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Ru(II)-Catalyzed Direct C(sp^2)−H Activation/Selenylation of Arenes with Selenyl Chlorides

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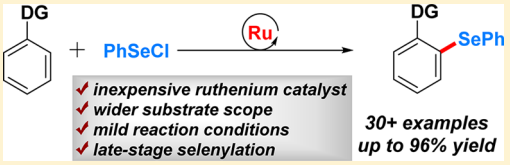
Supporting Information

ABSTRACT: A new ruthenium catalytic system was developed for the construction of a C(sp^2)−Se bond with the assistance of directing groups. This protocol features mild reaction conditions, wider substrate scope, and convenient late-stage selenylation of bioactive molecules.



INTRODUCTION

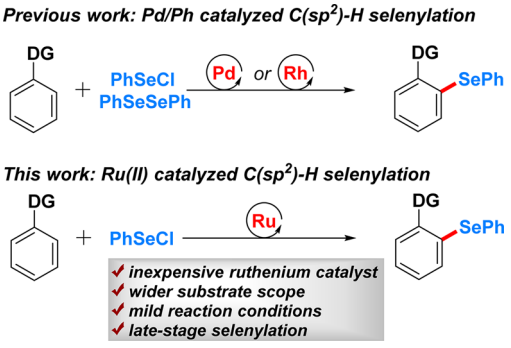
Since the development of their important applications in the preparation of organic catalysts,[1] pharmaceutical agents,[2] fluorescent probes,[3] and functional organic materials,[4] preparation of organoselenium compounds has attracted the extensive attention of synthetic chemists. It is known that the transition-metal-catalyzed cross-coupling reaction is the mostly used methodology for the incorporation of a Se atom into aromatic frameworks.[5] However, prefunctionalization of the substrate is generally requested. Recently, the development of direct C−H functionalization catalyzed by a transition metal has offered a ground-breaking technology in synthetic methodology with atom-/step-economy principles;[6,7] therefore, many C−X (heteroatom) bonds now can be readily established through the C−H functionalization strategy. Compared with other C−X bonds, nevertheless, similar methods of formation of C(sp^2)−Se bonds have been scarcely described.[8−10]

The chelation-assisted Pd(II)-catalyzed aromatic C−H selenylation of arenes has been successively reported by the Nishihara and Kambe groups.[8] In 2015, Li and co-workers developed a Rh(III)-catalyzed direct selenylation of arenes with readily available selenyl chlorides or diselenides.[9] Very recently, the Wang group disclosed a rhodium(III)-catalyzed intermolecular C7-selenylation of indolines.[10] Though these represent pioneering work in the transition-metal-catalyzed C−H selenylation, all of these approaches still suffer from some drawbacks, including (1) expensive Pd/Rh catalysts, (2) longer reaction time, and (3) low reactivity for substrates bearing a 5-membered directing group.[11] Therefore, it is of great importance to establish a new, general, and less expensive catalytic system for universal C−Se bond formation.

The pioneering ruthenium-catalyzed C−H functionalization reactions were initiated by Murai[12] and Oi and Inoue,[13] followed by contributions from the Ackermann,[14] Bruneau and Dixneuf,[15] and Jeganmohan[16] groups. It has been demonstrated that the cheaper ruthenium catalyst is also easily to transform into a cyclometalated species via C−H bond cleavage followed by subsequent oxidative addition and reductive elmination.[17]

With inspiration of these elegant works, we recently explored Ru(II)-catalyzed C−H selenylation of arenes with the assistance of various directing groups (DGs). This method features the cheaper ruthenium catalyst, mild reaction conditions, shorter reaction time, wider substrate scope, and utility in the late-stage selenylation of therapeutically useful molecules. To the best of our knowledge, this is the first example of employing the ruthenium catalytic system to construct C−Se bonds of arenes (Scheme 1).

Scheme 1. Transition-Metal-Catalyzed C(sp^2)−H Selenylation of Arenes



RESULTS AND DISCUSSION

Our initial investigation was carried out by treating 1-phenylpyrazole (**1a**) with PhSeCl using $[RuCl_2(p\text{-cymene})]_2$/$Cu(OAc)_2{\cdot}H_2O$ as the catalytic system in DCE at 75 °C for 8 h. The *ortho*-selenylated product **2a** was obtained in merely 10% yield (Table 1, entry 1). After screening a series of solvents, hexafluoroisopropyl alcohol (HFIP) was found to be optimal, and the yield of **2a** was enhanced to 39% (Table 1, entry 2).

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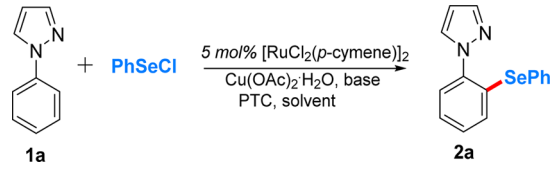
Table 1. Optimization of the Reaction Conditions[a]



1a 2a

entry	base	solvent	yield[b] (%)
1		DCE	10
2		HFIP	39
3		MeOH	19
4[c]		*t*AmOH	15
5		THF	17
6[c]		toluene	9
7	$NaHCO_3$	HFIP	75
8	K_2CO_3	HFIP	81
9	CsF	HFIP	46
10	Na_2HPO_4	HFIP	42
11	*t*BuOK	HFIP	64
12	NaOAc	HFIP	70
13[d]	K_2CO_3	HFIP	70
14[e]	**K_2CO_3**	**HFIP**	**92 (88)**[g]
15[f]	K_2CO_3	HFIP	86
16[e,h]	K_2CO_3	HFIP	78
17[e,i]	K_2CO_3	HFIP	64

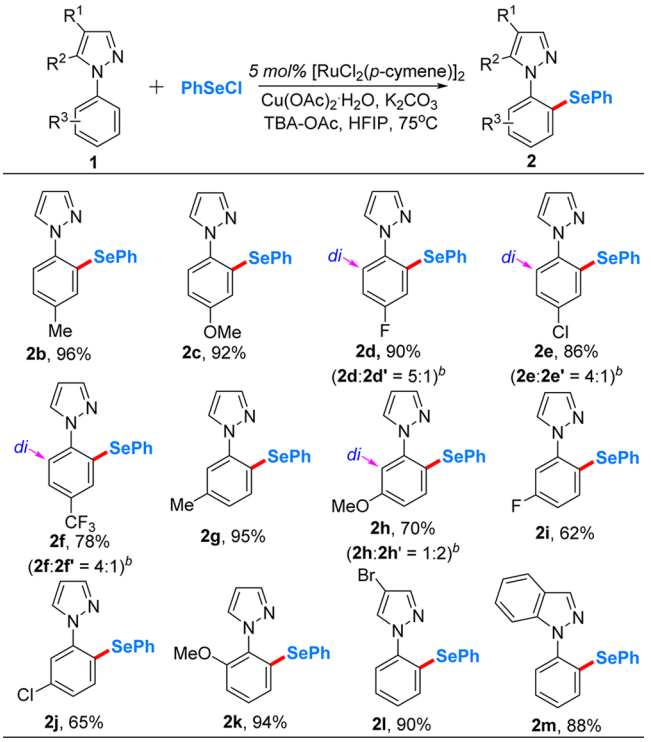
[a]Reaction conditions: **1a** (0.1 mmol), PhSeCl (0.2 mmol), [$RuCl_2$(*p*-cymene)]$_2$ (5 mol %), $Cu(OAc)_2·H_2O$ (2 equiv), base (1.5 equiv), and PTC (0.5 equiv) in solvent (1 mL) at 75 °C for 8 h in a sealed tube. [b]Yield was determined by ^{1}H NMR analysis using dibromomethane as an internal standard. [c]At 100 °C. [d]Using TBAB as the PTC. [e]Using TBA-OAc as the PTC. [f]Using TBA-HSO_4 as the PTC. [g]Isolated yield on 0.2 mmol scale. [h]Using 1.0 equiv of $Cu(OAc)_2·H_2O$. [i]Using 0.5 equiv of $Cu(OAc)_2·H_2O$. PTC = phase transfer catalyst, HFIP = hexafluoroisopropyl alcohol, TBAB = tetrabutylammonium bromide, TBA-OAc = tetrabutylammonium acetate, TBA−HSO_4 = tetrabutylammonium hydrogen sulfate, BQ = *p*-benzoquinone.

Different bases were also examined, and a ubiquitous increase in yield was observed with K_2CO_3 giving the highest yield of 81% (Table 1, entry 8). In addition, several phase-transfer catalysts (PTCs) were investigated. To our delight, an excellent yield of 88% was obtained when tetrabutylammonium acetate (TBA-OAc) was employed (Table 1, entry 14). The amounts of $Cu(OAc)_2·H_2O$ also were examined, and the yield of **2a** diminished when 1.0 or 0.5 equiv of $Cu(OAc)_2·H_2O$ was used (Table 1, entries 16 and 17). Therefore, the conditions of entry 14 was selected as the optimum reaction conditions.

With the optimized reaction conditions in hand, the scope of arylpyrazole substrates bearing diverse substituents either on the aryl or on the pyrazole component was investigated. As shown in Scheme 2, substrates containing various substituents at the *para*- or *meta*-position of the aryl component went through the reaction smoothly and afforded the desired products **2b−j** in 62−96% yields. Notably, bis-substituted products were also observed in the cases of substrates bearing an electron-withdrawing substituent at the *para*- (**2d−f**) or an electron-donating substituent at the *meta*-position (**2h**). We supposed that these substituents would provide the electron-rich *ortho*-position for dual C−H selenylation. In addition, the *o*-methyloxy-substituted substrate gave product **2k** in 94% yield.

Meanwhile, the effect of substituents on the pyrazole moiety was also investigated. The 4′-bromo-substituted pyrazole gave the selenylated product in 90% yield. Switching the pyrazole

Scheme 2. Substrate Scope of Arenes[a]



[a]Reaction conditions: **1** (0.2 mmol), PhSeCl (0.4 mmol), [$RuCl_2$(*p*-cymene)]$_2$ (5 mol %), $Cu(OAc)_2·H_2O$ (2 equiv), K_2CO_3 (1.5 equiv), and TBA-OAc (0.5 equiv) in HFIP (2.5 mL) at 75 °C for 8 h in a sealed tube. [b]The ratio of mono/diselenylated products is shown in parentheses.

moiety to indazole as the DG-promoted the selenylation as well, and the corresponding product **2m** was obtained in 88% yield.

Next, various *N*-heterocycles were tested as DGs (Scheme 3). Similar reactivity was observed when pyridine was used as the DG, and the corresponding products **4a−l** were obtained in 45−78% yields. Interestingly, only *ortho* monoselenylated products were observed due to the electron-withdrawing property of pyridinyl. Quinoline and isoquinoline were also suitable as the DG, giving products **4n** and **4o** in 75% and 63% yield, respectively. It was found that pyrimidine, benzoquinoline, and *O*-methyl oxime were also compatible as the DGs; however, the yields were somewhat lower, likely due to the steric effect on the formation and activity of the catalyst-chelated intermediates. It is of note that 2-phenoxypyridine bearing an oxygen linker also took part in the reaction, and the corresponding product **4s** was obtained in 47% yield. Overall, our current Ru catalytic system seems to have wider substrate scope than the Pd- or Rh-catalytic systems.[8−10]

The utility of the direct C−H selenylation reaction as a tool for late-stage modification of bioactive complex molecules was explored. First, direct selenylation of the estrone derivative **5** was conducted, and the corresponding product **6** was obtained in 48% yield (Scheme 4a). Meanwhile, the widely prescribed antidepressant drug diazepam was also employed as the selenylation substrate, and the product **8** was obtained in 62% yield (Scheme 4b).

To gain more insight on the reaction pathway, we conducted C−H selenylation with isotopically labeled substrates. The reaction of [D_5]-**3a** with PhSeCl gave the D/H partially

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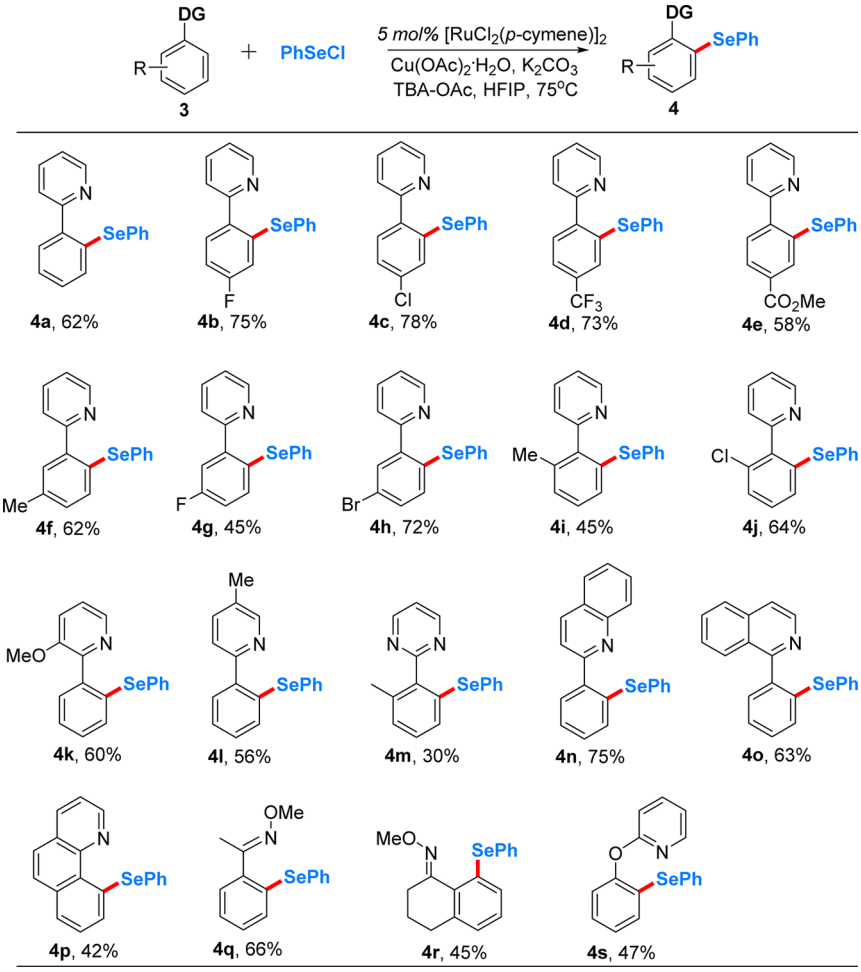
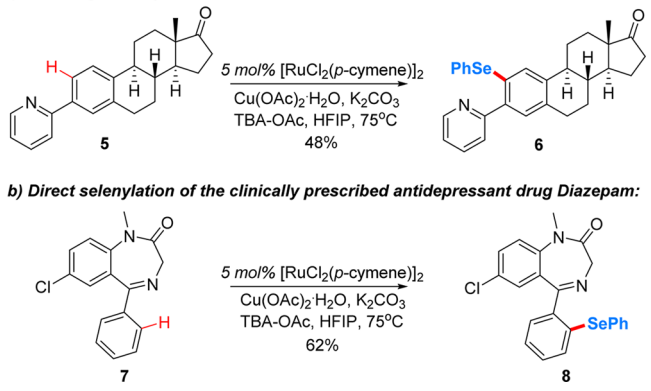
Scheme 3. Substrate Scope of Directing Groups[a]

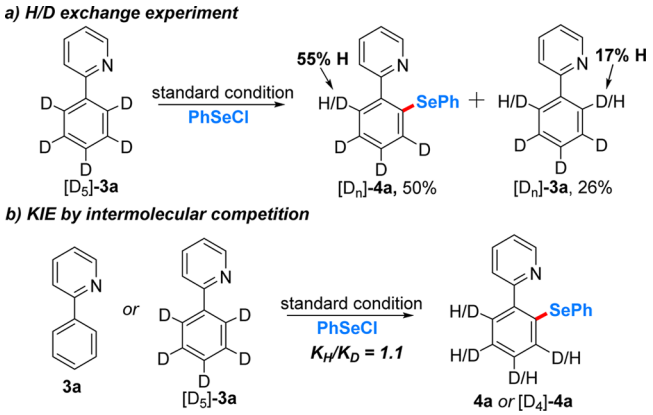


[a]Reaction conditions: **3** (0.2 mmol), PhSeCl (0.4 mmol), $[RuCl_2(p\text{-cymene})]_2$ (5 mol %), $Cu(OAc)_2{\cdot}H_2O$ (2 equiv), K_2CO_3 (1.5 equiv), and TBA-OAc (0.5 equiv) in HFIP (2.5 mL) at 75 °C for 8 h in a sealed tube.

Scheme 4. Late-Stage C−H Bond Selenylation



Scheme 5. Preliminary Mechanistic Studies



exchanged product $[D_n]$-**4a** in 50% yield and the partially *ortho*-deuterated substrate $[D_n]$-**3a** was recovered in 26% yield, indicating that the initial C−H ruthenation process was reversible (Scheme 5a). Moreover, the kinetic isotopic effect (KIE) by intermolecular competitions of **3a** and $[D_5]$-**3a** was determined to be 1.1, implying that the C−H cleavage may be not involved in the rate-limiting step (Scheme 5b).

A plausible mechanism for the Ru(II)-catalyzed C−H selenylation process is shown in Scheme 6.[9,18] The active catalyst **A** might be first formed from $[RuCl_2(p\text{-cymene})]_2$ and $Cu(OAc)_2$. A carboxylate-assisted *o*-C−H bond cleavage of **1a** then occurred to form ruthenacycle **C**,[18a,b] which was subsequently coordinated by PhSeCl, and the Se−Cl bond cleavage afforded the cationic species **E** (path a).[9,18c] An oxidative addition/reductive elimination process may represent

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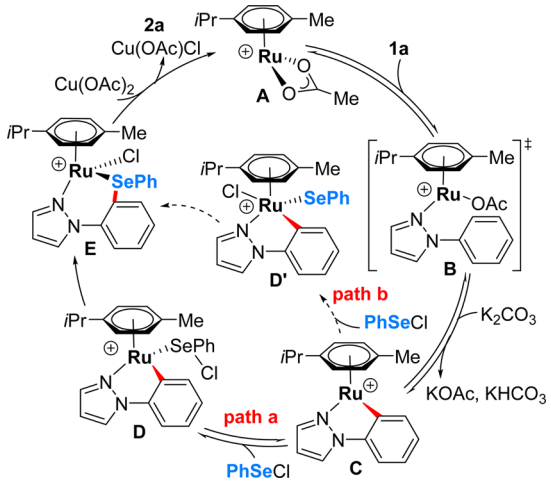
Scheme 6. Proposed Mechanism



an alternative pathway for the formation of **E** (path b).[18a,b] The selenylated product **2a** was yielded with $Cu(OAc)_2$ as the additive, and the active Ru(II) catalyst **A** was regenerated for further recycling.

CONCLUSION

In summary, we have developed the first ruthenium(II)-catalyzed C−H selenylation of arenes bearing various *N*-heterocycles as the directing groups. In this protocol, benzeneselenyl chloride was used as the selenylating reagent, and the transformation proceeds under mild reaction conditions with wide substrate scope. Moreover, late-stage selenylation was successfully applied to either biologically active estrone derivative or the marketed antidepressant drug.

EXPERIMENTAL SECTION

General Information. All reactions were performed in flame-dried glassware using sealed tubes or Schlenk tubes. Liquids and solutions were transferred with syringes. All solvents and chemical reagents were obtained from commercial sources and used without further purification. ^1H and ^{13}C NMR spectra were recorded with tetramethylsilane as an internal reference. Low- and high-resolution mass spectra were recorded on EI-TOF (electrospray ionization-time-of-flight). Flash column chromatography on silica gel (200−300 mesh) was used for the routine purification of reaction products. The column output was monitored by TLC on silica gel (100−200 mesh) precoated on glass plates (15 × 50 mm), and spots were visualized by UV light at 254 nM. Starting materials were prepared according to the literature procedures.[19]

General Procedure for Synthesis of Selenylated Products. To a stirred solution of substrate **1**, **3**, **5**, or **7** (0.20 mmol) in HFIP (2.5 mL) were added $Cu(OAc)_2·H_2O$ (80 mg, 0.40 mmol), K_2CO_3 (41 mg, 0.30 mmol), TBA-OAc (30 mg, 0.10 mmol), $[RuCl_2(p\text{-cymene})]_2$ (6 mg, 5 mol %), and PhSeCl (77 mg, 0.40 mmol). The mixture was heated at 75 °C for 8 h in a sealed tube until the starting material disappeared. After being cooled to room temperature, the reaction mixture was filtered and the filtrate was concentrated. The residue was purified on a silica gel column with petroleum ether/ethyl acetate as the eluent to afford the corresponding products **2**, **4**, **6**, or **8**.

Spectroscopic Data of All New Compounds. *1-(2-(Phenylselenyl)phenyl)-1H-pyrazole* (***2a***): white solid (52.6 mg, 88%); mp 52−54 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.78 (s, 2H), 7.58 (d, J = 6.8 Hz, 2H), 7.34 (q, J = 6.8, 5.6 Hz, 4H), 7.28−7.23 (m, 1H), 7.14 (q, J = 6.8, 5.4 Hz, 2H), 6.49 (s, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 142.4, 141.5, 137.7, 133.7, 132.4, 131.9, 131.5, 131.2, 130.5, 130.4, 128.7, 127.1, 108.9; IR (cm^{-1}) ν 1582, 1515, 1482, 1393, 939, 750, 689; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{12}N_2Se$ 300.0166, found 300.0165.

1-(4-Methyl-2-(phenylselenyl)phenyl)-1H-pyrazole (***2b***): white solid (60.1 mg, 96%); mp 47−49 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.73 (d, J = 8.1 Hz, 2H), 7.56−7.51 (m, 2H), 7.32 (d, J = 6.4 Hz, 3H), 7.26 (d, J = 7.7 Hz, 1H), 7.06 (d, J = 8.1 Hz, 1H), 6.97 (s, 1H), 6.45 (s, 1H), 2.23 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 140.4, 138.7, 137.6, 135.4, 132.5, 130.2, 129.8, 129.6, 129.5, 128.4, 127.8, 125.3, 106.7, 21.1; IR (cm^{-1}) ν 1595, 1516, 1491, 1394, 818, 742, 690; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{14}N_2Se$ 314.0322, found 314.0324.

1-(4-Methoxy-2-(phenylselenyl)phenyl)-1H-pyrazole (***2c***): white solid (60.6 mg, 92%); mp 68−70 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.74 (s, 1H), 7.68 (s, 1H), 7.58 (d, J = 7.5 Hz, 2H), 7.37−7.26 (m, 4H), 6.76 (dd, J = 8.6, 2.5 Hz, 1H), 6.62−6.59 (m, 1H), 6.45 (s, 1H), 3.62 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 159.4, 140.3, 136.0, 133.1, 132.3, 130.3, 129.6, 128.80, 128.77, 126.5, 116.5, 112.1, 106.7, 55.4; IR (cm^{-1}) ν 1592, 1570, 1516, 1490, 1277, 1218, 1033, 773, 741, 688; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{14}N_2OSe$ 330.0271, found 330.0271.

1-(4-Fluoro-2-(phenylselenyl)phenyl)-1H-pyrazole (***2d***): white solid (47.6 mg, 75%); mp 71−73 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.75 (d, J = 14.9 Hz, 2H), 7.61 (d, J = 7.1 Hz, 2H), 7.39 (q, J = 7.3, 6.2 Hz, 3H), 7.30 (dd, J = 8.5, 5.1 Hz, 1H), 6.97−6.85 (m, 1H), 6.71 (dd, J = 9.0, 2.2 Hz, 1H), 6.49 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 162.1 (d, J_{C-F} = 250.7 Hz), 140.7, 136.5, 135.4 (d, J_{C-F} = 1.5 Hz), 133.9 (d, J_{C-F} = 7.5 Hz), 130.1, 129.9, 129.3, 128.0, 126.5 (d, J_{C-F} = 7.5 Hz), 117.5 (d, J_{C-F} = 25.7 Hz), 113.4 (d, J_{C-F} = 22.7 Hz), 107.2; ^{19}F NMR (471 MHz, $CDCl_3$) δ −112.6; IR (cm^{-1}) ν 1596, 1580, 1548, 1505, 1489, 1395, 1202, 865, 767, 740, 691; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{11}FN_2Se$ 318.0071, found 318.0063.

1-(4-Fluoro-2,6-bis(phenylselenyl)phenyl)-1H-pyrazole (***2d′***): white solid (14.2 mg, 15%); mp 177−179 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.89−7.83 (m, 1H), 7.69 (d, J = 1.9 Hz, 1H), 7.59 (d, J = 6.5 Hz, 4H), 7.50−7.31 (m, 6H), 6.55 (s, 1H), 6.44 (d, J = 8.5 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 163.6 (d, J_{C-F} = 254.5 Hz), 141.8, 138.3 (d, J_{C-F} = 7.6 Hz), 137.2, 133.6 (d, J_{C-F} = 2.5 Hz), 132.2, 130.6, 130.1, 127.7, 115.1 (d, J_{C-F} = 26.5 Hz), 107.5; ^{19}F NMR (471 MHz, $CDCl_3$) δ −110.3; IR (cm^{-1}) ν 1566, 1515, 1461, 1215, 852, 744, 690; HRMS (EI) m/z [M^+] calcd for $C_{21}H_{15}FN_2Se_2$ 473.9550, found 473.9556.

1-(4-Chloro-2-(phenylselenyl)phenyl)-1H-pyrazole (***2e***): white solid (45.9 mg, 69%); mp 85−87 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.76 (d, J = 8.1 Hz, 2H), 7.60 (d, J = 7.3 Hz, 2H), 7.38 (q, J = 6.8, 6.3 Hz, 3H), 7.30−7.18 (m, 2H), 7.04−6.95 (m, 1H), 6.50 (s, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 141.5, 138.5, 136.9, 135.0, 133.4, 131.4, 130.6, 129.9, 129.0, 127.4, 126.6, 108.1; IR (cm^{-1}) ν 1576, 1517, 1479, 1393, 938, 814, 741, 688; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{11}ClN_2Se$ 333.9776, found 333.9775.

1-(4-Chloro-2,6-bis(phenylselenyl)phenyl)-1H-pyrazole (***2e′***): white solid (16.8 mg, 17%); mp 163−165 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.87−7.81 (m, 1H), 7.69−7.64 (m, 1H), 7.57 (d, J = 7.0 Hz, 4H), 7.38 (q, J = 7.9, 7.3 Hz, 6H), 6.74 (s, 2H), 6.54 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 141.2, 136.8, 136.3, 136.1, 135.6, 131.4, 130.0, 129.4, 127.5, 127.1, 106.9; IR (cm^{-1}) ν 1545, 1516, 1456, 1404, 936, 851, 738, 691; HRMS (EI) m/z [M^+] calcd for $C_{21}H_{15}ClN_2Se_2$ 489.9254, found 489.9249.

1-(2-(Phenylselenyl)-4-(trifluoromethyl)phenyl)-1H-pyrazole (***2f***): white solid (45.8 mg, 62%); mp 137−139 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.90−7.78 (m, 2H), 7.61 (d, J = 6.6 Hz, 2H), 7.47 (s, 2H), 7.39 (q, J = 7.6, 6.5 Hz, 3H), 7.30 (s, 1H), 6.54 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 141.6, 141.2, 136.2, 131.7, 130.1 (q, J_{C-F} = 33.2 Hz), 130.0, 129.7, 129.3, 128.5, 128.3 (q, J_{C-F} = 3.0 Hz), 124.5, 123.5 (q, J_{C-F} = 3.0 Hz), 123.4 (q, J_{C-F} = 273.3 Hz), 107.9; ^{19}F NMR (471 MHz, $CDCl_3$) δ −62.8; IR (cm^{-1}) ν 1602, 1521, 1502, 1438, 1395, 1327, 1121, 827, 765, 742, 690; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{11}F_3N_2Se$ 368.0040, found 368.0043.

1-(2,6-Bis(phenylselenyl)-4-(trifluoromethyl)phenyl)-1H-pyrazole (***2f′***). white solid (16.3 mg, 16%); mp 153−155 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.87 (s, 1H), 7.73 (d, J = 1.9 Hz, 1H), 7.57 (d, J = 6.7

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Hz, 4H), 7.50−7.30 (m, 6H), 7.02 (s, 2H), 6.57 (s, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 142.3, 140.6, 137.4, 137.0, 132.8 (q, J_{C-F} = 32.8 Hz), 132.0, 130.9, 130.3, 128.0, 125.7 (q, J_{C-F} = 2.5 Hz), 123.8 (q, J_{C-F} = 273.4 Hz), 108.1; ^{19}F NMR (471 MHz, $CDCl_3$) δ −63.2; IR (cm^{-1}) ν 1548, 1521, 1466, 1388, 1302, 1128, 1095, 871, 739, 688; HRMS (EI) m/z [M^+] calcd for $C_{22}H_{15}F_3N_2Se_2$ 523.9518, found 523.9526.

*1-(5-Methyl-2-(phenylselenyl)phenyl)-1H-pyrazole (**2g**):* colorless oil (59.5 mg, 95%); ^1H NMR (300 MHz, $CDCl_3$) δ 7.75 (s, 2H), 7.56−7.46 (m, 2H), 7.29 (d, J = 6.2 Hz, 3H), 7.23 (s, 1H), 7.09 (d, J = 8.1 Hz, 1H), 6.98 (d, J = 8.0 Hz, 1H), 6.45 (s, 1H), 2.33 (s, 3H).$^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 142.4, 141.9, 139.4, 136.9, 134.5, 132.01, 131.97, 131.4, 130.1, 128.0, 127.7, 108.7, 22.7; IR (cm^{-1}) ν 1601, 1577, 1516, 1489, 1475, 1400, 812, 742, 692; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{14}N_2Se$ 314.0322, found 314.0320.

*1-(5-Methoxy-2-(phenylselenyl)phenyl)-1H-pyrazole (**2h**):* white solid (15.3 mg, 23%); mp 104−106 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.67 (s, 2H), 7.50−7.38 (m, 1H), 7.24−7.14 (m, 3H), 7.14−7.05 (m, 3H), 6.97 (d, J = 8.3 Hz, 1H), 6.37 (s, 1H), 3.76 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 160.3, 144.6, 140.4, 132.2, 131.2, 130.6, 130.4, 128.8, 126.3, 119.5, 116.2, 111.2, 106.3, 56.4; IR (cm^{-1}) ν 1577, 1514, 1472, 1262, 1081, 1038, 833, 754, 692; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{14}N_2OSe$ 330.0271, found 330.0270.

*1-(3-Methoxy-2,6-bis(phenylselenyl)phenyl)-1H-pyrazole (**2h′**).* white solid (45.2 mg, 47%); mp 125−127 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.71 (s, 1H), 7.53−7.42 (m, 3H), 7.26 (dd, J = 13.8, 7.5 Hz, 6H), 7.18−7.09 (m, 3H), 6.85 (d, J = 8.7 Hz, 1H), 6.40 (s, 1H), 3.69 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 159.4, 143.8, 140.2, 134.6, 134.0, 131.8, 131.6, 131.2, 129.9, 129.5, 128.8, 128.1, 126.6, 124.3, 120.4, 113.1, 106.2, 56.5; IR (cm^{-1}) ν 1565, 1514, 1457, 1427, 1277, 1087, 952, 752, 740, 691; HRMS (EI) m/z [M^+] calcd for $C_{22}H_{18}N_2OSe_2$ 485.9750, found 485.9786.

*1-(5-Fluoro-2-(phenylselenyl)phenyl)-1H-pyrazole (**2i**):* white solid (39.3 mg, 62%); mp 49−51 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.77−7.64 (m, 2H), 7.47−7.38 (m, 1H), 7.37−7.26 (m, 3H), 7.23−7.11 (m, 4H), 6.42 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 162.9 (d, J_{C-F} = 247.6 Hz), 144.3 (d, J_{C-F} = 4.5 Hz), 140.8, 131.6, 131.0, 130.7 (d, J_{C-F} = 1.5 Hz), 130.4 (d, J_{C-F} = 9.1 Hz), 129.1, 127.3, 122.4 (d, J_{C-F} = 3.0 Hz), 115.8 (d, J_{C-F} = 25.7 Hz), 115.3 (d, J_{C-F} = 24.2 Hz), 106.8; ^{19}F NMR (471 MHz, $CDCl_3$) δ −95.5; IR (cm^{-1}) ν 1595, 1576, 1475, 1448, 1238, 1066, 862, 737, 690; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{11}FN_2Se$ 318.0071, found 318.0066.

*1-(5-Chloro-2-(phenylselenyl)phenyl)-1H-pyrazole (**2j**):* yellow solid (43.4 mg, 65%); mp 71−72 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.65 (s, 2H), 7.55 (dd, J = 5.9, 3.4 Hz, 1H), 7.41 (d, J = 3.4 Hz, 2H), 7.16 (s, 5H), 6.37 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 142.8, 138.7, 138.1, 128.8, 128.7, 128.4, 127.64, 127.60, 126.6, 125.4, 124.4, 123.3, 104.1; IR (cm^{-1}) ν 1573, 1514, 1463, 1424, 1029, 789, 761, 736, 689; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{11}ClN_2Se$ 333.9776, found 333.9778.

*1-(2-Methoxy-6-(phenylselenyl)phenyl)-1H-pyrazole (**2k**):* white solid (61.9 mg, 94%); mp 82−84 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.84−7.74 (m, 1H), 7.64 (d, J = 2.2 Hz, 1H), 7.61−7.54 (m, 2H), 7.32 (q, J = 6.4, 5.9 Hz, 3H), 7.12 (t, J = 8.2 Hz, 1H), 6.81 (d, J = 8.2 Hz, 1H), 6.64 (d, J = 8.0 Hz, 1H), 6.48 (s, 1H), 3.75 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 157.0, 142.1, 138.0, 137.5, 133.9, 131.7, 131.5, 130.62, 130.56, 130.3, 124.5, 111.4, 108.1, 58.1; IR (cm^{-1}) ν 1577, 1519, 1463, 1277, 1036, 833, 745, 690; HRMS (EI) m/z [M^+] calcd for $C_{16}H_{14}N_2OSe$ 330.0271, found 330.0272.

*4-Bromo-1-(2-(phenylselenyl)phenyl)-1H-pyrazole (**2l**):* white solid (68.1 mg, 90%); mp 116−118 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.79 (s, 1H), 7.71 (s, 1H), 7.56 (d, J = 7.3 Hz, 2H), 7.38−7.30 (m, 4H), 7.26 (s, 1H), 7.16 (d, J = 5.1 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 143.0, 141.0, 137.6, 134.0, 132.2, 132.0, 131.5, 130.91, 130.87, 130.6, 128.9, 127.1, 97.0; IR (cm^{-1}) ν 1580, 1482, 1436, 1380, 950, 844, 754, 737, 687; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{11}BrN_2Se$ 377.9271, found 377.9273.

*1-(2-(Phenylselenyl)phenyl)-1H-indazole (**2m**):* white solid (61.5 mg, 88%); mp 105−107 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.25 (s, 1H), 7.82 (d, J = 8.0 Hz, 1H), 7.55 (d, J = 7.3 Hz, 2H), 7.45 (q, J = 6.6, 5.5 Hz, 3H), 7.30 (q, J = 7.1, 5.8 Hz, 4H), 7.23 (dd, J = 8.6, 3.9 Hz, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 140.6, 138.9, 136.6, 135.7, 133.7, 132.6, 130.2, 129.7, 129.6, 129.2, 127.7, 127.5, 127.4, 125.2, 122.2, 121.9, 111.1; IR (cm^{-1}) ν 1579, 1477, 1414, 1198, 846, 746, 694; HRMS (EI) m/z [M^+] calcd for $C_{19}H_{14}N_2Se$ 350.0322, found 350.0322.

*2-(2-(Phenylselenyl)phenyl)pyridine (**4a**):* white solid (38.5 mg, 62%); mp 92−94 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.78−8.70 (m, 1H), 7.79 (t, J = 7.6 Hz, 1H), 7.68−7.54 (m, 4H), 7.32 (d, J = 6.2 Hz, 3H), 7.27 (d, J = 7.6 Hz, 2H), 7.15 (d, J = 6.6 Hz, 2H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 158.6, 148.3, 139.8, 136.5, 135.9, 134.3, 131.4, 131.3, 129.4, 129.3, 128.9, 128.2, 126.0, 122.7, 122.2; IR (cm^{-1}) ν 1584, 1570, 1462, 794, 738, 691; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{13}NSe$ 311.0213, found 311.0213. Spectral data matched those previously reported.[20a]

*2-(4-Fluoro-2-(phenylselenyl)phenyl)pyridine (**4b**):* brown solid (49.2 mg, 75%); mp 69−71 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.74 (d, J = 4.5 Hz, 1H), 7.80 (t, J = 7.6 Hz, 1H), 7.70−7.60 (m, 3H), 7.56 (dd, J = 8.4, 5.9 Hz, 1H), 7.37 (q, J = 5.8 Hz, 3H), 7.31−7.26 (m, 1H), 6.92 (td, J = 8.3, 2.3 Hz, 1H), 6.79 (dd, J = 9.7, 2.3 Hz, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 163.6 (d, J_{C-F} = 250.7 Hz), 158.3, 148.9, 138.1 (d, J_{C-F} = 6.3 Hz), 137.4, 137.2, 135.9 (d, J_{C-F} = 3.8 Hz), 131.2 (d, J_{C-F} = 3.8 Hz), 131.1, 130.4, 129.5, 123.1, 122.8, 118.2 (d, J_{C-F} = 23.9 Hz), 113.4 (d, J_{C-F} = 22.7 Hz); ^{19}F NMR (471 MHz, $CDCl_3$) δ −112.8; IR (cm^{-1}) ν 1591, 1463, 1425, 1196, 864, 779, 739, 690; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{12}FNSe$ 329.0119, found 329.0118. Spectral data matched those previously reported.[20a]

*2-(4-Chloro-2-(phenylselenyl)phenyl)pyridine (**4c**):* brown solid (53.8 mg, 78%); mp 64−66 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.74 (d, J = 4.4 Hz, 1H), 7.79 (t, J = 7.6 Hz, 1H), 7.62 (d, J = 5.6 Hz, 3H), 7.51 (d, J = 8.2 Hz, 1H), 7.37 (d, J = 6.7 Hz, 3H), 7.32−7.27 (m, 1H), 7.24−7.17 (m, 1H), 7.11−7.03 (m, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 157.5, 148.3, 137.7, 136.7, 136.2, 136.0, 135.1, 130.5, 130.4, 130.1, 129.7, 128.8, 125.9, 122.5, 122.4; IR (cm^{-1}) ν 1585, 1568, 1460, 1423, 1104, 782, 742, 692; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{12}ClNSe$ 344.9823, found 344.9824. Spectral data matched those previously reported.[20b]

*2-(2-(Phenylselenyl)-4-(trifluoromethyl)phenyl)pyridine (**4d**):* white solid (55.2 mg, 73%); mp 97−99 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.77 (d, J = 4.4 Hz, 1H), 7.90−7.77 (m, 1H), 7.68 (d, J = 7.9 Hz, 2H), 7.61 (d, J = 7.0 Hz, 2H), 7.47 (d, J = 8.0 Hz, 1H), 7.35 (t, J = 7.7 Hz, 5H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 158.0, 149.1, 143.1, 137.5, 136.84, 136.77, 131.5 (q, J_{C-F} = 32.8 Hz), 131.0, 130.4, 130.0, 129.6, 128.4 (q, J_{C-F} = 3.8 Hz), 124.4 (q, J_{C-F} = 272.2 Hz), 123.5, 123.4, 123.1 (q, J_{C-F} = 3.8 Hz); ^{19}F NMR (471 MHz, $CDCl_3$) δ −62.9; IR (cm^{-1}) ν 1587, 1485, 1468, 1325, 1120, 786, 740, 692; HRMS (EI) m/z [M^+] calcd for $C_{18}H_{12}F_3NSe$ 379.0087, found 379.0089. Spectral data matched those previously reported.[20b]

*Methyl 3-(phenylselenyl)-4-(pyridin-2-yl)benzoate (**4e**):* white solid (42.7 mg, 58%); mp 101−103 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.77 (d, J = 4.6 Hz, 1H), 7.96−7.77 (m, 3H), 7.71−7.63 (m, 2H), 7.63−7.57 (m, 2H), 7.35 (d, J = 6.5 Hz, 4H), 3.81 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 166.4, 157.7, 148.4, 143.6, 136.7, 135.8, 135.0, 132.6, 130.8, 130.3, 129.6, 129.2, 128.5, 126.9, 122.9, 122.8, 52.2; IR (cm^{-1}) ν 1714, 1585, 1570, 1425, 1279, 841, 759, 695; HRMS (EI) m/z [M^+] calcd for $C_{19}H_{15}NO_2Se$ 369.0268, found 369.0271.

*2-(5-Methyl-2-(phenylselenyl)phenyl)pyridine (**4f**):* colorless oil (40.2 mg, 62%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.72 (d, J = 4.7 Hz, 1H), 7.75 (t, J = 7.7 Hz, 1H), 7.62 (d, J = 7.9 Hz, 1H), 7.58−7.47 (m, 2H), 7.41 (s, 1H), 7.26 (dd, J = 11.8, 5.0 Hz, 4H), 7.12 (d, J = 8.0 Hz, 1H), 6.99 (d, J = 8.1 Hz, 1H), 2.35 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 158.8, 148.4, 140.4, 136.3, 136.1, 135.1, 132.2, 131.8, 130.2, 129.93, 129.89, 129.3, 127.8, 123.0, 122.1, 21.0; IR (cm^{-1}) ν 1587, 1473, 1425, 787, 742, 693; HRMS (EI) m/z [M^+] calcd for $C_{18}H_{15}NSe$ 325.0370, found 325.0371. Spectral data matched those previously reported.[20a]

*2-(5-Fluoro-2-(phenylselenyl)phenyl)pyridine (**4g**):* colorless oil (29.5 mg, 45%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.65 (d, J = 3.6 Hz, 1H), 7.70 (t, J = 7.6 Hz, 1H), 7.47 (d, J = 7.9 Hz, 1H), 7.38 (d, J =

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6.2 Hz, 2H), 7.29−7.22 (m, 3H), 7.20−7.07 (m, 4H).; $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 164.6 (d, J_{C-F} = 247.0 Hz), 160.3 (d, J_{C-F} = 2.5 Hz), 150.8, 148.7, 137.7, 134.1 (d, J_{C-F} = 2.5 Hz), 133.0, 131.9 (d, J_{C-F} = 8.8 Hz), 130.8, 128.5, 127.7 (d, J_{C-F} = 2.5 Hz), 126.1, 124.3, 119.3 (d, J_{C-F} = 21.4 Hz), 117.7 (d, J_{C-F} = 25.2 Hz); ^{19}F NMR (471 MHz, $CDCl_3$) δ −97.0; IR (cm^{-1}) ν 1583, 1477, 1454, 1439, 1238, 773, 737, 690; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{12}FNSe$ 329.0119, found 329.0120.

*2-(5-Bromo-2-(phenylselenyl)phenyl)pyridine (**4h**):* colorless oil (56.0 mg, 72%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.74 (d, J = 4.5 Hz, 1H), 7.81 (t, J = 7.7 Hz, 1H), 7.76−7.68 (m, 1H), 7.64 (d, J = 7.9 Hz, 1H), 7.58 (d, J = 7.7 Hz, 2H), 7.33 (q, J = 9.5, 7.9 Hz, 4H), 7.26−7.21 (m, 1H), 7.00 (d, J = 8.5 Hz, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 157.9, 149.1, 142.0, 137.4, 136.6, 134.4, 133.6, 132.6, 132.4, 131.6, 130.3, 129.2, 123.4, 123.3, 120.4; IR (cm^{-1}) ν 1587, 1572, 1473, 1423, 1018, 785, 741, 692; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{12}BrNSe$ 388.9318, found 388.9318.

*2-(2-Methyl-6-(phenylselenyl)phenyl)pyridine (**4i**):* colorless oil (29.2 mg, 45%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.71 (d, J = 4.3 Hz, 1H), 7.75 (t, J = 8.1 Hz, 1H), 7.49−7.41 (m, 2H), 7.33−7.25 (m, 5H), 7.17−7.08 (m, 3H), 2.11 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 159.2, 149.5, 141.7, 136.9, 136.2, 134.6, 132.8, 130.8, 129.5, 129.3, 128.8, 128.8, 127.7, 124.7, 122.3, 20.5; IR (cm^{-1}) ν 1589, 1564, 1475, 1022, 739, 692; HRMS (EI) m/z [M^+] calcd for $C_{18}H_{15}NSe$ 325.0370, found 325.0371. Spectral data matched those previously reported.[20a]

*2-(2-Chloro-6-(phenylselenyl)phenyl)pyridine (**4j**):* colorless oil (44.1 mg, 64%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.81−8.68 (m, 1H), 7.79 (t, J = 7.4 Hz, 1H), 7.57−7.48 (m, 2H), 7.43 (d, J = 7.7 Hz, 1H), 7.31 (t, J = 6.4 Hz, 5H), 7.07 (q, J = 7.7 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 157.7, 150.1, 140.1, 137.0, 136.2, 134.1, 130.5, 130.30, 130.27, 130.1, 129.2, 128.2, 125.9, 123.7; IR (cm^{-1}) ν 1589, 1566, 1550, 1475, 1417, 769, 741, 692; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{12}ClNSe$ 344.9823, found 344.9817.

*3-Methoxy-2-(2-(phenylselenyl)phenyl)pyridine (**4k**):* colorless oil (40.8 mg, 60%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.33−8.27 (m, 1H), 7.52 (d, J = 7.6 Hz, 1H), 7.48−7.41 (m, 2H), 7.37 (d, J = 7.9 Hz, 1H), 7.29 (dd, J = 14.2, 5.0 Hz, 3H), 7.26−7.13 (m, 4H), 3.79 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 153.4, 149.1, 140.7, 139.7, 134.1, 133.2, 133.1, 132.0, 130.3, 129.1, 128.9, 127.3, 126.7, 123.6, 118.0, 55.4; IR (cm^{-1}) ν 1577, 1475, 1460, 1423, 1275, 1018, 742; HRMS (EI) m/z [M^+] calcd for $C_{18}H_{15}NOSe$ 341.0319, found 341.0320.

*5-Methyl-2-(2-(phenylselenyl)phenyl)pyridine (**4l**):* brown solid (36.3 mg, 56%); mp 78−80 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.57 (s, 1H), 7.67−7.49 (m, 5H), 7.32 (d, J = 6.0 Hz, 3H), 7.25−7.19 (m, 1H), 7.12 (d, J = 7.4 Hz, 2H), 2.39 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 155.9, 148.6, 139.8, 137.2, 135.9, 134.2, 131.8, 131.4, 131.3, 129.4, 129.1, 128.7, 128.1, 125.9, 122.2, 18.3; IR (cm^{-1}) ν 1569, 1460, 1433, 838, 771, 734, 688; HRMS (EI) m/z [M^+] calcd for $C_{18}H_{15}NSe$ 325.0370, found 325.0373.

*2-(2-Methyl-6-(phenylselenyl)phenyl)pyrimidine (**4m**):* colorless oil (19.5 mg, 30%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.87 (d, J = 5.0 Hz, 2H), 7.50−7.42 (m, 2H), 7.28−7.22 (m, 5H), 7.18−7.14 (m, 2H), 2.21 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 168.3, 157.6, 141.4, 137.6, 135.0, 132.9, 132.0, 131.2, 129.94, 129.91, 129.86, 128.3, 119.9, 21.0; IR (cm^{-1}) ν 1564, 1475, 1439, 1402, 1022, 739, 692; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{14}N_2Se$ 326.0322, found 326.0319.

*2-(2-(Phenylselenyl)phenyl)quinolone (**4n**):* white solid (54.0 mg, 75%); mp 125−127 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.26 (d, J = 8.5 Hz, 2H), 7.91−7.73 (m, 4H), 7.65 (dd, J = 5.0, 2.4 Hz, 2H), 7.57 (t, J = 7.6 Hz, 1H), 7.42−7.27 (m, 4H), 7.19 (q, J = 8.1 Hz, 2H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 158.8, 147.6, 140.0, 137.4, 136.8, 136.5, 132.6, 132.2, 130.5, 130.1, 129.9, 129.9, 128.9, 128.2, 127.5, 127.4, 126.5, 121.1; IR (cm^{-1}) ν 1594, 1571, 1458, 1433, 827, 764, 694; HRMS (EI) m/z [M^+] calcd for $C_{21}H_{15}NSe$ 361.0370, found 361.0369. Spectral data matched those previously reported.[20a]

*1-(2-(Phenylselenyl)phenyl)isoquinoline (**4o**):* colorless oil (45.4 mg, 63%); ^1H NMR (300 MHz, $CDCl_3$) δ 8.62 (d, J = 5.7 Hz, 1H), 7.88 (d, J = 8.2 Hz, 1H), 7.82 (d, J = 8.4 Hz, 1H), 7.68 (t, J = 5.9 Hz, 2H), 7.54−7.48 (m, 1H), 7.44 (d, J = 6.5 Hz, 3H), 7.39−7.31 (m, 2H), 7.29 (d, J = 7.4 Hz, 1H), 7.23 (t, J = 6.1 Hz, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 160.4, 141.9, 140.4, 136.6, 134.9, 133.9, 132.4, 130.51, 130.46, 130.2, 129.3, 129.2, 127.9, 127.4, 127.3, 127.1, 127.0, 126.3, 120.5; IR (cm^{-1}) ν 1620, 1581, 1560, 1498, 1475, 1020, 974, 827, 733, 692; HRMS (EI) m/z [M^+] calcd for $C_{21}H_{15}NSe$, 361.0370, found 361.0367.

*10-(Phenylselenyl)benzo[h]quinolone (**4p**):* white solid (28.1 mg, 42%); mp 125−127 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 9.15 (d, J = 4.4 Hz, 1H), 8.24 (d, J = 8.0 Hz, 1H), 7.90−7.79 (m, 3H), 7.71 (d, J = 8.9 Hz, 2H), 7.58 (dd, J = 7.8, 4.4 Hz, 1H), 7.47 (d, J = 5.0 Hz, 3H), 7.38 (t, J = 7.8 Hz, 1H), 7.23 (s, 1H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 147.1, 145.8, 137.6, 135.9, 135.22, 135.18, 133.0, 129.7, 128.8, 128.7, 128.6, 127.72, 127.69, 127.0, 125.3, 125.1, 121.1; IR (cm^{-1}) ν 1578, 1554, 1434, 1412, 912, 832, 747, 694; HRMS (EI) m/z [M^+] calcd for $C_{19}H_{13}NSe$ 335.0213, found 335.0214. Spectral data matched those previously reported.[20a]

*(E)-1-(2-(Phenylselenyl)phenyl)ethanone O-methyl oxime (**4q**):* white solid (40.1 mg, 66%); mp 48−50 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.68−7.59 (m, 2H), 7.44−7.33 (m, 4H), 7.21 (t, J = 7.2 Hz, 1H), 7.11 (q, J = 8.4, 7.9 Hz, 2H), 4.09 (s, 3H), 2.30 (s, 3H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 155.3, 136.9, 135.7, 133.8, 131.6, 131.5, 129.5, 128.8, 128.4, 128.2, 125.9, 62.3, 14.5; IR (cm^{-1}) ν 1611, 1579, 1463, 1430, 1051, 895, 757, 691; HRMS (EI) m/z [M^+] calcd for $C_{15}H_{15}NOSe$ 305.0319, found 305.0320. Spectral data matched those previously reported.[9]

*(E)-8-(Phenylselenyl)-3,4-dihydronaphthalen-1(2H)-one O-methyl oxime (**4r**):* colorless oil (29.7 mg, 45%); ^1H NMR (300 MHz, $CDCl_3$) δ 7.76−7.64 (m, 2H), 7.45−7.32 (m, 3H), 6.97−6.87 (m, 2H), 6.87−6.79 (m, 1H), 4.14 (s, 3H), 2.81 (t, J = 6.7 Hz, 2H), 2.77−2.68 (m, 2H), 1.83 (p, J = 6.5 Hz, 2H); $^{13}C\{^1H\}$ NMR (151 MHz, $CDCl_3$) δ 154.4, 141.6, 136.9, 135.6, 132.4, 129.5, 129.1, 128.6, 128.2, 128.0, 125.2, 62.6, 30.9, 24.9, 20.9; IR (cm^{-1}) ν 1606, 1576, 1556, 1439, 1047, 879, 742; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{17}NOSe$ 331.0475, found 331.0472. Spectral data matched those previously reported.[9]

*2-(2-(Phenylselenyl)phenoxy)pyridine (**4s**):* brown solid (30.7 mg, 47%); mp 57−59 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.16 (d, J = 3.2 Hz, 1H), 7.67 (t, J = 7.6 Hz, 1H), 7.55−7.49 (m, 2H), 7.32−7.25 (m, 4H), 7.21 (d, J = 7.5 Hz, 1H), 7.14 (d, J = 7.8 Hz, 1H), 7.09−7.03 (m, 1H), 7.01−6.95 (m, 1H), 6.92 (d, J = 8.3 Hz, 1H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 164.0, 152.8, 148.3, 140.1, 135.6, 133.5, 130.1, 129.6, 128.9, 128.7, 127.1, 126.6, 123.1, 119.2, 112.0; IR (cm^{-1}) ν 1595, 1567, 1457, 1426, 1269, 878, 785, 736, 688; HRMS (EI) m/z [M^+] calcd for $C_{17}H_{13}NOSe$ 327.0162, found 327.0170. Spectral data matched those previously reported.[20b]

*13-Methyl-2-(phenylselenyl)-3-(pyridin-2-yl)-7,8,9,11,12,13,15,16-octahydro-6H-cyclopenta[a]phenanthren-17(14H)-one (**6**):* white solid (46.7 mg, 48%); mp 203−205 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 8.70 (d, J = 3.7 Hz, 1H), 7.74 (t, J = 7.6 Hz, 1H), 7.61 (d, J = 7.6 Hz, 1H), 7.57−7.41 (m, 2H), 7.35 (s, 1H), 7.29 (d, J = 3.7 Hz, 4H), 7.18 (s, 1H), 3.02−2.83 (m, 2H), 2.56−2.41 (m, 1H), 2.27−1.96 (m, 4H), 1.92 (d, J = 10.9 Hz, 1H), 1.83 (d, J = 11.0 Hz, 1H), 1.58−1.22 (m, 6H), 0.87 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 221.4, 159.3, 149.1, 141.5, 139.0, 136.9, 135.65, 135.63, 132.5, 130.7, 130.5, 130.3, 130.0, 128.5, 123.6, 122.6, 51.2, 48.6, 45.0, 38.7, 36.5, 32.2, 29.6, 27.1, 25.9, 22.3, 14.5; IR (cm^{-1}) ν 1735, 1586, 1467, 1425, 793, 741, 690; HRMS (EI) m/z [M^+] calcd for $C_{29}H_{29}NOSe$ 487.1414, found 487.1412.

*7-Chloro-1-methyl-5-(2-(phenylselenyl)phenyl)-1,3-dihydro-2H-benzo[e][1,4]diazepin-2-one (**8**):* white solid (54.5 mg, 62%); mp 138−140 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.54−7.40 (m, 3H), 7.38−7.28 (m, 4H), 7.28−7.20 (m, 4H), 7.20−7.18 (m, 1H), 4.93 (d, J = 10.9 Hz, 1H), 3.86 (d, J = 11.0 Hz, 1H), 3.40 (s, 3H). $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 169.0, 168.5, 142.0, 138.3, 134.8, 134.2, 132.3, 131.0, 130.9, 130.8, 130.0, 129.8, 129.0, 128.9, 127.6, 125.6, 122.2, 55.8, 34.4; IR (cm^{-1}) ν 1682, 1610, 1579, 1483, 1400, 1128, 816, 746, 692; HRMS (ESI) m/z [$M + H$]$^+$ calcd for $C_{22}H_{18}ClN_2OSe$ 441.0273, found 441.0271.

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■ ASSOCIATED CONTENT

Supporting Information

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H/D exchange experiment, KIE by intermolecular competition, and ^{1}H and ^{13}C NMR spectra for all new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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