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Isoselenazolones as Catalysts for the Activation of Bromine: Bromolactonization of Alkenoic Acids and Oxidation of Alcohols

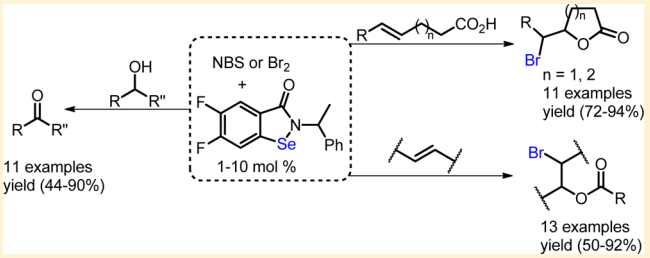
Shah Jaimin Balkrishna,[†] Ch Durga Prasad,[†] Piyush Panini,[†] Michael R. Detty,[‡] Deepak Chopra,[†] and Sangit Kumar*[,†,‡]

[†]Department of Chemistry, Indian Institute of Science Education and Research Bhopal (IISER), Bhopal, Madhya Pradesh 462 023, India

[‡]Department of Chemistry, University at Buffalo, The State University of New York, Buffalo, New York 14260-3000, United States

Supporting Information

ABSTRACT: Isoselenazolones were synthesized by a copper-catalyzed Se−N bond forming reaction between 2-halobenzamides and selenium powder. The catalytic activity of the various isoselenazolones was studied in the bromolactonization of pent-4-enoic acid. Isoselenazolone **9** was studied as a catalyst in several reactions: the bromolactonization of a series of alkenoic acids with bromine or *N*-bromosuccinimide (NBS) in the presence of potassium carbonate as base, the bromoesterification of a series of alkenes using NBS and a variety of carboxylic acids, and the oxidation of secondary alcohols to ketones using bromine as an oxidizing reagent. Mechanistic details of the isoselenazolone-catalyzed bromination reaction were revealed by ^{77}Se NMR spectroscopic and ES-MS studies. The oxidative addition of bromine to the isoselenazolone gives the isoselenazolone(IV) dibromide, which could be responsible for the activation of bromine under the reaction conditions. Steric effects from an *N*-phenylethyl group on the amide of the isoselenazolone and electron-withdrawing fluoro substituents on the benzo fused-ring of the isoselenazolone appear to enhance the stability of the isoselenazolone as a catalyst for the bromination reaction.



INTRODUCTION

The addition of bromine across carbon−carbon double bonds is one of the well-known reactions in organic chemistry and is well utilized in the synthesis of various organic molecules. The addition of bromine to alkenes is often done at ambient temperature or higher with stoichiometric quantities of the brominating agent. Other approaches that generate the brominating agent slowly in the presence of substrate include the use of metal bromide salts (MBr, M = Li, Na, and K) in combination with oxidizing agents (H_2O_2, $NaBrO_4$).[1] In yet other approaches, catalysts such as thiourea, phosphine sulfide, or hypervalent organoiodides (such as iodosobenzene and bromoiodinane), as examples, have been used for the bromolactonization of alkenes (Chart 1).[2−5] Organic brominating reagents such as *N*-bromosuccinimide and 1,3-dibromo-5,5-dimethylhydantoin have been utilized in these methods as sources of Br^+. According to recent surveys, the use of molecular bromine as a source of Br^+ is more economical with fewer waste products as compared to the use of organic brominating reagents.[6] Bromination of alkenes with bromine and a catalytic amount of an organoselenium compound at ambient temperature has not been described to date. Increased reactivity and selectivity using an organoselenium catalyst with Br_2 as a Br^+ source would be of practical significance for bromination reactions of alkenes and related substrates.

Organoselenium compounds are versatile reagents for a variety of synthetic transformations.[7−11] Of particular interest is the bromination of alkenes using hypervalent organoselenium compounds. Diaryl selenides react with bromine to form diarylselenium(IV) dibromides, which can then transfer Br^+.[12] However, the reaction of diarylselenium(IV) dibromides with alkenes has only been examined with stoichiometric amounts of the Se(IV) compound and requires higher temperatures for the transfer of bromine to the alkene.[12] Other classes of organoselenium compounds such as arylalkyl selenides (ArSeAlkyl), diaryl diselenides (ArSeSeAr) and arylselenenyl halides ArSeX (X = Cl, Br, I) also react with bromine to form intermediates that, in principle, could transfer Br^+ to alkenes. These organoselenium compounds in the presence of bromine form arylselenenyl bromides and arylselenenyl tribromides, which add to carbon−carbon double bonds to produce phenylseleno lactones.[9a−c,e,f,11,13] If the brominated intermediates formed in the reaction of organoselenium compounds with bromine were to give greater reactivity and selectivity for bromination than molecular bromine itself, then the organoselenium compounds could function catalytically in the presence of excess bromine. We report our preliminary results using isoselenazolones as catalysts for the bromolactonization

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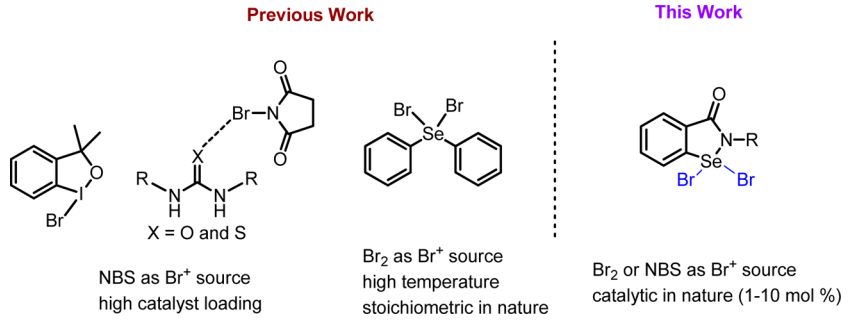
Chart 1. Catalysts for the Activation of NBS and Bromine

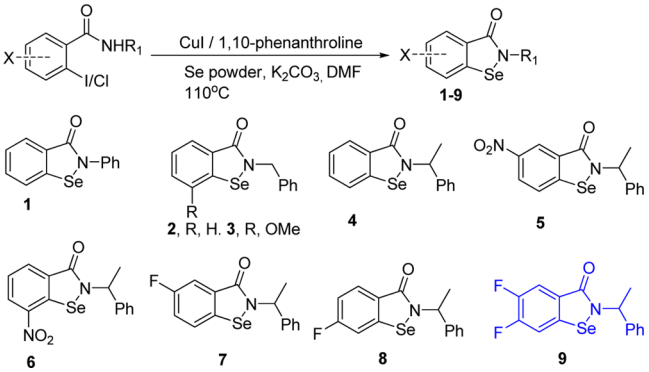


of alkenoic acids using bromine or NBS as the brominating agent and as catalysts for the bromoesterification of alkenes using NBS as a source of Br^+ and various carboxylates as nucleophiles. Isoselenazolones can also be employed as catalysts for the oxidation of secondary alcohols to ketones with bromine.

RESULTS AND DISCUSSION

Preparation of Isoselenazolones. The isoselenazolones **1**–**9** used in this study were prepared as shown in Scheme 1. A

Scheme 1. Synthesis of Isoselenazolones 1–9



2-chloro- or 2-iodobenzamide derivative was treated with CuI in the presence of 1,10-phenanthroline followed by the addition of selenium powder and potassium carbonate.[14] The variously substituted 2-halo-*N*-phenylethylbenzamide substrates underwent Se–N coupling reaction successfully to give the previously reported[14] isoselenazolones **1**–**4** and the new isoselenazolones **5**–**9** in 84–95% yield. The presence of Se–N bond in the isoselenazolones **1**–**9** was confirmed by ^{77}Se NMR chemical shifts (δ 840–855 ppm), which correlate well with the reported chemical shifts (δ 800–950 ppm) observed for other Se–N-containing heterocycles.[14]

The structure of isoselenazolone **9** was established unequivocally by single-crystal X-ray crystallographic analysis (Figure 1). The Se–C and Se–N bond distances [1.885(2) and 1.876(2) Å, respectively] and the C–Se–N bond angle [85.46 (10)°] in **9** correlate well with the reported distances and angles in related isoselenazolones.[14]

Bromolactonization of Alkenoic Acid Substrates. Bromolactonization of pent-4-enoic acid with 1.2 equiv of bromine to give bromolactone **10** was complete after 24 h in the presence of 1.5 equiv of potassium carbonate. After 3 h, only 35% of the pent-4-enoic acid had reacted (Table 1). The addition of base accelerates the cyclization of any 4,5-

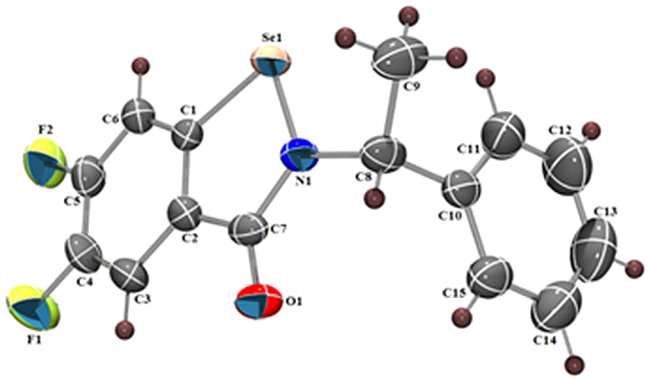
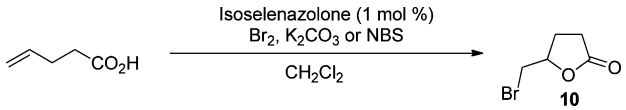


Figure 1. ORTEP diagram of isoselenazolone **9**.

Table 1. Catalytic Activity of Isoselenazolones 1–9 with Bromine and Pent-4-enoic Acid[a]



entry	catalyst	source of Br^+	reaction time (h)	isolated yield (%)
1	**1**	Br_2	7	67
2	**2**	Br_2	4	70
3	**3**	Br_2	3 (6)	76 (80)
4	**4**	Br_2	5	87
5	**5**	Br_2	24	nd
6	**6**	Br_2	6	nd
7	**7**	Br_2	3	90
8	**8**	Br_2	24	92
9	**9**	Br_2	3	94
10	none	Br_2	3	35[b]
11	none	NBS	40	85[c]

[a]Reactions were carried out using 1 mmol of pent-4-enoic acid, 1.2 mmol of Br_2 (from a 1 M stock solution in CH_2Cl_2) and 1.5 mmol K_2CO_3. Isoselenazolone concentrations were 1 mol % relative to pent-4-enoic acid. [b]A 35:65 ratio of bromolactone to pent-4-enoic acid was observed by ^1H NMR spectroscopy. Products were not isolated. [c]Reaction of 1.2 mmol of NBS in CH_2Cl_2. Complete conversion of pent-4-enoic acid into bromolactone **10** was observed by ^1H NMR spectroscopy. No pent-4-enoic acid was detected.

dibromopentanoic acid that might be formed as a second product upon initial addition of Br_2. Under identical conditions in the presence of 0.01 equiv (1 mol %) of isoselenazolone **1**, bromolactone **10** was isolated in 67% yield after 7 h (Table 1, entry 1). The reaction was sensitive to the nature of the base employed. In contrast to the use of K_2CO_3 as a base, the use of triethyl amine or pyridine as base gave only traces of

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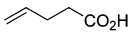
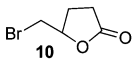
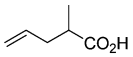
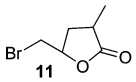
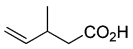
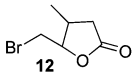
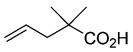
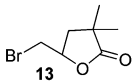
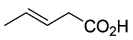
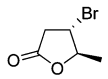
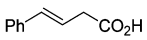
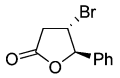
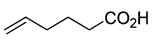
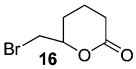
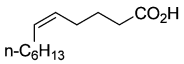
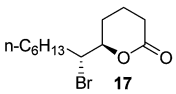
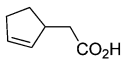
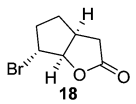
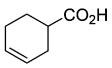
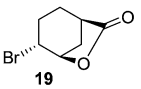
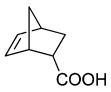
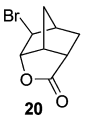
Table 2. Bromolactonization of Alkenoic Acids with Bromine and 1 mol % Isoselenazolone 9

Entry	Substrate	Product	Reaction Time (h)	Isolated Yield[a] (%)
1		 **10**	3	94
2		 **11**	3	92 (70:30)
3		 **12**	5	88 (68:32)
4		 **13**	3	95
5		 **14**	3	72[b] (85:15)
6		 **15**	3	95[b,c]
7		 **16**	5	89
8		 **17**	12	86[b]
9		 **18**	7	90[c]
10		 **19**	7	86[c]
11		 **20**	7	86[c]

[a]Values in parentheses are ratios of diastereomers determined by ^{1}H NMR. [b]No base (K_2CO_3) was used in this reaction. [c]Only one diastereomer detected by ^{1}H NMR.

bromolactone **10** after 7 h of reaction. Reactions were conducted with 1 mmol of pent-4-enoic acid, 1.2 mmol of Br_2, 1.5 mmol of base, and 0.01 mmol of isoselenazolone **1**.

The bromolactonization of pent-4-enoic acid was next examined in the presence of 1 mol % of the isoselenazolones **2**–**9** using 1 mmol of pent-4-enoic acid, 1.2 mmol of Br_2, and 1.5 mmol of K_2CO_3 as base (Table 1). Isoselenazolones **1**–**4** (Table 1, entries 1–4) and **7**–**9** (Table 1, entries 7–9) accelerated the bromination reaction as compared to the uncatalyzed reaction (Table 1, entry 10). The strongly electron-withdrawing nitro group found in isoselenazolones **5** and **6** destroyed catalytic activity with these compounds (Table 1, entries 5 and 6, respectively), and several unidentified side-products were formed during the course of the reaction. Isoselenazolones **1** and **2** with *N*-phenyl or *N*-benzyl substitution were partially converted into an undesired arylselenolactone sideproduct during the course of the bromination reaction (please see the Supporting Information, Figure S149). Replacing the *N*-benzyl group with an *N*-1-phenylethyl group in **3** gave comparable reactivity to **2**, but none of the undesired selenolactone side-product was observed. However, extended reaction times (6 vs 3 h) gave very little increase in product formation (76 vs 80%, respectively) suggesting a decreased activity in the catalyst. Isoselenazolones **7**–**9** also have *N*-1-phenylethyl substituents and showed good catalytic activity (Table 1, entries 7–9, respectively) and none of the side-product was formed. The increased steric bulk of the *N*-1-phenylethyl group relative to *N*-phenyl or *N*-benzyl substituents may decrease reactivity of the Se–N bond (i.e., increase catalyst lifetime) through steric shielding. The fluorinated isoselenazolones **7**–**9** provided nearly quantitative yields of brominated product and remained intact after the

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bromination reactions were complete (vide infra, mechanistic studies, and Supporting Information, Figure S153). Among these three compounds, which were all very similar, difluoro derivative **9** appeared to have the greatest catalytic activity kinetically, and no side products were formed from isoselenazolone **9**. For these reasons, isoselenazolone **9** was examined as the catalyst of choice in subsequent reactions.

The addition of Br^+ using Br_2 to the series of alkenoic acids shown in Table 2 was examined with 1 mol % of isoselenazolone **9**. Bromolactones **10**–**20** were the resulting products. Initially, K_2CO_3 was used as a base for all entries of Table 2, but pent-3-enoic acid (entry 5) and *E*-4-phenylbut-3-enoic acid (entry 6) failed to give measurable amounts of bromolactonization in the presence of K_2CO_3, and both substrates were recovered quantitatively as potassium salts from the reaction mixture. In the absence of K_2CO_3, bromolactonizaion occurred in both substrates in 3 h (Table 2, entries 5 and 6, respectively). 2-Methyl- and 3-methylpent-4-enoic acids each gave a diastereomeric mixture of bromolactonization products **11** and **12**, respectively (Table 2, entries 2 and 3). Pent-3-enoic acid gave an 85:15 mixture of *trans*- to *cis*-bromolactones **14** in 72% isolated yield. In contrast, 4-phenylbut-3-enoic acid gave a single diastereomer **15** upon bromolactonization in 95% isolated yield. The stereochemistry around the C–C bond in **15** was established unequivocally by single-crystal, X-ray crystallographic analysis (Figure 2) and demonstrated a *trans*-orientation of the bromine and phenyl substituents around the lactone ring.

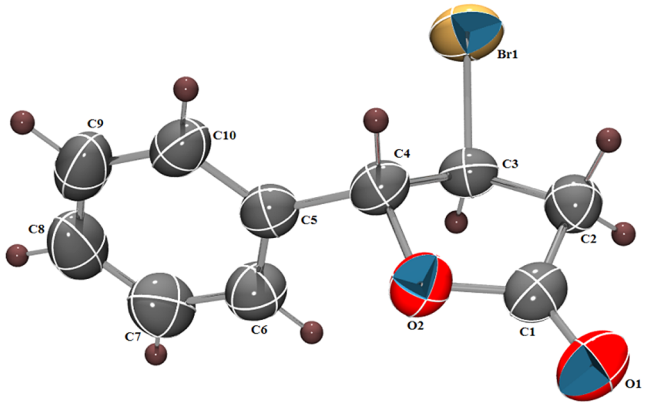

Figure 2. ORTEP diagram of bromolactone **15**.

Bromine could be replaced with NBS as a source of Br^+ in these reactions. For all substrates, yields and diastereomeric ratios were nearly identical with either Br_2 or NBS as a source of Br^+ and NBS was the more reactive reagent (Table S1 in the Supporting Information). The addition of K_2CO_3 was not necessary using NBS as the brominating agent. However, the bromolactone products were difficult to separate from the succinimide produced in the reaction.

Bromoesterification of Alkene Substrates. Bromolactonization of alkenoic acids is favored entropically when 5- or 6-membered rings are formed. Intermolecular bromoesterification of simple alkenes does not have the same entropic benefit. Bromoesterification of cyclooctene with 1.0 equiv of benzoic acid and 1.5 equiv of NBS gave <10% formation of bromoester **21** after 8 h. In the presence of 10 mol % isoselenazolone **9**, reaction of cyclooctene with 1.0 equiv of benzoic acid and 1.5 equiv NBS gave bromoester **21** in 84% isolated yield after 8 h (Table 3, entry 1). As presented in Table 3, various alkenes and acids were utilized as reaction partners in the isoselenazolone-catalyzed bromoesterification reaction. Bromoesters **21**–**29** were obtained as a single *trans*-isomer in the bromoesterification reactions of cyclohexene or cyclooctene (entries 1–9, Table 3). Vinylcyclohexane, (*Z*)-1,2-diphenylethene, and 2-methylbut-2-ene gave a mixture of regioisomers under the reaction conditions (Table 3, entries 10, 12, and 13, respectively). The alkyne 1-phenylpropyne gave addition across the triple bond to give a mixture *E*- and *Z*-stereoisomers in an 86:14 ratio. Dibromination products were detected in electron-rich vinylcyclohexane and 2-methylbut-2-ene.

Oxidation of Secondary Alcohols to Ketones. The oxidation of alcohols to ketones utilizing oxygen, oxone, NBS, or trichloroisocyanuric acid as an oxidizing reagent has been reported using a variety of catalysts: TEMPO, *ortho*-iodoxybenzoic acid (IBX), 2-iodosobenzoic acid, 2-iodoxybenzenesulfonic acid, iodosobenzene, diacetoxyiodobenzene, or thiourea.[16,17] In the absence of catalyst, these oxidations are slow or not observed. While NBS and the halogens are strong enough as oxidants to oxidize alcohols to carbonyl compounds, reactions with these oxidants are slow or are not sufficiently selective to avoid competing electrophilic additions. As an example, 1-phenylethyl alcohol shows no oxidation to acetophenone (**34**) with 1.5 equiv of Br_2 after 3 h at ambient temperature. However the addition of 10 mol % isoselenazolone **9** as a catalyst gave complete oxidation of 1-phenylethyl alcohol to **34**, which was isolated in 90% yield (Table 4, entry 1). To the best of our knowledge, oxidation of alcohols to ketones with Br_2 and an organoselenium catalyst has not been reported.

The series of alcohols in Table 4 was converted to the corresponding ketones utilizing 1 equiv of alcohol, 1.5 equiv of Br_2, and 0.1 equiv (10 mol %) of isoselenazolone **9**. Substituted 1-arylethyl alcohols showed similar reactivity in the bromination reaction; however, several side products, α-bromoacetophenones and bromoarylacetophenones were also produced along with the desired products. Lowering the reaction temperature to 10 to −35 °C, depending upon substrate, suppressed the formation of side products and the desired ketones **35**–**40** were isolated in 60–84% yield from their respective secondary alcohols. Similarly, diarylmethanols were converted into their respective benzophenones **41**–**43**. Cyclohexanol, the only alkyl secondary alcohol examined, reacted more slowly to give cyclohexanone **44** in 44% isolated yield after 16 h, while 46% of cyclohexanol was recovered from the reaction mixture (entry 11, Table 4).

Mechanistic Considerations. Possible reaction pathways for the isoselenazolone-catalyzed bromolactonization are depicted in Scheme 2. Support for these pathways was provided by ^{77}Se NMR spectroscopy and mass spectrometry. The chemical shift of the ^{77}Se nucleus was quite sensitive to the oxidation state of the molecule: isoselenazolones vs isoselenazolone(IV) dibromide.[15,18,19] Isoselenazolone **4** was examined by ^{77}Se NMR spectroscopy in this study. The reaction of bromine with isoselenazolone was fast and yielded the expected isoselenazolone(IV) dibromide **I** (δ 979 ppm), whose identity was also confirmed by mass spectrometry. The ^{77}Se NMR chemical shift for intermediate **I** correlates well with the reported ^{77}Se NMR chemical shift for the related structures **45** (δ 937 ppm) and **46** (1181 ppm).[18] The ^{77}Se NMR chemical shift for selenium(IV) dibromide **I** is significantly downfield ($\Delta\delta$ 139 ppm) relative to the parent selenium(II)

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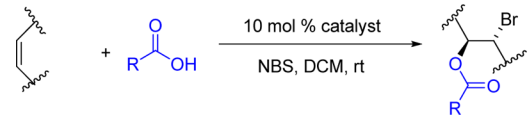
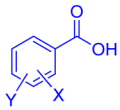
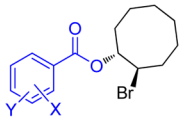
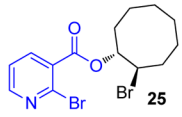
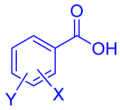
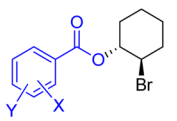
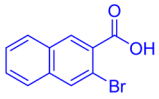
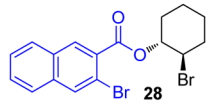
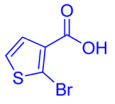
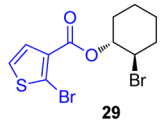
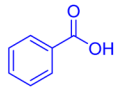
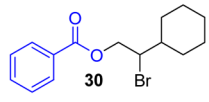
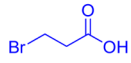
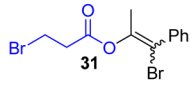
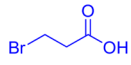
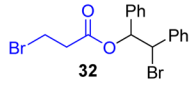
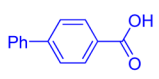
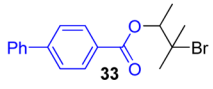
Table 3. Bromoesterification of Alkenes Catalyzed by Isoselenazolone 9[a]



Entry	Alkene	Carboxylic Acid	Product	Reaction Time (h)	Isolated Yield[b] (%)
1			 **21**, X = Y = H	8	84
2			**22**, X = 2-Br, Y = 5-OMe	16	62
3			**23**, X = 2-I, Y = 5-Me	10	72
4			**24**, X = 2-Cl, y = 4,5-F_2	8	56
5			 **25**	10	92
6			 **26**, X = 2-Cl, Y = 4-Cl	10	80
7			**27**, X = 2-Cl, Y = 5-NO_2	8	70
8			 **28**	10	70
9			 **29**	10	50
10			 **30**	10	68 (67:33)
11			 **31**	10	61 (86:14)
12			 **32**	10	74 (79:21)
13			 **33**	10	56 (76:24)

[a]Reactions conducted with 1.0 equiv each of alkene and carboxylic acid, 1.5 equiv of NBS, and 0.1 equiv (10 mol %) of isoselenazolone **9**. [b]Values in parentheses are ratios of regioisomers determined by ^{1}H NMR.

compound **4** (δ 840 ppm). Selenium(IV) dibromide **I** may be in equilibrium with its ionic form **III**. The existence of an equilibrium is suggested by the broad ^{1}H NMR signals (please see the Supporting Information, Figure S142, S145, S146 for ^{1}H of **I** and **II**). The intermediate selenium(IV) dibromide **I** is fairly stable in the solution as the ^{77}Se NMR chemical shift remains unchanged over a period of 24 h.

Addition of an equimolar amount of pent-4-enoic acid to the isoselenazolone(IV) dibromide **I** produced isoselenazolone **4** (840 ppm) and bromolactone **10** (confirmed by ^{1}H NMR spectroscopy) in the presence of K_2CO_3. Traces of a side product, presumably phenylselenolactone **VII** (δ 498 ppm) were observed in the reaction mixture. In the case of difluoro analogue **9**, traces of the corresponding side product (difluoro analogue of **VII**) were not observed by ^{77}Se NMR spectroscopy, indicating complete regeneration of isoselenazolone **9** from the corresponding isoselenazolone(IV) dibromide. This may be due to increased stability of the Se−N bond in the difluoro analogue **9** as compared to **4**.

Transfer of Br^+ to pent-4-enoic acid may occur by either of two pathways: (i) reversible generation of free Br^+ in the solution from selenium(IV) dibromide and then attack of Br^+ on carbon−carbon double bond, or (ii) formation of the associated intermediate **V** followed by intramolecular transfer of Br^+ to pent-4-enoic acid. Evidence for the transfer of Br^+ to pent-4-enoic acid via the associative pathway comes from mass spectrometry. An equimolar solution of pent-4-enoic acid and either selenium(IV) dibromide from **4** or **9**, when analyzed by ES-MS, gave peaks at m/z 434.0 from **4** (intermediate **V** in Scheme 2) or 518.0 (corresponding intermediate **V** from **9**). The importance of the carboxylate functionality and its interaction with the selenium(IV) nucleus can be inferred

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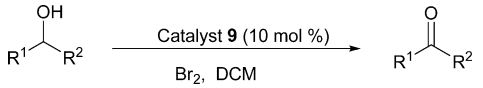
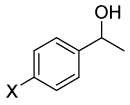
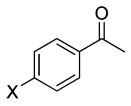
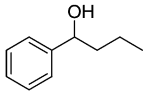
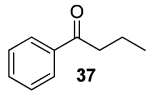
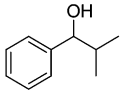
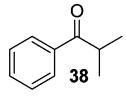
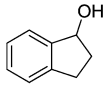
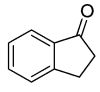
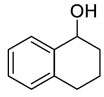
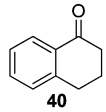
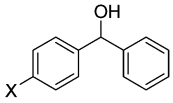
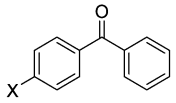
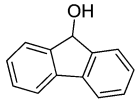
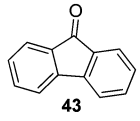
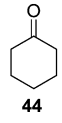
Table 4. Isoselenazolone 9 Catalyzed Oxidation of Alcohols to Ketones with Br_2 as Oxidant



Entry	Alcohol	Ketone	T, °C	Reaction Time (h)	Isolated Yield (%)
1		 **34**, X = H	25	0.5	90
2		**35**, X = Cl	10	30	85
3		**36**, X = Br	–10	30	64
4		 **37**	–35	24	72
5		 **38**	–20	35	60
6		 **39**	–35	16	76
7		 **40**	–35	14	84
8		 **41**, X = H	–20	35	60
9		**42**, X = Br	20	40	67
10		 **43**	–35	30	84
11		 **44**	–20	16	44

from the lack of reactivity of cyclohexene under the reaction conditions. No bromination of cyclohexene was observed under the same reaction conditions: addition of cyclohexene to either selenium(IV) dibromide prepared from **4** or **9**. If Br^+ were reversibly generated from the selenium(IV) intermediate, then one would expect some bromination of cyclohexene to occur, which was not observed. Furthermore, formation of 1,2-dibromopent-4-anoic acid was also not observed, as usually is the case when bromination occurs via attack of free Br^+ in solution.[1h] Therefore, it is perhaps reasonable to assume that bromolactonization occurs via the formation of intermediates **V** and **VI**.

We also compared the intermediates formed from NBS to those formed from bromine in the isoselenazolone-catalyzed bromination reaction using ^{77}Se NMR spectroscopy. Addition of NBS to isoselenazolone **4** yielded selenium(IV) bromide succinimide **II** (δ 1079 ppm), which is shifted 100 ppm downfield relative to intermediate **I** from Br_2 addition (δ 979 ppm). The ^{77}Se NMR chemical shift of **II** is comparable to that of structurally related **46** (1181 ppm).[18] The high reactivity of NBS in the isoselenazolone-catalyzed bromination reaction could be due to the electron-deficient selenium center in the selenium(IV) bromide succinimide **II**. The electron-deficient selenium atom would render a partial positive charge on the Br atom, which may facilitate faster transfer of bromine to the alkenoic acid.

Similarly, oxidation of secondary alcohols to ketones can be rationalized by considering proposed intermediates **I**/**III** in the bromination of alkenoic acids. The addition of the secondary alcohol to bromoselenonium intermediate **III** would give intermediate **VIII** via loss of HBr. Intermediate **VIII** could lead to ketone directly via loss of a second molecule of HBr regenerating the isoselenazolone or via loss of bromide to give a Swern-like oxoselenonium intermediate **IX**, which then can lose a proton to give ketone and isoselenazolone. Several stoichiometric reactions have invoked a Swern-like oxoselenonium intermediate for the oxidation of alcohols to ketones and aldehydes (Me_2Se and *N*-chlorosuccinimide[20] and $Me_2Se{=}O$[21]).

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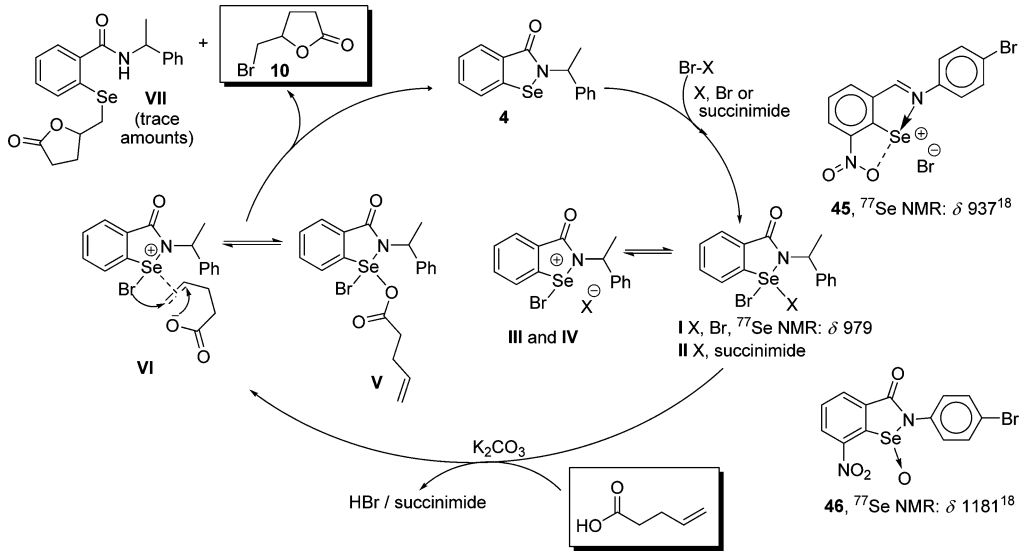
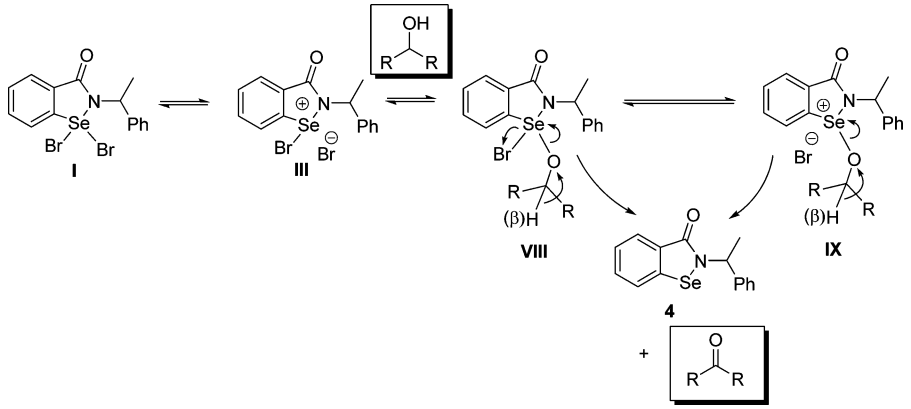
Scheme 2. Proposed Reaction Mechanism for Isoselenazolone Catalyzed Bromination



Scheme 3. Plausible Intermediates in the Oxidation of Secondary Alcohols to Ketones for Isoselenazolone-Catalyzed Oxidation with Bromine



SUMMARY

We have described examples of bromolactonization of alkenoic acids, bromoesterification of alkenes, and oxidation of secondary alcohols to ketones using Br_2 or NBS as oxidant and isoselenazolones as catalysts. The addition of Br^+ to alkenes via the selenium(IV) intermediate **VI** (Scheme 2) suggests a means to give diastereoselectivity in the formation of intermediates. This chemistry was developed with isoselenazolone **9**. Additional structure-active studies might provide more reactive and more selective catalysts for these transformations. Currently, we are exploring selective bromination reactions using chiral organoselenium compounds. Similarly, differential rates of oxidation of racemic secondary alcohols to give enantioselective enrichment of the secondary alcohol may be possible, as well, with chiral organoselenium compounds and diastereomeric intermediates **VIII** and/or **IX** (Scheme 3).

EXPERIMENTAL SECTION

All NMR experiments were carried out on 400 or 500 MHz spectrometers in $CDCl_3$, and NMR chemical shifts are reported in ppm referenced to the solvent peaks of $CDCl_3$ (7.26 ppm for ^{1}H and 77.16 (±0.06) ppm for ^{13}C, respectively). ^{77}Se NMR chemical shifts are reported relative to dimethyl selenide (0 ppm) in reference to diphenyl diselenide 461.0 ppm external standard. High resolution mass spectra (HRMS), electron spray mass spectra (ESMS), and low resolution mass spectra (LRMS) are reported for ions of ^{80}Se. Mass analysis is performed on quadruple-time-of-flight (Q-TOF) mass spectrometer equipped with an ESI source (+ve). Ground (mortar and pestel) anhydrous K_2CO_3 powder was dried in an oven at 160 °C for 6 h and stored in a desiccators prior to use. Silica gel (60 mesh size) was used for column chromatography. TLC analysis of reaction mixtures was performed using silica gel plates. Reactions were concentrated at reduced pressure on a rotary evaporator. Isoselenazolones **1**−**4** were synthesized by a reported procedure.[14]

2-Chloro-5-nitro-*N*-(1-phenylethyl)benzamide. The typical experimental procedure was followed as described below for the substrate of **9** using 2-chloro-5-nitro benzoyl chloride (0.5 g, 2.3 mmol) and phenylethyl amine (0.56 g, 4.6 mmol). The crude product was purified by column chromatography on silica gel using dichloromethane. Yield: 0.63 g (91%); mp 153−155 °C (155 °C);[22] ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.47 (d, J = 2.7 Hz, 1H), 8.20 (dd, J = 8.8, 2.7 Hz, 1H), 7.59 (d, J = 8.8 Hz, 1H), 7.37−7.44 (m, 4H), 7.30−7.35 (m, 1H), 6.50 (s, 1H), 5.35 (quintet, J = 7.0 Hz, 1H),1.66 (d, J = 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 146.5, 142.1, 137.5, 136.5, 131.4, 128.9, 127.8, 126.3, 126.0, 125.6, 125.2, 50.2, 21.3; HRMS-ES$^+$ m/z 327.0550 (Calculated for $C_{15}H_{13}N_2O_3Cl$ + Na^+ 327.0507).

5-Nitro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (5). Copper iodide (62 mg, 0.3 mmol) and 1,10-phenanthroline (59 mg, 0.3 mmol) were dissolved in DMF (8 mL), and the resulting mixture was stirred for 15 min. To this brown colored solution, 2-

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chloro-5-nitro-*N*-(1-phenylethyl)benzamide (0.5 g, 1.6 mmol), selenium powder (0.15 g, 2.0 mmol), and K_2CO_3 (0.34 g, 2.5 mmol) were added. The resulting reaction mixture was heated at reflux (110 °C) for 24 h. The progress of reaction was monitored by TLC. The reaction mixture was then poured into brine solution (80 mL) and stirred for 3 h. The product was extracted with ethyl acetate (3 × 50 mL). The combined organic extracts were washed with distilled water (2 × 50 mL), dried over sodium sulfate and concentrated. The resulting yellow oil was purified by column chromatography on SiO_2 eluted with dichloromethane. Yield: 0.48 g (84%); mp 163−165 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.90 (d, J = 2.3 Hz, 1H), 8.40 (dd, J = 2.3, 8.7 Hz, 1H), 7.76 (d, J = 8.6 Hz, 1H), 7.40 (m, 5H), 5.90 (q, J = 6.8 Hz, 1H), 1.80 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 146.8, 145.8, 140.6, 129.2, 128.97, 128.79, 127.4, 125.7, 124.99, 124.0, 53.6, 19.6; ^{77}Se NMR ($CDCl_3$) δ 853.3; HRMS-ES$^+$$m/z$ 370.9907 (Calculated for $C_{15}H_{12}N_2O_3{}^{80}Se$ + Na 370.9906).

2-Chloro-3-nitro-*N*-(1-phenylethyl) benzamide. The typical experimental procedure was followed as described for the substrate of **9** using 2-chloro-3-nitro benzoyl chloride (0.5 g, 2.3 mmol) and phenylethyl amine (0.56 g, 4.6 mmol). The crude product was purified by column chromatography on SiO_2 eluted with dichloromethane. Yield: 0.66 g (95%); mp 116−118 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (dd, J = 8.0, 1.6 Hz, 1H), 7.68 (dd, J = 7.7, 1.64 Hz, 1H), 7.44 (t, J = 7.9 Hz, 1H), 7.36−7.41 (m, 4H), 7.29−7.34 (m, 1H), 6.42 (s, 1H), 5.32 (quintet, J = 7.0 Hz, 1H), 1.63 (d, J = 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 149.0, 142.1, 138.6, 132.3, 128.8, 127.79, 127.77, 126.3, 126.0, 123.3, 49.9, 21.5; HRMS-ES$^+$$m/z$ 327.0554 (Calculated for $C_{15}H_{13}N_2O_3Cl$ + Na^+ 327.0507).

7-Nitro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (6). Nitro Se−N heterocycle **6** was synthesized from 2-chloro-3-nitro-*N*-(1-phenylethyl)benzamide (0.4 g) at 1.3 mmol scale using CuI (50 mg, 0.3 mmol), 1,10-phenanthroline (47 mg, 0.3 mmol), selenium powder (0.125 g, 1.6 mmol), and K_2CO_3 (0.27 g, 2.0 mmol) in DMF (6 mL) and refluxing for 14 h at 110 °C by following the procedure as described above for **5**. Yield: 0.41 g (90%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.4 (d, J = 8.1 Hz, 1H), 8.32 (d, J = 7.5 Hz, 1H), 7.60 (t, J = 7.8 Hz, 1H), 7.40 (m, 5H), 5.83 (q, J = 6.8 Hz, 1H), 1.80 (d, J = 6.9 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.8, 142.2, 140.8, 136.4, 134.5, 131.7, 128.9, 128.7, 128.6, 127.3, 127.1, 53.1, 19.9; ^{77}Se NMR ($CDCl_3$) δ 850.5; HRMS-ES$^+$$m/z$ 349.5665 (Calculated for $C_{15}H_{12}N_2O_3{}^{80}Se$ 349.0091).

2-Chloro-5-fluoro-*N*-(1-phenylethyl)benzamide. The typical experimental procedure was followed as described for the substrate of **9** from 2-chloro-5-fluoro benzoylchloride chloride (0.5 g, 2.6 mmol) and 1-phenylethanamine (0.63 g, 5.2 mmol). The crude product was purified by column chromatography on silica gel using dichloromethane. Yield: 0.63 g (88%); mp 118−120 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28−7.42 (m, 7H), 7.02−7.09 (m, 1H), 6.70 (s, 1H), 5.30 (quintet, J = 7.0 Hz, 1H), 1.62 (d, J = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.2, 162.4, 159.9, 142.5, 136.6, 136.5, 131.75, 131.67, 128.8, 127.6, 126.3, 125.6, 125.5, 118.5, 118.3, 117.5, 117.0, 49.5, 22.0; HRMS-ES$^+$$m/z$ 278.0791 (Calculated for $C_{15}H_{13}NFClO$ + H^+ 278.0742).

5-Fluoro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (7). Fluoro group containing Se−N heterocycle **7** was synthesized from 2-chloro-5-fluoro-*N*-(1-phenylethyl)benzamide (0.5 g, 1.8 mmol), CuI (68 mg, 0.36 mmol), 1,10-phenanthroline (65 mg, 0.36 mmol), selenium powder (0.17 g, 2.2 mmol), and K_2CO_3 (0.37 g, 2.7 mmol) in DMF (8 mL) and refluxing for 22 h at 110 °C under nitrogen atmosphere. Standard workup and purification procedure were followed as described for **5**. Yield: 0.49 g (85%); mp 112−114 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (dd, J = 2.6, 8.4 Hz, 1H), 7.55 (q, J = 4.3 Hz, 2H), 7.40 (m, 6H), 5.90 (q, J = 6.8 Hz, 1H), 1.75 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.8, 165.7, 162.8, 160.8, 141.1, 132.8, 132.78, 129.9, 128.8, 128.4, 127.3, 125.45, 125.39, 120.3, 120.1, 114.9, 114.7, 53.3, 19.8; ^{77}Se NMR ($CDCl_3$) δ 851.1; HRMS-ES$^+$$m/z$ 322.0147 (Calculated for $C_{15}H_{12}FNO$ ^{80}Se 322.0146).

2-Chloro-4-fluoro-*N*-(1-phenylethyl)benzamide. The typical experimental procedure was followed as described for the substrate of **9** using 2-chloro-4-fluoro benzoyl chloride (0.5 g, 2.6 mmol) and 1-phenylethyl amine (0.63 g, 5.2 mmol). The crude product was purified by column chromatography on silica gel using dichloromethane. Yield: 0.66 g (92%); mp 80−82 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (t, J = 7.4 Hz, 1H), 7.35−7.42 (m, 4H), 7.27−7.33 (m, 1H), 7.13 (dd, J = 8.5, 2.5 Hz, 1H), 7.02 (m, 1H), 6.60 (s, 1H), 5.32 (quintet, J = 7.1 Hz, 1H), 1.62 (d, J = 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.6, 164.4, 161.9, 142.7, 132.09, 132.01, 131.9, 131.8, 131.31, 131.27, 128.7, 127.5, 126.3, 117.6, 117.4, 114.6, 114.4, 49.2, 21.7; HRMS-ES$^+$$m/z$ 278.0794 (Calculated for $C_{15}H_{13}NFClO$ + H^+ 278.0742).

6-Fluoro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (8). Fluoro group containing Se−N heterocycle **8** was synthesized from 2-chloro-4-fluoro-*N*-(1-phenylethyl)benzamide (0.4 g, 1.4 mmol), CuI (55 mg, 0.3 mmol), 1,10-phenanthroline (52 mg, 0.3 mmol), selenium powder (0.14 g, 1.7 mmol), and K_2CO_3 (0.3 g, 2.2 mmol) in DMF (8 mL) and refluxing for 16 h at 110 °C under nitrogen atmosphere. Progress of reaction was monitored by TLC. Yield: 0.42 g (91%); mp 174−176 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.0 (t, J = 7.0 Hz, 1H), 7.4 (m, 6H), 7.10 (t, J = 8.7 Hz, 1H), 5.85 (q, J = 6.8 Hz, 1H), 1.70 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.05, 163.96, 141.2, 140.4, 140.3, 130.4, 130.3, 128.8, 128.3, 127.3, 126.3, 124.7, 114.7, 114.5, 111.4, 111.2, 53.1, 20.1; ^{77}Se NMR ($CDCl_3$) δ 843.9; HRMS-ES$^+$$m/z$ 322.0152 (Calculated for $C_{15}H_{12}FNO$ ^{80}Se + H^+ 322.0141).

Preparation of 2-Chloro-4,5-difluoro-*N*-(1-phenylethyl)-benzamide. 2-Chloro-4,5-difluoro benzoyl chloride (0.5 g, 2.4 mmol) was dissolved in dry CH_2Cl_2 (40 mL) in a single neck flask and cooled to 0 °C. 1-Phenylethanamine (0.58 g, 4.8 mmol in CH_2Cl_2, 20 mL) was slowly added to 2-chloro-4,5-difluoro benzoyl chloride solution by dropping funnel. The resulting reaction mixture was stirred for 1 h at 0 °C and 12 h at room temperature. After this, water (50 mL) was added to reaction flask, and the mixture was stirred for 30 min. CH_2Cl_2 (50 mL) was added to reaction mixture, and water layer was separated by separating funnel. CH_2Cl_2 layer was washed with 10% HCl (25 mL) and then with water (25 mL). Dichloromethane layer was dried over Na_2SO_4 and evaporated on rotary evaporator in vacuo. The resulting white solid was passed through silica gel using CH_2Cl_2 to obtain pure amide. Yield: 0.66 g (94%); mp 112−115 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47−7.42 (m, 1H), 7.39−7.28 (m, 5H), 7.23−7.17 (m, 1H), 6.90 (s, 1H), 5.25 (quintet, J = 7.2 Hz, 1H), 1.60 (d, J = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.4, 152.2, 152.03, 150.3, 150.2, 149.6, 149.5, 142.5, 131.75, 131.7, 128.8, 127.6, 126.2, 119.3, 119.2, 119.11, 119.10, 49.9, 21.5; HRMS-ES$^+$$m/z$ 318.0468 (Calculated for $C_{15}H_{12}F_2NClO$ + Na 318.0512).

5,6-Difluoro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (9). Difluoro group containing Se−N heterocycle **9** was synthesized from 2-chloro-4,5-difluoro-*N*-(1-phenylethyl)benzamide (0.35 g, 1.2 mmol), CuI (45 mg, 0.24 mmol), 1,10-phenanthroline (43 mg, 0.24 mmol), selenium powder (0.11 g, 1.4 mmol), and K_2CO_3 (0.25 g, 1.8 mmol) in DMF (5 mL) and refluxing for 12 h at 110 °C under nitrogen atmosphere. Yield: 0.37 g (92%); mp 170−172 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (t, J = 8.5 Hz, 1H), 7.40 (m, 6H), 5.83 (q, J = 6.7 Hz, 1H), 1.73 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.2, 154.3, 152.4, 152.3, 151.0, 150.9, 149.1, 148.9, 133.52, 133.46, 124.8, 124.7, 116.7, 116.5, 112.9, 112.7, 53.4, 19.7; ^{77}Se NMR ($CDCl_3$) δ =849.4 ppm; HRMS-ES$^+$$m/z$ 340.0042 (Calculated for $C_{15}H_{11}F_2NO$ ^{80}Se 340.0052).

Typical Procedure for Bromolactonization of Alkenoic Acids Using Bromine. In a 25 mL capacity round-bottom flask, 1.0 mol % (0.005 mmol) of isoselenazolone **9** was dissolved in dichloromethane (10 mL). To this solution, the unsaturated acid (1.0 mmol) was added followed by 1.5 mmol of K_2CO_3. Reaction mixture was stirred at room temperature for 10 min. Then, bromine (1.2 mL, 1.0 M solution in DCM) was added dropwise. Reaction mixture was stirred at room temperature for 3 h. Progress of reaction was monitored by TLC (hexane:ethyl acetate). Then, solvent was evaporated under reduced pressure at 40 °C. The resulted reaction mixture was extracted with Et_2O (10 mL × 3) and concentrated in vacuo to obtain pure bromolactone.

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Typical Procedure for Bromolactonization of Alkenoic Acids by Using NBS. In a 25 mL capacity round-bottom flask, 1.0 mol % (0.01 mmol) of 5,6-difluoro-2-(1-phenylethyl)benzo[d][1,2]selenazol-3(2*H*)-one (**9**) was dissolved in 10 mL of dry dichloromethane. To this solution, the unsaturated acid was added (1.0 mmol) followed by 1.5 mmol of K_2CO_3. Reaction mixture was stirred at room temperature for 10 min. To this, 1.2 mmol of NBS was added. Reaction mixture was stirred at room temperature for 3 h. Progress of reaction was monitored by TLC (hexane:ethyl acetate 8:2). Then, solvent was evaporated under reduced pressure at 40 °C. The obtained oily reaction mixture was extracted with hexane (10.0 mL × 4), which was evaporated in vacuo to obtain pure bromolactone.

5-(Bromomethyl)dihydrofuran-2(3*H*)-one (10). Brown oil.[1g] Yield: (166 mg, 94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.79−4.72 (m,1H), 3.61−3.52 (m, 2H), 2.72−2.58 (m, 2H), 2.51−2.41 (m,1H), 2.10−2.20 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.2, 77.8, 34.0, 28.4,26.2; ESMS *m*/*z* Calculated for $C_5H_7BrO_2$ [M] 177.9, found 177.9.

5-(Bromomethyl)-3-methyldihydrofuran-2(3*H*)-one (11). Brown oil.[23] In diastereomeric ratio of 7:3. Yield: (155 mg, 92%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.75−4.68 and 4.58−4.50 (m,1H), 3.60−3.53 and 3.51−3.43 (m, 2H), 2.84−2.67 (m, 1H), 2.64−2.55 and 2.42−2.32 (m,1H), 2.10−2.0 and 1.73−1.65 (m, 1H), 1.28 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 179.1, 178.4, 75.9, 75.8, 35.7, 35.6, 33.9, 33.85, 33.4, 16.2, 15.1; HRMS (ESI) *m*/*z* Calculated for $C_6H_9BrO_2$ [M + Na] 214.9678, found 214.9687.

5-(Bromomethyl)-4-methyldihydrofuran-2(3*H*)-one (12). Brown oil.[24] In diastereomeric ratio of 6.8:3.2. Yield: (150 mg, 88%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.70−4.62 and 4.28−4.20 (m,1H), 3.60−3.36 (m, 2H), 2.83−2.67 (m, 2H), 2.35−2.16 (m,1H), 1.20−1.08 (d, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.6, 175.3, 84.5, 80.9, 37.3, 36.6, 34.1, 32.6, 32.3, 28.6, 18.4, 13.0; ESMS *m*/*z* Calculated for $C_6H_9BrO_2$ [M] 191.9, found 191.9.

5-(Bromomethyl)-3,3-dimethyldihydrofuran-2(3*H*)-one (13). Light brown oil.[25] Yield: (74 mg, 95%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.64 (m,1H), 3.59 (dd, *J* = 10.7, 4.8 Hz, 1H), 3.49 (dd, *J* = 10.7, 6.4 Hz, 1H), 2.29 (dd, *J* = 13.0, 6.4 Hz,1H), 1.95 (dd, J = 13.0, 9.5 Hz, 1H), 1.30 (d, *J* = 8.9 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 180.9, 74.7, 41.9, 40.5, 33.6, 24.9; HRMS (ESI) *m*/*z* Calculated for $C_7H_{11}BrO_2$ [M + Na] 228.9835, found 228.9820.

4-Bromo-5-methyldihydrofuran-2(3*H*)-one (14). Colorless oil. Yield: (65 mg, 72%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.71 (quintet, *J* = 6.3 Hz, 1H), 4.07 (m, 1H), 3.15 (m, 1H), 2.88 (m, 1H), 1.45 (d, *J* = 6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.8, 166.7, 83.9, 73.0, 47.9, 44.2, 43.3, 39.2, 21.9, 18.4.

4-Bromo-5-phenyldihydrofuran-2(3*H*)-one (15). Colorless crystals.[4a] Yield: (277 mg, 95%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 (m, 5H), 5.70 (d, *J* = 5.25 Hz, 1H), 4.40 (m, 1H), 3.26 (dd, *J* = 18.2, 7.5 Hz, 1H), 3.0 (dd, *J* = 18.2, 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 172.9, 135.9, 129.4, 129.1, 125.4, 87.9, 45.7, 38.8; HRMS (ESI) *m*/*z* Calculated for $C_{10}H_9BrO_2$ [M + Na] 262.9678, found 262.9671.

6-(Bromomethyl)tetrahydro-2*H*-pyran-2-one (16). Colorless oil.[5a] Yield: (60 mg, 89%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.48 (m,1H), 3.48 (m, 2H), 2.65−2.55 (m, 1H), 2.51−2.40 (m,1H), 2.15−2.07 (m, 1H), 2.0−1.81 (m, 2H), 1.75−1.63 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 78.6, 33.7, 29.4, 26.3, 18.2; HRMS (ESI) *m*/*z* Calculated for $C_6H_9BrO_2$ [M + Na] 214.9678, found 214.9680.

6-(1-Bromoheptyl)tetrahydro-2*H*-pyran-2-one (17). Colorless oil. Yield: (480 mg, 86%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.42−4.34 (m,1H), 4.03−3.96 (m, 1H), 2.65−2.56 (m, 1H), 2.50−2.39 (m,1H), 2.05−1.8 (m, 7H), 1.63−1.50 (m, 1H), 1.31−1.21 (m, 6H), 0.86 (t, *J* = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 81.5, 56.7, 34.1, 31.6, 29.6, 28.6, 27.8, 25.2, 22.5, 18.4, 14.0; HRMS (ESI) *m*/*z* Calculated for $C_{12}H_{21}BrO_2$ [M + H] 277.0798, found 277.0804

6-Bromohexahydro-2*H*-cyclopenta[b]furan-2-one (18). Colorless oil.[5a] Yield: (164 mg, 90%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.05 (d, *J* = 6.2 Hz,1H), 4.42 (d, *J* = 4.4 Hz, 1H), 3.20−3.09 (m, 1H), 2.85 (dd, J = 18.5, 10.2 Hz, 1H), 2.41−2.02 (m, 4H), 1.63−1.54 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 176.4, 90.5, 52.8, 36.0, 35.9, 33.0, 31.4; ESMS *m*/*z* Calculated for $C_7H_9BrO_2$ [M] 204.0, found 204.0.

4-Bromo-6-oxabicyclo[3.2.1]octan-7-one (19). Colorless crystals.[26] Yield: (140 mg, 86%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.77 (t, *J* = 5.0 Hz,1H), 4.38 (t, *J* = 4.6 Hz, 1H), 2.64 (m, 2H), 2.37 (m, 2H), 2.12 (dd, *J* = 16.3, 5.15 Hz, 4H), 1.90 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.6, 79.1, 45.2, 38.3, 32.8, 28.3, 22.6; HRMS (ESI) *m*/*z* Calculated for $C_7H_9BrO_2$ [M + H] 204.9859, found 204.9836.

6-Bromohexahydro-2*H*-3,5-methanocyclopenta[b]furan-2-one (20). Brown oil.[27] Yield: (267 mg, 86%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.90 (d, *J* = 5.0 Hz,1H), 3.82 (d, *J* = 1.9 Hz, 2H), 3.20 (t, J = 4.7 Hz, 1H), 2.65 (s,1H), 2.54 (dd, *J* = 11.2, 4.2 Hz, 1H), 2.30 (d, *J* = 11.6 Hz, 2H), 2.16−2.06 (m, 1H), 1.80−1.70 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 179.1, 87.7, 53.5, 45.9, 45.5, 37.6, 35.8, 34.0; ESMS *m*/*z* Calculated for $C_8H_9BrO_2$ [M] 216.0, found 216.0.

Typical Procedure for Bromoesterification from Corresponding Benzoic Acids and Alkenes. In a 25 mL capacity round-bottom flask, (10.0 mol %, 0.16 mmol) of catalyst **9**, benzoic acid (1.6 mmol) and *N*-Bromosuccinamide (2.4 mmol) was dissolved in 10 mL of dichloromethane. This solution was stirred at room temperature for 10 min. Slowly, the reaction mixture turned brown-red. To this solution, alkene (0.18 g, 1.6 mmol) dissolved in 7 mL of dichloromethane was added dropwise. Reaction mixture was stirred at room temperature for 8 h. Progress of reaction was monitored by TLC (hexane:ethyl acetate, 8:2). Then, solvent was evaporated under reduced pressure at 40 °C, and product was purified by column chromatography.

2-Bromocyclooctyl benzoate (21). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. White solid. Yield: 0.42 g (84%); mp 42−44 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09 (m, 2H), 7.58 (m, 1H), 7.47 (m, 2H), 5.45(m, 1H), 4.51 (m, 1H), 2.40 (m, 1H), 2.16 (m, 1H), 1.94 (m, 3H), 1.77 (m, 4H), 1.62 (m, 1H), 1.48 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.7, 132.96, 130.4, 129.7, 128.4, 79.9, 57.4, 32.2, 31.6, 25.9, 25.4, 25.38, 24.7; HRMS (ESI) *m*/*z* Calculated for $C_{15}H_{19}BrO_2$ [M + Na] 333.0461, found 333.0463.

2-Bromocyclooctyl 2-bromo-5-methoxybenzoate (22). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. Colorless oil. Yield: 0.22 g (62%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J* = 8.8 Hz, 1H), 7.40 (d, *J* = 3.1 Hz, 1H), 6.90 (dd, *J* = 8.8, 3.1 Hz, 1H), 5.45(m, 1H), 4.48 (m, 1H), 3.84 (s, 3H), 2.38 (m, 1H), 2.15 (m, 1H), 2.04 (m, 1H), 1.93(m, 2H), 1.78 (m, 4H), 1.63 (m, 1H), 1.47 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.1, 158.5, 134.9, 132.98, 118.8, 116.4, 111.8, 80.8, 57.4, 55.6, 32.2, 31.6, 26.0, 25.4, 25.3, 24.6; HRMS (ESI) *m*/*z* Calculated for $C_{16}H_{20}Br_2O_3$ [M + Na] 440.9671, found 440.9682.

2-Bromocyclooctyl 2-iodo-3-methylbenzoate (23). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9.5:0.5 v/v) as mobile phase. White solid. Yield: 0.24 g (72%); mp 68−70 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (d, *J* = 7.3 Hz, 1H), 7.32 (m, 1H), 5.47 (t, *J* = 8.8, 1H), 4.45 (t, *J* = 8.1 Hz, 1H), 2.53 (s, 3H), 2.38 (m, 1H), 2.12 (m, 2H), 1.94 (m, 2H), 1.80 (m, 4H), 1.51(m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.3, 143.2, 138.6, 131.6, 127.8, 127.0, 99.8, 80.6, 57.4, 32.1, 31.7, 29.5, 25.9, 25.42, 25.39, 24.7; HRMS (ESI) *m*/*z* Calculated for $C_{16}H_{20}BrIO_2$ [M + Na] 472.9584, found 472.9584.

2-Bromocyclooctyl 2-chloro-4,5-difluorobenzoate (24). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. White solid. Yield: 0.32 g (56%); mp 40−42 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (t, *J* = 9.3 Hz, 1H), 7.32 (t, *J* = 8.3 Hz, 1H), 5.44 (t, *J* = 8.7 Hz, 1H), 4.46 (t, *J* = 8.0 Hz, 1H), 2.38 (m, 1H), 2.16 (m, 1H), 1.95 (m, 3H), 1.78 (m, 4H), 1.62(m, 1H), 1.47 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.6, 153.3, 153.2, 150.76, 150.63, 149.86, 149.73, 147.36, 147.24, 130.05, 129.9, 126.4, 120.7, 120.5, 120.4, 120.2, 81.1, 57.05, 32.2, 31.6, 25.9, 25.4, 25.3, 24.6; HRMS (ESI) *m*/*z* Calculated for $C_{15}H_{16}BrClF_2O_2$ [M + Na] 402.9893, found 402.9882.

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2-Bromocyclooctyl 2-bromonicotinate (25). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 8:2 v/v) as mobile phase. White solid. Yield: 0.28 g (92%); mp 52−55 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.48 (dd, J = 4.8, 2.0 Hz, 1H), 8.13 (dd, J = 7.7, 2.0 Hz, 1H), 7.36 (m, 1H), 5.46 (m, 1H), 4.45 (m, 1H), 2.36 (m, 1H), 2.14 (m, 1H), 2.02 (m, 1H), 1.92 (m, 2H), 1.77 (m, 4H), 1.61 (m, 1H), 1.46 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.0, 151.9, 140.5, 139.6, 129.9, 122.4, 81.3, 57.2, 32.1, 31.6, 25.9, 25.4, 25.3, 24.6; HRMS (ESI) m/z Calculated for $C_{14}H_{17}Br_2NO_2$ [M + H] 389.9699, found 389.9701.

2-Bromocyclohexyl 2,4-dichlorobenzoate (26). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. Colorless oil. Yield: 0.22 g (80%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, J = 8.5 Hz, 1H), 7.50 (d, J = 2.0 Hz, 1H), 7.33 (dd, J = 8.4, 2.0 Hz, 1H), 5.15(m, 1H), 4.14 (m, 1H), 2.43 (m, 1H), 2.32 (m, 1H), 1.96 (m, 1H), 1.82 (m, 2H), 1.53 (m, 2H), 1.41 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 138.3, 134.9, 132.6, 130.96, 128.5, 127.0, 52.0, 35.6, 31.1, 29.7, 25.4, 23.3; HRMS (ESI) m/z Calculated for $C_{13}H_{13}BrCl_2O_2$ [M + Na] 372.9368, found 372.9393.

2-Bromocyclohexyl 2-chloro-5-nitrobenzoate (27). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 8.5:1.5 v/v) as mobile phase. Colorless oil. Yield: 0.25 g (70%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.75 (d, J = 2.8 Hz, 1H), 8.30 (dd, J = 8.8, 2.8 Hz, 1H), 7.67(d, J = 8.8 Hz, 1H), 5.20 (m, 1H), 4.15 (m, 1H), 2.46 (m, 1H), 2.33 (m, 1H), 1.99 (m, 1H), 1.85 (m, 2H), 1.58 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.6, 146.2, 140.7, 132.3, 131.3, 126.8, 126.6, 78.2, 52.2, 35.8, 31.3, 29.7, 25.6, 23.4; HRMS (ESI) m/z Calculated for $C_{13}H_{13}BrClNO_4$ [M + Na] 383.9609, found 383.9612.

2-Bromocyclohexyl 3-bromo-2-naphthoate (28). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. White solid. Yield: 0.26 g (70%); mp 48−50 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.47 (d, J = 8.5 Hz, 1H), 7.87 (d, J = 8.1 Hz, 2H), 7.76(d, J = 8.5 Hz, 1H), 7.65 (m, 2H), 5.26 (m, 1H), 4.18 (m, 1H), 2.43 (m, 2H), 1.99 (m, 1H), 1.84 (m, 2H), 1.60 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.4, 135.2, 132.3, 131.5, 128.2, 128.12, 128.11, 127.9, 125.7, 122.4, 52.5, 35.6, 31.1, 29.70, 29.66, 25.5, 23.3; HRMS (ESI) m/z Calculated for $C_{17}H_{16}Br_2O_2$ [M + Na] 432.9409, found 432.9400.

2-Bromocyclohexyl 2-bromothiophene-3-carboxylate (29). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. Colorless oil. Yield: 0.17 g (50%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 (d, J = 5.8 Hz, 1H), 7.25 (d, J = 5.8 Hz, 1H), 5.13(m, 1H), 4.16 (m, 1H), 2.42 (m, 1H), 2.31 (m, 1H), 1.96 (m, 1H), 1.81 (m, 2H), 1.55 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.9, 131.0, 129.6, 125.9, 120.1, 52.3, 35.2, 30.8, 29.70, 25.1, 23.1; HRMS (ESI) m/z Calculated for $C_{11}H_{12}Br_2O_2S$ [M + Na] 390.8796, found 390.8809.

2-Bromo-2-cyclohexylethyl benzoate (30). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 9:1 v/v) as mobile phase. Colorless oil. Ratio of regioisomers 6.7:3.3. Yield: 0.25 g (68%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05−8.13 (m, 1H), 7.57−7.63 (m, 1H), 7.48 (m, 2H), 3.61−3.71 and 4.56−4.69 (m, 2H), 4.20−4.28 and 5.08−5.14 (q, J = 5.6 Hz, 1H), 1.68−1.85 (m, 5H), 1.06−1.39 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.06, 166.0, 133.22, 133.13, 129.77, 129.74, 128.47, 128.43, 76.6, 66.5, 58.5, 41.3, 39.8, 32.9, 30.9, 29.2, 28.8, 28.1, 26.15, 26.11, 25.9, 25.74; HRMS (ESI) m/z Calculated for $C_{15}H_{19}BrO_2$ [M + Na] 333.0441, found 333.0435.

1-Bromo-1-phenylprop-1-en-2-yl 3-bromopropanoate (31). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 8:2 v/v) as mobile phase. Colorless oil. Ratio of E/Z isomers 8.6:1.4. Yield: 0.18 g (61%); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56−7.53 (m, 2H), 7.36−7.39 (m, 3H), 3.60 (t, J = 6.7 Hz, 2H), 3.06 (t, J = 6.7 Hz, 2H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 167.9, 167.8, 143.6, 134.7, 132.9, 131.3, 129.2, 129.15, 129.0, 128.7, 128.4, 128.0, 127.95, 113.4, 37.6, 37.5, 25.2, 25.0, 24.0, 23.3; HRMS (ESI) m/z Calculated for $C_{12}H_{12}Br_2O_2$ [M + Na] 370.9061, found 370.9076.

2-Bromo-1,2-diphenylethyl 3-bromopropanoate (32). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 8:2 v/v) as mobile phase. White solid. Ratio of diastereomers 7.9:2.1. Yield: 0.39 g (74%); mp 78−80 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.11−7.42 (m, 10H), 6.23−6.38 (m, 1H), 5.17−5.26 (d, J = 9.0 Hz, 1H), 3.58−3.71 and 3.31−3.43 (m, 2H), 2.98−3.16 and 2.70−2.85 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.21, 168.76, 137.57, 137.4, 136.75, 136.22, 128.94, 128.62, 128.71, 128.66, 128.63, 128.52, 128.34, 127.78, 127.39, 79.2, 78.45, 56.4, 54.9, 37.9, 37.6, 25.4, 25.1; HRMS (ESI) m/z Calculated for $C_{17}H_{16}Br_2O_2$ [M + Na] 434.9390, found 434.9380.

3-Bromo-3-methylbutan-2-yl[1,1′-biphenyl]-4-carboxylate (33). The crude compound was purified by column chromatography on silica gel by using (hexane:ethyl acetate = 8:2 v/v) as mobile phase. White solid. Ratio of regioisomers 7.6:2.4. Yield: 0.19 g (56%); mp 74−76 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15−8.19 and 8.08−8.13 (m, 2H), 7.68−7.72 and 7.62−7.68 (m, 4H), 7.47−7.53 and 7.40−7.45 (m, 3H), 5.14−5.21 and 4.84−4.91 (q, J = 6.9 Hz, 1H) 2H), 1.85−1.87 and 1.51−1.54 (d, J = 2.1 Hz, 2H), 1.76−1.81 (m, 7H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.45, 165.34, 145.94, 145.6, 140.09, 140.01, 130.3, 130.1, 130.0, 128.96, 128.94, 128.81, 128.20, 128.12, 127.3, 127.2, 127.04, 83.8, 77.23, 66.7, 55.7, 30.6, 23.4, 23.2, 21.1, 16.7; HRMS (ESI) m/z Calculated for $C_{18}H_{19}BrO_2$ [M + Na] 369.0461, found 369.0444.

Typical Procedure for Oxidation of Secondary Alcohols. In a 10 mL capacity round-bottom flask, 10.0 mol % (0.08 mmol) of catalyst **9** was dissolved in 4 mL of dichloromethane. To this solution, the secondary alcohol (0.8 mmol) was added followed by 1.2 mmol of bromine in 1.5 mL of dichloromethane. Reaction mixture was stirred at −35 °C for 16 h. Progress of reaction was monitored by TLC. Then, solvent was evaporated under reduced pressure at 40 °C, and product was purified by column chromatography using hexane:ethyl acetate (8:2) mobile phase.

Synthesis and in Situ Characterization of Isoselenazolone Dibromide and Related Intermediates by ^{77}Se NMR and Mass Spectrometry. Isoselenazolone(IV) dibromide complex was prepared in dry dichloromethane by mixing equimolar amount of **4** (40 mg, 0.13 mmol) either with bromine (21 mg, 0.13 mmol) for **4.I** or with NBS (23 mg, 0.13 mmol) for **4.II** under N_2. The reaction mixture was allowed to stir at room temperature for 30 min. After this, CH_2Cl_2 was evaporated under reduced pressure at 25 °C, and product **4.I** (56 mg) was isolated as an oil and was used as such for NMR and ES-MS spectrometry. For **4.I** and **4.II**, ^{77}Se NMR spectroscopy showed a significant downfield shift of the ^{77}Se signal (by 139 and 238 ppm, respectively) for **4.I** and **4.II** compared to isoselenazolone **4**. Moreover, mass spectral data for **4.I** and **9.I** also supports formation of isoselenazolone dibromide complex. (Figure S144 and S151 in the Supporting Information) Characterization of catalyst-alkene complex **V** was done by mass spectrometry. Pent-4-enoic acid (10 mg, 0.1 mmol) was added to isoselenazolone dibromide **I** (50 mg, 0.1 mmol) in CH_2Cl_2 under N_2. The resulting reaction mixture was stirred for 30 min. After this, CH_2Cl_2 was evaporated in vacuo. The resulted viscous oil was analyzed by mass spectrometry. The alkene-catalyst complex obtained from isoselenazolone **9** shows a well-defined peak at m/z 571.9670 (calculated for $C_{20}H_{18}BrF_2NO_3Se+H^+$ 517.9674, please see Figure S152 in the Supporting Information). From isoselenazolone **4**, the alkene-catalyst complex shows a peak at m/z 434.0942 (calculated for $C_{20}H_{20}NO_3Se+CH_3OH$ 434.0866, please see Figure S148 in the Supporting Information), which is perhaps the result of bromine−methanol exchange.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Spectral (^{1}H, ^{13}C, ^{77}Se) NMR and mass spectra of isoselenazolones (**5**−**9**), bromolactones (**10**−**20**), bromoesters (**21**−**33**), and ketones (**34**−**44**), selected spectra for intermediates (**I**, **II**, and **V**), crystal structure data and CIF files for **9** and **15** (CCDC No. 888185 and 888186). This

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material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: sangitkumar@iiserb.ac.in.

Notes

The authors declare no competing financial interest.

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