Chlorinated polyhedral selenaboranes revisited by joint experimental/computational efforts: the formation of \textit{closo}-1-SeB_9Cl_9 and the crystal structure of \textit{closo}-SeB_{11}Cl_{11}†

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The recent success in the formation of chlorinated telluraboranes and the reactivities of pnictogenaboranes prompted us to re-examine the vacuum co-pyrolysis of B_2Cl_4 with Se_2Cl_2 at various molar ratios and temperatures in order to search for the generation of other polyhedral selenaboranes than \textit{closo}-SeB_3Cl_6 (1a) and \textit{closo}-SeB_{12}Cl_{12} (1b), the latter being observed earlier. Interestingly, a new compound with the elemental composition SeB_9Cl_9 (2) was detected, this time by high- and low-resolution mass spectrometry. Further characterization by 1- and 2-D \textit{^{11}B}-NMR spectroscopy suggests that 2 should adopt a closed bicapped square-antiprismatic geometry with selenium at the apical position. Moreover, vacuum sublimation gave suitable crystals of 1b, which were subjected to single-crystal X-ray structure determination. Crystallographic data analysis confirmed that 1b, consistent with its 26 skeletal electron count, adopts a distorted icosahedral structure close to the symmetry of C_{5v}. Computations at the DFT-D3 level have revealed that 33% of the total computed binding motifs in the grown 1b crystals are due to the very strong chalcogen bonding. Moreover, SAPT decomposition has shown that the bonding motifs in the crystals are stabilized mainly by dispersion and electrostatic terms. Homodecoupling and high resolution \textit{^{11}B} NMR and \textit{^{77}Se} NMR experiments have resolved both coupling constants \textit{J\textit{^{11}B}\textit{^{11}B}} and \textit{J\textit{^{77}Se}\textit{^{11}B}} as well as the \textit{^{77}Se} chemical shift of 1a and 1b, which are in reasonable agreement with the corresponding computed values. The computed \textit{^{11}B} chemical shifts of 2 were determined by the well-established DFT/GIAO/NMR structural tool based on its B3LYP/6-311+G** internal coordinates. They agree well with the experimental values and provide a good representation of the molecular structure of 2 in solution. The extraordinary downfield \textit{^{11}B} NMR chemical shift of B(10) in 2 has been ascribed to the intensive paramagnetic contribution to the shielding tensor in this bicapped square-antiprismatic motif. Calculations of the synproportionation free energies of smaller (n – 1) \textit{closo}-selenaboranes with larger-sized (n + 1) ones support the extraordinary stability of octahedral, bicapped square-antiprismatic and icosaheiral \textit{closo} motifs in the SeB_{n}Cl_{n} family (n = 4−12).

Introduction

Polyhedral borane and heteroborane clusters are known for the presence of delocalized electron-deficient bonding and characterized by forming three-center, two-electron (3c–2e) bonds. This bonding is quite different from the organic chemistry that is dominated by classical two-center, two-electron (2c–2e) bonds. The trigonal faces of boranes and the so-called heteroboranes are assembled to create various three-dimensional shapes. There exist \textit{closo}-, \textit{nido}-, \textit{arachno}- and \textit{hypho}-type cages according to the so-called electron count. The \textit{closo}-systems belong to the most researched clusters predominantly represented, e.g. by octahedral \textit{closo}-B_6H_6^2−, bicapped square-antiprismatic \textit{closo}-B_{10}H_{10}^2− and icosaheiral \textit{closo}-B_{12}H_{12}^2−,
recognized as well-designed building blocks of boron cluster chemistry.7 The systematic replacement of formally neutral BX vertices in the closo-BnX2+ (X = H and/or halogens, n = 6, 10, 12) can lead to a variety of n-vertex closo-heteroboranes, either the parent or with terminal halogens. For example, isoelectronic closo-1-EBnXn (n = 5, 9, 11), known as chalcogenaboranes.5 Conceivably, there is a sort of similarity of such 3D chalcogenaboranes with 2D heterocyclic compounds exemplified by thiophene, selenophene, etc. The presence of chalcogens in suitably designed structural moieties results in the detection of the so-called chalcogen bonds responsible for crystal packing not only for chalcogenaboranes.4,6 However, the area of chalcogenaboranes turned out to be under-researched and just a few polyhedral selenaboranes SeBnH2 are known.7 Recently, we have reported on the synthesis and DFT/GIAO/NMR study of the perhalogenated selenaboranes closo-SeB2Cl2 (1a) and closo-SeB11Cl11 (1b) by the co-pyrolysis reaction of a 9 : 1 mixture of B2Cl4 with Se2Cl2 in vacuo at 330 °C.8 It is well known from the thermal disproportionation reactions of B2Cl4 with n-vertex boron subchlorides BnCln (n = 8–12)9 that the size n and the distribution of products strongly depend on the reaction temperature and time under thermolytic conditions: higher pyrolysis temperatures augment the amount of active BCl species (see eqn (1)) and thus increase the probability of the formation of larger cages. In the co-pyrolysis of B2X4 (X = Cl, Br) with phosphorus trihalide PX3 (X = Cl, Br), it has been shown that the formation of the main product, closo-1,2-P2B4X4 (X = Cl10X = Br10v), is accompanied by the larger homologs closo-1,10-P2B4Cl810v and closo-1,7-P2B4X10 (X = Cl10X = Br10v) as well as conjuncto-3,3′-(1,2-P2B4X3)2 (X = Cl10X = Br10v) when the temperature rises from 330 °C to 400 °C and when the molar B2Cl4 content is augmented. Furthermore, extensions of the geometric motifs formed by co-pyrolysis have been found with exoskeletal dihaloboryl groups in perhalogenated carboranes.11 In order to create new homologs of polyhedral selenaboranes, we have now reexamined the co-pyrolysis reaction of B2Cl4 with Se2Cl2 both by increasing the temperature and by altering the molar ratio of the reactants with respect to the conditions of our previous report. Under such conditions, a novel chlorinated selenaborane, i.e. closo-1-SeB2Cl2 (2) (Fig. 1), has now been detected. In addition, it was our intention to extend the still quite limited spectroscopic data of closo-SeB2Cl2 and closo-SeB11Cl11 available so far to allow comparisons with the data of the very recently reported related octahedral and icosahedral closo-telluraboranes.12

Results and discussion

It has been shown in all previous formations of heteroboranes via co-pyrolysis of B2X4 with elemental halides in vacuo that the incorporation of heteroatoms can only occur in the gas phase,10,12 and therefore the temperature during pyrolysis has to be high enough to vaporize both starting components, but not too high to cause the thermal degradation of the prospective heteroborane products (e.g. as a reverse reaction of eqn (4)). Under pyrolytic conditions, both Se2Cl2 and B2Cl4 are unstable and disproportionate to elemental selenium (eqn (3))13 and intermediate [BCl] species14 (eqn (1)), from which the latter can aggregate to boron subchlorides BnCln (n = 8–12, eqn (2))9 in a homo-component reaction or incorporate selenium into condensing [BCl] particles to the selenaborane products (eqn (4) and (5)) in hetero-component reactions.

We have now reexamined the co-pyrolysis of B2Cl4 with Se2Cl2 in vacuo (10−3 mbar) by altering both the temperature and molar conditions of our first report from 330 °C and 9 : 1 to (a) 350 °C and 7 : 1 or (b) 400 °C and 10 : 1. After the reaction, the product mixtures were thoroughly extracted with liquid BCl3, after which the extractant was evaporated in vacuo. The residues were separated into the two fractions volatile upon heating to T ≈ 180 °C in vacuo or volatile between T ≈ 180 °C and T ≈ 350 °C under these conditions, and were analyzed by 11B NMR spectroscopy and mass spectrometry.

Both experiments revealed the formation of closo-selenaboranes and boron subhalides BnCln (n = 8–11), the latter consisting mainly of BnCl10. The selenaborane portion in case (a) contained approximately equal amounts of closo-SeB2Cl2 (1a) in the more volatile fraction and closo-SeB11Cl11 (1b) together with smaller amounts of closo-1-SeB2Cl2 (2) in the less volatile fraction. In case (b), the more volatile fraction contained only very small amounts of 1a, while the less volatile fraction contained 1b in amounts that were approximately the same as in case (a). 2 could not be detected in (b). These results indicate that the generation of selenaborane 1a is favored both by a lower pyrolysis temperature and by a lower molar content of B2Cl4 in the starting mixture compared with the formation of 1b. 2 requires temperatures as high as 350 °C for formation. Due to their similar volatilities compared to those of the boron subhalide side-products BnCln, the selenaboranes 1a, 1b and 2 could not be completely separated by vacuum fractionation, where they sublimed as white solids at approximately 50 °C.
(1a), 200 °C (2) and 350 °C (1b), respectively. The final crystallization step for the isolation of 1a and 1b afforded a slow cooling of the sealed, evacuated samples from 200 °C (for 1a) or 350 °C (for 1b) to room temperature over a period of 20 h. However, from the obtained crystalline materials, only crystals of 1b were suitable for X-ray diffraction analysis. Selenaborane 2 could only be enriched by the extraction of the less volatile fraction with BCl3. Selenaboranes 1a, 1b and 2 are soluble in common aprotic hydrocarbon solvents, such as benzene, toluene, methylene chloride and chloroform. They are thermally stable at least up to their formation temperature, i.e. 400 °C.

Eqn (4) and (5) describe the overall conversion, but not the course of molecular formation and possible side reactions. Based on eqn (5), the gross yield of 2 was only 1%.

\[ n\text{B}_2\text{Cl}_4 \rightarrow n[\text{BCL}] + n\text{BCl}_3 \] (1)

\[ n[\text{BCL}] \rightarrow \text{B}_2\text{Cl}_4 \quad (n = 8-12) \] (2)

\[ 2\text{Se}_2\text{Cl}_2 \approx 3\text{Se} + \text{SeCl}_4 \] (3)

\[ \text{Se} + n[\text{BCL}] \rightarrow \text{SeB}_n\text{Cl}_n \] (4)

\[ 19\text{B}_2\text{Cl}_4 + \text{Se}_2\text{Cl}_2 \rightarrow 2\text{SeB}_6\text{Cl}_9(2) + 20\text{BCl}_3 \] (5)

In order to predict the relative stability of each member of the closo-SeBmCln family (n = 4–12), we calculated the “synproportionation” energies of reactions between a smaller (n − 1) and a larger (n + 1) selenaborane according to eqn. (6)–(12) to form the member with the number n of B–Cl vertices in between at the B3LYP/6-311+G**/ZPE level. The computations of these energy balances use the most stable positional isomers within a particular closo-selenaborane (for the individual molecular shapes, see also ref. 15). These computations strongly support the extraordinary stabilities of octahedral, bicapped square-antiprismatic and icosahedral closo motifs, which is fully consistent with the trend observed for perhydrogenated carbonanes16 and perchlorinated phosphorabanes.10d

\[ \text{1-SeB}_3\text{Cl}_4 + 2\text{SeB}_6\text{Cl}_9 \rightarrow 2\text{SeB}_6\text{Cl}_9(1a) -19.7 \] (6)

\[ \text{SeB}_3\text{Cl}_4(1a) + \text{1-SeB}_3\text{Cl}_4 \rightarrow 2 \text{2-SeB}_6\text{Cl}_9 0.3 \] (7)

\[ 2\text{SeB}_6\text{Cl}_9 + \text{1-SeB}_3\text{Cl}_4 \rightarrow 2 \text{1-SeB}_7\text{Cl}_7 1.8 \] (8)

\[ \text{1-SeB}_7\text{Cl}_7 + \text{1-SeB}_3\text{Cl}_4(2) \rightarrow 2 \text{1-SeB}_6\text{Cl}_8 13.7 \] (9)

\[ \text{1-SeB}_6\text{Cl}_8 + 2\text{SeB}_{10}\text{Cl}_{10} \rightarrow 2 \text{1-SeB}_7\text{Cl}_9(2) -18.8 \] (10)

\[ \text{1-SeB}_7\text{Cl}_9(2) + \text{SeB}_{11}\text{Cl}_{11}(1b) \rightarrow 2 \text{2-SeB}_{10}\text{Cl}_{10} 38.2 \] (11)

\[ 2\text{SeB}_{10}\text{Cl}_{10} + 2\text{SeB}_{12}\text{Cl}_{12} \rightarrow 2 \text{SeB}_{11}\text{Cl}_{11}(1b) -68.8(12) \] (12)

The 11B experimental and computed chemical shifts of 1a and 1b have already been given in our previous report, but as experimental ones without specifications. In analogy with closo-TeB5Cl5,12 the 11B NMR spectrum of 1a shows the reported two broad signals in a 1 : 4 ratio at 23.2 ppm (h1/2 ≈ 110 Hz) for B(6) and at 4.6 ppm for B(2–5) with the expected cross-peak in the COSY 11B11B NMR spectrum. The latter signal resolves to a quartet either by homodecoupling or by applying the Lorentz–Gaussian transformation with a 1/J(11B11B) of 27 Hz (the computed J value is 30.6 Hz, see below and the ESIF), thereby indicating coupling with B(6). Satellites of the signal at 4.6 ppm assume the coupling of B(2–5) with selenium, given by 1/J(77Se11B) ≈ 36.5 Hz (the computed K value is 22 Hz, see below and the ESIF). The 77Se NMR signal of 1a is very broad (h1/2 ≈ 236 Hz) due to the scalar interaction of 77Se with the 11B (and 10B) of B(2–5) at −149 ppm (see below for the computed value).

The 11B NMR spectrum of 1b shows the reported three signals in a 5 : 5 : 1 ratio at −3.3 (B7–11), 3.9 ppm (B2–6) and 17.3 ppm (B12) and the cross-peaks between B(7–11)/B(2–6) and B(7–11)/B(12) in the 11B11B COSY NMR spectrum. The individual values indicate the same trend as in the parent closo-SeB3H3.75 The 77Se NMR signal of 1b is very broad (h1/2 ≈ 220 Hz) due to the scalar interaction of 77Se with the 11B (and 10B) of B(2–6) at −31 ppm (see below for the computed value).

The 11B NMR spectrum of 2 consists of three signals in an approximately 4 : 4 : 1 ratio at 1.7 ppm, 16.8 ppm and 53.0 ppm (for the computed values, see Table 3). The signal at 1.7 ppm shows 11B11B cross-peak correlation with the other two signals and thus can be assigned to B(6–9), the signal at 16.8 ppm can be assigned to B(2–5), and the intensity-one signal at 53.0 ppm (also indicative of its very strong antipodal downfield shift) can be assigned to B(10). The chemical shifts and assignments of 2 are in agreement with those established for the corresponding parent selenaborane closo-1-SeB9H9,77 namely −19.9 ppm (B(6–9)), −5.4 ppm (B(2–5)) and +73.3 ppm (B(10)), with the last one representing an extreme value of antipodal deshielding. This effect has already been explained in relation to the δ(11B) of B(10) in closo-1-SeB9H9 to the much less pronounced downfield chemical shift of B(12) in closo-TeB5Cl5.16

The mass spectrum of selenaborane 2 exhibits a strong parent ion envelope with minor cut-offs, indicating the step-wise abstraction of BCl2 and BCl3 fragments, whose intensity patterns are consistent with the calculated spectra based on natural isotopic abundances.

On the basis of the NMR data and simple skeletal-electron counting rules,2 2 should adopt a bicapped square-antiprismatic geometry with selenium on apical position 1 contributing four electrons and each B–Cl unit two electrons to the cluster bonding.

Vacuum sublimation has given suitable crystals of 1b, which could be subjected to one of the rare examples of the single-crystal X-ray structure determination of a reported selenaborane.

The compound crystallizes in the non-centrosymmetric space group P21 with two crystallographically independent molecules of essentially identical geometry in the asymmetric unit (Fig. 2). In contrast to the structure of closo-TeB5Cl5,12 there are no signs of modulation.

As expected, the crystal packing forces in the crystals of 1b cause a slight deviation from the symmetry of C5v adopted for a single molecule of this perchlorinated icosahedral selenaborane. Some important bond lengths are collected in Tables 1 and 2. There are two notable geometrical trends: first, a
decrease in the B–B bond lengths with increasing distance from the Se atom, and second, a shortening of the B–Cl distances involving boron atoms bound to Se with respect to the others. Se–B bonds range from 2.166(2) to 2.175(2) Å [mean 2.169(3) Å] in molecule 1 and from 2.162(2) to 2.172(2) Å [mean 2.168(3) Å] in molecule 2. These values are significantly longer than those reported for the gas-phase structure of the parent compound closo-SeB_{11}H_{11} (2.129(2) Å),^7 see also Fig. 2.

The shape of the solid-state structure of 1b agrees with that already computed at the B3LYP/6-311+G** level of theory^8 and with the gas-phase structures of the corresponding icosahedral chalcogenaborane hydrides closo-EB_{11}H_{11} (E = Se, S) based on gas-phase electron diffraction (E = Se,^7 S^18c) and microwave spectroscopy (E = S^18b). However, due to the entirely different physical meanings of the interatomic distances derived using the structural tools mentioned above, the direct comparison must be taken with caution.

We have also examined the bonding motifs and electrostatic properties of 1a, 1b and 2 in bonding in terms of employing intrinsic bond orbitals (IBOs) and electrostatic potential (ESP) molecular surfaces in line with the earlier use of this class of materials.^19,20 As shown in Fig. 3, the ESP computations of 1a, 1b and 2 provide different patterns. The IBO charges on Se are 0.43 for 1a, 0.57 for 1b and 0.69 for 2. The application of the IBO approach has revealed the nature of bonding in these chlorinated selenaboranes (see Fig. 4 for example). The selenium atom seems to play a decisive role in the three kinds of IBOs in each of these three systems. According to the expansion coefficients (ECs: contributions from individual atoms to a particular IBO to illustrate the nature of such orbitals) associated with the contributions of individual atoms to these orbitals, they may be grouped as follows: there are two emerging IBOs with ECs (the contributing atoms in parentheses): 1.05 (Se), 0.52 (B) and 0.25 (B) as well as one IBO with ECs of 1.19 (Se), 0.57 (B) and 0.10 (B) in 1a. Whereas the first pair of IBOs may be considered of almost a 3c–2e nature, the second one is more or less of the 2c–2e-type. In 1b, the three IBOs in which Se is involved have the following ECs (the contributing atoms in parentheses): 1.07 (Se), 0.52 (B), 0.20 (B), and 0.12 (B); 1.07 (Se), 0.42 (B), and

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**Table 1** B–B bond lengths [Å] in 1b. The values in square brackets refer to the second independent molecule

<table>
<thead>
<tr>
<th>Atoms involved</th>
<th>Range</th>
<th>Mean</th>
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<tbody>
<tr>
<td>{B(2)⋯B(6)}–{B(2)⋯B(6)}</td>
<td>1.928(3) [1.935(3)]⋯1.945(3) [1.946(3)]</td>
<td>1.938(6) [1.942(4)]</td>
</tr>
<tr>
<td>{B(7)⋯B(11)}–{B(7)⋯B(11)}</td>
<td>1.805(4) [1.810(3)]⋯1.819(3) [1.814(3)]</td>
<td>1.812(5) [1.812(1)]</td>
</tr>
<tr>
<td>{B(7)⋯B(11)}–B(12)</td>
<td>1.789(4) [1.791(3)]⋯1.797(4) [1.802(3)]</td>
<td>1.793(3) [1.796(4)]</td>
</tr>
<tr>
<td>{B(2)⋯B(6)}–{B(7)⋯B(11)}</td>
<td>1.769(4) [1.772(4)]⋯1.779(3) [1.782(3)]</td>
<td>1.774(3) [1.776(3)]</td>
</tr>
</tbody>
</table>

**Table 2** B–Cl bond lengths [Å] in 1b. The values in square brackets refer to the second independent molecule

<table>
<thead>
<tr>
<th>Bond(s)</th>
<th>Range</th>
<th>Mean</th>
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<tbody>
<tr>
<td>B(2)–Cl(2)⋯B(6)–Cl(6)</td>
<td>1.740(3) [1.736(2)]⋯1.746(2) [1.744(2)]</td>
<td>1.744(2) [1.741(3)]</td>
</tr>
<tr>
<td>B(7)–Cl(7)⋯B(11)–Cl(11)</td>
<td>1.757(2) [1.761(2)]⋯1.775(2) [1.772(2)]</td>
<td>1.765(6) [1.766(5)]</td>
</tr>
<tr>
<td>B(12)–Cl(12)</td>
<td>1.768(3) [1.762(3)]</td>
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**Fig. 2** ORTEP plots of the molecular structure of 1b. For a compilation of salient bond lengths (r, Å), see Tables 1 and 2.
While the first IBO may be viewed as an orbital somewhere between 4c–2e and 2c–2e, the other two are of a 3c–2e nature. Finally, the bonding in the newly formed 2 is also based on the three IBOs grouped in two patterns, i.e. one of a 2c–2e nature with the ECs 1.15 (Se) and 0.54 (B) and two of the 3c–2e-type with the ECs 1.1 (Se), 0.54 (B) and 0.26 (B). The bonding in the other hemispheres (and between the hemispheres in 1b and 2) is predominantly of a 3c–2e nature, and the corresponding ECs are in the range of ca. 0.50–0.70. All the relevant computational details are provided in the ESI.†

It is the σ-hole concept that connects the popular halogen bonding with chalcogen, pnictogen bondings and other related noncovalent interactions. It is characterized by its magnitude, abbreviated as $V_{s,max}$. $V_{s,max}$ is defined as the value of the most positive ESP of an electron density surface. Thus, the $V_{s,max}$ values of closo-SeB$_5$Cl$_5$ (1a), closo-SeB$_9$Cl$_9$ (2) and closo-SeB$_{11}$Cl$_{11}$ (1b) are computed to be 25.8, 41.1 and 44.8 kcal mol$^{-1}$, respectively. The last result shows that the icosahedral perchlorinated selenaborane has a more positive $V_{s,max}$ than closo-SeB$_{11}$H$_{11}$ ($V_{s,max}$ of 29.5 kcal mol$^{-1}$). The last value is comparable with that of nido-7,8,9,11-Sb$_2$C$_2$B$_6$H$_9$ ($V_{s,max}$ of 42.7 kcal mol$^{-1}$) and explains why the chalcogen bonding$^{24}$ in 1b is so strong in terms of the crystal packing of the corresponding solid-state structure.

The above B3LYP/6-311+G** geometry of 2 has also been used in NMR shift computations using the GIAO-PBE1PBE model chemistry with the same basis set as in the derivation of the molecular geometry of 2, likewise successfully utilized in previous studies. The most striking feature of the molecular geometry of 2 is the considerable expansion of the square belt adjacent to selenium (see Fig. 1), with the analogous pentagonal belt adjacent to Se in 1b exhibiting the same pattern.

We have also provided the computed $^{77}$Se NMR chemical shifts (in ppm, with respect to Me$_2$Se; experimental values of compounds 1a and 1b are given in parentheses; see Table 3), which are nicely related to the experimental values. The $^{11}$B NMR chemical shifts of 2 at the same GIAO-PBE1PBE/B3LYP/6-311+G** level are computed as shown in Table 3. Note that B(10) in 2 resonates at ca. 20 ppm less (in the upfield direction) with respect to the parent closo-1-SB$_5$H$_9$.Basically, there is very good agreement with the computed values, i.e. the B3LYP/6-311+G** internal coordinates represent a very good approximation of the molecular geometry of 2 in solution.

The most striking feature of the electronic structure of 2 is the resonation of the B(10) vertex in the $^{11}$B NMR spectrum at a frequency of ca. 52 ppm. This is a result of the intensive paramagnetic contribution to the shielding tensor in this bicapped square-antiprismatic system. Such a contribution arises from
Table 3  Computed* and experimental $^{77}\text{Se}$ and $^{11}\text{B}$ chemical shifts with respect to BF$_3$OEt$_2$ and Me$_2$Se, respectively, for a series of bicapped square-antiprismatic, octahedral, and icosahedral selenaboranes

<table>
<thead>
<tr>
<th>Bicapped square-antiprismatic motifs</th>
<th>$\delta$ (11B)</th>
<th>$\delta$ (77Se)</th>
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<tbody>
<tr>
<td>2</td>
<td>-511</td>
<td>16.6 16.8</td>
</tr>
<tr>
<td>Exp.</td>
<td>-231</td>
<td>-5.9 1.7</td>
</tr>
<tr>
<td>closo-SeB$_5$H$_4$</td>
<td>-519</td>
<td>-9.4 24.7</td>
</tr>
<tr>
<td>Exp.</td>
<td>-57</td>
<td>-5.4 7.0</td>
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<thead>
<tr>
<th>Octahedral motifs</th>
<th>$\delta$ (11B)</th>
<th>$\delta$ (77Se)</th>
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<tbody>
<tr>
<td>1a</td>
<td>-216</td>
<td>5.5' 18.2'</td>
</tr>
<tr>
<td>Exp.</td>
<td>-146.2</td>
<td>4.6' 23.2'</td>
</tr>
<tr>
<td>closo-SeB$_5$H$_4$</td>
<td>45</td>
<td>4.8 31.9</td>
</tr>
<tr>
<td>6-Cl-closo-SeB$_5$H$_4$</td>
<td>-406</td>
<td>1.7 26.6</td>
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<thead>
<tr>
<th>Icosahedral motifs</th>
<th>$\delta$ (11B)</th>
<th>$\delta$ (77Se)</th>
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<tbody>
<tr>
<td>1b</td>
<td>-92</td>
<td>3.4' 14.4'</td>
</tr>
<tr>
<td>Exp.</td>
<td>-31</td>
<td>3.9' 17.3'</td>
</tr>
<tr>
<td>closo-SeB$<em>{11}$H$</em>{12}$</td>
<td>213</td>
<td>-3.8' 25.2'</td>
</tr>
<tr>
<td>12-Cl-closo-SeB$<em>{11}$H$</em>{10}$</td>
<td>-57</td>
<td>-5.4 7.0</td>
</tr>
</tbody>
</table>

* GIAO-PBE1PBE/B3LYP/6-311+G**. † From ref. 7f. ‡ The computed $^{11}$B chemical shifts are compatible with those derived at GIAO-B3LYP/B3LYP/6-311+G** given in ref. 1. ‡ The experimental chemical shifts are compatible with those given in ref. 8, see also the ESL." The computed $^{11}$B chemical shifts are compatible with those given in ref. 7e and with the experimental values reported therein.

The computed $^{11}$B chemical shifts are known. They are computed to be zero for each of the Se–B and Se⋯B pairs for all the compounds under scrutiny, obviously due to a very large amount of Se isotopes. Therefore, the coupling constants $K$ are computed instead, i.e. exclusively those between the $^{77}$Se and $^{11}$B nuclei. Since spins of these nuclei differ, viz 3/2 for $^{11}$B and 1/2 for $^{77}$Se, the former exhibits four spin functions with eigenvalues of $-3/2$, $-1/2$, 1/2, and 3/2 in contrast to just two such functions for $^{77}$Se ($-1/2$, 1/2). For the algebraic derivation of such function for $^{11}$B, see ref. 26. On this basis the coupling constants $K$ for $^{77}$Se $^{11}$B are relatively small. However, computations of the coupling constants of the $J$-type between the B atoms were performed (the $^{10}$B isotope is also included in the computations) and the values obtained are obviously larger than the $K$ ones.

The coupling of suitably occupied and unoccupied MOs, i.e. the HOMO and the LUMO, with large coefficients on the antipodal atom B(10). For this overlap in 2, see Fig. 5. This explanation is also valid in the case of closo-1-SeB$_5$H$_4$, where the overlap is even more pronounced, which is in line with the higher downfield $^{11}$B NMR chemical shift of this atom, namely ca. 75 ppm. Interestingly, there is a significant correlation between $\delta$s ($^{77}$Se) and $\delta$s ($^{11}$B-antipodal) for 1a, 1b, and 2 (see Scheme 1), which indicates a direct transformation of the electron density from an obviously deshielded antipodal boron atom towards the shielded selenium through the corresponding body diagonal. The latter observation might serve as an additional proof of the antipodal effect for these three structural motifs. On the selenium bicapped square-antiprismatic front, we have also looked at closo-1-SeB$_5$H$_4$, for which the $^{11}$B chemical shifts are known. The downfield shift of B(10) in the latter compound is even larger than that in 2 and also that in closo-1-SeB$_5$H$_4$ mentioned earlier, see also Table 3. In contrast, the computed upfield shift of $^{77}$Se is less pronounced than that in 2, see also Scheme 1 that also shows a nice correlation between $\delta$s ($^{77}$Se) and $\delta$s ($^{11}$B-antipodal) for SeB$_5$H$_4$, 1-SeB$_5$H$_4$, and SeB$_5$H$_4$. In contrast, there is no such a correlation between $\delta$s ($^{77}$Se) and $\delta$s ($^{11}$B-antipodal) for 4-Cl-SeB$_5$H$_4$, 10-Cl-SeB$_5$H$_4$, and 12-Cl-SeB$_{11}$H$_{10}$ ($\rho^2 = 0.43$).

The coupling constants $J$ for $^{77}$Se $^{11}$B are computed to be zero for each of the Se–B and Se⋯B pairs for all the compounds under scrutiny, obviously due to a very large amount of Se isotopes. Therefore, the coupling constants $K$ are computed instead, i.e. exclusively those between the $^{77}$Se and $^{11}$B nuclei. Since spins of these nuclei differ, viz 3/2 for $^{11}$B and 1/2 for $^{77}$Se, the former exhibits four spin functions with eigenvalues of $-3/2$, $-1/2$, 1/2, and 3/2 in contrast to just two such functions for $^{77}$Se ($-1/2$, 1/2). For the algebraic derivation of such function for $^{11}$B, see ref. 26. On this basis the coupling constants $K$ for $^{77}$Se $^{11}$B are relatively small. However, computations of the coupling constants of the $J$-type between the B atoms were performed (the $^{10}$B isotope is also included in the computations) and the values obtained are obviously larger than the $K$ ones.

The HOMO (A) and the LUMO (B) of closo-1-SeB$_5$Cl$_9$ (2).
Cules within 5 Å of the first layer. The obtained overall binding of molecule 2 is summarized in Table 4. Molecule 1 is expected to exhibit very similar energetic balances. Concerning the energy criteria in the crystals of 1b, the $\Delta E^2$ values of the most favorable interaction motifs in the reported X-ray crystal structure of 1b are summarized in Table 5. The chalcogen-bonding motifs (i.e. the motifs 2:A and 2:B) had $\Delta E^2$ values of $-7.93$ and $-7.20$ kcal mol$^{-1}$ at the DFT-D3 level, thus accounting for about 33% of the total computed binding of 1b. The SAPT0 decomposition showed that the chalcogen-bonding motifs were stabilized mainly by dispersion, which formed approximately 57% of the attractive terms. The second most important term was electrostatic, forming about 31% of the attractive terms. The remaining motifs had considerably less negative $\Delta E^2$ values with a very large contribution of the dispersion energy (about 84%).

### Conclusions

The successful chemistry of chlorinated telluraboranes and pnictogenaboranes initiated the repetition of the vacuum co-pyrolysis of B$_2$Cl$_4$ with Se$_2$Cl$_2$ at various molar ratios and temperatures in search of the generation of other polyhedral closo-selenaboranes than SeB$_5$Cl$_5$ (1a) and SeB$_{11}$Cl$_{11}$ (1b). Indeed, bicapped square-antiprismatic closo-1-SeB$_6$Cl$_6$ (2) was detected this time by 1- and 2-D $^{11}$B NMR spectroscopy and exact mass spectrometry. In addition, vacuum sublimation provided suitable crystals of 1b, which were successfully diffraction by means of the single-crystal X-ray technique, and the first solid-state structure in the family of chlorinated selenaboranes was determined; in it, the structure of 1b slightly departs from the symmetry of $C_{5v}$, apparently due to the corresponding crystal packing. Interestingly, the computations at the DFT-D3 level have revealed that 33% of the total computed binding motifs in the 1b crystal are caused by very strong chalcogen bonding. The subsequent SAPT decomposition illustrates that the bonding motifs in the crystals are mainly attributable to the dispersion and electrostatic terms. The more refined techniques of $^{11}$B NMR and $^{77}$Se NMR spectroscopy have resolved the coupling constants and $^{77}$Se chemical shifts of 1a and 1b, which are in good agreement with their computed values. The extraordinary downfield $^{11}$B NMR chemical shift of B(10) in 2 has been ascribed to the intensive paramagnetic contribution to the shielding tensor in this bicapped square-antiprismatic

### Table 4

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\sum \Delta E^2$ (1st layer)</th>
<th>$\sum \Delta E^{MB}$ (1st layer)</th>
<th>$\sum \Delta E^2$ (2nd layer)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeB$<em>4$Cl$</em>{11}$ (1b)</td>
<td>-46.87</td>
<td>5.46</td>
<td>-4.09</td>
<td>-45.50</td>
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</table>

### Table 5

<table>
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<th></th>
<th>DFT-D3</th>
<th>SAPTO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>$E_{\text{elec}}$</td>
</tr>
<tr>
<td>2:A</td>
<td>-7.93</td>
<td>-9.34</td>
</tr>
<tr>
<td>2:B</td>
<td>-7.20</td>
<td>-8.12</td>
</tr>
<tr>
<td>2:C</td>
<td>-3.98</td>
<td>-3.32</td>
</tr>
</tbody>
</table>
motif. Attempts at obtaining other perhalogenated heteroboranes and the subsequent structural studies are in progress in our laboratories, in particular, in relation to 2D-aromatic heterocycles.

Conflicts of interest
There are no conflicts to declare.

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