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Sulfimidation of thioether groups – a versatile method for modifying and linking thia/oxa crowns

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Reaction of the mixed thioether/ether crowns [9]aneO₂S **1**, [12]aneO₃S **2** and [18]aneO₄S₂ **3** with one mol. equiv. of the aminating agent MSH (*o*-mesitylsulfonylhydroxylamine) in Et₂O results in the formation of the mono-sulfimidated systems {[9]aneO₂(S=NH₂)}⁺ **1a**, {[12]aneO₃(S=NH₂)}⁺ **2a** and {[18]aneO₄(S=NH₂)}⁺ **3a**, while using two mol. equivalents of MSH with **3** gives the disulfimidium cation {[18]aneO₄(S=NH₂)₂}²⁺ **3b**. All of these species have been isolated in good yields as the [mesSO₃][−] (mes = 2,4,6-Me₃C₆H₂) salts and can be readily converted readily to the [BPh₄][−] salts by metathesis with Na[BPh₄]. Treatment of **1a** or **2a** with lithium diisopropylamide (LDA) and N-bromosuccinimide (NBS) at −78°C, followed by addition of a further equivalent of the parent thia/oxa crown, gives monocationic N-bridged sulfimide bicyclic compounds (**4** and **5** respectively), in which the crowns are linked by the sulfimidic nitrogen. Reaction of **3a** with LDA and NBS leads to formation of the {[18]aneO₄(S₂N)}⁺ cation **6** which exhibits an intramolecular S–N–S bridge. Crystallographic studies on representative examples of each compound type are described, together with their spectroscopic properties.

20 Introduction

The importance of crown ether systems to all areas of the chemical community continues to grow.¹ Their significance stems from the range of properties they display (not the least of which is their ability to encapsulate metal cations) and has inspired the preparation of a wide range of examples of derivatised versions of archetypal crowns such as 18-crown-6. These are generally prepared through modification of the carbon backbones *via* incorporation of functionalised groups into the macrocycle. Although this can involve a range of different groups, and the resulting products can, in turn, react to derivatise the systems still further, in all such cases the variation upon the basic crown ether unit is brought about by modification to the carbon backbone **prior** to cyclisation. This is because the inertness of both the backbone, and of the oxygen atoms, precludes derivatisation **post** ring closure.

Mixed thia/oxa crowns have been studied widely, again, mainly due to their ability to encapsulate metal cations. Thus the transition metal chemistry of [18]aneO₅S and [18]aneO₄S₂ (**3**) (and, indeed, of the Se/O and Te/O analogues of the former) has been explored extensively by one of the authors (GR).² In contrast to the crowns containing only oxa-ether units, these mixed systems do have the potential to undergo derivatisation thanks to the presence of the more reactive thia-ether centre(s). Despite this clear possibility, post ring-closure modification of these types of macrocycles is still poorly documented. In one example, Dann *et al*³ reported oxidised versions of **3**, formed by reacting the ‘free’ macrocycle with Chloramine-T and with hydrogen peroxide, generating [18]aneO₄(S=NTs)₂ and [18]aneO₄(S=O)₂ respectively. Some subsequent work on this sulfoxide was

reported,⁴ as were studies into examples of thia-crowns bearing S=O units,⁵ but until a recent preliminary report on our part, no examples were known of systems wherein this methodology had been used to extend functional derivatisation of crowns.

In that preliminary report we showed that reaction of [18]aneO₅S with the aminating agent MSH resulted in the formation of the sulfimidium cation, {[18]aneO₅(S=NH₂)}⁺ (Scheme 1).⁶ Deprotonation and bromination, using, consecutively, lithium diisopropylamide (LDA) and N-bromosuccinimide (NBS), allowed the *in situ* generation of [18]aneO₅(S=NBr). The known temperature-sensitive nature of dialkylsulfimides necessitated the one-pot reaction be carried out at low temperature (−78°C) and the product reacted immediately, in this case with the parent crown. This resulted in the linked crown system [([18]aneO₅(S₂N))]⁺, in which the two crowns are joined *via* a sulfimide nitrogen. Despite the additional charge on the linked crowns imparted by the S–N–S bridge, importantly we were also able to demonstrate that the molecule was still able to accommodate a sodium cation bound *via* the ether O atoms.

The aforementioned report thus confirmed the viability of an entirely new class of reaction within crown ether chemistry, namely significant post ring-closure derivatisation. Here we demonstrate that this technique is applicable to a range of other ring systems and, in addition, that within the dithiacrown [18]aneO₄S₂ intramolecular sulfimidation is also possible.

80 Experimental

Instrumentation and conditions

Infrared spectra were recorded as pressed KBr pellets over the range 4000–200 cm^{−1} on a Perkin-Elmer System 2000 Fourier-

transform spectrometer, ^1H (400 MHz) and $^{13}\text{C}\{^1\text{H}\}$ NMR spectra (100 MHz) on a Bruker DPX-400 FT spectrometer with chemical shifts in ppm to high frequency of SiMe_4 and coupling constants (J) in Hz. Elemental analyses (Perkin-Elmer 2400 CHN or Exeter Analytical, Inc. CE-440 Elemental Analyzers) were performed by the Loughborough University Analytical Service within the Department of Chemistry; FAB mass spectra were recorded on a JEOL SX102 mass spectrometer, ES^+ and ES^- mass spectra (MeCN solution) were recorded using a VG Biotech platform or carried out by the EPSRC Mass Spectrometry Service at the University of Wales, Swansea.

All reactions were performed under an atmosphere of dry nitrogen using standard Schlenk techniques and appropriately dried solvents. $[9]\text{aneO}_2\text{S}$ and $[18]\text{aneO}_4\text{S}_2$ were prepared via the literature procedure, and $[12]\text{aneO}_3\text{S}$ was prepared using a similar method.⁷ Q -mesitylsulfonylhydroxylamine (MSH) was prepared by the literature route,⁸ while lithium diisopropylamide (LDA) and N-bromosuccinimide (NBS) were used as received (Aldrich).

SAFETY NOTE!: MSH can spontaneously (and unpredictably) decompose, resulting in an explosive pressure change. Samples should be kept in small amounts in loosely sealed containers, thereby minimising the risks should decomposition occur.

Preparations

Reactions of $[9]\text{aneO}_2\text{S}$ (1)

[1a][mesSO₃]: $[9]\text{aneO}_2\text{S}$ (1.0 g, 6.75 mmol) was dissolved in Et_2O (15 cm^3), and MSH (1.82 g, 8.43 mmol) added as a solid in several portions. The mixture was stirred overnight, after which the white solid produced was filtered, washed with further Et_2O (2 x 25 cm^3) and dried *in vacuo*. Yield: 2.13 g (87%). Found: C, 49.39; H, 6.95; N, 3.48. $\text{C}_{15}\text{H}_{25}\text{O}_4\text{S}_3\text{N} \cdot 0.5\text{Et}_2\text{O}$ requires C, 49.02; H, 7.26; N, 3.36%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3195, 3026, 1603, 1451, 1184, 1012, 845, 746, 682, 580, 549. ^1H NMR (CDCl_3): δ_{H} = 6.72 (s, 2H, Ar-H), 6.30 (br s, 2H, S=NH₂), 3.30–4.11 (m, 12H, CH₂), 2.56 (s, 6H, 2 x CH₃), 2.14 (s, 3H, 1 x CH₃). $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3) δ_{C} = 139.0, 137.2 (quaternary Ar-C), 130.8 (2 x Ar-CH), 71.3, 70.3 (OCH₂), 48.3 (CH₂SNH₂), 23.0 (2 x CH₃), 20.8 (1 x CH₃). FAB MS (3-nitrobenzyl alcohol): m/z = 164.0 ($\text{C}_6\text{H}_{14}\text{S}_2\text{ON}$ requires 164.2).

[1a][BPh₄]: **[1a][mesSO₃]** (0.52 g, 1.43 mmol) was dissolved in MeOH (10 cm^3). Na[BPh₄] (0.61 g, 1.79 mmol) was dissolved separately in MeOH (5 cm^3) and added dropwise to the stirring crown solution. After stirring for 3 h, the resulting white precipitate was filtered, the solid recrystallised from $\text{CH}_2\text{Cl}_2/\text{Et}_2\text{O}$, refiltered and dried *in vacuo*. Yield: 0.59 g (85%). Found: C, 71.34; H, 6.68; N, 2.62. $\text{C}_{30}\text{H}_{34}\text{O}_2\text{SNB} \cdot 0.25\text{CH}_2\text{Cl}_2$ (504.7) requires C, 71.99; H, 6.89; N, 2.78%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3216, 3055, 3002, 1579, 1479, 1427, 1391, 1266, 1152, 1086, 851, 739, 708, 626, 602. ^1H NMR (d^6 -DMSO) δ_{H} = 7.21–6.82 (br m, 20H, BPh₄ Ar-CH), 3.39–4.15 (m, 12H, CH₂). $^{13}\text{C}\{^1\text{H}\}$ NMR (d^6 -DMSO) δ_{C} = 163.5 (1:1:1:1

q , BPh₄ *ipso*-C), 135.5, 125.3, 121.5 (Ar-C), 70.1, 64.9 (OCH₂), 46.2 (CH₂SNH₂). FAB MS (3-nitrobenzyl alcohol): m/z = 164.0 ($\text{C}_6\text{H}_{14}\text{S}_2\text{ON}$ requires 164.2).

Reactions of $[12]\text{aneO}_3\text{S}$ (2)

These were prepared using an analogous method to those of **1**. **[2a][mesSO₃]**. Yield: 79%. Found: C, 49.08; H, 6.62; N, 3.30. $\text{C}_{15}\text{H}_{25}\text{O}_4\text{S}_3\text{N}$ requires C, 50.10; H, 7.17; N, 3.44%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3180, 3044, 2964, 2924, 2853, 1457, 1376, 1210, 1179, 1087, 1014, 918, 858, 681. ^1H NMR (d^6 -DMSO) δ_{H} = 6.78 (s, 2H, Ar-H), 6.04 (s, 2H, NH₂), 3.37–4.00 (m, 16H, 70 CH₂), 2.52 (s, 6H, CH₃), 2.18 (s, 3H, CH₃). $^{13}\text{C}\{^1\text{H}\}$ NMR (d^6 -DMSO) δ_{C} = 142.2, 136.6, 135.9 (quaternary Ar-C), 129.9 (Ar-CH), 70.0, 69.6, 63.8 (OCH₂), 49.0 (CH₂SNH₂), 22.7 (2 x CH₃), 20.3 (1 x CH₃). FAB MS (3-nitrobenzyl alcohol): m/z = 208.0 ($\text{C}_8\text{H}_{18}\text{SO}_3\text{N}$ requires 208.3). **[2a][BPh₄]** Yield: 69%. Found: C, 70.49; H, 7.01; N, 2.59. $\text{C}_{32}\text{H}_{38}\text{O}_3\text{SNB} \cdot 0.25\text{CH}_2\text{Cl}_2$ requires C, 70.59; H, 7.03; N, 2.55%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3284, 3161, 3059, 2986, 1580, 1476, 11323, 1112, 1065, 920, 846, 828, 756, 735, 702, 613. ^1H NMR (d^6 -DMSO) δ_{H} = 7.18–6.80 (br m, 20H, BPh₄ Ar-CH), 3.39–4.02 (m, 16H, CH₂). $^{13}\text{C}\{^1\text{H}\}$ NMR (d^6 -DMSO) δ_{C} = 163.6 (1:1:1:1 q , BPh₄ *ipso*-C), 135.5, 125.3, 121.5 (Ar-C), 70.1, 69.7, 63.8 (OCH₂), 49.2 (CH₂SNH₂). FAB MS (3-nitrobenzyl alcohol): m/z = 208.0 ($\text{C}_8\text{H}_{18}\text{O}_3\text{SN}$ requires 208.3).

Reactions of $[18]\text{aneO}_4\text{S}_2$ (3)

[3a][mesSO₃]: $[18]\text{aneO}_4\text{S}_2$ (0.750 g, 2.53 mmol) was dissolved in $\text{CH}_2\text{Cl}_2/\text{MeOH}$ (1:1, 25 cm^3). Separately, MSH (0.545 g, 2.53 mmol) was dissolved in CH_2Cl_2 and added dropwise to the stirring thiocrown solution. After stirring overnight, the solution was reduced to *ca.* 2–3 cm^3 , after which Et_2O (60 cm^3) was added and the resulting white solid filtered and dried *in vacuo*. Yield: 0.799 g (62%). Found: C, 48.29; H, 6.81; N, 3.45; $\text{C}_{21}\text{H}_{37}\text{O}_7\text{S}_3\text{N} \cdot 0.25\text{CH}_2\text{Cl}_2$ requires C, 47.89; H, 7.09; N, 2.63%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3497, 3210 (br, -NH), 2936, 1473, 1456, 1209, 1175, 1088, 1016, 850 and 858, 682, 583, 549. ^1H NMR (d^6 -DMSO): δ_{H} = 6.78 (s, 2H, Ar C-H), 6.04 (s, 2H, NH₂), 3.37–4.00 (m, 16H, CH₂), 2.52 (s, 6H, 2 x Ar-CH₃), 2.18 (s, 3H, Ar-CH₃). ES^+ MS (MeCN): m/z = 312.5 ($\text{C}_{12}\text{H}_{26}\text{S}_2\text{O}_4\text{N}$ requires 312.5).

[3a][BPh₄]: $\{[18]\text{aneO}_4\text{S}_2(\text{NH}_2)_2\}\{\text{MSH}\}_2$ (0.529 g, 0.73 mmol), was dissolved in MeOH (10 cm^3). Separately, NaBPh₄ (0.250 g, 0.75 mmol) was dissolved in MeOH (5 cm^3) and added dropwise to the stirring sulfimide solution. A bright white solid appeared almost immediately, the mixture was allowed to stir for *ca.* 1 h, after which the solid was filtered and dried *in vacuo*. Yield: 0.395 g (86%). Found: C, 67.64; H, 5.24; N, 1.82; $\text{C}_{36}\text{H}_{46}\text{BNO}_4\text{S}_2$ requires C, 68.45; H, 7.34; N, 2.22%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3341, 3221, 3052, 2983, 1578, 1477, 1424, 1133, 1109, 1031, 845, 737, 709, 612. ^1H NMR (d^6 -DMSO): δ_{H} = 7.40–6.82 (br m, 20H, BPh₄ Ar-CH), 3.43–4.05 (m, 24H, CH₂). ES^+ MS (MeCN): m/z = 312.5 ($\text{C}_{12}\text{H}_{26}\text{S}_2\text{O}_4\text{N}$ requires 312.5).

[3b][mesSO₃]₂ was prepared using the same method as used for [4b][mesSO₃] except that 2.25 equivalents of MSH were employed. Yield: 0.834 g (71%) Found: C, 48.36; H, 6.84; N, 3.78. C₃₀H₅₀O₁₀S₄N₂·0.25CH₂Cl₂ requires C, 48.56; H, 6.80; N, 3.74%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3498, 3205, 2935, 1455, 1208, 1179, 1089, 1016, 858, 849, 682, 584, 549. ¹H NMR (d⁶-DMSO): δ_{H} = 6.77 (s, 4H, Ar C–H), 3.36–4.08 (m, 24H, CH₂), 2.51 (s, 12H, CH₃), 2.18 (s, 6H, CH₃). ¹³C{¹H} NMR (d⁶-DMSO): δ_{C} = 142.4, 136.5, 135.9 (quaternary Ar–C), 129.9 (Ar C–H), 69.1, 69.0, 62.1 (OCH₂), 47.5 (SCH₂), 22.7 (2 x CH₃), 20.3 (1 x CH₃). FAB MS: m/z = 328.5 (C₁₂H₂₈S₂O₄N₂ requires 328.5).

[3b][BPh₄]₂ was prepared by metathesis of [3a][mesSO₃]₂ with Na[BPh₄] in analogous manner to salts of 1a. Yield: 0.415 g, (90%). Found: C, 73.11; H, 6.99; N, 3.01; C₆₀H₆₈B₂N₂O₄S₂·CH₃OH requires C, 73.34, H, 7.26; N, 2.80%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3340, 3220, 3053, 2915, 1578, 1477, 1424, 1132, 1424, 1133, 1098, 1031, 845, 737, 704, 612. ¹H NMR (d⁶-DMSO): δ_{H} = 7.40–6.82 (br m, 40H, Ar–H), 3.20–3.98 (m, 24H, CH₂). ¹³C{¹H} NMR (d⁶-DMSO): δ_{C} = 164.1–162.6 (1:1:1:1 q, BPh₄ ipso–C), 135.5, 125.3, 121.5 (Ar–C), 69.1, 62.1 (OCH₂), 47.6 (H₂NSCH₂). ES⁺ MS (MeCN): m/z = 328.5 (C₁₂H₂₈S₂O₄N₂ requires 328.5).

Bridged systems

{([9]aneO₂S)₂N}[BPh₄] 4: [1a][BPh₄] (0.250 g, 0.47 mmol) was dissolved in THF (15 cm³), and the temperature reduced to –78°C. LDA (0.24 cm³ of a 2 M solution, 0.47 mmol) was added, and the mixture stirred for 1 h. NBS (0.084 g, 0.47 mmol) was added as a solid, and after 1 h stirring, [9]aneO₂S (0.070 g, 0.47 mmol) was added. The yellow solution was stirred overnight, during which time the temperature was gradually raised to r.t. The solution was reduced to dryness *in vacuo*, after which H₂O (25 cm³) was added along with CH₂Cl₂ (2 x 25 cm³). The combined organic layers were dried over MgSO₄, reduced to *ca.* 2–3 cm³, and Et₂O (60 cm³) added. The resulting off-white solid was filtered and dried *in vacuo*. Yield: 0.127 g (43%). Found: C, 69.45; H, 7.30; N, 1.84. C₃₆H₄₄BNO₄S₂ requires C, 68.67; H, 7.04; N, 2.22%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3422, 1683, 1478, 1426, 1391, 1300, 1203, 1153, 1087, 940, 927, 858, 736, 707. ¹H NMR (d⁶-DMSO): δ_{H} = 7.21–6.76 (br m, 20H, BPh₄ Ar–CH), 3.17 (m, 24H, CH₂). ¹³C{¹H} NMR (d⁶-DMSO): δ_{C} = 163.6 (1:1:1:1 q, BPh₄ Ar–C), 135.4, 124.9, 121.2 (Ar–C), 69.7, 63.8 (OCH₂), 48.2 (NSCH₂). FAB MS (3-nitrobenzyl alcohol): m/z = 310.0 (C₁₂H₂₄O₄S₂N requires 310.4).

{([12]aneO₃S)₂N}[BPh₄] 5 was prepared using the same method as for 4, using [2a][BPh₄]. Yield: 0.101 g (38%). Found: C, 66.38; H, 7.06; N, 2.49. C₄₀H₅₂O₆S₂NB requires C, 66.93; H, 7.30; N, 1.95%; IR $\nu_{\text{max}}/\text{cm}^{-1}$: 3284, 3161, 3055, 3035, 2926, 2871, 1578, 1475, 1457, 1423, 1397, 1154, 1136, 1107, 1092, 927, 844, 733, 710, 612. ¹H NMR (d⁶-DMSO): δ_{H} = 7.19–6.81 (br m, 20H, BPh₄ Ar–CH), 3.24–4.02 (m, 12H, CH₂). ¹³C{¹H} NMR (d⁶-DMSO): δ_{C} = 163.6 (1:1:1:1 q, BPh₄ ipso–C), 135.5, 125.3, 121.5 (Ar–C), 69.9, 69.6, 64.3 (OCH₂),

51.9 (NSCH₂). ES⁺ MS (MeCN): m/z = 398.2 (C₁₆H₃₂S₂O₆N requires 398.6); ES[–] MS: m/z = 319.2 (C₂₄H₂₀B requires 319.2).

{([18]aneO₄S)₂N}[BPh₄] 6: [3a][BPh₄] (0.250 g, 0.26 mmol) was dissolved in THF (15 cm³), the temperature reduced to –78°C and LDA (0.13 cm³ of a 2 M solution, 0.26 mmol) was added. After stirring for 30 min., NBS (0.046 g, 0.26 mmol) was added as a solid, and the mixture stirred overnight, slowly warming to room temperature. The mixture was reduced to dryness under reduced pressure, H₂O (25 cm³) added, and the product extracted into CH₂Cl₂ (2 x 25 cm³). The combined organic extracts were dried over MgSO₄, reduced to *ca.* 2–3 cm³, and Et₂O added. The resulting off-white precipitate was filtered and dried *in vacuo*. Yield: 0.098 g (60%). Found: C, 67.41; H, 6.71; N, 3.15; C₃₆H₄₄BNO₄S₂·0.25CH₂Cl₂ requires C, 66.89; H, 6.89; N, 2.15%. IR $\nu_{\text{max}}/\text{cm}^{-1}$: 2853, 1457, 1376, 1210, 1179, 1087, 1014, 918, 858 681. ¹H NMR (d⁶-DMSO): δ_{H} = 7.38–6.79 (br m, 20H, BPh₄ Ar–CH), 3.30–3.50 (br m, 24H, CH₂). ¹³C{¹H} NMR (d⁶-DMSO): δ_{C} = 163.6 (1:1:1:1 q, BPh₄ ipso–C), 135.5, 125.3, 121.5 (Ar–C), 68.7, 64.3 (OCH₂), 51.1 (NSCH₂). FAB⁺ MS (3-nitrobenzyl alcohol): m/z = 310.5 (C₁₂H₂₄S₂O₄N requires 310.5).

X-Ray Crystallography

Details of the crystallographic data collection and refinement parameters are given in Table 1. Data for [2a][BPh₄] and [6][BPh₄] were collected using a Bruker AXS SMART 1000 CCD area-detector diffractometer using sealed-tube graphite-monochromated Mo–K α radiation and narrow frame exposures (0.3°). Cell parameters were refined from the observed (ω) angles of all strong reflections in each data set. Intensities were corrected semi-empirically for absorption, based on symmetry-equivalent and repeated reflections. All structures were solved by direct methods and refined on F^2 values for all unique data by full-matrix least-squares.⁹ Data for [3b][BPh₄], [4][BPh₄] and [5][BPh₄] were collected at 93 K by using a Rigaku MM007 High brilliance RA generator (Mo K α radiation, confocal optics) and Mercury CCD system. At least a full hemisphere of data was collected using ω or ω/ϕ scans. Intensities were corrected for Lorentz-polarisation and for absorption. The structures were solved by direct methods. Hydrogen atoms bound to carbon were idealised. Structural refinements were performed with full-matrix least-squares based on F^2 by using the program SHELXTL.^{10,11}

Supplementary data

Crystallographic data have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC XXX XXXX. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (Fax: +44-1223-336033; email: deposit@ccdc.cam.ac.uk or [www: http://www.ccdc.cam.ac.uk](http://www.ccdc.cam.ac.uk)).

Results and discussion

Reaction of crowns **1** and **2** with MSH in Et₂O results in rapid formation of the [mesSO₃][−] salts of the aminated cations {[9]aneO₂S(NH₂)}⁺ **1a** and {[12]aneO₃S(NH₂)}⁺ **2a**, both of which precipitate from the ether as waxy, colourless solids (Scheme 2). In both cases, treatment of a methanolic solution of the material with a slight excess of Na[BPh₄] readily precipitates the corresponding [BPh₄][−] salts; these are more crystalline in nature and more readily handled. The sulfimidation and metathesis reactions proceed very cleanly, giving yields often in excess of 80%. Such results echo those we reported previous for the analogous reaction of the larger crown [18]aneO₅S,¹¹ thereby confirming that the amination reactions are equally viable for all ring sizes.

Slow diffusion of Et₂O into a CDCl₃/dmsO solution of [2a][BPh₄] generated crystals suitable for X-ray crystallography, and the latter technique confirms the expected structure (Fig.2). The S–N bond length in this case (1.635(14) Å) is in the range expected for sulfimidium units. The sulfimidium NH₂⁺ unit is oriented *exo* to the ring, with no intra- or intermolecular H-bonding interactions to the ether O atoms evident.

Four resonances are seen in the solution ¹³C{¹H} NMR spectrum as expected (indicating the time-averaged symmetry in solution). Also as expected, within the spectrum of [2a][BPh₄] resonances associated with the SCH₂ carbon atom are most affected by the sulfimidation reaction, shifting substantially (by *ca.* 15 ppm) to high frequency – undoubtedly a consequence of the presence of formally S(IV) in the product (cf. S(II) in the parent crown).

The ease with which colourless, powdered [BPh₄][−] salts of **1a** and **2a** can be obtained by metathesis, is a key to further reactivity. Not only are such compounds easier to handle than the corresponding [mesSO₃][−] salts, they also possess inert counterions; in our experience the [mesSO₃][−] is often less than "innocent" in terms of reactivity. Treatment of a solution of [1a][BPh₄] or [2a][BPh₄] with LDA in diethyl ether solution at −78°C, followed by bromination using NBS and addition of a further equivalent of the parent thia/oxa crown leads to (Scheme 3) the formation of the intermolecularly N-bridged bicyclic cations {[9]aneO₂S₂N}⁺ (**4**) and {[12]aneO₃S₂N}⁺ (**5**), which are readily isolated as their [BPh₄][−] salts. These compounds have also been characterised by ¹H and ¹³C{¹H} NMR and IR spectroscopy, mass spectrometry and microanalyses. We note that formation of the S–N–S bridge leads to a further small high frequency shift for the SCH₂ group in the ¹³C{¹H} NMR spectrum compared to the corresponding sulfimidium cations. The crystal structures of the [BPh₄][−] salts of **4** (Fig. 3) and **5** (Fig 4) provide further evidence for the formulations of these unusual examples of coupled macrocyclic species (albeit the crystal quality of the latter is rather poor, hence detailed comparisons of bond lengths *etc* are not justified, though connectivity is certainly established). As noted earlier, the ¹³C{¹H} spectra show a number of lines equivalent to the number of chemically

independent carbons. Thus while the solid state structure in Fig.3 is clearly asymmetric in terms of the disposition of the carbons about the central nitrogen, in solution the environments are equivalent, hence only three ¹³C signals are observed. The two pairs of crystallographically independent S–N bond distances within cation **4** and cation **5** are very similar (*ca.* 1.64 Å), consistent with delocalisation of electron density across the SNS linkage. These distances are *ca.* 0.02 Å longer than d(S–N) within the sulfimidium cation, {[12]aneO₃S(NH₂)}⁺.

In contrast to the larger system {[18]aneO₅S₂N}⁺,¹¹ we have not seen any evidence for coordination of Na⁺ upon addition of excess Na[BPh₄] to either **4** or **5**. Thus crystallisation of 1:1 mixtures of **4** or **5** with Na[BPh₄] in methanol, by slow ether diffusion, simply yields crystals of the starting materials. This contrast in results presumably reflects the fact that smaller rings are involved in these systems. In the sodium adduct of {[18]aneO₅S₂N}⁺ all five oxygen atoms of one ring exhibit significant interactions with the sodium cation, but only two (the most distant from the sulfur) from the other ring are involved in bonding. So even with such large rings present, the limiting action of the "hinge" at the nitrogen atom precludes symmetric coordination to the enclosed sodium. It is therefore not surprising that within **4** and **5** encapsulation of the sodium is not observed.

In the case of the dithiacrown **3** the presence of two potential reaction sites provides the opportunity for variation on the sulfimidation reactions seen thus far. The simplest reaction is, of course, that with one molar equivalent of MSH, and as expected this results in amination of one of the sulfur atoms to give the ionic species {[18]aneO₄S₂(NH₂)}⁺ (**3a**) in good yield (Scheme 2). As with the previous examples, addition of a slight excess of Na[BPh₄] to solutions of the [mesSO₃][−] salt results in the formation of [3a][BPh₄]. The latter was characterised by ¹H NMR and IR spectroscopy, ES⁺ MS and by microanalysis.

The reaction of MSH with **3** also generates small amounts of the dication which results from oxidation of both ring sulfurs by MSH (as shown by mass spectrometry). This product may be prepared directly by reaction of [18]aneO₄S₂ with two equivalents of MSH, thereby generating {[18]aneO₄(S=NH₂)₂}²⁺ (**3b**) cation in excellent yield. This observation indicates that although cation **3a** has a positive charge this does not preclude further reaction and increase in this charge. The ¹³C{¹H} NMR spectrum of **3b** reflects the high solution symmetry of the cation, leading to three distinct resonances; two due to the CH₂O groups at 69.1 and 62.1 ppm and the third at 47.6 ppm due to the H₂NSCH₂ unit. Further authentication of this species comes from its X-ray structure which is shown in Fig. 5. The {[18]aneO₄(S=NH₂)₂}²⁺ cation is centrosymmetric, with the NH₂⁺ units oriented in opposite directions relative to the O₄S₂ plane. The S–N bond distance (1.624(4) Å) is similar to that in **2a** and related protonated sulfimidium species within this work.

The sulfimidium cation **3a** can be deprotonated by addition of LDA at low temperatures to give the 'free' sulfimide *in situ*, which can subsequently be brominated using NBS. Upon

bromination, the presence of the second thioether S atom enables the pendant S=NBr group to bridge across the molecule to form the {[18]aneO₄S₂) μ-N }⁺ cation (**6**) via an intramolecular process. The spectroscopic features of this product parallel those for the other species in this work, with the ES⁺ MS clearly showing the cation peak two mass units below that for the sulfimidium cation {[18]aneO₄S₂(NH₂)⁺ as expected. Crystals of [6][BPh₄] suitable for X-ray crystallography were grown by vapour diffusion of Et₂O into a CDCl₃/dmsO solution. As Fig. 6 shows, the molecule forms a 'basket' shape, with the S–N–S linkage bridged over the molecule. The nitrogen atom lies, on average 2.96 Å above the plane of the four oxygen atoms. The S–N bond lengths are very similar to each other [1.6465(17) and 1.6469(17) Å], and to those of other compounds containing 'bridged' sulfimide groups (*vide supra*). As Fig.6 highlights, the structure of the cation effectively consists of two, fused, 11-membered macrocycles, and it is worth noting that the individual macrocycles are themselves unique. The formation of this cation thus mirrors the formation of {[9]aneS(NH₂)S₂(μ-N)}²⁺ in the reaction of [9]aneS₃ with excess MSH.¹² In the latter case the formation of the transannular bridge was unexpected; it most likely occurs *via* loss of [NH₄]⁺ from the initial product, {[9]ane(SNH₂)₃}³⁺. In contrast, the formation of (**6**) is a rational synthesis that can be expected to be applicable to all crown systems bearing two sulfur atoms.

Conclusions

The formation of the simple sulfimidium derivatives of crowns **1–3** confirms the general viability of MSH as aminating agent for mixed thia/oxa crown systems. In conjunction with the preliminary work on reactions of [18]aneO₅S it confirms that this constitutes a very effective new route for derivatisation of such crowns. The amenable bridging reactions have great potential for further utilisation, both from the point of the view of the linked crown systems such as **4** and the intramolecularly bridged species such as **6**. In terms of the former class of compound, it is clear that a wide variety of arrangements is possible, depending upon the crowns chosen as starting materials. The demonstrated ability of the larger ring systems to coordinate to a Na⁺ guest ion indicates that a significant new area of macrocyclic coordination chemistry should result from this approach. In terms of the intramolecular bridge motif it is clear that many variations on **6** should be possible. The presence of unique macrocycles within this structure also suggests that linking of the ends of chain thia/oxa ethers should be possible, with sulfimide nitrogen atoms forming bridges that generate new cyclic structures. Work on all these fascinating possibilities is underway.

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Notes and references

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Fig.1 The structure of crowns 1-3.

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Scheme 1 Linkage reactions of [18]aneO₅S performed in our initial study.¹¹

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Scheme 2 Sulfimide reactions of **1-3** using MSH.

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 Scheme 3 Bridging reactions of crown sulfimidium salts. *i* LDA, NBS (-78°C) followed by addition of parent crown; *ii* LDA, NBS (-78°C).

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Fig.2 View of the structure of the cation within **[2a][BPh₄]** (in all figures crossed lined atoms are oxygen; most H atoms and any disorder are omitted for clarity).

Fig.3 View of the structure of the cation in **[4][BPh₄]**.

Fig.4 X-ray crystal structure of the cation within $[5][BPh_4] \cdot CHCl_3$ with atom numbering scheme.

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20 Fig.5 X-ray crystal structure of the dication within $[3b][BPh_4]_2$.

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Fig.6 The X-ray crystal structure of one of the independent cations in **[6][BPh₄]**.

Table 1. Crystallographic parameters^a

Compound	[2a][BPh ₄]	[4][BPh ₄]	[5][BPh ₄]	[3b][BPh ₄] ₂	[6][BPh ₄]
Formula	C ₃₂ H ₃₈ BNO ₃ S	C ₃₆ H ₄₄ BNO ₄ S ₂	C ₄₁ H ₅₃ BCl ₃ NO ₆ S ₂	C ₆₀ H ₆₈ B ₂ N ₂ O ₄ S ₂	C ₃₆ H ₄₄ BNO ₄ S ₂
M	527.50	629.65	837.12	966.90	629.65
Crystal dimensions	0.23 × 0.21 × 0.13	0.15 × 0.15 × 0.15	0.13 × 0.03 × 0.03	0.10 × 0.10 × 0.08	0.65 × 0.32 × 0.12
Crystal morphology and colour	Block, colourless	Prism, colourless	Needle, colourless	Prism, colourless	Block, colourless
Crystal system	Monoclinic	Monoclinic	Monoclinic	Monoclinic	Triclinic,
Space Group	<i>P</i> 2 ₁ / <i>n</i>	<i>P</i> 2 ₁ / <i>c</i>	<i>P</i> 2 ₁ / <i>c</i>	<i>P</i> 2 ₁ / <i>c</i>	<i>P</i> $\bar{1}$
<i>a</i> /Å	12.9446(3)	10.7110(11)	14.046(3)	12.854(3)	10.6347(5)
<i>b</i> /Å	12.0724(3)	27.872(2)	11.934(2)	12.341(3)	14.3378(7)
<i>c</i> /Å	18.1166(5)	11.0118(12)	25.163(6)	16.969(4)	22.9147(11)
α /°	90	90	90	90	78.764(2)
β /°	98.060(4)	101.127(3)	98.981(6)	108.861(10)	81.805(2)
γ /°	90	90	90	90	71.051(2)
<i>V</i> /Å ³	2803.16(18)	3225.6(6)	4166.5(16)	2547.2(11)	3229.5(3)
Z	4	4	4	2	4
μ /mm ⁻¹	0.149	0.206	0.367	0.155	0.206
θ Range/°	1.82 to 30.56	2.02 to 25.35	1.89 to 25.38	2.54 to 25.35	0.91 to 28.90
Measured reflections	32677	20502	22437	14321	28453
Independent reflections	8548	5821	6919	4600	14816
<i>R</i> _{int}	0.0260	0.0278	0.0567	0.1030	0.0238
<i>R</i> [<i>F</i> ² > 2 σ (<i>F</i> ²)] ^a	0.0438	0.0375	0.1066	0.0849	0.0464
<i>wR</i> 2 [all data] ^b	0.1206	0.0927	0.2964	0.2254	0.1268
Largest difference map features/eÅ ⁻³	0.524, -0.303	0.294, -0.315	0.889, -0.846	1.132, -0.361	0.570, -0.349

^a $R = \sum |F_o| - |F_c| / \sum |F_o|$. ^b $wR2 = \{\sum [w(F_o^2 - F_c^2)^2] / \sum [w(F_o^2)^2]\}^{1/2}$.