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Experimental and Theoretical Studies on the Nature of Weak Nonbonded Interactions between Divalent Selenium and Halogen Atoms

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To investigate the nature of weak nonbonded selenium⋯halogen interactions (Se⋯X interactions; X = F, Cl, and Br), three types of model compounds [2-(CH_2X)C_6H_4SeY (**1**−**3**), 3-(CH_2X)-2-$C_{10}H_6$-SeY (**4**−**6**), and 2-$XC_6H_4CH_2$SeY (**7**−**9**); Y = CN, Cl, Br, SeAr, and Me] were synthesized, and their ^{77}Se NMR spectroscopic behaviors were analyzed in $CDCl_3$. The gradual upfield shifts of ^{77}Se NMR absorptions observed for series **1**−**3** and **4**−**6** suggested that the strength of Se⋯X interaction decreases in the order of Se⋯F > Se⋯Cl > Se⋯Br. The quantum chemical calculations at the B3LYP/631H level using the polarizable continuum model (PCM) revealed that the most stable conformer for **1**−**3** is the one with an intramolecular short Se⋯X atomic contact in $CHCl_3$ ($\epsilon = 4.9$) and also that the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction ($E_{Se\cdots X}$) can reasonably explain the order of strength for the Se⋯X interactions. On the other hand, the ^{77}Se NMR absorptions observed for series **7**−**9** did not shift significantly from the reference compounds ($C_6H_5CH_2$SeY), indicating the absence of the Se⋯X interaction for **7**−**9** presumably due to attenuation of basicity for the halogen atom that is substituted directly to the aromatic ring. These observations suggested that the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction is a dominant factor for formation of weak Se⋯X interactions. Electron correlation was also suggested to be important for the stability.

Introduction

The high reactivity of organoselenium reagents allows the insertion of various functional groups to organic compounds under mild conditions with high stereoselectivity. For this reason, organoselenium chemistry has been widely applied in the synthesis of various organic compounds.[1] In view of the molecular design of useful selenium reagents, it is of valuable importance to investigate weak nonbonded interactions involving a divalent selenium (Se) atom because the interactions should play a role in the molecular recognition to a substrate as well as in the molecular conformation. Nonbonded interactions involving a divalent Se have also attracted much attention not only because they have been successfully applied to asymmetric synthesis[2] but also because they may play an important role in the catalytic cycle of glutathione peroxidase mimics.[3] Moreover, the nonbonded interactions would serve as potential analogues to those involving a divalent sulfur (S) atom, which exists commonly in biomolecules.[4]

We have recently succeeded in evaluation of nonbonded interactions between Se and second-row atoms (N, O, and

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[1] (a) *Organoselenium Chemistry: A Practical Approach*; Back, T. G., Ed.; Oxford University Press: New York, 1999. (b) *Organoselenium Chemistry: Modern Developments in Organic Synthesis*; Wirth, T., Ed.; Springer-Verlag: Berlin, 2000.

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10.1021/jo048436a CCC: $30.25

CHART 1

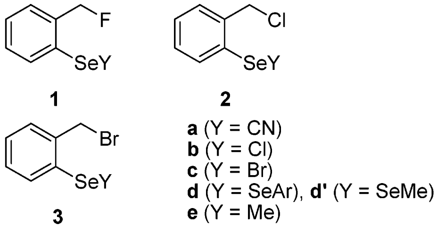
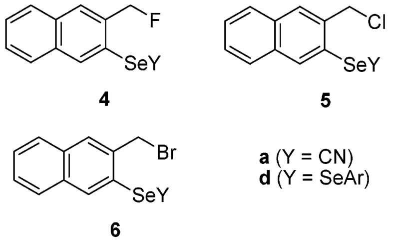


CHART 2

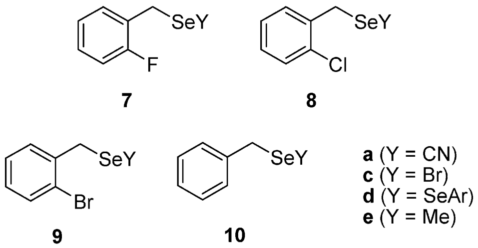


F).[5−7] It was found that the strength of the interactions decreases in the order of Se···N > Se···O > Se···F as the electron-donating ability of the second-row atom decreases. However, the general properties of the nonbonded interactions between Se and heavy-row atoms have not been well elucidated though such interactions may be important for the excellent high asymmetric induction reported by Tiecco and co-workers:[8] The chiral selenium reagent, which may possibly have an intramolecular Se···S interaction, exhibited much better asymmetric yields than the corresponding chiral selenium reagent with an Se···O interaction. In our previous paper,[9] heavy-row atom effects on the strength of nonbonded Se···X (X = F, Cl, and Br) interactions were studied for the first time by use of series of 2-(halomethyl)benzeneselenenyl derivatives [2-($\mathrm{CH_2X}$)$\mathrm{C_6H_4SeY}$, **1**−**3**] (Chart 1). The Se···X interactions were suggested to attenuate as the X atom goes down in the periodic table. Herein, we present the full account on the Se···halogen interactions, including extended studies by use of the naphthalene analogues [3-($\mathrm{CH_2X}$)-2-$\mathrm{C_{10}H_6SeY}$, **4**−**6**] (Chart 2) and (2-halophenyl)methaneselenenyl derivatives [2-$\mathrm{XC_6H_4CH_2SeY}$, **7**−**9**] (Chart 3), which have the halogen atom (X) and the selenenyl group (SeY) interchanged in the parent compounds **1**−**3**.

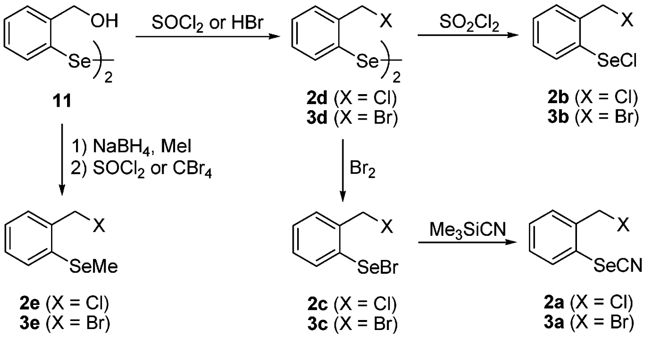
Results and Discussion

Synthesis of Model Compounds. 2-(Fluoromethyl)benzeneselenenyl derivatives (**1a**−**e**) have been fully characterized in the literature.[7] The other two series of 2-(halomethyl)benzeneselenenyl derivatives (**2a**−**e** and **3a**−**e**) were synthesized according to Scheme 1. Diselenide **2d** was synthesized from bis[2-(hydroxymethyl)phenyl] diselenide (**11**) by use of thionyl chloride. Similarly, diselnide **3d** was prepared by the reaction of **11** with hydrobromic acid in acetic acid at 90 °C. Obtained **2d** and **3d** were then converted to selenenyl chlorides **2b** and **3b**, selenenyl bromides **2c** and **3c**, and selenenyl cyanides **2a** and **3a**, respectively, by common procedures.[5−7] Methyl selenides **2e** and **3e** were synthesized from **11** by reductive methylation of the diselenide linkage followed by halogenation of the hydroxyl group. All compounds were identified with ^{1}H, ^{13}C, and ^{77}Se NMR spectra, although selenenyl chloride **3b** was contaminated with a small amount of **2b** and selenenyl chloride **2b** slowly decomposed to diselenide **2d** at room temperature. For these selenenyl chlorides, further purification was not performed because of the instability.

CHART 3



SCHEME 1



To investigate Se···X (X = F, Cl, and Br) interactions in other series of compounds, 3-halomethyl-2-naphthaleneselenenyl derivatives (**4a**,**d**, **5a**,**d**, and **6a**,**d**) were also synthesized from bis(3-hydroxymethy-2-naphthyl) diselenides (**14**), which was prepared from methyl 3-amino-2-naphthoate (**12**), according to the similar procedures to the syntheses of **1a**,**d**, **2a**,**d**, and **3a**,**d** (Scheme 2). The X-ray crystal structure of **6d** have revealed that the intramolecular nonbonded Se···Br interaction really exists though it should be very weak [$r_{\mathrm{Se\cdots Br}} = 3.7356(4)$ Å].[9]

The common procedures were also employed for the syntheses of (2-halophenyl)methaneselenenyl derivatives (**7**−**9**), which have X and SeY groups at the mutually opposite sites upon the benzyl fragment of **1**−**3**, and the reference compounds **10** (Scheme 3). In these compounds, the basicity of the halogen atom (X) is largely decreased, compared with that in the parent compounds **1**−**3**, due to the resonance effect between the lone pair of the halogen atom (n_X) and the aromatic π electrons. Compounds **7**−**10** were identified with ^{1}H, ^{13}C, and ^{77}Se NMR spectra, although phenylmethaneselenenyl bromide (**10c**)

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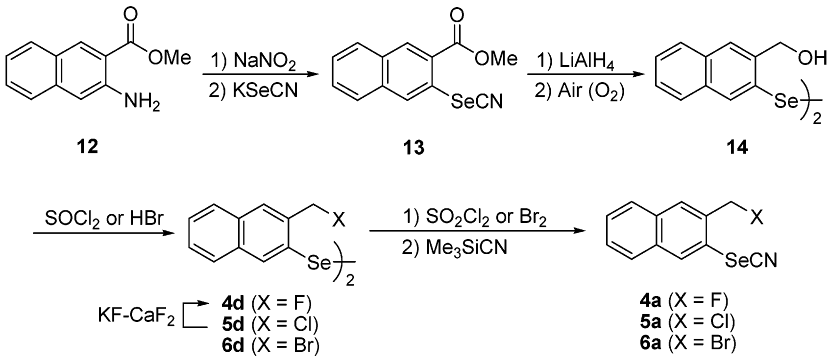
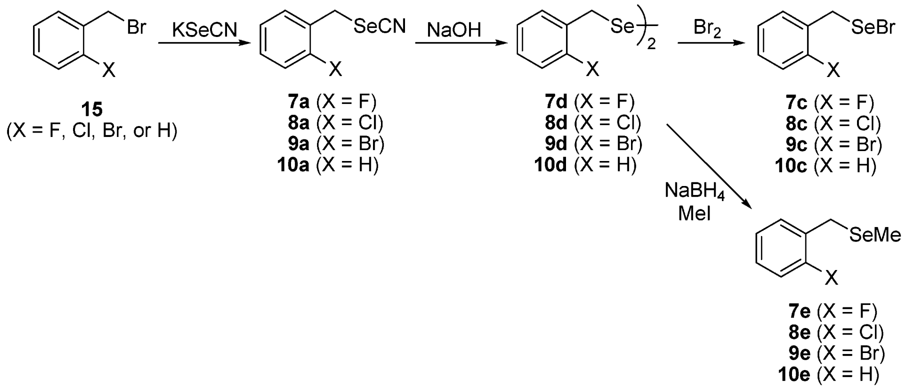
SCHEME 2



SCHEME 3



could not be obtained as a pure product probably due to the high reactivity. Selenenyl chloride derivatives (Y = Cl) were not synthesized because they are highly labile and could not be obtained as pure materials.

^{77}Se NMR Chemical Shifts. It is well established that ^{77}Se NMR chemical shifts (δ_{Se}) are sensitive to the environment around the Se atom.[10] We recently demonstrated that the magnitude of the downfield shift of ^{77}Se NMR can be used as a quantitative experimental probe for the strength of nonbonded Se···O interactions.[11] Therefore, the δ_{Se} values observed for the model compounds were analyzed to characterize the nature of Se···halogen interactions.

The ^{77}Se NMR chemical shifts (δ_{Se}) observed for a benzene series **1**–**3** and a naphthalene series **4**–**6** are listed in Table 1 along with the values of $J_{Se\cdots F}$ coupling constants observed for fluorine compounds **1a**–**e** and **4a**,**d**. As reported previously,[7] the strength of the Se···F interaction for **1a** and **1e** is 1.23 and 0.85 kcal/mol, respectively, in CD_2Cl_2, and the observation of the *J* coupling between Se and F atoms is a direct experimental evidence for the presence of an intramolecular Se···F interaction for **1a**–**e**. Comparison of the $J_{Se\cdots F}$ values suggested that the strength of the Se···F interaction decreases in the order **a** (Y = CN) > **b** (Y = Cl) > **c** (Y = Br) > **d** (Y = SeAr) > **e** (*Y* = Me).

When the ^{77}Se NMR chemical shifts (δ_{Se}) for **1a**–**e** (X = F) are compared with those for **2a**–**e** (X = Cl) and **3a**–**e** (X = Br), it is clear that the ^{77}Se NMR absorptions (δ_{Se}) shift toward upfield ($\Delta\delta_{Se} < 0$) with the periodic row of halogen atom X going down, although those for compounds **d** (Y = SeAr) and **e** (*Y* = Me) remain approximately in the same position. Since the downfield shift of δ_{Se} can be a good index for the strength of nonbonded Se···O interactions,[11] the observed tendency of δ_{Se} suggested that the strength of the Se···X interactions for **a**–**c** decreases in the order of Se···F > Se···Cl > Se···Br, while those for **d** and **e** would not change significantly by the periodic row of X.

TABLE 1. ^{77}Se NMR Data (δ_{Se} and $J_{Se\cdots F}$) for 2-(CH_2X)C_6H_4SeY (1–3) and 3-(CH_2X)-2-$C_{10}H_6$SeY (4–6)[a]

	X = F			X = Cl		X = Br	
Y	compd	δ_{Se}	$J_{Se\cdots F}$ (Hz)	compd	δ_{Se}	compd	δ_{Se}
CN	**1a**	288.6[b]	84.2[b]	**2a**	284.1	**3a**	280.0
	4a	289.6	80.4	**5a**	285.6	**6a**	282.1
Cl	**1b**	978.5[b]	80.1[b]	**2b**	966.5	**3b**	956.1
Br	**1c**	801.0[b]	43.1[b]	**2c**	798.2	**3c**	788.6
SeAr	**1d**	437.3[b]	23.6[b]	**2d**	442.2[c]	**3d**	437.0
	4d	454.0	19.0	**5d**	460.6	**6d**	459.6
Me	**1e**	161.1[b]	22.7[b]	**2e**	165.1	**3e**	165.2

[a] ^{77}Se NMR spectra were measured at 95.35 MHz in $CDCl_3$ at 298 K with Me_2Se as an external standard. [b] The data from ref 7. [c] The data from ref 5a.

Almost the same argument can be applied to naphthalene analogues **4**–**6**. Thus, the presence of the similar Se···X (X = F, Cl, and Br) interactions was characterized for **4**–**6**.

The above considerations were reasonably supported, at least in part, when the δ_{Se} values for series **1**–**3** were compared with those for the corresponding reference compounds (i.e., 2-MeC_6H_4SeY; Y = CN, Cl, Br, SeAr,

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(10) Luthra, N. P.; Odom, J. D. In *The Chemistry of Organic Selenium and Tellurium Compounds Volume 1*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: Chichester, 1986; Chapter 6, pp 189–241.

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TABLE 2. ^{77}**Se NMR Data (**δ_{Se} **and** $J_{Se\cdots F}$**) for 2-**$XC_6H_4CH_2SeY$ **(7−10)**[a]

		7 (X = F)		**8** (X = Cl)	**9** (X = Br)	**10** (X = H)
	Y	δ_{Se}	$J_{Se\cdots F}$ (Hz)	δ_{Se}	δ_{Se}	δ_{Se}
a	CN	292.9 (295.7)[b]	8.6	287.7 (284.7)[b]	288.5 (285.0)[b]	286.0 (291)[c]
c	Br	1166.7	*d*	1166.6	1166.1	1167.4
d	SeAr	406.1	*d*	400.1 (395.1)[b]	402.3 (395.9)[b]	405.7 (401.4)[b]
e	Me	174.3	*d*	168.1	168.6	172.8 (173)[c]

[a] ^{77}Se NMR spectra were measured at 95.35 MHz in $CDCl_3$ at 298 K with Me_2Se as an external standard. [b] The data from ref 12. [c] The data from ref 13. [d] The nuclear spin coupling was not observed between ^{77}Se and ^{19}F.

and Me). Although only one δ_{Se} value was reported in the literature for these references ($\delta_{Se} = 162$ for 2-MeC_6H_4SeMe[10]), those for others could be roughly estimated by the following procedures. First, the δ_{Se} value for C_6H_5SeMe, which does not have a methyl substituent at the ortho position, was 202.[10] Second, comparison of the δ_{Se} value with that for 2-MeC_6H_4SeMe ($\delta_{Se} = 162$) led to the assumption that the 2-Me group causes about 40 ppm upfield shift of ^{77}Se NMR. Third, application of the same substituent effect allowed estimation of the δ_{Se} values for 2-MeC_6H_4SeY (Y = CN, Cl, Br, and SeAr) as 282, 1002, 829, and 424, respectively, by using the δ_{Se} values of 322, 1042, 869, and 464 reported for nonsubstituted C_6H_5SeY (Y = CN, Cl, Br, and SeAr).[10] Thus, for the cases of selenocyanates (**a**, Y = CN) and diselenides (**d**, Y = SeAr), the presence of weak intramolecular Se···X interactions for series **1**−**3** is supported by the downfield shifts of ^{77}Se NMR with respect to the reference compounds, i.e., 2-MeC_6H_4SeCN [$\delta_{Se} = 282$ (estimated)] and 2-$MeC_6H_4SeSeC_6H_4$(2-Me) [$\delta_{Se} = 424$ (estimated)]. For methyl selenides (**e**, Y = Me), the δ_{Se} values for **1**−**3e** are not essentially different from that for the reference, i.e., 2-MeC_6H_4SeMe ($\delta_{Se} = 162$). This suggests that the Se···X interactions must be very weak. On the other hand, for selenenyl chlorides (**b**, Y = Cl) and selenenyl bromides (**c**, Y = Br), the ^{77}Se NMR absorptions of **1**−**3** appear in upfield with respect to the reference compounds, i.e., 2-MeC_6H_4SeCl [$\delta_{Se} = 1002$ (estimated)] and 2-MeC_6H_4SeBr [$\delta_{Se} = 829$ (estimated)]. The reasons for the upfield shifts of ^{77}Se NMR, which may be inconsistent with the presence of Se···X interactions, are not clear. However, we tentatively assume that the upfield shifts are due to the effect of electron correlation, which should be small for the reference compounds but would be large for **1**−**3**. The significance of electron correlation for formation of weak Se···halogen interactions is discussed later.

Table 2 lists the ^{77}Se NMR data (δ_{Se} and $J_{Se\cdots F}$) observed for **7**−**10** along with the literature values[12,13] in parentheses. The values of δ_{Se} for **7**−**9** were almost unchanged from the reference compounds **10** except for **7a**, suggesting that the Se···X interactions are not present in this type of selenium compounds. Only for the case of **7a**, a significant downfield shift of δ_{Se} ($\Delta\delta_{Se} = 6.9$ ppm) and a small $J_{Se\cdots F}$ coupling ($J_{Se\cdots F} = 8.6$ Hz) were observed. This suggested the presence of weak Se···F interaction for **7a** in solution. However, the $J_{Se\cdots F}$ coupling could not be detected for **7c**−**e**.

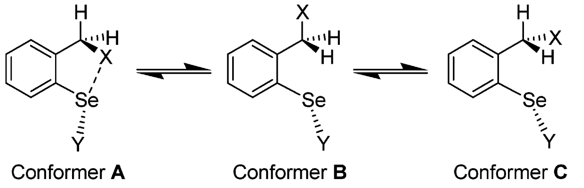

FIGURE 1. Rapid equilibrium between three possible conformers **A**, **B**, and **C** for **1**−**3**.

Possible Conformers in Solution. Under the conditions of NMR measurements (in $CDCl_3$ at 298 K), **1**−**3** must attain an equilibrium among more than two conformers (Figure 1): Conformer **A** has close atomic contact between Se and X with an almost linear X···Se−Y atomic alignment, conformer **B** has the C−X bond away from the Se−Y bond, and conformer **C** has both the C−X and Se−Y bonds titled out of the aromatic plane to the same direction. The values of δ_{Se} observed for **1**−**3**, therefore, represent the weighted average of the δ_{Se} values over these conformers: they should be affected by both the relative stability of Conformer **A** to the other conformers (ΔE_A) and the degree of the nonbonded Se···X contact [i.e., $r_{rel} = r_{Se\cdots X}/(vdw_{Se} + vdw_X)$, where $r_{Se\cdots X}$ is a nonbonded distance between Se and X atoms and vdw_X is the van der Waals radius of X].

QC Calculations and the NBO Analysis. To interpret the observed ^{77}Se NMR data, quantum chemical (QC) calculations were performed on **1**−**3** by using the Gaussian 98 program package.[14] The three possible conformers (conformers **A**, **B**, and **C**) were reasonably located for each model compound. For diselenide **d** (Y = SeAr), the Ar group was simplified to a Me group to save on computation time. As illustrated in Figure 2, the two possible subconformers were further considered for conformer **A** of **d′** (Y = SeMe): One has the SeMe group tilted inward with respect to the aromatic plane (endo) and the other has the SeMe group tilted outward (exo). Similarly, endo and exo subconformers were defined for conformers **B** and **C**. Relative energies (in kcal/mol) of all possible conformers obtained for **1**−**3** both in vacuo and in $CHCl_3$ ($\epsilon = 4.9$) are listed in Table 3.

At the B3LYP/631H level (see the Experimental Section for this abbreviation) in vacuo, conformer **A** with an intramolecular Se···X interaction was found to be energetically lowest except for **1d′**, **1e**, **2e**, and **3e**: conformer **B**-*exo* is the most stable conformer for diselenide **1d′** ($\Delta E_A = +0.17$ kcal/mol), and conformer **C** is a global energy minimum for methyl selenides **1e**, **2e**, and **3e** ($\Delta E_A = +0.03$, +0.30, and +0.36 kcal/mol, respectively).

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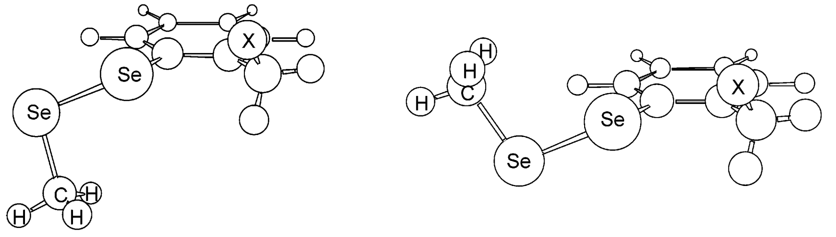

(a) Conformer **A-*endo***　　(b) Conformer **A-*exo***

FIGURE 2. Two possible structures of conformer **A** for diselenides **1**−**3d′** (Y = SeMe): (a) endo conformer, (b) exo conformer.

TABLE 3. Relative Energies of Three Possible Conformers Calculated for 1−3[a]

			1 (X = F)		**2** (X = Cl)		**3** (X = Br)	
	Y	conformer	vacuo[b]	$CHCl_3$[c]	vacuo[b]	$CHCl_3$[c]	vacuo[b]	$CHCl_3$[c]
a	CN	**A**	0.00	0.00	0.00	0.00	0.00	0.00
		B	1.21	1.44	1.41	1.80	*d*	*d*
		C	3.66	2.36	2.01	1.09	1.66	1.05
b	Cl	**A**	0.00	0.00	0.00	0.00	0.00	0.00
		B	0.51	0.83	0.49	1.11	*d*	*d*
		C	3.70	2.96	1.16	1.04	1.19	1.22
c	Br	**A**	0.00	0.00	0.00	0.00	0.00	0.00
		B	1.14	1.45	*d*	*d*	*d*	*d*
		C	2.91	2.16	1.13	1.03	1.13	1.37
d′	SeMe	**A-*endo***	0.17	0.00	0.00	0.00	0.00	0.00
		A-*exo*	0.62	0.36	0.44	1.10	0.28	0.03
		B-*endo*	0.82	1.14	*d*	*d*	*d*	*d*
		B-*exo*	0.00	0.39	0.67	2.08	*d*	*d*
		C-*endo*	0.74	0.74	0.25	1.61	0.44	2.74
		C-*exo*	1.85	1.44	0.83	1.72	0.85	2.69
e	Me	**A**	0.03	0.00	0.30	0.00	0.36	0.00
		B	0.23	0.63	*d*	*d*	*d*	*d*
		C	0.00	0.48	0.00	0.20	0.00	0.28

[a] The values are given in kcal/mol. [b] The relative energies with unscaled zero-point energies (ZPE) calculated in vacuo at the B3LYP/631H//B3LYP/631H level. [c] The relative energies calculated in $CHCl_3$ at the B3LYP/631H (SCRF = PCM, solvent = $CHCl_3$)//B3LYP/631H level with the same ZPE as in vacuo. [d] Optimized structures could not be located.

The unique character of the methyl selenides may be due to intramolecular C−H···Se and C−H···X hydrogen bonds as discussed previously.[7b] In contrast, it was found that conformer **A** is always most stable at the B3LYP/631H (SCRF = PCM) level using Tomasi's polarizable continuum model (PCM)[15] in $CHCl_3$ solution (ϵ = 4.9), suggesting that conformer **A** must be a major conformer for all compounds under the conditions of NMR measurements. Thus, the δ_{Se} values for **1**−**3** (Table 1) would be mostly reflected by the degree of the nonbonded Se···X contact (r_{rel}), i.e., the strengths of the Se···X interactions.

Structural parameters obtained for conformer **A** of model compounds **1**−**3** are summarized in Table 4. It is obvious that the smaller the relative nonbonded Se···X atomic distance to the sum of the van der Waals radii (r_{rel}), the more linear the nonbonded X···Se−Y angle ($\theta_{\mathrm{X\cdots Se-Y}}$) and the smaller the dihedral angle between the aromatic plane and the CH_2−X bond ($\omega_{\mathrm{Ar-C}}$). Although the extent of the atomic contact was only marginal especially for **2a**−**e** and **3a**−**e**, the tendency suggested the presence of linear and weak X···Se−Y interactions. Indeed, the X-ray structure of **6d** has shown a small but distinct Se···Br atomic contact as described earlier.[9] It is also important to note that the r_{rel} values obtained at the Hartree−Fock level were significantly larger than those obtained at the B3LYP level. This strongly suggests that the electron correlation plays significant roles in the stability of Se···X interactions.

TABLE 4. Selected Structural Parameters and $n_X \rightarrow \sigma^*_{\mathrm{SeY}}$ Orbital Interaction Energies ($E_{\mathrm{Se\cdots X}}$) Obtained for Conformer A's of 1−3[a]

X	compd	Y	$r_{\mathrm{Se\cdots X}}$[b] (Å)	r_{rel}[c]	$\theta_{\mathrm{X\cdots Se-Y}}$[d] (deg)	$\omega_{\mathrm{Ar-C}}$[e] (deg)	$E_{\mathrm{Se\cdots X}}$[f] (kcal/mol)
F	**1a**	CN	2.79	0.83	168.8	49.4	4.33
	1b	Cl	2.69	0.80	170.7	47.0	7.03
	1c	Br	2.76	0.82	168.6	51.2	5.71
	1d′	SeMe[g]	2.94	0.87	171.4	55.9	2.68
	1e	Me	2.99	0.89	169.6	58.1	1.89
Cl	**2a**	CN	3.48	0.95	165.9	72.9	1.96
	2b	Cl	3.86	1.06	132.2	85.4	0.27
	2c	Br	3.89	1.07	129.8	87.1	0.18
	2d′	SeMe[g]	3.65	1.00	165.1	79.1	1.00
	2e	Me	3.68	1.01	168.7	80.2	0.62
Br	**3a**	CN	3.65	0.97	166.3	76.6	1.82
	3b	Cl	4.13	1.10	122.7	92.6	0.12
	3c	Br	4.09	1.09	125.1	91.2	0.16
	3d′	SeMe[g]	3.80	1.01	165.7	81.7	1.03
	3e	Me	3.85	1.03	170.0	83.7	0.67

[a] The geometry optimization and NBO analysis were carried out at the B3LYP/631H level. See Figure 1 for the definition of conformer **A**. [b] Nonbonded Se···X atomic distances. [c] Nonbonded Se···X atomic distances normalized by the sum of the van der Waals radii ($\mathrm{vdw_{Se}} + \mathrm{vdw_X}$): Se···F 3.37 Å; Se···Cl 3.65 Å; Se···Br 3.75 Å. [d] The X···Se−Y angles. [e] The dihedral angles along the Ar−CH_2X bond. [f] The second-order perturbation energies due to the $n_X \rightarrow \sigma^*_{\mathrm{SeY}}$ orbital interaction. [g] Data for the endo conformer.

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To evaluate the magnitude of the Se⋯X orbital interaction, natural bond orbital (NBO) analysis[16] was performed for conformers **A**'s. The calculated NBO second-order perturbation energies due to the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction ($E_{Se\cdots X}$) are listed in the last column of Table 4. The $E_{Se\cdots X}$ values decreased in the order of **1** > **2** ≈ **3** for all substituents Y. The trend is not only in accord with the tendency of the structural parameters (r_{rel}, $\theta_{X\cdots Se-Y}$, and ω_{Ar-C}) but also consistent with the tendency of ^{77}Se NMR chemical shifts observed for **1**−**3**, except for the cases of **d** and **e**. As to the δ_{Se} values for **d** and **e**, contributions from the other conformers than Conformer **A** may be significant (Table 3).

The Nature of Se⋯X Interactions. According to the NMR analysis and QC calculations, it is proved that the linear (or hypervalent) Se⋯halogen interactions are very weak in general, but there is the distinct tendency that the interaction gets weaker as the interacting halogen atom (X) gets heavier; i.e., Se⋯F > Se⋯Cl > Se⋯Br. The tendency seems to be simply explained by the electrostatic character of the Se⋯X interactions at a glance. However, more elaborate considerations should be required for understanding the nature of the interactions.

The electrostatic hypothesis should not work for several reasons. First, even for the case of Se⋯F interaction characterized for **1a**−**e**,[7] it has been clearly demonstrated on the basis of the observed marginal polar solvent effects that the major stabilization factor is not the electrostatic interaction between a positively charged Se and a negatively charged F atom but the $n_X \rightarrow \sigma^*_{Se-F}$ orbital interaction. Second, the relative stability of conformer **A** (ΔE_A), which has an intramolecular Se⋯X interaction, with respect to the other conformers increases in CHCl$_3$ from that in vacuo (see Table 3). This is opposed to the electrostatic hypothesis because conformer **A** must be destabilized in CHCl$_3$ if the electrostatic character is important. Third, the δ_{Se} values for **7**−**9** are almost unchanged from the reference compounds **10**, suggesting that the Se⋯X interactions are not present for the model compounds that have the SeY and X groups interchanged upon the benzyl fragment of **1**−**3**. Since the atomic charges of the Se and X atoms should not change largely by the replacement, contribution from the other factors than the electrostatic one is strongly suggested to the stability of the Se⋯X interactions.

On the other hand, the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction can reasonably explain the tendency of strength for the Se⋯X interactions. It has recently been demonstrated that the basicity of organic halides decreases as the X goes from F to Br.[17] The data of $E_{Se\cdots X}$ listed in Table 4 are in accord with the order of the basicity. We suggest that the basicity of the heavier halogen atom is reduced by the larger exchange repulsions between the lone pairs of the Se atom and those remained on the halogen atom. This would result in the weaker $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction although the energy level of the n_X orbital is higher for the heavier atom. In addition, absence of Se⋯X interactions for **7**−**9**, whose halogen atom possesses significantly reduced basicity due to the resonance with the benzene ring, also supports importance of the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction.

It should be noted that the effect of electron correlation is also important for the stability of Se⋯halogen interactions because the nonbonded Se⋯F[7b] and Se⋯O[6b] atomic distances were significantly longer at the Hartree−Fock level which does not include the effect of electron correlation sufficiently. On the other hand, the effect of structural constraints (e.g., the difference in the C−X bond lengths) would be small because the QC calculations at B3LYP/631H level revealed that the values of r_{rel} for the bimolecular complex between CH$_3$X and PhSeCl were 0.84, 0.94, and 0.95 for the CH$_3$F, CH$_3$Cl, and CH$_3$Br complexes, respectively,[9] reproducing the tendency of the r_{rel} values calculated for **1**−**3** (see Table 4).

Conclusions

The nature of nonbonded Se⋯halogen interactions were investigated by using three types of model compounds: 2-(CH$_2$X)C$_6$H$_4$SeY (**1**−**3**), 2-(CH$_2$X)C$_{10}$H$_6$SeY (**4**−**6**), and 2-XC$_6$H$_4$CH$_2$SeY (**6**−**8**). The ^{77}Se NMR analyses and the theoretical calculations revealed the following points.

1. On the basis of the ^{77}Se NMR analysis of model compounds **1**−**3**, the strength of the Se⋯X interactions decreases in the order of Se⋯F > Se⋯Cl > Se⋯Br.
2. The similar Se⋯X interactions can be characterized for **4**−**6** by comparison of the ^{77}Se NMR chemical shifts.
3. QC calculations of **1**−**3** at the B3LYP/631H level using the polarizable continuum model (PCM) in CHCl$_3$ solution (ϵ = 4.9) suggested that conformer **A** with an intramolecular Se⋯X interaction is the most stable conformer in the solutions.
4. The order of the strength, i.e., Se⋯F > Se⋯Cl > Se⋯Br, is consistent with the NBO second-order perturbation energies due to the $n_X \rightarrow \sigma^*_{Se-Y}$ orbital interaction ($E_{Se\cdots X}$) calculated for **1**−**3**.
5. With much lower halogen basicity, Se⋯X interactions do not exist for **7**−**9**, except for **7a**.
6. Electron correlation should also play an important role in the weak nonbonded Se⋯X interactions.

According to these considerations, it can be concluded that the strength of Se⋯X interactions decreases as the X atom goes down in the periodic table. The heavy-row atom effect would be mainly attributed to the decrease of basicity for heavier halogen atoms. The-heavier-the-weaker rule found for Se⋯halogen interactions will be useful not only for molecular design of various types of organoselenium compounds but also for understanding other types of noncovalent interactions, in which a halogen atom is involved as an electron donating group.

Experimental Section

General experimental methods and synthetic procedures for **1**−**10** are provided in the Supporting Information.

Calculation and NBO Analysis. All computational calculations were carried out by using the Gaussian 98 program package.[14] Geometries were fully optimized with Beck's three-parameter hybrid functional method (B3LYP).[20] Huzinaga's

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43321/4321/311 basis sets[21] were used for Se and Br, and standard 6-31G(d,p) basis sets were employed for other atoms. Combination of these basis sets is denoted here as 631H. Vibrational frequencies and zero-point energies (ZPE) were also calculated. All structures were characterized as potential energy minimums at the B3LYP/631H level by verifying that all vibrational frequencies are real. Single-point energies with ZPE were calculated at the same level in vacuo and at the B3LYP/631H (SCRF = PCM) level using Tomasi's polarizable continuum model (PCM)[15] in the $CHCl_3$ solution ($\epsilon = 4.9$). To evaluate the orbital interaction energy between the halogen lone pair (n_X) and the selenium antibonding orbital (σ^*_{SeY}), NBO second order-perturbation analysis[16] was performed at the B3LYP/631H level by applying the value of 0.05 for the *eval* parameter.

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Supporting Information Available: General experimental methods, synthetic procedures for **1**−**10**, copies of ^{1}H, ^{13}C, and ^{77}Se NMR spectra for **2a**−**c**,**e**, **3a**−**c**,**e**, **5a**, **6a**, **7a**,**c**,**e**, **8c**,**e**, **9c**,**e**, and **10c**,**e** and Cartesian coordinates for conformers **A**−**C** of **1a**−**e**, **2a**−**e**, and **3a**−**e** and those for the bimolecular complexes of PhSeCl with CH_3F, CH_3Cl, or CH_3Br. This material is available free of charge via the Internet at http://pubs.acs.org.

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