

# Schroeter and Vossen's red salt revealed

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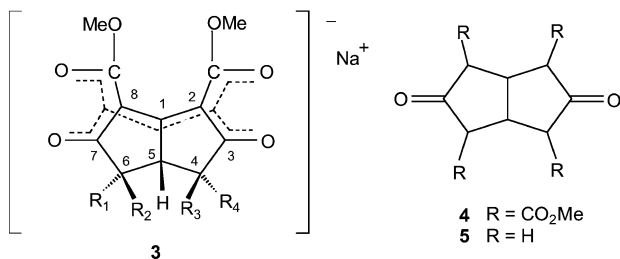
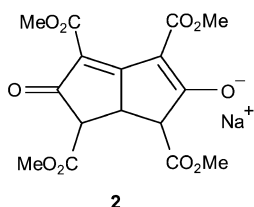
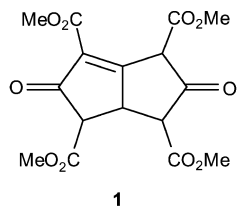
The structure of the red salt first reported by Schroeter and Vossen in 1910 has been determined fully for the first time using X-ray and other methods.

## Introduction

Vossen, working in Schroeter's laboratory, studied various condensation reactions involving chloral and dimethyl malonate, which were reported in his 1910 dissertation.<sup>1</sup> One unexpected outcome was the discovery of a beautiful red compound,  $C_{16}H_{15}O_{10}Na$ , which is now referred to as Schroeter and Vossen's red salt. We describe here the complete structure of this novel compound for the first time.

The journey towards uncovering this structure has involved contributions from a number of chemists over a long period of time. In 1922, Schroeter published the first journal account of the red salt. Showing considerable chemical insight, he described it as being a sodium salt formed from 2,4,6,8-tetracarboxymethoxybicyclo[3.3.0]oct-1-ene-3,7-dione **1**, although the precise proton removed and the actual structure of the resulting salt were not provided. Strangely, this paper contained no experimental instructions for obtaining the red salt and gave only sketchy details in support of this structural assignment.<sup>2</sup>

Over thirty years later, investigations by Wanzlick,<sup>3</sup> and by Yates and Bhat,<sup>4</sup> confirmed beyond doubt the presence of the bicyclo[3.3.0]octane ring system which had been proposed by Schroeter. Furthermore, Yates and Bhat were able to use IR and visible spectroscopy to demonstrate that the red compound was the conjugated enolate salt **2** or, more accurately, structure **3** if electron delocalisation is taken into account.



- a**  $R_1 = R_4 = H$   $R_2 = R_3 = CO_2Me$   
**b**  $R_2 = R_3 = H$   $R_1 = R_4 = CO_2Me$   
**c**  $R_1 = R_3 = H$   $R_2 = R_4 = CO_2Me$

Schroeter and Vossen's red salt has been used as a key intermediate for the preparation of various bicyclo[3.3.0]octane compounds (including approaches to pentalene derivatives) by Paul and Wendel,<sup>5</sup> the Boekelheide group,<sup>6</sup> and Yates *et al.*<sup>7</sup> In particular, it provides a convenient route to useful synthetic materials such as the tetraester **4** and bicyclo[3.3.0]octane-3,7-dione **5**.<sup>8</sup> This simple entry to the bicyclo[3.3.0]octane system has not, however, been widely adopted. In part, this is probably due to no preparative details being available in the primary literature until the 1960 paper by the Yates group.<sup>7</sup>

## Results and discussion

Despite the above detective work, there remained several issues concerning the red salt which interested us. (i) Does NMR spectroscopic data support the proposed structure? (ii) The crystalline nature of the product suggests that only one isomer is produced, but, if so, is the material **3a**, **3b** or **3c**? (iii) Is the red salt achiral (as in the delocalised structures **3a** or **3b**), or does the molecule exist in an unsymmetrical chiral form? (iv) Nothing is known about the sites in the molecule that coordinate with the sodium ion. (v) The red salt is normally prepared as its methanol solvate, but absolutely no data was available regarding the structural role played by this included molecule.

It therefore became our aim to answer these questions by obtaining definitive structural information. The red tetraethyl ester analogue of **2**, and also its red-orange potassium and green-yellow copper salts, have been described by Tanaka.<sup>9</sup> Since no solvent inclusion was reported for any of these substances, our investigation here deals with only the original tetramethyl Schroeter and Vossen compound. This was prepared by the method of Yates *et al.*<sup>7</sup> and crystallised from methanol.

The  $^{13}C$  NMR spectrum of the red salt in  $d_6$ -DMSO shows only nine signals, indicating that in solution the material has a time-averaged mirror plane running through C1 and C5 of the bicyclo[3.3.0]octane skeleton (see the structural diagram of **3** for the compound numbering system). This observation, and the carbon multiplicities from DEPT measurements, are compatible with structure **3** provided that the two carbomethoxy groups attached to C4 and C6 are *syn* (*i.e.* either structure **3a** or **3b**, but not **3c**). A crystal structure determination confirmed the general features expected, but revealed for the first time that both these ester groups are *syn* to the C5 hydrogen atom. Hence, in solution, the achiral structure **3a** is the correct one.

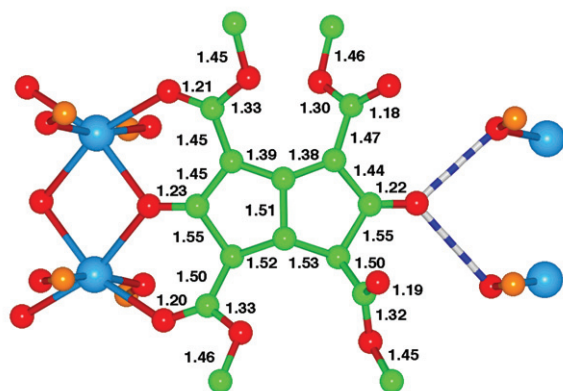
Numerical details of the solution and refinement of the crystal structure of **3a**·2MeOH are presented in Table 1. In the

**Table 1** Numerical details of the solution and refinement of the crystal structure of **3a**·2MeOH

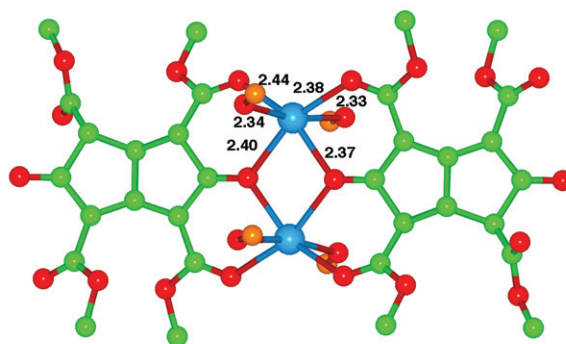
Formula	(C <sub>16</sub> H <sub>15</sub> O <sub>10</sub> Na)·(CH <sub>4</sub> O) <sub>2</sub>
Formula mass	454.4
Space group	<i>P</i> $\bar{1}$
<i>a</i> /Å	9.680(6)
<i>b</i> /Å	10.925(7)
<i>c</i> /Å	11.553(8)
$\alpha$ /°	66.78(3)
$\beta$ /°	73.38(3)
$\gamma$ /°	76.74(3)
<i>V</i> /Å <sup>3</sup>	1066(1)
<i>T</i> /°C	21(1)
<i>Z</i>	2
<i>D</i> <sub>calc</sub> /g cm <sup>-3</sup>	1.41
Radiation, $\lambda$ /Å	Mo-K $\alpha$ , 0.71073
$\mu$ /cm <sup>-1</sup>	1.28
Scan mode	$\theta/2\theta$
$2\theta_{\max}$ /°	44
No. of intensity measurements	2601
Criterion for observed reflection	<i>I</i> / $\sigma$ ( <i>I</i> ) > 3
No. of independent obsd. reflections	1849
No. of reflections ( <i>m</i> )	1849
No. variables ( <i>n</i> ) in final refinement	280
$R = \Sigma^m  \Delta F  / \Sigma^m  F_o $	0.055
$R_w = [\Sigma^m w  \Delta F ^2 / \Sigma^m w  F_o ^2]^{1/2}$	0.073
$s = [\Sigma^m w  \Delta F ^2 / (m - n)]^{1/2}$	1.63
Crystal decay	1 to 0.64

solid state, each of the bicyclo[3.3.0]octane units is chiral due to different co-ordination modes at opposite ends of the molecule. The precise arrangement is illustrated in Fig. 1. At one end, the C3 oxygen accepts hydrogen bonds from two neighbouring methanol molecules. These interactions are facilitated since the ring oxygen atom carries a partial negative charge. At the other end of the molecule, the carbonyl groups of the esters at C6 and C8 each co-ordinate to a different sodium ion, while the centrally located C7 oxygen atom provides an oxygen bridge linking both these ions. The latter interaction is favoured since this oxygen atom also has a partial negative charge.

Each sodium ion in the structure is co-ordinated to six oxygen atoms. Two molecules of **3a** with opposite chirality are linked, as described above, to two adjacent sodium ions. The central C7 oxygen of each of these **3a** molecules joins the two sodium ions as a doubly oxygen-bridged dimer. The C6 and C8 ester carbonyls of the **3a** molecules provide the remain-



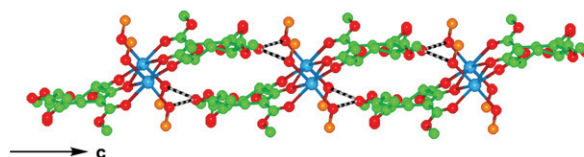
**Fig. 1** Structure of the bicyclo[3.3.0]octane region of the Schroeter and Vossen compound **3a**·2MeOH showing the bond lengths (Å) determined by X-ray crystallography. Black and white lines represent the hydrogen bonds between methanol and the C3 oxygen atom. Colour code: C of **3a** green, methanol C orange, O red and Na<sup>+</sup> blue. All hydrogen atoms are omitted for clarity.



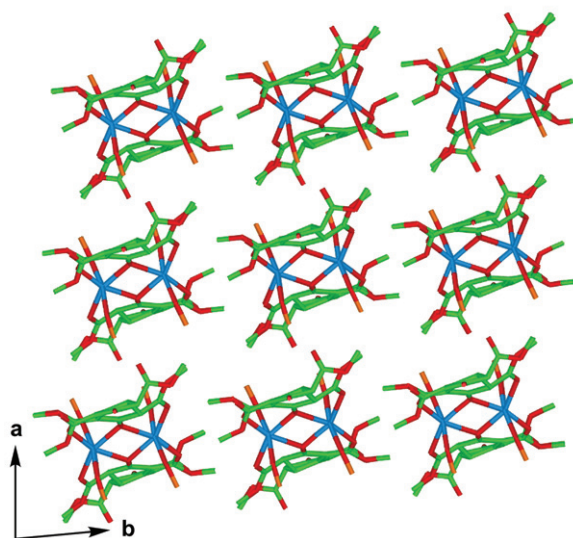
**Fig. 2** Structure of the sodium ion region of **3a**·2MeOH showing details of the octahedral oxygen co-ordination and the bond lengths (Å) determined by X-ray crystallography.

ing two equatorial ligands attached to each sodium ion. Two molecules of methanol are complexed with the axial sites of each sodium ion (Fig. 2).

Combination and repetition of these sub-units affords the unidirectional structure illustrated in Fig. 3, the configuration of which is similar to that of a non-cyclised bicycle chain. Molecules of **3a** constitute the links of the chain, with sodium ions connecting the individual links. A significant structural difference results, however, from the chirality of **3a** in the crystal. Molecules of the same handedness comprise one edge of the chain structure, while those of the opposite handedness form its second edge. The crystal structure is completed by identical chains packing in parallel along the *z* axis (Fig. 4).



**Fig. 3** The structure of **3a**·2MeOH which results when the features described in Fig. 1 and 2 are combined. The infinite unidirectional bicycle-chain structure, along the *c* direction, contains molecules of **3a** of one handedness along the top edge and opposite handedness along the bottom edge. Centres of symmetry are present in the middle of each chain link and between the pairs of adjacent sodium ions.



**Fig. 4** The lattice arrangement of the methanol solvate of the Schroeter and Vossen red salt showing how the chains (seen here as cross-sectional projections) pack parallel to each other in the *ab* plane.

The  $^1\text{H}$  NMR spectrum of the red salt in  $d_6$ -DMSO solution is dominated by three six-proton singlets at  $\delta$  3.35, 3.51 and 3.60. For reasons explored below, the  $\delta$  3.51 and 3.60 peaks are due to the two different types of ester methyl groups, while that at  $\delta$  3.35 arises from methanol co-ordinated to a sodium ion. In addition, an aliphatic two-proton doublet at  $\delta$  3.49 and an aliphatic one-proton triplet at  $\delta$  3.64 were present, as expected for structure **3a**. In the chiral solid state structure, the two aliphatic H–C–C–H torsional angles observed are  $-159.6$  and  $+142.2^\circ$ , which would correspond to vicinal  $^1\text{H}$  NMR coupling constants of around 8 and 6 Hz, respectively. The solution  $^1\text{H}$  NMR value observed for achiral **3a** was  $J = 7.9$  Hz, which therefore is fully compatible with the stereochemistry.

Slow crystallisation of **3a** from methanol solution affords the unstable red crystals of **3a**·2MeOH described above. This solid exists for a few hours at room temperature but slowly turns into a mauve–red powder. Microanalysis of the latter substance indicates that methanol has been lost in this process yielding **3a**·MeOH. Mass spectroscopy (MS) also confirms that the methanol ligands are readily lost from the red salt, with electrospray ionisation MS yielding three peaks corresponding to  $\text{Na}^+$  complexed with one, two or three molecules of **3a**, respectively.

Rapid crystal growth of **3a** from methanol produces red crystals that quickly turn opaque on standing, an observation again suggesting loss of included solvent, but without initially turning into a powder. Solution  $^{13}\text{C}$  and  $^1\text{H}$  NMR spectra of these rapidly grown crystals were identical to those of **3a**·2MeOH, except that one of the proton singlets had roughly doubled in intensity and shifted from  $\delta$  3.35 to 3.40, while the other two singlet peaks at  $\delta$  3.51 and 3.60 were unaffected either in chemical shift or integration value. This variable peak is therefore assigned to methanol complexed to a sodium ion, while the invariant peaks are assigned to the carbomethoxy groups of **3a**.

Unit cell data were collected for a rapidly grown crystal coated in Araldite. Since the cell parameters gave a volume within about 1% of that of the original sample, it is concluded that the lattice structure of the rapidly grown crystals is also the same. The additional methanol present cannot occupy interstitial sites between the parallel chains giving a new clathrate inclusion compound, since this would increase the  $a$  and  $b$  dimensions and could even lead to a different crystal space group being adopted. Instead, it is proposed that the extra solvent is trapped in small faults or voids within the crystal. Loss of this occluded methanol on standing causes localised structural damage that results in these crystals turning opaque.

In conclusion, the nature of the Schroeter and Vossen red salt has puzzled chemists since its chance discovery in 1910. Only now has the complete structure of this remarkable substance been revealed.

## Experimental

### General

$^1\text{H}$  (300 MHz) and  $^{13}\text{C}$  (75 MHz) NMR spectra were recorded with a Bruker ACF300 instrument at  $25^\circ\text{C}$  and are reported as chemical shifts relative to TMS. The substitution of the carbon atoms was determined by the DEPT procedure. Electrospray ionisation mass spectra were recorded by Dr Keith Fisher with a Finnegan LCQ ion trap instrument. The microanalysis was carried out at the Australian National University, Canberra.

### Schroeter and Vossen's red salt

Following the procedure of Yates *et al.*,<sup>7</sup> dimethyl (2,2,2-trichloroethylidene)malonate and dimethyl malonate were reacted with a solution of sodium methoxide in methanol to produce the red salt. Slow recrystallisation from methanol gave bright red crystals of **3a**·2MeOH, m.p.  $206\text{--}208^\circ\text{C}$ . IR (paraffin mull):  $\bar{\nu}$  3500 s, 1710 m, 1680 s, 1620 m, 1600 m, 1525 s, 1320 m, 1225 s, 1190 m, 1145 s, 1115 m, 1025 m, 990 s, 815 w, 785 w, 750 w, 705 w  $\text{cm}^{-1}$ .  $^1\text{H}$  NMR ( $d_6$ -DMSO):  $\delta$  3.35 (s, 6H), 3.49 (d, 2H,  $J = 7.9$  Hz), 3.51 (s, 6H), 3.60 (s, 6H), 3.64 (t, 1H,  $J = 7.9$  Hz).  $^{13}\text{C}$  NMR ( $d_6$ -DMSO):  $\delta$  47.4 (CH), 50.6 ( $\text{CH}_3$ ), 52.1 ( $\text{CH}_3$ ), 56.9 (CH), 104.5 (C), 165.7 (C), 171.4 (C), 180.4 (C), 191.5 (C). MS (electrospray):  $m/z$  413 (36%)  $[(\text{C}_{16}\text{H}_{15}\text{O}_{10}\text{Na})\cdot\text{Na}]^+$ , 803 (100)  $[(\text{C}_{16}\text{H}_{15}\text{O}_{10}\text{Na})_2\cdot\text{Na}]^+$ , 1193 (24)  $[(\text{C}_{16}\text{H}_{15}\text{O}_{10}\text{Na})_3\cdot\text{Na}]^+$ . A sample of the mauve–red powder (recrystallised red salt after standing for 6 days at room temperature) analysed for **3a**·MeOH. Found: C, 48.24; H, 4.53%. Calc. for  $\text{C}_{17}\text{H}_{19}\text{O}_{11}\text{Na}$  (422.3): C, 48.35; H, 4.53%.

### Structure determination

Reflection data were measured with an Enraf-Nonius CAD-4 diffractometer in  $\theta/2\theta$  scan mode using graphite monochromated molybdenum radiation ( $\lambda = 0.71073$  Å). Data were corrected for decomposition, but not for absorption. Reflections with  $I > 3\sigma(I)$  were considered observed. The structure was determined by direct phasing (SIR92)<sup>10</sup> and Fourier methods, with hydrogen atoms included in calculated positions. Refinement of the non-hydrogen atoms was anisotropic.<sup>11</sup> Reflection weights used were  $1/\sigma^2(F_o)$ , with  $\sigma(F_o)$  being derived from  $\sigma(I_o) = [\sigma^2(I_o) + (0.04I_o)^2]^{1/2}$ . The weighted residual is defined as  $R_w = (\sum w\Delta^2 / \sum wF_o^2)^{1/2}$ . Atomic scattering factors and anomalous dispersion parameters were from *International Tables for X-Ray Crystallography*.<sup>12</sup>

CCDC reference number 178772. See <http://www.rsc.org/suppdata/nj/b1/b111448d> for crystallographic data in CIF or other electronic format.

### Acknowledgements

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