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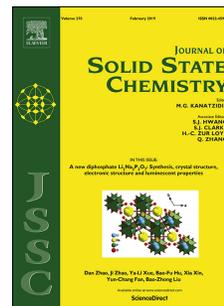
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The S ... Hal and Se ... Hal chalcogen bonding in a series of thiourea, selenourea and their derivatives

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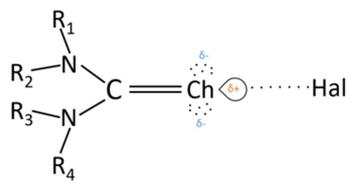
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Contribution of the authors:

Maria Chernysheva was responsible for synthesis and structural analysis of 1 and 2. She also wrote the initial manuscript.

Matti Haukka was planning the project, finalize the structure solutions of 1 and 2, act as supervisor and was responsible for revising the manuscript.

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where Ch = S or Se; Hal = Cl, Br, I; R = H or CH₃

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The S···Hal and Se···Hal Chalcogen Bonding in a Series of Thiourea, Selenourea and Their Derivatives

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Abstract

The chalcogen bonding (ChB) in a series of thiourea, selenourea and their derivatives has been investigated in the present paper. Thus, selenourea and dimethylselenourea undergo dimerization and trimerization processes in the presence of various halogen species (**1-5**). Selenourea and dimethylselenourea form trimers **3-4** in the presence of lighter halogens (chlorine and bromine) through Se···Se chalcogen bonding. When moving to heavier halogen (iodine), the dimers **1-2** are formed. Thiourea and its derivatives also tend to make very strong S···S bonds and form dimers in the case of lighter halogens chlorine and bromine (compounds **6-7**). However, the monomers separated by the iodine species are formed upon interaction with iodine *via* very strong S···I bonding (compounds **9-12**). Furthermore, among all the crystal structures of **1-12**, only iodine cations I⁺ in **10** and **12** act as electron density acceptors, while in the remaining compounds **1-9** and **11** halogen species act as electron density donors.

Keywords: chalcogen bonding, halogen, selenourea, thiourea.

1. Introduction

The term “chalcogen bonding” (ChB) is quite new and has appeared only in recent years, being known as “secondary bonding interactions” for a long time [1]. It is closely related to hydrogen bonding (HB) and halogen bonding (XB), and can be described by similar parameters as a noncovalent interaction between an electrophilic chalcogen atom Ch = O, S, Se, Te and a nucleophilic electron donor D (see Scheme 1). Chalcogen bonding has found applications in catalysis [2–4], drug design [5,6], crystal engineering [7,8] and synthesis [4].



Scheme 1. Schematic representation of chalcogen bonding: Ch = O, S, Se, Te; D = electron donor; R = C, N etc.

Analogous to halogen and pnictogen bonding, the formation of chalcogen bonds can be explained by a redistribution of the electron density on the covalently bound chalcogen atom, thus, making electrostatic potential on the latter to become anisotropic. This means that electron density decreases in the directions of the covalent bonds' elongations. This, in turn, may lead to the formation of a so-called "σ-hole", i.e. a region of positive electrostatic potential, and an "electron belt", i.e. a region of negative electrostatic potential, on the chalcogen atom Ch (Scheme 1) [4,9]. The size of the σ-hole is proportional to the polarizability of chalcogen and increases in a row $O < S < Se < Te$. The chalcogen atom can be considered as a ChB donor (electron density acceptor), when it participates in a chalcogen bonding *via* σ-hole. The R-Ch-D angle should be close to 180° , when a chalcogen atom acts as the ChB donor and accepts electron density from the electron donor D. On the contrary, the R-Ch-D angle should be close to 90° , when a chalcogen atom acts as the ChB acceptor by donating electron density to D.

Chalcogen bonding is not the matter of theoretical interest only. It reveals the real practical application. In particular, the formation of ChB upon *in vivo* complexation of thiourea and its derivatives with iodine results in antithyroid activity of these complexes [10–13]. We assume that similar compounds, able to form stronger chalcogen bonds, may reveal even higher antithyroid activity. We decided to choose a more polarizable chalcogen atom, i.e. selenium, and compare the behavior of thiourea/selenourea and their derivatives in the analogous chemical environment.

In the present work, we have obtained and studied the X-ray structures of selenourea iodide (**1**) and 1,1-dimethylselenourea triiodide (**2**). We have also compared the structures of **1** and **2** with the known structures of similar thiourea and selenourea derivatives: tris(selenourea) dichloride monohydrate (**3**) [14], tris(selenourea) dibromide monohydrate (**4**) [14], tris(selenourea) sulfate selenourea solvate dihydrate (**5**) [15], α,α'-dithiobis(formamidinium) dichloride (**6a** [16], **6b** [17]), bis(dithiodiformamidinium) aqua-pentachloro-rhenium(iv) trichloride dihydrate (**7**) [18], dithio-bis(1,1,3,3-tetramethylformamidinium) bis(tetraiodo-iron(iii)) (**8**) [19], (diaminomethylene)sulfonium triiodide (**9**) [20], bis(1,3-dimethyl-2-thiourea-S)iodonium tri-iodide (**10**) [13], 1,3-bis(thiourea)tri-iodonium thiourea-di-iodine di-iodine tri-iodide (**11**) [13] and bis(thiourea)iodine(i) iodide (**12**) [21], (Figure 1) found in literature. We have chosen iodine as an electron donor due to its higher polarizability in comparison with other halogens, availability and convenience of handling. Selenourea and 1,1-dimethylselenourea were chosen as electron acceptors, because they are commercially

available, easy to handle, and are promising agents in terms of possible antithyroid activity upon complexation with iodine. The studied compounds **1-12** are summarized in Figure 1.

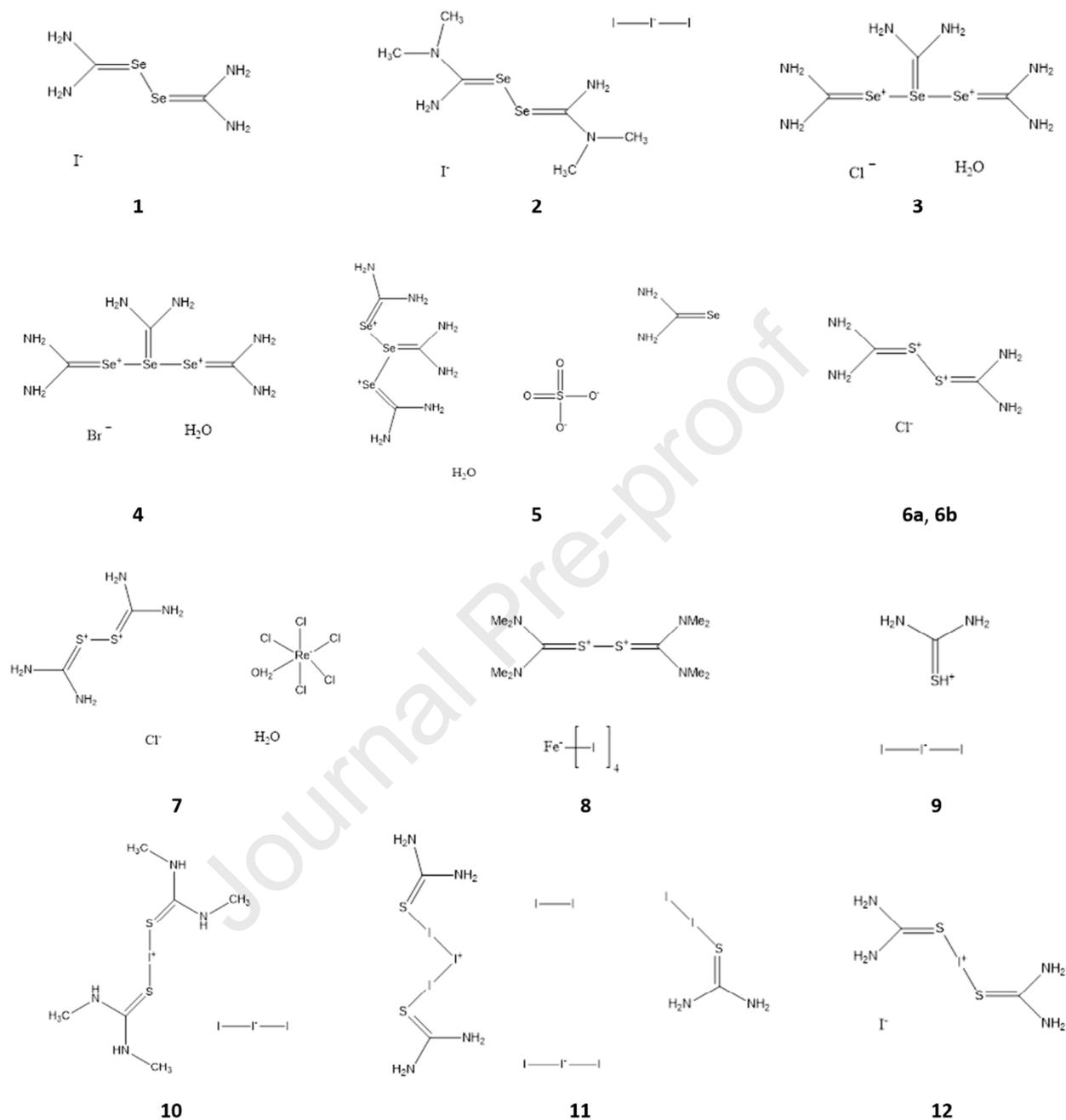


Figure 1. Schematic representation of the investigated molecules **1-12**.

2. Results and Discussion

In the structure of **1** (Figure 2) selenourea molecules form dimers with the $Se \cdots Se$ distance equal to 2.4001 (4) Å, which is much shorter than the sum of Bondi's van der Waals (vdW) radii being 3.80 Å [22]. This interaction can be considered to be strong and can be referred to as a covalent bond [23]. The selenourea fragments are shifted relative to each other with

a torsion angle C1-Se1-Se1-C1 being $87.4(1)^\circ$. There is also a chalcogen bonding between selenium and iodine (Se1-I1 = $3.3732(4)$ Å and C1-Se1-I1 = $77.15(8)^\circ$, Se1-I1* = $3.7386(4)$ Å and C1-Se1-I1* = $163.37(9)^\circ$). The sum of the corresponding van der Waals radii is reasonably bigger, being 3.88 Å [22]. The C1-Se1 bond length becomes somewhat longer upon dimerization ($1.939(3)$ Å for **1** vs. average 1.862 Å for selenourea [24][25]).

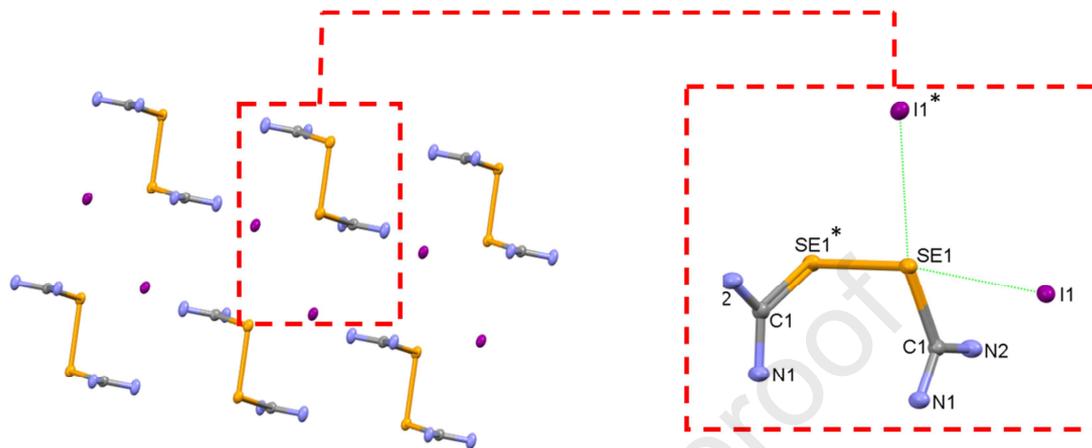


Figure 2. Crystal structure of **1**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles ($^\circ$): Se1-Se1*⁽ⁱ⁾ $2.4001(4)$, Se1-I1 $3.3732(4)$, Se1-I1*⁽ⁱⁱ⁾ $3.7386(4)$, C1-Se1-Se1*⁽ⁱ⁾ = C1⁽ⁱⁱ⁾-Se1*⁽ⁱ⁾-Se1 $94.16(9)$, C1-Se1-I1 $77.15(8)$, C1-Se1-I1*⁽ⁱ⁾ $163.37(9)$. Equivalent positions: (i) $1-x, y, 1/2-z$; (ii) $1.5-x, -1/2+y, 1/2-z$.

The molecules of 1,1-dimethylselenourea make similar dimers (**2**) upon complexation with iodine (see Figure 3). The Se1...Se2 distance is $2.313(1)$ Å, being much smaller than the sum of the corresponding van der Waals radii 3.80 Å, can, thus, be called a covalent bond. Same as in **1**, the C-Se bond length becomes longer upon dimerization (C1-Se1 = $1.945(7)$ Å and C4-Se2 = $1.954(9)$ Å for **1** vs. 1.866 Å for dimethylselenourea [26]). The torsion angle C1-Se1-Se2-C4 between the dimethylselenourea fragments is $104.9(3)^\circ$.

A chalcogen bonding is also present in **2**. The selenium atoms interact with the iodine atoms of iodonium ions, I_3^+ , *via* chalcogen bonding and form fragments C1=Se1...I2 (Se1-I2 = $3.5590(9)$ Å, C1-Se1-I2 = $165.7(2)^\circ$, I3-I2-Se1 = $74.60(2)^\circ$) and C4=Se2...I2 (Se2-I2 = $3.581(1)$ Å, C4-Se2-I2 = $175.3(2)^\circ$, I3-I2-Se2 = $110.73(2)^\circ$). Unlike structure **1**, iodines in **2** form two types of ions, the iodide ions I^- and the iodonium ions I_3^+ . The iodide ions I^- do not have any weak contacts. The iodonium ions I_3^+ interact with each other *via* halogen bonding (I2-I2 = $3.5285(7)$ Å, I3-I2-I2 = $169.00(2)^\circ$), although iodonium ions do not form infinite chains but dimers (Figure 3).

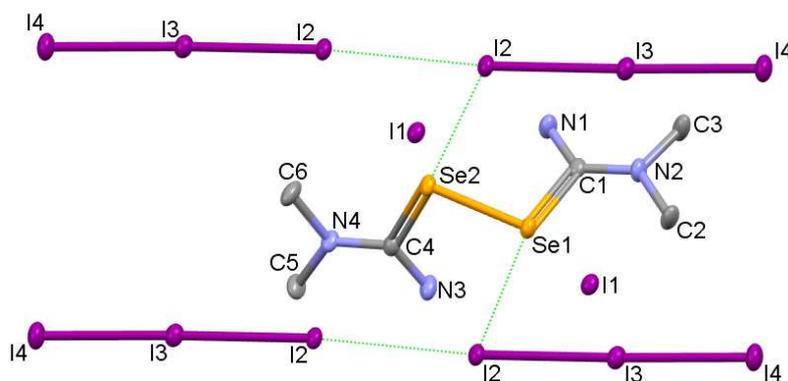


Figure 3. Crystal structure of **2**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles ($^{\circ}$): Se1-Se2 2.313 (1), Se1-I2⁽ⁱ⁾ 3.5590 (9), Se2-I2 3.581 (1), I2-I2⁽ⁱⁱ⁾ 3.5285 (7), C1-Se1-Se2 100.1 (2), C4-Se2-Se1 100.0 (2), C1-Se1-I2⁽ⁱ⁾ 165.7 (2), C4-Se2-I2 175.3 (2), I3-I2-I2⁽ⁱⁱ⁾ = I3⁽ⁱⁱ⁾-I2⁽ⁱⁱ⁾-I2 169.00 (2). Equivalent positions: (i) 1+x, y, z; (ii) -x, -y, 1-z.

Hauge with colleagues have obtained three more salts of selenourea, i.e. tris(selenourea) dichloride hydrate (**3**) [14], tris(selenourea) dibromide hydrate (**4**) [14] and tris(selenourea) sulfate (**5**) [15]. In all the structures **3-5** three selenium atoms are almost linearly bonded to each other (see Figures 4 and 5) with a Se-Se-Se angle equal to 173.81° , 173.89° and 168.29° for **3**, **4** and **5**, respectively. The selenourea molecules form trimers upon crystallization. The intramolecular Se...Se distances for the compounds **3-5** are present in Table 1. The sum of van der Waals radii for selenium is 3.80 Å, which is much smaller than the Se-Se bond length in **3-5**. Therefore, these intramolecular bonds can be referred to as covalent bonds.

Besides the intramolecular bonding, there is also the halogen bonding in the case of the chloride (**3**) and the bromide (**4**) salts (Figure 4, Table S1). In both structures the middle selenium atoms Se2 act as ChB donors with the C2=Se2...Hal angle equal to 174.61° for chloride and 175.01° for bromide. The Se2...Hal distance is 5% smaller than the sum of vdW radii (3.457 Å vs. 3.65 Å for Se2...Cl1 and 3.530 Å vs. 3.73 Å for the Se2...Br1). Also, in the case of the bromide there is another weak interaction C3-Se3-Br2 = 164.64° , Se3-Br2 = 3.720 Å. The corresponding sum of van der Waals radii is 3.73 Å, thus, the Se3...Br2 interaction could be considered as an extremely weak one.

Table 1. Intramolecular chalcogen bonding in structures **3-5**.

| Compound | Atoms | Distance, Å | Angles, $^{\circ}$ |
|----------|-----------|-------------|--|
| 3 | Se1...Se2 | 2.597 | C1-Se1-Se2 = 96.24, C2-Se2-Se1 = 88.94 |
| | Se2...Se3 | 2.717 | C2-Se2-Se3 = 89.27, C3-Se3-Se2 = 96.54 |
| 4 | Se1...Se2 | 2.624 | C1-Se1-Se2 = 96.45, C2-Se2-Se1 = 89.34 |
| | Se2...Se3 | 2.712 | C2-Se2-Se3 = 88.98, C3-Se3-Se2 = 96.20 |

| | | | |
|---|-----------|--------|--|
| 5 | Se1...Se2 | 2.6336 | C1-Se1-Se2 = 97.96, C2-Se2-Se1 = 86.56 |
| | Se2...Se3 | 2.6638 | C2-Se2-Se3 = 85.65, C3-Se3-Se2 = 98.06 |

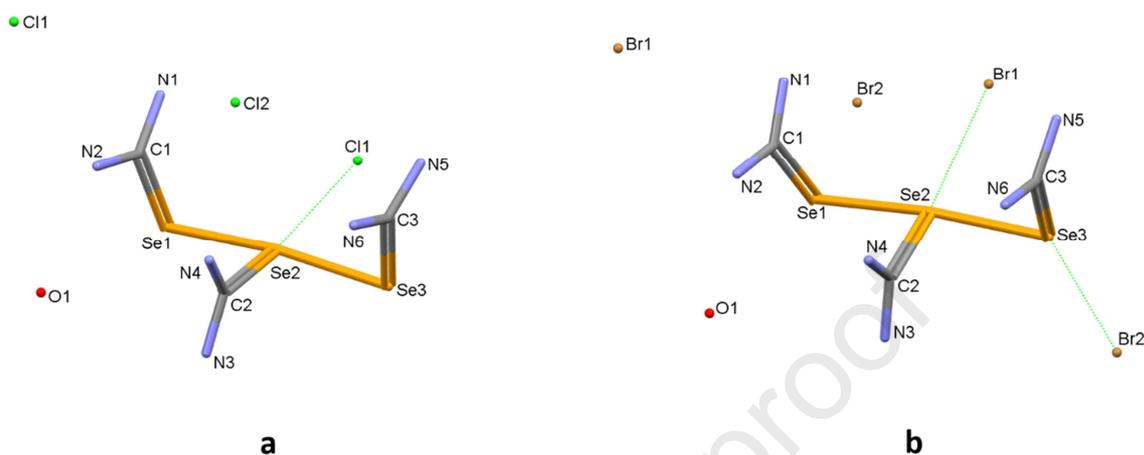


Figure 4. Crystal structures of **3** (a) and **4** (b). Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles (°): (a) Se1-Se2 2.597, Se2-Se3 2.717, Se2...Cl1⁽ⁱ⁾ 3.457, C1-Se1-Se2 96.24, C2-Se2-Se1 88.94, C2-Se2-Se3 89.27, C3-Se3-Se2 96.54, C2-Se2-Cl1⁽ⁱ⁾ 174.61; (b) Se1-Se2 2.624, Se2-Se3 2.712, Se2...Br1⁽ⁱ⁾ 3.530, Se3...Br2⁽ⁱⁱⁱ⁾ 3.720, C1-Se1-Se2 96.45, C2-Se2-Se1 89.34, C2-Se2-Se3 88.98, C3-Se3-Se2 96.20, C2-Se2-Br1⁽ⁱ⁾ 175.01, C3-Se3-Br2⁽ⁱⁱⁱ⁾ 164.64. Equivalent positions: (i) $x, 1/2-y, -1/2+z$; (ii) $1/2-x, 1-y, -1/2+z$.

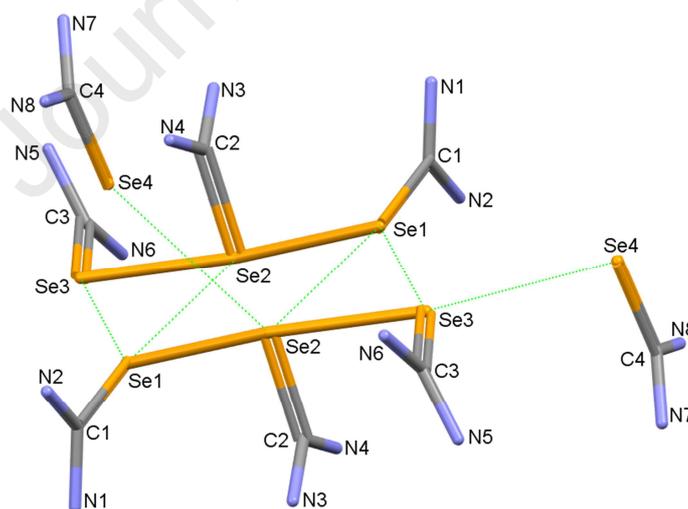


Figure 5. Crystal structure of **5**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles (°): Se1-Se2 2.6336, Se2-Se3 2.6638, Se2...Se4 3.7711, Se1-Se2⁽ⁱ⁾ 3.5836, Se1-Se3⁽ⁱ⁾ 3.6616, Se3-Se4⁽ⁱⁱⁱ⁾ 3.7760, C1-Se1-Se2 97.96, C2-Se2-Se1 86.56, C2-Se2-Se3 85.65, C3-Se3-Se2 98.06, C2-Se2-Se4 152.34, C4-Se4-Se2 156.06, C1-Se1-Se2⁽ⁱ⁾ 174.03, C2⁽ⁱ⁾-Se2⁽ⁱ⁾-Se1 94.24, C1-Se1-Se3⁽ⁱ⁾ 141.29, C3⁽ⁱ⁾-Se3⁽ⁱ⁾-Se1 164.70, C3-Se3-Se4⁽ⁱⁱ⁾ 70.84, C4⁽ⁱⁱ⁾-Se4⁽ⁱⁱ⁾-Se3 80.25. Equivalent positions: (i) $-x, 1-y, -z$; (ii) $1-x, 1-y, -z$.

Unlike trimeric structures of **3-5**, the selenourea/dimethylselenourea molecules form only dimers in the case of **1** and **2**. The Se...Se distance is slightly shorter (2.4001 Å for **1** and 2.313 Å for **2** vs. mean values of 2.657 Å for **3**, 2.668 Å for **4** and 2.6487 Å for **5**). There is also a difference in the chalcogen bonding in **1-2** and **3-4**. Thus, the Se...I distance is approx. 3.5% and 8% for **2** and 13% for **1** shorter than the sum of van der Waals radii, while in **3** and **4** the Se...Hal is 5% shorter than the sum of van der Waals radii. This can serve as an evidence of a better ability of iodine to participate in weak interactions in comparison with chlorine and bromine.

In order to have a better understanding of the selenourea behavior in terms of ChB, we decided to take a look at the known analogous compounds, but with an another chalcogen atom, i.e. the thiourea. Thus, sulfur behaves similarly to selenium and forms thiourea dimers in the crystal structures of **6-8**. The S...S distances in structures of **6-8** are present in Table 2. It can be seen from the Table 2 that for all the structures of **6-8** the S-S bond length is much shorter than the sum of van der Waals radii.

Table 2. Intramolecular chalcogen bonding in structures of **6-8**.

| Compound | Atoms | Distance, Å | Angles, ° | Sum of vdW radii, Å |
|-----------|---------|-------------|--|---------------------|
| 6a | S1...S2 | 2.017 | C1-S1-S2 = 104.31, C2-S2-S1 = 103.49 | 3.60 |
| 6b | S1...S2 | 2.0246 (4) | C1-S1-S2 = 104.20 (4), C2-S2-S1 = 103.34 (4) | 3.60 |
| 7 | S1...S2 | 2.0256 | C1-S1-S2 = 102.37, C2-S2-S1 = 102.87 | 3.60 |
| 8 | S1...S2 | 2.052 (5) | C1-S1-S2 = 102.1 (4), C6-S2-S1 = 101.2 (4) | 3.60 |

The compounds **6a** and **6b** are represented by two isomers of thiourea chloride hydrates (Figure 6). In both structures **6a** [16] and **6b** [17] the ChB is present in a C1=S1...Cl2 fragment (S1-Cl2 = 3.505 Å and C1-S1-Cl2 = 157.60 ° for **6a**; S1-Cl2 = 3.5107 (6) Å, C1-S1-Cl2 = 157.42 (4) ° for **6b**). The S...Cl distance is only 1% shorter than the sum of vdW radii (3.55 Å [22]). This evidences on a rather weak chalcogen bonding.

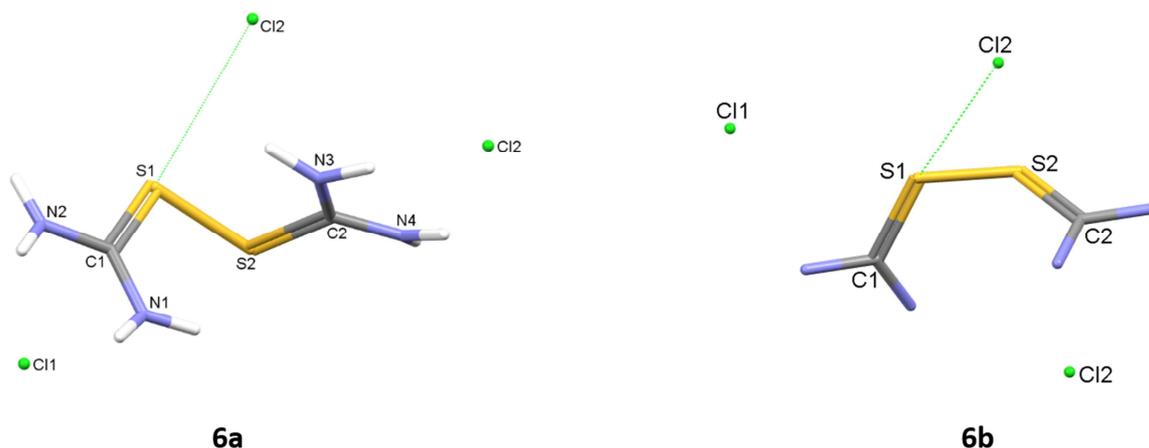


Figure 6. Crystal structures of **6a** and **6b** isomers. Selected bond lengths (Å) and angles ($^{\circ}$) for **6a**: S1-Cl2⁽ⁱ⁾ 3.505, C1-S1-Cl2⁽ⁱ⁾ 157.60. Selected bond lengths (Å) and angles ($^{\circ}$) for **6b**: S1-Cl2⁽ⁱⁱ⁾ 3.5107 (6), C1-S1-Cl2⁽ⁱⁱ⁾ 157.42 (4). Equivalent positions: (i) $-x, 1/2+y, 1/2-z$; (ii) $1/2-x, -1/2+y, z$.

The compound **7** (Figure 7) was obtained by T. Lis in 1980 [18]. It is represented by a bis(thiourea) trichloride salt with a rhenium(IV) pentachloride complex. However, the rhenium metal complex does not interact with thiourea and can, thus, be omitted from our consideration as being unimportant. In the structure **7** both sulfur atoms, S1 and S2, participate in ChB with the chlorine ions Cl5 and Cl4, correspondingly, acting as ChB donors. The bond lengths, bond angles and equivalent positions are represented in Table 3. Additionally, the sulfur atom S2 participates in a weak interaction with the oxygen atom O3 from a crystallized water molecule (Table 3, Figure 7) with the S...O distance being very close to the sum of vdW radii. It can be noted that the S...Cl distance is 6.5% smaller than the sum of vdW radii (3.55 Å) in case of S1 and 0.7% smaller than the sum of vdW radii in case of S2. This can evidence that the chalcogen bonding is slightly stronger in the case of S1 than in the case of S2.

Table 3. Chalcogen bonding in the structure **7**.

| Atoms | Distance, Å | Angles, $^{\circ}$ | Sum of vdW radii, Å | Equivalent position of (i)-(ii) |
|-------------------------|-------------|-----------------------------------|---------------------|---------------------------------|
| S1...Cl5 | 3.319 | C1-S1-Cl5 = 90.72 | 3.55 | |
| S2...Cl4 ⁽ⁱ⁾ | 3.523 | C2-S2-Cl4 ⁽ⁱ⁾ = 172.98 | 3.55 | $1/2-x, -1/2+y, -z$ |
| S2...O3 ⁽ⁱⁱ⁾ | 3.290 | C2-S2-O3 ⁽ⁱⁱ⁾ = 81.20 | 3.32 | $1/2-x, 1/2+y, -z$ |

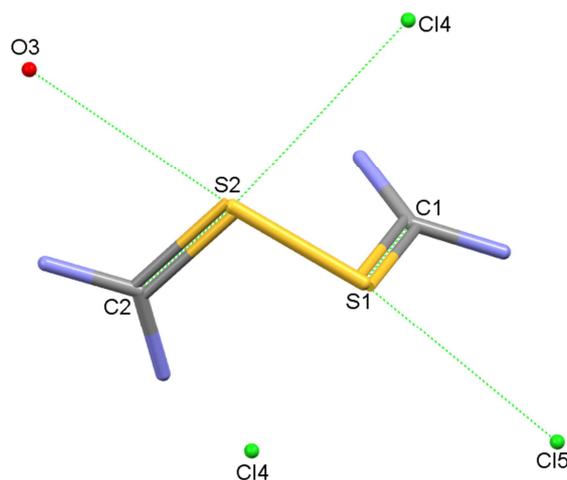


Figure 7. Crystal structure of **7**. Hydrogens and rhenium(IV) pentachloride complex are omitted for clarity. Selected bond lengths (Å) and angles (°): S2-Cl4⁽ⁱ⁾ 3.523, S1-Cl5 3.319, S2-O3⁽ⁱⁱ⁾ 3.290, C2-S2-Cl4⁽ⁱ⁾ 172.98, C1-S1-Cl5 90.72, C2-S2-O3⁽ⁱⁱ⁾ 81.20. Equivalent positions: (i) $1/2-x, -1/2+y, -z$; (ii) $1/2-x, 1/2+y, -z$.

Another metal containing thiourea complex is represented by a bis(tetraiodo-iron(III)) complex with tetramethylthiourea dimer **8** (Figure 8) [19]. Two tetramethylthiourea molecules form dimers with the S...S distance equal to 2.052 (5) Å being much smaller than the sum of vdW radii for sulfur (3.60 Å). The corresponding angles are C1-S1-S2 = 102.1 (4)°, C6-S2-S1 = 102.1 (4)°. Both sulfur atoms participate in a chalcogen bonding making the fragments C1=S1...I1, C1=S1...I7 and C6-S2...I3. The corresponding S...I distances are present in Table 4. It can be seen from the Table 4 that the S...I distances are 1.7%, 2% and 1.6% smaller than the sum of van der Waals radii and are rather weak.

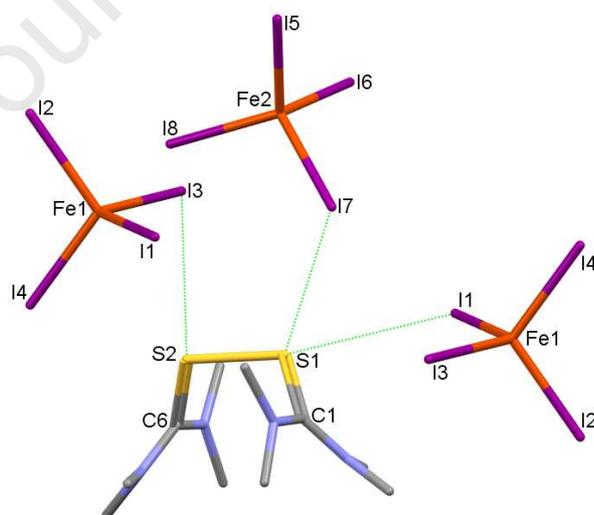


Figure 8. Crystal structure of **8**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles (°): S1-I1 3.716 (4), S1-I7 3.696 (4), S2-I3⁽ⁱ⁾ 3.718 (4), C1-S1-I1 84.0 (4), Fe1-I1-S1 120.17 (8), C1-S1-I7 150.0 (4), Fe2-I7-S1 138.91 (9), C6-S2-I3⁽ⁱ⁾ 157.0 (4), Fe1⁽ⁱ⁾-I3⁽ⁱ⁾-S2 92.96 (8). Equivalent positions: (i) $-x, 1-y, -z$.

Table 4. Chalcogen bonding in the structure **8**.

| Atoms | Distance, Å | Angles, ° | Sum of vdW radii, Å | Equivalent position of (i) |
|------------------------|-------------|---|---------------------|----------------------------|
| S1...I1 | 3.716 (4) | C1-S1-I1 = 84.0 (4), Fe1-I1-S1 = 120.17 (8) | 3.78 | |
| S1...I7 | 3.696(4) | C1-S1-I7 = 150.0 (4), Fe2-I7-S1 = 138.91 (9) | 3.78 | |
| S2...I3 ⁽ⁱ⁾ | 3.718 | C6-S2-I3 ⁽ⁱ⁾ = 157.0 (4), Fe1 ⁽ⁱ⁾ -I3 ⁽ⁱ⁾ -S2 = 92.96 (8) | 3.78 | -x, 1-y, -z |

In order to complete the series of thiourea...halogen derivatives, the crystal structures **9-12** were taken into consideration. All four compounds are represented by the thiourea-iodine cocrystals.

Thus, in the thiourea triiodide salt **9** [20] (Figure 9) thiourea does not form neither dimers nor trimers. The sulfur atom S1 participates in ChB by making a C=S...I fragment with the I1 atom of the triiodide ion: S1-I1 = 3.7687 (9) Å. The S...I distance is only slightly smaller than the sum of vdW radii (3.78 Å), so the interaction seems to be rather weak. The hydrogen bonding between the hydrogen atoms and the iodine atoms are out of the scope of the current investigation, and, thus, will not be considered in the present paper.

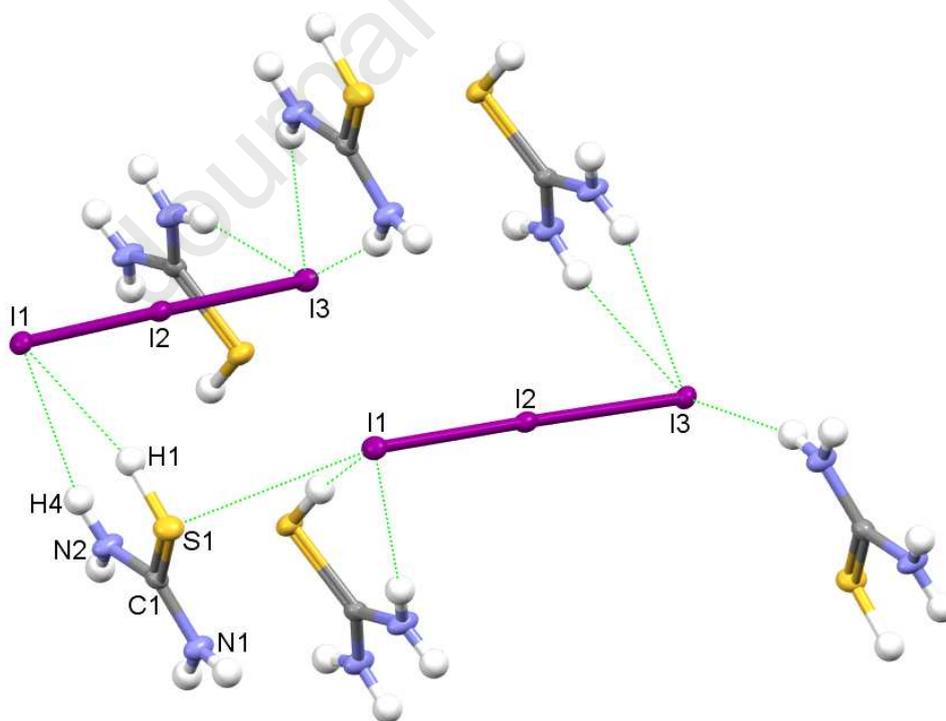


Figure 9. Crystal structure of **9**. Selected bond lengths (Å) and angles (°): S1-I1⁽ⁱ⁾ 3.7687 (9), C1-S1-I1⁽ⁱ⁾ 85.8 (1), I2⁽ⁱ⁾-I1⁽ⁱ⁾-S1 165.71 (1). Equivalent positions: (i) x, 1/2-y, 1/2+z.

Another triiodide salt of thiourea is represented by the structure of **10** [13] (Figure 10). In the compound **10** the thiourea molecules form dimer-like structures *via* interaction with the

iodine cation I^+ with S-I bond length being approximately 2.6 Å. It is 31% smaller than the sum of vdW radii (3.78 Å) and is indeed a strong interaction, which most probably defines the overall structure of **10**. Besides this, there is a weak chalcogen bonding in a $C1=S1\cdots I3$ fragment ($S1-I3 = 3.711$ (5) Å, $C1-S1-I3 = 83.0$ (4)°, $I4-I3-S1 = 169.38$ (7)°).

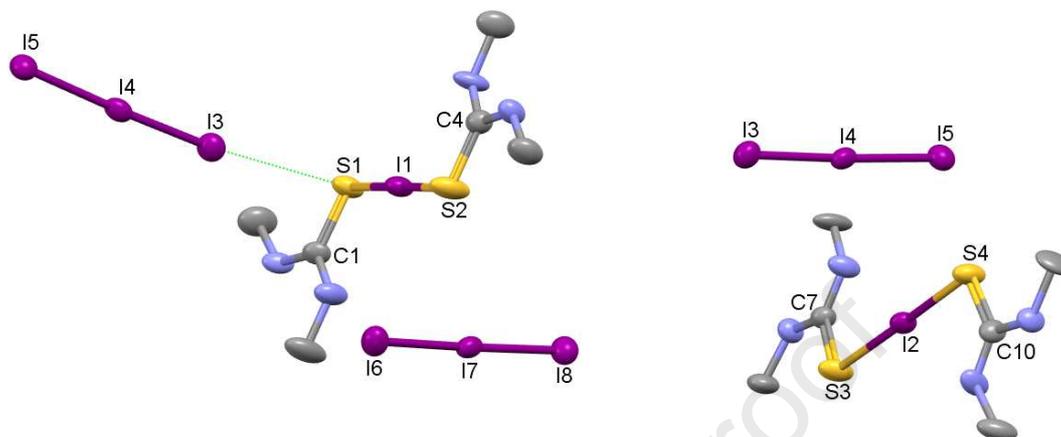


Figure 10. Crystal structure of **10**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles (°): $S1-I3^{(i)}$ 3.711 (5), $S1-I1$ 2.654 (3), $S2-I1$ 2.602 (3), $S3-I2$ 2.623 (3), $S4-I2$ 2.635 (3), $C1-S1-I3^{(i)}$ 83.0 (4), $I4^{(i)}-I3^{(i)}-S1$ 169.38 (7), $S1-I1-S2^{(i)}$ 179.1 (1), $S3-I2-S4$ 178.8 (1). Equivalent positions: (i) $x, 1/2-y, -1/2+z$.

The compound **11** [13] (Figure 11) is similar to the compound **10** and also forms strong interactions between sulfur from thiourea and iodine in di- and triiodide species in the $C1=S1\cdots I2$, $C2=S2\cdots I3$ and $C3=S3\cdots I6$ fragments. The $S\cdots I$ distances are approximately 35% less than the sum of vdW radii (3.78 Å): $S1-I2 = 2.466$ (3) Å, $S2-I3 = 2.437$ (3) Å, $S3-I6 = 2.507$ (3) Å. The weak chalcogen bonding is present in structure of **10** as well and is represented by the $C2=S2\cdots I4$ and $C3=S3\cdots I9$ fragments. The $S\cdots I$ distances are close to the sum of vdW radii ($S2-I4 = 3.724$ (4) Å, $S3-I9 = 3.687$ (3) Å, sum of vdW radii is 3.78 Å), thus, confirming that both interactions are rather weak. The halogen bonding between different iodine species in the structure of **11** are out of the scope of the current investigation, and, thus, will not be considered in the present paper.

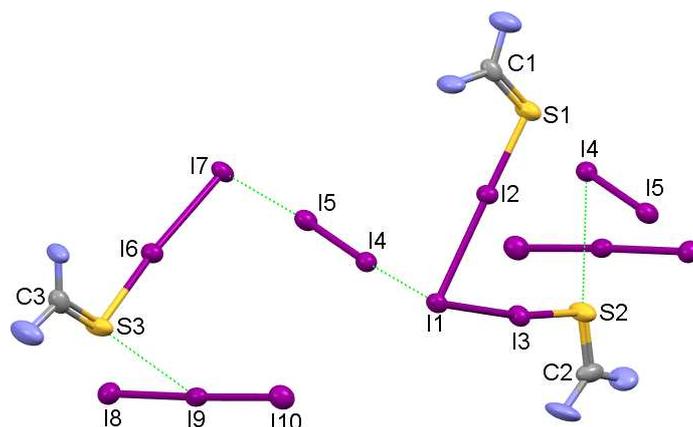


Figure 11. Crystal structure of **11**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles ($^{\circ}$): S2-I4⁽ⁱ⁾ 3.724 (4), S3-I9⁽ⁱⁱ⁾ 3.687 (3), S1-I2 2.466 (3), S2-I3 2.437 (3), S3-I6 2.507 (3), C2-S2-I4⁽ⁱ⁾ 165.8 (4), I5⁽ⁱ⁾-I4⁽ⁱ⁾-S2 73.29 (5), C3-S3-I9⁽ⁱⁱ⁾ 167.7 (4), I10⁽ⁱⁱ⁾-I9⁽ⁱⁱ⁾-S3 100.43 (5), C1-S1-I2 104.2 (3), I1-I2-S1 176.08 (8), C2-S2-I3 105.9 (4), I1-I3-S2 171.59 (8), C3-S3-I6 104.9 (4), I7-I6-S3 173.69 (8). Equivalent positions: (i) 1-x, 1-y, 1-z; (ii) 1-x, 2-y, 1-z.

George Hung-Yin Lin and Håkon Hope reported another example of the formation of an iodine cation I^+ upon interaction of iodine with molecules of thiourea (structure **12** [21,27,28], Figure 12). The iodine cation I^+ is a strong electrophile and can be formed, when a stronger nucleophile is present in the solution [21]. It explains the geometry of the structure **12** with a linear fragment S1-I1-S1E (the S1-I1-S1E angle is 180.0°). Thus, sulfur atoms act as electron density donors and not as ChB donors. Surprisingly, neither S1 nor S1E interact with the resting iodine anion I^- (I2) and do not participate in any other weak interactions.

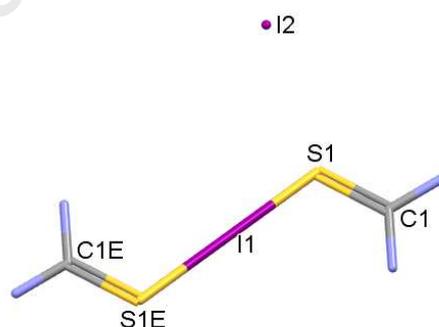


Figure 12. Crystal structure of **12**. Hydrogens are omitted for clarity. Selected bond lengths (Å) and angles ($^{\circ}$): S1-I1 2.629, S1E-I1 2.629, C1-S1-I1 106.25, C1E-S1E-I1 106.25.

3. Conclusions

We have demonstrated that thiourea, selenourea and their derivatives can result in a variety of different compounds upon interaction with halogens (compounds **1-12**). Two

main trendlines can be outlined from the investigation of crystal structures of **1-12**. First trendline concerns the nature of a halogen atom. Thus, we have shown that in the case of lighter halogens (chlorine and bromine) thiourea molecules and its derivatives form dimers through S...S bonds (structures **6a**, **6b** and **7**) upon interaction with chlorine or bromine. The S...S distance varies from 2.017 Å to 2.0256 Å. The redistribution of electron density takes place during dimerization process, which results in a higher interaction ability of one sulfur atom in comparison with the other sulfur atom within one dimer. No strong bonding was evidenced between sulfur and the halogen atom, only weak interactions with the S...Hal distances being 0.7-6.5% less than the sum of vdW radii.

Selenourea and its derivatives are expected to follow the same trend as thiourea and its derivatives due to the similar chemical properties of sulfur and selenium. Indeed, the behavior of selenourea and its derivatives is very similar to that of thiourea and its derivatives, but yet not exactly the same. Thus, in the crystal structures of selenourea chloride (**3**) and bromide (**4**) selenourea tends to undergo trimerization (unlike dimerization in the case of thiourea) with the Se...Se distances varying from 2.597 Å to 2.717 Å. An unequal redistribution of the electron density between the selenourea molecules happens upon trimerization. This makes some selenium atoms to become more reactive than the other selenium atoms. Weak Se...Hal interactions are present in the compounds **3** and **4**. The Se...Hal distances are 5% shorter than the sum of van der Waals radii.

However, in the case of heavier halogen (iodine) no S...S interactions were observed in the crystal structures of **9-12**. On the contrary, the iodine atoms tend to form very strong bonds with sulfur atoms. The S...I distances are up to 35% shorter than the sum of van der Waals radii.

In the case of an interaction of selenourea/dimethylselenourea with iodine, selenourea molecules form dimers in obtained compounds **1** and **2**, and not trimers like in selenourea complexes with lighter halogens **3-5**. The Se...Se distance becomes even shorter being 2.4001 (4) Å for **1** and 2.313 (1) Å for **2**. The selenium atoms in the structure of **1** are not equal: only one selenium atom is participating in weak interactions with the iodine atoms, the other selenium atom from the same dimer stays intact. In the structure of the iodine complex of dimethylselenourea (**2**), both selenium atoms seem to behave similarly and participate in weak interactions with the iodonium ions I_3^+ . The corresponding Se...I distances are 3.6% and 13% shorter than the sum of van der Waals radii for **1** and approximately 8% shorter than that for **2**.

A clear correlation between the nature of a halogen atom and the strength of chalcogen bonding is observed. Thus, a heavier halogen atom with a larger polarizability (iodine) reveals higher tendency to break the chalcogen...chalcogen bonds and to form strong chalcogen...halogen bonds instead. Consequently, the dimers turn into monomers in the case of thiourea and its derivatives (structures of **6-12**), and the trimers turn into the dimers in the case of selenourea and dimethylselenourea **1-5**.

It should be noted that among all the crystal structures of **1-12**, only iodine cations I^+ in **10** and **12** act as electron density acceptors (or ChB donors), while in the remaining compounds **1-9** and **11** halogen species act as electron density donors (or ChB acceptors).

Second trendline concerns nature of chalcogen atom. Thus, selenourea and dimethylselenourea form trimers **3-5** and dimers **1-2**, while thiourea and its derivatives form dimers **6-8** and monomers separated by the iodine species **9-12**. This could be explained by a higher polarizability of the selenium atoms in comparison with the sulfur atoms. Which may result in a stronger tendency of selenium to form very strong $Se \cdots Se$ bonds than in the case of the $S \cdots S$ bonding.

However, despite all the differences between thiourea and selenourea, the similarities in their behavior suggest us to expect similar properties, e.g. antithyroid activity, which is already known for the thiourea derivatives.

4. Experimental details

4.1. Synthesis of **1**

Selenourea (123.05 mg; 1 mmol) was dissolved in 9 ml of acetonitrile and stirred until complete dissolution. Reaction vessel was covered with aluminum foil all the time. Iodine (30.00 mg; 0.12 mol) was dissolved in 5 ml of anhydrous acetonitrile to make a concentrated solution. Then the iodine solution was added to the selenourea solution. An immediate residue formation was observed. The resulting mixture was stirred for additional 30 minutes in order to guarantee the complete precipitation. The residue was filtered, washed with acetonitrile and dried under vacuum. The residue represented yellow needle crystals of **1** (Figure S1).

4.2. Synthesis of **2**

1,1-dimethylselenourea (151.10 mg; 1 mmol) was dissolved in 10 ml of acetonitrile and stirred until complete dissolution. Reaction vessel was covered with aluminum foil all the time. Iodine (30.00 mg; 0.12 mol) was dissolved in 5 ml of anhydrous acetonitrile to make a concentrated solution. Then the iodine solution was added to the dimethylselenourea solution. An immediate residue formation was observed. The resulting mixture was stirred for additional 30 minutes in order to guarantee the complete precipitation. The residue was filtered, washed with acetonitrile and dried under vacuum. The residue represented orange needle crystals of **2** (Figure S2).

Selenourea and 1,1-dimethylselenourea were purchased from Sigma-Aldrich. Iodine was purchased from Mallinckrodt.

The isolated yields are 96 % for **1** and 97 % for **2**. Elemental analysis of **1**: found C 5.114 %, H 1.724 %, N 11.35 %; calculated C 4.806 %, H 1.613 %, N 11.209 %. Elemental analysis of **2**: found C 8.642 %, H 1.917 %, N 7.133 %; calculated C 8.899 %, H 1.992 %, N 6.919 %. The obtained crystals of **1** and **2** were analyzed with SuperNova Dual X-ray diffractometer using

Mo source for crystals of **1** and Cu source for crystals of **2**. Details on the XRD experiments can be found in ESI.

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Graphical Abstract caption

Chalcogen bonding between selenourea, thiourea and their derivatives as bond donors and halogen species as bond acceptors.

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The S \cdots Hal and Se \cdots Hal Chalcogen Bonding in a Series of Thiourea, Selenourea and Their Derivatives

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Highlights:

- Previously unknown selenourea iodide (**1**) and 1,1-dimethylselenourea triiodide (**2**) crystal structures have been obtained and characterized.
- Extensive study on the complexation of thiourea, selenourea and their derivatives with halogens has been carried out.
- Thiourea molecules and its derivatives form dimers through the S \cdots S bond in the case of lighter halogens (chlorine and bromine) and monomers in the case of heavier iodine atoms.
- Selenourea and 1,1-dimethylselenourea undergo trimerization through the Se \cdots Se bond upon interaction with lighter halogens (chlorine and bromine) and dimerization upon interaction with iodine atoms.
- A clear correlation between the nature of a halogen atom and the strength of chalcogen bonding is observed. Thus, a heavier halogen atom with a larger polarizability (iodine) reveals higher tendency to break the chalcogen \cdots chalcogen bonds and to form strong chalcogen \cdots halogen bonds instead.
- In all the investigated compounds **1-12**, only iodine cations I⁺ in **10** and **12** act as electron density acceptors (or ChB donors), while in the remaining compounds **1-9** and **11** halogen species act as electron density donors (or ChB acceptors).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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