Heterocyclic 1,3-diazepine-based thiones and selones as versatile halogen-bond acceptors

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Utilizing the N-heterocyclic chalcogenones hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-thione (SDiazMesS) and hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-selone (SDiazMesSe) as halogen-bond acceptors, a total of 24 new cocrystals were prepared. The solid-state structures of the parent molecules were also determined, along with those of their acetonitrile solvates. Through the reaction of the chalcogen atom with molecular diiodine, a variety of S—I—I and Se—I—I fragments were formed, spanning a wide range of I—I bond orders. With acetone as a reaction solvent, molecular diiodine causes the oxidative addition of acetone to the chalcogen atom, resulting in new C—S, C—Se and C—C covalent bonds under mild conditions. The common halogen-bond donors, iodopentafluorobenzene, 1,2-, 1,3- and 1,4-diiodotetrafluorobenzene, 1,3,5-trifluorotriiodobenzene and tetraiodoethylene resulted in halogen-bond-driven cocrystal formation. In most cases, the analogous SDiazMesS and SDiazMesSe cocrystals are isomorphic.

1. Introduction

Halogen bonding has long been known, and formally defined by the International Union of Pure and Applied Chemistry (IUPAC) in 2013, as an attractive interaction between an electrophilic region on a halogen atom (halogen-bond donor) and a nucleophilic region on another atom or molecule (halogen-bond acceptor) (Desiraju et al., 2013). The electrophilic region is referred to as the σ hole and is located at the ‘cap’ on the halogen end of the covalent bond, and is accompanied by a ‘belt’ of relatively higher electrostatic potential orthogonal to the bond (Murray et al., 2009; Politzer et al., 2010; Politzer & Murray, 2017). A similar electron density distribution is observed for the chalcogen atoms and is particularly pronounced for thiones and selones (Vogel et al., 2019). If the chalcogen atoms of these functional groups act as halogen-bond acceptors, the location of the higher electrostatic potential drives the halogen bond away from the terminus of the thione or selone double bond. Conversely, a chalcogen bond, an interaction analogous to a halogen bond involving the σ hole of a chalcogen atom, can occur at the terminus of the thione or selene double bond (Aakeroy et al., 2019).

As halogen-bond acceptor atoms, nitrogen and oxygen have received considerably more attention than the heavier chalcogens. For example, a survey of the Cambridge Structural Database (CSD, Version 5.42, update 3; Groom et al., 2016), limited to organics, yields 918 results involving an N···I
halogen bond (where the N···I distance is less than the sum of the van der Waals radii of the two atoms) to a pyridine-based nitrogen atom. A similar search with urea-, thiourea- or selenourea-based acceptors yields 36, 100 and 19 results, respectively. Amongst the limited published data involving Se···I interactions, the oxidative addition of interhalogens to diselenones, resulting in I—Se—X hypervalent systems is notable (Juárez-Pérez et al., 2011). Our group has been particularly interested in the cooperation of halogen and chalcogen bonding as a versatile crystal engineering tool (Peloquin, McMillen et al., 2021a,b; Peloquin, McCollum et al., 2021; Peloquin, Alapati et al., 2021).

Motivated by the lack of published structural data involving halogen bonds to thioureas, and especially selenoureas, this work serves to further catalog the intermolecular interactions of these functionalities with common organoiodine compounds (Scheme 1 shows the organic halogen-bond acceptors and donors utilized in this study), as well as to investigate their reactivity and resulting halogen bonding with molecular diiodine.

To this end, the sterically encumbered diazepine chalcogenone derivatives hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-thione (SDiazMesS) and hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-selone (SDiazMesSe) were prepared, the latter of which has not yet been reported in the synthetic literature, and structurally characterized. These were subsequently utilized as halogen-bond acceptors, to explore their halogen bonding tendencies. Each of these parent molecules was reacted with molecular diiodine, which depending on reaction stoichiometry and solvent choice, provided a variety of C=S−I−I, C=Se−I−I and C=Se−I derivatives. When acetone was utilized as the reaction solvent with I2, new S−C, Se−C and C−C bonds were formed via oxidation by I2. Utilizing the six most common commercially available halogen bond donors, 1,2-diodotetrafluorobenzene (1,2-F4DIB), 1,3-diodotetrafluorobenzene (1,3-F4DIB), 1,4-diodotetrafluorobenzene (1,4-F4DIB), 1,3,5-trifluorotriiodobenzene (1,3,5-F3I3B), iodopentafluorobenzene (IF5B), and tetraiodoethylene (TIE), the molecular structures of 14 new cocrystals were determined. In most cases, the analogous SDiazMesS and SDiazMesSe cocrystals are isomorphic. No significant chalcogen···chalcogen (ch···ch) or chalcogen···iodine (ch···I) chalcogen bonding or I···F halogen bonding is observed within this series of structures.

2. Experimental

2.1. Materials and instrumentation

All reactions were performed under aerobic conditions unless otherwise stated. Solvents were purified and degassed by standard procedures, and all commercially available reagents were used as received. The bis(mesityl)formamidine MesN = CHNHMes (MesForm) was synthesized as reported (Kuhn & Grubbs, 2008) and its corresponding diazepinium bromide derivative (SDiazMesH)Br (Kolychev et al., 2009) was prepared by a modification of a literature procedure (Iglesias et al., 2008). 1H and 13C NMR spectra were obtained on Jeol ECX-300 (300 MHz) or Jeol ECA-500 (500 MHz) FT spectrometers. Chemical shifts are reported in p.p.m. relative to SiMe4 (δ = 0 p.p.m.) and were referenced internally with respect to the solvent resonances (1H: δ 2.05 for d5-acetone; 13C: δ 29.84 for (CD3)2CO; coupling constants are given in hertz (Hz). IR spectra were recorded on a PerkinElmer Spectrum 100 spectrometer using an attenuated total reflectance (ATR) accessory and are reported in cm−1; relative intensities of the absorptions are indicated in parentheses (v = very strong, s = strong, m = medium, w = weak). Elemental analyses were determined by Atlantic Microlab, Inc. (Norcross, GA, USA).

For single-crystal X-ray analysis, crystals were mounted on low-background cryogenic loops using paratone oil. Data were collected at 100 K using Mo Kα radiation (λ = 0.71073 Å) on a Bruker D8 Venture diffractometer with an Incoatec Iμs microfocus source and a Photon 2 detector. Diffraction data were collected using θ and ω scans and subsequently processed and scaled using the APEX3 (SAINT/SADAB3) (Bruker, 2017) software. The structures were solved with the SHELXT structure solution program and refined utilizing SHELXL, both incorporated in the OLEX2 (v1.5) program package (Sheldrick, 2015a,b; Dolomanov et al., 2009). Hydrogen atoms were placed in geometrically optimized positions using the appropriate riding models. In (SDiazMesS) (MeCN), (SDiazMesSe) (MeCN), (SDiazMesS) (1,3-F4DIB), (SDiazMesSe) (1,3-F4DIB), 2(SDiazMesS) (1,3-F4DIB), (SDiazMesSe) (1,3,5-F3I3B), 2(SDiazMesS) (TIE) and 2(SDiazMesSe) (TIE), positional disorder of the C=C=C=C portion of the diazepine ring and/or a mesityl substituent was modeled in two parts, utilizing the SIMU restraint as appropriate.

2.2. Preparation of SDiazMesS and SDiazMesSe

The bis(mesityl)formamidine MesN = CHNHMes (MesForm) was synthesized as reported (Kuhn & Grubbs, 2008) and its corresponding diazepinium bromide derivative
(SDiazMesH)Br, SDiazMesS and SDiazMesSe were prepared by a modification of literature procedures (Iglesias et al., 2008; Rais et al., 2016).

2.2.1. (SDiazMesH)Br. A stirred mixture of 1,4-dibromobutane (5.939 g, 27.506 mmol), the formamidine FormStor (7.000 g, 24.963 mmol), and potassium carbonate (1.989 g, 14.392 mmol) in acetonitrile (100 ml) was heated to reflux under argon for 24 h. The resulting solution was cooled to room temperature and concentrated under reduced pressure to ~2 ml to give a very viscous tan-colored residue.

Di-chloromethane (25 ml) was added to the residue and the mixture stirred overnight, facilitating the separation of a fluff, white precipitate. The resulting suspension was concentrated under reduced pressure to half volume, treated with cold diethyl ether (60 ml), and the sticky, peach-colored product was isolated by vacuum filtration and dried in vacuo for 24 h (7.820 g, 72%). 1H NMR data (in CDCl3): δ 2.27 (s, 6H, CH3), 2.41 (s, 12H, CH3), 2.56 (m, 4H, CH2), 4.65 (m, 4H, CH2), 6.94 (s, 4H, C6H2), 7.21 (s, 1H, NCHN); 13C NMR data (in d6-acetone): δ 2.28 (s, 6H, CH3), 2.45 (s, 12H, CH3), 2.55 (m, 4H, CH2), 4.52 (m, 4H, CH2), 7.05 (m, 4H, C6H2), 8.13 (s, 1H, NCHN).

2.2.2. SDiazMesS. A stirred mixture of (SDiazMesH)Br (5.106 g, 12.292 mmol), elemental sulfur (0.433 g, 13.506 mmol) and potassium carbonate (2.208 g, 15.976 mmol) in n-propanol (75 ml) was heated to reflux for 48 h. The resulting yellow suspension was concentrated to ~2 ml under reduced pressure to give a beige viscous residue. The product was extracted into dichloromethane (50 ml) and the extract was treated with activated carbon (~1 g) and filtered. The pale orange filtrate was washed with deionized water (3 ~30 ml), and the organic phase was dried over magnesium sulfate (~1 g) and filtered. Concentration of the solution under vacuum to ~1 ml and addition of hexanes (20 ml) led to the precipitation of the pale brown product, which was separated by filtration and dried in vacuo for 24 h (3.543 g, 79%). Mp = 179–181 °C (dec.). NMR data (in d6-acetone): 1H δ 2.09 (m, 4H, CH2), 2.23 (s, 6H, CH3), 2.29 (s, 12H, CH3), 3.90 (m, 4H, CH2), 6.85 (s, 6H, C6H2); 13C δ 19.0 (q, 1JCH = 126, 4C, CH3), 20.9 (q, 1JCH = 128, 2C, CH2), 26.4 (t, 1JCH = 127, 2C, CH2), 55.0 (t, 1JCH = 138, 2C, NCH2), 130.1 (d, 1JCH = 164, 4C, C6H2, in C6H2), 135.5 (s, 4C, C2 in C6H2), 136.5 (s, 2C, C4 in C6H2), 145.5 (s, 2C, Cqps in C6H2), C=Se not observed. IR data: 3141 (w), 2939 (w), 2916 (m), 2854 (w), 2726 (w), 1679 (w), 1643 (s), 1607 (w), 1551 (m), 1488 (m), 1478 (m), 1465 (s), 1426 (m), 1381 (w), 1369 (m), 1359 (w), 1330 (w), 1308 (s), 1287 (vs), 1267 (m), 1214 (m), 1200 (w), 1182 (w), 1148 (w), 1121 (w), 1102 (w), 1032 (w), 1011 (w), 997 (w), 979 (w), 957 (w), 914 (w), 863 (w), 849 (s), 767 (m), 748 (w), 740 (w), 729 (w), 709 (w). Anal. Calc.: for C23H30I2N2S: C, 44.5; H, 4.9; N, 6.7%. Samples for single-crystal X-ray characterization were obtained from EtOH/DCM or MeCN.

2.3. Reaction of SDiazMesS and SDiazMesSe with I2

2.3.1. (SDiazMesS)I2. Diethyl ether (10 ml) was added to a mixture of SDiazMesS (0.150 g, 0.409 mmol) and elemental iodine (0.104 g, 0.405 mmol), resulting in the formation, within minutes, of a dark-orange solid and a dark-red solution. After stirring the suspension for 17 h, the product was isolated by filtration and dried in vacuo for 24 h (0.154 g, 61%). Mp = 141–143 °C (dec.). NMR data (in d6-acetone): 1H δ 2.27 (s, 10 H, CH3 + CH2), 2.37 (s, 12H, CH3), 4.12 (s, 4H, CH2) 6.96 (s, 4H, C6H2); 13C δ 18.5 (q, 1JCH = 127, 4C, CH3), 20.5 (q, 1JCH = 128, 2C, CH2), 23.7 (t, 1JCH = 130, 2C, CH2), 54.7 (t, 1JCH = 143, 2C, CH2), 129.6 (d, 1JCH = 157, 4C, C6H2 in C6H2), 133.7 (d, 1JCH = 6, 4C, C6H2 in C6H2), 136.7 (s, 2C, C6 in C6H2), 142.6 (s, 2C, Cqps in C6H2), 176.3 (s, 1C, C=S). IR data: 2948 (w), 2910 (w), 2868 (w), 2730 (w), 1608 (w), 1506 (s), 1474 (m), 1452 (w), 1432 (m), 1393 (m), 1373 (w), 1365 (w), 1354 (w), 1337 (m), 1306 (s), 1286 (vs), 1270 (vs), 1211 (w), 1202 (w), 1187 (w), 1153 (w), 1105 (w), 1036 (w), 1014 (w), 999 (w), 978 (w), 966 (w), 937 (w), 926 (w), 910 (w), 892 (w), 855 (s), 841 (m), 798 (w), 756 (w), 745 (w), 729 (w), 706 (w). Anal. Calc.: for C23H30I2S2: C, 44.5; H, 4.9; N, 4.5; found: C, 44.3; H, 4.9; N, 4.5%. Crystals suitable for X-ray diffraction analysis were obtained through the slow evaporation of an ethanolic solution of the compound.

2.3.2. (SDiazMesSeI2). A mixture of SDiazMesSe (0.144 g, 0.349 mmol) and elemental iodine (0.093 g, 0.366 mmol) in diethyl ether (10 ml) was stirred overnight at room temperature. The resulting reddish-brown suspension was concentrated under reduced pressure to ~1 ml, treated with diethyl ether (5 ml), and the dark orange product was isolated by filtration, washed with diethyl ether (2 ml), and dried in vacuo.
for 18 h (0.210 g, 91%). Mp = 195–198 °C (dec.). 1H NMR data (in d6-acetone): δ 2.28 (s, 3H, CH3), 2.32 (s, 4H, CH2), 2.37 (s, 6H, CH3), 4.22 (s, 4H, CH2), 6.98 (s, 2H, C6H2); 13C NMR data (in d6-DMSO): δ 17.9 (q, J C–H = 128, 4C, CH3), 20.0 (q, J C–H = 127, 2C, CH3), 22.6 (t, J C–H = 131, 2C, CH2), 55.5 (t, J C–H = 146, 2C, CH2), 129.5 (d, J C–H = 158, 2C, C6 in C6H2), 133.4 (s, J C–H = 160, 4C, C6 in C6H2), 138.1 (s, 4C, C6 in C6H2), 142.2 (s, 2C, Cipso in C6H2), C==Se not observed. IR data: 2950 (0.15 mmol) and 1,3-F4DIB (29 mg, 0.073 mmol) were combined to yield yellow, needle-like crystals.

In a 20 ml glass vial, SDiazMesS (30 mg, 0.082 mmol) and 1,2-F4DIB (33 mg, 0.082 mmol) were combined to yield colorless, needle-like crystals. 2.4. Preparation of cocrystals

2.4.1. (SDiazMesS)-(1,2-F4DIB). In a 20 ml glass vial, SDiazMesS (30 mg, 0.082 mmol) and 1,2-F4DIB (33 mg, 0.082 mmol) were dissolved in a 1:1 mixture of ethanol and dichloromethane (5 ml) with gentle heating. The solvent was allowed to slowly evaporate under ambient conditions (18–20 °C) until colorless, needle-like crystals were observed.

2.4.2. (SDiazMesS)-(1,3-F4DIB). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesS (30 mg, 0.082 mmol) and 1,3-F4DIB (66 mg, 0.16 mmol) were combined to yield colorless, plate-like crystals.

2.4.3. (SDiazMesSe)-(1,3-F4DIB). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesSe (30 mg, 0.073 mmol) and 1,3-F4DIB (58 mg, 0.15 mmol) were combined to yield yellow, needle-like crystals.

2.4.4. 2(SDiazMesS)-(1,3-F4DIB). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesS (60 mg, 0.16 mmol) and 1,3-F4DIB (33 mg, 0.082 mmol) were combined to yield colorless, needle-like crystals.

2.4.5. 2(SDiazMesSe)-(1,3-F4DIB). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesSe (60 mg, 0.15 mmol) and 1,3-F4DIB (29 mg, 0.073 mmol) were combined to yield colorless, needle-like crystals.

2.4.6. 2(SDiazMesS)-(1,4-F4DIB) and 2(SDiazMesS)-(1,4-F4DIB)mo. Using the same procedure as (SDiazMesS)-(1,2-F4DIB), SDiazMesS (60 mg, 0.16 mmol) and 1,4-F4DIB (33 mg, 0.082 mmol) were combined to yield colorless, needle-like crystals.

2.4.7. 2(SDiazMesSe)-(1,4-F4DIB). Using the same procedure as (SDiazMesS)-(1,2-F4DIB), SDiazMesSe (60 mg, 0.15 mmol) and 1,4-F4DIB (29 mg, 0.073 mmol) were combined to yield colorless, plank-like crystals.

2.4.8. (SDiazMesS)-(1,3,5-F3I3B). Using the same procedure as (SDiazMesS)-(1,2-F4DIB), SDiazMesS (30 mg, 0.082 mmol) and 1,3,5-F3I3B (42 mg, 0.082 mmol) were combined to yield colorless, needle-like crystals.

2.4.9. (SDiazMesSe)-(1,3,5-F3I3B). Using the same procedure as (SDiazMesS)-(1,2-F4DIB), SDiazMesSe (30 mg, 0.073 mmol) and 1,3,5-F3I3B (37 mg, 0.073 mmol) were combined to yield yellow, needle-like crystals.

2.4.10. (SDiazMesS)-(IF5B). Using the same procedure as (SDiazMesS)-(1,2-F4DIB), SDiazMesS (30 mg, 0.082 mmol) and IF5B (120 mg, 0.41 mmol) were combined to yield colorless, plate-like crystals.

2.4.11. 2(SDiazMesSe)-5(IF5B). In a 1 ml glass tube, SDiazMesSe (30 mg, 0.073 mmol) was dissolved in IF5B (0.25 ml, 1.8 mmol). The solvent was allowed to slowly evaporate under ambient conditions, yielding yellow, plate-like crystals after approximately one week.

2.4.12. 2(SDiazMesS)-(TIE). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesS (60 mg, 0.16 mmol) and TIE (44 mg, 0.082 mmol) were combined to yield yellow, plate-like crystals.

2.4.13. 2(SDiazMesSe)-(TIE). Using the same procedure as for (SDiazMesS)-(1,2-F4DIB), SDiazMesSe (60 mg, 0.15 mmol) and TIE (39 mg, 0.073 mmol) were combined to yield yellow, block-like crystals.

3. Results and discussion

3.1. Synthesis of SDiazMesS and SDiazMesSe

The N-heterocyclic chalcogenones SDiazMesE (E = S, Se), envisioned to have good solubility in common organic solvents and exhibit simple 1H and 13C NMR spectra to facilitate characterization of products, were synthesized in three steps (Scheme 2).

![Scheme 2](image-url)
SDiazMesS I2
SDiazMesSe I2
(SDiazMesSe)·MeCN I2
(SDiazMesSe)·DMK I2

3.3. Reaction of SDiazMesS and SDiazMesSe with I2

The reaction of molecular iodine with SDiazMesS and SDiazMesSe provided a rich series of products depending on the ratio of I2 to thione or selone and the solvent choice (Scheme 3).

The reaction of SDiazMesS or SDiazMesSe with a stoichiometric amount of I2 in diethyl ether provides SDiazMesS·I2 or SDiazMesSe·I2, both crystallizing in the trigonal space group P31. In both cases, short chalcogen···iodine distances are observed [S···I = 2.6738 (9) Å and Se···I = 2.7559 (4) Å], with concomitant lengthening of the I—I bond to 2.8794 (4) Å in SDiazMesS·I2 and 2.9106 (4) Å in SDiazMesSe·I2. These I—I distances correspond to bond orders of 0.59 and 0.53, respectively, as calculated using the expression of Pauling, 

\[ D(n') = D(1) - 0.71 \log(n') \] 

with a D(1) of 2.72 Å (Pauling, 1960).
A series of weak C−H···I hydrogen bonds consolidate the packing.

The reaction with 2.5 molar equivalents of I2 in a 1:1 mixture of ethanol and dichloromethane provides different products from SDiazMesS and SDiazMesSe. When the reaction was conducted with SDiazMesS, the cocrystal (SDiazMesS−I2) (1) was obtained in the triclinic space group P1. The bond distances within the S−I···I fragment are reduced from those in SDiazMesS, with the S−I distance shrinking to 2.5052 (5) Å while the I···I distance further elongates to 3.0803 (4) Å. This change in bond geometries is indicative of further progression towards the dipolar I+···I− extreme, with a calculated bond order of 0.31. The consolidation of the negative charge on the terminal iodine atom of the S−I···I fragment contributes to its increased ability to serve as a halogen-bond acceptor. The incorporation of a diiodine molecule within the structure aids in the formation of chains in the [011] direction through I···I halogen bonding. There are two such unique I···I halogen bonds formed at each terminal iodine atom of the S−I···I, both of which are similar in length [I···I = 3.4171 (4) Å and 3.4694 (5) Å]. In contrast to the reaction of SDiazMesS with excess I2, the reaction of 2.5 molar equivalents of I2 with SDiazMesSe in 1:1 ethanol:dichloromethane provides the salt [(SDiazMesSe−I) (I3)]. Crystalline [(SDiazMesSe−I) (I3)] forms within five minutes, and if this material is recrystallized from dichloromethane, the crystalline solvate [(SDiazMesSe−I) (I3) (DCM)] is obtained. In both cases, the Se−I···I fragment is better represented as (Se−I) (I3). This assignment is supported by the further contraction of the Se−I distance to 2.5807 (14) Å and expansion of the I···I− distance to 3.2052 (10) Å relative to SDiazMesSe−I2. This I···I− distance would correspond to a calculated bond order of only 0.20. The C−Se length remains relatively unchanged [1.921 (10) Å] compared to SDiazMesSe−I2 (1.8973 (16) Å). The triiodide anion in both salts is asymmetric, with the two I···I lengths of 3.0222 (10) Å and 2.8492 (10) Å in [(SDiazMesSe−I) (I3)] and 3.0998 (6) Å and 2.8426 (6) Å in [(SDiazMesSe−I) (I3)] (DCM). This degree of asymmetry is in line with other reported triiodide salts (Kobra et al., 2018). In [(SDiazMesSe−I) (I3)], halogen bonding does not contribute to the long-range packing motif, beyond the aforementioned connection of one end of I3− to the Se−I fragment; however, in [(SDiazMesSe−I) (I3) (DCM)], a combination of I···I halogen bonding and Se···I chalcogen bonding contributes to the formation of chains along the a axis (Fig. 2).

The use of acetone as the reaction solvent allowed access to new organic products resulting from forming a new covalent bond between the chalcogen atom and a methyl carbon of acetone (Fig. 3). When the reaction of SDiazMesSe and 2.5 molar equivalents of diiodine was conducted in acetone, the salt [(SDiazMesSe−DMK) (I3)] (1) was obtained, displaying an added dimethylketone (DMK) fragment, resulting from the diiodine-promoted addition of an acetone molecule to the selenium atom. The slight elongation of the C−Se bond and negligible change in the C−N lengths suggest the positive charge is primarily localized to the selenium atom (Table 1). If a 1:1 mixture of ethanol and acetone was utilized as the reaction solvent for the reaction with 2.5 molar equivalents of I2, the isomorphic products [(SDiazMesS−MBK) (I3)] and [(SDiazMesSe−MBK) (I3)] were obtained, both crystallizing in the triclinic space group P1. The methylisobutylketone (MBK) fragment bound to the chalcogen atom results from the further bond formation of the methyl carbon of [(SDiazMesSe−DMK) (I3)] (1) with the carbonyl carbon of an additional acetone molecule along with deoxygenation. A related reaction involving the addition of acetone to a sulfur atom in 1,4-dithiane has been previously reported (Peloquin, Alapati et al., 2021). Just as in [(SDiazMesSe−DMK) (I3)] (1), the only slight lengthening of C−S and C−Se distances, along with a negligible change in C−N distances, relative to the parent molecule indicate the positive charge is primarily localized on the chalcogen atom. The triiodide anion is pinned in place by weak type I halogen bonds with the I2 molecule. While all attempts to isolate the analogous SDiazMesS-containing structure to [(SDiazMesSe−DMK) (I3)] (1) were unsuccessful, the isolation of [(SDiazMesSe−MBK) (I3)] does suggest its formation occurs. Adding ethanol to the reaction mixture reduces the overall solvent polarity and likely supports the solubility of the increased aliphatic character of the MBK fragment over DMK.

Figure 2
Views of the molecular structures of the products of the reaction of I2 with SDiazMesS and SDiazMesSe in non-acetone solvents. Intermolecular I···I and Se···I interactions are indicated by magenta and black dotted lines, respectively. Displacement ellipsoids are drawn at the 50% probability level. Hydrogen atoms are omitted for clarity.
3.4. Cocrystallization of SDiazMesS and SDiazMesSe with iodofluorobenzenes

The cocrystal (SDiazMesS)-(1,2-F₄DIB) crystallizes in the orthorhombic space group Pna₂₁ with one molecule each of SDiazMesS and 1,2-F₄DIB within the asymmetric unit (Fig. 4). C—I···S halogen bonding occurs between the thione sulfur atom and only one iodine atom of 1,2-F₄DIB, leading to the formation of discrete halogen bonded dimers. The halogen bond distance in this cocrystal, 3.2092 (12) Å, is significantly shorter than measured in the ternary cocrystal of thiourea, 1,2-F₄DIB, and 18-crown-6 [3.4680 (6) Å] (Topić & Rissanen, 2016). The lack of I···S halogen bonding to the second iodine atom is likely due to a combination of the steric bulk of SDiazMesS and the proximity of the iodine atoms in 1,2-F₄DIB. Neighboring dimers consolidate through a combination of weak C—H···I and C—H···S interactions. All attempts to isolate the corresponding SDiazMesSe cocrystal were unsuccessful.

With 1,3-F₄DIB as the halogen bond donor, four cocrystalline structures were obtained (Fig. 5). The first two, (SDiazMesS)-(1,3-F₄DIB) and (SDiazMesSe)-(1,3-F₄DIB), are isomorphic. Both cocrystals are obtained in the orthorhombic space group P2₁2₁2₁ with one molecule of either SDiazMesS or SDiazMesSe along with one molecule of 1,3-F₄DIB. A pair of nearly identical length C—I···S halogen bonds connect SDiazMesS or SDiazMesSe molecules with molecules of 1,3-F₄DIB in alternating fashion to form helical chains propagating along the b axis. The packing is consolidated along the a axis by weak C—H···π interactions and in the c direction by C—H···F interactions, both involving hydrogen atoms of the heterocyclic ring. The addition of a second equivalent of SDiazMesS or SDiazMesSe results in the cocrystals 2(SDiazMesS)-(1,3-F₄DIB) and 2(SDiazMesSe)-(1,3-F₄DIB). Just as in the 1:1 cocrystals, the 2:1 cocrystals are isomorphic with one another, crystallizing in the monoclinic space group C2/c. Discrete halogen bonding units are formed with only one halogen bond observed at each chalcogen atom. These units stack along the c axis through π···π stacking of the 1,3-F₄DIB rings, with ring plane-to-ring plane distances of 3.2840 (10) Å and 3.3046 (12) Å and slippage of 2.359 Å and 2.337 Å in 2(SDiazMesS)-(1,3-F₄DIB) and 2(SDiazMesSe)-(1,3-F₄DIB) respectively. These four cocrystals represent the first reported examples of...
halogen-bonded cocrystals of 1,3-F₄DIB with a thiourea or selenourea molecule.

The reaction with the common halogen bond donor 1,4-F₄DIB yielded two polymorphic structures with SDiazMesS: 2(SDiazMesS)-1,4-F₄DIB, which crystallized in the triclinic space group P̅1, and 2(SDiazMesS)-1,4-F₄DIB, which crystallized in the monoclinic space group P2₁/c. The triclinic isomorph, 2(SDiazMesSe)-1,4-F₄DIB, was obtained with SDiazMesSe (Fig. 6). All attempts to isolate the monoclinic isomorph with SDiazMesSe were unsuccessful. In all three cases, a single halogen bond is observed at each chalcogen atom, forming discrete units from two thione or selone molecules and one molecule of 1,4-F₄DIB. For the triclinic isomorphs, the halogen-bond geometry is nearly linear, with a C—I·S angle of 175.67 (9)° in 2(SDiazMesS)-1,4-F₄DIB and a C—I·Se angle of 173.97 (4)° in 2(SDiazMesSe)-1,4-F₄DIB. The iodine···chalcogen distances in these triclinic polymorphs [I···S = 3.2318 (7) Å and I···Se = 3.2553 (3) Å] are shorter than the analogous cocrystals with thiourea [I···S = 3.287 (12) Å] or selenourea [I···Se = 3.3151 (17) Å] (Arman et al., 2010; Chernysheva & Haukka, 2021). Weak chalcogen···hydrogen interactions contribute to the stacking of these discrete units along the a axis. In the monoclinic polymorph, while the discrete 2:1 halogen bonding units are maintained, the C—I···S halogen bond is elongated relative to the triclinic polymorph, and deviates significantly from linearity [143.57 (6)°]. This geometric arrangement may suggest an intermediate between true halogen and chalcogen bonds. The (C—)I iodine atom is also involved in a weak I···π interaction [3.646 (2) Å]. The repositioning of the 1,4-F₄DIB between the two SDiazMesS molecules in the monoclinic polymorph compared to the triclinic polymorph enable the iodine atoms to be involved in weak I···π interactions [3.646 (2) Å].

While the diiodotetrafluorobenzene-containing cocrystal systems discussed thus far show roughly equivalent behavior between sulfur and selenium, the 1,3,5-F₃I₃B cocrystals (SDiazMesS)-1,3,5-F₃I₃B and (SDiazMesSe)-1,3,5-F₃I₃B do display a subtle, but important difference (Fig. 7). In this pair, the structures are not isomorphic, with (SDiazMesS)-1,3,5-F₃I₃B crystallizing in the monoclinic space group P2₁/c and (SDiazMesSe)-1,3,5-F₃I₃B in space group P2₁/n. In both cases, a pair of iodine···chalcogen halogen bonds are observed at each chalcogen atom. Each of

![Figure 5](image-url)

Halogen bonding in the 1,3-F₄DIB-containing cocrystals. Intermolecular I···S and I···Se halogen bonding is indicated by magenta dotted lines. Displacement ellipsoids are drawn at the 50% probability level. Hydrogen atoms are omitted for clarity.
these interactions ranges in normalized distance parameter, $R_{XB}$, from 0.85 to 0.92. The third iodine atom of each 1,3,5-F$_3$I,B molecule drives the differences in the overall packing motif. Of the three symmetry unique 1,3,5-F$_3$I$_3$B molecules in (SDiazMesS)-(1,3,5-F$_3$I$_3$B), the third iodine atom of two of these (I2 and I8) have the appropriate geometric orientation to participate in a C—I···S halogen bond [C—I···S = 170.5 (2)$^\circ$ and 177.9 (2)$^\circ$], but the iodine···sulfur distance is well beyond the sum of the van der Waals radii ($R_{XB} = 1.12$ and 1.14). This series of interactions contributes to the formation of ring-link units consisting of six SDiazMesS and six 1,3,5-F$_3$I$_3$B molecules. The third iodine atom of the final symmetry unique 1,3,5-F$_3$I$_3$B molecule participates in a weak type I, I···I interaction. In (SDiazMesSe)-(1,3,5-F$_3$I$_3$B), two primary C—I···S halogen bonds ($R_{XB} = 0.90$ and 0.92) again occur at each selenium atom. However, the third iodine atom of each 1,3,5-F$_3$I$_3$B molecule drives a difference in the overall packing motif. In this case, a weak C—I···Se halogen bond occurs roughly at the sum of the van der Waals radii ($R_{XB} = 1.01$). This weak contact, probably enabled by the increased van der Waals radius of selenium over sulfur, and therefore decreased steric congestion around the chalcogen atom, is enough to consolidate the halogen bonding motif into a ladder-like chain propagating in the $c$ direction. These two cocrystals represent the first reported examples of halogen-bonded cocrystals of 1,3,5-F$_3$I$_3$B with a thiourea or selenourea.

With the halogen bond donor iodopentafluorobenzene (IF$_5$B), different reaction conditions were required for SDiazMesS and SDiazMesSe, resulting in dramatically
3.5. Co-crystallization of SDiazMesS and SDiazMesSe with tetaiodoethylene

The final pair of cocrystals, 2(SDiazMesS)-(TIE) and 2(SDiazMesSe)-(TIE), are both obtained in the triclinic space group P1, with one thione or selone molecule and one half of a TIE molecule in asymmetric unit. A single halogen bond is observed to the chalcogen atom, contributing to discrete 2:1 units within the structure (Fig. 9). The remaining two iodine atoms of each TIE molecule appear to be pinned in place by weak C—H···I interactions from methyl groups of a neighboring SDiazMesE molecule, contributing to the formation of ribbons in the bc plane.

4. Conclusions

The heterocyclic molecules hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-thione and hexahydro-1,3-bis(2,4,6-trimethylphenyl)-2H-1,3-diazepine-2-selone provided a robust template for halogen and/or chalcogen bonding interactions, yielding a total of 24 new cocrystal structures. The reaction with molecule diiodide provided products incorporating S—I—I and Se—I—I fragments with a wide range of bond orders. When this reaction was conducted in acetone, oxidative addition of acetone to the chalcogen atom allowed the formation of new C—S, C—Se and C—C covalent bonds under mild conditions. Co-crystallization with iodopentafluorobenzene, 1,2-, 1,3- and 1,4-diiodotetrafluorobenzene, 1,3,5-trifluorotriiodobenzene, and tetraiodoethylene reveals structures that, in most cases, show a preference for halogen over chalcogen bonding and are typically isomorphic. This series of structural data supports the power of crystallographic study to reveal unexpected and unique interactions and reaction pathways.

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References


