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α-Hydroxy and α-Oxo Selenoamides: Synthesis via Nucleophilic Selenocarbamoylation of Carbonyl Compounds and Characterization

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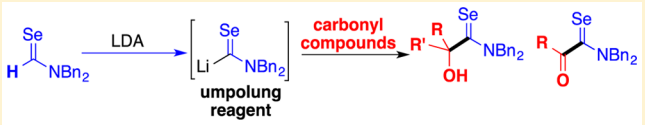
Supporting Information

ABSTRACT: Carbonyl compounds were added to selenocarbamoyllithiums to generate α-hydroxy and α-oxo selenoamides. Their conformations were determined by X-ray analyses. These compounds adopted conformations that were almost identical to those of ordinary amides. Unlike the consistency of the chemical shifts of the C═Se groups of the selenoamides in ^{13}C NMR spectra and the ^{1}J coupling constants of the C═Se groups, the substituents far from the selenium atom influenced the chemical shifts in ^{77}Se NMR.



Replacement of an oxygen atom in ordinary organic compounds with heavier elements, such as sulfur or selenium, allows for unique reactivities and properties in the resulting compounds. Selenium isologues of carbonyl compounds, i.e., selenocarbonyl compounds,[1] such as selenoaldehydes and -ketones,[2,3] have absorption spectra in the visible region, and they are less stable than their parent compounds. In fact, in the isolated selenoaldehydes, sterically bulky substituents are introduced to the carbon atoms that are close to the C═Se groups.[4] Alternatively, the introduction of heteroatoms with lone pair electrons, such as oxygen, nitrogen, and sulfur atoms, to the carbon atoms attached to the C═Se groups results in the formation of stabilized selenocarbonyl compounds, such as selenoamides,[5] selenoic acid esters, and their sulfur and selenium isologues.[6] Whether these compounds can be handled in air at room temperature strongly depends on the introduced substituents. To better understand all aspects of the stabilities and reactivities of selenoamides, those with a variety of substituents should be studied. Syntheses of selenoamides[7,8] and their use as starting materials for generating selenium-containing compounds[9] are topics of great interest in organoselenium chemistry. One available method for the synthesis of selenoamides is the direct conversion of ordinary amides to the corresponding selenium isologues with phosphorus-containing reagents such as P_2Se_5[9k] and Woollins reagent.[8] We have also developed new synthetic reactions that generate selenoamides from ordinary amides through the combination of elemental selenium, hydrochlorosilanes, and amines.[10] As an alternative method for preparing selenoamides with a range of heteroatom-containing functional groups, carbanions derived from selenoamides can be used. In this context, we have developed a method for generating carbanions from selenoamides[11−13] and used these reagents as key precursors to functionalized selenoamides in a series of our recent studies on thioamides[14] and selenoamides.[15] In particular, we found, for the first time, that the deprotonation of selenoformamides with lithium diisopropylamide (LDA) generated selenocarbamoyllithiums as umpolung reagents.[12] To further demonstrate the applicability of our selenocarbamoyllithiums in relation to the chemistry of carbamoyllithums[16] and thiocarbamoyllithiums,[17] we reacted a variety of oxygen-containing acceptors. We report herein the synthesis of α-hydroxy and α-oxo selenoamides from the reaction of selenocarbamoyllithiums with carbonyl compounds and the characterization of these products.

Initially, selenoformamide **1** reacted with LDA at −78 °C to generate **2**. To the reaction mixture was added cyclohexanone (**3a**) at the same temperature, and the mixture was stirred for several hours (Table 1). However, the desired product **4a** was obtained at a low yield. The reaction of **2** with **3a** was then performed at −40 °C for 2 h to give the corresponding product **4a**, which was successfully isolated by column chromatography (entry 1). To the best of our knowledge, this is the first example of an isolated α-hydroxy selenoamide.[18] In this case, the yield of **4a** was improved by the use of 2.5 equiv of **3a** (entry 2). As a ketone, adamantanone (**3b**) was used to give the corresponding product **4b** at a high yield (entry 3), but a longer reaction time reduced the yield of **4b** (entry 4), which was probably because of the lability of **4b** under the reaction conditions. Aldehydes also participated in the addition reaction to selenocabamoyllithium **2**. For the reaction with benzenecarbaldehyde (**3c**), either the use of excess **3c** or a longer reaction time with 1 equiv of **3c** gave the product **4c** in good yields (entries 5 and 6). In contrast, the reaction of **2** and 2-methylpropanal (**3d**) required a lower reaction temperature (entry 7). The starting aldehyde **3d** was efficiently consumed at −40 °C, but the product **4d** was isolated at a reduced yield. 2-Phenylpropanal was also subjected to the addition reaction to **2** to generate the corresponding adduct **4e** as a diastereomeric mixture in an 84:16 ratio.

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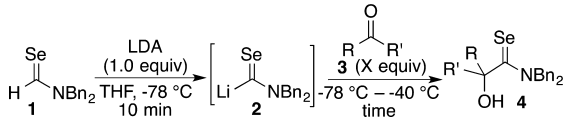
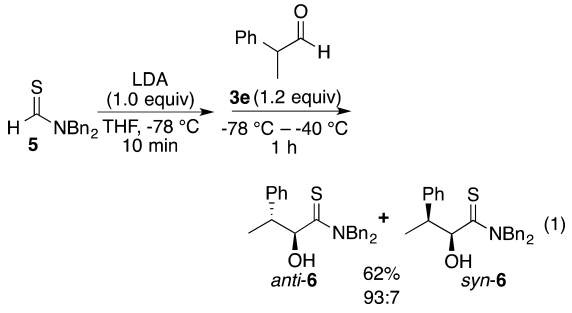
Table 1. Reaction of Selenoformamide 1 with LDA and Carbonyl Compounds[a]



entry	3	(X equiv)	time (h)	4	yield (%)[b]
1	3a	1.2	2	4a	45
2		2.5	2		64
3	3b	1.0	5	4b	62[c]
4		1.0	6		48[c]
5	3c	1.5	2	4c	55
6		1.0	6		69
7	3d	1.2	1	4d	54[d]
8	3e	1.2	1	4e[e]	64 (84:16)[f]

[a]The reaction was performed using LDA and **3**. [b]Isolated yields. [c]Isolated by gel permeation chromatography. [d]The reaction was continued at −78 °C. [e]The structure of the major isomer is shown. [f]The ratio of the diastereomers of **4e** is shown in parentheses.

To compare the diastereoselectivity of the reaction of the sulfur isologue of **2**, thioformamide **5** was deprotonated, and aldehyde **3e** was added to the reaction mixture to give the adducts in a 93:7 ratio (eq 1).

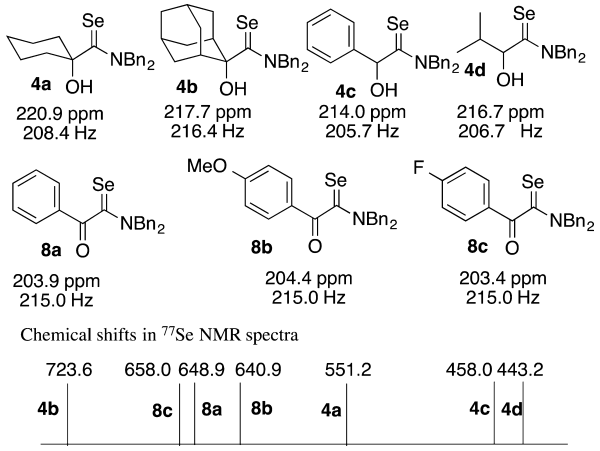


To determine the stereochemistry of the product **4e**, we attempted unsuccessfully to prepare single crystals of the major isomer of **4e** at low temperatures. Instead, the single crystal of *anti*-**6** was successfully prepared, and the molecular structure was unequivocally determined by the X-ray analyses (Figure S1 of the Supporting Information). On the basis of the similarity of the ^3J coupling constants between the protons attached to the carbon atoms α and β to the C═Se and C═S groups of the major isomers of **4e** and **6**, the stereochemistry of **4e** was further determined (Chart S1 of the Supporting Information).

For the synthesis of rare examples of α-oxo selenoamides,[19] aromatic acid chlorides **7** were used as electrophiles in the reaction for **2** (Table 1). To enhance the yields of the products **8**, the reaction was performed at higher temperatures and/or for longer reaction times, but the yields were not improved, which was partly because the further addition reaction of **2** to the obtained products **8** may be involved. In contrast, the isolated products **8** were stable under an inert atmosphere and were stored at room temperature.

The chemical shifts of C═O groups of the obtained selenoamides **4** and **8** in ^{13}C and ^{77}Se NMR[20] are shown in Chart 1, along with the ^1J coupling constants of their C═Se

Chart 1. ^{13}C and ^{77}Se NMR Spectra of α-Hydroxy and α-Oxo Selenoamides and ^1J Coupling Constants of Their C═Se Bonds[a]



[a]Chemical shifts of C═Se in ^{13}C NMR spectra and ^1J coupling constants of C═Se bonds are shown below each compound.

bonds. The signals of the carbon atom of α-oxo selenoamides **6** were observed at fields slightly higher than those of α-hydroxy selenoamides **4**. While the ^1J coupling constants of C═Se groups for all α-oxo selenoamides were identical (^1J = 215 Hz), that of selenoamide with an adamantyl group **4b** was slightly higher than those of other α-hydroxy selenoamides **4a**, **4c**, and **4d**. Likewise, the signal of **4b** in the ^{77}Se NMR spectra was shifted to a region lower than those of **4a**, **4c**, and **4d** by more than 170 ppm. Even though the functional groups such as fluorine and a methoxy group are attached to a position that is far from the selenium atom in **8**, these groups influenced the chemical shifts at approximately 20 ppm in the ^{77}Se NMR spectra.

Finally, to determine the stable conformation of α-hydroxy and α-oxo selenoamides, X-ray structure analyses of **4b** and **8a** were performed. Their molecular structures are shown in Figures 1 and 2. For a comparison of the conformation, a molecular structure of α-hydroxy amide **9** is also shown in Figure 3.

Interestingly, selenoamide **4b** and amide **9** are isostructural, and no inter- or intramolecular hydrogen bonding interactions were observed in either case. They adopted an almost eclipsed conformation, and the hydroxyl groups were oriented in a plane that deviated from the Se1(O1)−C1−C2 plane by approximately 113 ± 3°, which is in marked contrast to the presence of hydrogen bonding interactions between the hydrogen atom in the hydroxyl group and the selenium atom in the C═Se group in 3-hydroxy-2(1*H*)-pyridineselone.[18b] Likewise, the oxygen atom in **8a** was oriented in a plane that deviated from the Se1−C1−C2 plane by 97.9°. No significant difference was found among the selenoamide, ordinary α-oxo amides,[21] and α-oxo thioamides.[22] Two benzylic carbon atoms in **8a** are located in nearly the same plane as the Se1−C1−N1 plane. As a

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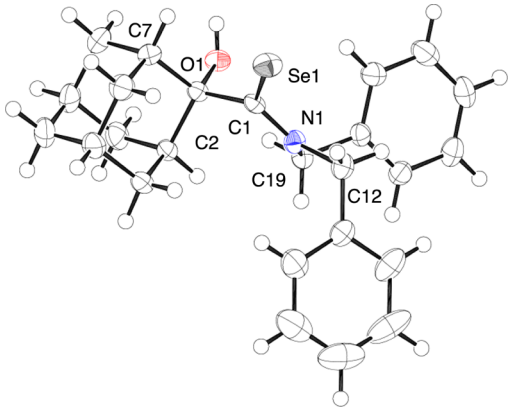

Figure 1. Molecular structure of α-hydroxy selenoamide **4b**. Ellipsoids are drawn at 50% probability. Selected bond lengths (angstroms) and angles (degrees): Se1−C1, 1.8378(15); C1−C2, 1.558(2); C2−O1, 1.4409(19); C1−N1, 1.3411(19); N1−C1−Se1, 120.15(11); C2−C1−Se1, 121.47(10); Se1−C1−C2−O1, 110.33(12); Se1−C1−C2−C7, −10.68(17); Se1−C1−N1−C12, −15.8(2); Se1−C1−N1−C19, 154.79(12).

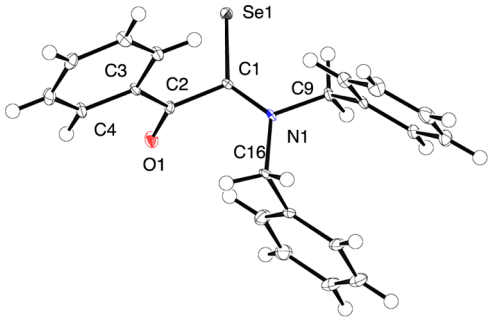

Figure 2. Molecular structure of *α-oxo* selenoamide **8a**. Ellipsoids are drawn at 50% probability. Selected bond lengths (angstroms) and angles (degrees): Se1−Cl, 1.823(3); C1−C2, 1.506(4); C2−O1, 1.224(4); C1−N1, 1.324(4); N1−C1−Se, 128.8(2); C2−C1−Se1, 111.9(2); Se1−C1−C2−O1, 97.9(3); Se1−C1−C2−C3, −79.2(3); O1−C2−C3−C4, 1.3(5); Se1−C1−N1−C, 9 0.7(4); Se1−C1−N1−C16, −172.8(2).

result, the lone pair electrons on the nitrogen atom are almost perpendicular to the C═Se group. In contrast, those in **4b** are located in a plane that deviates from the Se1−C1−N1 plane. In summary, α-hydroxy and α-oxo selenoamides were successfully synthesized by the reaction of in situ-generated selenocarbamoyllithium, and they were isolated in a pure form. Their NMR spectroscopic properties and conformations in the solid state were determined unequivocally. These results constitute important findings about the fundamental properties of selenocarbonyl compounds in the areas of theoretical and structural organic chemistry.

EXPERIMENTAL SECTION

General Remarks. The ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$. Chemical shifts of protons are reported in δ values referenced to tetramethylsilane as an internal standard in $CDCl_3$, and the following abbreviations were used: s, singlet; d, doublet; t, triplet; m, multiplet. ^{77}Se NMR (76 MHz) spectra were measured in $CDCl_3$ with Me_2Se as an external standard. All spectra were acquired in the proton-decoupled mode. The HRMS spectra were recorded on a double-focusing mass spectrometer (EI). Column chromatography was performed on silica gel 60 N (spherical neutral) 100−210 μm. Flash column chromatography was performed on silica gel 60 N (spherical neutral) 40−50 μm. All manipulations were conducted under an argon atmosphere.

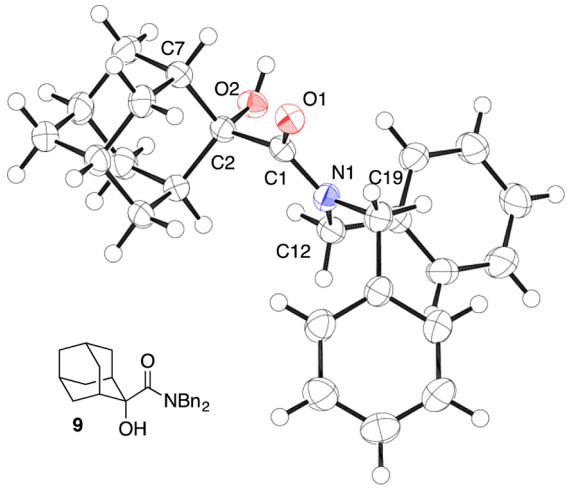

Figure 3. Molecular structure of α-hydroxy amide. Ellipsoids are drawn at 50% probability. Selected bond lengths (angstroms) and angles (degrees): O1−Cl, 1 241(2); C1−C2, 1.559(3); C2−O2, 1.437(2); C1−N1, 1.357(3); N1−C1−O1, 121.03(18); C2−C1−O1, 119.20(19); O1−C1−C2−O2, −116.6(2); O1−C1−C2−C7, 3.5(3); O1−C1−N1−C12, −169.35(18); Q1−C1−N1−C19, 5.7(3).

Preparation of α-Hydroxy and α-Oxo Selenoamides. *Typical Procedure for the Preparation of N,N-Bis(phenylmethyl)-1-hydroxycyclohexanecarboselenoamide (**4a**).* To a solution of diisopropylamine (0.14 mL, 1.00 mmol) in THF (4.0 mL) was added *n*-butyllithium (1.6 M solution in hexane, 0.65 mL, 1.00 mmol) at −78 °C under an Ar atmosphere, and the mixture was stirred for 30 min. To the reaction mixture was added a solution of *N,N*-bis-(phenylmethyl) selenoformamide (0.29 g, 1.00 mmol) in THF (1.0 mL) at −78 °C, and the mixture was stirred for 10 min. To the reaction mixture was added a solution of cyclohexanone (0.28 g, 2.50 mmol) at −40 °C, and the mixture was stirred for 2 h. The reaction mixture was poured into water and extracted with Et_2O. The organic layer was dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (40:1 hexane:EtOAc) to give *N,N*-bis(phenylmethyl)-1-hydroxycyclohexane-1-carboselenoamide (0.25 g, 64%) as a yellow solid.

*N,N-Bis(phenylmethyl)-1-hydroxycyclohexanecarboselenoamide (**4a**).* Yellow solid: 64% yield (0.25 g); mp 125.3−126.0 °C; ^{1}H NMR ($CDCl_3$) δ 1.22 (m, 1H), 1.69 (m, 5H), 1.92 (d, 2H, J = 13.2 Hz), 2.27 (m, 2H), 3.53 (brs, 1H), 5.17 (s, 2H), 5.48 (s, 2H), 7.16 (m, 4H), 7.35 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 22.0, 24.8, 37.0, 56.8, 62.0, 80.4, 126.7, 127.4, 127.7, 127.9, 128.8, 129.1, 134.6, 135.3, 220.9 (J_{C-Se} = 208.4 Hz); ^{77}Se NMR ($CDCl_3$) δ 551.2; MS (EI) m/z 386 [M^+]; HRMS (EI) calcd for $C_{21}H_{25}NOSe$ m/z 387.1101, found m/z 387.1104.

*N,N-Bis(phenylmethyl)-1-hydroxyadamantanecarboselenoamide (**4b**).* Yellow solid: 62% yield (0.27 g); mp 164.6−166.5 °C; ^{1}H NMR ($CDCl_3$) δ 1.43−1.88 (m, 12H), 2.31 (d, J = 11.7 Hz, 2H), 3.49 (s, 1H), 5.24 (s, 2H), 5.38 (s, 2H), 7.08−7.19 (m, 4H), 7.26−7.35 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 26.3, 26.7, 32.7, 37.4, 57.7, 60.9, 83.2, 126.7, 127.5, 128.5, 128.7, 135.2, 135.9, 217.7 ($^{1}J_{C-Se}$ = 216.4 Hz); ^{77}Se NMR ($CDCl_3$) δ 723.6; MS (EI) m/z 438 [M^+]; HRMS (EI) calcd for $C_{25}H_{29}NOSe$ m/z 439.1414, found m/z 439.1412.

*N,N-Bis(phenylmethyl)-2-hydroxy-2-phenylmethaneselenoamide (**4c**).* Orange solid: 69% yield (0.27 g); mp 84.5−87.7 °C; ^{1}H NMR ($CDCl_3$) δ 4.34 (d, J = 16.1 Hz, 1H), 4.68 (d, J = 14.6 Hz, 1H), 4.85 (d, J = 16.1 Hz, 1H), 5.21 (m, 2H), 6.21 (d, J = 14.6 Hz, 2H), 6.98 (d, J = 5.9 Hz, 2H), 7.21−7.34 (m, 10H), 7.53 (d, J = 6.3 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 54.3, 60.6, 76.1, 126.2, 127.4, 127.7, 128.1, 128.3, 128.6, 128.7, 128.9, 129.1, 129.2, 129.5, 132.8, 133.0, 134.0, 134.2, 134.3, 139.6, 214.0 ($^{1}J_{C-Se}$ = 205.7 Hz); ^{77}Se NMR ($CDCl_3$) δ 458.2;

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MS (EI) m/z 438 [M^+]; HRMS (EI) calcd for $C_{22}H_{21}NOSe$ m/z 395.0788, found m/z 395.0772.

*N,N-Bis(phenylmethyl)-2-hydroxy-3-methylbutaneselenoamide (**4d**).* Yellow solid: 54% yield (0.20 g); mp 72.9−74.0 °C; ^{1}H NMR ($CDCl_3$) δ 0.99 (d, 3H, J = 6.8 Hz), 1.07 (d, 3H, J = 6.8 Hz), 1.98 (m, 1H), 3.87 (br, 1H), 4.22 (d, 1H), 4.38 (d, 1H, J = 14.3 Hz), 4.42 (t, 2H, J = 15.13, 16.1 Hz), 6.37 (d, 1H, J = 14.1 Hz), 7.12 (d, 2H, J = 6.7 Hz), 7.28−7.41 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 16.4, 20.1, 35.3, 53.9, 60.0, 126.7, 128.2, 128.3, 128.6, 129.0, 129.4, 133.1, 134.6, 216.7 ($^1J_{C-Se}$ = 206.7 Hz); ^{77}Se NMR ($CDCl_3$) δ 443.2; MS (EI) m/z 360 [M^+]; HRMS (EI) calcd for $C_{19}H_{23}NOSe$ m/z 361.0945, found m/z 361.0967.

*N,N-Bis(phenylmethyl)-2-hydroxy-3-phenylbutaneselenoamide (**4e**).* Yellow oil: 64% yield (0.27 g) as a diastereomeric mixture. Spectral data for the major isomer are shown: ^{1}H NMR ($CDCl_3$) δ 1.31 (d, J = 7.18 Hz, 3H), 1.61 (br, 1H) 3.20 (quintet, J = 7.18, 14.2 Hz, 1H), 4.32 (d, J = 14.0 Hz, 1H), 4.37 (d, J = 16.6 Hz, 1H), 5.05 (m, 2H), 6.41 (d, J = 14.2 Hz, 1H), 6.96−7.02 (m, 4H), 7.19−7.25 (m, 3H), 7.25−7.35 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 16.6, 47.8, 53.5, 59.8, 78.1, 126.4, 126.9, 127.8, 127.9, 128.0, 128.2, 128.4, 128.5, 128.7, 129.0, 132.8, 141.9, 216.2 ($^1J_{C-Se}$ = 207.6 Hz); ^{77}Se NMR ($CDCl_3$) δ 422.6; MS (EI) m/z 422 [M^+]; HRMS (EI) calcd for $C_{24}H_{25}NOSe$ m/z 423.1101, found m/z 423.1103.

*N,N-Bis(phenylmethyl)-2-oxo-2-phenylethaneselenoamide (**8a**).* Yellow solid: 31% (0.12 g); mp 87.9−88.5 °C; ^{1}H NMR ($CDCl_3$) δ 4.49 (s, 2H), 5.30 (br, 2H), 7.23 (m, 2H), 7.34−7.49 (m, 10H), 7.59 (m, 1H), 8.07 (d, J = 6.8 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 54.2, 56.8, 128.4, 128.5, 128.6, 128.7, 128.8, 128.9, 129.1, 129.2, 129.9, 132.5, 133.6, 133.9, 134.0, 188.8, 203.9 ($^1J_{C-Se}$ = 215.0 Hz); ^{77}Se NMR ($CDCl_3$) δ 648.9; MS (EI) m/z 393 [M^+]; HRMS (EI) calcd for $C_{22}H_{19}NOSe$ m/z 393.0632, found m/z 393.0624.

*N,N-Bis(phenylmethyl)-2-(4-methoxyphenyl)-2-oxoethaneselenoamide (**8b**).* Yellow solid: 44% (0.18 g); mp 105.0−107.1 °C; ^{1}H NMR ($CDCl_3$) δ 3.85 (s, 3H), 4.51 (br, 3H), 5.88 (br, 1H), 6.94 (d, 2H, J = 8.8 Hz), 7.24 (m, 2H), 7.34−7.48 (m, 8H), 8.06 (d, 2H, J = 8.8 Hz); ^{13}C NMR ($CDCl_3$) δ 54.1, 55.6, 114.1, 126.4, 128.4, 128.5, 128.7, 128.9, 129.1, 132.4, 134.2, 188.4, 204.4 ($^1J_{C-Se}$ = 215.0 Hz); ^{77}Se NMR ($CDCl_3$) δ 640.9; MS (EI) m/z 422 [M^+]; HRMS (EI) calcd for $C_{23}H_{21}NO_2Se$ m/z 423.0738, found m/z 423.0725.

*N,N-Bis(phenylmethyl)-2-(4-fluorophenyl)-2-oxoethaneselenoamide (**8c**).* Yellow solid: 29% (0.12 g); mp 84.5−87.2 °C; ^{1}H NMR ($CDCl_3$) δ 4.49 (s, 2H), 5.34 (br, 2H), 7.13 (m, 2H), 7.23 (m, 2H), 7.34 (m, 4H), 7.41−7.48 (m, 4H), 8.10 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 54.4, 56.7, 116.0, 116.1, 128.5, 128.7, 129.0, 129.1, 129.2, 132.6, 132.7, 134.0, 164.9, 167.5, 187.4, 203.4 ($^1J_{C-Se}$ = 215.0 Hz); ^{77}Se NMR ($CDCl_3$) δ 658.0; MS (EI) m/z 411 [M^+]; HRMS (EI) calcd for $C_{22}H_{18}FNOSe$ m/z 411.0538, found m/z 411.0520.

Preparation of *N,N*-Bis(phenylmethyl)-2-hydroxy-3-phenylbutanethioamide (5). To a solution of diisopropylamine (0.14 mL, 1.00 mmol) in THF (4.0 mL) was added *n*-butyllithium (1.6 M solution in hexane, 0.65 mL, 1.00 mmol) at −78 °C under an Ar atmosphere, and the mixture was stirred for 30 min. To the reaction mixture was added a solution of *N,N*-dibenzyl thioformamide (0.24 g, 1.00 mmol) in THF (1.0 mL) at −78 °C, and the mixture was stirred for 10 min. To the reaction mixture was added a solution of 2-phenyl propionaldehyde (0.16 g, 1.20 mmol) at −78 °C, and the mixture was stirred for 1 h. The reaction mixture was poured into water and extracted with Et_2O. The organic layer was dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was subjected to column chromatography on silica gel (40:1 hexane:EtOAc) to give *N,N*-bis(phenylmethyl)-2-hydroxy-3-phenylbutanethioamide (0.23 g, 62%, R_f = 0.35, dr = 93:7). It solidified around rt. Spectral data for the major isomer are shown: ^{1}H NMR ($CDCl_3$) δ 1.45 (d, J = 6.73 Hz, 3H), 1.57 (br, 1H), 3.17 (quintet, J = 7.2, 14.4 Hz, 1H), 3.89 (d, J = 16.6 Hz, 1H), 4.15 (d, J = 14.4 Hz, 1H), 4.63 (m, 2H), 6.12 (d, J = 14.4 Hz, 1H), 7.00−7.03 (m, 4H), 7.18−7.21 (m, 3H), 7.25−7.37 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 16.2, 46.9, 52.3, 55.7, 75.8, 126.3, 126.7, 127.6, 127.7, 127.9, 128.0, 128.3, 128.4, 129.0, 133.7, 134.4, 142.3, 208.2; MS (EI) m/z 375 [M^+]; HRMS (EI) calcd for $C_{24}H_{25}NOS$ m/z 375.1657, found m/z 375.1644.

Preparation of *N,N*-Bis(phenylmethyl)-2-hydroxyadamananamide (9). To a 50 mL two-neck flask were added *N,N*-bis(phenylmethyl)-2-hydroxyadamataneselenoamide (0.23 g, 0.53 mmol), CH_2Cl_2 (1.0 mL), and hydrogen peroxide (30% aqueous solution, 0.24 mL, 2.20 mmol). The reaction mixture was stirred under reflux in THF for 30 min, poured into water, and extracted with Et_2O. The organic layer was dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (10:1 hexane:EtOAc) to give *N,N*-bis(phenylmethyl)-2-hydroxyadamatanamide (0.09 g, 44%) as a white solid: mp 168.2−169.5 °C; ^{1}H NMR ($CDCl_3$) δ 1.42−1.91 (m, 12H), 2.17 (d, J = 12.2 Hz, 2H), 3.49 (br, 1H), 4.50 (s, 2H), 4.90 (s, 2H), 7.13−7.17 (m, 5H), 7.24−7.30 (m, 5H); ^{13}C NMR ($CDCl_3$) δ 26.6, 26.7, 32.8, 35.2, 35.9, 37.6, 79.1, 127.1, 128.5, 137.6, 174.2; MS (EI) m/z 375 [M^+]; HRMS (EI) calcd for $C_{25}H_{29}NO_2$ m/z 375.2198, found m/z 375.2167.

■ ASSOCIATED CONTENT

Supporting Information

Crystal data and structural refinement for **4b**, **5**, **8a**, and **9** and copies of ^{1}H NMR and ^{13}C NMR spectra of products. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b00969.

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Notes

The authors declare no competing financial interest.

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