Formation of Complex $\alpha$-Imino Esters via Multihetero-Cope Rearrangement of $\alpha$-Keto Ester Derived Nitrones

Samuel L. Bartlett1
Kimberly M. Keiter2
Blane P. Zavesky
Jeffrey S. Johnson* 0000-0001-8882-9881

Department of Chemistry, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3290, USA
js@unc.edu

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Abstract A sequential benzoylation and multihetero-Cope rearrangement of $\alpha$-keto ester derived nitrones has been developed. The reaction furnishes a diverse array of complex $\alpha$-imino ester derivatives. The products can be transformed into amino alcohols via LiAlH4 reduction.

Key words rearrangement, ketones, imines, oxygenations, esters

Fragmentation of weak N–O $\sigma$-bonds (bond strength ~57 kcal/mol) can be leveraged during the synthesis of complex organic frameworks, and a comprehensive review of the rearrangement of N-oxygenamine derivatives has been penned by Tabolin and Ioffe.3 Within this subclass of N–O bond-cleaving reactions, sigmatropic rearrangements of O-acyl- and O-imidoyl-N-oxygenamines can provide $\alpha$-hydroxy or $\alpha$-amino carbonyl derivatives, which are valuable intermediates and key structural elements of natural and unnatural bioactive compounds. An early report by Coates and Cummins provided a method for the rearrangement of $\alpha$-hydroxy carbonyl derivatives, which is valuable.

Table 1 Optimization of the Reaction Conditions

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reactants</th>
<th>Baseb</th>
<th>Catalyst</th>
<th>Temp (°C)</th>
<th>Solvent</th>
<th>Yield (%)c</th>
</tr>
</thead>
<tbody>
<tr>
<td>1d</td>
<td>1a/A</td>
<td>none</td>
<td>none</td>
<td>55</td>
<td>DMSO (0.375 M)</td>
<td>0</td>
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<tr>
<td>2f</td>
<td>2a/B</td>
<td>Et3N</td>
<td>DMAP</td>
<td>0; 23</td>
<td>MTBE (0.06 M)</td>
<td>48</td>
</tr>
<tr>
<td>3n</td>
<td>2a/B</td>
<td>PS</td>
<td>DMAP</td>
<td>0; 23</td>
<td>MTBE (0.06 M)</td>
<td>86</td>
</tr>
<tr>
<td>4n</td>
<td>2a/B</td>
<td>PS</td>
<td>DMAP</td>
<td>0; 23</td>
<td>MTBE (0.06 M)</td>
<td>63</td>
</tr>
</tbody>
</table>

Table 1 Optimization of the Reaction Conditions

an All reactions run using 0.15 mmol of 1a or 2a.
bn PS = Proton-sponge®.
nc Yield of product isolated via column chromatography.
dn 1.0 equiv A used.
ne 2.0 equiv DMAP employed.
of 5.0 equiv Et3N employed with 3.0 equiv B.
ng 2.5 equiv Proton-sponge® employed with 2.0 equiv of B.

We initially chose to focus on the $\beta$-benzoylation of $\alpha$-keto ester derived O-benzoyl-N-oxygenamines. We first tested condensation of $\alpha$-keto ester 1a with the Tomkinson reagent A (Table 1, entry 1). Presumably this reaction was...
prevented by the sterically hindered ketone of 1a coupled with low nucleophilicity of the free base of A. Heating a mixture of N-benzylhydroxylamine and α-keto ester 1a furnished nitrone 2a, which upon treatment with benzoyl chloride (B) in the presence of triethylamine and the nucleophilic catalyst 4-(dimethylamino)pyridine (DMAP) delivered the desired β-benzoylated imino ester 3a in 48% yield (Table 1, entry 2). In this experiment, the corresponding α-keto ester resulting from hydrolysis of 3a by adventitious water was observed in the 1H NMR spectrum of the unpurified materials. Sequestration of acid is apparently crucial to the stability of 3a under the reaction conditions as replacing triethylamine with the thermodynamically stronger base Proton-sponge® suppresses hydrolysis, allowing isolation of 3a in 86% yield (Table 1, entry 3). Despite the sensitivity of 3a under the conditions, it is completely stable toward chromatography on untreated silica gel. The reaction proceeds in the absence of DMAP, however the yield of 3a is lower (Table 1, entry 4).

With suitable reaction conditions in hand, we began to explore the scope of α-imino esters that could be prepared (Scheme 2). The p-halogen series imines 3b–d were obtained in high yield. In addition, an α-fluoro-substituted nitrone underwent the reaction in good yield to afford imino benzoate 3e. Electron-rich nitrones were also viable substrates, and representative examples include imines 3f–3h.

Biographical Sketches

**Samuel L. Bartlett** received his B.S. in chemistry from Oregon State University in 2012 where he conducted research with Prof. Chris Beaudry. He completed his Ph.D. in the laboratory of Prof. Jeffrey S. Johnson at the University of North Carolina at Chapel Hill where he explored new catalytic enantioconvergent reactions. During his doctoral studies, he was also an NSF EAPSI Fellow with Prof. Mikiko Sodeoka and Dr. Yoshihiro Sohtome at RIKEN in Japan. There he worked on the development of new asymmetric reactions employing catalytically generated transition-metal enolates. He is currently a Medicinal Chemist at Enanta Pharmaceuticals.

**Kimberly M. Keiter** received her M.S. in analytics from North Carolina State University and her B.S. in applied mathematics and chemistry from the University of North Carolina at Chapel Hill. During her undergraduate years, she was a research assistant in the Johnson Group where she received the Matthew Neely Jackson Undergraduate Research Award. She is currently a Data Scientist at Elder Research where she analyzes clients’ data to find actionable insights.

**Blane P. Zavesky** received his B.S. in chemistry from the University of Michigan in 2014 with high distinction and honors in chemistry, where he conducted research under Prof. John P. Wolfe. He began his Ph.D. studies at the University of North Carolina in 2014, working in the laboratories of Prof. Jeffrey S. Johnson. His research focuses on the total synthesis of biologically active alkaloid natural products.

**Jeffrey S. Johnson** received his B.S. in chemistry from the University of Kansas in 1994 with highest distinction and honors in chemistry. He was a graduate student at Harvard University as an NSF Graduate Fellow in the laboratories of Prof. David A. Evans, receiving his Ph.D. in 1999. He conducted postdoctoral research at the University of California at Berkeley from 1999 to 2001 as an NIH Postdoctoral Fellow under the direction of Prof. Robert G. Bergman. He joined the faculty of the Department of Chemistry at the University of North Carolina at Chapel Hill in 2001, where he is currently the A. Ronald Gallant Distinguished Professor and the department chairperson.
Larger alkyl substituents were tolerated at the β-position, and β-benzyl-substituted tertiary benzoate 3i as well as the ethyl derivative 3j could be obtained in good and moderate yield, respectively. The secondary benzoate 3m could be formed under the reaction conditions; however, this product decomposed on silica gel and an NMR yield is provided in Scheme 2.10 All other products were stable toward chromatography on untreated silica gel. The cyclobexyl derivative 3l was furnished in less than 35% yield (NMR yield) and could not be separated from impurities, while the desired pyridyl-substituted derivative 3n was not formed under the reaction conditions. Other aryl chlorides could also be used in the reaction, and p-methylbenzoate 3o, m-chlorobenzoate 3p, as well as o-bromobenzoate 3q were obtained in high yield.

Preliminary attempts to selectively functionalize the azaomethine functionality in the rearrangement products have been unsuccessful, most likely due to the sterically encumbered nature of these electrophiles. At this stage, the utility of the products has been demonstrated by exhaustive LiAlH4 reduction of 3a and 3f, which delivered the corresponding amino alcohols 4a and 4f in intermediate yield and diastereoselectivity (Scheme 3). The relative stereochemistry of the major diastereomer was established via synthesis of the cyclic carbamate 5f, which exhibited the illustrated NOESY interactions between the methyl protons and the methine proton. In summary, we have developed a sequential benzylation–multihetero-Cope rearrangement of α-keto ester derived nitrones. The reaction furnishes complex α-imino ester derivatives in good to excellent yield. The products can be transformed into complex amino alcohols via LiAlH4 reduction. Further exploration of the reactivity of these products, with a particular focus on accessing complex amino acid derivatives via selective functionalization of the imino moiety, is currently underway in our laboratory.

Unless noted otherwise, all experiments were carried out in a flame-dried round-bottomed flask under a stream of nitrogen gas. H and 13C NMR spectra were obtained on a Bruker DRX 600 (1H, 600 MHz; 13C, 150 MHz), Bruker 500 (1H, 500 MHz; 13C, 125 MHz), or Bruker DRX 400 (>H, 400 MHz; 13C, 100 MHz) spectrometer. 1H NMR data are reported as follows: chemical shift, multiplicity (standard abbreviations), coupling constant(s) (Hz), and relative integration. For HRMS, all samples were prepared in MeOH. The HPLC system consisted of an Agilent 1200 binary pump (G1312A) operating at a flow rate of 0.3 mL·min⁻¹. The solvents were degassed using an on-line membrane degasser system (Agilent G1379A). The column was maintained in a thermostated compartment at 40 °C (Agilent G1316A). The diode array detector (Agilent G1315D) was operated at three wavelengths (250, 254, and 280 nm). Separation was performed on a Waters Acquity UPLC BEH C18 column (2.1 × 50 mm, 1.7 μm particle size). The injection (5 μL) was performed using an autosampler (Agilent G1329A). LC conditions were set at water with 0.1% formic acid (A) for 1 min, before ramping linearly over 5 min to 100% acetonitrile with 0.1% formic acid (B), and then switched back to 100% A and allowed to re-equilibrate until 10 min. The HPLC system was coupled to the Q-TOF system via a dual ESI interface operating in positive ion mode using a capillary voltage of +3.5 kV. The other optimum values of the ESI-TOF parameters were drying gas temperature 325 °C, drying gas flow 5 L·min⁻¹, and nebulizing gas pressure 15 psi. Detection was carried out considering a mass range of 100–1500 m/z. Prior to acquiring samples, an external instrument calibration was performed using Agilent ESI-L Low Concentration Tuning Mix. MassHunter Quantitative Analysis (Agilent) was used to analyze the data. Solutions were dissolved in MeOH at 0.1 mg·mL⁻¹ or less, and diluted appropriately based on responsiveness to the ESI mechanism. Molecular formula assignments were determined with Molecular Formula Calculator (v 1.2.3). The success of mass data for molecular ions was considered based on the widely accepted accuracy threshold for confirmation of elemental compositions established at 5 ppm. All observed species were singly charged, as verified by unit m/z separation between mass spectral peaks corresponding to the 12C and 13C/12C⁻ ions, isotope for each elemental composition. IR spectra were obtained using a Jasco 460 Plus Fourier transform infrared spectrometer. TLC was performed on Sorbtech plastic-backed 0.20 mm silica gel 60 plates. Visualization was accomplished with UV light and either an aqueous ceric ammonium molybdate (CAM) or KMnO4 solution, followed by heating. Flash chromatography was performed under positive nitrogen pressure using SiliaFlash-P60 silica gel (40–63 μm) purchased from Silicycle. Et3N was purified and dried by passing through a column of activated alumina. DMAP and BuOH were purchased from Sigma-Aldrich and used without further purification. Benzyl chloride was purchased from Acros and used without further purification. Methyl tert-butyl ether (MTBE) was purified via distillation from calcium hydride and stored over activated 13X-type molecular sieves (bead form). The pro-
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Feature

procedures for the preparation of tert-butyl 2-oxo-4-phenylbutanoate (1k)\textsuperscript{11} and tert-butyl 2-oxo-4-phenyl-3-(4-(trifluoromethyl)phenyl)-butanoate (1i)\textsuperscript{12} are reported in the literature.

**Scheme 2** Scope of the rearrangement reaction. \textsuperscript{4} All reactions were conducted on 0.15 mmol scale. The reactions were monitored by silica gel TLC and were generally complete within 4 h. \textsuperscript{13} Product is unstable to silica gel; yield was obtained via \textsuperscript{1}H NMR analysis using mesitylene as an internal standard. \textsuperscript{5} Product could not be separated from impurities; yield was obtained via \textsuperscript{1}H NMR analysis using mesitylene as an internal standard.

**Scheme 3** LiAlH\textsubscript{4} reduction of products 3a and 3f and determination of diastereoselectivity via NOESY experiments with the derived cyclic carbamate 5f

tert-Butyl α-Keto Esters 1; General Procedure
Step 1: The ethyl 2-oxo-3-arylbutanoate (4.46 mmol), prepared in two steps via a literature method,\textsuperscript{11} was added neat to a 25-mL round-bottomed flask equipped with a stir bar. Next, aqueous NaOH (3 M, 4 mL) was added and the reaction mixture was stirred for 24 h at rt. The mixture was then acidified (pH ~5) with aqueous HCl (3 M), and the aqueous layer was extracted with CH\textsubscript{2}Cl\textsubscript{2} (3 × 15 mL). The combined organic layers were dried over MgSO\textsubscript{4}. Filtration through a plug of cotton and concentration delivered the corresponding α-keto acid which was carried on without purification. Step 2: The crude α-keto acid from step 1 was dissolved in CH\textsubscript{2}Cl\textsubscript{2} (4.5 mL), and several small drops of DMF were added. The reaction mixture was cooled to 0 °C using an ice–water bath, and oxalyl chloride (0.57 mL, 6.69 mmol, 1.5 equiv) was slowly added. The reaction mixture was stirred for 20 h and concentrated. Residual oxalyl chloride was removed under reduced pressure. The acid chloride was immediately used in the next step without purification. Step 3: \textsuperscript{1}BuOH (1.27 mL, 13.4 mmol, 3.0 equiv) and pyridine (719 μL, 8.92 mmol, 2.0 equiv) were dissolved in CH\textsubscript{2}Cl\textsubscript{2} (4.5 mL, 1 M), and the mixture was cooled to 0 °C using an ice–water bath. The acid chloride from step 2 was slowly added in CH\textsubscript{2}Cl\textsubscript{2} (1.96 mL, 2.3 M). The reaction mixture was stirred for 24 h, then diluted with water. The aqueous phase was extracted three times with CH\textsubscript{2}Cl\textsubscript{2} (20 mL), and the combined organic layers were dried over MgSO\textsubscript{4}. The product was purified by silica gel column chromatography.

tert-Butyl 2-Oxo-3-phenylbutanoate (1a)
Prepared from ethyl 2-oxo-3-phenylbutanoate. Purified by silica gel column chromatography using 5% EtOAc/hexanes (636 mg, 61% yield).
**t-BuButyl 3-(4-Fluorophenyl)-2-oxobutanoate (1b)**
Prepared from ethyl 3-(4-fluorophenyl)-2-oxobutanoate. Purified by silica gel column chromatography using 2.5% EtOAc/hexanes (g). Yield.

**t-BuButyl 3-(4-Chlorophenyl)-2-oxobutanoate (1c)**
Prepared from ethyl 3-(4-chlorophenyl)-2-oxobutanoate. Purified by silica gel column chromatography using 2.5% EtOAc/hexanes (g). Yield.

**t-BuButyl 3-(4-Bromophenyl)-2-oxobutanoate (1d)**
Prepared from ethyl 3-(4-bromophenyl)-2-oxobutanoate using Procedure A. Purified by silica gel column chromatography using 2.5% ethyl acetate/hexanes (331 mg, 48% yield).

**t-BuButyl 3-(2-Fluorophenyl)-2-oxobutanoate (1e)**
Prepared from ethyl 3-(2-fluorophenyl)-2-oxobutanoate. Purified by silica gel column chromatography using 2.5% EtOAc/hexanes (681 mg, 61% yield).

**ethyl-Butyl 2-Oxo-3-(m-tolyl)butanoate (1j)**
Prepared from ethyl 2-oxo-3-(m-tolyl)butanoate. Purified by silica gel column chromatography using 2.5% EtOAc/hexane. Yield.

**t-BuButyl 2-Cyclohexyl-2-oxoacetate (1l)**
Compound 1l was prepared via the procedure employed for compound 1k with slight modification. Magnesium turnings (0.31 g, 12.7 mmol) were added to a flame-dried 25 mL round-bottomed flask equipped with a reflux condenser and a stir bar. The flask containing the magnesium turnings was held under direct flame using a Bunsen burner for 1 min while being flushed with nitrogen gas. Once the flask had returned to room temperature, THF (12.7 mL) was added. Bromocyclohexane (2.00 g, 12.7 mmol, 1.53 mL) was slowly added via a burette, and the mixture was heated on a steam bath until the mixture started to boil. The mixture was then cooled to room temperature, and water (12.7 mL) was added. The mixture was then extracted with dichloromethane (2 x 30 mL), and the combined organic layers were washed with water (20 mL), dried over anhydrous sodium sulfate, and concentrated in vacuo. The crude product was then purified by silica gel column chromatography using 2.5% EtOAc/hexane and subsequently CHCl3 (2.20 g, 60% yield).
syringe. The mixture was stirred for approximately 15 min at room temperature and initiation of Grignard formation was not observed. The flask was heated using a heat gun to initiate Grignard formation. Once the magnesium turnings had been visibly consumed, the solution of the Grignard reagent was added dropwise to a separate solution of tert-butyl-2-(1H-imidazol-1-yl)-2-oxoacetate in THF (25.4 mL) that had been pre-cooled to -78 °C using a dry ice/acetone bath. The resulting mixture was allowed to stir at -78 °C for 1 h prior to being quenched at -78 °C with 10 mL of 1M HCl. Upon warming to room temperature, the reaction mixture was quenched with 40 mL of water, and the aqueous phase was extracted several times with diethyl ether. Purification by silica gel column chromatography delivered tert-butyl-2-cyclohexyl-2-oxoacetate 11 (869 mg, 32% yield).

**1H NMR (CDCl3, 400 MHz):** δ 2.90–2.98 (m, 1 H), 1.31–1.91 (m, 19 H).

**tert-Butyl 2-Oxo-3-(pyridin-3-yl)butanoate (1m)**

The procedure for the preparation of this compound is reported in the literature.8

**α-Benzyl-1-(tert-butoxy)-1-oxo-3-phenylbutan-2-imine Oxide (2f)**

Purified by silica gel column chromatography using 80:20 hexan/ethyl acetate as eluent (137 mg, 66% yield) Prepared using procedure B. Purified via silica gel column chromatography using 80:20 hexanes/EtOAc (89.0 mg, 48% yield).

**HRMS (ESI):** calcd for C21H24ClNO3: [M + H]: 374.1520; found: 374.1520.

**E-N-Benzyl-1-(tert-butoxy)-3-(4-chlorophenyl)-1-oxobutan-2-imine Oxime (2c)**

Purified by silica gel column chromatography using 80:20 hexan/ethyl acetate as eluent (89.0 mg, 48% yield).

**IR (thin film):** 3033, 2978, 2935, 2852, 2786, 1684, 1595, 1558, 1454, 1314, 1114, 845, 758 cm–1.

**13C NMR (150 MHz, CDCl3):** δ 162.1, 158.4, 146.9, 133.7, 132.7, 124.6, 113.3, 83.7, 66.8, 37.5, 27.4, 14.0.

**HRMS (ESI):** m/z calcd for C23H23NO2 [M + H]: 358.1813; found: 358.1823.

**E-N-Benzyl-1-(tert-butoxy)-3-(4-fluorophenyl)-1-oxobutan-2-imine Oxime (2e)**

Purified by silica gel column chromatography using 80:20 hexanes/EtOAc (89.0 mg, 48% yield).

**IR (thin film):** 2926, 2978, 2935, 2852, 2786, 1684, 1595, 1558, 1454, 1314, 1114, 845, 758 cm–1.

**13C NMR (150 MHz, CDCl3):** δ 162.0, 146.7, 140.8, 133.8, 128.7, 128.6, 128.4, 128.2, 127.6, 126.6, 83.7, 66.8, 37.5, 27.4, 14.0.

**HRMS (ESI):** m/z calcd for C23H23NO2 [M + H]: 340.1907; found: 340.1916.

**1H NMR (400 MHz, CDCl3):** δ = 7.40–7.43 (m, 2 H), 7.34–7.36 (m, 3 H), 7.23–7.26 (m, 2 H), 6.96–7.00 (m, 2 H), 5.42 (d, J = 13.0 Hz, 1 H), 5.25 (d, J = 13.0 Hz, 1 H), 4.76 (q, J = 7.0 Hz, 1 H), 1.52 (d, J = 7.0 Hz, 3 H), 1.24 (s, 9 H).

**13C NMR (150 MHz, CDCl3):** complex spectrum due to 19F–13C coupling (see the Supporting Information).

**HRMS (ESI):** m/z calcd for C23H23NO2 [M + H]: 340.1907; found: 340.1916.

**E-N-Benzyl-1-(tert-butoxy)-3-(4-bromophenyl)-1-oxobutan-2-imine Oxime (2d)**

Purified by silica gel column chromatography using 80:20 hexan/ethyl acetate as eluent (137 mg, 66% yield).

**1H NMR (CDCl3, 400 MHz):** δ 7.70–7.71 (m, 4 H), 7.15 (d, J = 7.7 Hz, 2 H), 5.42 (d, J = 13.0 Hz, 1 H), 5.26 (d, J = 13.0 Hz, 1 H), 4.72 (q, J = 7.1 Hz, 1 H), 1.50 (d, J = 7.1 Hz, 3 H), 1.24 (s, 9 H).

**13C NMR (150 MHz, CDCl3):** δ = 161.8, 146.0, 139.4, 133.6, 132.4, 129.0, 128.6, 128.5, 128.3, 84.0, 66.9, 37.1, 27.5, 14.4.

**HRMS (ESI):** m/z calcd for C23H18ClNO3 [M + H]: 374.1517; found: 374.1520.

**E-N-Benzyl-1-(tert-butoxy)-3-(2-fluorobenzenyl)-1-oxobutan-2-imine Oxime (2e)**

Purified by silica gel column chromatography using 80:20 hexanes/EtOAc (89.0 mg, 50% yield).

**IR (thin film):** 3033, 2978, 2935, 2852, 2855, 2786, 1684, 1595, 1558, 1454, 1457, 1312, 1113, 844, 758 cm–1.

**1H NMR (600 MHz, CDCl3):** δ = 6.97–7.42 (m, 9 H), 5.38 (d, J = 13.1 Hz, 1 H), 5.32 (d, J = 13.1 Hz, 1 H), 4.91 (q, J = 7.1 Hz, 1 H), 1.56 (d, J = 7.1 Hz, 3 H), 1.21 (s, 9 H).

**13C NMR (150 MHz, CDCl3):** complex spectrum due to 19F–13C coupling (see the Supporting Information).

**HRMS (ESI):** m/z calcd for C22H22FNO2 [M + H]: 358.1813; found: 358.1817.

**E-N-Benzyl-1-(tert-butoxy)-3-(4-methoxyphenyl)-1-oxobutan-2-imine Oxime (2f)**

Purified by silica gel column chromatography using 80:20 hexanes/EtOAc (137 mg, 66% yield).

**1H NMR (400 MHz, CDCl3):** δ = 7.43–7.46 (m, 2 H), 7.33–7.39 (m, 3 H), 7.20–7.31 (m, 5 H), 5.46 (d, J = 13.0 Hz, 1 H), 5.25 (d, J = 13.0 Hz, 1 H), 4.82 (q, J = 7.1 Hz, 1 H), 1.55 (d, J = 7.1 Hz, 3 H), 1.17 (s, 9 H).

**13C NMR (150 MHz, CDCl3):** δ = 162.0, 146.7, 140.8, 133.8, 128.7, 128.6, 128.4, 128.2, 127.6, 126.6, 83.7, 66.8, 37.5, 27.4, 14.0.

**HRMS (ESI):** m/z calcd for C22H22NO3 [M + H]: 340.1907; found: 340.1916.
HRMS (ESI): m/z calcd for C_{22}H_{27}NO_4 [M + H]: 370.2013; found: 370.18.  

(E)-N-Benzyl-1-(tert-butoxy)-1-oxo-3-(p-tolyl)butan-2-imide Oxide (2g)  
Purified by silica gel column chromatography using 80:20 hexanes/EtOAc (128 mg, 72% yield).  

1^H NMR (400 MHz, CDCl_3): δ = 7.46–7.45 (m, 2 H), 7.34–7.37 (m, 3 H), 7.08–7.16 (m, 4 H), 7.52 (d, J = 13.0 Hz, 1 H), 1.52 (d, J = 7.0 Hz, 3 H), 1.19 (s, 9 H).  

IR (thin film): 3476, 2964, 2246, 1725, 1512, 1457, 1297, 1136, 1013 cm–1.  

HRMS (ESI) m/z calcd for C_{29}H_{33}NO_4 [M + Na]: 444.1679; found: 444.1661.

(E)-N-Benzyl-1-(tert-butoxy)-1-oxo-4-phenylbutan-2-imide Oxide (2k)  
Purified by silica gel column chromatography using 80:20 hexanes/EtOAc (146 mg, 86% yield).  

1^H NMR (500 MHz, CDCl_3): δ = 7.48–7.49 (m, 2 H), 7.32–7.40 (m, 3 H), 7.21–7.24 (m, 2 H), 7.15–7.18 (m, 1 H), 7.10–7.12 (m, 2 H), 5.63 (s, 2 H), 2.96–2.99 (m, 2 H), 2.82–2.86 (m, 2 H), 1.40 (s, 9 H).  

IR (thin film): 3476, 2964, 2246, 1725, 1512, 1457, 1297, 1137, 1013 cm–1.  

HRMS (ESI): m/z calcd for C_{29}H_{33}NO_4 [M + Na]: 444.1733; found: 444.1722.

(E)-N-Benzyl-2-(tert-butoxy)-1-cyclohexyl-2-oxoethan-1-imine Oxide (2l)  
Prepared using procedure B. Purified via silica gel column chromatography using 80:20 hexanes/ethyl acetate as eluent (103 mg, 65% yield).  

1^H NMR (CDCl_3, 400 MHz): δ 7.37–7.39 (m, 2 H), 7.29–7.33 (m, 3 H), 3.18–3.26 (m, 1 H), 1.29–1.82 (m, 19 H).  

IR (thin film): 2977, 1709, 1540, 1497, 1456, 1369, 1299, 1254, 1136 cm–1.  

HRM (ESI): m/z calcd for C_{22}H_{22}N_2O_4 [M + H]: 354.2064; found: 354.2070.
Purified by silica gel column chromatography using 5% and then 10% EtOAc/hexane (51.9 mg, 72% yield).

IR (thin film): 2926, 1748, 1733, 1715, 1684, 1558, 1541, 1508, 1497, 1459, 1395, 1371, 1214, 1125, 1113, 844, 758 cm⁻¹.

¹H NMR (600 MHz, CDCl₃): δ = 8.15–8.16 (m, 2 H), 7.60–7.63 (m, 1 H), 7.54–7.57 (m, 2 H), 7.49–7.51 (m, 2 H), 7.35–7.38 (m, 4 H), 7.27–7.31 (m, 1 H), 7.06–7.09 (m, 2 H), 4.81 (d, J = 14.9 Hz, 1 H), 4.68 (d, J = 14.9 Hz, 1 H), 2.20 (s, 3 H), 1.26 (s, 9 H).

¹³C NMR (150 MHz, CDCl₃): complex spectrum due to ¹³F–¹⁹⁷Cu coupling (see the Supporting Information).

HRMS (ESI): m/z calcd for C₉H₁₃FNO₃ [M + H]: 462.2075; found: 462.2070.

Z)-3-(Benzylimino)-4-(tert-butoxy)-2-(4-fluorophenyl)-4-oxobutan-2-yl Benzoate (3b)

Purified by silica gel column chromatography using 5% and then 10% EtOAc/hexane (65.2 mg, 95% yield).

IR (thin film): 3062, 3030, 2979, 2935, 2870, 1731, 1453 cm⁻¹.

¹H NMR (600 MHz, CDCl₃): δ = 8.16–8.17 (m, 2 H), 7.59–7.61 (m, 1 H), 7.46–7.50 (m, 4 H), 7.35–7.38 (m, 4 H), 7.27–7.29 (m, 1 H), 7.19–7.20 (m, 2 H), 4.80 (d, J = 14.9 Hz, 1 H), 4.68 (d, J = 14.9 Hz, 1 H), 2.36 (s, 3 H), 1.24 (s, 9 H).

¹³C NMR (150 MHz, CDCl₃): δ = 164.7, 164.6, 162.9, 138.8, 137.2, 133.1, 130.9, 129.7, 128.9, 128.4, 128.3, 127.8, 126.8, 125.1, 85.5, 83.5, 57.4, 27.8, 25.4.

HRMS (ESI): m/z calcd for C₂₉H₂₃NO₅[M + H]: 458.2326; found: 458.2323.

(Z)-3-(Benzylimino)-4-(tert-butoxy)-4-oxo-2-(p-tolyl)butan-2-yl Benzoate (3g)

Purified by silica gel column chromatography using 5% and then 10% EtOAc/hexane (60.5 mg, 83% yield).

IR (thin film): 3030, 2977, 2934, 2874, 2735, 1733, 1699, 1563, 1558, 1541, 1552, 1507, 1457, 1315, 1135, 841, 702 cm⁻¹.

¹H NMR (400 MHz, CDCl₃): δ = 8.00–8.01 (m, 2 H), 7.54–7.62 (m, 5 H), 7.45–7.48 (m, 4 H), 7.32–7.35 (m, 1 H), 7.04–7.07 (m, 1 H), 6.95–6.96 (m, 2 H), 6.60–6.61 (m, 2 H), 4.94 (d, J = 14.8 Hz, 1 H), 4.76 (d, J = 14.8 Hz, 1 H), 4.42 (d, J = 14.6 Hz, 1 H), 3.73 (d, J = 14.6 Hz, 1 H), 1.15 (s, 9 H).

¹³C NMR (150 MHz, CDCl₃): complex spectrum due to ¹³F–¹⁹⁷Cu coupling (see the Supporting Information).

HRMS (ESI): m/z calcd for C₂₉H₂₃NO₅[M + H]: 458.2326; found: 458.2316.
(Z)-2-(Benzylimino)-1-((tert-butoxy)-1-oxo-3-phenylpentan-3-yl)benzoate (3j)

Purified by silica gel column chromatography using 20% EtOAc/hexane (68.8 mg, 96% yield).

1H NMR (600 MHz, CDCl3): δ = 8.21 (d, J = 7.5 Hz, 2 H), 7.59–7.64 (m, 3 H), 7.51 (t, J = 7.5 Hz, 2 H), 7.36–7.42 (m, 6 H), 7.28–7.34 (m, 2 H), 4.83 (d, J = 14.9 Hz, 1 H), 4.68 (d, J = 14.9 Hz, 1 H), 3.14 (dq, J = 7.4, 14.8 Hz, 1 H), 2.54 (dq, J = 7.4, 14.8 Hz, 1 H), 1.21 (s, 9 H), 0.73 (app t, 3 H).

13C NMR (150 MHz, CDCl3): δ = 134.6, 133.1, 132.5, 129.8, 129.7, 128.3, 128.2, 127.8, 127.7, 127.5, 126.9, 125.5, 88.1, 83.3, 57.4, 29.1, 27.7, 6.96.

HRMS (ESI): m/z calcd for C21H23NO4 [M + H]: 302.1746; found: 302.1743.

Purified by silica gel column chromatography using 5% EtOAc/hexane (46.7 mg, 68% yield).

1H NMR (600 MHz, CDCl3): δ = 8.08 (d, J = 8.2 Hz, 2 H), 7.60–7.61 (m, 2 H), 7.28–7.41 (m, 10 H), 4.84 (d, J = 15 Hz, 1 H), 4.70 (d, J = 15.0 Hz, 1 H), 2.45 (s, 3 H), 2.22 (s, 3 H), 1.24 (s, 9 H).

13C NMR (150 MHz, CDCl3): δ = 164.7, 164.5, 162.7, 143.8, 141.8, 138.7, 129.7, 129.1, 128.3, 128.1, 128.0, 127.8, 127.4, 126.8, 125.2, 85.3, 83.4, 57.3, 27.8, 25.5, 21.7.

s2-(Benzylinino)-3-phenylbutane-1,3-diol (4a)

α-Imino ester 3a (146 mg, 0.329 mmol) was used as starting material, to give the major diastereomer of 4a (51.8 mg isolated, 58% yield).

1H NMR (600 MHz, CDCl3): δ = 7.39–7.40 (m, 2 H), 7.33–7.36 (m, 6 H), 7.25–7.30 (m, 2 H), 3.96 (d, J = 13.0 Hz, 1 H), 3.88 (d, J = 13.0 Hz, 1 H), 3.48 (dd, J = 4.1, 11.5 Hz, 1 H), 3.37 (dd, J = 3.3, 11.5 Hz, 1 H), 2.78–2.80 (m, 1 H), 1.61 (s, 3 H).

13C NMR (150 MHz, CDCl3): δ = 145.8, 140.0, 128.5, 128.3, 128.2, 127.2, 126.8, 124.7, 77.1, 64.9, 61.1, 53.4, 27.9.

syn-2-(Benzylinino)-3-phenylbutane-1,3-diol (4a)

A flame-dried vial was cooled under N2, and charged with alcohol (±)-4f (34.0 mg, 0.113 mmol, 1 equiv), imidazole (23.0 mg, 0.338 mmol, 3 equiv), and CH2Cl2 (1 mL). The solution was cooled to 0 °C, and TBSCI (37.4 mg, 0.248 mmol, 2.2 equiv) was added. The reaction mixture was allowed to warm to rt slowly overnight, and stirred for a total of 16 h. The reaction mixture was passed through a plug of silica gel, and the plug was washed with ETOAc (3 × 2 mL), then concentrated. The crude product was purified by silica gel column chromatography (ETOAc/hexanes, 10:90), which afforded (±)-S1 (39.0 mg, 83% yield) as a clear and colorless liquid.

HRMS (ESI): m/z calcd for C18H23NO3 [M + H]: 302.1756; found: 302.1746.

(±)-(2R,3S)-3-Benzylinino)-4-((tert-butyldimethylsilyloxy)-2-(4-methoxyphenyl)butan-2-ol (±)-S1)

A flame-dried vial was cooled under N2, and charged with amino alcohol (±)-5f (43.0 mg, 0.111 mmol, 1 equiv), 4-methoxyphenylboronic acid pinacol ester (22.4 mg, 0.111 mmol, 1.02 equiv), and TBAB (13.5 mg, 0.038 mmol, 0.333 equiv). The mixture was stirred for 12 h, and then quenched with saturated aqueous sodium carbonate solution (1 mL) and stirred for 30 min. The reaction mixture was passed through a plug of Celite using EtOAc to rinse. The resulting product was purified by silica gel column chromatography (EtOAc/hexanes, 10:90 to 5:10), which afforded (±)-S1 (29.2 mg, 91% yield) as a clear and colorless liquid.
1H NMR (600 MHz, CDCl3): δ = 7.34−7.39 (m, 2 H), 7.30−7.35 (m, 3 H), 7.23−7.28 (m, 2 H), 6.85 (d, J = 8.8 Hz, 2 H), 4.98 (d, J = 15.0 Hz, 1 H), 4.09 (d, J = 15.0 Hz, 1 H), 3.80 (s, 3 H), 3.39 (app t, J = 4.1 Hz, 1 H), 3.25 (app qd, J = 11.0, 4.2 Hz, 2 H), 1.63 (s, 3 H), 0.80 (s, 9 H), −0.15 (s, 3 H), −0.26 (s, 3 H).

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Supporting Information

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(1) Current address: Enanta Pharmaceuticals, 500 Arsenal Street, Watertown, MA 02472, USA.
(2) Current address: Elder Research, 14 E Peace St., Suite 302, Raleigh, NC 27604, USA.
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