 729 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{14}N_4O_2S_2$ requires 275.0603, observed 275.0612.

(1-((Azidosulfonyl)(methyl)amino)pentan-3-yl)benzene


(*rac*)-

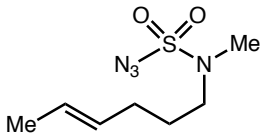
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.35 – 7.28 (m, 2H), 7.25 – 7.19 (m, 1H), 7.17 – 7.12 (m, 2H), 3.18 (ddd, *J* = 13.8, 9.5, 6.3 Hz, 1H), 2.97 (ddd, *J* = 13.8, 9.5, 5.2 Hz, 1H), 2.85 (s, 3H), 2.47 (tt, *J* = 9.8, 5.2 Hz, 1H), 1.99 (dddd, *J* = 13.4, 9.5, 6.3, 5.0 Hz, 1H), 1.88 (dtd, *J* = 13.5, 9.6, 5.3 Hz, 1H), 1.76 – 1.65 (m, 1H), 1.65 – 1.57 (m, 1H), 0.78 (t, *J* = 7.4 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.0, 128.7, 127.7, 126.6, 50.3, 45.1, 36.0, 33.8, 29.9, 12.1 ppm. IR: 2962, 2931, 2875, 2120, 1453, 1379, 1203, 1164, 963, 760, 700 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_4O_2S$ requires 283.1229, observed 283.1200.

1-((Azidosulfonyl)(methyl)amino)-3-methylpentane


(*rac*)-

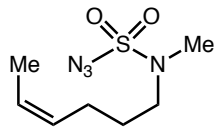
Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 3.32 – 3.19 (m, 2H), 2.93 (s, 3H), 1.64 (ddd, *J* = 9.0, 8.0, 6.9 Hz, 1H), 1.47 – 1.30 (m, 3H), 1.20 (qd, *J* = 7.3, 6.1 Hz, 1H), 0.95 – 0.84 (m, 6H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 49.9, 35.7, 33.7, 31.9, 29.4, 19.0, 11.3 ppm. IR: 2962, 2931, 2876, 2121, 1463, 1380, 1205, 1162, 940, 743 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{16}N_4O_2S$ requires 221.1072, observed 221.1075.

(*E*)-6-((Azidosulfonyl)(methyl)amino)hex-2-ene



Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.52 – 5.44 (m, 1H), 5.42 – 5.35 (m, 1H), 3.25 – 3.18 (m, 2H), 2.93 (s, 3H), 2.07 – 1.98 (m, 2H), 1.71 – 1.61 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 129.6, 126.6, 51.1, 35.9, 29.4, 27.1, 18.1 ppm. IR: 2937, 2120, 1454, 1373, 1202, 1163, 966, 755, 732 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{14}N_4O_2S$ requires 219.0916, observed 219.0918.

(*Z*)-6-((Azidosulfonyl)(methyl)amino)hex-2-ene

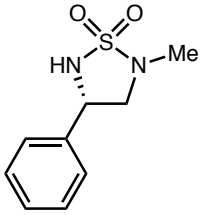


Purified by Biotage (50 g SNAP cartridge, 0-10% EtOAc/hexanes for 6 CV, then 10% EtOAc/hexanes for 5 CV) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.52 (dqt, J = 10.8, 6.7, 1.5 Hz, 1H), 5.35 (dtq, J = 10.8, 7.2, 1.7 Hz, 1H), 3.28 – 3.19 (m, 2H), 2.94 (s, 3H), 2.15 – 2.05 (m, 2H), 1.68 (tt, J = 9.1, 6.6 Hz, 2H), 1.61 (ddt, J = 6.8, 1.8, 0.9 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 128.7, 125.6, 51.2, 35.9, 27.1, 23.8, 13.0 ppm. IR: 3015, 2939, 2121, 1461, 1382, 1202, 1163, 968, 733, 709 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{14}N_4O_2S$ requires 219.0916, observed 219.0913.

VI. Characterization data for C–H amination products

Racemic products were synthesized on a 0.2-0.4 mmol scale using the commercially available catalyst 5,10,15,20-Tetraphenyl-21H,23H-porphine cobalt(II) in 5-30% yield according to previously reported procedure.[8] Enantioenriched products were synthesized by enzymatic reaction according to general procedure as described above.

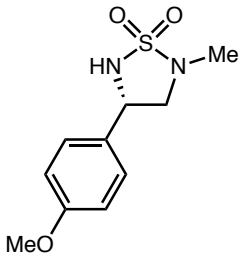
(*S*)-2-Methyl-4-phenyl-1,2,5-thiadiazolidine 1,1-dioxide (2a)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.45 – 7.42 (m, 3H), 7.42 – 7.37 (m, 2H), 4.92 – 4.82 (m, 1H), 4.68 (s, 1H), 3.72 (dd, J = 9.5, 7.2 Hz, 1H), 3.26 (dd, J = 9.6, 8.0 Hz, 1H), 2.79 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.7, 129.2, 129.0, 126.6, 58.0, 55.9, 32.9 ppm. Spectral data match those previously reported.[8]

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 20 min) indicated > 99.9% ee: t_R = 116 (major), 119 (minor) min. Chiral HPLC analysis (OD-H column, 70:30 hexanes: *i*-PrOH, 1.0 mL/min) indicated 99% ee: t_R = 13.9 (minor), 15.9 (major) min. Based on the chiral GC assay, when the final variant $P411_{Diane1}$ I327P Y263W Q437F ($P411_{Diane2}$) was used, the minor enantiomer of **2a** was not observed (peak area < 1) when the peak area of the major enantiomer of **2a** was 4282. Thus, the we concluded that the ee of **2a** was >99.9%.

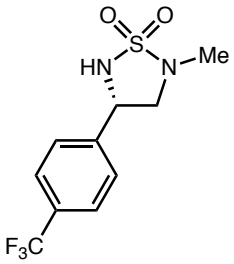
(*S*)-4-(4-Methoxyphenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2b)



Purified by column chromatography (2:1 hexanes:EtOAc) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.33 (d, J = 8.6 Hz, 2H), 6.88 (d, J = 8.6 Hz, 2H), 4.91 (d, J = 6.4 Hz, 1H), 4.83 – 4.71 (m, 1H), 3.78 (s, 3H), 3.63 (dd, J = 9.5, 7.1 Hz, 1H), 3.18 (dd, J = 9.5, 8.2 Hz, 1H), 2.72 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 159.9, 130.6, 127.9, 114.4, 58.1, 55.4, 55.4, 32.8 ppm. IR: 3255, 2926, 1513, 1286, 1198, 1151, 1028, 832, 899 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_2O_3S$ requires 243.0803, observed 243.0807.

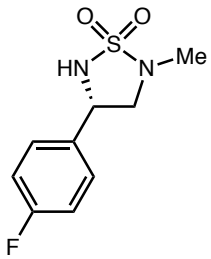
GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 80 min) indicated 98% ee: t_R = 144 (major), 148 (minor) min.

(*S*)-2-Methyl-4-(4-(trifluoromethyl)phenyl)-1,2,5-thiadiazolidine 1,1-dioxide (2c)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.65 (d, J = 8.2 Hz, 2H), 7.57 (d, J = 8.2 Hz, 2H), 4.99 – 4.85 (m, 2H), 3.81 – 3.70 (m, 1H), 3.20 – 3.09 (m, 1H), 2.75 (s, 3H) ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ: -62.7 ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.87, 131.1 (q, J = 32 Hz), 126.91, 126.1 (q, J = 4.0 Hz), 123.9 (q, J = 274 Hz), 57.6, 55.2, 32.9 ppm. IR: 3216, 2326, 2926, 1404, 1327, 1119, 1069, 980, 846, 705 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{11}F_3N_2O_2S$ requires 281.0572, observed 281.0543.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 20 min) indicated 98% ee: t_R = 119 (major), 122 (minor) min.



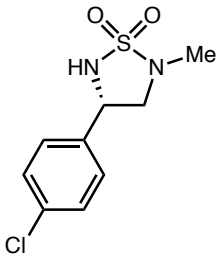
(*S*)-4-(4-Fluorophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2d)

Purified by column chromatography (2:1 hexanes:EtOAc) to afford the product as a white solid. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.45 – 7.35 (m, 2H), 7.11 – 6.98 (m, 2H), 5.02 (d, J = 6.4 Hz, 1H), 4.83 (q, J = 7.2 Hz, 1H), 3.69

(dd, J = 9.6, 7.2 Hz, 1H), 3.20 – 3.08 (m, 1H), 2.72 (s, 3H) ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ: -113.01 – -113.11 (m, 1F) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 162.9 (d, J = 248 Hz), 134.6 (d, J = 3.0 Hz), 128.4 (d, J = 8.0 Hz), 116.1 (d, J = 21 Hz), 58.0 (d, J = 1.0 Hz), 55.1, 32.8 ppm. IR: 3263, 2925, 2854, 1511, 1285, 1152, 975, 836, 630 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}FN_2O_2S$ requires 231.0603, observed 231.0575.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 97% ee: t_R = 116 (major), 119 (minor) min.

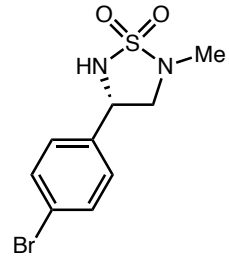
(*S*)-4-(4-Chlorophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2e)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.40 – 7.32 (m, 4H), 4.91 – 4.75 (m, 2H), 3.70 (ddd, J = 9.6, 6.6, 1.0 Hz, 1H), 3.15 (dd, J = 9.6, 7.7 Hz, 1H), 2.74 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 137.3, 134.8, 129.4, 128.0, 57.8, 55.2, 32.9 ppm. IR: 3261, 2967, 2922, 2886, 1398, 1304, 1157, 1145, 1016, 901, 750, 707 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}ClN_2O_2S$ requires 247.0308, observed 247.0301.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 80 min) indicated 97% ee using the $P411_{Diane1}$ Y263W I327P variant: t_R = 146 (major), 150 (minor) min. Use of the $P411_{Diane1}$ Y263W I327P Q437F variant provided 83% ee.

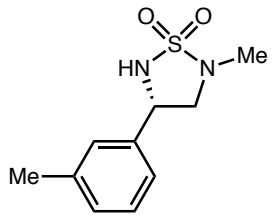
(*S*)-4-(4-Bromophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2f)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.51 (d, J = 8.5 Hz, 2H), 7.31 (d, J = 8.5 Hz, 2H), 4.84 – 4.78 (m, 2H), 3.71 (dd, J = 9.6, 7.6 Hz, 1H), 3.15 (dd, J = 9.6, 7.7 Hz, 1H), 2.74 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 137.8, 132.3, 128.3, 122.9, 57.7, 55.2, 32.9 ppm. IR: 3262, 2921, 2852, 1303, 1396, 1304, 1228, 1156, 1121, 1011, 900, 743, 705 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{11}BrN_2O_2S$ requires 290.9803, observed 290.9799.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 190 °C (60 °C/min) and hold for 160 min) indicated 96% ee using the $P411_{Diane1}$ Y263W I327P variant: t_R = 224 (major), 234 (minor) min. Use of the $P411_{Diane1}$ Y263W I327P Q437F variant provided 81% ee.

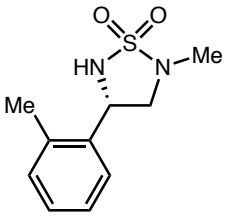
(*S*)-2-Methyl-4-(*m*-tolyl)-1,2,5-thiadiazolidine 1,1-dioxide (2g)



Purified by column chromatography (2:1 hexanes:EtOAc) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.31 – 7.07 (m, 4H), 4.94 (d, J = 6.7 Hz, 1H), 4.79 (dt, J = 8.2, 6.7 Hz, 1H), 3.65 (dd, J = 9.5, 7.2 Hz, 1H), 3.18 (dd, J = 9.5, 8.2 Hz, 1H), 2.71 (s, 3H), 2.35 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 139.0, 138.6, 129.6, 129.0, 127.1, 123.6, 57.9, 55.8, 32.9, 21.5 ppm. IR: 3266, 2925, 2862, 1457, 1287, 1154, 978, 880, 704 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_2O_2S$ requires 227.0854, observed 227.0857.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 94% ee using the $P411_{Diane1}$ Y263W I327P variant: t_R = 117 (major), 120 (minor) min. Use of the $P411_{Diane1}$ Y263W I327P Q437F variant provided 40% ee.

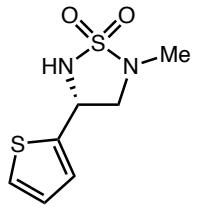
(*S*)-2-Methyl-4-(*o*-tolyl)-1,2,5-thiadiazolidine 1,1-dioxide (2h)



Purified by column chromatography (2:1 hexanes:EtOAc) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.64 (dd, J = 7.5, 1.6 Hz, 1H), 7.32 – 7.20 (m, 2H), 7.20 – 7.11 (m, 1H), 5.17 – 5.05 (m, 1H), 4.68 (s, 1H), 3.71 (dd, J = 9.4, 7.2 Hz, 1H), 3.23 – 3.11 (m, 1H), 2.75 (s, 3H), 2.36 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 136.6, 135.0, 130.8, 128.6, 127.1, 126.1, 56.9, 52.4, 32.9, 19.1 ppm. IR: 3267, 2925, 2855, 1460, 1337, 1153, 1052, 975, 9229, 757 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{14}N_2O_2S$ requires 227.0854, observed 227.0831.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 97% ee: t_R = 121 (major), 123 (minor) min.

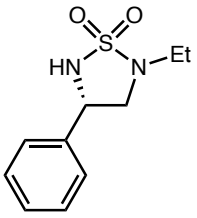
(*R*)-2-Methyl-4-(thiophen-2-yl)-1,2,5-thiadiazolidine 1,1-dioxide (2i)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a colorless oil which turned into a colorless solid upon standing. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.29 (dd, J = 5.1, 1.2 Hz, 1H), 7.10 (dd, J = 3.5, 1.2 Hz, 1H), 6.98 (dd, J = 5.1, 3.5 Hz, 1H), 5.14 – 5.05 (m, 1H), 4.99 (d, J = 6.2 Hz, 1H), 3.71 (dd, J = 9.5, 6.9 Hz, 1H), 3.37 (dd, J = 9.5, 7.6 Hz, 1H), 2.75 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 141.6, 127.3, 126.2, 126.0, 58.0, 51.7, 32.9 ppm. IR: 3261, 2924, 1457, 1281, 1195, 1151, 973, 896, 699 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{10}N_2O_2S_2$ requires 219.0262, observed 219.0246.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 99% ee: t_R = 113 (major), 117 (minor) min.

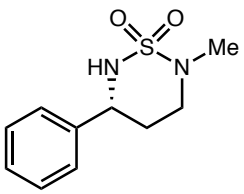
(*S*)-2-Ethyl-4-phenyl-1,2,5-thiadiazolidine 1,1-dioxide (2j)



Purified by column chromatography (2:1 hexanes:EtOAc) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.47 – 7.27 (m, 5H), 4.94 (d, J = 6.8 Hz, 1H), 4.83 (dt, J = 8.2, 6.8 Hz, 1H), 3.78 – 3.67 (m, 1H), 3.25 – 3.08 (m, 2H), 2.97 (dq, J = 12.8, 7.2 Hz, 1H), 1.25 (t, J = 7.2 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 138.7, 129.1, 128.8, 126.6, 55.9, 55.5, 41.8, 13.2 ppm. Spectral data match those previously reported.[7]

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 91% ee: t_R = 115 (major), 118 (minor) min.

(*R*)-2-Methyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (2k)

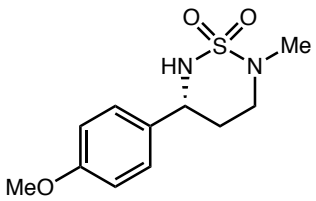


Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.42 – 7.28 (m, 5H), 4.71 (ddd, J = 11.6, 6.8, 2.6 Hz, 1H), 4.33 (d, J = 8.2 Hz, 1H), 3.64 (td, J = 13.2, 2.8 Hz, 1H), 3.25 (ddd, J = 13.2, 4.5, 2.6 Hz, 1H), 2.80 (s,

3H), 2.10 (dddd, J = 14.1, 13.0, 12.2, 4.5 Hz, 1H), 1.88 (dq, J = 14.1, 2.8 Hz, 1H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.3, 129.0, 128.6, 126.4, 59.8, 52.0, 36.6, 29.1 ppm. Spectral data match those previously reported.[5]

HPLC analysis (IC column, 80:20 hexanes: *i*-PrOH, 1.0 mL/min) indicated 99% ee using the $P411_{Diane1}$ variant: t_R = 11.6 (minor), 12.7 (major) min.

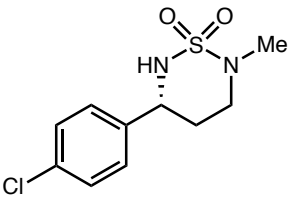
(*R*)-5-(4-Methoxyphenyl)-2-methyl-1,2,6-thiadiazinane 1,1-dioxide (2l)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.28 (d, J = 8.4 Hz, 2H), 6.89 (d, J = 8.4 Hz, 2H), 4.67 (ddd, J = 11.4, 7.5, 2.8 Hz, 1H), 4.19 (d, J = 8.4 Hz, 1H), 3.80 (s, 3H), 3.63 (td, J = 13.2, 2.8 Hz, 1H), 3.25 (ddd, J = 13.2, 4.5, 2.4 Hz, 1H), 2.82 (s, 3H), 2.10 (dddd, J = 14.1, 13.2, 12.2, 4.5 Hz, 1H), 1.92 – 1.80 (m, 1H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 159.7, 131.5, 127.7, 114.4, 59.3, 55.5, 52.0, 36.6, 29.2 ppm. IR: 3240, 2924, 2840, 1612, 1514, 1311, 1294, 1156, 1031, 947, 755 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{11}H_{16}N_2O_3S$ requires 257.0960, observed 257.0937.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 180 °C (60 °C/min) and hold for 100 min) indicated 98% ee using the $P411_{Diane1}$ variant: t_R = 189 (minor), 193 (major) min.

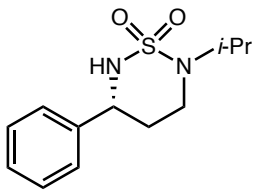
(*R*)-5-(4-Chlorophenyl)-2-methyl-1,2,6-thiadiazinane 1,1-dioxide (2m)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.37 – 7.27 (m, 4H), 4.68 (ddd, J = 11.8, 7.9, 2.9 Hz, 1H), 4.40 (d, J = 8.2 Hz, 1H), 3.62 (td, J = 13.2, 2.9 Hz, 1H), 3.24 (ddd, J = 13.2, 4.5, 2.8 Hz, 1H), 2.78 (s, 3H), 2.06 (dddd, J = 14.1, 12.9, 11.8, 4.5 Hz, 1H), 1.86 (dq, J = 14.1, 2.8 Hz, 1H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 137.8, 134.4, 129.2, 127.9, 59.2, 51.9, 36.6, 29.0 ppm. IR: 3227, 2922, 2863, 1494, 1427, 1330, 1147, 1061, 949, 764 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{10}H_{13}ClN_2O_2S$ requires 261.0464, observed 261.0450.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 180 °C (60 °C/min) and hold for 100 min) indicated 91% ee using the $P411_{Diane1}$ variant: t_R = 185 (minor), 190 (major) min.

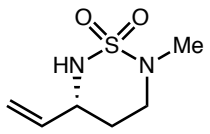
(*R*)-2-Isopropyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (2n)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.44 – 7.28 (m, 5H), 4.77 (ddd, *J* = 12.6, 10.2, 2.8 Hz, 1H), 4.22 (p, *J* = 6.8 Hz, 1H), 4.06 (d, *J* = 10.2 Hz, 1H), 3.43 (td, *J* = 12.6, 2.8 Hz, 1H), 3.33 (ddd, *J* = 12.9, 4.8, 2.6 Hz, 1H), 2.13 (dq, *J* = 13.8, 2.8 Hz, 1H), 1.99 (dtd, *J* = 13.8, 12.3, 4.8 Hz, 1H), 1.23 (d, *J* = 6.8 Hz, 3H), 1.21 (d, *J* = 6.8 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 139.3, 129.0, 128.5, 126.4, 59.5, 48.6, 41.7, 32.3, 21.1, 19.0 ppm. IR: 3214, 2971, 2870, 1456, 1319, 1293, 1167, 1141, 741, 695 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_2S$ requires 255.1167, observed 255.1140.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 175 °C (60 °C/min) and hold for 100 min) indicated 70% ee using the $P411_{Diane1}$ I327P variant: t_R = 174 (major), 175 (minor) min. Use of P411Diane1 provided 38% ee.

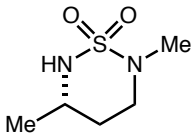
(*R*)-2-Methyl-5-vinyl-1,2,6-thiadiazinane 1,1-dioxide (2o)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.81 (ddd, *J* = 17.3, 10.6, 5.0 Hz, 1H), 5.33 – 5.17 (m, 2H), 4.19 (dddt, *J* = 12.7, 9.5, 5.1, 1.7 Hz, 1H), 4.07 (d, *J* = 9.5 Hz, 1H), 3.55 – 3.40 (m, 1H), 3.17 (dt, *J* = 13.1, 3.8 Hz, 1H), 2.75 (s, 3H), 1.80 – 1.70 (m, 2H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 136.1, 116.7, 57.8, 51.8, 36.5, 28.3 ppm. IR: 3227, 2865, 1326, 1147, 1055, 855, 758, 693 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_6H_{12}N_2O_2S$ requires 177.0698, observed 177.0674.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min)) indicated 92% ee: t_R = 72 (minor), 89 (major) min.

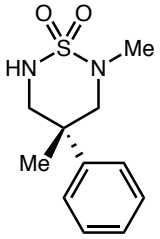
(*S*)-2,5-Dimethyl-1,2,6-thiadiazinane 1,1-dioxide (2p)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid . ^{1}H NMR (400 MHz, $CDCl_3$) δ: 4.00 (d, J = 10.2 Hz, 1H), 3.71 (tdd, J = 10.2, 6.6, 3.9 Hz, 1H), 3.48 – 3.34 (m, 1H), 3.12 (ddd, J = 13.0, 4.4, 2.9 Hz, 1H), 2.73 (s, 3H), 1.70 – 1.56 (m, 2H), 1.23 (d, J = 6.6 Hz, 3H) ppm. Spectral data match those previously reported.[5]

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min)) indicated -96% ee using variant $P411_{Diane1}$ L82M A87I I327S Y263W and +71% ee using variant $P411_{Diane1}$ I327T: t_R = 53 (minor), 79 (major) min.

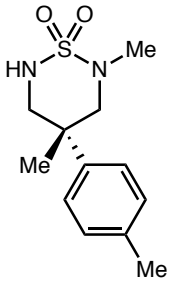
(*R*)-2,4-Dimethyl-4-phenyl-1,2,6-thiadiazinane 1,1-dioxide (4a)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.42 – 7.36 (m, 4H), 7.33 – 7.26 (m, 1H), 4.27 (t, J = 7.8 Hz, 1H), 3.78 (ddd, J = 14.6, 6.5, 2.0 Hz, 1H), 3.60 – 3.46 (m, 2H), 3.17 (dd, J = 12.7, 1.0 Hz, 1H), 2.77 (s, 3H), 1.36 (s, 3H ppm). ^{13}C NMR (101 MHz, $CDCl_3$) δ: 142.4, 129.1, 127.4, 126.1, 62.1, 55.5, 38.7, 36.6, 24.5 ppm. Spectral data match those previously reported.[5]

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 99% ee: t_R = 114 (major), 116 (minor) min.

(*R*)-2,4-Dimethyl-4-(*p*-tolyl)-1,2,6-thiadiazinane 1,1-dioxide (4b)

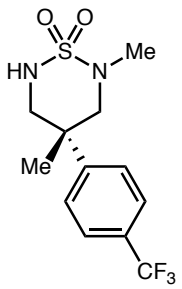


Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as an off-white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.28 (d, J = 8.4 Hz, 2H), 7.20 (d, J = 8.4 Hz, 2H), 4.35 – 4.22 (m, 1H), 3.76 (ddd, J = 14.5, 6.6, 1.9 Hz, 1H), 3.59 – 3.45 (m, 2H), 3.15 (dd, J = 12.6, 1.1 Hz, 1H), 2.77 (s, 3H), 2.35 (s, 3H), 1.35 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 139.4, 137.1, 129.7, 126.0, 62.2, 55.5, 38.3, 36.6, 24.5, 21.0 ppm. IR: 3273, 2970, 2925, 1517,

1326, 1156, 1092, 1019, 814, 727 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_2S$ requires 255.1167, observed 255.1138.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 30 min) indicated 91% ee: t_R = 116.0 (major), 116.6 (minor) min.

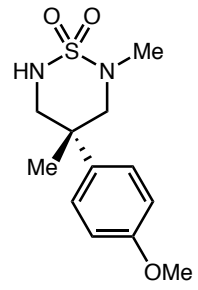
(*R*)-2,4-Dimethyl-4-(4-(trifluoromethyl)phenyl)-1,2,6-thiadiazinane 1,1-dioxide (4c)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as an off-white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.65 (d, *J* = 8.2 Hz, 2H), 7.52 (d, *J* = 8.2 Hz, 2H), 4.28 (dd, *J* = 9.2, 6.5 Hz, 1H), 3.76 (ddd, *J* = 14.7, 6.5, 2.0 Hz, 1H), 3.64 – 3.45 (m, 2H), 3.21 (dd, *J* = 12.7, 1.0 Hz, 1H), 2.77 (s, 3H), 1.38 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.7, 129.7 (q, *J* = 32 Hz), 126.8, 126.0 (q, *J* = 4.0 Hz), 124.0 (q, *J* = 274 Hz), 61.9, 55.3, 39.0, 36.7, 24.4 ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ -62.7 ppm. IR: 3271, 2971, 2876, 1410, 1324, 1158, 1115, 1068, 836, 724 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{15}F_3N_2O_2S$ requires 309.0885, observed 309.0894.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 20 min) indicated 81% ee: t_R = 113.8 (major), 114.5 (minor) min.

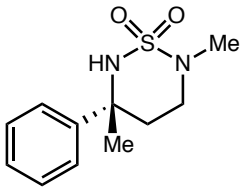
(*R*)-4-(4-Methoxyphenyl)-2,4-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (4d)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a pale yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.30 (d, *J* = 8.9 Hz, 2H), 6.91 (d, *J* = 8.9 Hz, 2H), 4.34 – 4.17 (m, 1H), 3.81 (s, 3H), 3.71 (ddd, *J* = 14.5, 6.6, 2.0 Hz, 1H), 3.56 – 3.43 (m, 2H), 3.13 (dd, *J* = 12.6, 1.1 Hz, 1H), 2.76 (s, 3H), 1.34 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 158.7, 134.3, 127.3, 114.4, 62.4, 55.6, 55.4, 38.1, 36.6, 24.5 ppm. IR: 3270, 2962, 1610, 1515, 1325, 1253, 1154, 1029, 828, 734 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_3S$ requires 271.1116, observed 271.1119.

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 200 °C (60 °C/min) and hold for 20 min) indicated 99% ee: t_R = 140 (major), 141 (minor) min.

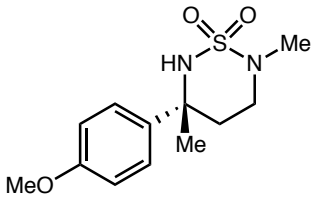
(*R*)-2,5-Dimethyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5a)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a colorless oil that turned into white solid upon standing in the fridge. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.52 – 7.44 (m, 2H), 7.38 (dd, *J* = 8.4, 6.8 Hz, 2H), 7.33 – 7.27 (m, 1H), 4.35 (s, 1H), 3.50 (ddd, *J* = 12.8, 9.6, 3.0 Hz, 1H), 3.31 (ddd, *J* = 13.6, 6.4, 3.7 Hz, 1H), 2.75 (s, 3H), 2.39 (ddd, *J* = 13.6, 9.6, 3.7 Hz, 1H), 2.14 – 2.01 (m, 1H), 1.65 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 145.1, 128.8, 127.8, 124.8, 62.0, 49.4, 36.4, 33.2, 29.9 ppm. Spectral data match those reported previously.[5]

GC analysis (cyclosil B column, isothermal at 130 °C for 60 min, then ramp to 150 °C (1 °C/min) and hold for 15 min, then ramp to 175 °C (60 °C/min) and hold for 50 min) indicated 99% ee: t_R = 146 (minor), 148 (major) min.

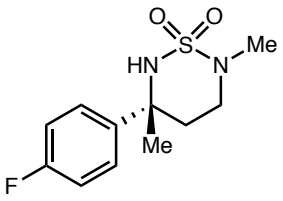
(*R*)-5-(4-Methoxyphenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5b)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.39 (d, *J* = 8.9 Hz, 2H), 6.89 (d, *J* = 8.9 Hz, 2H), 4.37 – 4.27 (m, 1H), 3.80 (s, 3H), 3.48 (ddd, *J* = 13.0, 9.5, 3.0 Hz, 1H), 3.30 (ddd, *J* = 13.3, 6.5, 3.6 Hz, 1H), 2.75 (s, 3H), 2.37 (ddd, *J* = 14.1, 9.5, 3.6 Hz, 1H), 2.04 (ddd, *J* = 14.1, 6.5, 3.0 Hz, 1H), 1.62 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ 159.0, 137.1, 126.1, 114.0, 61.7, 55.4, 49.5, 36.4, 33.3, 30.0 ppm. IR: 3252, 2962, 2934, 1610, 1513, 1320, 1248, 1113, 1083, 1030, 831, 717 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_3S$ requires 271.1116, observed 271.1118.

SFC analysis (IC column, 5 – 45% *i*-PrOH in $scCO_2$ for 4 min, then 45% *i*-PrOH in $scCO_2$ for 4 min, 3.5 mL/min) indicated 98% ee: t_R = 6.8 (major), 7.3 (minor) min.

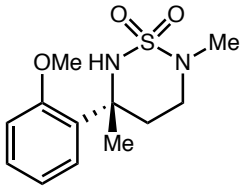
(*R*)-5-(4-Fluorophenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5c)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.45 (dd, *J* = 9.0, 5.2 Hz, 2H), 7.04 (dd, *J* = 9.0, 8.4 Hz, 2H), 4.51 (s, 1H), 3.42 (ddd, *J* = 13.3, 8.2, 3.3 Hz, 1H), 3.31 (ddd, *J* = 13.3, 7.6, 3.4 Hz, 1H), 2.73 (s, 3H), 2.38 (ddd, *J* = 14.3, 8.2, 3.4 Hz, 1H), 2.07 (ddd, *J* = 14.3, 7.6, 3.3 Hz, 1H), 1.58 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 162.1 (d, *J* = 247 Hz), 140.2 (d, *J* = 4.0 Hz), 126.9 (d, *J* = 8.0 Hz), 115.5 (d, *J* = 22 Hz), 61.7, 49.4, 36.4, 33.0, 31.0 ppm. ^{19}F NMR (282 MHz, $CDCl_3$) δ -115.01 – -115.09 (m, 1F) ppm. IR: 3247, 2967, 1511, 1320, 1225, 1155, 1082, 1030, 835, 715 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{11}H_{15}FN_2O_2S$ requires 259.0917, observed 259.0893.

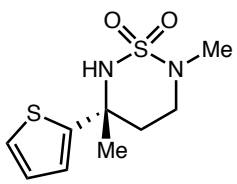
SFC analysis (IC column, 5 – 45% *i*-PrOH in $scCO_2$ for 4 min, then 45% *i*-PrOH in $scCO_2$ for 4 min, 3.5 mL/min) indicated 98% ee: t_R = 5.0 (major), 5.6 (minor) min.

(*R*)-5-(2-Methoxyphenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5d)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.33 – 7.29 (m, 2H), 7.03 – 6.94 (m, 2H), 5.98 (s, 1H), 3.93 (s, 3H), 3.64 (ddd, *J* = 14.2, 9.9, 3.1 Hz, 1H), 3.43 (ddd, *J* = 14.0, 6.1, 3.8 Hz, 1H), 2.85 (s, 3H), 2.54 (ddd, *J* = 14.0, 9.9, 3.8 Hz, 1H), 1.80 (s, 3H), 1.73 (ddd, *J* = 14.2, 6.1, 3.1 Hz, 1H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 156.9, 131.6, 129.3, 126.2, 121.4, 112.0, 62.0, 55.6, 49.3, 36.7, 30.1, 25.8 ppm. IR: 3284, 2924, 1340, 1322, 1234, 1159, 1140, 1019, 908, 753, 726 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_3S$ requires 271.1116, observed 271.1090.

SFC analysis (IA column, 5 – 45% *i*-PrOH in $scCO_2$ for 4 min, then 45% *i*-PrOH in $scCO_2$ for 4 min, 3.5 mL/min) indicated 98% ee: t_R = 4.0 (major), 4.3 (minor) min.



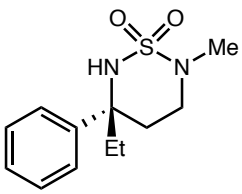
(*R*)-2,5-Dimethyl-5-(thiophen-2-yl)-1,2,6-thiadiazinane 1,1-dioxide (5e)

Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.25 (dd, *J* = 5.1, 1.2 Hz, 1H), 7.03 (dd, *J* = 3.6, 1.2 Hz, 1H), 6.96 (dd, *J* = 5.1, 3.6 Hz,

1H), 4.52 (s, 1H), 3.57 (ddd, J = 13.7, 10.0, 3.0 Hz, 1H), 3.36 (ddd, J = 13.7, 5.9, 3.8 Hz, 1H), 2.78 (s, 3H), 2.40 (ddd, J = 14.0, 10.0, 3.8 Hz, 1H), 2.08 – 1.94 (m, 1H), 1.79 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 150.1, 126.9, 125.0, 123.4, 60.5, 49.3, 36.5, 34.1, 29.8 ppm. IR: 3250, 2927, 1407, 1318, 1152, 1083, 921, 866, 700, 636 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_9H_{14}N_2O_2S_2$ requires 247.0575, observed 247.0560.

SFC analysis (IC column, 5 – 45% *i*-PrOH in $scCO_2$ for 4 min, then 45% *i*-PrOH in $scCO_2$ for 4 min, 3.5 mL/min) indicated 98% ee: t_R = 5.8 (major), 6.0 (minor) min.

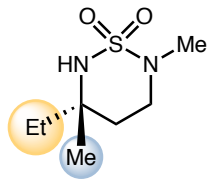
(*R*)-5-Ethyl-2-methyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5f)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.44 – 7.34 (m, 4H), 7.32 – 7.27 (m, 1H), 4.40 (d, J = 3.6 Hz, 1H), 3.41 (ddd, J = 13.3, 8.3, 3.4 Hz, 1H), 3.29 (ddd, J = 13.3, 7.6, 3.4 Hz, 1H), 2.73 (s, 3H), 2.35 (ddd, J = 14.4, 8.3, 3.6 Hz, 1H), 2.17 – 2.04 (m, 2H), 1.82 (dq, J = 13.7, 7.4 Hz, 1H), 0.68 (t, J = 7.4 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 141.9, 128.4, 127.6, 125.9, 65.3, 49.4, 36.4, 34.9, 31.7, 8.0 ppm. IR: 3252, 2968, 2934, 1447, 1319, 1165, 1029, 881, 858, 699 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_{12}H_{18}N_2O_2S$ requires 255.1167, observed 255.1177.

SFC analysis (IC column, 5 – 45% *i*-PrOH in $scCO_2$ for 4 min, then 45% *i*-PrOH in $scCO_2$ for 4 min, 3.5 mL/min) indicated 99% ee: t_R = 5.6 (major), 6.1 (minor) min.

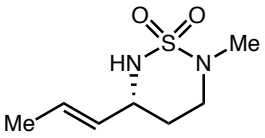
(*S*)-5-Ethyl-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5g)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 3.93 (s, 1H), 3.35 (ddd, J = 13.4, 8.5, 3.8 Hz, 1H), 3.27 (ddd, J = 13.4, 6.7, 4.1 Hz, 1H), 2.74 (s, 3H), 1.80 (dt, J = 14.1, 7.4 Hz, 1H), 1.71 (ddd, J = 18.2, 8.3, 4.1 Hz, 1H), 1.62 (ddd, J = 14.1, 6.7, 3.8 Hz, 1H), 1.54 – 1.43 (m, 1H), 1.32 (s, 3H), 0.95 (t, J = 7.5 Hz, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 59.5, 49.3, 36.5, 34.0, 33.7, 24.4, 7.7 ppm. IR: 3255, 2971, 2927, 1467, 1419, 1318, 1166, 1142, 927, 858, 717, 625 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{16}N_2O_2S$ requires 193.1011, observed 193.0995.

GC analysis (cyclosil B column, isothermal at 155 °C for 22 min) indicated 87% ee: t_R = 17.0 (minor), 17.4 (major) min.

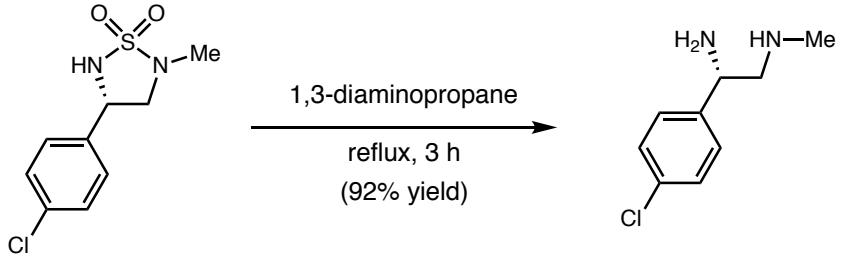
(*R*,*E*)-2-Methyl-5-(prop-1-en-1-yl)-1,2,6-thiadiazinane 1,1-dioxide (6a)



Purified by column chromatography (3:3:1 hexanes:CH_2Cl_2:acetone) to afford the product as a white solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 5.73 (dqd, *J* = 15.5, 6.5, 1.4 Hz, 1H), 5.42 (ddd, *J* = 15.4, 5.9, 1.7 Hz, 1H), 4.20 – 4.06 (m, 1H), 3.89 (d, *J* = 9.0 Hz, 1H), 3.53 – 3.40 (m, 1H), 3.22 – 3.09 (m, 1H), 2.75 (s, 3H), 1.78 – 1.65 (m, 5H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 129.2, 128.7, 57.7, 51.8, 36.6, 28.7, 17.9 ppm. IR: 3234, 2925, 1322, 1158, 1063, 965, 857, 720 cm^{-1}. HRMS (ESI) (m/z) for $[M+H]^+$ $C_7H_{14}N_2O_2S$ requires 191.0854, observed 191.0830.

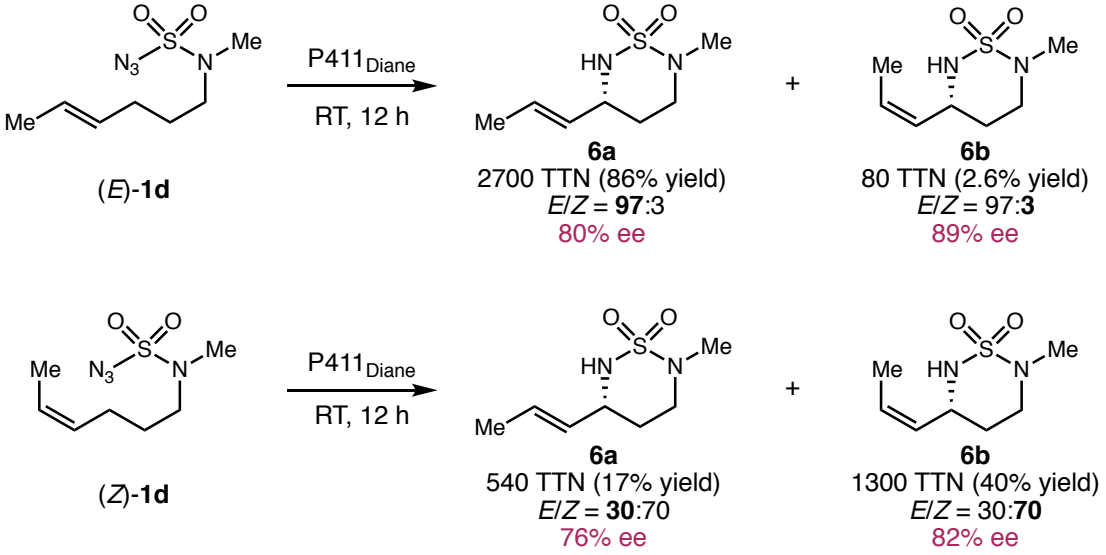
Using (*E*)-**1d** as the substrate, GC analysis (cyclosil B column, isothermal at 155 °C for 22 min) indicated 80% ee for the $P411_{Diane1}$ I327P variant and 74% ee for the $P411_{Diane1}$ variant: t_R = 15.8 (minor), 17.2 (major) min.

VII. Experimental procedure for the conversion of cylic sulfamides to diamines



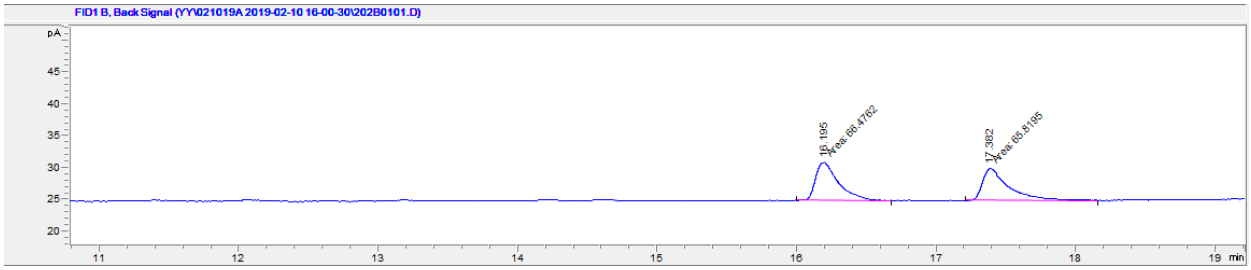
The sulfamide (0.1 mmol) was refluxed in 1,3-diaminopropane (0.4 mL) for 3 h and then allowed to cool to room temperature. The residue was taken up with CH_2Cl_2 and washed with water for three times. The combined aqueous layers were then extracted with CH_2Cl_2 for three times. Organic layers were then combined, dried over Na_2SO_4 and concentrated *in vacuo* to afford the diamine in 91% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.31 – 7.27 (m, 4H), 4.02 (dd, *J* = 7.9, 5.1 Hz, 1H), 2.76 – 2.63 (m, 2H), 2.42 (s, 3H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$) δ: 143.3, 132.9, 128.7, 128.0, 60.1, 54.9, 36.6 ppm.

VIII. Scrambling of C=C double bond stereochemistry during the allylic C-H amination



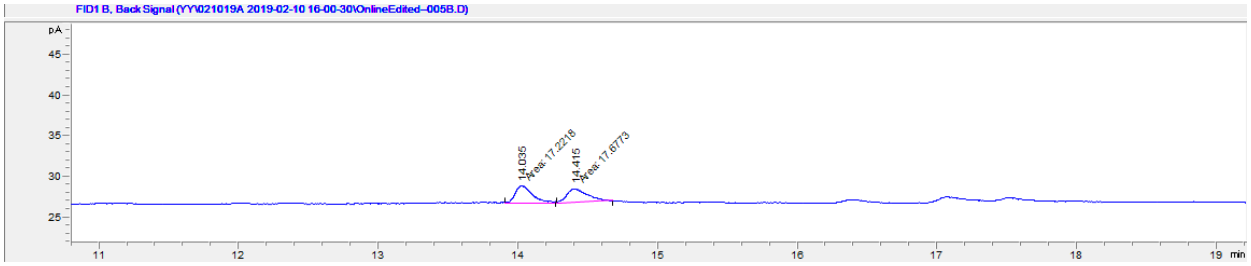
The yield and ratio of *E*- and *Z*-products were determined by GC analysis (cyclosil B column, isothermal at 155 °C for 22 min). The chiral GC traces are shown below.

rac-**6a**:



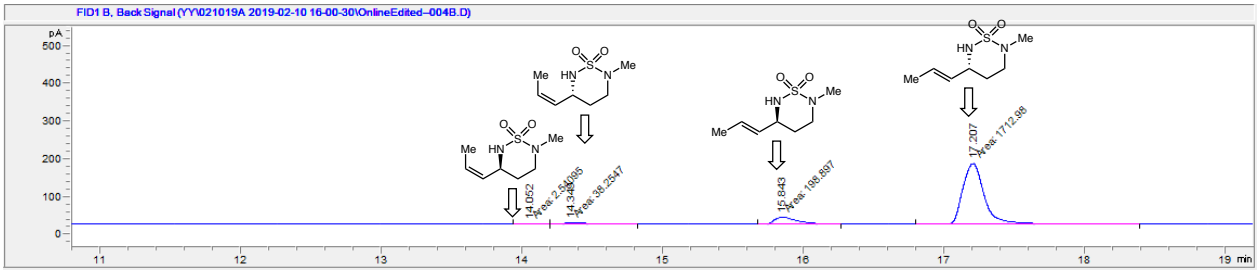
#	Time	Area	Height	Width	Area%	Symmetry
1	16.195	66.5	6	0.1845	50.248	0.567
2	17.382	65.8	5	0.2211	49.752	0.356

rac-**6b**:



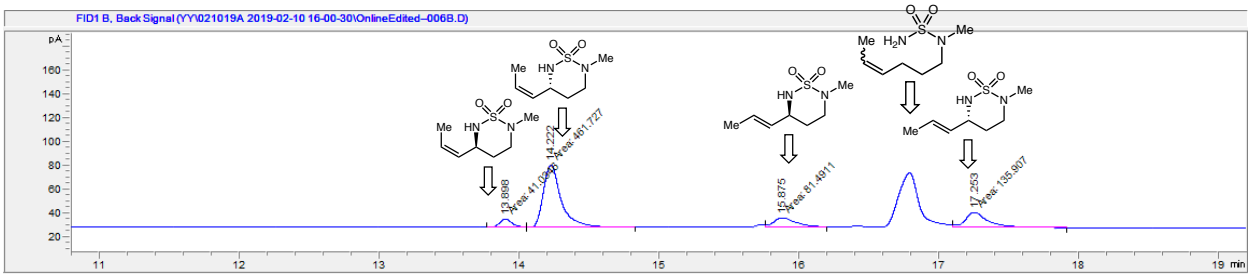
#	Time	Area	Height	Width	Area%	Symmetry
1	14.035	17.2	2.1	0.1356	49.348	0.653
2	14.415	17.7	1.7	0.1701	50.652	0.743

Enzymatic reaction using (*E*)-**1d** as the substrate (unpurified reaction mixture):



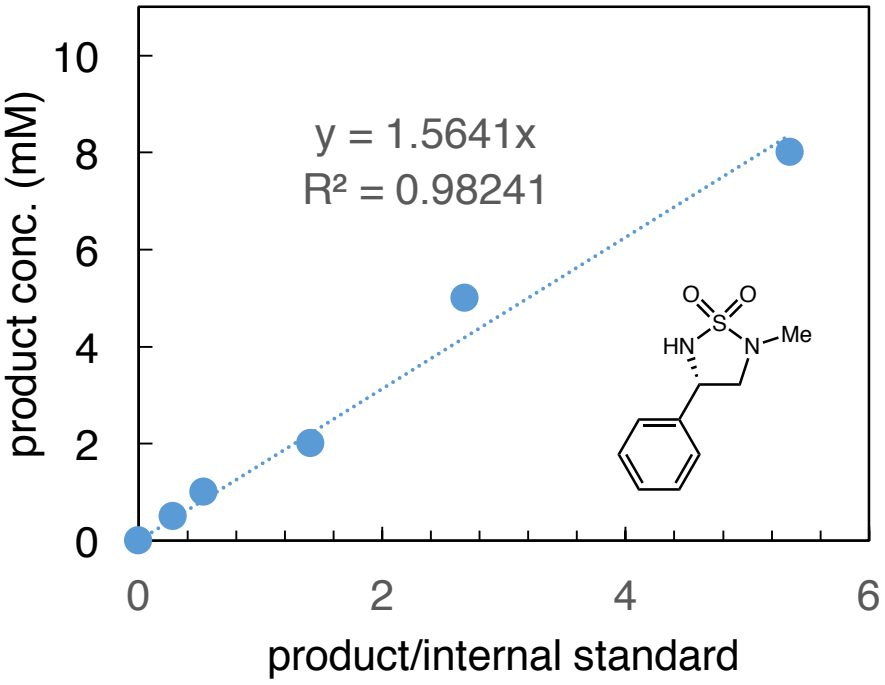
#	Time	Area	Height	Width	Area%	Symmetry
1	14.052	2.5	4.5E-1	0.0949	0.130	0.614
2	14.349	38.3	3.8	0.1685	1.959	0.422
3	15.843	198.9	19	0.1744	10.186	0.483
4	17.207	1713	161.3	0.177	87.725	0.915

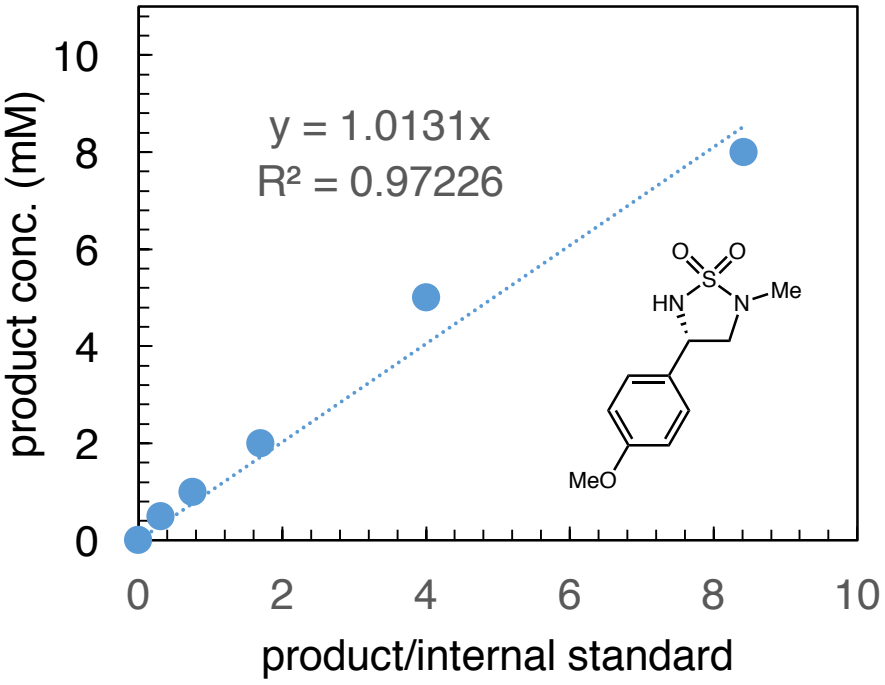
Enzymatic reaction using (*Z*)-**1d** as the substrate (unpurified reaction mixture):

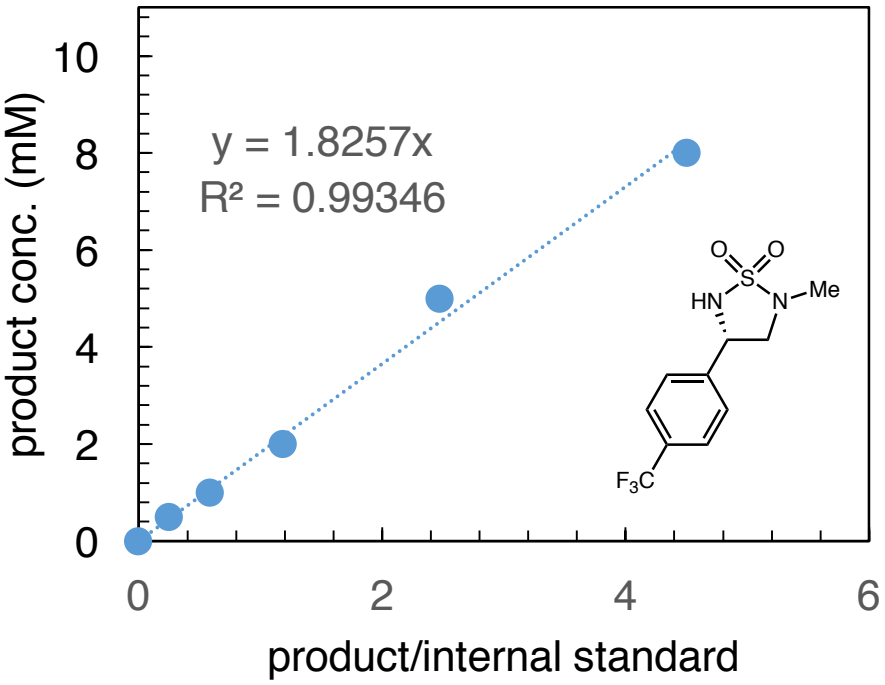


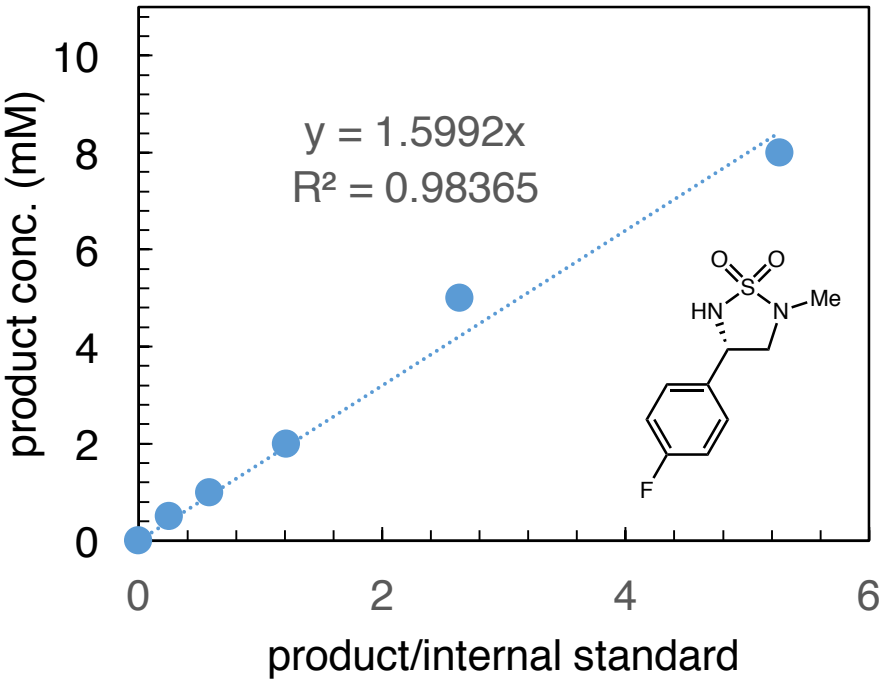
#	Time	Area	Height	Width	Area%	Symmetry
1	13.898	41	6.6	0.1034	5.698	0.911
2	14.222	461.7	52.4	0.1468	64.115	0.678
3	15.875	81.5	7.7	0.1765	11.316	0.617
4	17.253	135.9	12.3	0.184	18.872	0.669

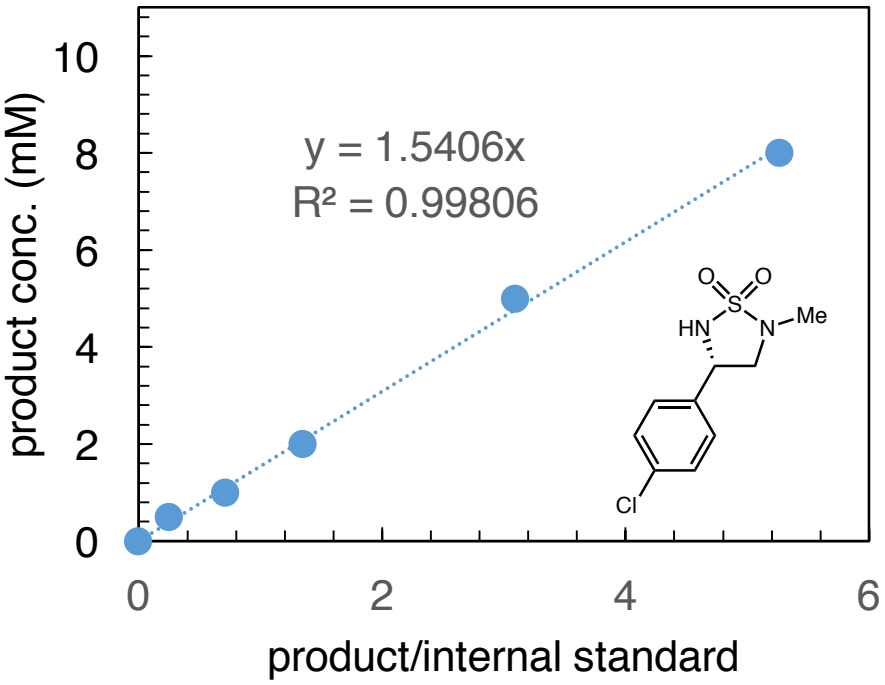
IX. Product GC/MS calibration curves

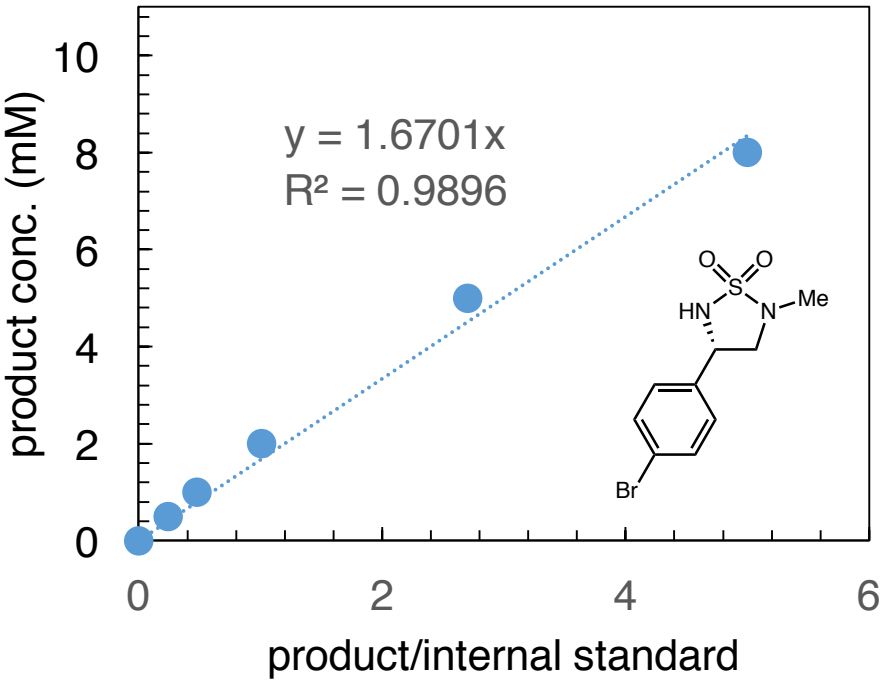


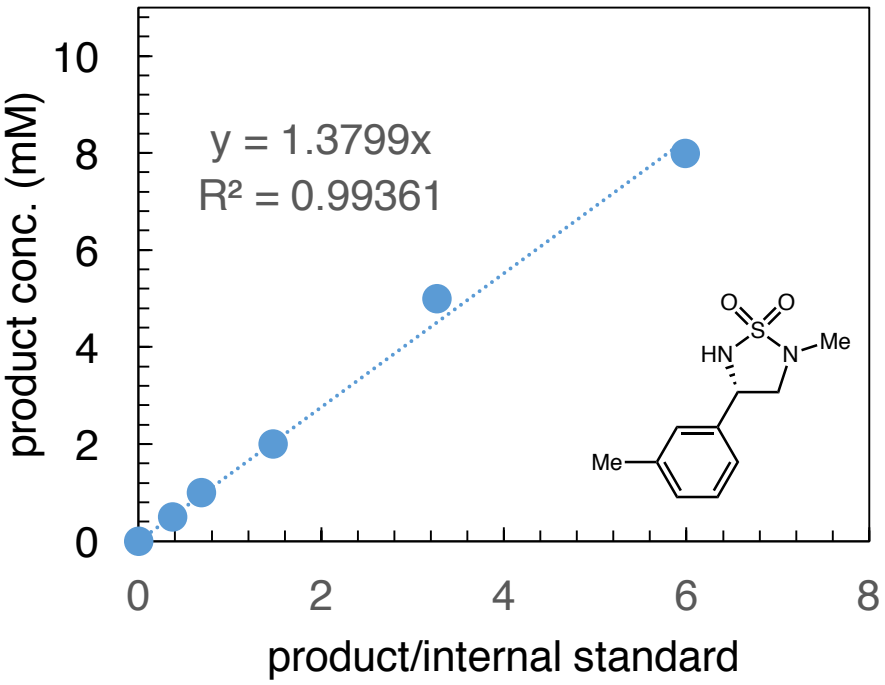


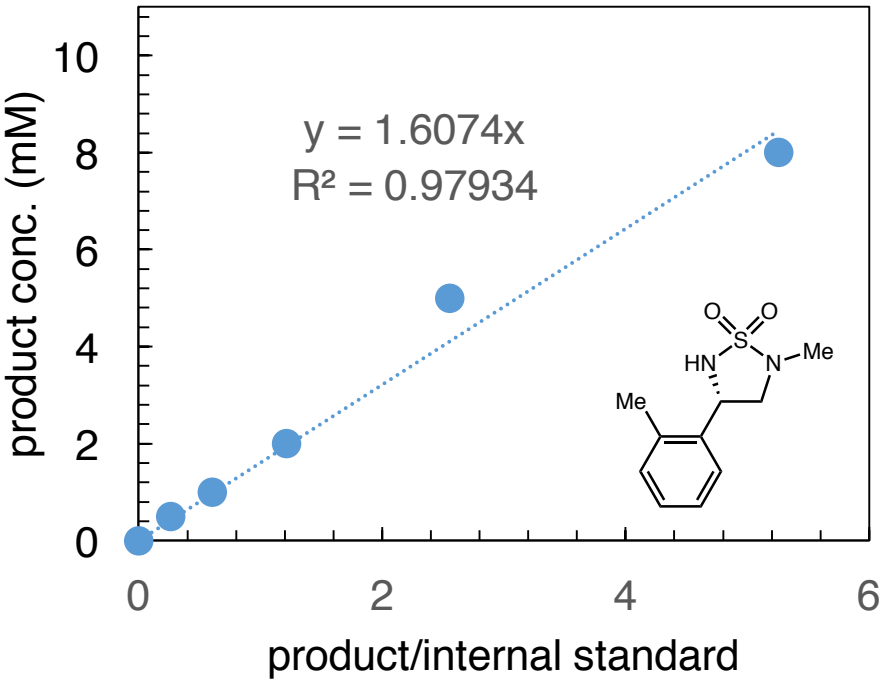

y = 1.8257x
R² = 0.99346
product conc. (mM)
product/internal standard
0
2
4
6
8
10
HN
S
O
O
N
Me
F3C


y = 1.5992x
R² = 0.98365
product conc. (mM)
product/internal standard
0
2
4
6
8
10
HN
S
O
O
N
Me
F


y = 1.5406x
R² = 0.99806
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Cl


y = 1.6701x
R² = 0.9896
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Br


y = 1.3799x
R² = 0.99361
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Me


y = 1.6074x
R² = 0.97934
product conc. (mM)
product/internal standard
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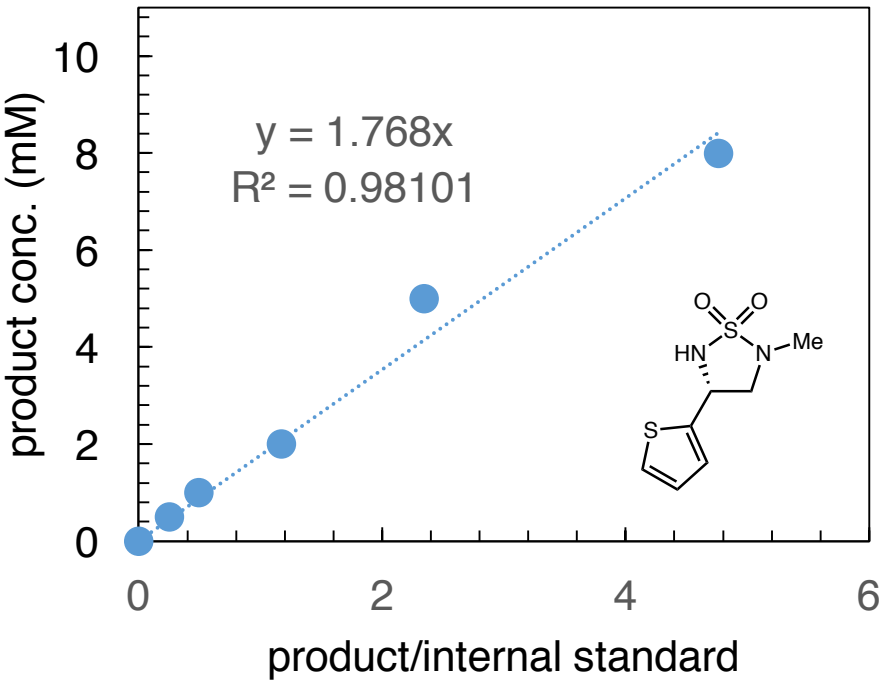
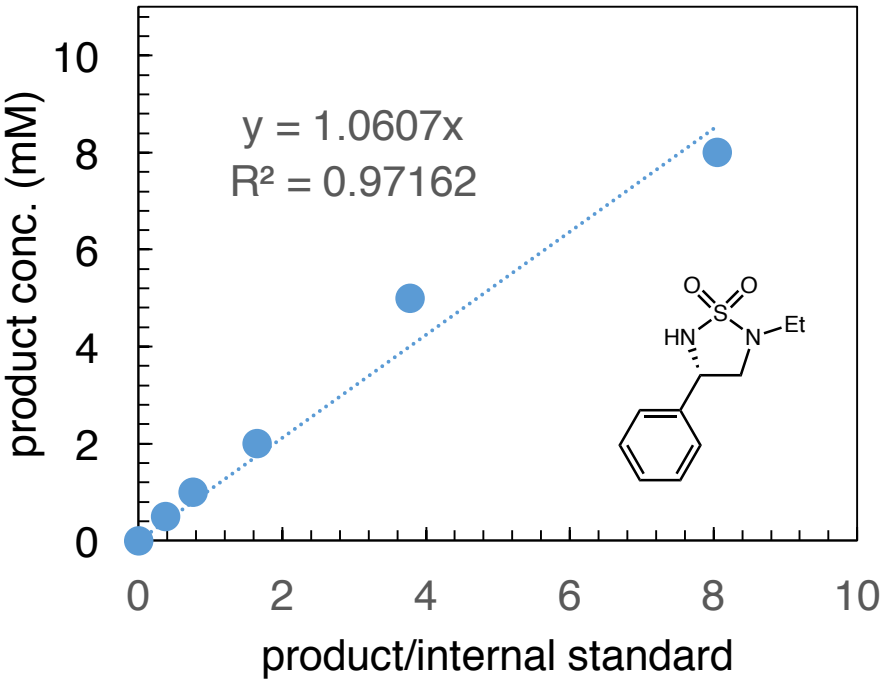
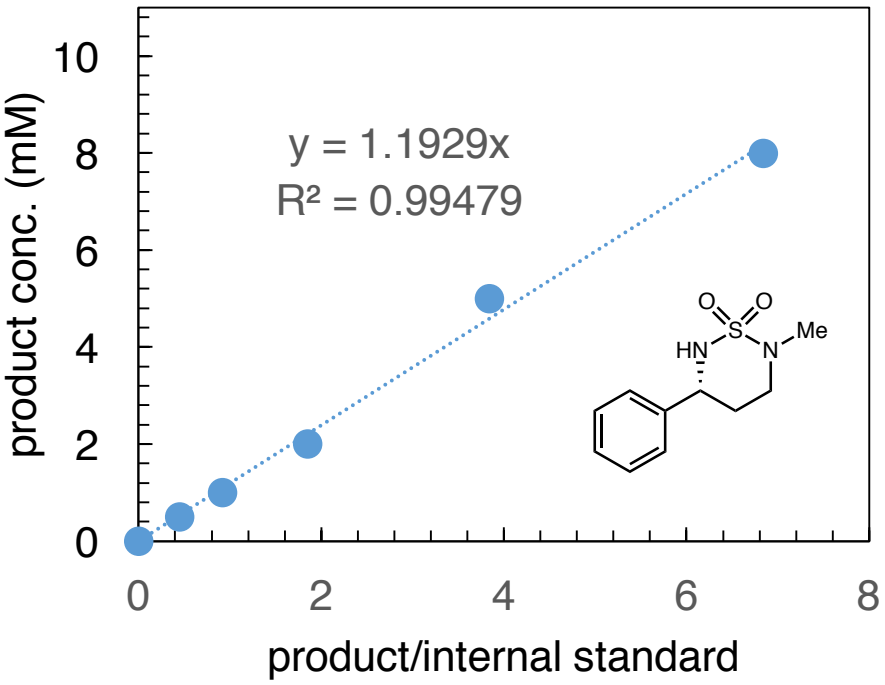
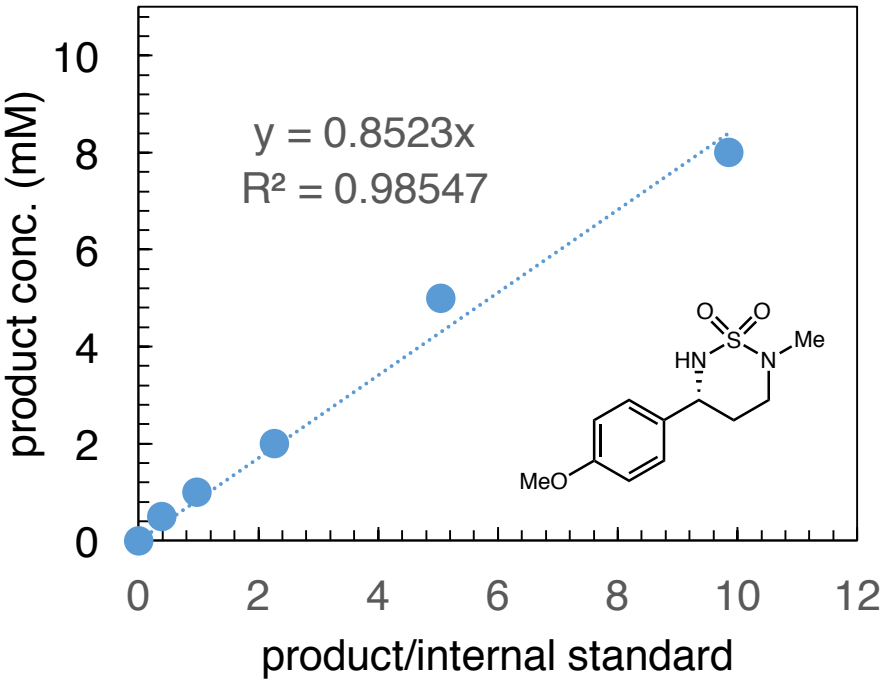
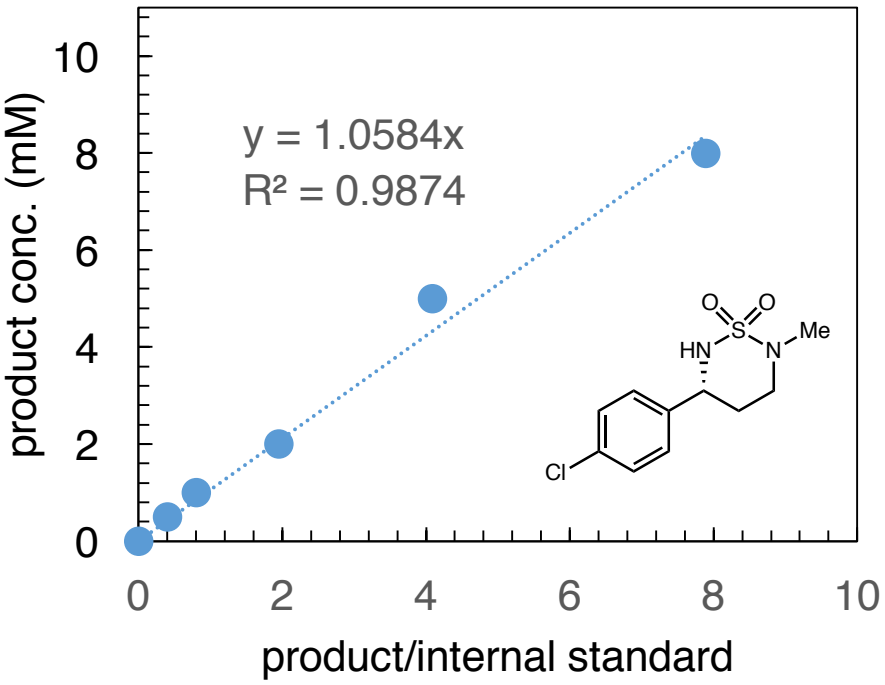
2
4
6
8
10
O
O
S
HN
N
Me
Me

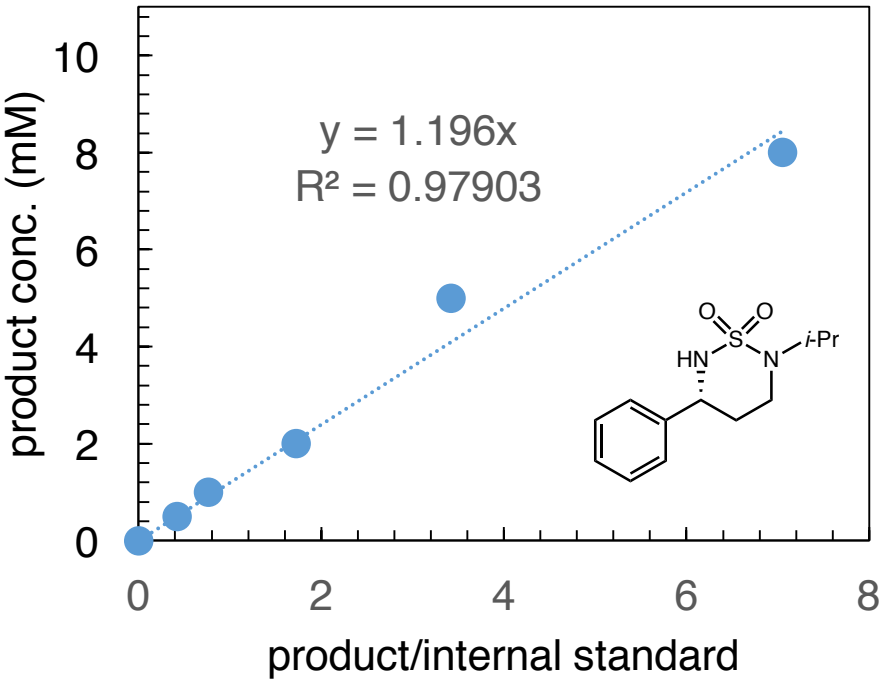

y = 1.768x
R² = 0.98101
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
S

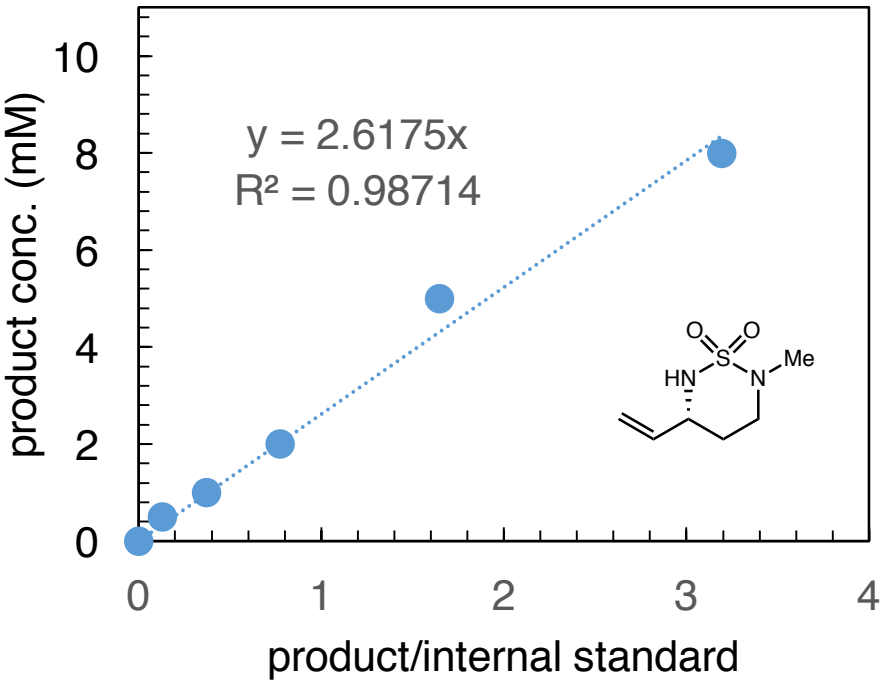

y = 1.0607x
R² = 0.97162
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Et

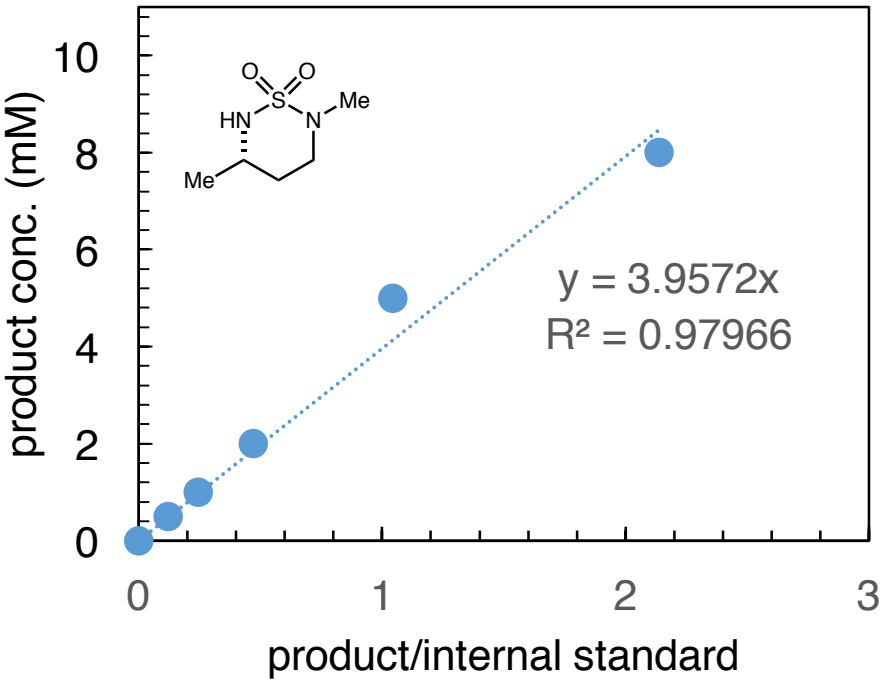

y = 1.1929x
R² = 0.99479
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me

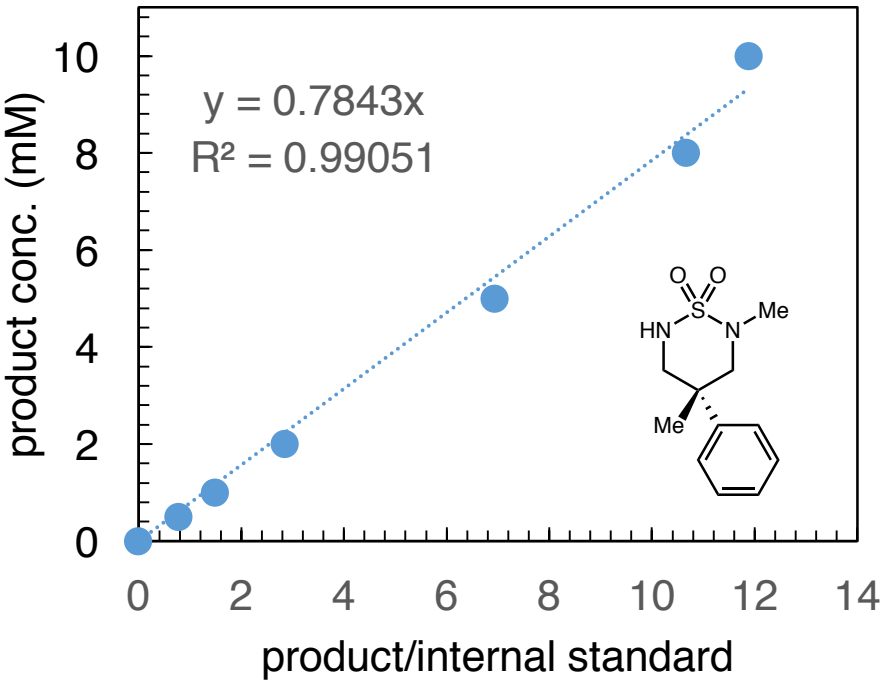

y = 0.8523x
R² = 0.98547
product conc. (mM)
product/internal standard
0
2
4
6
8
10
12
O
O
S
HN
N
Me
MeO

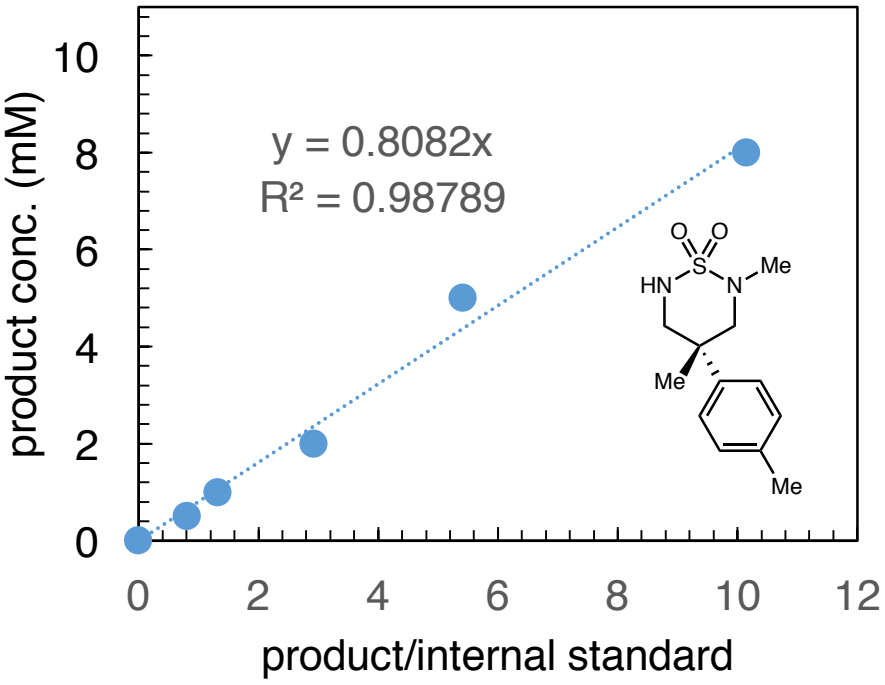

y = 1.0584x
R² = 0.9874
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Cl

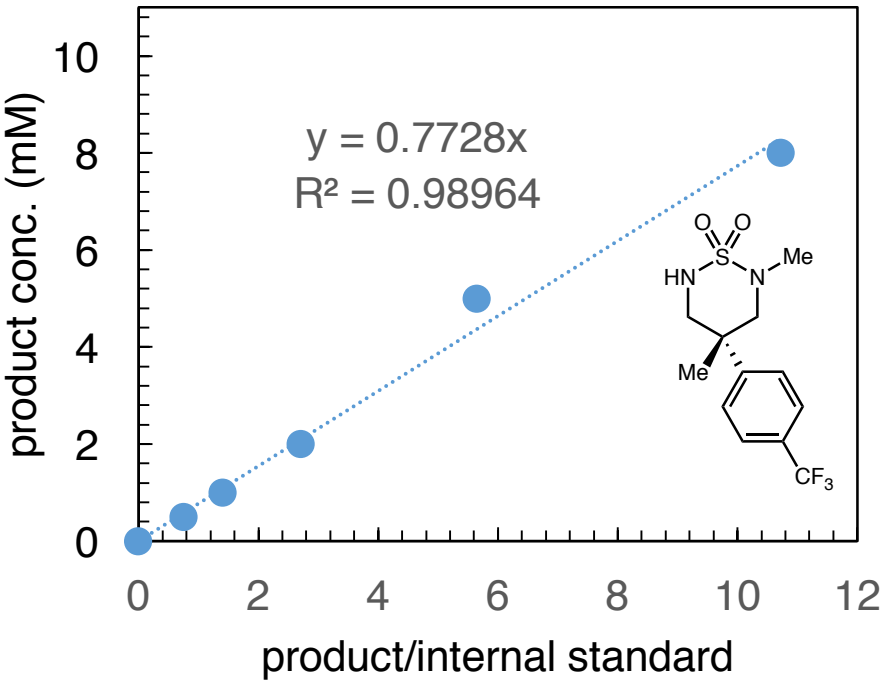

y = 1.196x
R² = 0.97903
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
i-Pr

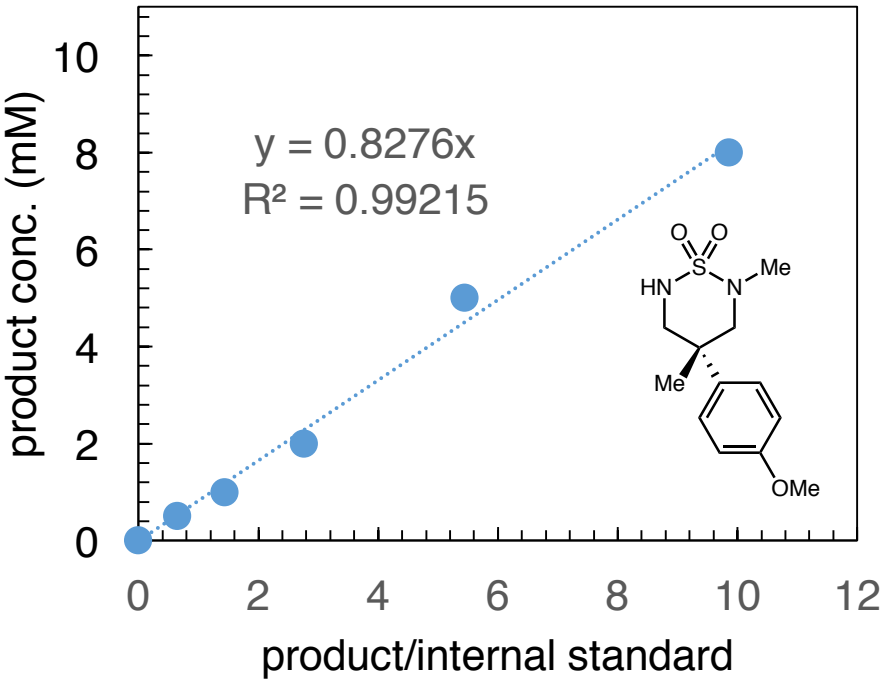

y = 2.6175x
R² = 0.98714
product conc. (mM)
product/internal standard
0
2
4
6
8
10
0
1
2
3
4
O
O
S
HN
N
Me

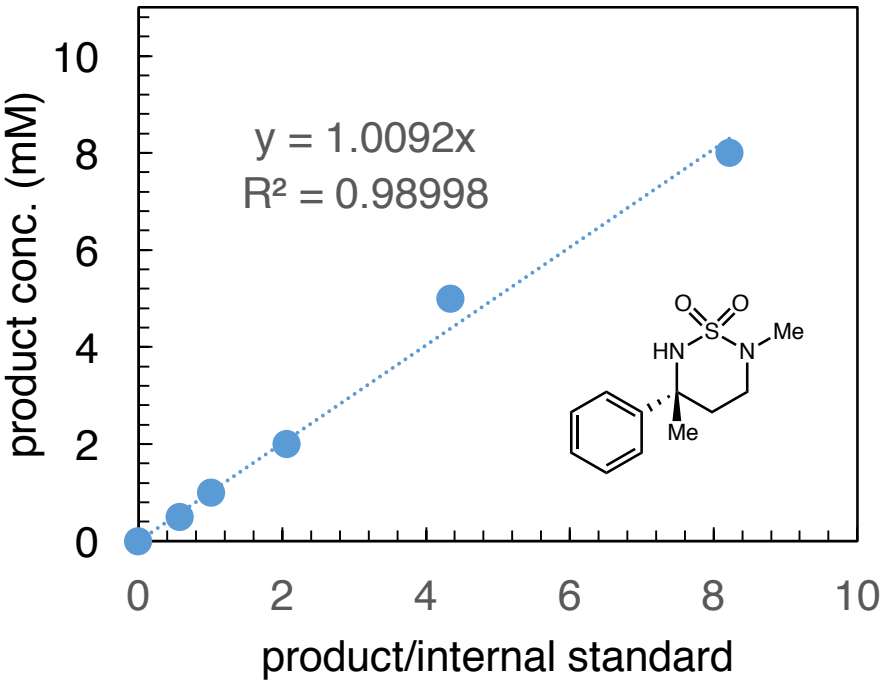

y = 3.9572x
R² = 0.97966
product conc. (mM)
product/internal standard
0
2
4
6
8
10
0
1
2
3
O
O
S
HN
N
Me
Me

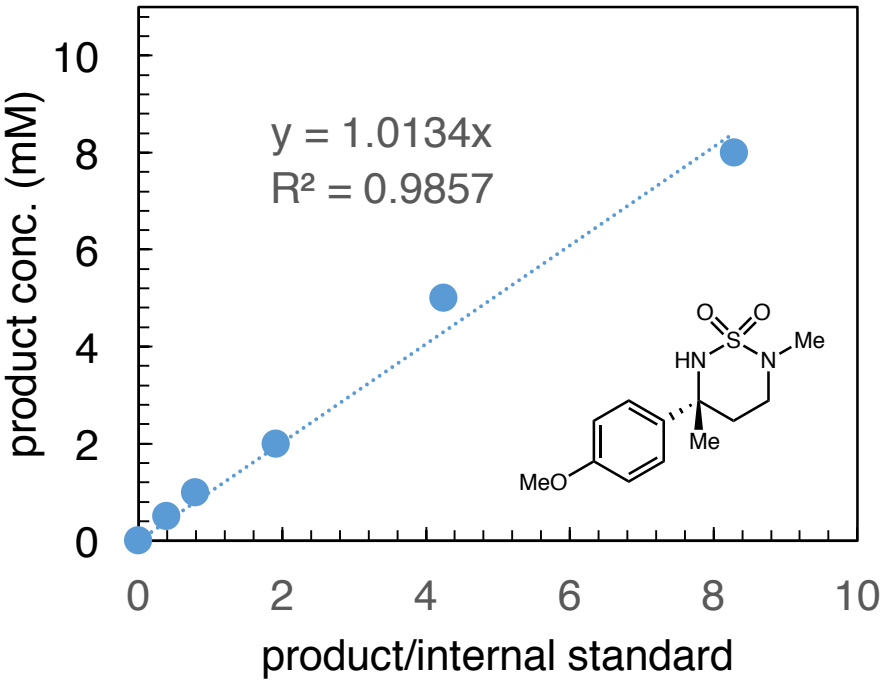

y = 0.7843x
R² = 0.99051
product conc. (mM)
product/internal standard
0
2
4
6
8
10
12
14
O
O
S
HN
N
Me
Me

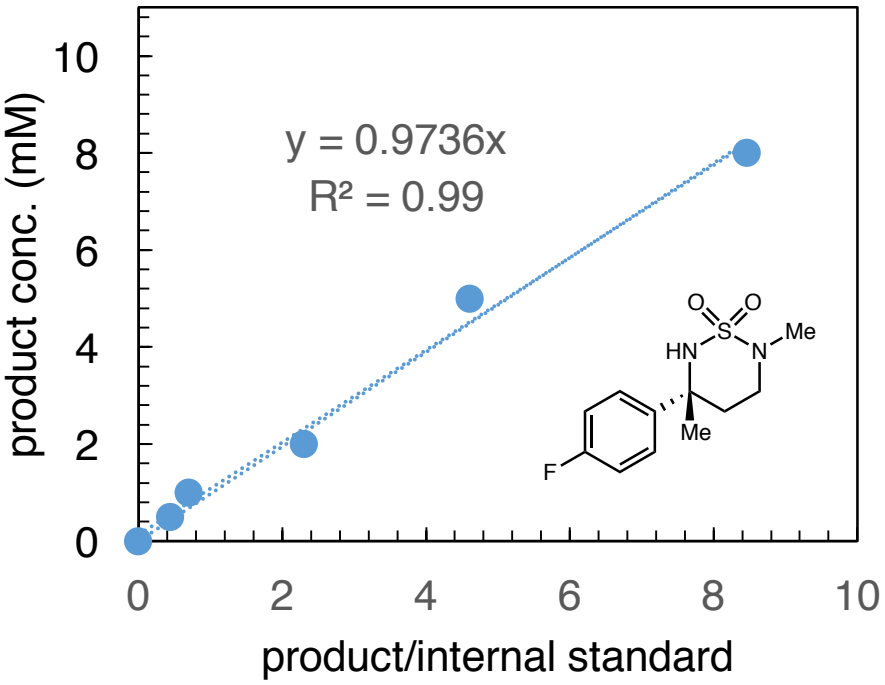

y = 0.8082x
R² = 0.98789
product conc. (mM)
product/internal standard
0
2
4
6
8
10
12
O
O
S
HN
N
Me
Me
Me

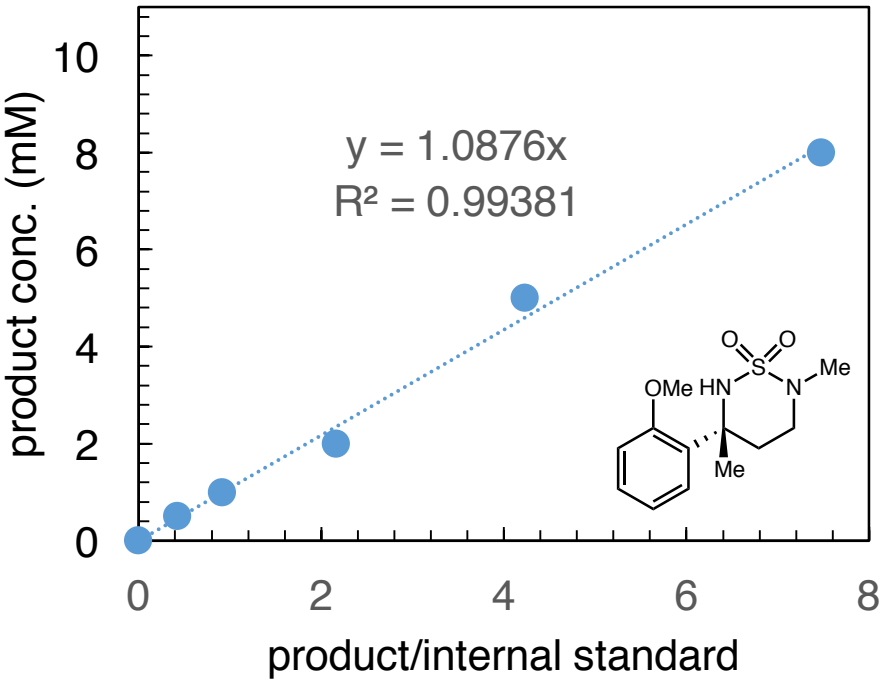

y = 0.7728x
R² = 0.98964
product conc. (mM)
product/internal standard
0
2
4
6
8
10
12
HN
S
O
O
N
Me
Me
CF3

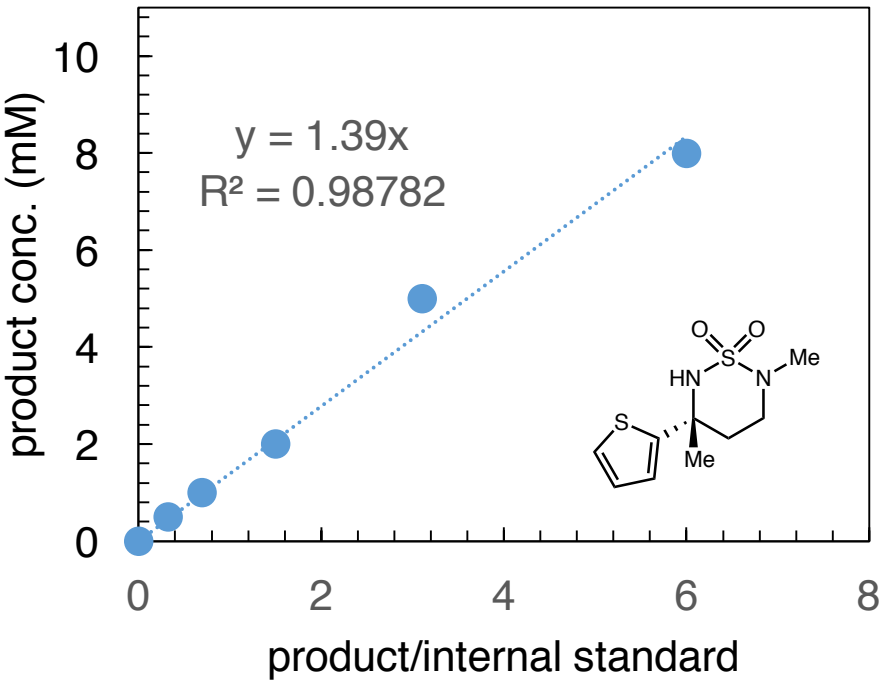

y = 0.8276x
R² = 0.99215
product conc. (mM)
product/internal standard
0
2
4
6
8
10
12
HN
S
O
O
N
Me
Me
OMe

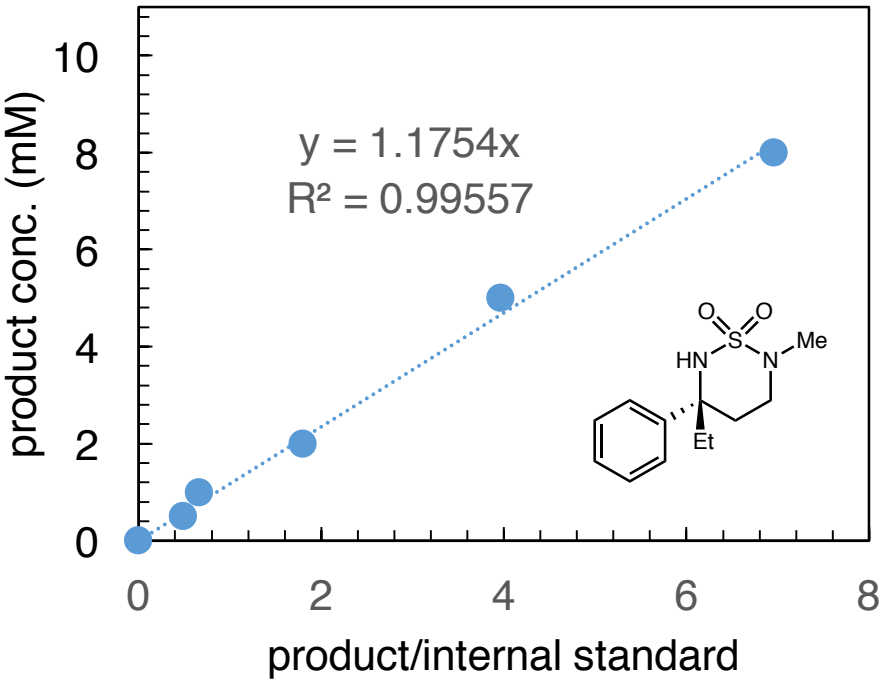

y = 1.0092x
R² = 0.98998
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Me

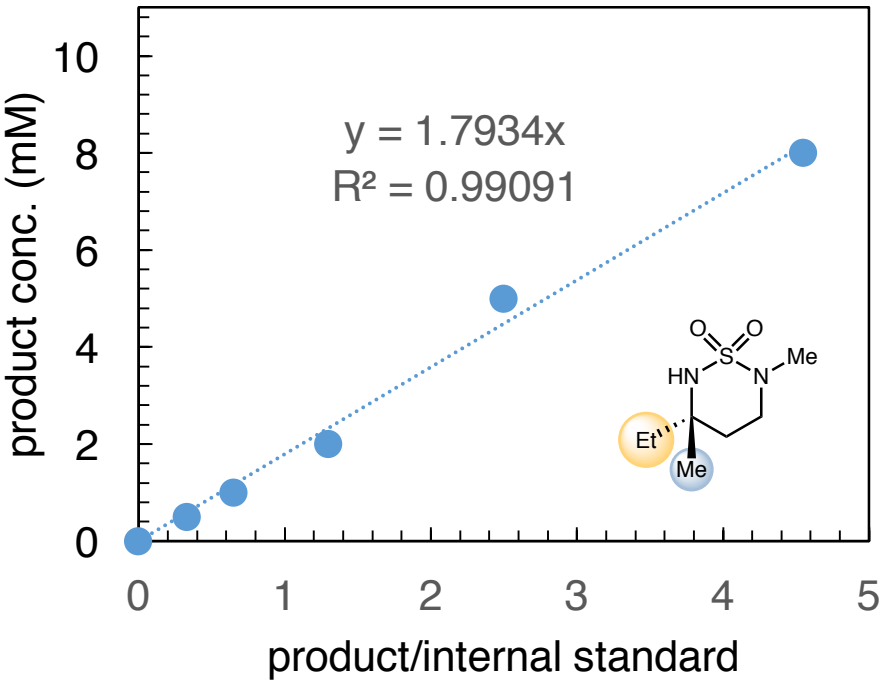

y = 1.0134x
R² = 0.9857
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Me
MeO

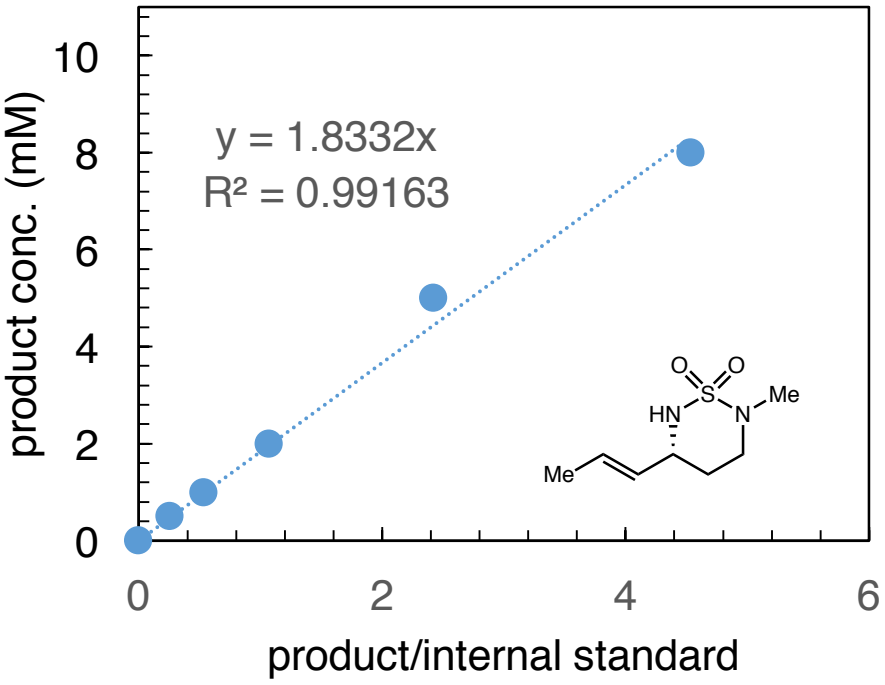

y = 0.9736x
R² = 0.99
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Me
F


y = 1.0876x
R² = 0.99381
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
OMe HN
N
Me
Me


y = 1.39x
R² = 0.98782
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
S
Me

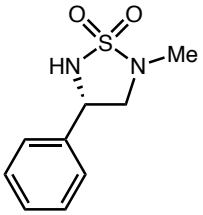

y = 1.1754x
R² = 0.99557
product conc. (mM)
product/internal standard
0
2
4
6
8
10
O
O
S
HN
N
Me
Et


y = 1.7934x
R² = 0.99091
product conc. (mM)
product/internal standard
0
2
4
6
8
10
0
1
2
3
4
5
O
O
S
HN
N
Me
Et
Me

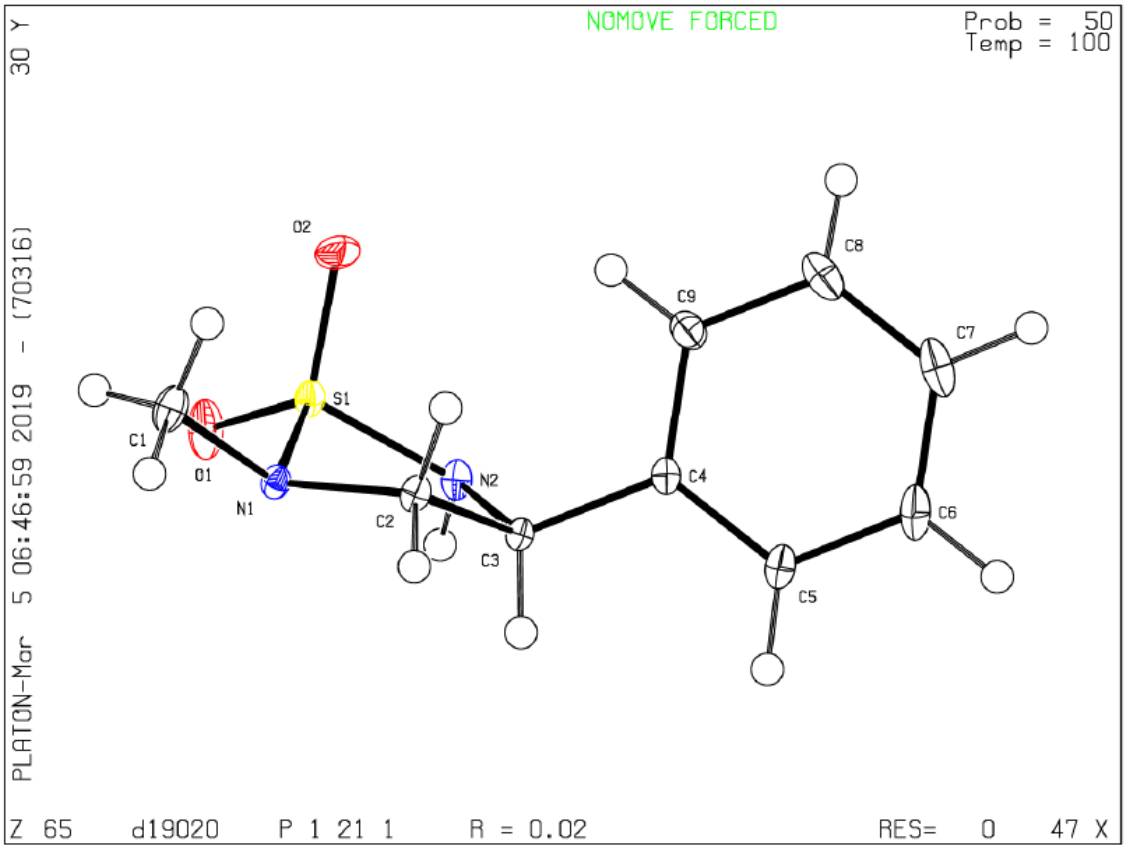

y = 1.8332x
R² = 0.99163
product conc. (mM)
product/internal standard
0
2
4
6
8
10
0
2
4
6
O
O
S
HN
N
Me
Me

X. X-ray crystal structure for the determination of absolute stereochemistry

(*S*)-2-Methyl-4-phenyl-1,2,5-thiadiazolidine 1,1-dioxide (2a) (CCDC 1905551)



Datablock d19020 - ellipsoid plot



checkCIF/PLATON report

Structure factors have been supplied for datablock(s) d19020

THIS REPORT IS FOR GUIDANCE ONLY. IF USED AS PART OF A REVIEW PROCEDURE FOR PUBLICATION, IT SHOULD NOT REPLACE THE EXPERTISE OF AN EXPERIENCED CRYSTALLOGRAPHIC REFEREE.

No syntax errors found. CIF dictionary Interpreting this report

Datablock: d19020

```
Bond precision:  C-C = 0.0009 A          Wavelength=0.71073

Cell:            a=6.0557(15)    b=7.1317(19)          c=11.530(3)
                 alpha=90        beta=101.285(10)      gamma=90
Temperature:     100 K

                 Calculated                Reported
Volume           488.3(2)                  488.3(2)
Space group      P 21                      P 1 21 1
Hall group       P 2yb                     P 2yb
Moiety formula   C9 H12 N2 O2 S            C9 H12 N2 O2 S
Sum formula      C9 H12 N2 O2 S            C9 H12 N2 O2 S
Mr               212.27                    212.27
Dx,g cm-3        1.444                     1.444
Z                2                         2
Mu (mm-1)        0.306                     0.306
F000             224.0                     224.0
F000'            224.34
h,k,lmax         11,14,22                  11,14,22
Nref             7949[ 4183]               7850
Tmin,Tmax        0.879,0.932               0.938,1.000
Tmin'            0.850

Correction method= # Reported T Limits: Tmin=0.938 Tmax=1.000
AbsCorr = MULTI-SCAN

Data completeness= 1.88/0.99       Theta(max)= 44.761

R(reflections)= 0.0192( 7667)      wR2(reflections)= 0.0555( 7850)

S = 1.097                  Npar= 163
```

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

Alert level G

```
PLAT019_ALERT_1_G _diffrn_measured_fraction_theta_full/*_max < 1.0      0.984 Report
PLAT033_ALERT_4_G Flack x Value Deviates > 3.0 * sigma from Zero .      0.018 Note
PLAT791_ALERT_4_G Model has Chirality at C3          (Chiral SPGR)          S Verify
PLAT933_ALERT_2_G Number of OMIT Records in Embedded .res File ...          1 Note
```

```
   0 ALERT level A = Most likely a serious problem - resolve or explain
   0 ALERT level B = A potentially serious problem, consider carefully
   0 ALERT level C = Check. Ensure it is not caused by an omission or oversight
   4 ALERT level G = General information/check it is not something unexpected

   1 ALERT type 1 CIF construction/syntax error, inconsistent or missing data
   1 ALERT type 2 Indicator that the structure model may be wrong or deficient
   0 ALERT type 3 Indicator that the structure quality may be low
   2 ALERT type 4 Improvement, methodology, query or suggestion
   0 ALERT type 5 Informative message, check
```

It is advisable to attempt to resolve as many as possible of the alerts in all categories. Often the minor alerts point to easily fixed oversights, errors and omissions in your CIF or refinement strategy, so attention to these fine details can be worthwhile. In order to resolve some of the more serious problems it may be necessary to carry out additional measurements or structure refinements. However, the purpose of your study may justify the reported deviations and the more serious of these should normally be commented upon in the discussion or experimental section of a paper or in the "special_details" fields of the CIF. checkCIF was carefully designed to identify outliers and unusual parameters, but every test has its limitations and alerts that are not important in a particular case may appear. Conversely, the absence of alerts does not guarantee there are no aspects of the results needing attention. It is up to the individual to critically assess their own results and, if necessary, seek expert advice.

Publication of your CIF in IUCr journals

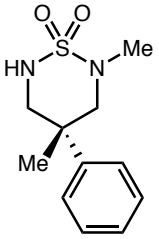
A basic structural check has been run on your CIF. These basic checks will be run on all CIFs submitted for publication in IUCr journals (*Acta Crystallographica*, *Journal of Applied Crystallography*, *Journal of Synchrotron Radiation*); however, if you intend to submit to *Acta Crystallographica Section C* or *E* or *IUCrData*, you should make sure that full publication checks are run on the final version of your CIF prior to submission.

Publication of your CIF in other journals

Please refer to the *Notes for Authors* of the relevant journal for any special instructions relating to CIF submission.

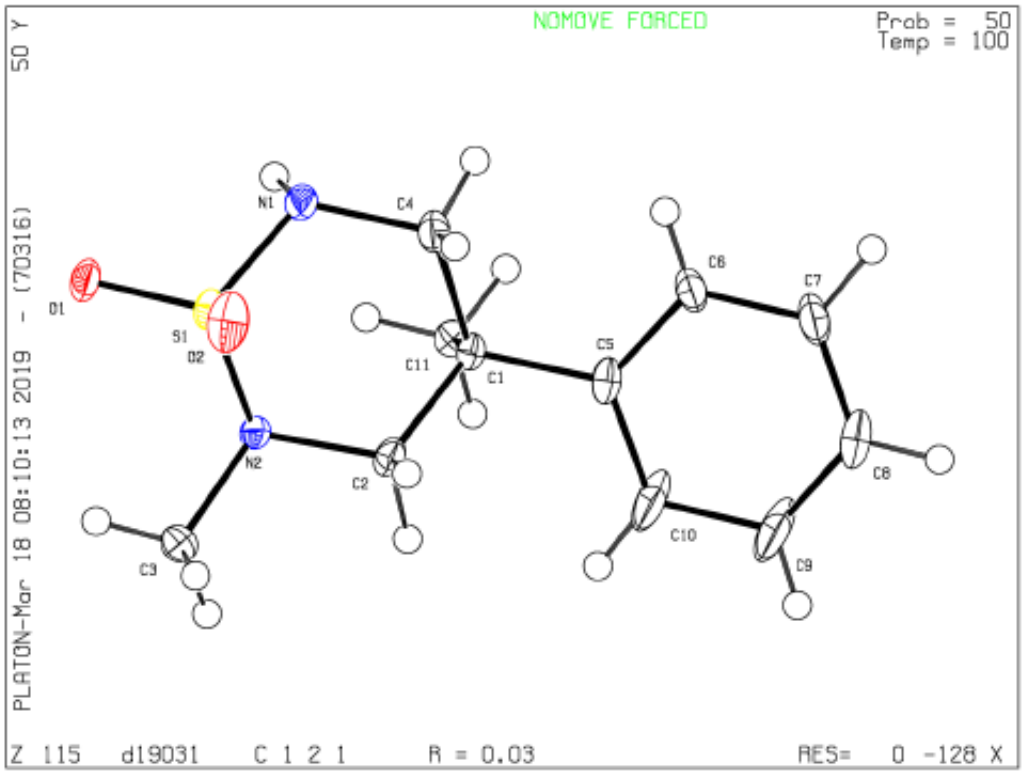
PLATON version of 18/02/2019; check.def file version of 18/02/2019

(*R*)-2,4-Dimethyl-4-phenyl-1,2,6-thiadiazinane 1,1-dioxide (4a) (CCDC 1905553)



PLATON version of 18/02/2019; check.def file version of 18/02/2019

Datablock d19031 - ellipsoid plot



checkCIF/PLATON report

Structure factors have been supplied for datablock(s) d19031

THIS REPORT IS FOR GUIDANCE ONLY. IF USED AS PART OF A REVIEW PROCEDURE FOR PUBLICATION, IT SHOULD NOT REPLACE THE EXPERTISE OF AN EXPERIENCED CRYSTALLOGRAPHIC REFEREE.

No syntax errors found. CIF dictionary Interpreting this report

Datablock: d19031

```
Bond precision:  C-C = 0.0019 A          Wavelength=0.71073

Cell:            a=17.277(8)    b=6.4054(14)          c=11.991(3)
                 alpha=90       beta=118.590(14)      gamma=90
Temperature:     100 K

                Calculated                Reported
Volume          1165.2(7)                 1165.2(7)
Space group     C 2                       C 1 2 1
Hall group      C 2y                      C 2y
Moiety formula  C11 H16 N2 O2 S           C11 H16 N2 O2 S
Sum formula     C11 H16 N2 O2 S           C11 H16 N2 O2 S
Mr              240.32                    240.32
Dx,g cm-3       1.370                     1.370
Z               4                         4
Mu (mm-1)       0.265                     0.265
F000            512.0                     512.0
F000'           512.69
h,k,lmax        29,11,20                  29,10,20
Nref            6192[ 3306]               5984
Tmin,Tmax       0.921,0.956               0.954,1.000
Tmin'           0.876

Correction method= # Reported T Limits: Tmin=0.954 Tmax=1.000
AbsCorr = MULTI-SCAN

Data completeness= 1.81/0.97      Theta(max)= 37.654

R(reflections)= 0.0270( 5846)     wR2(reflections)= 0.0713( 5984)

S = 1.071                 Npar= 194
```

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

```
Alert level C
PLAT213_ALERT_2_C Atom C9              has ADP max/min Ratio .....        3.4 prolat
PLAT213_ALERT_2_C Atom C10             has ADP max/min Ratio .....        3.4 prolat
PLAT220_ALERT_2_C Non-Solvent  Resd 1  C   Ueq(max)/Ueq(min) Range       3.6 Ratio
PLAT242_ALERT_2_C Low    'MainMol' Ueq as Compared to Neighbors of        C8 Check
PLAT250_ALERT_2_C Large U3/U1 Ratio for Average U(i,j) Tensor ....        2.6 Note
PLAT911_ALERT_3_C Missing FCF Refl Between Thmin & STh/L=    0.600         3 Report

Alert level G
PLAT128_ALERT_4_G Alternate Setting for Input Space Group  C2              I2 Note
PLAT791_ALERT_4_G Model has Chirality at C1          (Chiral SPGR)         R Verify
PLAT883_ALERT_1_G No Info for _atom_sites_solution_primary .......     Please Do !
PLAT912_ALERT_4_G Missing # of FCF Reflections Above STh/L=  0.600        70 Note
PLAT913_ALERT_3_G Missing # of Very Strong Reflections in FCF ....         1 Note
PLAT978_ALERT_2_G Number C-C Bonds with Positive Residual Density.         9 Info

   0 ALERT level A = Most likely a serious problem - resolve or explain
   0 ALERT level B = A potentially serious problem, consider carefully
   6 ALERT level C = Check. Ensure it is not caused by an omission or oversight
   6 ALERT level G = General information/check it is not something unexpected

   1 ALERT type 1 CIF construction/syntax error, inconsistent or missing data
   6 ALERT type 2 Indicator that the structure model may be wrong or deficient
   2 ALERT type 3 Indicator that the structure quality may be low
   3 ALERT type 4 Improvement, methodology, query or suggestion
   0 ALERT type 5 Informative message, check
```

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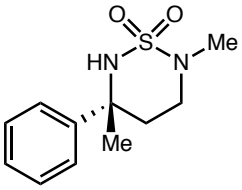
A basic structural check has been run on your CIF. These basic checks will be run on all CIFs submitted for publication in IUCr journals (*Acta Crystallographica*, *Journal of Applied Crystallography*, *Journal of Synchrotron Radiation*); however, if you intend to submit to *Acta Crystallographica Section C* or *E* or *IUCrData*, you should make sure that full publication checks are run on the final version of your CIF prior to submission.

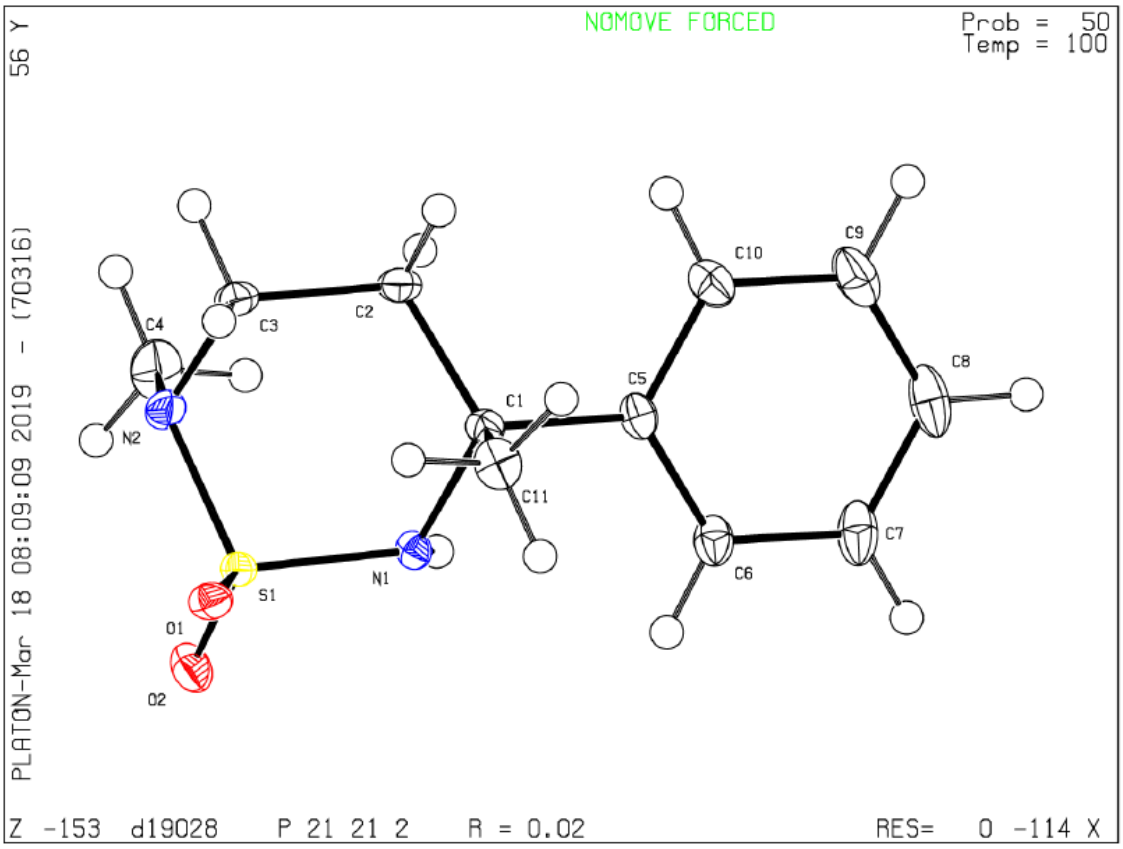
Publication of your CIF in other journals

Please refer to the *Notes for Authors* of the relevant journal for any special instructions relating to CIF submission.

(*R*)-2,5-Dimethyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5a) (CCDC 1905552)



Datablock d19028 - ellipsoid plot



checkCIF/PLATON report

Structure factors have been supplied for datablock(s) d19028

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No syntax errors found. CIF dictionary Interpreting this report

Datablock: d19028

```
Bond precision:  C-C = 0.0019 A          Wavelength=0.71073

Cell:            a=9.9738(19)     b=18.878(6)     c=6.1429(11)
                 alpha=90         beta=90         gamma=90
Temperature:     100 K

                 Calculated                Reported
Volume           1156.6(5)                 1156.6(5)
Space group      P 21 21 2                 P 21 21 2
Hall group       P 2 2ab                   P 2 2ab
Moiety formula   C11 H16 N2 O2 S           C11 H16 N2 O2 S
Sum formula      C11 H16 N2 O2 S           C11 H16 N2 O2 S
Mr               240.32                    240.32
Dx,g cm-3        1.380                     1.380
Z                4                         4
Mu (mm-1)        0.267                     0.267
F000             512.0                     512.0
F000'            512.69
h,k,lmax         15,29,9                   15,29,9
Nref             4454[ 2558]               4273
Tmin,Tmax        0.947,0.984               0.936,1.000
Tmin'            0.880

Correction method= # Reported T Limits: Tmin=0.936 Tmax=1.000
AbsCorr = MULTI-SCAN

Data completeness= 1.67/0.96      Theta(max)= 33.236

R(reflections)= 0.0238( 4163)     wR2(reflections)= 0.0592( 4273)

S = 1.112                 Npar= 194
```

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

Alert level C

```
PLAT911_ALERT_3_C Missing FCF Refl Between Thmin & STh/L=    0.600         11 Report
PLAT913_ALERT_3_C Missing # of Very Strong Reflections in FCF ....          10 Note
PLAT934_ALERT_3_C Number of (Iobs-Icalc)/SigmaW > 10 Outliers ....          1 Check
```

Alert level G

```
PLAT791_ALERT_4_G Model has Chirality at C1          (Chiral SPGR)         R Verify
PLAT883_ALERT_1_G No Info for _atom_sites_solution_primary .......     Please Do !
PLAT910_ALERT_3_G Missing # of FCF Reflection(s) Below Theta(Min).          1 Note
PLAT912_ALERT_4_G Missing # of FCF Reflections Above STh/L=  0.600         69 Note
PLAT978_ALERT_2_G Number C-C Bonds with Positive Residual Density.         10 Info
```

```
   0 ALERT level A = Most likely a serious problem - resolve or explain
   0 ALERT level B = A potentially serious problem, consider carefully
   3 ALERT level C = Check. Ensure it is not caused by an omission or oversight
   5 ALERT level G = General information/check it is not something unexpected

   1 ALERT type 1 CIF construction/syntax error, inconsistent or missing data
   1 ALERT type 2 Indicator that the structure model may be wrong or deficient
   4 ALERT type 3 Indicator that the structure quality may be low
   2 ALERT type 4 Improvement, methodology, query or suggestion
   0 ALERT type 5 Informative message, check
```

It is advisable to attempt to resolve as many as possible of the alerts in all categories. Often the minor alerts point to easily fixed oversights, errors and omissions in your CIF or refinement strategy, so attention to these fine details can be worthwhile. In order to resolve some of the more serious problems it may be necessary to carry out additional measurements or structure refinements. However, the purpose of your study may justify the reported deviations and the more serious of these should normally be commented upon in the discussion or experimental section of a paper or in the "special_details" fields of the CIF. checkCIF was carefully designed to identify outliers and unusual parameters, but every test has its limitations and alerts that are not important in a particular case may appear. Conversely, the absence of alerts does not guarantee there are no aspects of the results needing attention. It is up to the individual to critically assess their own results and, if necessary, seek expert advice.

Publication of your CIF in IUCr journals

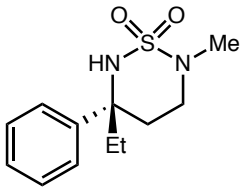
A basic structural check has been run on your CIF. These basic checks will be run on all CIFs submitted for publication in IUCr journals (*Acta Crystallographica*, *Journal of Applied Crystallography*, *Journal of Synchrotron Radiation*); however, if you intend to submit to *Acta Crystallographica Section C* or *E* or *IUCrData*, you should make sure that full publication checks are run on the final version of your CIF prior to submission.

Publication of your CIF in other journals

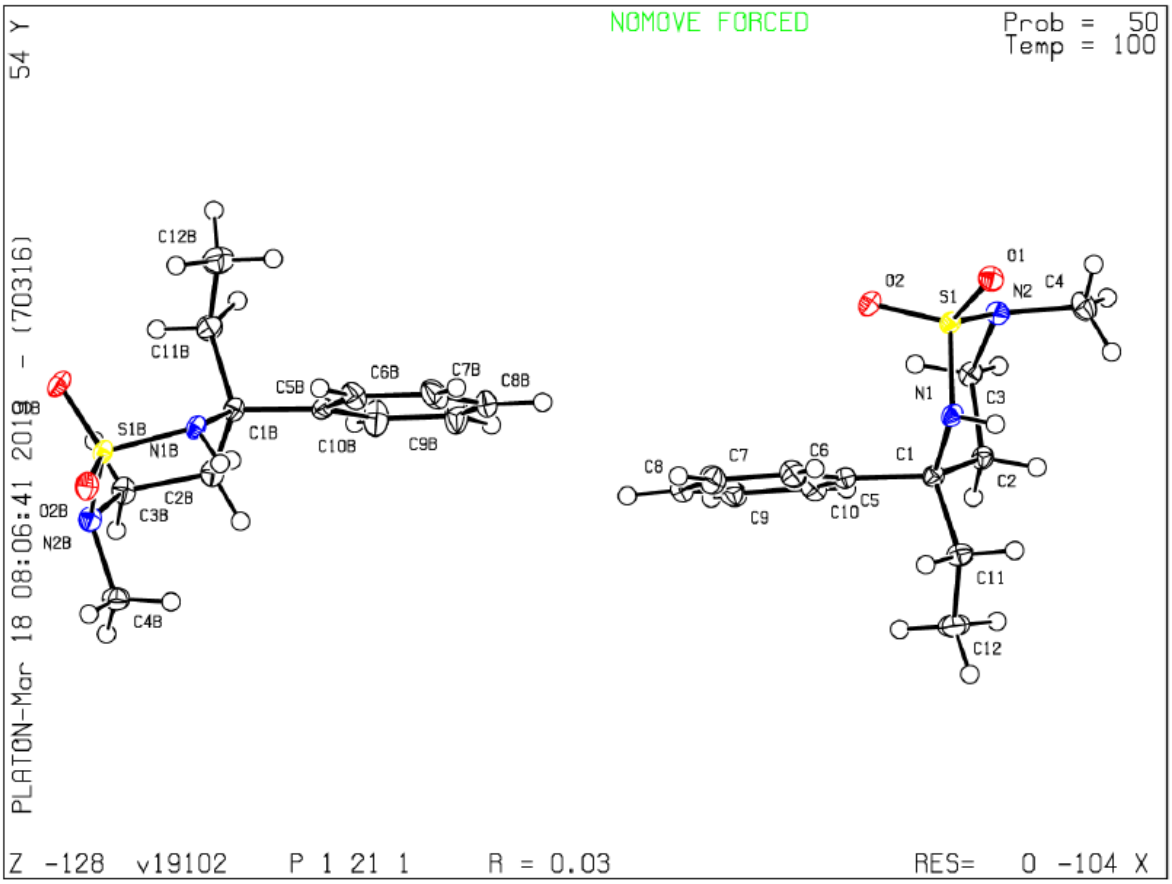
Please refer to the *Notes for Authors* of the relevant journal for any special instructions relating to CIF submission.

PLATON version of 18/02/2019; check.def file version of 18/02/2019

(*R*)-5-Ethyl-2-methyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5f) (CCDC 1905554)



Datablock v19102 - ellipsoid plot



checkCIF/PLATON report

Structure factors have been supplied for datablock(s) v19102

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No syntax errors found. CIF dictionary Interpreting this report

Datablock: v19102

```
Bond precision:  C-C = 0.0036 A          Wavelength=1.54178

Cell:            a=6.2335(4)    b=9.6871(6)        c=21.0972(19)
                 alpha=90       beta=97.451(5)     gamma=90
Temperature:     100 K

                 Calculated                Reported
Volume           1263.19(16)               1263.19(16)
Space group      P 21                      P 1 21 1
Hall group       P 2yb                     P 2yb
Moiety formula   C12 H18 N2 O2 S           C12 H18 N2 O2 S
Sum formula      C12 H18 N2 O2 S           C12 H18 N2 O2 S
Mr               254.34                    254.34
Dx,g cm-3        1.337                     1.337
Z                4                         4
Mu (mm-1)        2.221                     2.221
F000             544.0                     544.0
F000'            546.76
h,k,lmax         7,12,26                   7,12,26
Nref             5501[ 2915]               5281
Tmin,Tmax        0.576,0.856               0.782,1.000
Tmin'            0.523

Correction method= # Reported T Limits: Tmin=0.782 Tmax=1.000
AbsCorr = MULTI-SCAN

Data completeness= 1.81/0.96      Theta(max)= 80.253

R(reflections)= 0.0265( 5215)     wR2(reflections)= 0.0671( 5281)

S = 1.066                  Npar= 417
```

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

Alert level B

```
PLAT351_ALERT_3_B Long   C-H (X0.96,N1.08A)  C11B     - H11D     .       1.17 Ang.
```

Alert level C

```
PLAT089_ALERT_3_C Poor Data / Parameter Ratio (Zmax < 18) ........      6.94 Note
PLAT390_ALERT_3_C Deviating Methyl C4        X-C-H Bond Angle ....       116 Degree
PLAT987_ALERT_1_C The Flack x is >> 0 -  Do a BASF/TWIN Refinement    Please Check
```

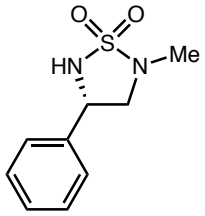
Alert level G

```
PLAT033_ALERT_4_G Flack x Value Deviates > 3.0 * sigma from Zero .     0.099 Note
PLAT791_ALERT_4_G Model has Chirality at C1          (Chiral SPGR)         R Verify
PLAT791_ALERT_4_G Model has Chirality at C1B         (Chiral SPGR)         R Verify
PLAT883_ALERT_1_G No Info for _atom_sites_solution_primary .......    Please Do !
PLAT910_ALERT_3_G Missing # of FCF Reflection(s) Below Theta(Min).         2 Note
PLAT912_ALERT_4_G Missing # of FCF Reflections Above STh/L=  0.600        21 Note
PLAT913_ALERT_3_G Missing # of Very Strong Reflections in FCF ....         1 Note
PLAT961_ALERT_5_G Dataset Contains no Negative Intensities .......    Please Check
PLAT978_ALERT_2_G Number C-C Bonds with Positive Residual Density.        10 Info
```

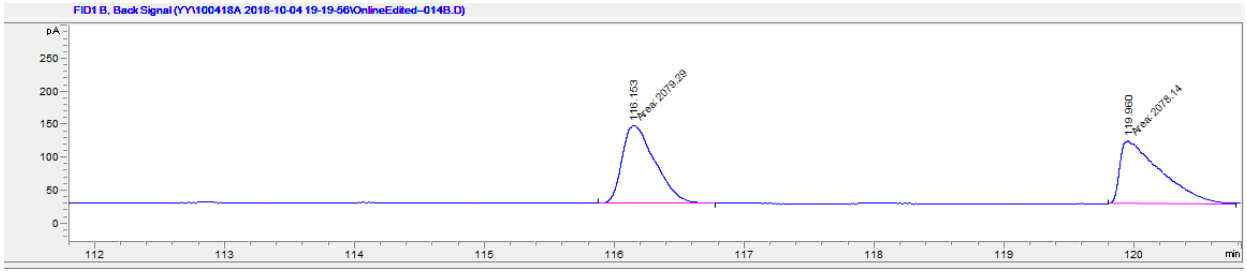
```
   0 ALERT level A = Most likely a serious problem - resolve or explain
   1 ALERT level B = A potentially serious problem, consider carefully
   3 ALERT level C = Check. Ensure it is not caused by an omission or oversight
   9 ALERT level G = General information/check it is not something unexpected

   2 ALERT type 1 CIF construction/syntax error, inconsistent or missing data
   1 ALERT type 2 Indicator that the structure model may be wrong or deficient
   5 ALERT type 3 Indicator that the structure quality may be low
   4 ALERT type 4 Improvement, methodology, query or suggestion
   1 ALERT type 5 Informative message, check
```

XI. Chiral GC, HPLC and SFC traces

(*S*)-2-Methyl-4-phenyl-1,2,5-thiadiazolidine 1,1-dioxide (2a)

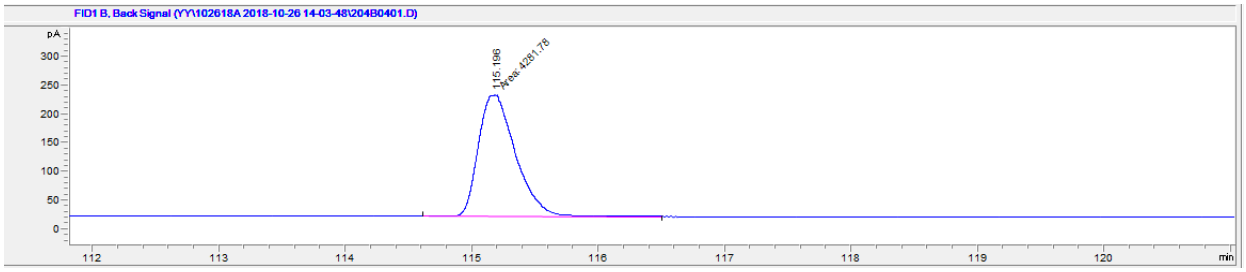


Racemic 2a:



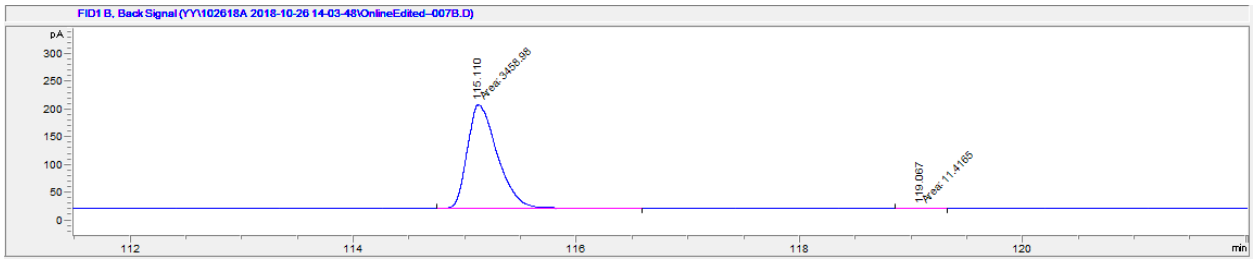
#	Time	Area	Height	Width	Area%	Symmetry
1	116.153	2079.3	118.5	0.2924	50.014	0.523
2	119.96	2078.1	95.1	0.3641	49.986	0.235

Enantioenriched 2a using P411$_{Diane1}$ I327P Y263W Q437P (P411$_{Diane2}$): 99.9% ee



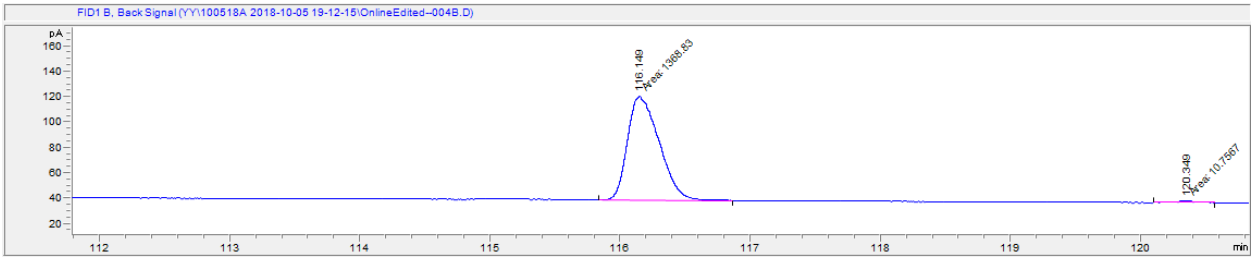
#	Time	Area	Height	Width	Area%	Symmetry
1	115.196	4281.8	211	0.3383	100.000	0.913

Enantioenriched 2a using $P411_{Diane1}$ I327P Y263W: 99.4% ee



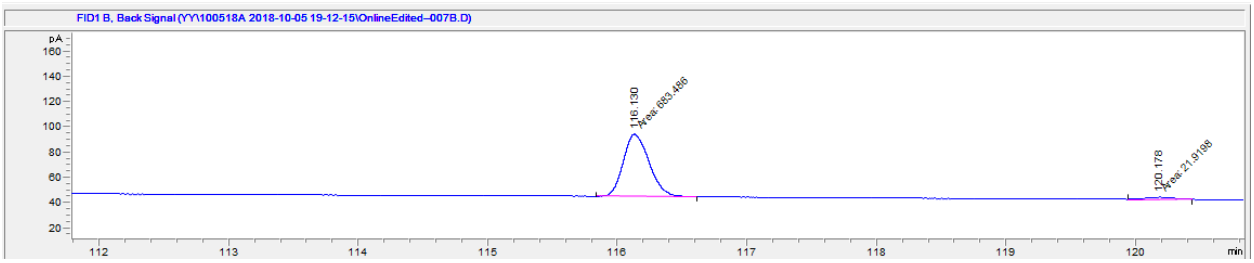
#	Time	Area	Height	Width	Area%	Symmetry
1	115.11	3459	186.1	0.3097	99.671	0.52
2	119.067	11.4	8.6E-1	0.2221	0.329	0.965

Enantioenriched 2a using $P411_{Diane1}$ I327P: 98.5% ee



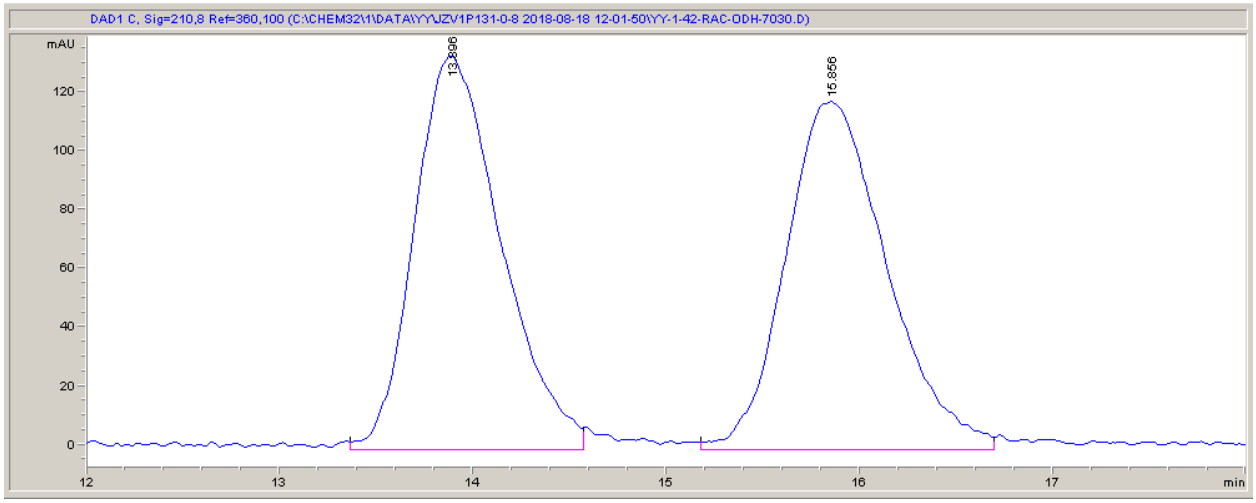
#	Time	Area	Height	Width	Area%	Symmetry
1	116.149	1368.8	81.5	0.2799	99.220	0.626
2	120.349	10.8	9.6E-1	0.1872	0.780	1.337

Enantioenriched 2a using $P411_{Diane1}$: 94% ee



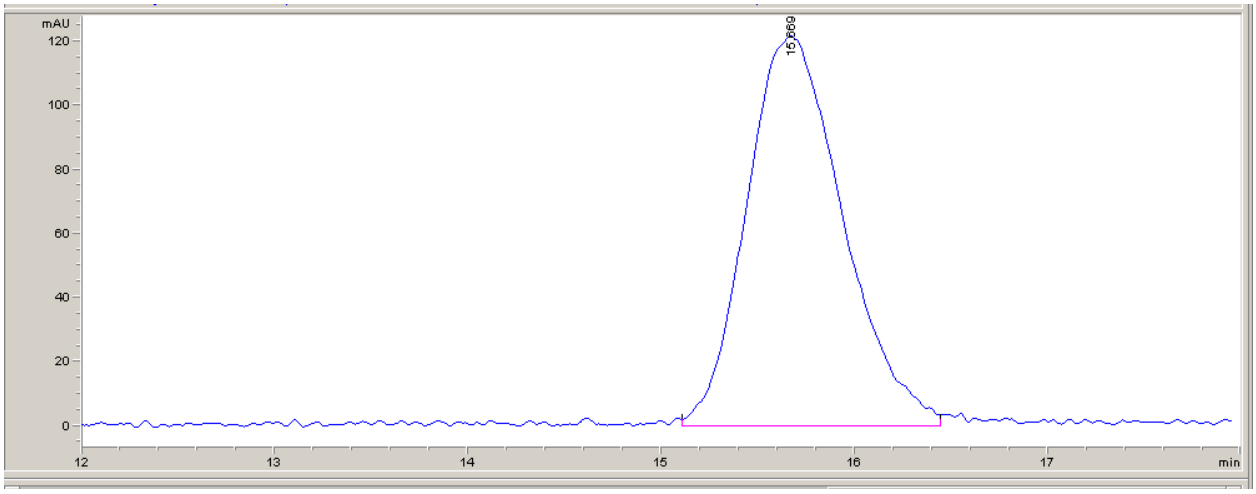
#	Time	Area	Height	Width	Area%	Symmetry
1	116.13	683.5	49.4	0.2307	96.893	0.761
2	120.178	21.9	1.7	0.216	3.107	1.195

Racemic 2a (HPLC):



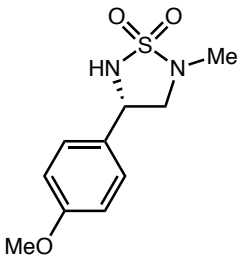
#	Time	Area	Height	Width	Area%	Symmetry
1	13.896	4196.8	134.2	0.3888	49.195	0.74
2	15.856	4334.2	118.6	0.4303	50.805	0.788

Enantioenriched 2a using $P411_{Diane1}$ I327P Y263W Q437P ($P411_{Diane2}$) (HPLC): >99% ee

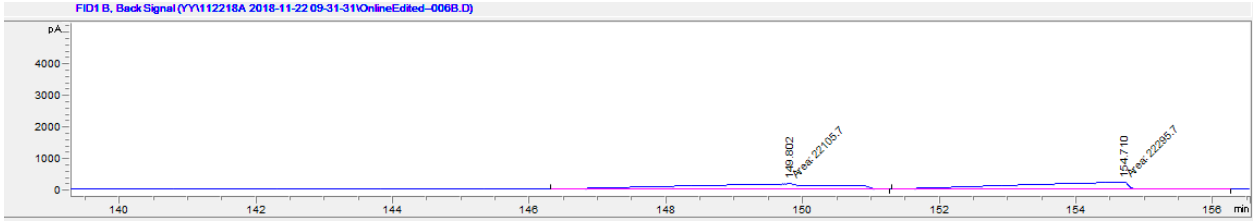


#	Time	Area	Height	Width	Area%	Symmetry
1	15.669	4242.7	122.1	0.4153	100.000	0.797

(*S*)-4-(4-Methoxyphenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2b)

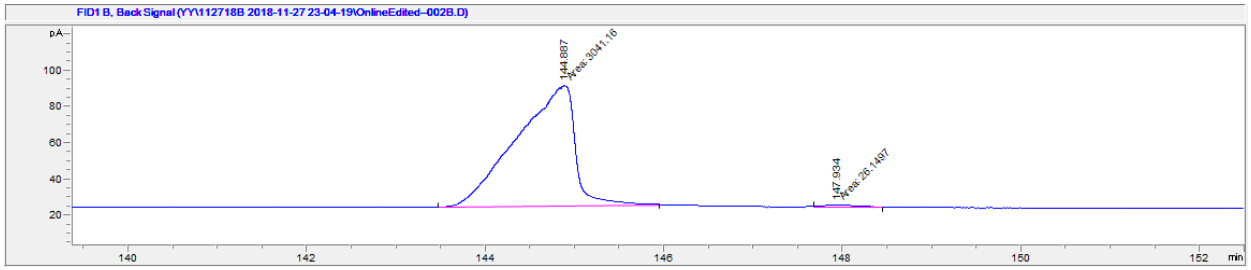


Racemic 2b:



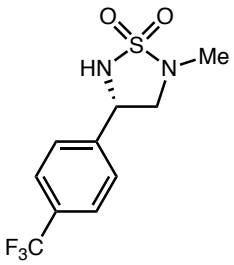
#	Time	Area	Height	Width	Area%	Symmetry
1	149.802	22105.7	153.4	2.4021	49.786	2.31
2	154.71	22295.7	205.8	1.8053	50.214	19.734

Enantioenriched 2b: 98% ee

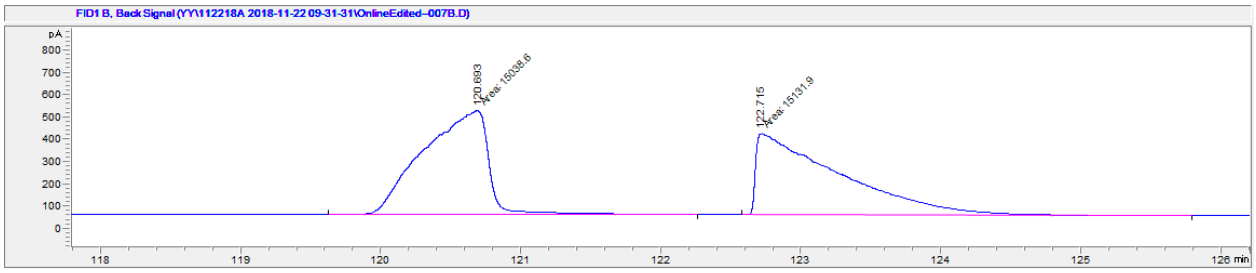


#	Time	Area	Height	Width	Area%	Symmetry
1	144.887	3041.2	66.5	0.762	99.147	3.578
2	147.934	26.1	9.7E-1	0.448	0.853	0.708

(*S*)-2-Methyl-4-(4-(trifluoromethyl)phenyl)-1,2,5-thiadiazolidine 1,1-dioxide (2c)

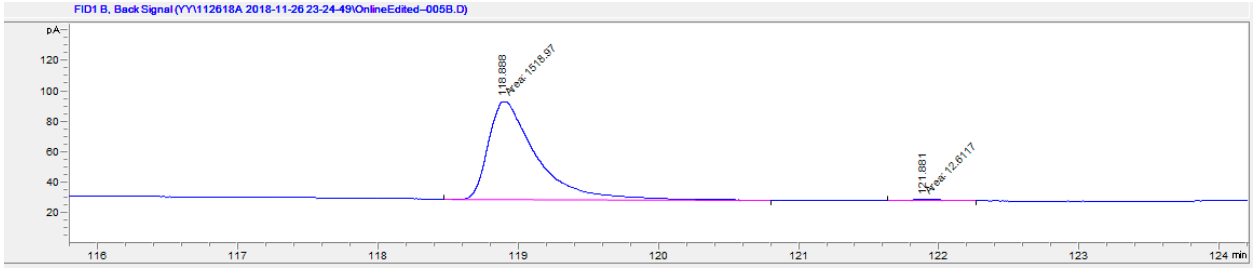


Racemic 2c:



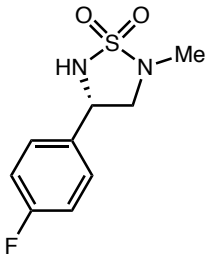
#	Time	Area	Height	Width	Area%	Symmetry
1	120.693	15038.6	467.6	0.536	49.845	4.398
2	122.715	15131.9	364.9	0.6911	50.155	6.66E-2

Enantioenriched 2c: 98% ee

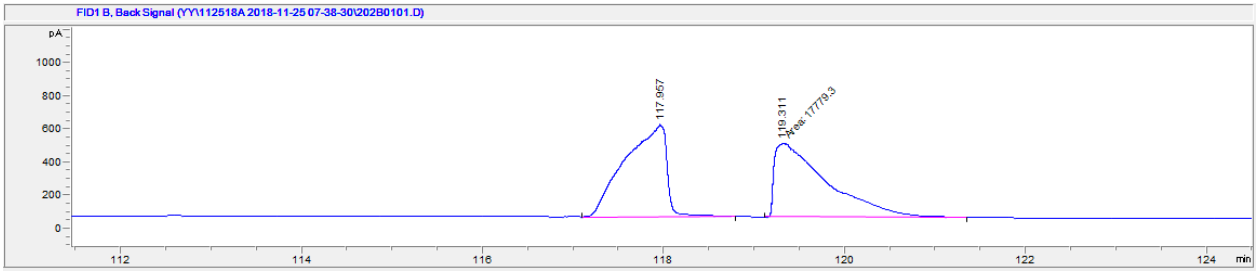


#	Time	Area	Height	Width	Area%	Symmetry
1	118.888	1519	64.4	0.3933	99.177	0.435
2	121.881	12.6	9.3E-1	0.2266	0.823	0.573

(*S*)-4-(4-Fluorophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2d)

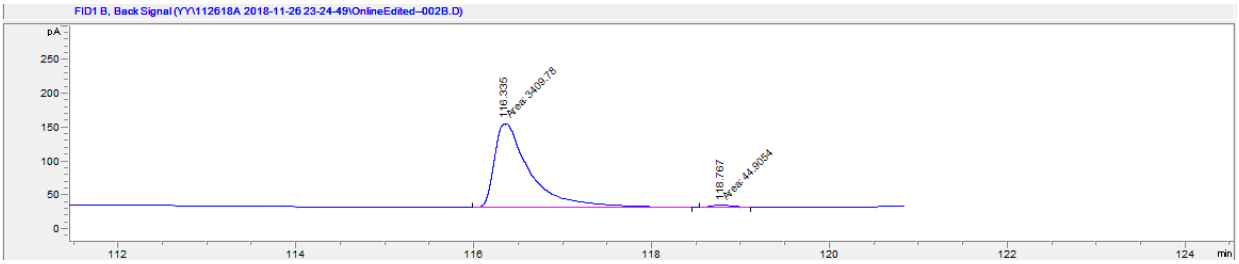


Racemic 2d:



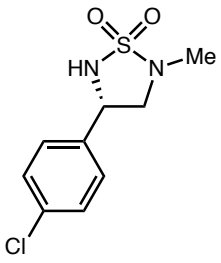
#	Time	Area	Height	Width	Area%	Symmetry
1	117.957	17745.4	554.8	0.3796	49.952	4.557
2	119.311	17779.3	443	0.6688	50.048	0.178

Enantioenriched 2d: 98% ee

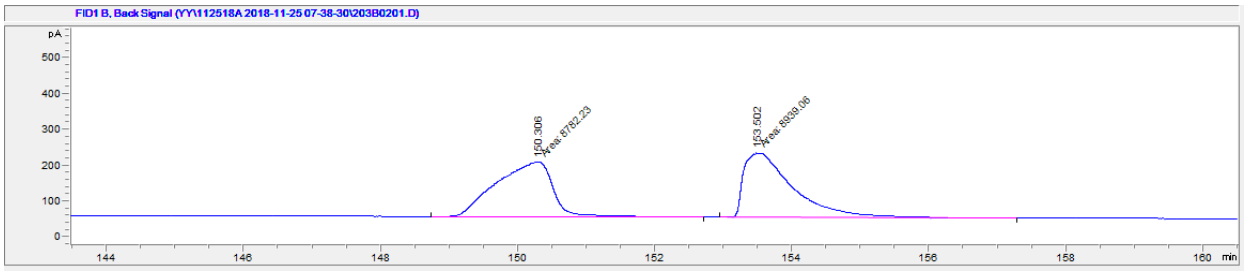


#	Time	Area	Height	Width	Area%	Symmetry
1	116.335	3409.8	124	0.4584	98.700	0.349
2	118.767	44.9	3.1	0.2384	1.300	0.761

(*S*)-4-(4-Chlorophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2e)

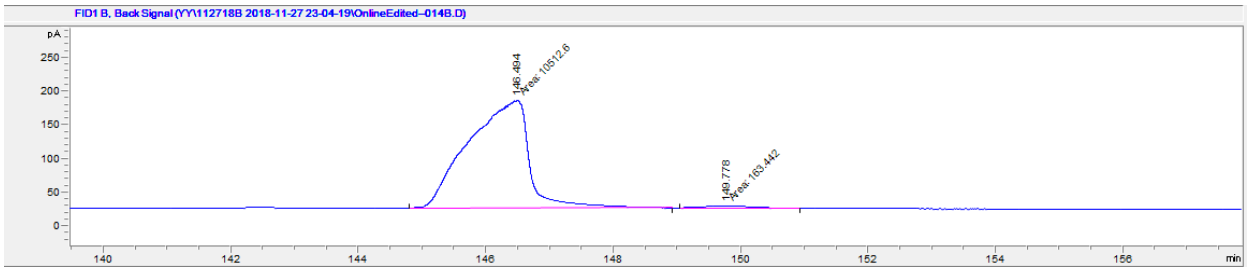


Racemic 2e:



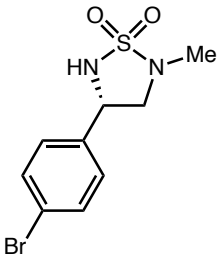
#	Time	Area	Height	Width	Area%	Symmetry
1	150.306	8782.2	153.3	0.9546	49.557	2.486
2	153.502	8939.1	180	0.8276	50.443	0.354

Enantioenriched 2d: 97% ee

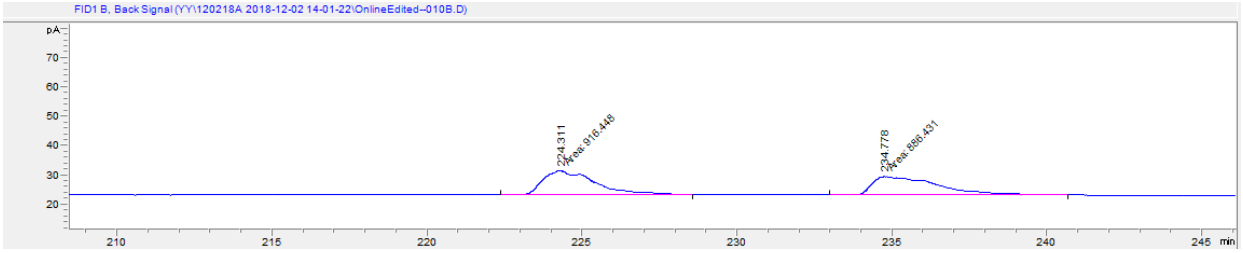


#	Time	Area	Height	Width	Area%	Symmetry
1	146.494	10512.6	160	1.0947	98.469	3.292
2	149.778	163.4	3.2	0.8601	1.531	0.648

(*S*)-4-(4-Bromophenyl)-2-methyl-1,2,5-thiadiazolidine 1,1-dioxide (2f)

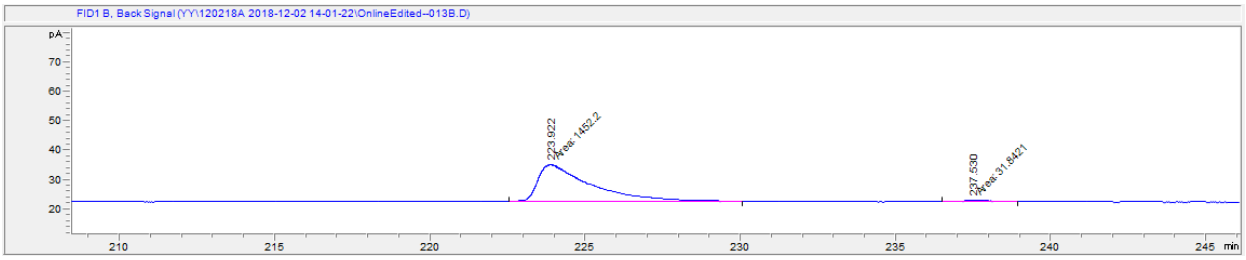


Racemic 2f:



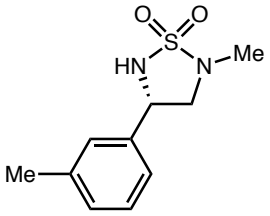
#	Time	Area	Height	Width	Area%	Symmetry
1	224.311	916.4	8.2	1.8659	50.832	0.497
2	234.778	886.4	6.2	2.3686	49.168	0.231

Eantioenriched 2f: 96% ee

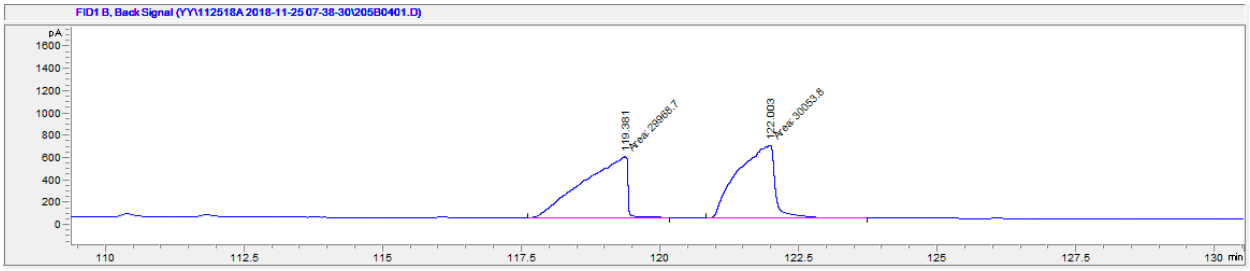


#	Time	Area	Height	Width	Area%	Symmetry
1	223.922	1452.2	12.5	1.9432	97.854	0.314
2	237.53	31.8	4E-1	1.3169	2.146	0.832

(*S*)-2-Methyl-4-(*m*-tolyl)-1,2,5-thiadiazolidine 1,1-dioxide (2g)

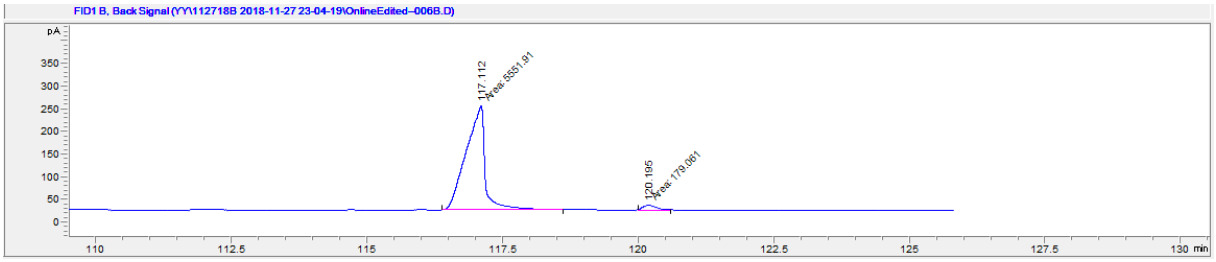


Racemic 2g:



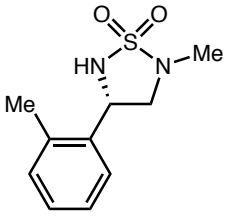
#	Time	Area	Height	Width	Area%	Symmetry
1	119.381	29968.7	542.1	0.9214	49.929	12.988
2	122.003	30053.8	652.1	0.7681	50.071	5.632

Enantioenriched 2g: 94% ee

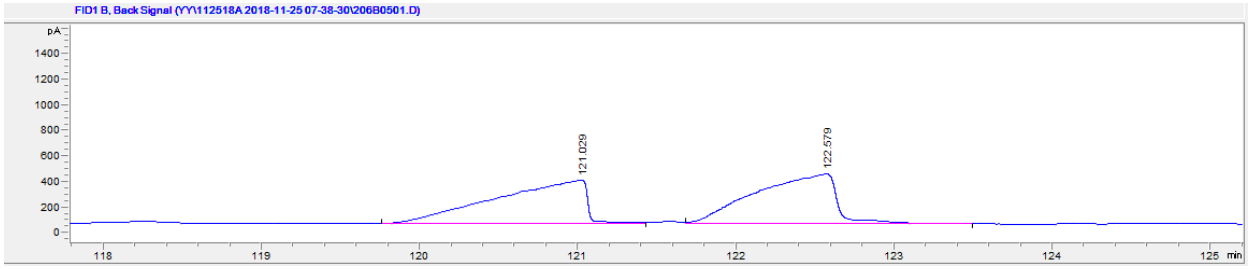


#	Time	Area	Height	Width	Area%	Symmetry
1	117.112	5551.9	229.2	0.4037	96.876	2.987
2	120.195	179.1	10.9	0.2741	3.124	0.706

(*S*)-2-Methyl-4-(*o*-tolyl)-1,2,5-thiadiazolidine 1,1-dioxide (2h)

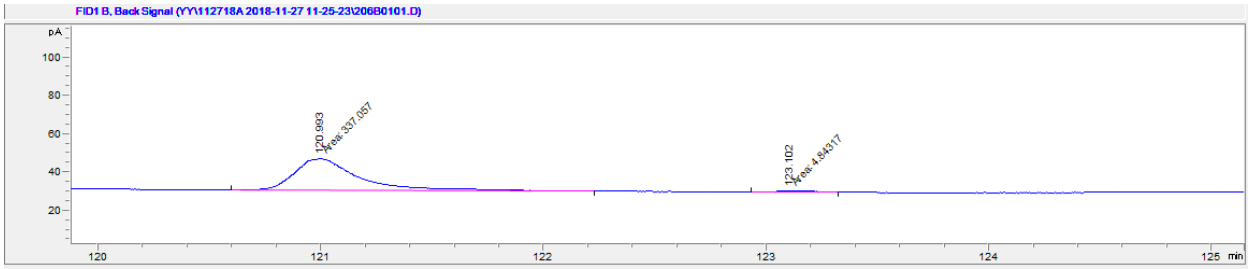


Racemic 2h:



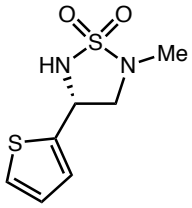
#	Time	Area	Height	Width	Area%	Symmetry
1	121.029	13806.5	341.6	0.4852	49.429	11.611
2	122.579	14125.6	392.3	0.4393	50.571	5.407

Enantioenriched 2h: 97% ee

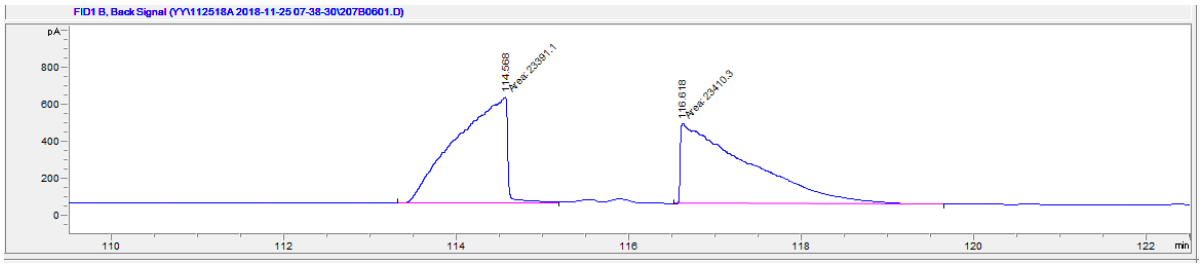


#	Time	Area	Height	Width	Area%	Symmetry
1	120.993	337.1	16.5	0.34	98.583	0.603
2	123.102	4.8	3.8E-1	0.2144	1.417	0.394

(*R*)-2-Methyl-4-(thiophen-2-yl)-1,2,5-thiadiazolidine 1,1-dioxide (2i)

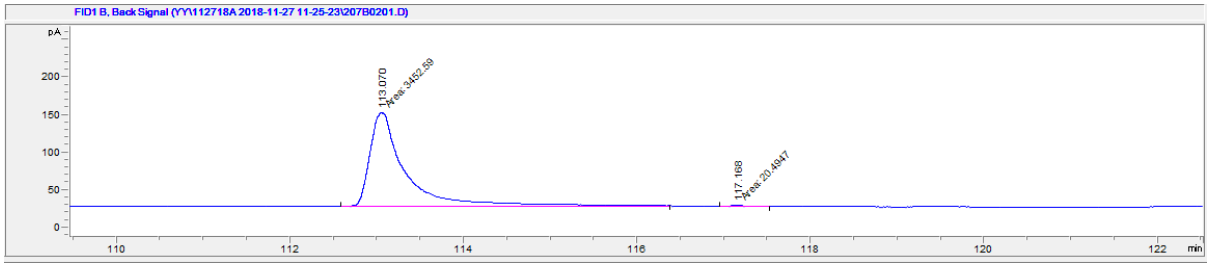


Racemic 2i:



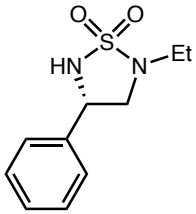
#	Time	Area	Height	Width	Area%	Symmetry
1	114.568	23391.1	571.6	0.6821	49.980	16.862
2	116.618	23410.3	429.7	0.908	50.020	3.18E-2

Enantioenriched 2i: 99% ee

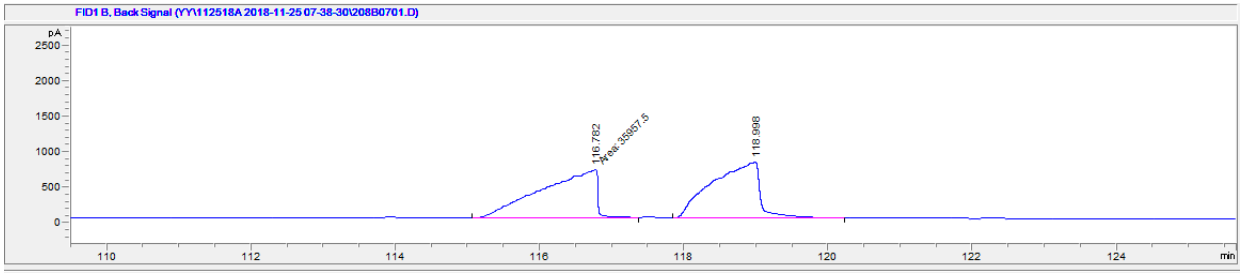


#	Time	Area	Height	Width	Area%	Symmetry
1	113.07	3452.6	124.4	0.4625	99.410	0.497
2	117.168	20.5	1.3	0.2694	0.590	0.958

(*S*)-2-Ethyl-4-phenyl-1,2,5-thiadiazolidine 1,1-dioxide (2j)

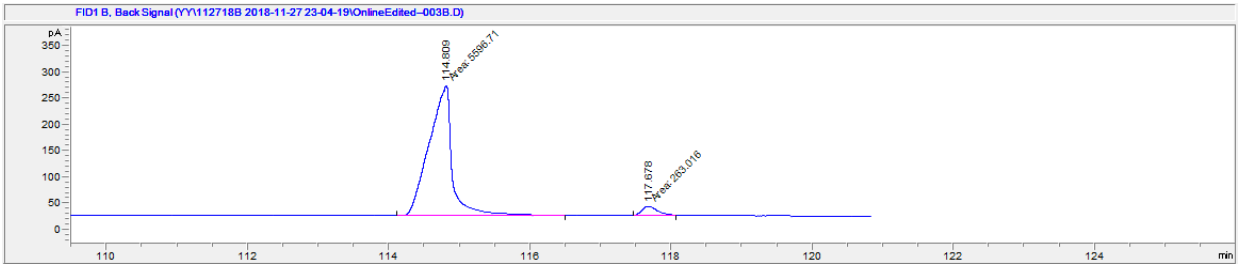


Racemic 2j:



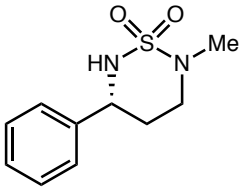
#	Time	Area	Height	Width	Area%	Symmetry
1	116.782	35957.5	668.6	0.8963	49.851	17.385
2	118.998	36172.6	780.7	0.5454	50.149	6.315

Enantioenriched 2j: 91% ee

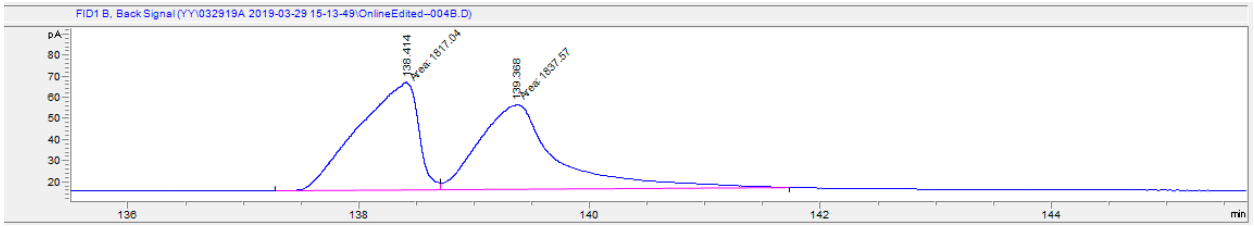


#	Time	Area	Height	Width	Area%	Symmetry
1	114.809	5596.7	246.2	0.3789	95.511	2.445
2	117.678	263	17.2	0.2551	4.489	0.747

(*R*)-2-Methyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (2k)

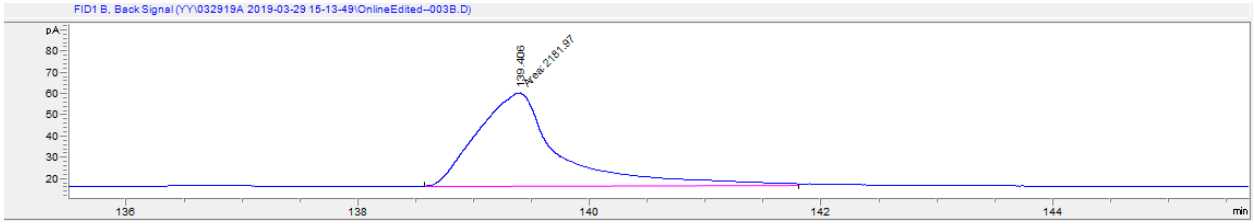


Racemic 2k:



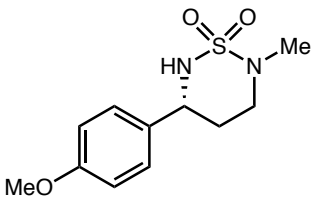
#	Time	Area	Height	Width	Area%	Symmetry
1	138.414	1817	51	0.5938	49.719	0
2	139.368	1837.6	40	0.7665	50.281	0.861

Enantioenriched 2k: 99% ee

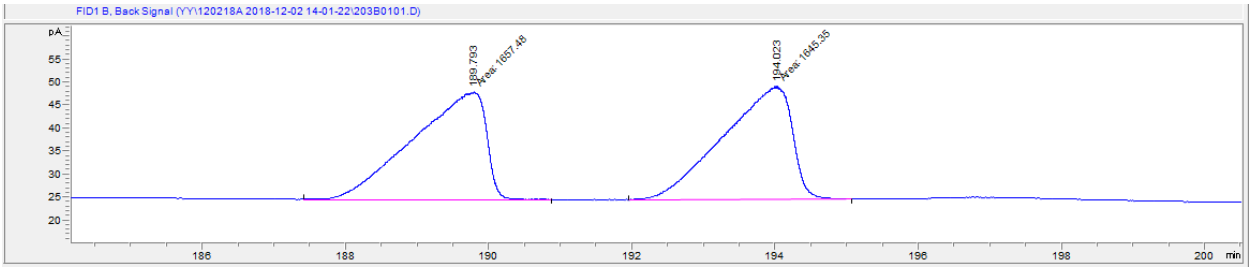


#	Time	Area	Height	Width	Area%	Symmetry
1	139.406	2182	44.2	0.8237	100.000	1.005

(*R*)-5-(4-Methoxyphenyl)-2-methyl-1,2,6-thiadiazinane 1,1-dioxide (2l)

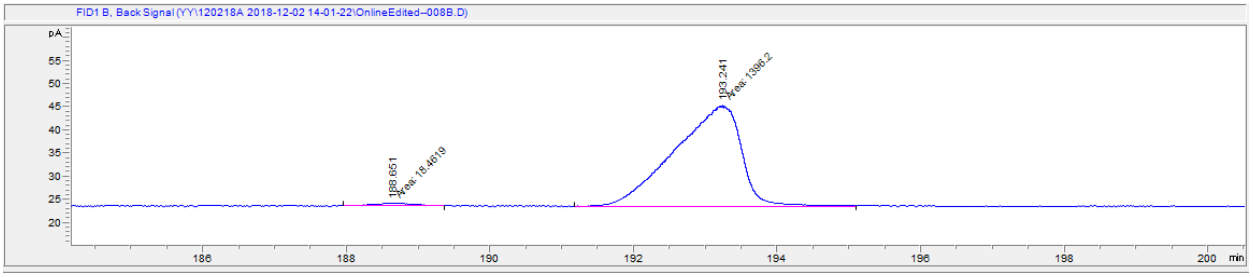


Racemic 2l:



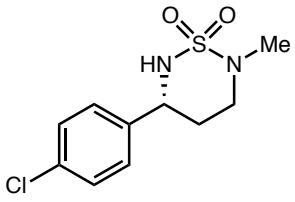
#	Time	Area	Height	Width	Area%	Symmetry
1	189.793	1657.5	23.4	1.1787	50.184	4.65
2	194.023	1645.4	24.6	1.1153	49.816	3.288

Enantioenriched 2l: 97% ee

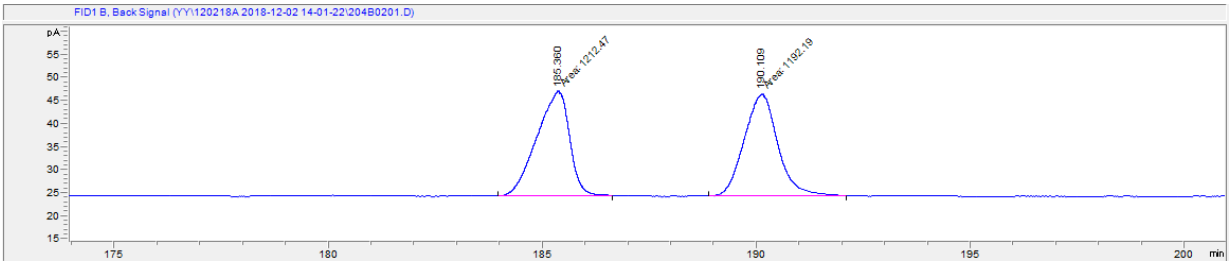


#	Time	Area	Height	Width	Area%	Symmetry
1	188.651	18.5	4.8E-1	0.6358	1.305	1.064
2	193.241	1396.2	21.7	1.0705	98.695	2.449

(*R*)-5-(4-Chlorophenyl)-2-methyl-1,2,6-thiadiazinane 1,1-dioxide (2m)

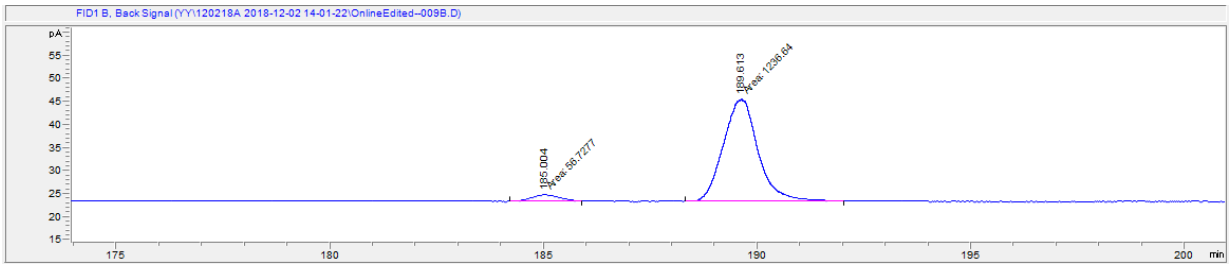


Racemic 2m:



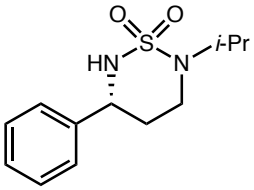
#	Time	Area	Height	Width	Area%	Symmetry
1	185.36	1212.5	22.7	0.8885	50.422	1.745
2	190.109	1192.2	22.1	0.8996	49.578	1

Enantioenriched 2m: 91% ee

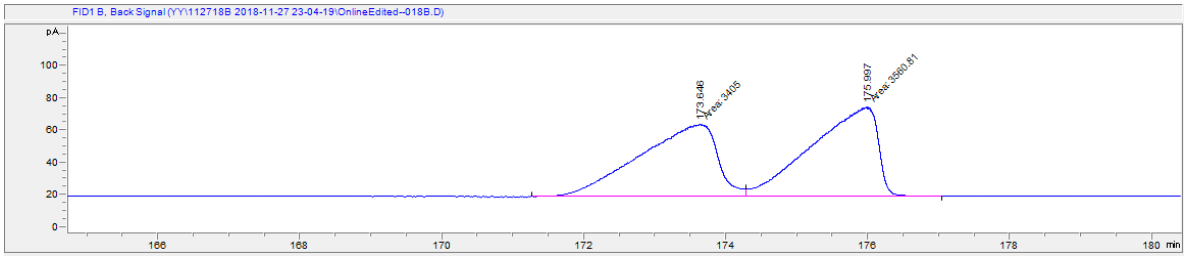


#	Time	Area	Height	Width	Area%	Symmetry
1	185.004	56.7	1.3	0.7026	4.386	0.838
2	189.613	1236.6	22.2	0.9295	95.614	0.984

(*R*)-2-Isopropyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (2n)

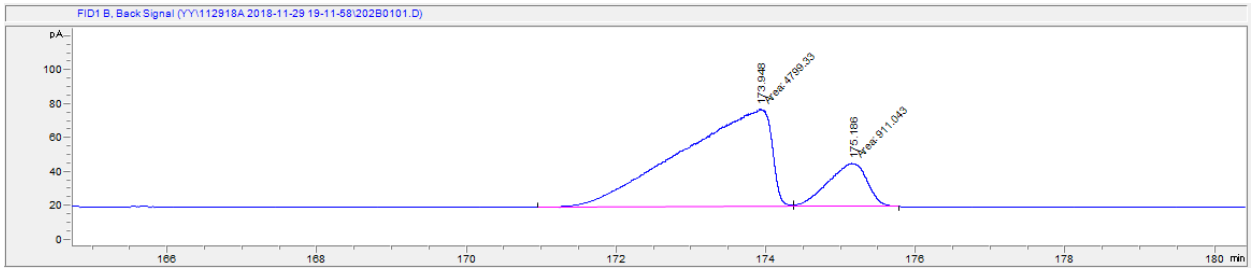


Racemic 2n:



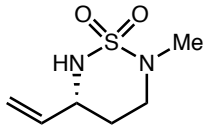
#	Time	Area	Height	Width	Area%	Symmetry
1	173.646	3405	44.7	1.2686	48.882	0
2	175.997	3560.8	55.3	1.0727	51.118	4.472

Enantioenriched 2n: 70% ee

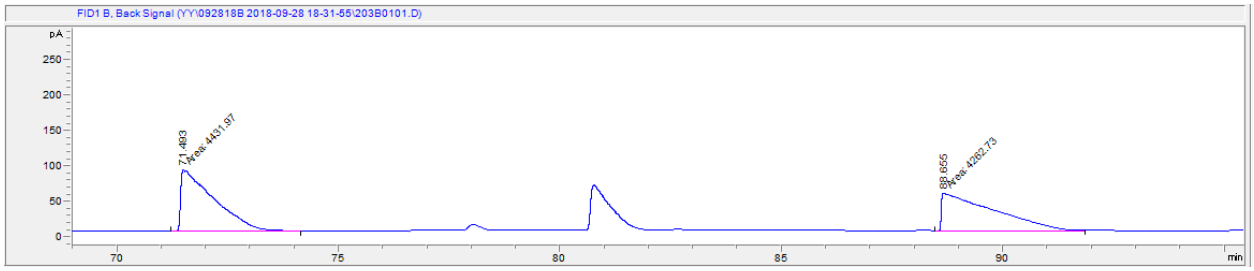


#	Time	Area	Height	Width	Area%	Symmetry
1	173.948	4799.3	57.6	1.3887	84.046	0
2	175.186	911	25.2	0.6021	15.954	1.823

(*R*)-2-Methyl-5-vinyl-1,2,6-thiadiazinane 1,1-dioxide (2o)

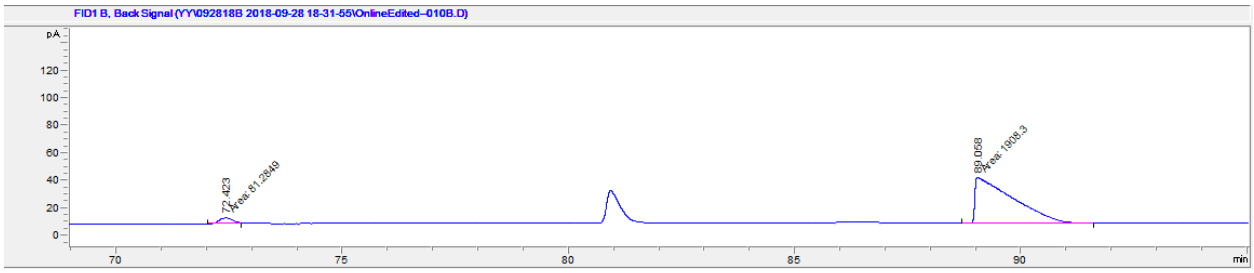


Racemic 2o:



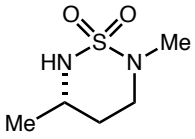
#	Time	Area	Height	Width	Area%	Symmetry
1	71.493	4432	86	0.8594	50.973	8.66E-2
2	88.655	4262.7	52.5	1.3539	49.027	4.22E-2

Enantioenriched 2o: 92% ee

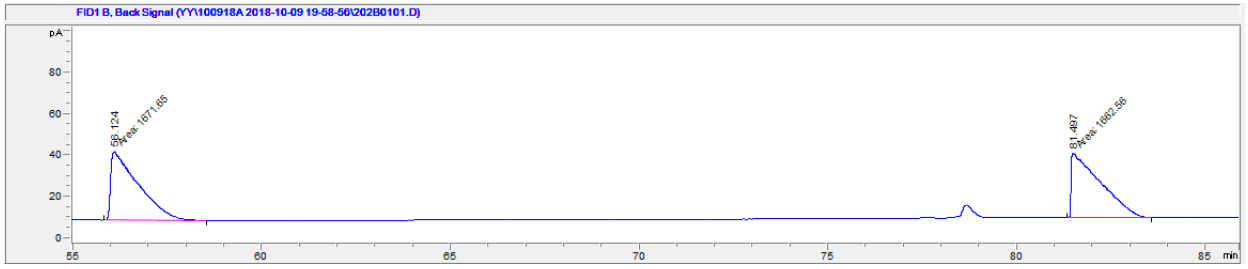


#	Time	Area	Height	Width	Area%	Symmetry
1	72.423	81.3	4.1	0.3272	4.086	0
2	89.058	1908.3	33.3	0.9561	95.914	6.93E-2

(*S*)-2,5-Dimethyl-1,2,6-thiadiazinane 1,1-dioxide (2p)

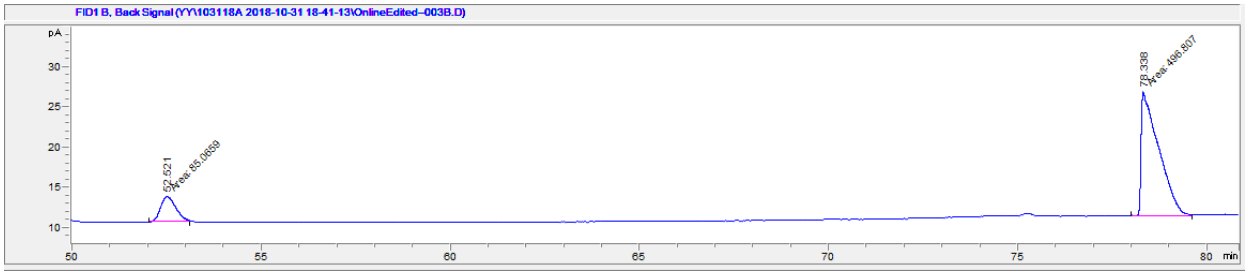


Racemic 2p:



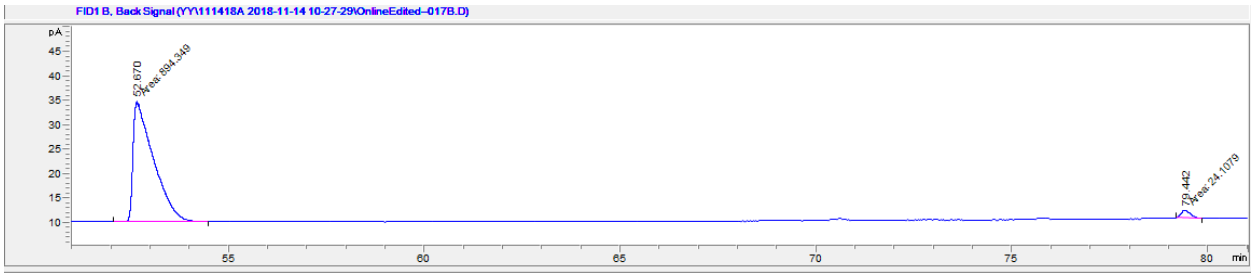
#	Time	Area	Height	Width	Area%	Symmetry
1	56.124	1671.7	33.2	0.8401	50.136	0.16
2	81.497	1662.6	31.2	0.8874	49.864	8.09E-2

Enantioenriched 2p using the P411$_{Diane1}$ I327T variant: 72% ee



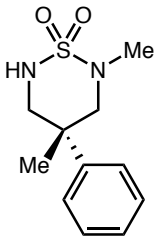
#	Time	Area	Height	Width	Area%	Symmetry
1	52.521	85.1	3.1	0.4585	14.619	0.834
2	78.338	496.8	15.5	0.5358	85.381	0.134

Enantioenriched 2p using the P411$_{Diane1}$ L82M A87I Y263W I327S variant: -96% ee

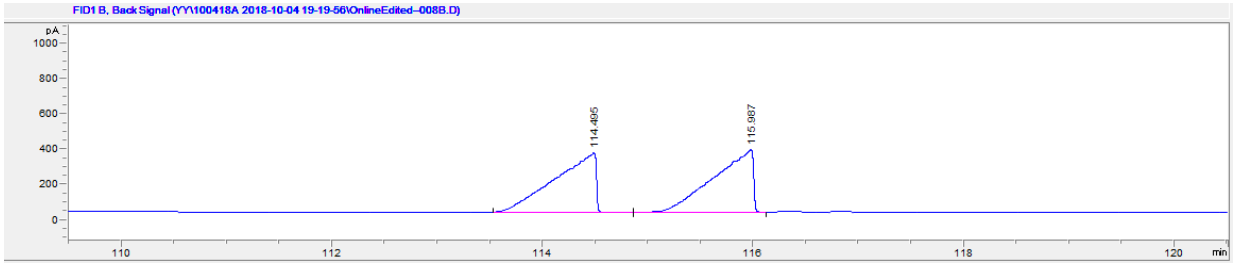


#	Time	Area	Height	Width	Area%	Symmetry
1	52.67	894.3	24.7	0.6045	97.375	0.263
2	79.442	24.1	1.6	0.2569	2.625	0.756

(*R*)-2,4-Dimethyl-4-phenyl-1,2,6-thiadiazinane 1,1-dioxide (4a)

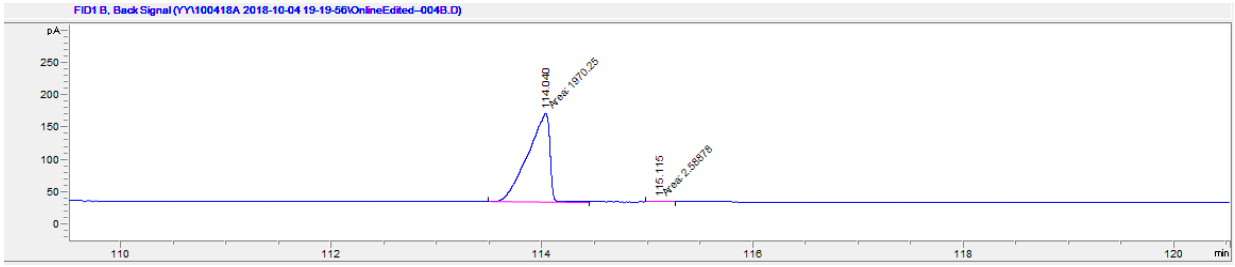


Racemic 4a:



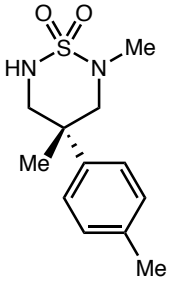
#	Time	Area	Height	Width	Area%	Symmetry
1	114.495	9114.7	336.7	0.3271	49.914	14.456
2	115.987	9146.2	355.1	0.3125	50.086	13.694

Enantioenriched 4a: 99.8% ee

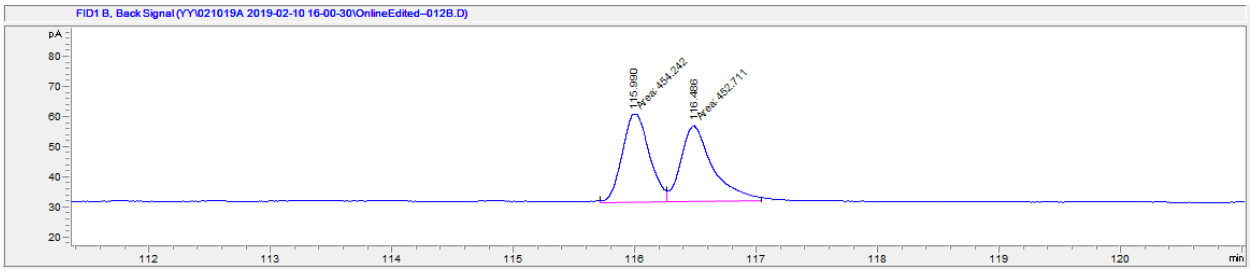


#	Time	Area	Height	Width	Area%	Symmetry
1	114.04	1970.3	136.3	0.2409	99.869	4.019
2	115.115	2.6	4E-1	0.1082	0.131	1.516

(*R*)-2,4-Dimethyl-4-(*p*-tolyl)-1,2,6-thiadiazinane 1,1-dioxide (4b)

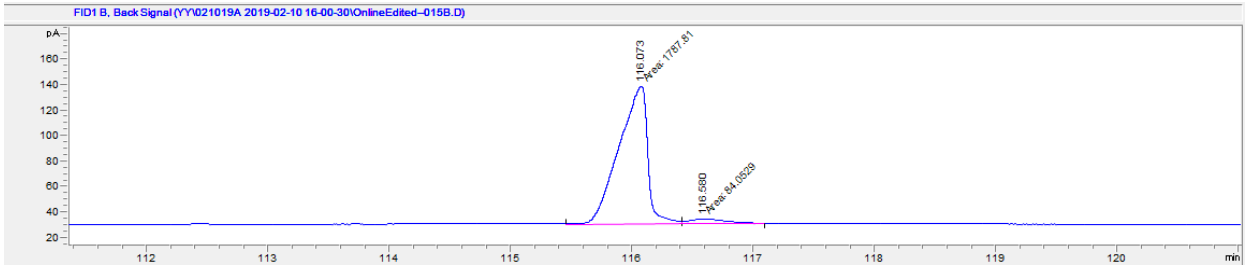


Racemic 4b:



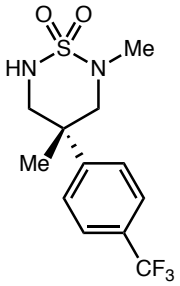
#	Time	Area	Height	Width	Area%	Symmetry
1	115.99	454.2	29.3	0.2582	50.084	0
2	116.486	452.7	25.2	0.2998	49.916	0.705

Enantioenriched 4b: 91% ee

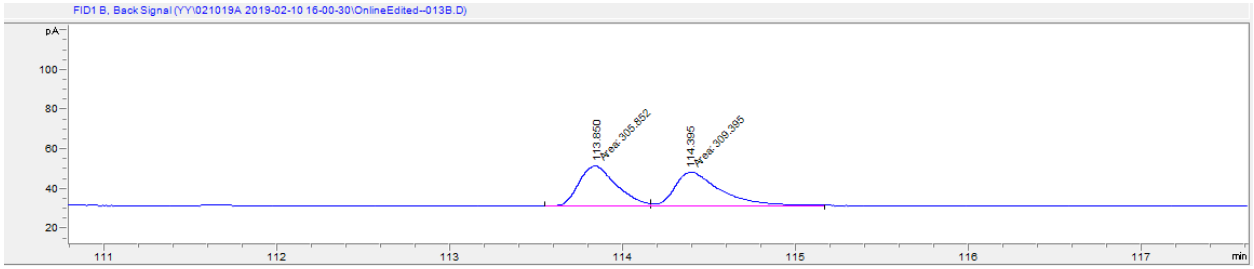


#	Time	Area	Height	Width	Area%	Symmetry
1	116.073	1787.8	108.2	0.2753	95.510	2.965
2	116.58	84.1	3.9	0.3616	4.490	0

(*R*)-2,4-Dimethyl-4-(4-(trifluoromethyl)phenyl)-1,2,6-thiadiazinane 1,1-dioxide (4c)

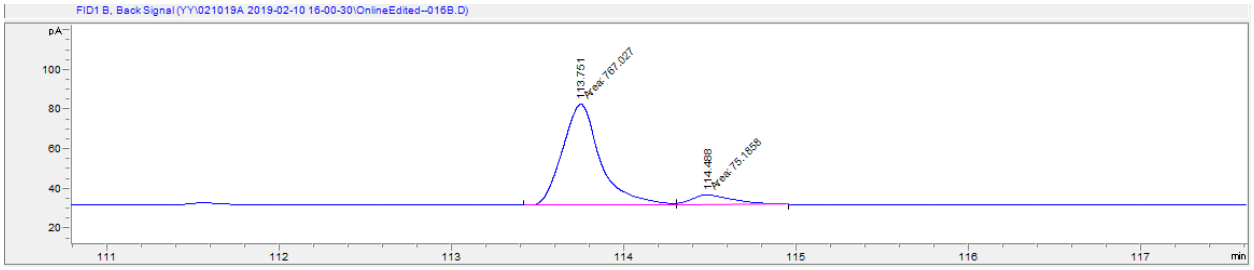


Racemic 4c:



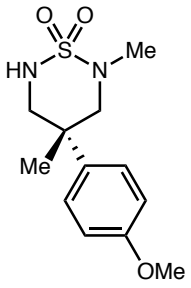
#	Time	Area	Height	Width	Area%	Symmetry
1	113.85	305.9	20.5	0.2481	49.712	0
2	114.395	309.4	17	0.3028	50.288	0.502

Enantioenriched 4c: 82% ee

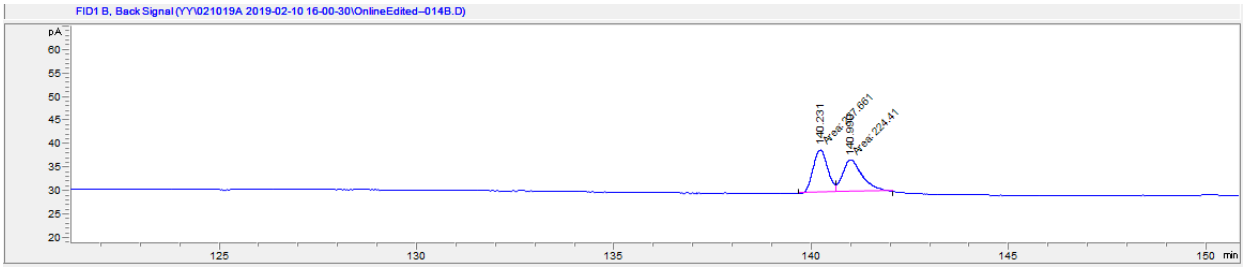


#	Time	Area	Height	Width	Area%	Symmetry
1	113.751	767	50.7	0.2521	91.073	0
2	114.488	75.2	4.8	0.2637	8.927	0.616

(*R*)-4-(4-Methoxyphenyl)-2,4-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (4d)

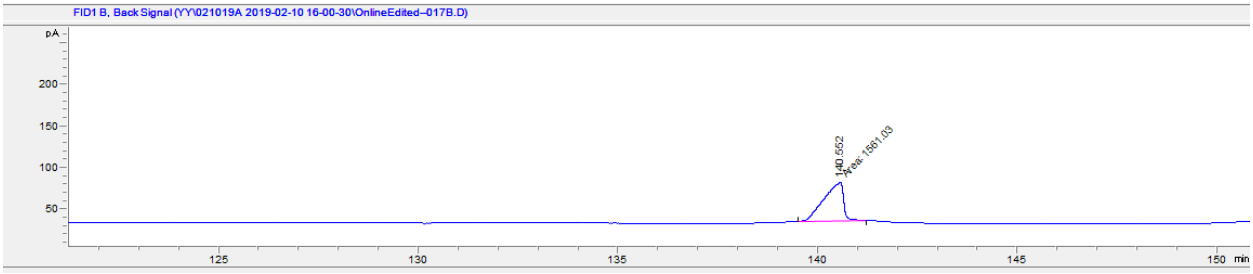


Racemic 4d:



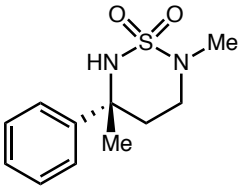
#	Time	Area	Height	Width	Area%	Symmetry
1	140.231	227.7	9	0.4229	50.360	0
2	140.99	224.4	6.7	0.5574	49.640	0.701

Enantioenriched 4d: 99% ee

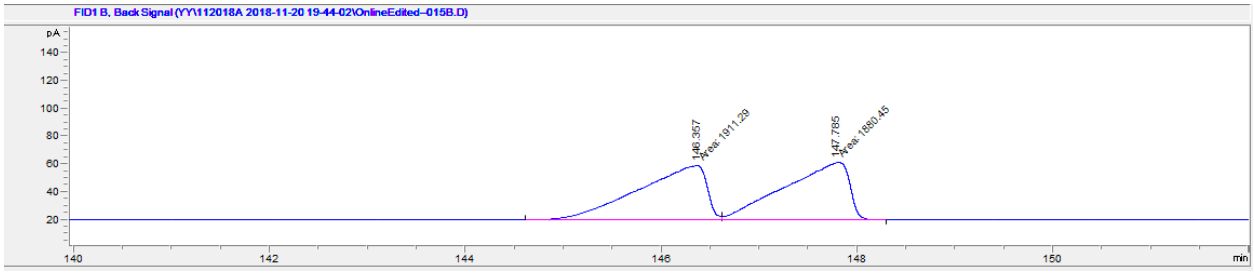


#	Time	Area	Height	Width	Area%	Symmetry
1	140.552	1561	46	0.5655	100.000	4.292

(*R*)-2,5-Dimethyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5a)

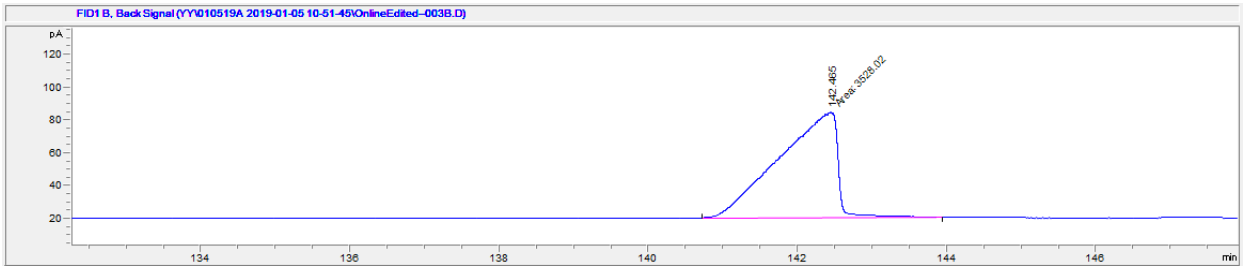


Racemic 5a:



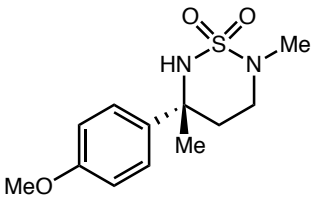
#	Time	Area	Height	Width	Area%	Symmetry
1	146.357	1911.3	39.1	0.8139	50.407	0
2	147.785	1880.4	41	0.7638	49.593	3.825

Enantioenriched 5a: 99% ee

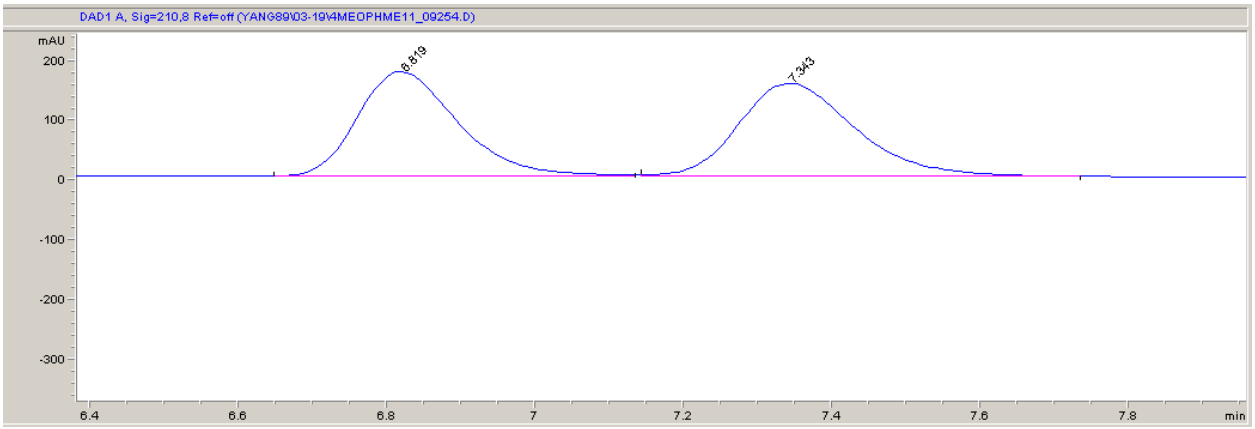


#	Time	Area	Height	Width	Area%	Symmetry
1	142.465	3528	64.3	0.9146	100.000	6.919

(*R*)-5-(4-Methoxyphenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5b)

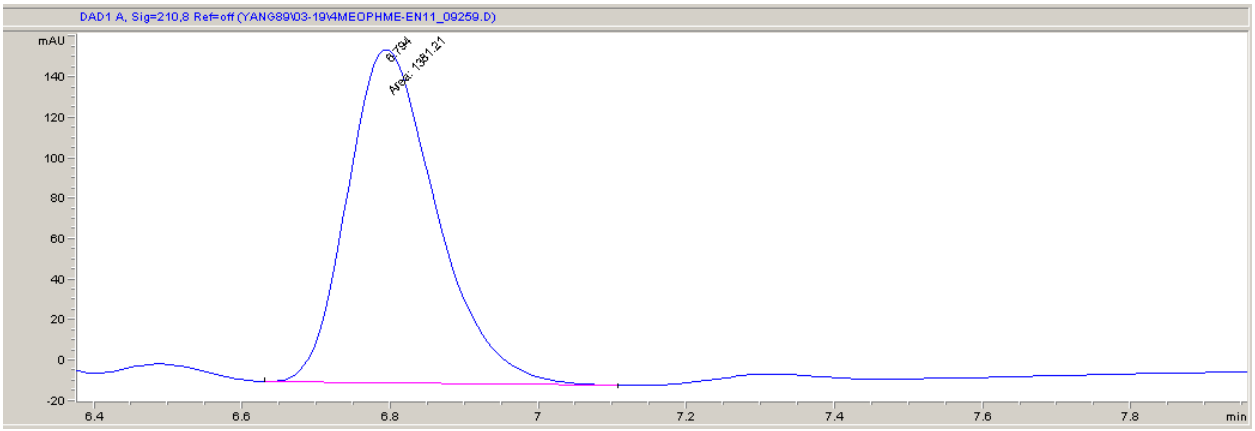


Racemic 5b:



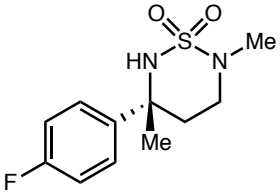
#	Time	Area	Height	Width	Area%	Symmetry
1	6.819	1650.2	174.8	0.1461	49.140	0.712
2	7.343	1707.9	155.6	0.168	50.860	0.734

Enantioenriched 5b: 98% ee

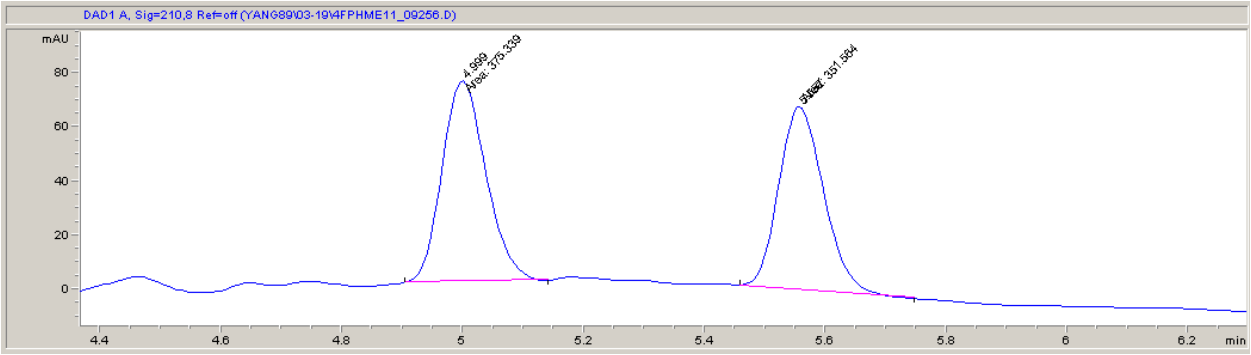


#	Time	Area	Height	Width	Area%	Symmetry
1	6.794	1381.2	165.3	0.1393	100.000	0.781

(*R*)-5-(4-Fluorophenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5c)

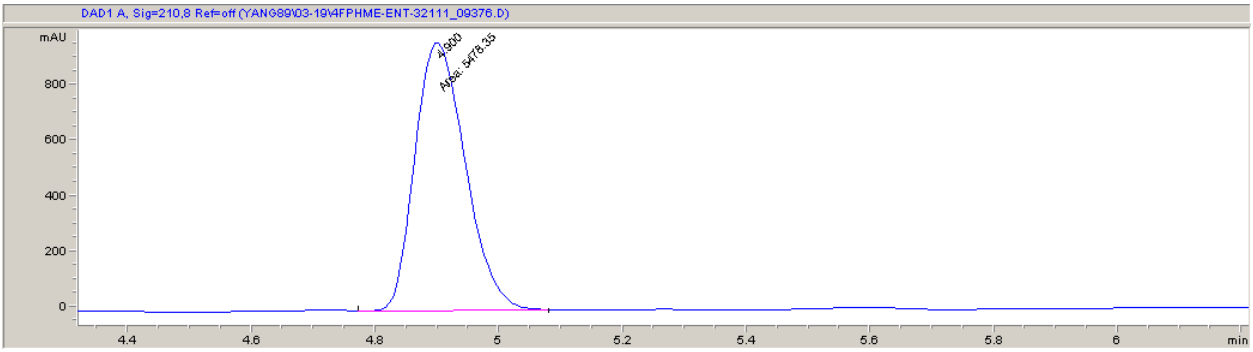


Racemic 5c:



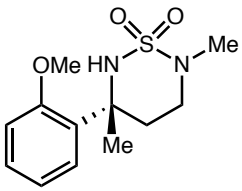
#	Time	Area	Height	Width	Area%	Symmetry
1	4.999	375.3	74.9	0.0835	51.635	0.869
2	5.557	351.6	68.2	0.0859	48.365	0.767

Enantioenriched 5c: 99% ee

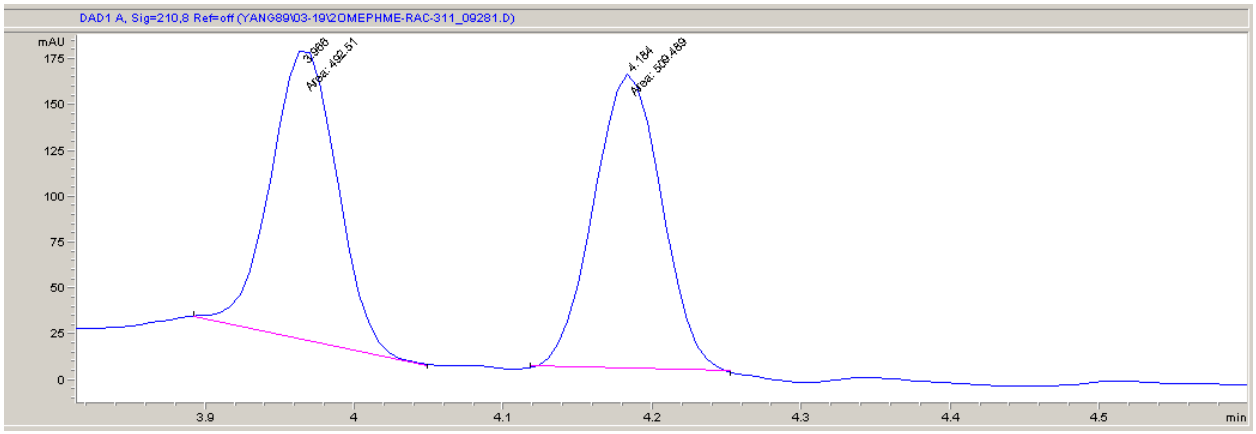


#	Time	Area	Height	Width	Area%	Symmetry
1	4.9	5478.3	974.7	0.0937	100.000	0.703

(*R*)-5-(2-Methoxyphenyl)-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5d)

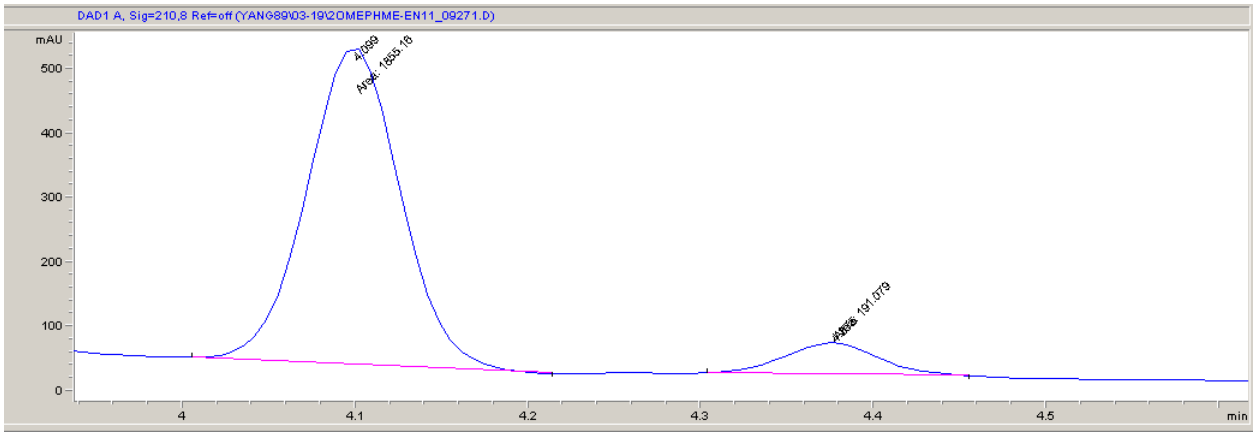


Racemic 5d:



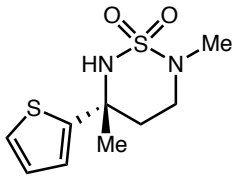
#	Time	Area	Height	Width	Area%	Symmetry
1	3.966	492.5	159.9	0.0513	49.153	0.871
2	4.184	509.5	161.4	0.0526	50.847	1.258

Enantioenriched 5d: 81% ee

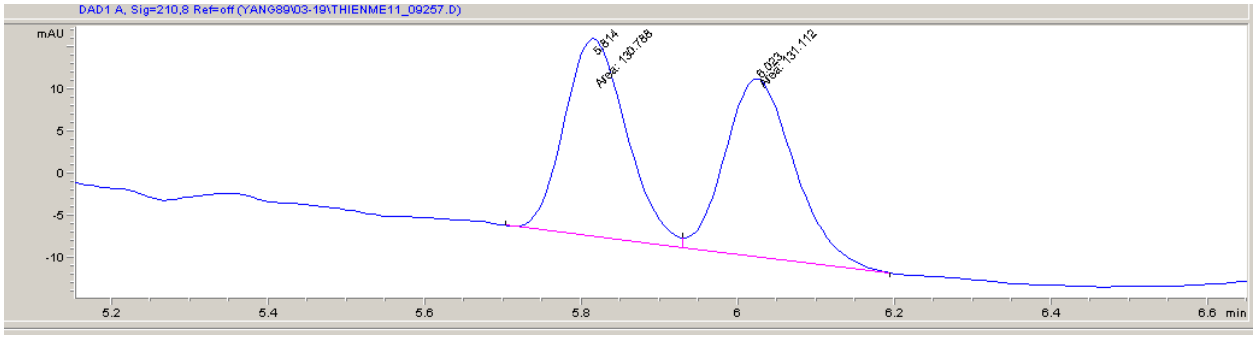


#	Time	Area	Height	Width	Area%	Symmetry
1	4.099	1855.2	497.2	0.0622	90.662	1.072
2	4.375	191.1	49.9	0.0638	9.338	0.984

(*R*)-2,5-Dimethyl-5-(thiophen-2-yl)-1,2,6-thiadiazinane 1,1-dioxide (5e)

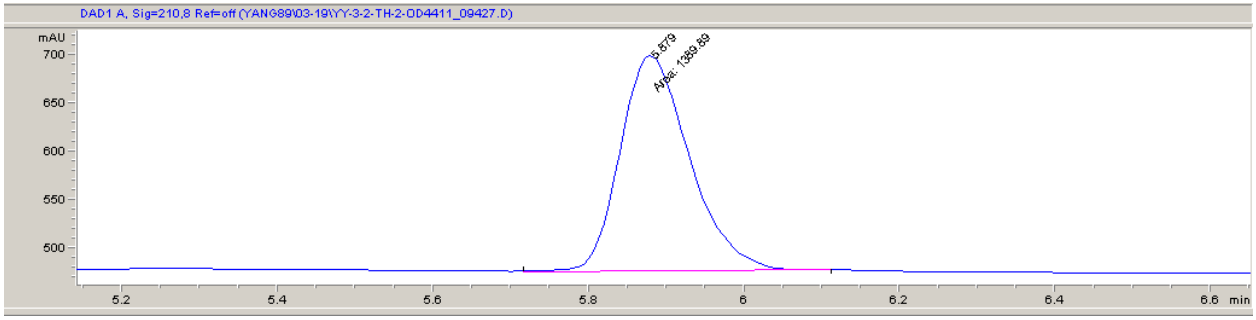


Racemic 5e:



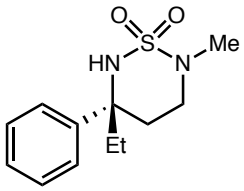
#	Time	Area	Height	Width	Area%	Symmetry
1	5.814	130.8	23.6	0.0924	49.938	0.802
2	6.023	131.1	21.2	0.1029	50.062	0.85

Enantioenriched 5e: 99% ee

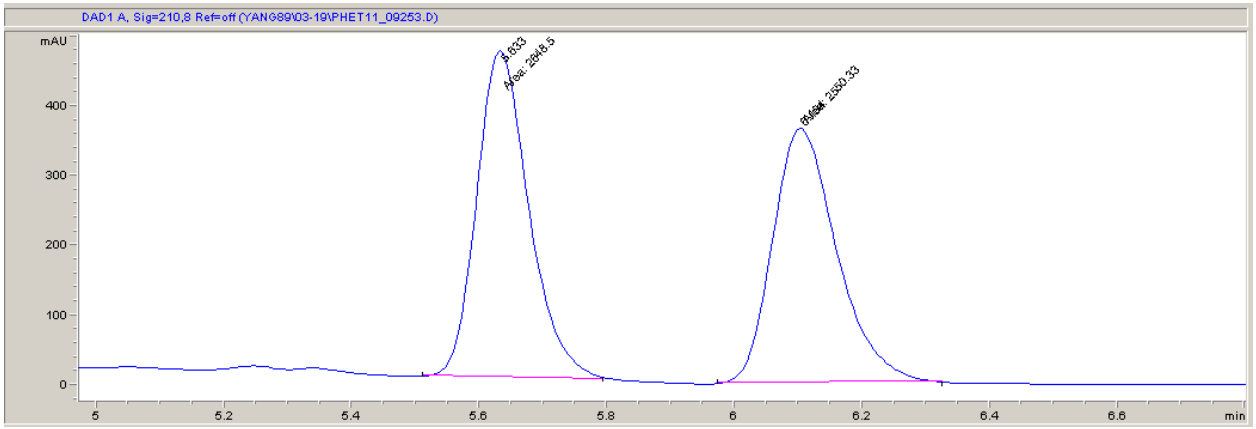


#	Time	Area	Height	Width	Area%	Symmetry
1	5.879	1389.9	224.2	0.1033	100.000	0.764

(*R*)-5-Ethyl-2-methyl-5-phenyl-1,2,6-thiadiazinane 1,1-dioxide (5f)

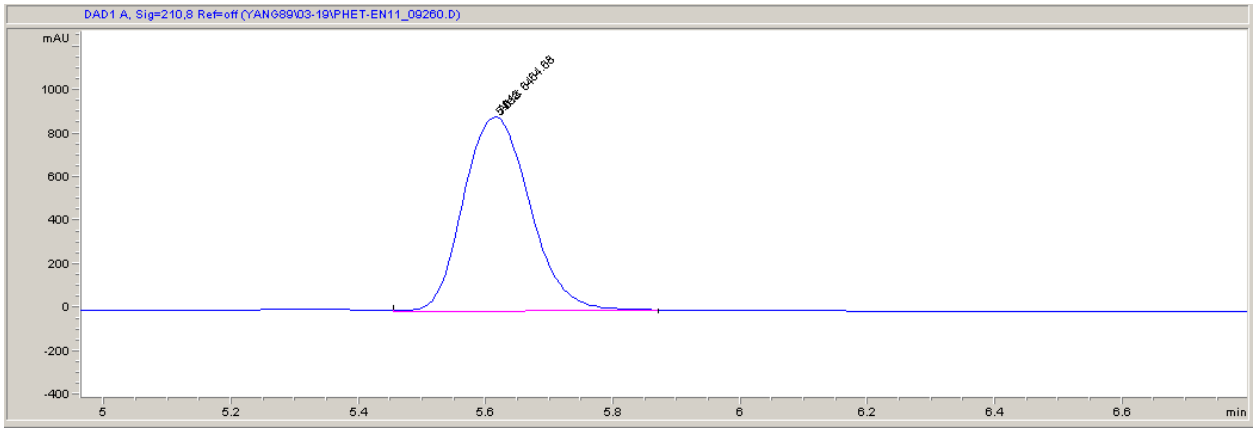


Racemic 5f:



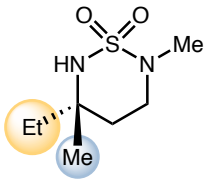
#	Time	Area	Height	Width	Area%	Symmetry
1	5.633	2648.5	470.5	0.0938	50.944	0.783
2	6.104	2550.3	367.1	0.1158	49.056	0.691

Enantioenriched 5g: 99% ee

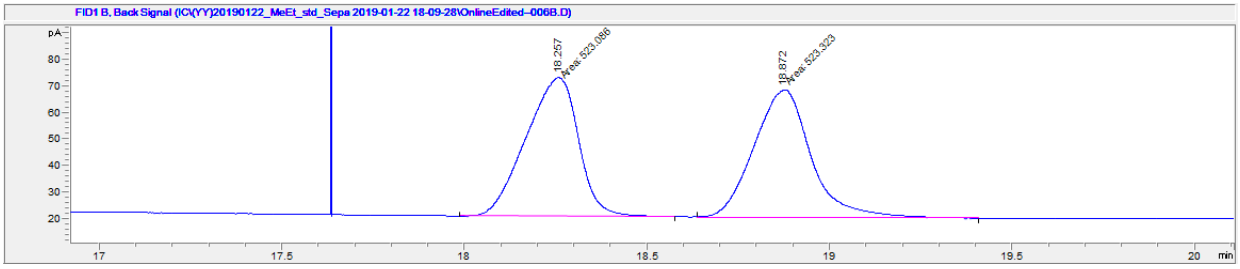


#	Time	Area	Height	Width	Area%	Symmetry
1	5.613	6464.7	894.4	0.1205	100.000	0.807

(*S*)-5-Ethyl-2,5-dimethyl-1,2,6-thiadiazinane 1,1-dioxide (5g)

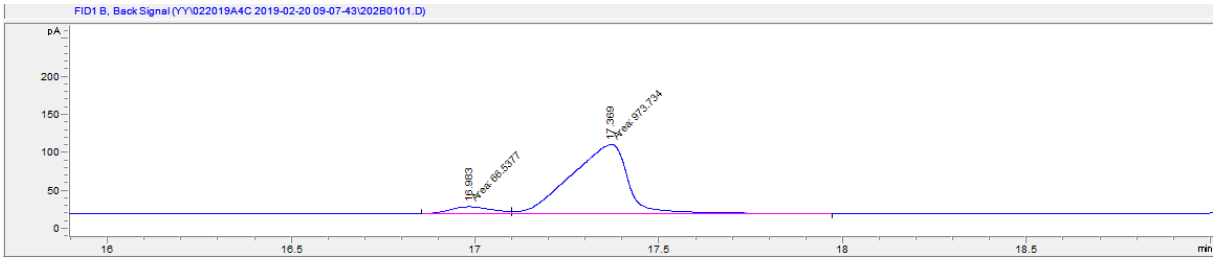


Racemic 5g:



#	Time	Area	Height	Width	Area%	Symmetry
1	18.257	523.1	52.4	0.1663	49.989	1.584
2	18.872	523.3	48	0.1817	50.011	1.014

Enantioenriched 5g: 87% ee



#	Time	Area	Height	Width	Area%	Symmetry
1	16.983	66.5	8.7	0.128	6.396	0
2	17.369	973.7	91.1	0.1781	93.604	2.162

XII. Computational studies

Computational methods

Density functional theory (DFT) calculations were carried out using Gaussian 16.[9] Geometries of intermediates and transition states were optimized using the (U)B3LYP[10,11] functional with a mixed basis set of LANL2DZ for Fe and 6-31+G(d) for other atoms in the gas phase. Dispersion corrections were considered in geometry optimization using Grimme's D3(BJ) method.[12,13] Vibrational frequency calculations were performed for all the stationary points to confirm if each optimized structure is a local minimum or a transition state structure. Solvation energy corrections were calculated in chlorobenzene ($\varepsilon = 5.7$) solvent with the SMD[14] continuum solvation model based on the gas-phase optimized geometries. This solvent was chosen to simulate the dielectric permittivity in the enzyme active site, as recommended in previous computational studies of enzymatic reactions.[15-17] The (U)B3LYP-D3(BJ) functional with a mixed basis set of LANL2TZ(f)[18] for Fe and 6-311+G(d,p) for other atoms was used for solvation single-point energy calculations.

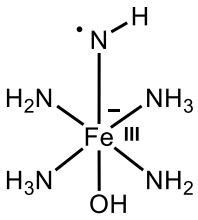
In the DFT calculations, porphine was used a model for the porphyrin ligand. Similar model systems have been used in previous computational studies of heme-containing enzymes.[19-21] The initial guess for the molecular orbital coefficients of open-shell singlet (OSS) structures was generated using the "guess=mix" keyword in Gaussian 16 to destroy α/β symmetries. Wavefunction stability tests were carried out with "stable=opt" to ensure the calculated wavefunctions in all open-shell calculations are stable. The stability test suggested that the closed-shell singlet (CSS) wavefunction is unstable in this iron porphyrin nitrene system. The closed-shell singlet structures lead to much higher energies than corresponding open-shell singlet states. All singlet structures discussed in this study are open-shell singlet structures.

Benchmark results

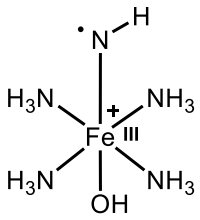
In the computed energy profiles presented in the main text, the dispersion-corrected (U)B3LYP-D3(BJ) functional is used to investigate the mechanism of iron porphyrin-catalysed C–H amination. The B3LYP functional has been widely used in iron porphyrin carbene and oxo systems[19-24] because previous benchmark studies indicated B3LYP is among the most accurate density functional theory methods for studying iron-porphyrin systems. To ensure the relatively

reliable performance of B3LYP is transferrable to the present iron porphyrin nitrenoid system, we performed benchmark calculations of various DFT methods using several model iron-nitrenoid complexes (Table 7). In the model complexes used in our benchmark studies, the porphyrin ligand in iron porphyrin nitrenoid **7** is further truncated to smaller nitrogen-containing ligands.[25-27] These model structures were optimized at the (U)B3LYP/6-311G(d)–LANL2DZ level of theory in gas phase. The "guess=mix" keyword was used for optimizing open-shell singlet structures and "stable=opt" was used to ensure all these open-shell calculations adopted stable wavefunctions. The stability test suggested that the closed-shell singlet (CSS) is unstable for these model complexes. Therefore, these model complexes were optimized at open-shell singlet, triplet, and quintet states, respectively. Using the (U)B3LYP optimized structures, single-point energy calculations were performed using (U)B3LYP-D3(BJ), (U)B2PLYP-D3(BJ),[28] (U)OLYP,[29,30] (U)OPBE,[31,32] and (U)ω-B97XD[33,34] methods with the same basis set. These DFT methods were reported to give relatively reasonable energy gaps between different spin states of iron complexes.[35-37] Coupled-cluster methods,[38-40] KS-UCCSD(T)[38] and KS-UCCSD(T)-F12,[41-43] were employed in single-point energy calculations to provide a reference for the benchmark study.[44] The coupled-cluster calculations were carried out using Molpro 2018.[45] The coupled-cluster calculations were performed based on the ROB3LYP reference orbital. A mixed basis set of aug-cc-pVTZ for Fe and cc-pVDZ for other atoms was employed in the KS-UCCSD(T) calculations. In the explicitly correlated KS-UCCSD(T)-F12 calculations, the cc-pwCVTZ basis set was used for Fe and the cc-pVDZ-F12 basis set was used for other atoms. The def2-QZVP/JKFIT[46] basis set (for Fe) and the aug-cc-pVDZ/JKFIT[47] basis set (for other atoms) were used as Coulomb and exchange fitting basis sets in the KS-UCCSD(T)-F12 calculations. For the correlation fitting, the cc-pwCVTZ/MP2FIT[48] basis set was used for Fe and cc-pVDZ/MP2FIT[49,50] basis set was used for other atoms. For the OptRI approximation, the cc-pwCVTZ/MP2FIT basis set was used for Fe and cc-pVDZ-F12/OptRI[51] basis set was used for other atoms. Although a relatively small mixed double-ζ/triple-ζ basis set was used in the CCSD(T) calculations, recent benchmark calculations from Harvey suggested the CCSD(T) calculations of similar iron model complexes are not highly sensitive to the basis set size.[44]

Table 7. Benchmark of DFT methods.[a]



10



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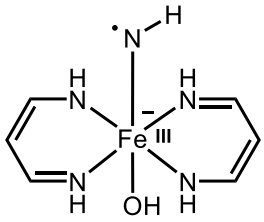
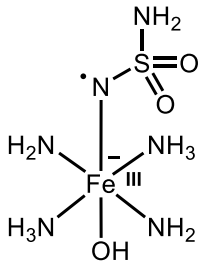


12



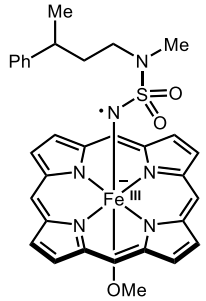
13

	KS-UCCSD(T)	**KS-UCCSD(T) -F12**	**B3LYP -D3**	**OLYP**	**OPBE**	**ω-B97XD**	**B2PLYP-D3**
ΔE_{ST}(10)	4.8	4.9	1.2	-4.0	-5.1	3.2	25.2
ΔE_{TQ}(10)	-15.2	-18.1	-11.5	-18.3	-18.5	-11.9	-45.3
ΔE_{ST}(11)	3.8	3.0	-0.9	-4.8	-5.8	0.2	4.5
ΔE_{TQ}(11)	-3.3	-3.2	2.4	-1.1	-1.5	4.0	-13.3
ΔE_{ST}(12)	1.0	-[b]	-0.3	-3.6	-4.3	0.7	3.0
ΔE_{TQ}(12)	17.7	-[b]	8.8	14.6	15.5	8.3	-3.6
ΔE_{ST}(13)	-12.1	-11.2	-7.8	-11.3	-13.4	-3.3	8.1
ΔE_{TQ}(13)	-5.2	-7.4	-2.9	-6.2	-5.4	-3.7	-20.2
		MAE($\Delta\Delta E_{ST}$)	3.5	5.7	6.5	3.5	10.8
		MAE($\Delta\Delta E_{QT}$)	5.2	2.4	1.9	5.4	19.1
		MSE($\Delta\Delta E_{ST}$)	-1.3	-5.3	-6.5	0.8	10.8
		MSE($\Delta\Delta E_{QT}$)	0.7	-1.2	-1.0	0.7	-19.1

[a] $\Delta E_{ST} = E_{triplet} - E_{singlet}$; $\Delta E_{TQ} = E_{quintet} - E_{triplet}$. $\Delta\Delta E_{ST} = \Delta E_{ST}$(DFT) – ΔE_{ST}(KS-UCCSD(T)), $\Delta\Delta E_{QT} = \Delta E_{QT}$(DFT) – ΔE_{QT}(KS-UCCSD(T)). Geometries were optimized at the (U)B3LYP/6-311G(d)–LANL2DZ level of theory in gas phase. [b] The KS-UCCSD(T)-F12 calculations of complex **12** were not successful because of the size of the system.

The energy gaps between open-shell singlet and triplet structures (ΔE_{ST}) and between triplet and quintet structures (ΔE_{TQ}) calculated using different methods are summarized in Table 7. The energy gaps calculated using KS-UCCSD(T) and KS-UCCSD(T)-F12 are generally similar. Because the KS-UCCSD(T)-F12 calculations for **12** were unsuccessful due to the size of the system, we used the energy gaps computed using KS-UCCSD(T) as the reference to evaluate the performance of different density functionals. The calculated mean absolute error (MAE) and mean signed error (MSE) of ΔE_{ST} and ΔE_{TQ} are also shown in Table S7. The benchmark results suggest that the mean absolute errors for B3LYP-D3(BJ), ω-B97XD, OLYP, and OPBE are comparable. The MSE of these functionals are all within several kcal/mol, which is in agreement with other benchmark results for spin-state energetics of iron complexes.[37,44] The double-hybrid functional B2PLYP-D3 gave much larger MAE(ΔE_{ST}) and MAE(ΔE_{QT}) values for the iron nitrene model systems. Based on these benchmark results, the more commonly used functional (U)B3LYP-D3(BJ) is chosen to calculate iron porphyrin nitrene complexes. Therefore, the B3LYP-D3(BJ)/6-311+G(d,p)–LANL2TZ(f)/SMD(chlorobenzene)//B3LYP-D3(BJ)/6-31+G(d)–LANL2DZ method is chosen to study the mechanism of the iron porphyrin-catalysed C(sp^3)–H amination.

Table 8. Spin state energetics of iron porphyrin nitrenoid 7 calculated using different DFT methods[a]



7

	B3LYP-D3	OLYP	OPBE	ω-B97XD	B2PLYP-D3
ΔE_{ST}(7)	-3.3	-8.2	-9.2	-0.9	2.0
ΔE_{TQ}(7)	13.7	10.3	9.0	14.3	3.7

[a] $\Delta E_{ST} = E_{triplet} - E_{singlet}$; $\Delta E_{TQ} = E_{quintet} - E_{triplet}$.

Different DFT methods were employed to calculate the single-point energies of iron porphyrin nitrenoid **7** to determine its ground state electronic structure (Table 8). A mixed basis set of LANL2TZ(f) for Fe and 6-311+G(d,p) for other atoms was used for single-point energy calculations. The single-point energy calculations were carried out in chlorobenzene solvent with the SMD continuum solvation model. As shown in Table S8, all functionals tested indicate the triplet iron porphyrin nitrenoid **7** is more stable than the quintet state. Moreover, except for B2PLYP-D3, all methods support that the triplet **7** is more stable than the open-shell singlet. Therefore, these DFT studies suggest that the triplet state is the most stable spin state for iron porphyrin nitrenoid **7**.

Singlet, triplet, and quintet free energy profiles of the iron porphyrin-catalysed C(sp^3)–H amination

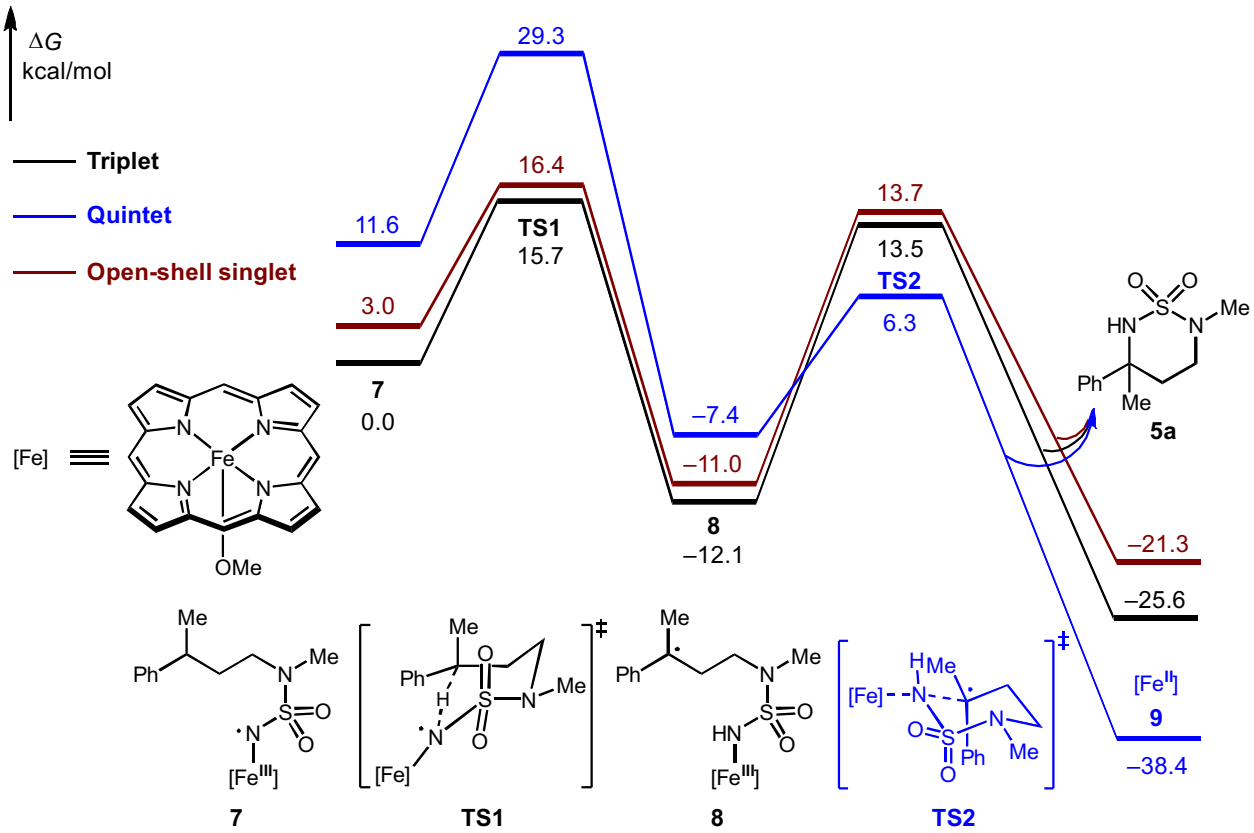


Fig. 2. Singlet, triplet, and quintet free energy profiles of the iron porphyrin-catalysed C–H amination

The singlet, triplet, and quintet Gibbs free energy profiles of the iron porphyrin-catalysed C(sp^3)–H amination were calculated at the B3LYP-D3(BJ)/6-311+G(d,p)–LANL2TZ(f)/SMD(chlorobenzene)//B3LYP-D3(BJ)/6-31+G(d)–LANL2DZ level of theory (Fig. 2). This reaction proceeds through hydrogen atom transfer (HAT, **TS1**) followed by radical rebound **(TS2)** to form the C–N bond. Both cyclic transition states involve chair-type geometries. Therefore, we have considered different ring-flip conformers in both the HAT and the radical rebound transition states. Computational results suggest that the Ph group prefers to be pseudo-equatorial in the HAT transition state (**TS1**). In the radical rebound transition state, the Fe-porphyrin unit prefers to be pseudo-equatorial and the Ph group prefers to be pseudo-axial to avoid unfavourable steric repulsions with the Fe-porphyrin moiety (Fig. 3). The singlet, triplet, and quintet free energy profiles are shown in red, black, and blue, respectively in Fig. 2. The ground state electronic structure of iron porphyrin nitrenoid **7** is found to be triplet. The corresponding quintet and open-shell singlet structures are higher in energy by 11.6 kcal/mol and 3.0 kcal/mol, respectively. The HAT step occurs via a triplet transition state **TS1**, generating a triplet radical intermediate **8**. The open-shell singlet and quintet HAT transition states have higher activation free energies than that of the triplet transition state. The C-N bond forming radical rebound step in this iron porphyrin-catalysed C–H amination shows a two-state reactivity.[21,52,53] Although radical intermediate **8** is a triplet, the quintet radical rebound transition state **TS2** is more stable than the triplet and open-shell singlet states by 7.2 and 7.4 kcal/mol, respectively. This is consistent with the relative stability of the quintet state of the generated iron(II) porphyrin complex **9**. Taken together, our computational results reveal that the iron porphyrin-catalysed C–H amination occurs through a triplet HAT transition state **TS1** from a triplet iron porphyrin nitrenoid, and the following radical rebound occurs through a quintet transition state **TS2** to afford the C–H amination product and the quintet Fe-porphyrin complex **9**.

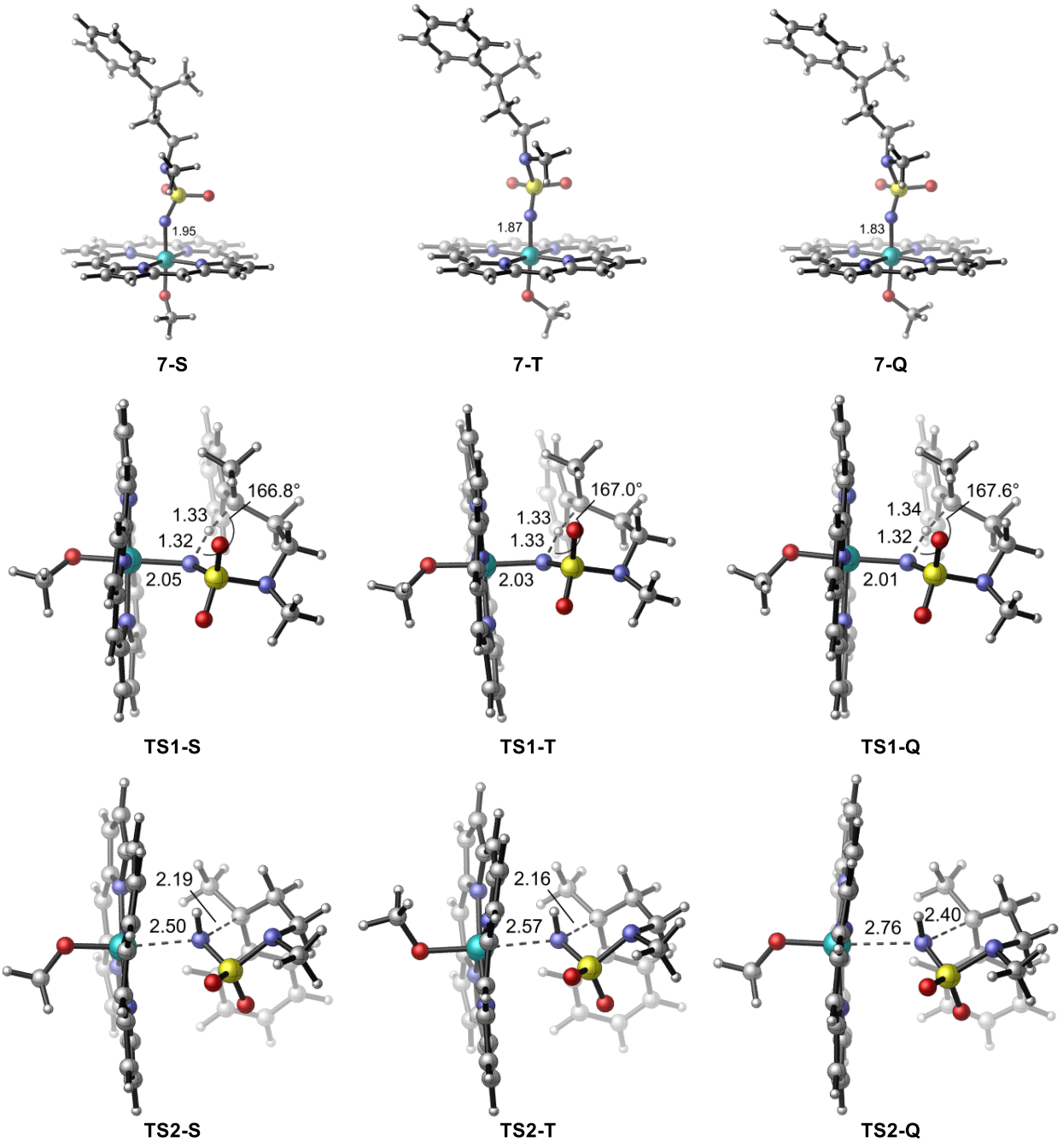


Fig. 3. Optimized structures of iron porphyrin nitrenoid **7**, HAT transition states **TS1**, and radical rebound transition states **TS2** in open-shell singlet (S), triplet (T), quintet (Q) states.

Cartesian coordinates and energies of optimized structures

10-S

B3LYP-D3(BJ) SCF energy: -479.73009237 a.u.
B3LYP-D3(BJ) enthalpy: -479.561968 a.u.
B3LYP-D3(BJ) free energy: -479.612184 a.u.
B3LYP-D3(BJ) SCF energy in solution: -479.75952115 a.u.
B3LYP-D3(BJ) enthalpy in solution: -479.591397 a.u.
B3LYP-D3(BJ) free energy in solution: -479.641613 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -478.636986 a.u.
OLYP SCF energy in solution: -479.729254 a.u.
OPBE SCF energy in solution: -479.766269 a.u.
wB97XD SCF energy in solution: -479.576961 a.u.
KS-UCCSD(T) energy in gas phase: -1618.05650973 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -1618.56057823 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.004666	-0.034030	0.074353
O	-0.244610	0.785768	-1.709365
N	0.245945	-0.817566	1.747402
H	0.533742	1.348242	-1.802091
N	-1.214929	-1.531693	-0.499807
H	-1.191729	-1.396806	-1.513331
H	-0.742506	-2.424867	-0.341734
N	1.235055	1.519191	0.523687
H	1.432288	1.423329	1.521615
H	0.707464	2.391778	0.442980
N	1.760132	-0.857821	-0.503955
H	1.745301	-1.160590	-1.469187
H	2.300547	0.000740	-0.375943
N	-1.769634	0.861442	0.434844
H	-1.779499	1.384295	-0.440886
H	-2.363370	0.035620	0.361893
H	2.058992	-1.588094	0.130669
H	-1.952823	1.432903	1.249256
H	-0.708826	-1.062781	2.063312

10-T

B3LYP-D3(BJ) SCF energy: -479.72816435 a.u.
B3LYP-D3(BJ) enthalpy: -479.560021 a.u.
B3LYP-D3(BJ) free energy: -479.611054 a.u.
B3LYP-D3(BJ) SCF energy in solution: -479.75767429 a.u.
B3LYP-D3(BJ) enthalpy in solution: -479.589531 a.u.
B3LYP-D3(BJ) free energy in solution: -479.640564 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -478.596822 a.u.
OLYP SCF energy in solution: -479.735598 a.u.
OPBE SCF energy in solution: -479.774322 a.u.
wB97XD SCF energy in solution: -479.571835 a.u.
KS-UCCSD(T) energy in gas phase: -1618.04887858 a.u.

KS-UCCSD(T)-F12 energy in gas phase: -1618.55278883 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.010872	0.012686	0.096124
O	0.080354	-0.157320	-1.863409
N	-0.058274	0.161069	1.911118
H	-0.731308	-0.640023	-2.064755
N	1.318690	1.541184	-0.051204
H	1.088302	1.964643	-0.951625
H	1.037612	2.208716	0.667496
N	-1.345569	-1.521743	0.030130
H	-1.510027	-1.856789	0.982065
H	-0.887184	-2.309076	-0.435426
N	-1.653780	1.125680	-0.133716
H	-1.582532	1.620214	-1.014027
H	-2.303732	0.340438	-0.195585
N	1.734669	-1.029425	0.040769
H	1.726510	-1.344424	-0.925011
H	2.298410	-0.175676	0.130089
H	-1.846692	1.736758	0.648568
H	1.969502	-1.755837	0.704001
H	-0.154502	-0.797578	2.282594

10-Q

B3LYP-D3(BJ) SCF energy: -479.74841032 a.u.
B3LYP-D3(BJ) enthalpy: -479.581009 a.u.
B3LYP-D3(BJ) free energy: -479.638739 a.u.
B3LYP-D3(BJ) SCF energy in solution: -479.77601932 a.u.
B3LYP-D3(BJ) enthalpy in solution: -479.608618 a.u.
B3LYP-D3(BJ) free energy in solution: -479.666348 a.u.
B2PLYP-D3(BJ) SCF energy in solution: - a.u.
OLYP SCF energy in solution: - a.u.
OPBE SCF energy in solution: - a.u.
wB97XD SCF energy in solution: - a.u.
KS-UCCSD(T) energy in gas phase: - a.u.
KS-UCCSD(T)-F12 energy in gas phase: - a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.351123	0.171319	0.052316
O	0.814436	-1.171677	-0.714033
N	-1.500666	1.436794	0.640235
H	0.576534	-2.002523	-0.284633
N	0.890996	1.523524	-0.529537
H	1.453388	1.113243	-1.271792
H	0.458302	2.375929	-0.872865
N	-0.837736	-1.094670	1.483119
H	-1.339044	-0.649787	2.247981
H	-0.005004	-1.525773	1.885480
N	-2.091948	-0.684794	-1.142297
H	-1.956045	-1.144627	-2.032041

H	-2.242986	-1.356673	-0.394487
N	3.494355	-0.271764	0.274724
H	2.657763	-0.780700	-0.040645
H	3.101752	0.653758	0.447777
H	-2.839121	-0.003741	-1.163301
H	4.062413	-0.160285	-0.564391
H	-0.999253	2.036676	1.311262

11-S

B3LYP-D3(BJ) SCF energy: -480.77025055 a.u.
B3LYP-D3(BJ) enthalpy: -480.570480 a.u.
B3LYP-D3(BJ) free energy: -480.621058 a.u.
B3LYP-D3(BJ) SCF energy in solution: -480.80255088 a.u.
B3LYP-D3(BJ) enthalpy in solution: -480.602780 a.u.
B3LYP-D3(BJ) free energy in solution: -480.653358 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -479.691201 a.u.
OLYP SCF energy in solution: -480.773068 a.u.
OPBE SCF energy in solution: -480.816322 a.u.
wB97XD SCF energy in solution: -480.629307 a.u.
KS-UCCSD(T) energy in gas phase: -1619.09923125 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -1619.58279294 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.011675	-0.002602	0.054099
O	0.433107	-0.034355	-1.777698
N	-0.392921	0.053534	1.845761
H	-0.230629	0.055630	-2.468892
N	1.536333	-1.329412	0.179110
H	1.763717	-1.393315	-0.815153
H	2.369734	-1.037853	0.682236
N	-1.558574	1.333940	-0.179052
H	-1.908010	1.500648	0.763931
H	-2.337636	1.004849	-0.743456
N	1.370588	1.494358	0.148649
H	1.656101	1.524393	-0.831023
H	1.010178	2.407875	0.410895
N	-1.405818	-1.496753	-0.118992
H	-1.792828	-1.558275	-1.057133
H	-1.038499	-2.419715	0.097523
H	2.190643	1.337674	0.727438
H	-2.161085	-1.332530	0.542736
H	-1.284129	2.227653	-0.579016
H	1.316085	-2.261772	0.518805
H	0.437786	-0.102445	2.437774

11-T

B3LYP-D3(BJ) SCF energy: -480.77169191 a.u.
B3LYP-D3(BJ) enthalpy: -480.571413 a.u.
B3LYP-D3(BJ) free energy: -480.625898 a.u.

B3LYP-D3(BJ) SCF energy in solution: -480.80399083 a.u.
B3LYP-D3(BJ) enthalpy in solution: -480.603712 a.u.
B3LYP-D3(BJ) free energy in solution: -480.658197 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -479.684032 a.u.
OLYP SCF energy in solution: -480.780751 a.u.
OPBE SCF energy in solution: -480.825539 a.u.
wB97XD SCF energy in solution: -480.628975 a.u.
KS-UCCSD(T) energy in gas phase: -1619.09322373 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -1619.57796815 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.027227	-0.007435	0.098213
O	0.319928	0.145782	-1.773863
N	-0.168729	-0.137390	1.852583
H	-0.332329	-0.123781	-2.428762
N	1.961593	0.411695	0.138624
H	2.137389	0.516761	-0.862905
H	2.220541	1.269981	0.615797
N	-2.046183	-0.354154	-0.160190
H	-2.505467	-0.123453	0.717790
H	-2.305636	-1.312985	-0.377222
N	-0.380623	2.008783	0.067456
H	-0.097446	2.296518	-0.867314
H	-1.350288	2.279897	0.205627
N	0.402947	-1.990203	-0.130025
H	0.689418	-2.023754	-1.107767
H	1.169650	-2.336295	0.440007
H	0.153261	2.521577	0.763002
H	-0.364379	-2.642708	0.005027
H	-2.457512	0.221724	-0.890962
H	2.577329	-0.309448	0.502424
H	0.230922	-0.778101	2.543507

11-Q

B3LYP-D3(BJ) SCF energy: -480.76641627 a.u.
B3LYP-D3(BJ) enthalpy: -480.569316 a.u.
B3LYP-D3(BJ) free energy: -480.626347 a.u.
B3LYP-D3(BJ) SCF energy in solution: -480.80010223 a.u.
B3LYP-D3(BJ) enthalpy in solution: -480.603002 a.u.
B3LYP-D3(BJ) free energy in solution: -480.660033 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -479.705192 a.u.
OLYP SCF energy in solution: -480.782495 a.u.
OPBE SCF energy in solution: -480.827974 a.u.
wB97XD SCF energy in solution: -480.622678 a.u.
KS-UCCSD(T) energy in gas phase: -1619.09855074 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -1619.58299806 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.014167	-0.018987	0.072190
O	0.211457	0.334415	-1.758202

N	-0.150835	-0.199611	1.833096
H	-0.073475	-0.293589	-2.429923
N	0.459821	2.085935	0.186166
H	0.521699	2.323909	-0.802872
H	-0.264196	2.649816	0.621574
N	-0.518373	-2.131540	-0.181927
H	-1.295438	-2.341900	0.439449
H	0.237145	-2.748206	0.104844
N	-2.191612	0.502350	-0.048369
H	-2.340598	1.294677	-0.667241
H	-2.811016	-0.233221	-0.377664
N	2.173809	-0.468126	0.023349
H	2.343718	-0.173160	-0.936921
H	2.771164	0.078315	0.637649
H	-2.497512	0.753541	0.888378
H	2.483387	-1.432698	0.107178
H	-0.786119	-2.414321	-1.121472
H	1.331135	2.341872	0.640564
H	0.647105	-0.509739	2.398930

12-S

B3LYP-D3(BJ) SCF energy: -708.41671330 a.u.
B3LYP-D3(BJ) enthalpy: -708.210933 a.u.
B3LYP-D3(BJ) free energy: -708.268801 a.u.
B3LYP-D3(BJ) SCF energy in solution: -708.46805270 a.u.
B3LYP-D3(BJ) enthalpy in solution: -708.262272 a.u.
B3LYP-D3(BJ) free energy in solution: -708.320140 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -706.855652 a.u.
OLYP SCF energy in solution: -708.352699 a.u.
OPBE SCF energy in solution: -708.362600 a.u.
wB97XD SCF energy in solution: -708.177648 a.u.
KS-UCCSD(T) energy in gas phase: -1846.06364258 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.000348	0.001388	0.011785
O	0.001773	-0.177814	-1.905936
N	-0.000516	0.158082	1.921518
H	0.026274	0.725187	-2.247191
C	-3.357267	0.004988	-0.002720
C	-2.690665	1.238407	0.018246
C	-2.688116	-1.227936	0.010937
H	-4.442117	0.003676	-0.014091
H	-3.324197	2.132215	0.075990
H	-3.319714	-2.123514	-0.037445
N	-1.391982	-1.397088	0.084213
H	-1.108088	-2.367944	0.010699
N	-1.392658	1.409455	-0.023909
H	-1.110017	2.375873	0.098758
C	3.356703	0.004253	-0.003398
C	2.690626	1.237977	0.015272
C	2.687341	-1.228545	0.017371

H	4.441553	0.002521	-0.015463
H	3.324616	2.131614	0.070984
H	3.318961	-2.124418	-0.024940
N	1.391236	-1.397234	0.091135
H	1.107332	-2.368807	0.028218
N	1.392584	1.409422	-0.026303
H	1.110621	2.376039	0.096665
H	-0.012739	-0.829326	2.238069

12-T

B3LYP-D3(BJ) SCF energy: -708.41680623 a.u.
B3LYP-D3(BJ) enthalpy: -708.210760 a.u.
B3LYP-D3(BJ) free energy: -708.268697 a.u.
B3LYP-D3(BJ) SCF energy in solution: -708.46855834 a.u.
B3LYP-D3(BJ) enthalpy in solution: -708.262512 a.u.
B3LYP-D3(BJ) free energy in solution: -708.320449 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -706.850837 a.u.
OLYP SCF energy in solution: -708.358401 a.u.
OPBE SCF energy in solution: -708.369516 a.u.
wB97XD SCF energy in solution: -708.176459 a.u.
KS-UCCSD(T) energy in gas phase: -1846.06202741 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	0.008796	-0.006318	0.041123
O	0.061831	-0.130916	-1.893995
N	-0.106849	0.046180	1.916388
H	0.326042	0.749812	-2.189770
C	-3.344692	0.000210	-0.002823
C	-2.679330	1.233685	-0.019251
C	-2.674423	-1.234730	-0.059796
H	-4.429442	-0.000884	-0.009462
H	-3.312423	2.129094	-0.027778
H	-3.304778	-2.127281	-0.153428
N	-1.379436	-1.401659	-0.015943
H	-1.081114	-2.356896	-0.175611
N	-1.378736	1.402403	-0.029469
H	-1.094436	2.375336	-0.055868
C	3.365457	0.001018	-0.041408
C	2.700136	1.229727	0.009409
C	2.696831	-1.231014	0.066793
H	4.449388	-0.001009	-0.085741
H	3.331494	2.126006	0.047828
H	3.330200	-2.125404	0.110205
N	1.404382	-1.392702	0.142344
H	1.116883	-2.354659	0.281695
N	1.397746	1.398718	0.030640
H	1.121078	2.359198	0.203519
H	-1.119858	0.074314	2.111918

12-Q

B3LYP-D3(BJ) SCF energy: -708.40130406 a.u.
B3LYP-D3(BJ) enthalpy: -708.196787 a.u.
B3LYP-D3(BJ) free energy: -708.258762 a.u.
B3LYP-D3(BJ) SCF energy in solution: -708.45456630 a.u.
B3LYP-D3(BJ) enthalpy in solution: -708.250049 a.u.
B3LYP-D3(BJ) free energy in solution: -708.312024 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -706.856609 a.u.
OLYP SCF energy in solution: -708.335092 a.u.
OPBE SCF energy in solution: -708.344803 a.u.
wB97XD SCF energy in solution: -708.163213 a.u.
KS-UCCSD(T) energy in gas phase: -1846.03374462 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-0.003827	0.031197	-0.069487
O	-0.088954	0.039779	-1.945431
N	0.106731	0.099542	1.869286
H	0.815721	0.212503	-2.233357
C	-3.513977	0.162552	0.053565
C	-2.735029	1.300635	0.269969
C	-3.007003	-1.142430	-0.135852
H	-4.591562	0.292772	0.022712
H	-3.294777	2.226959	0.454917
H	-3.767980	-1.903862	-0.372772
N	-1.753750	-1.493586	-0.045275
H	-1.624254	-2.473876	-0.285700
N	-1.421583	1.390149	0.269821
H	-1.073985	2.306782	0.523716
C	3.494732	-0.212449	0.161577
C	3.041050	1.108623	-0.058615
C	2.682914	-1.346183	0.226570
H	4.562769	-0.358554	0.292103
H	3.836310	1.871954	-0.073616
H	3.214223	-2.292325	0.394455
N	1.372248	-1.414139	0.098824
H	1.010120	-2.355944	0.192207
N	1.802160	1.467332	-0.246961
H	1.712324	2.469939	-0.392154
H	-0.504545	-0.695271	2.124448

13-S

B3LYP-D3(BJ) SCF energy: -1083.79392383 a.u.
B3LYP-D3(BJ) enthalpy: -1083.591027 a.u.
B3LYP-D3(BJ) free energy: -1083.652332 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1083.84094939 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1083.638053 a.u.
B3LYP-D3(BJ) free energy in solution: -1083.699358 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -1082.151886 a.u.
OLYP SCF energy in solution: -1083.745948 a.u.
OPBE SCF energy in solution: -1083.705461 a.u.
wB97XD SCF energy in solution: -1083.560685 a.u.

KS-UCCSD(T) energy in gas phase: -2221.01318414 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -2221.95077841 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	1.110252	-0.000960	0.046144
O	2.938605	-0.333814	-0.477086
N	-0.650907	0.433981	0.690183
S	-1.997469	0.038586	-0.055983
O	-2.393923	1.132856	-0.979381
O	-2.123885	-1.326798	-0.619952
N	-3.124626	-0.006862	1.248189
H	-3.170992	0.924286	1.649759
H	-4.032393	-0.253257	0.861913
H	3.020877	0.240726	-1.248948
N	1.562463	-0.881230	1.759821
H	2.581858	-0.842418	1.761431
H	1.237774	-0.306360	2.537598
N	0.878172	0.860154	-1.718313
H	-0.061583	1.241488	-1.820424
H	0.964201	0.165486	-2.460669
N	1.688122	1.827002	0.681524
H	2.652456	1.730542	0.975279
H	1.631078	2.350610	-0.188081
N	0.736793	-1.862385	-0.569496
H	1.518968	-2.094614	-1.169716
H	0.836651	-2.317198	0.336782
H	1.097806	2.221698	1.402737
H	-0.180222	-2.025971	-0.973678

13-T

B3LYP-D3(BJ) SCF energy: -1083.80518129 a.u.
B3LYP-D3(BJ) enthalpy: -1083.600822 a.u.
B3LYP-D3(BJ) free energy: -1083.661148 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1083.85331087 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1083.648952 a.u.
B3LYP-D3(BJ) free energy in solution: -1083.709278 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -1082.139024 a.u.
OLYP SCF energy in solution: -1083.763972 a.u.
OPBE SCF energy in solution: -1083.72678518 a.u.
wB97XD SCF energy in solution: -1083.565998 a.u.
KS-UCCSD(T) energy in gas phase: -2221.03248851 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -2221.96862206 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	-1.094004	0.022190	0.036696
O	-2.854662	0.113239	-0.612268
N	0.588110	-0.089814	0.781132
S	1.929841	-0.056185	-0.023836
O	2.385976	-1.386086	-0.521481
O	2.074827	1.026895	-1.042187

N	3.061833	0.420011	1.209528
H	2.905479	-0.210779	1.990713
H	3.989126	0.231515	0.833270
H	-2.796212	-0.545436	-1.319352
N	-1.735378	1.206241	1.533071
H	-2.729073	0.983010	1.606308
H	-1.287210	0.844034	2.375680
N	-0.761122	-1.149699	-1.554766
H	0.103932	-1.664387	-1.385023
H	-0.517900	-0.548716	-2.343892
N	-1.603177	-1.699588	0.965138
H	-2.495344	-1.593920	1.430909
H	-1.667949	-2.361237	0.196630
N	-0.687471	1.749314	-0.846308
H	-1.352519	1.901340	-1.593714
H	-0.905228	2.336723	-0.040048
H	-0.859177	-1.946925	1.606241
H	0.290032	1.809154	-1.137526

13-Q

B3LYP-D3(BJ) SCF energy: -1083.80877247 a.u.
B3LYP-D3(BJ) enthalpy: -1083.606799 a.u.
B3LYP-D3(BJ) free energy: -1083.671663 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1083.85798832 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1083.656015 a.u.
B3LYP-D3(BJ) free energy in solution: -1083.720879 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -1082.171199 a.u.
OLYP SCF energy in solution: -1083.773906 a.u.
OPBE SCF energy in solution: -1083.735421 a.u.
wB97XD SCF energy in solution: -1083.571891 a.u.
KS-UCCSD(T) energy in gas phase: -2221.04083815 a.u.
KS-UCCSD(T)-F12 energy in gas phase: -2221.98047784 a.u.

Cartesian coordinates

ATOM	X	Y	Z
Fe	1.128981	-0.053323	0.062055
O	2.903341	-0.442044	-0.441262
N	-0.581971	0.451126	0.590591
S	-1.951491	0.041128	-0.039738
O	-2.254070	0.761124	-1.312655
O	-2.271950	-1.411985	-0.101357
N	-3.085348	0.617317	1.144689
H	-2.939499	1.620331	1.218590
H	-4.012634	0.460093	0.754980
H	3.026663	0.062056	-1.255423
N	1.648163	-0.574684	1.841420
H	2.642504	-0.384517	1.939491
H	1.126855	-0.038767	2.529560
N	0.884258	0.527287	-1.807276
H	-0.102127	0.709588	-1.986918
H	1.143790	-0.254479	-2.407569
N	1.685240	2.260150	0.304921

H	2.570620	2.630894	0.625343
H	1.590434	2.351516	-0.703224
N	0.525093	-2.247628	-0.230181
H	0.996693	-2.790708	-0.941157
H	0.862975	-2.499335	0.692614
H	0.905464	2.708629	0.767673
H	-0.488018	-2.338674	-0.278554

5a

B3LYP-D3(BJ) SCF energy: -1196.39318382 a.u.
B3LYP-D3(BJ) enthalpy: -1196.100257 a.u.
B3LYP-D3(BJ) free energy: -1196.170307 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1196.64512779 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1196.352201 a.u.
B3LYP-D3(BJ) free energy in solution: -1196.422251 a.u.

Cartesian coordinates

ATOM	X	Y	Z
N	2.139686	1.241810	-0.634313
S	2.916136	-0.332534	-0.327491
O	4.234757	-0.050863	0.232379
O	2.715167	-1.067580	-1.564786
N	1.985267	-1.032623	0.845533
C	2.033886	-0.400022	2.168911
H	1.597489	-1.103176	2.883212
H	1.469430	0.540934	2.206505
H	3.072542	-0.216143	2.445640
C	0.700730	-1.637705	0.432349
H	0.892288	-2.189660	-0.487419
H	0.463497	-2.371494	1.212516
C	-0.454390	-0.646697	0.261445
H	-0.588429	-0.072930	1.186469
H	-0.200599	0.076097	-0.521567
C	-1.790704	-1.338954	-0.084396
H	-1.980781	-2.102410	0.684166
N	2.786420	2.206393	-0.190595
N	3.306691	3.150410	0.172182
C	-2.933752	-0.340343	-0.016057
C	-3.963376	-0.496607	0.920296
C	-2.983406	0.762932	-0.881998
C	-5.016714	0.419944	0.994463
H	-3.941579	-1.347344	1.598354
C	-4.031942	1.681716	-0.812303
H	-2.197411	0.907982	-1.618825
C	-5.053930	1.513884	0.127471
H	-5.805813	0.277591	1.728263
H	-4.051593	2.529430	-1.492265
H	-5.870532	2.228666	0.181359
C	-1.744911	-2.046956	-1.451701
H	-1.009711	-2.858848	-1.464325
H	-1.478746	-1.343937	-2.249541
H	-2.723012	-2.475760	-1.693956

7S

B3LYP-D3(BJ) SCF energy: -2314.13017662 a.u.
B3LYP-D3(BJ) enthalpy: -2313.511166 a.u.
B3LYP-D3(BJ) free energy: -2313.625618 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.72307438 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.104064 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.218516 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -2310.23772378 a.u.
OLYP SCF energy in solution: -2314.024231 a.u.
OPBE SCF energy in solution: -2313.920653 a.u.
wB97XD SCF energy in solution: -2313.87459 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	2.669564	-2.676171	0.941307
C	2.541675	-3.595590	2.053435
C	2.134171	-2.857691	3.125004
C	2.018279	-1.489454	2.665979
H	2.730276	-4.660972	1.996755
H	1.917875	-3.189596	4.133352
C	3.051501	-3.049279	-0.339857
H	3.255016	-4.102767	-0.510130
C	3.157616	-2.198838	-1.433127
C	3.505889	-2.630313	-2.769360
C	3.485752	-1.517613	-3.560375
H	3.723169	-3.654321	-3.048735
C	3.131081	-0.406595	-2.703928
H	3.688061	-1.438506	-4.621979
C	3.028664	0.913292	-3.127514
H	3.211951	1.116738	-4.179119
C	2.722677	1.994801	-2.308882
C	2.635805	3.368070	-2.757117
C	2.310924	4.116383	-1.661523
H	2.801901	3.697697	-3.775988
C	2.194516	3.196988	-0.549114
H	2.152389	5.186485	-1.597394
N	2.940073	-0.847848	-1.421132
N	2.342477	-1.410351	1.340562
N	2.461345	1.922367	-0.967713
Fe	2.410228	0.252843	0.189884
C	1.828490	3.569644	0.739837
H	1.648467	4.626678	0.917275
C	1.650373	2.707112	1.815529
C	1.251024	3.132067	3.142651
C	1.186733	2.006039	3.910070
H	1.049360	4.157895	3.427783
C	1.551013	0.898075	3.051313
H	0.920812	1.914008	4.956368
N	1.818479	1.350808	1.790492
C	1.637696	-0.423502	3.468151
H	1.389287	-0.639830	4.503324

O	4.146863	0.483942	0.746396
C	5.178451	0.766898	-0.145512
H	6.117552	0.872356	0.425360
H	5.325115	-0.033660	-0.891523
H	5.013645	1.706419	-0.701326
N	0.559053	0.102755	-0.388111
S	-0.510559	-1.022081	0.005086
O	-0.176631	-2.303883	-0.667502
O	-0.864904	-1.082542	1.438203
N	-1.950093	-0.396041	-0.743826
C	-1.781959	-0.189237	-2.182207
H	-1.746947	-1.141529	-2.738522
H	-2.618571	0.412662	-2.553361
H	-0.853967	0.359873	-2.351533
C	-3.135508	-1.191493	-0.407237
H	-3.043403	-1.482378	0.642729
H	-3.166498	-2.114289	-1.011545
C	-4.422962	-0.379702	-0.589552
H	-4.628594	-0.212816	-1.655436
H	-4.269949	0.607586	-0.137539
C	-5.656630	-1.046357	0.058054
H	-5.427948	-1.186824	1.123717
C	-6.864147	-0.129515	-0.024846
C	-7.478232	0.159446	-1.253776
C	-7.385967	0.471258	1.128600
C	-8.577545	1.016934	-1.326305
H	-7.090479	-0.287701	-2.165441
C	-8.486592	1.331014	1.063998
H	-6.918215	0.265352	2.088965
C	-9.088405	1.607322	-0.165805
H	-9.034563	1.227338	-2.290455
H	-8.870194	1.785912	1.974168
H	-9.943246	2.276683	-0.221439
C	-5.956202	-2.433906	-0.539146
H	-6.091753	-2.377122	-1.626473
H	-5.134165	-3.129729	-0.344366
H	-6.871825	-2.854768	-0.106992

7T

B3LYP-D3(BJ) SCF energy: -2314.13349037 a.u.
B3LYP-D3(BJ) enthalpy: -2313.514266 a.u.
B3LYP-D3(BJ) free energy: -2313.628435 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.72830920 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.109085 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.223254 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -2310.23459477 a.u.
OLYP SCF energy in solution: -2314.037303 a.u.
OPBE SCF energy in solution: -2313.935324 a.u.
wB97XD SCF energy in solution: -2313.876006 a.u.

Cartesian coordinates

ATOM	X	Y	Z

C	1.713821	-0.370566	3.082035
C	1.215419	0.192790	4.320405
C	0.932473	1.501931	4.067235
C	1.270016	1.737122	2.676859
H	1.093462	-0.360436	5.243884
H	0.535465	2.252057	4.740851
C	2.085617	-1.698065	2.920598
H	1.998488	-2.348499	3.786226
C	2.505260	-2.278918	1.731682
C	2.811604	-3.683838	1.575259
C	3.140581	-3.872013	0.264734
H	2.757486	-4.416811	2.371175
C	3.045778	-2.580336	-0.377215
H	3.415756	-4.790742	-0.238957
C	3.334728	-2.344548	-1.714307
H	3.618094	-3.198876	-2.322400
C	3.303727	-1.100353	-2.330632
C	3.652609	-0.857401	-3.713507
C	3.520502	0.486059	-3.919888
H	3.955086	-1.623496	-4.417470
C	3.082005	1.059705	-2.664749
H	3.691146	1.049951	-4.829435
N	2.660475	-1.633292	0.533925
N	1.734307	0.585410	2.108026
N	2.967197	0.077151	-1.719303
Fe	2.347974	0.323154	0.198742
C	2.798491	2.408292	-2.477444
H	2.944716	3.067949	-3.328751
C	2.310566	2.979318	-1.307401
C	1.966822	4.379980	-1.163157
C	1.487476	4.535674	0.105278
H	2.077926	5.126743	-1.940622
C	1.549628	3.231928	0.734063
H	1.125731	5.437004	0.585888
N	2.052179	2.313801	-0.142886
C	1.165735	2.969304	2.043828
H	0.775466	3.799093	2.626863
O	4.045089	0.733785	0.799815
C	5.189108	0.131175	0.284429
H	6.063060	0.486444	0.858103
H	5.159689	-0.969574	0.363456
H	5.358795	0.378759	-0.778298
N	0.597869	0.055408	-0.389389
S	-0.442247	-1.112291	-0.071013
O	-0.082216	-2.345894	-0.818443
O	-0.808843	-1.287156	1.350615
N	-1.883192	-0.456287	-0.789381
C	-1.715400	-0.175003	-2.215075
H	-1.689224	-1.097246	-2.820420
H	-2.547477	0.452490	-2.552826
H	-0.783069	0.374105	-2.356852
C	-3.067589	-1.268223	-0.493270
H	-2.973664	-1.613651	0.539736
H	-3.099277	-2.158077	-1.145321

C	-4.355118	-0.447992	-0.631898
H	-4.560059	-0.222824	-1.687206
H	-4.202438	0.513089	-0.126423
C	-5.589137	-1.149195	-0.022513
H	-5.361148	-1.347417	1.034080
C	-6.796732	-0.229391	-0.056330
C	-7.410923	0.124621	-1.268081
C	-7.318343	0.309409	1.127454
C	-8.509991	0.985071	-1.294886
H	-7.023165	-0.273393	-2.202229
C	-8.418692	1.171750	1.108699
H	-6.850495	0.052723	2.075466
C	-9.020593	1.513149	-0.104618
H	-8.966952	1.246587	-2.246483
H	-8.802036	1.577840	2.041790
H	-9.875194	2.184844	-0.124529
C	-5.887798	-2.502272	-0.694572
H	-6.020908	-2.386737	-1.777557
H	-5.066225	-3.207761	-0.536007
H	-6.804422	-2.945687	-0.287744

7Q

B3LYP-D3(BJ) SCF energy: -2314.11090803 a.u.
B3LYP-D3(BJ) enthalpy: -2313.493276 a.u.
B3LYP-D3(BJ) free energy: -2313.609263 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.70645447 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.088822 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.204809 a.u.
B2PLYP-D3(BJ) SCF energy in solution: -2310.22878393 a.u.
OLYP SCF energy in solution: -2314.020857 a.u.
OPBE SCF energy in solution: -2313.921034 a.u.
wB97XD SCF energy in solution: -2313.853014 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	1.572139	-0.134083	3.160048
C	1.074750	0.556490	4.338732
C	0.873388	1.859778	3.979945
C	1.250772	1.975596	2.579505
H	0.900800	0.093141	5.302823
H	0.506441	2.674056	4.593983
C	1.902731	-1.492126	3.092392
H	1.759097	-2.067683	4.003389
C	2.361532	-2.202538	1.978484
C	2.654149	-3.623655	1.937218
C	3.049951	-3.913570	0.659934
H	2.551996	-4.303120	2.775234
C	3.006793	-2.670491	-0.087383
H	3.336560	-4.875243	0.250934
C	3.349425	-2.507741	-1.434139
H	3.642698	-3.407719	-1.968760
C	3.348755	-1.320481	-2.175436

C	3.706605	-1.203428	-3.577381
C	3.573207	0.116052	-3.914249
H	4.009598	-2.028292	-4.211664
C	3.129438	0.815801	-2.721144
H	3.747965	0.580811	-4.877780
N	2.589769	-1.672258	0.742470
N	1.656936	0.754685	2.132536
N	3.020506	-0.083070	-1.699243
Fe	2.318259	0.322885	0.218343
C	2.844459	2.185898	-2.645305
H	2.994426	2.757082	-3.558678
C	2.363643	2.896865	-1.537643
C	2.041097	4.315213	-1.504856
C	1.577901	4.585435	-0.245793
H	2.153848	5.001245	-2.336626
C	1.618079	3.334098	0.495238
H	1.237651	5.535108	0.150963
N	2.100696	2.355857	-0.318221
C	1.223310	3.157412	1.827820
H	0.860882	4.043684	2.343650
O	4.009239	0.719929	0.869047
C	5.168645	0.160203	0.334174
H	6.019810	0.478571	0.960864
H	5.142983	-0.942135	0.335554
H	5.364062	0.490231	-0.699767
N	0.608319	0.072483	-0.378199
S	-0.417698	-1.134414	-0.139798
O	-0.042336	-2.315576	-0.957379
O	-0.786795	-1.394727	1.266656
N	-1.851234	-0.437799	-0.828471
C	-1.674478	-0.071752	-2.234214
H	-1.632244	-0.956533	-2.891849
H	-2.511829	0.564370	-2.540708
H	-0.748576	0.496498	-2.336828
C	-3.036508	-1.267456	-0.587804
H	-2.943081	-1.683146	0.419030
H	-3.069379	-2.110223	-1.299324
C	-4.322200	-0.436682	-0.667663
H	-4.526191	-0.135376	-1.703978
H	-4.167224	0.484793	-0.093982
C	-5.557558	-1.177720	-0.110449
H	-5.328262	-1.455876	0.927669
C	-6.761902	-0.253807	-0.071929
C	-7.376762	0.193471	-1.252045
C	-7.279650	0.194808	1.150508
C	-8.472952	1.057034	-1.211085
H	-6.991931	-0.133487	-2.214560
C	-8.377140	1.059550	1.199597
H	-6.811069	-0.134804	2.075312
C	-8.979830	1.494376	0.016953
H	-8.930557	1.391890	-2.139083
H	-8.757563	1.394575	2.161636
H	-9.832175	2.168400	0.049939
C	-5.862601	-2.475128	-0.882092

H	-5.998634	-2.277441	-1.952756
H	-5.043112	-3.193412	-0.780010
H	-6.779501	-2.945146	-0.507108

TS1-S

B3LYP-D3(BJ) SCF energy: -2314.11932513 a.u.
B3LYP-D3(BJ) enthalpy: -2313.506556 a.u.
B3LYP-D3(BJ) free energy: -2313.609282 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.70709261 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.094323 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.197049 a.u.
Imaginary frequency: -2027.2844 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.558218	0.156549	0.975174
C	4.312718	1.017634	1.858225
C	3.422857	1.540425	2.750658
C	2.129074	0.979393	2.427698
H	5.376946	1.202974	1.776231
H	3.606237	2.239251	3.557965
C	4.093690	-0.531413	-0.104761
H	5.159095	-0.427395	-0.288311
C	3.352792	-1.269200	-1.017653
C	3.890533	-1.869977	-2.218624
C	2.839457	-2.442578	-2.873770
H	4.931847	-1.829547	-2.514958
C	1.664516	-2.214062	-2.056943
H	2.841068	-2.981230	-3.814058
C	0.406421	-2.733484	-2.339610
H	0.305076	-3.314899	-3.252325
C	-0.705949	-2.657724	-1.506976
C	-1.927776	-3.414333	-1.703229
C	-2.716272	-3.169889	-0.616997
H	-2.127056	-4.057321	-2.552697
C	-1.990616	-2.240176	0.222532
H	-3.708057	-3.547271	-0.401281
N	2.005592	-1.495831	-0.943662
N	2.237084	0.153349	1.340492
N	-0.780084	-1.947885	-0.342906
Fe	0.730903	-0.876295	0.490505
C	-2.476624	-1.693151	1.401451
H	-3.474483	-1.984175	1.714406
C	-1.804605	-0.763679	2.186545
C	-2.337610	-0.168844	3.392002
C	-1.375155	0.673938	3.873582
H	-3.320447	-0.376270	3.798283
C	-0.249850	0.578229	2.967664
H	-1.402427	1.294376	4.761603
N	-0.548747	-0.276144	1.942388
C	0.975877	1.204214	3.167548
H	1.055479	1.880521	4.014308

O	1.035802	-2.367585	1.522327
C	2.308010	-2.858358	1.798994
H	2.935153	-2.134155	2.347101
H	2.860324	-3.148694	0.888827
H	2.201058	-3.758020	2.429909
N	0.187891	0.653470	-0.754738
S	1.166298	1.909987	-1.033602
O	2.445836	1.449561	-1.603324
O	1.248197	2.897371	0.076665
N	0.409573	2.773617	-2.369010
C	1.406891	3.585970	-3.076526
H	1.774293	4.435835	-2.474501
H	0.934674	3.976234	-3.986122
H	2.253551	2.958881	-3.354752
C	-0.732180	3.597824	-1.947840
H	-0.469315	4.231356	-1.086335
H	-0.941766	4.269464	-2.789358
C	-2.002339	2.788812	-1.692790
H	-2.849214	3.496842	-1.662264
H	-2.162474	2.147748	-2.564679
C	-2.077624	1.953657	-0.409238
H	-0.993852	1.190266	-0.492385
C	-3.242295	1.022111	-0.460976
C	-4.268107	1.049442	0.500538
C	-3.370712	0.112973	-1.529061
C	-5.392980	0.230629	0.381028
H	-4.187631	1.718008	1.350544
C	-4.491413	-0.703746	-1.650551
H	-2.558382	0.019929	-2.243710
C	-5.516496	-0.645233	-0.700287
H	-6.173640	0.277664	1.137761
H	-4.549564	-1.410866	-2.473291
H	-6.390388	-1.286201	-0.793301
C	-1.915122	2.771712	0.857714
H	-2.045510	2.158326	1.750459
H	-0.913699	3.205647	0.904266
H	-2.652955	3.591782	0.890748

TS1-T

B3LYP-D3(BJ) SCF energy: -2314.11918855 a.u.
B3LYP-D3(BJ) enthalpy: -2313.506391 a.u.
B3LYP-D3(BJ) free energy: -2313.610175 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.70730228 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.094505 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.198289 a.u.
Imaginary frequency: -2021.2121 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.575698	0.134990	0.933231
C	4.353657	0.999105	1.792238
C	3.481998	1.552078	2.685041

C	2.176084	1.006475	2.386874
H	5.419622	1.166195	1.695132
H	3.685567	2.262520	3.477208
C	4.085696	-0.576433	-0.145241
H	5.149565	-0.489230	-0.345766
C	3.322143	-1.316552	-1.035915
C	3.835600	-1.941023	-2.235865
C	2.769892	-2.515209	-2.864907
H	4.872380	-1.914063	-2.549194
C	1.610086	-2.263667	-2.032735
H	2.752011	-3.069034	-3.796172
C	0.344253	-2.781218	-2.282598
H	0.222210	-3.381153	-3.180622
C	-0.751604	-2.679840	-1.431087
C	-1.980738	-3.432400	-1.587476
C	-2.749834	-3.155749	-0.494944
H	-2.198543	-4.094163	-2.417740
C	-2.006059	-2.210737	0.309671
H	-3.740678	-3.520377	-0.254667
N	1.973422	-1.530089	-0.937089
N	2.260295	0.159379	1.313594
N	-0.801043	-1.941516	-0.282504
Fe	0.728532	-0.866890	0.504895
C	-2.471677	-1.631712	1.480756
H	-3.467339	-1.907818	1.813619
C	-1.781436	-0.689011	2.235010
C	-2.293675	-0.057606	3.431609
C	-1.315978	0.786263	3.879241
H	-3.273475	-0.243552	3.855363
C	-0.203066	0.653527	2.962087
H	-1.325226	1.429761	4.751064
N	-0.524860	-0.222704	1.963220
C	1.034129	1.265610	3.132811
H	1.133528	1.960353	3.962391
O	1.045043	-2.301513	1.609115
C	2.281911	-2.929873	1.714578
H	3.076213	-2.248210	2.064142
H	2.621326	-3.368251	0.760280
H	2.192231	-3.747471	2.450968
N	0.206160	0.661043	-0.727129
S	1.173666	1.913488	-1.036002
O	2.461282	1.449607	-1.584956
O	1.243294	2.931572	0.047360
N	0.416905	2.734438	-2.398616
C	1.413307	3.527942	-3.128461
H	1.777235	4.396608	-2.551704
H	0.941604	3.889165	-4.050232
H	2.262325	2.895309	-3.386112
C	-0.729319	3.566244	-2.005974
H	-0.474739	4.219466	-1.156884
H	-0.933462	4.218423	-2.863957
C	-1.999911	2.760337	-1.743206
H	-2.847503	3.468086	-1.727461
H	-2.156045	2.105102	-2.605286

C	-2.077894	1.945955	-0.446861
H	-0.988419	1.189537	-0.503530
C	-3.240834	1.011653	-0.486364
C	-4.268565	1.053256	0.472684
C	-3.367156	0.085990	-1.540399
C	-5.393277	0.232676	0.363434
H	-4.190084	1.734867	1.312431
C	-4.487642	-0.732332	-1.651731
H	-2.553725	-0.017706	-2.252361
C	-5.514913	-0.659183	-0.704744
H	-6.175356	0.291231	1.117909
H	-4.544215	-1.452090	-2.463564
H	-6.388552	-1.301593	-0.789795
C	-1.923749	2.786197	0.807130
H	-2.049418	2.186066	1.709560
H	-0.926377	3.229727	0.847777
H	-2.669027	3.599930	0.826188

TS1-Q

B3LYP-D3(BJ) SCF energy: -2314.09480305 a.u.
B3LYP-D3(BJ) enthalpy: -2313.483639 a.u.
B3LYP-D3(BJ) free energy: -2313.589307 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.68200363 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.070840 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.176508 a.u.
Imaginary frequency: -2071.1013 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-3.617635	-0.208699	0.910146
C	-4.423830	-1.087396	1.738827
C	-3.575402	-1.666457	2.643212
C	-2.250447	-1.132908	2.379317
H	-5.490778	-1.242696	1.628997
H	-3.814964	-2.385942	3.417538
C	-4.072239	0.577667	-0.154681
H	-5.132681	0.516172	-0.385646
C	-3.304287	1.392552	-0.991824
C	-3.816873	2.134295	-2.128239
C	-2.756753	2.790483	-2.688712
H	-4.851475	2.134854	-2.450723
C	-1.587293	2.467253	-1.889342
H	-2.753996	3.440972	-3.555676
C	-0.313323	3.019032	-2.079175
H	-0.215887	3.720104	-2.905012
C	0.819967	2.839732	-1.274586
C	2.052813	3.610618	-1.345492
C	2.830643	3.205925	-0.295424
H	2.272620	4.372502	-2.084901
C	2.087014	2.173244	0.406637
H	3.819704	3.553652	-0.022571
N	-1.959682	1.618067	-0.886172

N	-2.322325	-0.274560	1.324410
N	0.897011	1.976342	-0.227340
Fe	-0.703224	0.808421	0.525340
C	2.507362	1.485752	1.547564
H	3.500133	1.725652	1.917742
C	1.797977	0.517309	2.271139
C	2.277088	-0.140666	3.472363
C	1.274544	-0.968680	3.901728
H	3.250652	0.020870	3.920517
C	0.170667	-0.812412	2.971426
H	1.265213	-1.611523	4.774344
N	0.543024	0.059196	1.988263
C	-1.094091	-1.397984	3.119945
H	-1.202332	-2.093854	3.948647
O	-1.008177	2.163230	1.740448
C	-2.169819	2.934853	1.739131
H	-3.082985	2.326500	1.839976
H	-2.273897	3.552649	0.831851
H	-2.118554	3.612365	2.609154
N	-0.200461	-0.629921	-0.782745
S	-1.193516	-1.852526	-1.159046
O	-2.460157	-1.338763	-1.707765
O	-1.291517	-2.907016	-0.116514
N	-0.423963	-2.621479	-2.539935
C	-1.420256	-3.340422	-3.343966
H	-1.828443	-4.228126	-2.829562
H	-0.929514	-3.663405	-4.269717
H	-2.240987	-2.667752	-3.591160
C	0.689822	-3.503991	-2.162917
H	0.402765	-4.178645	-1.341925
H	0.886959	-4.130100	-3.041408
C	1.977316	-2.743540	-1.853618
H	2.805432	-3.474309	-1.846925
H	2.166363	-2.065468	-2.691109
C	2.056155	-1.973603	-0.530915
H	0.968498	-1.197630	-0.565723
C	3.221707	-1.042928	-0.538652
C	4.259404	-1.132867	0.405611
C	3.336496	-0.067667	-1.548615
C	5.383792	-0.308378	0.323535
H	4.188594	-1.854582	1.212166
C	4.454388	0.757462	-1.630018
H	2.514869	0.069336	-2.245366
C	5.492062	0.636800	-0.699010
H	6.174651	-0.404213	1.064893
H	4.500990	1.518823	-2.403506
H	6.363669	1.284606	-0.760333
C	1.888294	-2.851191	0.694955
H	2.017546	-2.282080	1.616855
H	0.886078	-3.285508	0.717787
H	2.623825	-3.674003	0.689875

8S

B3LYP-D3(BJ) SCF energy: -2314.15508605 a.u.
B3LYP-D3(BJ) enthalpy: -2313.536629 a.u.
B3LYP-D3(BJ) free energy: -2313.649048 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.74683776 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.128381 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.240800 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	1.840335	2.207091	-2.146759
C	1.590265	2.401715	-3.561779
C	1.591104	1.161880	-4.130527
C	1.836644	0.215511	-3.061699
H	1.440091	3.364494	-4.035855
H	1.438570	0.893591	-5.169055
C	1.941904	3.240595	-1.221941
H	1.804253	4.252674	-1.593476
C	2.210161	3.096718	0.135236
C	2.309562	4.200048	1.066764
C	2.583829	3.658811	2.290432
H	2.182953	5.243417	0.803036
C	2.649955	2.225615	2.103866
H	2.728811	4.166275	3.236777
C	2.906953	1.307222	3.116507
H	3.070078	1.697176	4.117429
C	2.961290	-0.072323	2.948501
C	3.202080	-1.023243	4.012209
C	3.147977	-2.264822	3.446101
H	3.379523	-0.759814	5.048152
C	2.878126	-2.070467	2.037593
H	3.271311	-3.229978	3.922742
N	2.421551	1.912131	0.789691
N	1.968022	0.874697	-1.872554
N	2.776174	-0.732856	1.761937
Fe	2.389021	0.067702	-0.061948
C	2.743531	-3.103077	1.116528
H	2.845599	-4.117116	1.493407
C	2.497703	-2.955175	-0.243286
C	2.412311	-4.060095	-1.179808
C	2.203436	-3.511350	-2.409534
H	2.499702	-5.105758	-0.910021
C	2.151556	-2.075812	-2.219275
H	2.077344	-4.011897	-3.361982
N	2.328948	-1.770424	-0.900765
C	1.931439	-1.158076	-3.235939
H	1.796396	-1.546440	-4.241392
O	4.161686	0.147043	-0.530933
C	5.145947	0.572293	0.358036
H	6.119719	0.542462	-0.161045
H	4.984606	1.605736	0.711270
H	5.221089	-0.072108	1.251336
N	0.466227	-0.019222	0.448983
S	-0.851088	-0.675936	-0.162639

O	-0.636631	-1.073651	-1.566743
O	-1.498012	-1.673177	0.726437
N	-1.993340	0.644739	-0.151334
C	-1.553835	1.743993	-1.014905
H	-1.585901	1.486121	-2.085193
H	-2.203149	2.607870	-0.829618
H	-0.530687	2.011906	-0.752658
C	-3.364670	0.188824	-0.424347
H	-3.368972	-0.695889	-1.076438
H	-3.883749	0.982957	-0.973735
C	-4.133103	-0.111395	0.883564
H	-4.293361	0.829094	1.420935
H	-3.470882	-0.729081	1.497100
C	-5.407042	-0.856841	0.620778
C	-6.674435	-0.216009	0.504656
C	-7.874015	-0.966204	0.304704
C	-6.820947	1.203248	0.576774
C	-9.112012	-0.345818	0.192519
H	-7.818785	-2.048150	0.245663
C	-8.062441	1.813581	0.459284
H	-5.941215	1.822077	0.715329
C	-9.224422	1.050156	0.267674
H	-10.002323	-0.953492	0.044526
H	-8.130192	2.897932	0.513964
H	-10.194014	1.532582	0.176770
H	0.325467	0.116504	1.448407
C	-5.268401	-2.342297	0.420703
H	-5.735469	-2.683847	-0.514049
H	-4.212395	-2.626679	0.395888
H	-5.745653	-2.908863	1.237101

8T

B3LYP-D3(BJ) SCF energy: -2314.15695302 a.u.
B3LYP-D3(BJ) enthalpy: -2313.538448 a.u.
B3LYP-D3(BJ) free energy: -2313.650933 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.74857539 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.130070 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.242555 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	2.306385	-2.224050	1.903139
C	2.081646	-2.678133	3.261845
C	1.655200	-1.592311	3.968790
C	1.616426	-0.481686	3.039663
H	2.237957	-3.693085	3.607828
H	1.384652	-1.530129	5.016026
C	2.776173	-3.035124	0.875938
H	2.964147	-4.078486	1.115450
C	3.033956	-2.630123	-0.429520
C	3.525511	-3.506073	-1.471595
C	3.653623	-2.744570	-2.598255

H	3.738488	-4.560568	-1.341581
C	3.238504	-1.405157	-2.242185
H	3.993376	-3.045352	-3.582237
C	3.218579	-0.324298	-3.117585
H	3.538819	-0.501739	-4.140559
C	2.810557	0.963547	-2.787168
C	2.766290	2.076496	-3.710775
C	2.285083	3.146031	-3.011188
H	3.060116	2.027088	-4.752541
C	2.039947	2.686179	-1.661038
H	2.102297	4.154850	-3.361580
N	2.869695	-1.362993	-0.923206
N	2.000418	-0.896769	1.796237
N	2.372960	1.362284	-1.550940
Fe	2.201430	0.240157	0.131002
C	1.537113	3.485725	-0.640919
H	1.313566	4.519788	-0.888795
C	1.301796	3.083729	0.668415
C	0.820895	3.964582	1.716291
C	0.758721	3.216879	2.853842
H	0.568012	5.008812	1.576821
C	1.191040	1.880984	2.495778
H	0.438208	3.516315	3.844383
N	1.508843	1.830377	1.169197
C	1.247908	0.812649	3.378763
H	0.955093	0.997156	4.408407
O	3.882890	0.668825	0.728448
C	4.984669	0.708425	-0.122686
H	5.874188	0.978682	0.472490
H	5.185782	-0.263698	-0.605785
H	4.876619	1.458257	-0.925745
N	0.376227	-0.223210	-0.519356
S	-1.102956	-0.121433	0.064516
O	-1.080875	0.118225	1.519163
O	-2.008208	0.736094	-0.742504
N	-1.748096	-1.719982	-0.204290
C	-0.989067	-2.736072	0.530056
H	-1.126986	-2.667333	1.620678
H	-1.314243	-3.724415	0.184112
H	0.070564	-2.617421	0.305675
C	-3.199280	-1.779757	0.031333
H	-3.513981	-1.056125	0.795498
H	-3.432861	-2.774642	0.429360
C	-3.996991	-1.553081	-1.274282
H	-3.758008	-2.374448	-1.961574
H	-3.618095	-0.634601	-1.728026
C	-5.478272	-1.488972	-1.037481
C	-6.105318	-0.280190	-0.606743
C	-7.515239	-0.203396	-0.400243
C	-5.349773	0.906749	-0.357329
C	-8.124819	0.973835	0.018538
H	-8.130961	-1.079781	-0.577827
C	-5.972616	2.073907	0.066218
H	-4.271101	0.904990	-0.481050

C	-7.361756	2.125476	0.256785
H	-9.203265	0.996833	0.162535
H	-5.363750	2.954587	0.255370
H	-7.839779	3.043791	0.588629
H	0.321579	-0.246166	-1.536015
C	-6.282010	-2.750617	-1.199113
H	-5.630945	-3.598157	-1.437235
H	-6.844836	-3.008882	-0.289146
H	-7.024631	-2.669846	-2.009950

8Q

B3LYP-D3(BJ) SCF energy: -2314.14472623 a.u.
B3LYP-D3(BJ) enthalpy: -2313.526680 a.u.
B3LYP-D3(BJ) free energy: -2313.640725 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.73899843 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.120952 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.234997 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	4.198623	-0.227336	-0.173656
C	5.138516	-1.314622	0.000502
C	4.535405	-2.229843	0.813264
C	3.228604	-1.701162	1.140089
H	6.116122	-1.364643	-0.463236
H	4.916423	-3.184661	1.154179
C	4.429634	0.894722	-0.962074
H	5.394262	0.960567	-1.457308
C	3.522521	1.921145	-1.202741
C	3.772987	3.056506	-2.063040
C	2.629887	3.805798	-2.070939
H	4.700839	3.237302	-2.592251
C	1.682225	3.130593	-1.211497
H	2.432090	4.727287	-2.605415
C	0.383514	3.564648	-0.961168
H	0.061721	4.479538	-1.450925
C	-0.535079	2.932398	-0.129879
C	-1.874489	3.415691	0.128779
C	-2.446558	2.545570	1.011773
H	-2.308784	4.301249	-0.319559
C	-1.458875	1.527274	1.291372
H	-3.448756	2.559551	1.420343
N	2.251362	1.997322	-0.698602
N	3.056545	-0.487829	0.532630
N	-0.314889	1.780908	0.579237
Fe	1.410094	0.701645	0.642230
C	-1.663240	0.448991	2.144200
H	-2.627073	0.386936	2.640308
C	-0.753489	-0.576004	2.381837
C	-1.000166	-1.715787	3.236406
C	0.107012	-2.512429	3.161233
H	-1.911124	-1.878302	3.799173

C	1.036124	-1.854729	2.270754
H	0.290197	-3.460208	3.652581
N	0.487062	-0.687945	1.810515
C	2.299957	-2.336932	1.954281
H	2.581565	-3.299600	2.370311
O	2.092894	1.662885	2.170600
C	2.719907	1.111514	3.276487
H	3.010196	1.904679	3.990527
H	2.064343	0.401325	3.816329
H	3.637813	0.556891	3.003400
N	0.735490	-0.379568	-1.368988
S	0.702041	-1.867704	-1.898794
O	1.726410	-2.197396	-2.923569
O	0.569711	-2.802513	-0.752990
N	-0.809627	-1.988353	-2.819705
C	-0.779190	-3.069769	-3.805618
H	-0.771885	-4.072679	-3.340366
H	-1.676315	-2.986016	-4.433463
H	0.108815	-2.967454	-4.428996
C	-1.997076	-2.124775	-1.966319
H	-1.982714	-3.097518	-1.446229
H	-2.863878	-2.126207	-2.641934
C	-2.176987	-0.998082	-0.932837
H	-2.133211	-0.036171	-1.443595
H	-1.318070	-1.013095	-0.259517
C	-3.420933	-1.184409	-0.120156
H	0.970452	0.228533	-2.154106
C	-4.538890	-0.302473	-0.173768
C	-4.565777	0.855454	-1.009781
C	-5.701483	-0.525984	0.628159
C	-5.658071	1.710907	-1.034213
H	-3.707684	1.085695	-1.628722
C	-6.788731	0.338923	0.599008
H	-5.740320	-1.393980	1.277722
C	-6.783341	1.469549	-0.230787
H	-5.631539	2.585574	-1.680537
H	-7.652227	0.132194	1.228225
H	-7.634054	2.145814	-0.251049
C	-3.440816	-2.386991	0.784729
H	-3.734452	-2.127799	1.810880
H	-4.151451	-3.153940	0.435949
H	-2.450446	-2.846050	0.835651

TS2-S

B3LYP-D3(BJ) SCF energy: -2314.12823678 a.u.
B3LYP-D3(BJ) enthalpy: -2313.510799 a.u.
B3LYP-D3(BJ) free energy: -2313.615264 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.71433637 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.096899 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.201364 a.u.
Imaginary frequency: -462.6797 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	1.917524	0.793201	-2.695363
C	1.564383	0.801149	-4.099564
C	0.613496	-0.163534	-4.272612
C	0.413391	-0.787231	-2.983290
H	1.976088	1.482317	-4.834545
H	0.097641	-0.447389	-5.182174
C	2.806735	1.680631	-2.101321
H	3.303926	2.393636	-2.753229
C	3.013180	1.819289	-0.733800
C	3.790317	2.877935	-0.122215
C	3.675595	2.718804	1.229490
H	4.325159	3.645754	-0.668467
C	2.860097	1.541585	1.441036
H	4.111877	3.319230	2.019353
C	2.600264	0.962585	2.679687
H	2.979409	1.476027	3.559738
C	1.989486	-0.273629	2.876345
C	1.905883	-0.961385	4.144399
C	1.359704	-2.190201	3.890514
H	2.248455	-0.559203	5.090818
C	1.081758	-2.238067	2.471154
H	1.150124	-2.991600	4.589298
N	2.454310	1.030894	0.234006
N	1.198024	-0.171186	-2.039821
N	1.457633	-1.060010	1.882675
Fe	1.370701	-0.644742	-0.103948
C	0.454713	-3.298977	1.821106
H	0.212265	-4.174937	2.416935
C	0.031564	-3.295933	0.493302
C	-0.747012	-4.345188	-0.126512
C	-1.018204	-3.936007	-1.404553
H	-1.057965	-5.257736	0.368019
C	-0.384357	-2.652334	-1.576967
H	-1.581691	-4.454979	-2.171198
N	0.234909	-2.276804	-0.405066
C	-0.349481	-1.928460	-2.763337
H	-0.906732	-2.326553	-3.607108
O	2.948064	-1.561341	-0.346460
C	3.099744	-2.463122	-1.399159
H	4.129481	-2.859063	-1.359694
H	2.406135	-3.319806	-1.330921
H	2.953859	-1.997829	-2.389073
N	-0.542101	0.860909	0.462071
S	-0.927026	2.104777	-0.538685
O	0.215713	2.747065	-1.202653
O	-2.055069	1.681616	-1.385353
N	-1.454511	3.339813	0.581626
C	-1.513178	4.656956	-0.061101
H	-2.332079	4.735790	-0.796437
H	-1.670264	5.407404	0.722631
H	-0.565170	4.854483	-0.560933
C	-2.711465	3.016684	1.264817

H	-3.511840	2.819801	0.537253
H	-2.991701	3.914194	1.829888
C	-2.559286	1.859672	2.256804
H	-3.463948	1.832921	2.893046
H	-1.723455	2.094100	2.926357
C	-2.338301	0.493856	1.661101
H	0.063700	1.266506	1.182039
C	-3.337458	-0.039427	0.731978
C	-4.651553	0.470989	0.657726
C	-3.010545	-1.127955	-0.102575
C	-5.593138	-0.085274	-0.208061
H	-4.954653	1.293058	1.298400
C	-3.944085	-1.671526	-0.975298
H	-1.994374	-1.495321	-0.098932
C	-5.245839	-1.157389	-1.035304
H	-6.601081	0.323835	-0.237810
H	-3.645399	-2.491687	-1.622190
H	-5.974685	-1.579858	-1.723126
C	-1.687836	-0.499792	2.576377
H	-2.407697	-0.781207	3.365795
H	-1.407384	-1.411237	2.052313
H	-0.797900	-0.095265	3.064038

TS2-T

B3LYP-D3(BJ) SCF energy: -2314.12465507 a.u.
B3LYP-D3(BJ) enthalpy: -2313.508117 a.u.
B3LYP-D3(BJ) free energy: -2313.614951 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.71140283 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.094865 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.201699 a.u.
Imaginary frequency: -556.3017 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-2.061913	1.045455	2.643529
C	-1.760986	1.254614	4.046315
C	-0.766399	0.379803	4.368011
C	-0.487642	-0.386828	3.168265
H	-2.239385	1.994792	4.676647
H	-0.264685	0.244304	5.318612
C	-2.961238	1.810056	1.912319
H	-3.512864	2.577478	2.448504
C	-3.131367	1.752686	0.533804
C	-3.934525	2.680945	-0.231991
C	-3.782417	2.344997	-1.547184
H	-4.518274	3.488604	0.193582
C	-2.911783	1.188630	-1.578857
H	-4.224115	2.811795	-2.419656
C	-2.595808	0.463067	-2.723934
H	-2.982219	0.829751	-3.671179
C	-1.913088	-0.751141	-2.736666
C	-1.758182	-1.602317	-3.895877

C	-1.129437	-2.737954	-3.465351
H	-2.107649	-1.361531	-4.892985
C	-0.874387	-2.565451	-2.052527
H	-0.848501	-3.611303	-4.042202
N	-2.519132	0.862139	-0.306061
N	-1.273683	0.049891	2.138506
N	-1.354813	-1.350638	-1.636081
Fe	-1.371819	-0.685021	0.271686
C	-0.168210	-3.468204	-1.262127
H	0.160022	-4.389796	-1.735837
C	0.218482	-3.259481	0.058245
C	1.070409	-4.152144	0.818242
C	1.267534	-3.564208	2.035056
H	1.467650	-5.091065	0.451028
C	0.516407	-2.325683	2.023418
H	1.850498	-3.927030	2.873357
N	-0.093858	-2.158759	0.810440
C	0.380730	-1.470261	3.111618
H	0.942214	-1.709892	4.010388
O	-2.854144	-1.799034	0.769884
C	-3.945822	-1.930076	-0.074904
H	-4.731781	-2.526529	0.429333
H	-4.402567	-0.959755	-0.350777
H	-3.700801	-2.450329	-1.022173
N	0.628690	0.713431	-0.531453
S	0.899732	2.103013	0.317808
O	-0.301871	2.700626	0.916917
O	2.060338	1.874777	1.195275
N	1.325217	3.259178	-0.922327
C	1.262847	4.633951	-0.414850
H	2.065605	4.857837	0.308248
H	1.359079	5.313338	-1.269947
H	0.297141	4.795706	0.063822
C	2.612776	2.974971	-1.564864
H	3.414950	2.900890	-0.816542
H	2.834100	3.838208	-2.204319
C	2.554180	1.727963	-2.451958
H	3.471910	1.701493	-3.069450
H	1.719857	1.854119	-3.152274
C	2.394942	0.408292	-1.740990
H	-0.024810	0.970807	-1.278753
C	3.425196	-0.009150	-0.784656
C	3.162571	-1.065009	0.114042
C	4.704287	0.585320	-0.738427
C	4.127475	-1.501062	1.013626
H	2.169714	-1.492008	0.137017
C	5.675897	0.139838	0.157944
H	4.956299	1.390160	-1.421605
C	5.394816	-0.904965	1.043239
H	3.878537	-2.300528	1.705905
H	6.655371	0.614031	0.165578
H	6.147110	-1.243036	1.752216
C	1.791948	-0.679975	-2.584085
H	0.862662	-0.363022	-3.065726

H	2.504904	-0.954116	-3.382414
H	1.586319	-1.578756	-2.005481

TS2-Q

B3LYP-D3(BJ) SCF energy: -2314.12143641 a.u.
B3LYP-D3(BJ) enthalpy: -2313.506234 a.u.
B3LYP-D3(BJ) free energy: -2313.617479 a.u.
B3LYP-D3(BJ) SCF energy in solution: -2314.71717362 a.u.
B3LYP-D3(BJ) enthalpy in solution: -2314.101971 a.u.
B3LYP-D3(BJ) free energy in solution: -2314.213216 a.u.
Imaginary frequency: -457.8664 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	1.887395	0.840501	-2.738749
C	1.551436	0.752705	-4.147082
C	0.755158	-0.347251	-4.292962
C	0.622728	-0.941897	-2.975556
H	1.867101	1.458927	-4.905648
H	0.295021	-0.729129	-5.196500
C	2.657419	1.841851	-2.153611
H	3.057492	2.606124	-2.813832
C	2.882295	2.013348	-0.790190
C	3.572044	3.148189	-0.213727
C	3.516572	2.999903	1.142568
H	4.012311	3.956894	-0.784506
C	2.812365	1.759364	1.399281
H	3.910997	3.657048	1.908612
C	2.584631	1.224132	2.667515
H	2.939101	1.804846	3.515137
C	2.000992	-0.013549	2.945283
C	1.887341	-0.614696	4.259008
C	1.340178	-1.855932	4.076954
H	2.201450	-0.149529	5.186146
C	1.101039	-2.002292	2.655934
H	1.110349	-2.604072	4.826649
N	2.439272	1.192230	0.210534
N	1.305006	-0.191184	-2.063322
N	1.499655	-0.868632	2.005738
Fe	1.584655	-0.629485	-0.056886
C	0.507127	-3.107482	2.047182
H	0.234909	-3.939358	2.691597
C	0.179141	-3.226793	0.695931
C	-0.527091	-4.347503	0.113941
C	-0.702492	-4.061261	-1.212318
H	-0.855550	-5.223752	0.660078
C	-0.094094	-2.770600	-1.449408
H	-1.195676	-4.661036	-1.968151
N	0.422602	-2.288257	-0.274264
C	-0.035822	-2.136329	-2.691004
H	-0.525692	-2.640354	-3.519742
O	3.229829	-1.577087	-0.292479

C	3.472951	-2.483939	-1.312493
H	4.514444	-2.854776	-1.257836
H	2.807041	-3.367831	-1.258689
H	3.334538	-2.039492	-2.317000
N	-0.640565	0.921537	0.442921
S	-1.058291	2.102634	-0.562713
O	0.062857	2.871050	-1.146316
O	-2.071925	1.588746	-1.507363
N	-1.820443	3.308082	0.475341
C	-1.938804	4.601587	-0.205263
H	-2.675760	4.585391	-1.027407
H	-2.253921	5.349209	0.533528
H	-0.966609	4.883193	-0.609145
C	-3.115914	2.876627	1.010515
H	-3.782126	2.550588	0.199005
H	-3.567362	3.765342	1.469519
C	-3.001602	1.802215	2.102809
H	-3.968819	1.773385	2.641565
H	-2.257932	2.144473	2.831867
C	-2.643526	0.412766	1.656428
H	-0.055166	1.353453	1.163674
C	-3.463720	-0.264574	0.673194
C	-4.784030	0.152266	0.372966
C	-2.966971	-1.393093	-0.021508
C	-5.565064	-0.530188	-0.556451
H	-5.214417	1.001905	0.892982
C	-3.743943	-2.063000	-0.957106
H	-1.937952	-1.685928	0.132421
C	-5.052214	-1.642874	-1.232085
H	-6.578950	-0.189535	-0.757150
H	-3.315751	-2.907669	-1.489367
H	-5.656062	-2.165542	-1.970275
C	-1.855613	-0.407321	2.628901
H	-2.505778	-0.695843	3.476385
H	-1.476798	-1.325914	2.184982
H	-1.007076	0.146070	3.040777

9S

B3LYP-D3(BJ) SCF energy: -1227.19251992 a.u.
B3LYP-D3(BJ) enthalpy: -1226.856862 a.u.
B3LYP-D3(BJ) free energy: -1226.928263 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1227.56352574 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1227.227868 a.u.
B3LYP-D3(BJ) free energy in solution: -1227.299269 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	1.371625	2.747483	-0.156444
C	2.666485	3.400166	-0.138893
C	3.603200	2.407936	-0.153707
C	2.875895	1.153355	-0.175852
H	2.819162	4.473270	-0.117697

H	4.683502	2.497886	-0.146163
C	0.154876	3.420502	-0.161245
H	0.188677	4.507304	-0.137047
C	-1.101695	2.826387	-0.222936
C	-2.350779	3.556865	-0.287046
C	-3.346345	2.624343	-0.361240
H	-2.437701	4.637440	-0.278284
C	-2.700750	1.328263	-0.335810
H	-4.416998	2.782681	-0.422359
C	-3.372329	0.110647	-0.371278
H	-4.457829	0.141845	-0.428186
C	-2.772900	-1.143135	-0.333726
C	-3.497029	-2.397577	-0.361975
C	-2.561370	-3.389662	-0.296912
H	-4.575586	-2.488754	-0.420972
C	-1.268536	-2.738393	-0.235610
H	-2.714437	-4.462877	-0.294357
N	-1.338059	1.474734	-0.252646
N	1.523999	1.384597	-0.182432
N	-1.420497	-1.373444	-0.254414
Fe	0.047016	0.005003	-0.060069
C	-0.052932	-3.412304	-0.187374
H	-0.089125	-4.499150	-0.170732
C	1.204913	-2.818114	-0.185981
C	2.456807	-3.548477	-0.175716
C	3.452703	-2.614393	-0.182437
H	2.544318	-4.628998	-0.163141
C	2.803196	-1.318488	-0.192622
H	4.525469	-2.770425	-0.175417
N	1.440224	-1.467493	-0.201899
C	3.475795	-0.101032	-0.180283
H	4.562794	-0.132900	-0.167765
O	0.124217	0.024647	1.872469
C	-1.053075	-0.107272	2.581068
H	-0.850372	-0.013361	3.669312
H	-1.810811	0.667548	2.334128
H	-1.553424	-1.090122	2.436593

9T

B3LYP-D3(BJ) SCF energy: -1227.19564672 a.u.
B3LYP-D3(BJ) enthalpy: -1226.860587 a.u.
B3LYP-D3(BJ) free energy: -1226.932889 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1227.56894980 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1227.233890 a.u.
B3LYP-D3(BJ) free energy in solution: -1227.306192 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	0.504158	3.018698	-0.134247
C	1.554112	4.019600	-0.104680
C	2.738801	3.347651	-0.099597
C	2.415160	1.932300	-0.123357

H	1.384101	5.090223	-0.097979
H	3.745346	3.749615	-0.088245
C	-0.847262	3.320432	-0.203592
H	-1.120643	4.372935	-0.195540
C	-1.885714	2.394167	-0.301069
C	-3.287121	2.727228	-0.373165
C	-3.971400	1.540115	-0.422455
H	-3.686977	3.734923	-0.372925
C	-2.978383	0.493085	-0.379283
H	-5.042322	1.380187	-0.471568
C	-3.255993	-0.874440	-0.371358
H	-4.300380	-1.172335	-0.420499
C	-2.309384	-1.885014	-0.308133
C	-2.631977	-3.298935	-0.345293
C	-1.448291	-3.972519	-0.303065
H	-3.637127	-3.699770	-0.406513
C	-0.398908	-2.974567	-0.240519
H	-1.279168	-5.043130	-0.320941
N	-1.720888	1.033331	-0.321753
N	1.051937	1.755117	-0.130823
N	-0.945031	-1.709030	-0.225943
Fe	0.049210	0.022746	-0.011893
C	0.954918	-3.275675	-0.238020
H	1.228575	-4.328056	-0.245352
C	1.994419	-2.346574	-0.251058
C	3.398556	-2.677526	-0.255575
C	4.081450	-1.489452	-0.236249
H	3.799245	-3.684859	-0.260769
C	3.085932	-0.443560	-0.219423
H	5.153148	-1.327438	-0.224739
N	1.827891	-0.985384	-0.243087
C	3.364500	0.921700	-0.160740
H	4.410336	1.218179	-0.144695
O	0.001959	0.106946	1.961217
C	-0.999226	-0.521244	2.673979
H	-0.860345	-0.379105	3.768101
H	-2.012660	-0.130875	2.432917
H	-1.043704	-1.618506	2.500875

9Q

B3LYP-D3(BJ) SCF energy: -1227.21663400 a.u.
B3LYP-D3(BJ) enthalpy: -1226.882210 a.u.
B3LYP-D3(BJ) free energy: -1226.957830 a.u.
B3LYP-D3(BJ) SCF energy in solution: -1227.58540998 a.u.
B3LYP-D3(BJ) enthalpy in solution: -1227.250986 a.u.
B3LYP-D3(BJ) free energy in solution: -1227.326606 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	1.345321	2.805825	-0.252667
C	2.626990	3.493680	-0.272005
C	3.592413	2.525161	-0.230726

C	2.898601	1.247624	-0.184637
H	2.760045	4.568883	-0.319618
H	4.669221	2.653531	-0.237395
C	0.094354	3.434124	-0.318900
H	0.101150	4.521604	-0.358198
C	-1.162004	2.816074	-0.373325
C	-2.434764	3.508618	-0.501745
C	-3.403292	2.542919	-0.546344
H	-2.560694	4.584452	-0.554547
C	-2.720034	1.262469	-0.446690
H	-4.475330	2.675369	-0.642393
C	-3.344950	0.008455	-0.480807
H	-4.429813	0.011113	-0.565607
C	-2.726149	-1.248596	-0.447075
C	-3.415642	-2.525724	-0.546533
C	-2.451801	-3.496102	-0.501980
H	-4.488345	-2.652983	-0.642163
C	-1.175636	-2.809706	-0.374220
H	-2.582969	-4.571324	-0.554471
N	-1.374740	1.468267	-0.338098
N	1.549448	1.456873	-0.191382
N	-1.381847	-1.460890	-0.339077
Fe	0.049792	-0.000017	0.361657
C	0.077728	-3.433840	-0.320098
H	0.079226	-4.521336	-0.359544
C	1.331754	-2.811671	-0.253830
C	2.610062	-3.505770	-0.273595
C	3.580203	-2.541996	-0.231937
H	2.737867	-4.581589	-0.321686
C	2.892609	-1.261109	-0.185288
H	4.656370	-2.675621	-0.238689
N	1.542482	-1.463778	-0.192007
C	3.519801	-0.008241	-0.165240
H	4.607955	-0.010826	-0.159936
O	-0.163617	-0.002010	2.259952
C	-1.410918	-0.000301	2.863484
H	-1.315922	-0.001040	3.969240
H	-2.018437	0.889550	2.596073
H	-2.021269	-0.887921	2.595130

XIII. ^{1}H, ^{19}F and ^{13}C NMR spectra of compounds

(attached as a separate .pdf file)

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