Heavy-Row Atom Effects on the Strength of the Weak Nonbonded Interactions between Divalent Selenium and Halogen Atoms

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The ^{77}Se NMR chemical shifts observed for 2-selenobenzyl halide derivatives and the density functional theoretical calculation revealed that the strength of intramolecular nonbonded interactions between a divalent selenium and halogen atoms decreases in the order, $\mathrm{Se\cdots F > Se\cdots Cl \geq Se\cdots Br}$.

Nonbonded interactions involving a divalent selenium (Se)[1] present unique chemical reactivity and biological activity of organoselenium compounds. Our previous studies on intramolecular Se···N,[2] Se···O,[3] and Se···F[4] interactions demonstrated that the interactions become weaker as the electron-donating ability of the interacting heteroatom (X) decreases (i.e., $\mathrm{Se\cdots N > Se\cdots O > Se\cdots F}$) and that a donor-acceptor orbital interaction mechanism may be still predominant for the weakest Se···F interaction.[4b] T-shaped Cl–Se···Cl and Br–Se···Br interactions in the solid state were also characterized recently.[5] However, general properties of the nonbonded interactions between Se and heavy-row atoms have not been well elucidated. In this paper, we report the first systematic study of the heavy-row atom effects on the strength of nonbonded Se···X interactions by using a series of 2-selenobenzyl halide derivatives [2-$(CH_2X)C_6H_4SeY$, **1–3**].

The Se···F interactions of **1a–e** (X = F) have been unambiguously characterized previously.[4,6] In order to characterize similar nonbonded Se···Cl and Se···Br interactions, **2a–e** (X = Cl) and **3a–e** (X = Br) were synthesized.[7] The ^{77}Se NMR chemical shifts (δ_{Se}) observed for **1–3** are compared in Table 1.

It is clearly seen that the δ_{Se}'s for selenocyanates (**a**, Y = CN), selenenyl chlorides (**b**, Y = Cl), and selenenyl bromides (**c**, Y = Br), which have strong ability to accept an electron pair from a nearby atom, shifted toward upfield ($\Delta\delta_{Se} < 0$) with the periodic row of X going down, while those for diselenides (**d**, Y = SeAr) and methyl selenides (**e**, Y = Me), which have low ability to accept an electron pair, remained almost unchanged ($\Delta\delta_{Se} \approx 0$). Since a downfield shift of ^{77}Se NMR signal can be a good measure of the existence of nonbonded Se···X interactions,[2,8] the observed tendency suggested that the strength of the interactions for **a–c** decreases in the order, $\mathrm{Se\cdots F > Se\cdots Cl > Se\cdots Br}$, while that for **d** and **e** would not change significantly by halogens.

Table 1. ^{77}Se NMR chemical shifts (δ_{Se}) of 2-$(CH_2X)C_6H_4SeY$ (**1–3**)[a]

		1 (X = F)	**2** (X = Cl)		**3** (X = Br)	
	Y	δ_{Se}[b]	δ_{Se}	$(\Delta\delta_{Se})$[c]	δ_{Se}	$(\Delta\delta_{Se})$[c]
a	CN	288.6	284.1	(−4.5)	280.0	(−8.6)
b	Cl	978.5	966.5	(−12.0)	956.1	(−22.4)
c	Br	801.0	798.2	(−2.8)	788.6	(−12.4)
d	SeAr	437.3	442.2[d]	(+4.9)	437.0	(−0.3)
e	Me	161.1	165.1	(+4.0)	165.2	(+4.1)

[a]Measured at 95.35 MHz in $CDCl_3$ at 298 K with Me_2Se as an external standard. [b]The data from Ref. 4a. [c]^{77}Se NMR chemical shifts relative to **1**. [d]The data from Ref. 2a.

Under the conditions of NMR measurements (in $CDCl_3$ at 298 K), **1–3** may establish a rapid equilibrium among more than two conformers (Figure 1). Conformer **A** has X and Y substituents above and below the aromatic plane, respectively, with an intramolecular Se···X interaction. Conformer **B** has Y out of the aromatic plane. Conformer **C** has X and Y out of the plane to the same direction. The observed values of δ_{Se} represent weighted averages over these conformers, hence they must be reflected by both the importance of conformer **A** relative to the other conformers (ΔE_A) and the degree of the nonbonded Se···X contact. The latter can be inferred simply from the relative Se···X atomic distance ($r_{Se\cdots X}$) to the sum of the corresponding van der Waals radii ($vdw_{Se} + vdw_X$, where vdw_X means the van der Waals radius of the interacting atom X).

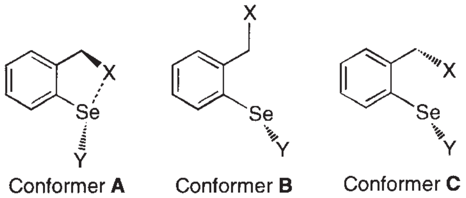

Figure 1. Three possible conformers of model compounds **1–3**.

All possible conformers were sought for **1–3** by quantum chemical (QC) calculations[9] applying the density functional theory [at the B3LYP/6-31G(d,p) level using Huzinaga's 43321/4321/311 basis sets[10] for Se and Br]. Table 2 summarizes the obtained values of ΔE_A and $r_{Se\cdots X}$. For most of model compounds, except for **1d′** and **1–3e**, conformer **A** was found to be most stable, suggesting that the values of δ_{Se} in $CDCl_3$ (Table 1) roughly represent those for conformer **A**. Significant stabilization of conformer **C** observed for **1–3e** (Y = Me) is due to the dual intramolecular C–H···Se[11] and C–H···X hydrogen bonds as discussed previously.[4b] The values of ΔE_A for **1–3** ranged from −1.66 to +0.36 kcal/mol, indicating that the strength of the Se···X interactions must be very weak in any cases. The values of r_{rel} [$= r_{Se\cdots X}/(vdw_{Se} + vdw_X)$] for conformer **A** increased with the periodic row of X going down. Thus, the strength of Se···X interactions would attenuate in the order, $\mathrm{Se\cdots F > Se\cdots Cl \geq Se\cdots Br}$. The tendency was consistent with the experimental observation that the δ_{Se}'s for **a–c** gradually shifted to upfield with this order, whereas similar tendency was not observed for **d** and **e**. This is probably because conformer **A**'s of **d** and **e** are not the major conformers in solution.

Since the Se···F interactions of **1a–e** are very weak (ca. 1 kcal/mol),[4b] the above result gave rise to a question as to the

Table 2. Relative energies of conformer **A** (ΔE_A) and the nonbonded Se···X atomic distances ($r_{Se\cdots X}$) calculated for 2-(CH_2X)C_6H_4SeY (**1–3**)[a]

		1 (X = F)			**2** (X = Cl)			**3** (X = Br)		
	Y	ΔE_A[b,c]	$r_{Se\cdots F}$[c,d]	r_{rel}[e]	ΔE_A[b]	$r_{Se\cdots Cl}$[d]	r_{rel}[e]	ΔE_A[b]	$r_{Se\cdots Br}$[d]	r_{rel}[e]
a	CN	−1.21 (B)	2.79	0.83	−1.41 (B)	3.48	0.95	−1.66 (C)	3.65	0.97
b	Cl	−0.51 (B)	2.69	0.80	−0.49 (B)	3.86	1.06	−1.19 (C)	4.13	1.10
c	Br	−1.14 (B)	2.76	0.82	−1.13 (C)	3.89	1.07	−1.13 (C)	4.09	1.09
d′	SeMe	+0.17 (B)	2.94	0.87	−0.25 (C)	0.65	1.00	−0.44 (C)	3.80	1.01
e	Me	+0.03 (C)	2.99	0.89	+0.30 (C)	3.68	1.01	+0.36 (C)	3.85	1.03

[a]Calculated at B3LYP/6-31G(d,p)//B3LYP/6-31G(d,p) using Huzinaga's 43321/4321/311 basis sets for Se and Br. [b]Energies of conformer **A** relative to conformer **B** or **C** (shoen in parentheses) corrected with zero-point energies. The more stable conformer was chosen as the standard. The values are give in kcal/mol. [c]The data from Ref. 4b. [d]Nonbonded atomic distances in Å for conformer **A**. [e]Nonbonded atomic distances for conformer **A** normalized by the sum of the van der Waals radii ($vdw_{Se} + vdw_X$); 3.37 Å for Se···F, 3.65 Å for Se···Cl and 3.75 Å for Se···Br (Ref. 13).

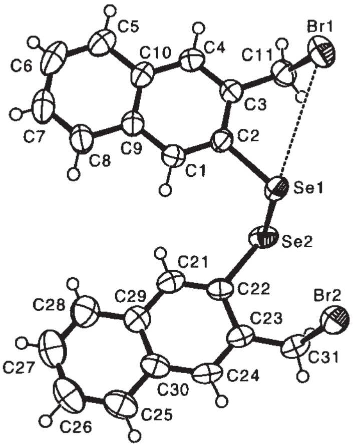

Figure 2. Molucular structure of **4** determined by X-ray analysis.

existence of nonbonded Se···Cl and Se···Br interactions for **2a–e** and **3a–e**. We, therefore, synthesized bis[3-(bromomethyl)-2-naphthyl] diselenide (**4**)[12] as an analogue of **3d**. The molecular structure determined by X-ray analysis is shown in Figure 2. It is seen that each naphthyl moiety of **4** adopts a mutually different molecular structure corresponding to conformer **A** or **C** in the solid state. The result is consistent with the calculation result for **3d′** in that the conformers **A** and **C** are significantly more stable than the conformer **B**. The nonbonded Se1···Br1 atomic distance was 3.7356(4) Å, which is slightly shorter than the sum of the van der Waals radii (3.75 Å).[13] Thus, the intramolecular nonbonded Se···Br interaction may really exist for **3d**, although it should be very weak. QC calculations for **3d′** reasonably reproduced the molecular structure of **4** determined in the solid state: the value of $r_{Se\cdots X}$ calculated for the conformer **A** of **3d′** was 3.80 Å. The agreement supported accuracy of the calculation results.

There are some possible explanations for the observed attenuation of the strength of the Se···X interactions. First, the decrease of an electrostatic interaction between the nonbonded atoms (i.e., Se and X) might control the strength of the interaction. However, this may be unlikely since electrostatic nature would not be predominant even for the Se···F interactions of **1a–e** as previously suggested by the marginal polar solvent effects.[4b] Second, the order of the strength might be influenced by the structural constraints of the model compounds. In order to eliminate this possibility, similar QC calculations were performed on the bimolecular complexes of CH_3X with PhSeCl. The values of r_{rel} were 0.84, 0.94 and 0.95 for the CH_3F, CH_3Cl and CH_3Br complexes, respectively, which have a linear X···Se–Cl alignment perpendicular to the phenyl ring. The result suggests that the strength of Se···X interactions intrinsically decreases in the order, Se···F > Se···Cl ≥ Se···Br.[14] A reasonable explanation may be that the $n_X \rightarrow \sigma^*_{Se\text{–}Y}$ orbital interaction decreases as the X is going from F to Br since the basicity of organic halides decreases in the same order.[15] It should also be noted that the effect of electron correlation is of importance in the stability of Se···Cl and Se···Br interactions: the calculations at the Hartree-Fock level proved significant destabilization of conformer **A** relative to conformers **B** and **C**.

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7 **2d** was synthesized according to the literature method.[2a] **3d** was synthesized in 96% yield from bis[(2-hydroxymethyl)phenyl] diselenide[2a] by the treatment with 48% HBr in acetic acid at 90 °C. Other compounds were easily derived from **2d** and **3d** by applying common procedures.[2b,4b]
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12 **4** was synthesized in 20% yield from 3-amino-2-naphthoic acid by applying similar procedures to the synthesis of **3d**. Crystal data of **4**: $C_{22}H_{16}Br_2Se_2$, $M = 598.09$, triclinic, $a = 7.6446(3)$, $b = 9.0924(4)$, $c = 15.7055(6)$ Å, $\alpha = 104.256(1)$, $\beta = 97.872(1)$, $\gamma = 104.501(1)$, $V = 1001.12(7)$ Å^3, $T = 300$ K, space group P–1 (no. 2), $Z = 2$, μ(Mo-Kα) $= 7.688$ mm^{-1}, 13440 reflections measured, 4599 unique ($R_{int} = 0.0335$) which were used in all calculations. The final $wR(F^2)$ was 0.0663 (all data). Crystallographic data reported in this paper have been deposited with Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-182934.
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