Directed Dehydration as Synthetic Tool for Generation of a New Na₄SnS₄ Polymorph: Crystal Structure, Na⁺ Conductivity, and Influence of Sb-Substitution

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Abstract: We present the convenient synthesis and characterization of the new ternary thiostannate Na₄SnS₄ (space group I4₁/acd) by directed removal of crystal water molecules from Na₄SnS₄·14H₂O. The compound represents a new kinetically stable polymorph of Na₄SnS₄, which is transformed into the known, thermodynamically stable form (space group P4₂_1/c) at elevated temperatures. Thermal co-decomposition of mixtures with Na₃SbS₉·9H₂O generates solid solution products Na₄₋ₓSnₓ₋₁SbₓS₄ (x = 0.01, 0.10) isostructural to the new polymorph (x = 0). Incorporation of Sb⁺⁺ affects the bonding and local structural situation noticeably evidenced by X-ray diffraction, ¹¹¹Sn and ⁷⁷Na NMR, and ¹¹¹Sn Mössbauer spectroscopy. Electrochemical impedance spectroscopy demonstrates an enormous improvement of the ionic conductivity with increasing Sb content for the solid solution (σ₂₅°C = 2 × 10⁻³, 2 × 10⁻², and 0.1 mS cm⁻¹ for x = 0, 0.01, and 0.10), being several orders of magnitude higher than for the known Na₄SnS₄ polymorph.

Introduction

The structures of thioantimonate compounds include different anionic units like [SnS₄]⁻, [SnS₄]⁺, [Sn₂S₆]⁻, [Sn₂S₆]⁺, [Sn₃S₄]⁻, [Sn₃S₄]⁺, [Sn₄S₈]⁻, [Sn₄S₈]⁺, or [Sn₅S₁₂]⁺, which are charge compensated by metal cations. The structural versatility of thioantannate anions is due to the variable coordination number as well as the variable oxidation state of Sn. In the above-mentioned thioantannate anions Sn exhibits the coordination number 4 (tetrahedron), 5 (trigonal bipyramid), or 6 (octahedron). In addition, Sn occurs mainly in the oxidation state IV, but compounds with different oxidation states like II/IV or III/IV were also reported. Thiostannates with metal cations as counter ions were mainly synthesized using the molten-flux approach or via high-temperature syntheses. Thiostannates with protonated amine molecules, transition metal cations, or transition metal complexes as counter ions compensating the negative charge of the [SnS₄]⁻ anions were mostly prepared under solvothermal conditions. Applying suitable precursors, the preparation of thiostannates at room temperature was also reported. These examples demonstrate the broad variety of synthetic approaches established in the thiostannate chemistry.

Motivated by the intense research in the field of all-solid-state batteries (ASSBs), where sulfidic compounds came into the focus including thiosulfates or thioantimonate based solid electrolytes, we searched for possible solid-state electrolytes (SSEs) on the basis of chalcogeniosostannates. Indeed, first steps in this direction were reported for Li⁺ SSEs: Li⁺ ion conducting thio- and selenostannates were prepared by a high-temperature route combined with extraction or thermal evaporation of electrolyte. Methods of intermediately synthesized solvates.

More recently, mixed quaternary Na⁺ superionic conductors based on the thiostannate chemistry were discovered, e.g., the series of compounds Na₄₋ₓSnₓ₋₁SbₓS₄ and Na₁₋ₓSnₓPS₁₂ show promising room temperature Na⁺ ion conductivities > 0.5 mS cm⁻¹. Moreover, excellent cycling and rate stabilities were observed using Na₄₋ₓSnₓPS₁₂ and Na₁₋ₓSnₓPS₁₂ as SSEs in ASSB full cells. In addition, such thioantimonate based SSEs exhibit broad electrochemical windows, e.g., no redox reactions occur for Na₁₋ₓSnₓPS₁₂ vs. Na⁺/Na between 0.3–3.2 V. The preparation of such SSEs is mainly performed applying classic high-temperature solid-state methods or sintering processes of appropriate...
precursors at high temperatures. The directed removal of crystal water molecules from hydrated solids is an elegant alternative synthetic approach. This was also applied for Na$_3$SbS$_4$·9H$_2$O yielding dehydrated Na$_3$SbS$_4$ with remarkable high ionic conductivity and an excellent electrochemical stability between 0–5.0 V vs. Na$^+$/Na. However, hydrated thiospinates comprising transition metal complexes or organic cations are often irreversibly destroyed during removal of water molecules, and thus suitable “pure” inorganic crystal water containing compounds have to be identified as possible candidates for Na$^+$ ion conductors like already demonstrated for the lighter homologue Li. A prominent example is Na$_4$SnS$_4$·14H$_2$O which was reported already decades ago. Here, we report on the thermal properties of this compound, the crystal structure of a new metastable polymorph of Na$_4$SnS$_4$, the co-decomposition of Na$_4$SnS$_4$·14H$_2$O and Na$_3$SbS$_4$·9H$_2$O, the ionic conduction properties, $^{119}$Sn Mössbauer, and $^{23}$Na as well as $^{119}$Sn magic-angle spinning (MAS) NMR characterization of the materials.

Results and Discussion

The thermal properties of Na$_3$SnS$_4$·14H$_2$O (I) were investigated using simultaneously thermogravimetry (TG) and differential thermoanalysis (DTA). Upon heating I to 300°C, two steps are observed in the TG curve accompanied by intense and broad endothermic events in the DTA curve ($T_p=66$ and 142°C) (Figure 1a). The mass loss of 42.4 % at 170°C matches well with that calculated for the removal of all H$_2$O molecules (42.6 %), which is confirmed by $^1$H MAS NMR (Figure S1). The X-ray powder diffraction (XRPD) pattern of the product obtained at 300°C (Figure S2) is dominated by reflections of a new compound with composition Na$_4$SnS$_4$ (II) with small amounts (~4 wt %) of literature known Na$_4$SnS$_4$ (III), which was prepared at elevated temperatures. A second thermal experiment was stopped at 170°C and the XRPD pattern reveals only reflections of II (Figure 1b). A suitable structural model for II was refined via Rietveld method (Figure 1c, details in Supporting Information). The preparation of phase-pure II is scalable, as confirmed by further syntheses using an inert gas furnace.

We hypothesize that II formed by heating of I with a rate of 4 K min$^{-1}$ up to 170°C is kinetically stabilized. Hence, I was heated to 300°C with a lower heating rate of 1 K min$^{-1}$ (Figure 2a) exhibiting significant differences in the TG curve compared to that recorded with 4 K min$^{-1}$, showing at least three not well resolved reaction steps accompanied by two broad endothermic events in the DTA curve ($T_p=62$ and 92°C). The weight loss (41.4 %) is already finished at

Figure 1. a) TG, DTA and derivative TG (DTG) curves of I (heating rate: 4 K min$^{-1}$, N$_2$ atmosphere); b) XRPD pattern of a TG product of I recovered at 170°C (4 K min$^{-1}$) compared to simulated (sim.) patterns of the known Na$_4$SnS$_4$ polymorph (III) and of I; c) final Rietveld plot revealing the new polymorph Na$_4$SnS$_4$ (II), the inset shows a magnification at high angles.
\(\approx 105^\circ C\) in reasonably good agreement with the emission of all crystal water molecules. A second TG run was performed to 140°C and independent from the final temperature (140 or 300°C), the XRPD patterns show reflections of II and of III (Figure 2b). Quantitative analyses (Figure S3) reveal that the amount of III increases during heating from \(\approx 54\) wt % at 140°C to \(\approx 67\) wt % at 300°C, thus the kinetically stabilized polymorph II transforms into III.

Further TG experiments were performed up to 620°C and 700°C (heating rate: 1 K min\(^{-1}\)) showing a broad exothermic event at \(T_p = 563^\circ C\) (Figure S4). The XRPD patterns (Figure S5) are now dominated by reflections of III (+95 wt % in TG product recovered at 700°C, Figure S6).

These investigations evidence that III is the thermodynamically stable polymorph over the entire temperature range.

The new Na\(_4\)SnS\(_4\) polymorph (II) crystallizes in the tetragonal space group (SG) \(I_4/1\text{acd}\) (no. 142) with \(a = 13.8413(2)\), \(c = 27.4232(4)\) Å, \(V = 5253.80(12)\) Å\(^3\) and \(Z = 24\) (Table S1 and S2). The structure of II (Figure 3) comprises two unique Sn atoms located on special positions, three crystallographically independent S atoms on general positions, four Na atoms on special positions, and one Na atom on a general position (Table S2). A sixth “interstitial” Na site in loose coordination to eight S atoms (“Na\(_6\) void” in Figure S7), which is partially occupied in Na\(_{11}\)Sn\(_2\)MS\(_{12}\) (M =...
Sb and P).[^47,48,50,67] is not detected for II. One has to keep in mind that reliable information about low-level occupation of light elements can hardly be extracted from in-house XRPD data. Both Sn\(^{4+}\) cations are tetrahedrally coordinated by \(\text{S}^2-\) anions and can be described as \(\text{Na}_3\text{Sn}_2\text{PS}_{12}\) with Sn1 located in \([\text{SnS}_4]\) (Table S6, dark blue in Figure 3) and Sn2 in \([\text{SnS}_4]\) (light blue in Figure 3), respectively. According to literature, P and Sb are located on a special position in \(\text{Na}_{11}\text{Sn}_2\text{PS}_{12}\) and \(\text{Na}_{11}\text{Sn}_2\text{SbS}_{12}\) and substitution of Sn\(^{4+}\) by \(>1/3\) P\(^{4+}\) or Sb\(^{5+}\) leads to formation of additional phases (e.g. Na\(_4\)PS\(_{12}\) or Na\(_4\)SbS\(_{12}\))[^46-50,50] or results in another crystal structure (e.g. Na\(_8\)Sn\(_3\)PS\(_{12}\)).[69] Using a general notation \(\text{Na}_{12-3x-3y}\text{Sn}_x\text{P}_{12-x}\text{Sb}_{3y}\text{S}_{12}\), corresponding to the formula \(\text{Na}_{4-x-...\text{Sb}_{3y}}\text{Sb}_{x}\text{S}_{y}\) II can be described as the new pure thiostannate \((x = 0, y = 0)\) of this structural family.

Na–S distances are observed at 2.7–3.3 Å (Table S6) and a distance gap occurs between 3.3 and 3.7 Å (Figure S10) for II, indicating that ionic bonding interactions are present <3.3 Å and very weak interactions in an enlarged environment. Taking the sum of ionic radii as a limit for ionic bonds, the Na\(^+\) cations are in three different coordination environments (Table S6): Na1 is in a distorted trigonal-bipyramidal \(\text{S}^2-\) coordination (Na–S between 2.849–3.189 Å), and a sixth \(\text{S}^2-\) anion is located at Na1–S1: 3.810 Å. Na2 is tetrahedrally surrounded by \(\text{S}^2-\) (Na–S: 2.793–2.924 Å) with additional weak interactions to two \(\text{S}^2-\) (Na2–S2: 3.696 Å). Na3, Na4, and Na5 are in a highly distorted octahedral geometry of \(\text{S}^2-\) (Na–S: 2.719–3.270 Å). Considering also weak interactions <4 Å, all Na\(^+\) cations are located in highly distorted Na\(_x\)S\(_y\) octahedra. Noticeably, the longest Na–S distance in these Na\(_x\)S\(_y\) polyhedra is distinctly larger for II (Na1–S1: 3.810 Å), than those reported for Na\(_3\)Sn\(_2\)MS\(_{12}\) (M=Sb and P, Na–S ≤ 3.572 Å and ≤3.361 Å, respectively).[^59]

A three-dimensional network is generated by edge- and corner-sharing of Na\(_x\)S\(_y\) polyhedra, and a detailed description of interconnections is given in the Supporting Information (see Figure S7). This network exhibits nearly linear and zigzag Na\(^+\) cation chains along the c-axis and in the ab-plane (Figure 3a and b) with interatomic Na–Na distances of 3.297–3.593 Å (Figure 3c, Table S6). Each Na\(^+\) is in almost square planar environment of four Na\(^+\), leading to a distorted NbO-topology substructure prominent for, e.g., Na\(_3\)Sn\(_3\)PS\(_{12}\).[48,67]

The literature known Na\(_4\)Sn\(_2\)S\(_4\) polymorph (III) crystalizes in the tetragonal SG P4\(_2\)c (no. 114) with \(a = 7.84679(3)\) and \(c = 6.95798(4)\) Å, \(V = 428.42(1)\) Å\(^3\) and \(Z = 2\) (Table S1, S5), close to values already reported.[8,90] In this structure (Figure 4, 2 × 2 × 4 unit cells for comparability with II) all Sn\(^{4+}\) cations are located on one special position and are tetrahedrally coordinated by \(\text{S}^2-\) (Sn–S: 2.380 Å). The Na\(^+\) cations are located on one general position and are surrounded by five \(\text{S}^2-\) (Na–S: 2.809–3.113 Å, Table S7). These Na\(_x\)S\(_y\) units are linked by sharing common edges and joined to the Sn\(_x\)S\(_y\) tetrahedra by edge-sharing. In contrast to II, several Na\(^+\) cations are located in the voids between Sn\(_x\)S\(_y\) units. The Na–Na contacts in III (Figure 4c) are similar in the ab-plane (3.425–3.534 Å) to those in II (3.463–3.525 Å), but significantly longer along the c-axis (dotted lines in Figure 4c) (III: 3.669 Å vs. II: 3.293 and 3.595 Å, see Figure S11).

Applying the same fast and moderate temperature approach as for II (\(x = 0\)), samples containing Sb (IIa, \(x = 0.01\), IIb \(x = 0.10\)) were prepared by co-decomposition of stoichiometric amounts of Na\(_x\)Sn\(_2\)S\(_4\)·14H\(_2\)O and

![Figure 4](https://example.com/figure4.png)  
**Figure 4.** Structure of III: 2 × 2 × 4 unit cells a) along [001], b) along [100] (note: Na–S bonds are hidden), c) Na–Na connections (dotted lines represent connections >3.6 Å).
Na₃SbS₄·9H₂O at 170 °C (details in Supporting Information) to obtain Na₄ₓSn₁ₓSbₓS₄ with low Sb contents.

Rietveld refinements (Figure S8) reveal that this easy, scalable, and cost-effective synthetic approach yields phase-pure products IIa and IIb crystallizing isostructurally to II in I₄₁/acd with lattice parameters a = 13.8399(3) and 13.8284(3) Å, c = 27.4273(8) and 27.4679(8) Å, V = 5253.51(22) and 5252.55(24) Å³, respectively (Tables S1, S3 and S4), in good agreement with values reported for, e.g., Na₃.95Sn₀.95Sb₀.05S₄ (a = 13.8362 Å, c = 27.4499 Å, V = 5255 Å³).

The lattice parameters for IIa are between those for II and IIb (Figure S9), evidencing that even the substitution of only x = 0.01 was successful. Some structural features should be discussed for this solid solution with increasing Sb content: i) expansion of the unit cell along the c-axis and contraction in the ab-plane (Figure S9); ii) a narrower gap between near and far Na–S distances assuming highly distorted NaS₆ octahedra with the longest distance in all NaS₆ polyhedra to be 3.810, 3.754, and 3.666 Å for x = 0, 0.01, and 0.10 (Figure S10 and Table S6); iii) a more uniform distribution of distances along the c-axis in the NbO-like Na⁺ cation sublattice (longest-shortest Na–Na separation: 0.30, 0.23, and only 0.04 Å for x = 0, 0.01, and 0.10, Figure S11, Table S6); iv) only small changes (<0.03 Å) of Na–Na separations in the ab-plane (Figure S11, Table S6).

The local environments of Sn⁴⁺ and Na⁺ cations in II, IIa, and IIb were further investigated by solid-state ¹¹⁹Sn and ²³Na MAS NMR (Figure 5a and b, also Figure S12) and ¹¹⁹Sn Mössbauer spectroscopy (Figure 5c). Parameters derived from these experiments are given in Table 1. The ¹¹⁹Sn MAS NMR peaks p₁ p₁' p₂ p₃ p₄

|                | II (x = 0)   | IIa (x = 0.01) | IIb (x = 0.10) |
|----------------|--------------|----------------|----------------|
| ¹¹⁹Sn MAS NMR  | δ [ppm]      | δ [ppm] IS [mm s⁻¹] I [mm s⁻¹] | δ [ppm] IS [mm s⁻¹] I [mm s⁻¹] | δ [ppm] IS [mm s⁻¹] I [mm s⁻¹] |
| p₁ (75.6)      | 84.7(1)      | 84.6(1)        | 84.3(1)        |
| p₁' (75.6)     | 81.4(1)      | 81.4(1)        | 81.4(1)        |
| p₂ (75.6)      | 75.6(1)      | 75.5(1)        | 75.4(1)        |
| p₃ (75.6)      | 75.6(1)      | 75.5(1)        | 75.4(1)        |
| p₄ (75.6)      | 75.6(1)      | 75.5(1)        | 75.4(1)        |

Table 1: Results of ¹¹⁹Sn and ²³Na MAS NMR and ¹¹⁹Sn Mössbauer spectroscopy for II, IIa, and IIb (Na₄ₓSn₁ₓSbₓS₄, x = 0, 0.01, 0.10): chemical shift δ, isomer shift IS, and line width I.
The NMR spectrum (Figure 5a) for II exhibits two peaks at 84.7(1) ppm (p1) and 75.6(1) ppm (p2) with an intensity ratio of \( A_{p1} : A_{p2} \approx 2:1 \). Hence, p1 is assigned to Sn\(^{4+} \) cations on the crystallographic Sn1 site and p2 to those located on the Sn2 site. The chemical shifts are comparable to values reported for SnS\(_4\) tetrahedra in the solid polymorph III\(^{[38]} \) and for [SnS\(_4\)]\(^{2-} \) units in the liquid-state.\(^{[2,7]} \) With increasing Sb content (IIa and IIb), a shift of p1 and p2 to lower values, broader signals, and a higher degree of peak asymmetry is observed. Additionally, a third peak (p1') close to p1 appears. These observations point towards an increased shielding around Sn\(^{4+} \) cations and local distortion of the polyhedra caused by Sn\(^{4+} \) cations in the nearby environment. An intensity ratio of \( A_{p1+p1'} : A_{p2} \approx 2:1 \) is determined for all samples, leading to the conclusion, that p1' represents Sn\(^{4+} \) cations on the Sn1 site which are in close proximity to Sn\(^{4+} \) cations, thus being in a different local environment than Sn\(^{4+} \) cations close to other Sn\(^{4+} \) cations only. In all \(^{23}\)Na MAS NMR spectra (Figure 5b), two peaks at \( \approx 12.8 \) (p3) and \( \approx 6.9 \) ppm (p4) are detected. No \(^{23}\)Na MAS NMR data is reported for Na\(_2\)SnS\(_4\)S\(_2\), but a single and sharp \(^{23}\)Na MAS NMR signal is observed for Na\(_2\)SnP\(_4\)S\(_8\)\(^{[40]} \) and Na\(_4\)Sn\(_2\)P\(_4\)S\(_8\)\(_{2+}\)\(^{[40]} \) despite six crystallographically distinct Na sites, resulting from fast ionic motion in the NMR time frame. We assume a comparable situation for Na\(_4\)Sn\(_2\)S\(_8\)S\(_2\). A distinctly lower peak intensity of p4 in IIa and IIb compared to II is a good hint that more Na\(^{+} \) cations participate in the ion motion if Sn\(^{4+} \) is substituted by Sn\(^{4+} \).

All \(^{119}\)Sn Mössbauer spectra (Figure 5c) can be well fitted with a singlet with isomer shifts in the range 1.15(1) \( \text{mm s}^{-1} \) and a full width at half maximum of about 0.9 \( \text{mm s}^{-1} \). Similar values have been reported for III\(^{[4]} \) and Li\(_2\)SnP\(_4\)S\(_8\)\(^{[73]} \). This peak is thus assigned to Sn\(^{4+} \) cations in the tetrahedral S\(^2- \) environments. The different Sn environments in the crystal structure are too similar to be discriminated by Mössbauer spectroscopy. Nonetheless, the spectra show a broadening of the line for the sample with the highest Sb content (IIb) indicating a local structural distortion in good agreement with the \(^{119}\)Sn MAS NMR results.

The structural features observed for II, IIa, and IIb promise a potential application as SSEs in ASSBs. Hence, the Na\(^{+} \) cation conductivities were determined by electrochemical impedance spectroscopy (EIS) between \(-10 \) to \(+70 \) \( ^\circ \text{C} \). Representative results are shown in Figure 6. In the Nyquist plots recorded at 0 \( ^\circ \text{C} \) (Figure 6a) for II, IIa, and IIb, single depressed semicircles and sloping lines at small frequencies are observed. The deconvolution of contributions from bulk and grain boundaries is not possible and all AC impedance spectra were fitted with an equivalent circuit (details in Supporting Information). The Na\(^{+} \) cation conductivities \( \sigma \) and capacitances \( C \) at different temperatures are shown in Table 2. Values for \( \sigma \) correspond to averaged bulk and grain boundary transport behavior if compared to empirical characteristics reported in ref.\(^{[74]} \) (\( \sigma_{\text{bulk}} \approx 0.001 \text{nF} \) \( \mu \text{m} \) \( \text{cm} \)) and \( \sigma_{\text{grain boundary}} \approx 4 \text{nF} \) \( \mu \text{m} \) \( \text{cm} \)). The EIS experiments demonstrate good (II) to superior (IIb) Na\(^{+} \) cation motion in the whole temperature regime with \( \sigma \) covering several orders of magnitude. The substitution of Sn\(^{4+} \) by Sn\(^{5+} \) has a highly beneficial impact on the Na\(^{+} \) cation motion and \( \sigma \) of II is already enhanced by one order of magnitude for \( x = 0.01 \) (e.g. \( \sigma(\text{II})_{x=0.01} = 3.0 \mu\text{S cm}^{-1} \), \( \sigma(\text{IIa})_{x=0.01} = 26 \mu\text{S cm}^{-1} \) despite it is isostructural. For \( x = 0.10, \) \( \sigma \) is \( > 40 \) times larger than for II (\( \sigma(\text{IIb})_{x=0.10} = 0.1 \text{mS cm}^{-1} \)) enabling superionic conduction properties comparable to findings for high-temperature products of Na\(_2\)Sn\(_2\)S\(_8\)S\(_2\) (e.g. \( \sigma_{\text{bulk}} \approx 0.1 \mu\text{S cm}^{-1} \) for Na\(_{10}\)Sn\(_4\)S\(_8\)S\(_2\))\(^{[4]} \). In contrast, the AC resistance for III is too high for a reasonable determination of \( \sigma \) at \( T < 25 \) \( ^\circ \text{C} \). Even at \( T > 25 \) \( ^\circ \text{C} \), only approximate values for \( \sigma \) can be calculated (inset in Figure 6b), similar to those reported for III\(^{[4]} \). \( \sigma \) is at least two orders of magnitude lower in III (\( \sigma(\text{III})_{x=0.8} \approx 0.02 \mu\text{S cm}^{-1} \)) compared to II.

The temperature-dependent \( \sigma \) follow the Arrhenius law for all samples (Figure 6c). The activation energy \( E_{a} \) is 0.65 eV for III comparable to literature data (0.58 eV\(^{[39]} \)) and larger than for II (0.51 eV). Substitution of Sn\(^{4+} \) by Sn\(^{5+} \) reduces \( E_{a} \) to 0.41 eV for IIa and IIb close to data reported for superionic conductors, e.g., Na\(_2\)SnP\(_4\)S\(_8\) (0.39 eV\(^{[46]} \)) 0.25 eV\(^{[40]} \)), Na\(_2\)SnP\(_4\)S\(_8\) (0.36 eV\(^{[66]} \)), Na\(_2\)SnS\(_4\)B\(_4\) (0.34 eV\(^{[42]} \)), Na\(_2\)PS\(_4\) (0.38 eV, 0.35 eV\(^{[44]} \)) and Na\(_2\)Sb\(_2\) (0.25 eV\(^{[41]} \), 0.22 eV\(^{[52]} \)).

The results from EIS highlight the pronounced impact of structural differences, in particular the different three-dimensional Na\(^{+} \) cation topology on the ion motion properties comparing II and III. Moreover, the significantly enhanced Na\(^{+} \) cation mobility with increasing Sb content in Na\(_4\)Sn\(_2\)S\(_8\)S\(_2\) needs to be discussed. One reason is certainly the lower total Na occupation inevitably coming along with the substitution, hence statistically more vacant sites are present for Na\(^{+} \) ion hopping. Another reason is the more regular distribution of Na–Na connections with increasing Sb content (Figure S11), being beneficial for the ionic conduction along the \( c \)-axis. One bottleneck debated for the ionic conduction in Na\(_{12}\)Sn\(_{12}\)S\(_{24}\)P\(_4\)Sb\(_8\) is the Na\(^{+} \) cation hopping through a Na\(_6\) void (see Figure S7) limited by the shortest S–S distances between shared faces of Na\(_6\)S\(_8\).

### Table 2: Ionic conductivities \( \sigma \) and capacitances \( C \) at various temperatures for II, IIa, IIb (Na\(_2\)Sn\(_2\)S\(_8\)S\(_2\), \( x = 0, 0.01, 0.10 \)), and III (Na\(_2\)SnS\(_4\)).

| Temperature (°C) | \( \sigma \) [μS cm\(^{-1} \)] | \( C \) [nF] |
|------------------|-------------------|-------------|
| 10               | 2.8(4)            | 0.6(1)     |
| 20               | 3.2(4)            | 0.6(1)     |
| 30               | 3.7(4)            | 0.6(1)     |
| 40               | 4.3(4)            | 0.6(1)     |

[a] EIS spectra < 25 °C are too noisy for reliable calculations. [b] C(IIa) and C(IIb) cannot be extracted at \( T \geq 40 \) and \( T \leq 25 \) °C, respectively (indistinct semicircles).
Figure 6. Nyquist plots recorded at a) 0 °C and b) 30 °C; c) Arrhenius plots for II, Ila, llb (Na$_{x}$Sn$_{1-x}$Sb$_{x}$S$_{4}$, x = 0, 0.01, 0.10), and III (Na$_{4}$SnS$_{4}$). An equivalent circuit for these AC impedance spectra is shown in (b).
and Na1S or Na2S (Figure S13).[50] The S–S barrier for the Na1–Na6–Na1 pathway is almost the same (±0.01 Å) and increases only slightly (+0.06 Å) for the Na2–Na6–Na2 pathway if Sn+ is replaced by Sb+ (Table S8). These small changes in contradiction to the extremely different ionic conductivity in this series confirm the previous observations that these pathways are less important for the ionic conduction in this structural family.[50]

Additionally, the paddle-wheel mechanism is long debated for superionic conductors, e.g., explaining an enhanced Na+ cation conduction property for Na1[Sn3PS12] vs. Na3SnSbS3 by less hindered PS4 rotational dynamics compared to those of SbS4 units.[57] The results of NMR and Mössbauer experiments indicate larger SnS4 distortions and improved Na+ cation mobility with increasing Sb content, in agreement with the EIS results. However, calculations and modeling are now necessary to understand the SnS4 dynamics, its relation to SbS4 incorporation and Na+ mobility.

To this end, we performed quantum calculations to elucidate the role of [SnS4]4+ and [SbS4]3+ tetrahedrons for coordinating interstitial Na+ ions. As a proxy model featuring Na+ coordination by the edges of two MS4 motifs, we characterized Na+ ion incorporation between two charge neutral Na4[SnS4] species. This was compared to Na+ incorporation between adjacent Na4[SnS4] and Na4[SbS4] tetrahedrons. Strikingly, we find latter scenario (i.e. the [Na4[SnS4]]-Na-[SbS4][Na+] hetero-pair) to be preferred by 0.3 eV, hence suggesting significant lowering of the interstitial formation energy. This may be rationalized by the larger formal charge of the Sb+ species that gives rise to the more compact SbS4 tetrahedron as compared to SnS4— with the Sb–S and Sn–S distances being 2.53 and 2.44 Å, respectively (see Supporting Information for details of the quantum calculations). Thus, SbS4 incorporation in Na1–Sn–Sn–SbS4 offers additional space to the neighboring SnS4 tetrahedrons—which is suggested to not only facilitate rotation in support of Na+ hopping, but also helps Frenkel defect formation (producing Na vacancies as the suggested mobile species).

### Conclusion

Here we demonstrated that the new, kinetically stabilized Na2SnS4 polymorph is obtained via directed removal of crystal water from Na2SnS4·14H2O at 170 °C. This process at relatively moderate temperature is very easy, cost-effective, and scalable, and also provides an economic preparation method for the solid solution Na1–Sn–Sn–SbS4 by co-decomposition with Na2SbS3·9H2O. In contrast to recent claims in literature, we here report that this solid solution exhibits no lower Sb limit using the presented syntheses, but slow heating to higher temperatures inevitably causes structural transformation of the new Na2SnS4 polymorph into the known, thermodynamically stabilized form. These findings enabled a systematic study at the lower Sb substitution boundary for the first time. Combined XRPD, 23Na and 119Sn NMR, 188Sn Mössbauer, and EIS experiments shed light on the local and crystallographic structure for x = 0, 0.01, and 0.10 and their relation to the Na+ cation mobility. Compared to the known Na4SnS4 polymorph, the room temperature Na+ conductivity of the new form is considerably improved by two orders of magnitude to $\sigma_{25°C} = 2 \times 10^{-3}$ mS cm$^{-1}$. Incorporation of minor Sb+ amounts (x = 0.01) in the new polymorph already enhances the Na+ conductivity significantly and further substitution to x = 0.10 enables room temperature superionic conduction properties ($\sigma_{25°C} = 0.1$ mS cm$^{-1}$, $E_a = 0.41$ eV). The synthetic approach presented here opens new avenues to syntheses of SSE by thermal co-decomposition using other precursor mixtures to access compounds of this thiostannate family with methodical low-level cation and anion doping, e.g., by incorporation of P6+, Sb5+, Cl−, and Br− in Na2SnS4, which was difficult until now because of the temperature-dependent polymorphism.

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### Conflict of Interest

The authors declare no conflict of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Keywords:

Mössbauer Spectroscopy · Na+ Ionic Conductivity · NMR Spectroscopy · Thermal Co-Decomposition · X-Ray Diffraction

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