New Contributions to the Chemistry of 2,2-Bis(chlorothio)propanedioic Diesters and Diamides

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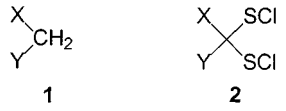
The mechanism of the formation of *gem*-disulfenyl dichlorides **2** from active methylene compounds **1** and sulfur dichloride (via the chlorodithio derivatives **12**) has been elucidated. Reduction of **2** under a variety of conditions yields, in varying amounts, the corresponding 1,2,4,5-tetrathianes **14** with concomitant formation of the tetrasulfides **15** and/or the desulfurated disulfides **16**. The pyrolysis of **2** and of the corresponding bis(disulfides) **5** leads to **14**, arguably via the corresponding thiosulfines **4**. When compounds **2** are treated with cyanide ions, reduction takes place rather than substitution, leading to the corresponding 1,2,4-trithiolanes **19**. The halogenation of **5** leads to mixtures of hexathiocanes **17**, hexathiepanes **18**, and tetrathiolanes **7** which, however, could not be obtained in pure form. The single-crystal structures of the key compounds **2a**, **5ad**, **5bd**, and **16b** have been determined by X-ray diffraction.

Introduction

Our renewed interest in geminal disulfenyl dichlorides **2**,[1] derived from active methylene compounds **1** (X = EWG, Y = EWG), stems from the following considerations:

1. Known compounds of type **2** are either liquid or solids where failure to prepare single crystals of appropriate dimensions and purity has prevented the obtaining of useful X-ray data. Thus, we wished to prepare a new compound **2** for which a single-crystal X-ray structure determination would be possible. A firm reference point in the form of a known crystal structure of a key compound **2** is important in the light of the fact that standard spectroscopic and chemical evidence is insufficient to discern rigorously between **2** and isomeric **12** (vide infra).

2. Previous suggestions concerning the mechanism of the formation of **2** from active methylene compounds **1** and sulfur dichloride are not totally convincing.[2] In the present investigation we hoped to be able to shed new light on this reaction sequence.



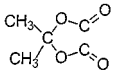
1 **2**

a, X = Y = COOMe

b, X = Y = COOEt

c, X = Y = $COOCH_2CCl_3$

d, X = Y = $COOCH_2CBr_3$

e, X + Y = 

f, X = Y = CONHPh

g, X = Y = CONH*t*Bu

3. Assuming that compounds **2** should be convenient precursors for the formation of dithiiranes **3** and thiosulfines **4**,[3] cf. Equation (1), we wished to elaborate this aspect further.

3 **4** (1)

4. Cleavage of the 2,2-bis(acyldithio) derivatives **5** (R = COMe or COPh; readily prepared from **2** and the corresponding thiocarboxylic acids) with chlorine should yield the unprecedented 2,2-bis(chlorodithio) compounds **6**,

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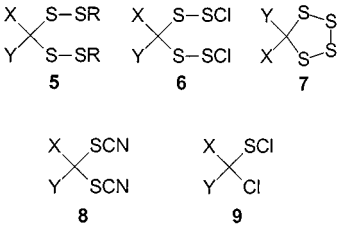


which might in turn be transformed into the elusive tetrathiolanes **7**[4] upon dechlorination.

5. In view of the interesting properties of the industrial microbiocide methylene bis(thiocyanate) **8a** (X = Y = H),[5] and of the fact that **8a** is still the only compound of type **8** known, we assumed that **2** might be converted into the corresponding compounds **8** by reaction with cyanide and wished to test this proposition experimentally.

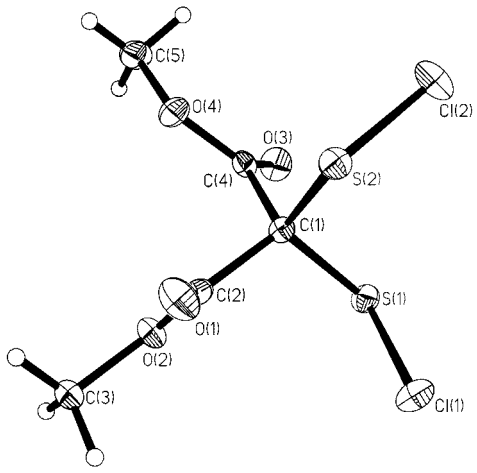


Figure 1. The molecular structure of **2a** with 50% probability ellipsoids

Results and Discussion

When performing the standard reaction between a series of active methylene compounds and sulfur dichloride,[2,6] we noted the highly individual reactivities of otherwise closely related propanedioic acid derivatives (cf. Table 1). Bannister and Rees had already noted that, while many compounds of type **2** obtained in this way cannot be completely purified, the crude products are satisfactory for many synthetic purposes.[6]

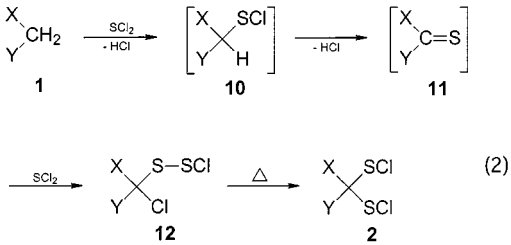
Table 1. Reactions of propanedioic acid derivatives **1** with SCl_2

Starting material	Product (yield in %)	Comments
1a	**2a** (88)	analytically pure
1b	**2b** (99)[1]	crude product
1c	unidentified	no **2c** formed
1d	unidentified	no **2d** formed
1e	**1e**	no reaction
1f	**2f** (34)[5]	not analytically pure[2]
1g	**9g** (61)[7]	analytically pure

To our delight, the seemingly trivial substrate change from diethyl propanedioate (**1b**) to the dimethyl ester **1a** (the former yields liquid **2b** as an inseparable mixture with other products[1]) resulted in the formation of the new, solid compound **2a** which could be purified by recrystallization to the most exacting standards, including the harvest of single crystals suitable for X-ray work. Thus, it was possible to determine the single-crystal structure of **2a** (cf. Figure 1). Apart from its unambiguous confirmation of the chemical structure of **2a**, this single-crystal structure is, as expected, dominated by intramolecular repulsion between the two carbonyl groups, resulting in near orthogonality [the angle between the two planes C(1)−C(2)−O(1) and C(1)−C(4)−O(3) is 82.6(2)°], and between the two chlorothio groups [the angle between the two planes C(1)−S(1)−Cl(1) and C(1)−S(2)−Cl(2) is 88.69(7)°]. In addition, a weak C−H···Cl interaction can be observed; i.e. the distance H(33)···Cl(1) is 3.680(3) Å with a C(3)−H(33)−Cl(1) angle of 147(3)°.

On the other hand, bis(2,2,2-trichloroethyl) propanedioate (**1c**) and bis(2,2,2-tribromoethyl) propanedioate (**1d**) (both of which gave unidentifiable products not including **2c** and **2d**, respectively), as well as *N*,*N*-di-*tert*-butylpropanediamide (**1g**) [unexpected formation of *N*,*N*-di-*tert*-butyl-2-chloro-2-(chlorothio)propanediamide (**9g**)[7]], failed to yield the corresponding compound **2** upon treatment with sulfur dichloride in boiling benzene. Our experiments with the known 2,2-bis(chlorothio)propanedianilide (**2f**)[2,6] confirmed earlier observations that it is difficult to purify and difficult to handle in substitution reactions.[2,5] Meldrum's acid (**1e**) did not react with SCl_2 under these conditions.

We were able to demonstrate that the formation of **2a** (and most probably of all other analogous compounds) takes place in the following manner [Equation (2)]. The first step is the formation of the corresponding sulfenyl chloride **10a**, which spontaneously loses HCl to form the corresponding thione **11a** (it is remarkable that no cyclization products derived from **11a** are observed). This in turn adds sulfur dichloride with formation of the corresponding α-chloro-substituted thiosulfenyl chloride **12a**, which can be directly observed in the reaction mixture by TLC (**12a** is also accessible by an independent synthesis; vide infra). Intermediate **12a** thus prepared slowly rearranges to **2a** upon heating in boiling benzene. Corresponding rearrangements have previously been observed in the opposite direction; i.e. **2** → **12**.[8]



Reduction (and related substitution) of **2a** was carried out in a multitude of ways in the hope of generating dithiiranes **3** and thiosulfines **4**. A particularly simple reduction of **2** can be carried out electrochemically,[9] yielding pure **14** as the only product. Treatment of **2a** with sodium *p*-toluenesulfinate yielded three products: dimethyl 2,2-bis(*p*-tolylsulfonylthio)propanedioate (**13a**) (40% yield), tetramethyl 1,2,4,5-tetrathiane-3,3,6,6-tetracarboxylate (**14a**) (30% yield), and tetramethyl 1,6-dichloro-2,3,4,5-tetrathiahexane-1,1,4,4-tetracarboxylate (**15a**) (12% yield); cf. Scheme 1. While **14a** could well have been formed by two-step dimerization of the corresponding thiosulfine **4a** (for precedents see ref.[3]), other pathways leading to its formation cannot be rigorously ruled out. The formation of **15a** is surprising and so far its mechanism must remain a matter of speculation. If one assumes an equilibrium between **2a** and **12a**, straightforward reduction of the latter would yield **15a**. Although the poor quality of the crystals of **15a** prevented a single-crystal structure determination, the structure of **15a** follows readily from the NMR equivalence of its methyl groups, as well as from the fact that its mass-spectral fragmentation shows the subsequent loss of the four sulfur atoms without concomitant loss of the two chlorine atoms. The chlorination of **15a** with sulfuryl chloride yields **2a**, a result consistent with a symmetrical cleavage of the tetrasulfide bridge of **15a** and subsequent spontaneous rearrangement of the thiosulfenyl chloride **12a** thus formed. The reduction of **2b** led to **14b** (54% yield) and tetraethyl 1,4-dichloro-2,3-dithiabutane-1,1,4,4-tetracarboxylate (**16b**) (31% yield). Compound **16b** was subjected to a single-crystal X-ray structure determination (Figure 2).

One notes the near orthogonality of the C(1)−Cl(1) and C(8)−Cl(2) bonds as well as the near antiperiplanarity of the two pairs of carbonyl groups [C(2)−O(1) plus C(5)−O(3) and C(9)−O(6) plus C(12)−O(7)], as expected in the absence of significant intermolecular forces. The C(1)−S(1)−S(2)−C(8) torsion angle is 100.8(2)°, which is within the range of values found in comparable acyclic systems (i.e. 50−119°).[10] The nature of the desulfurization step required for the formation of the reduction product **16** (for more on the chemistry of **16** and the related **9**, see ref.[7]) so far remains obscure.

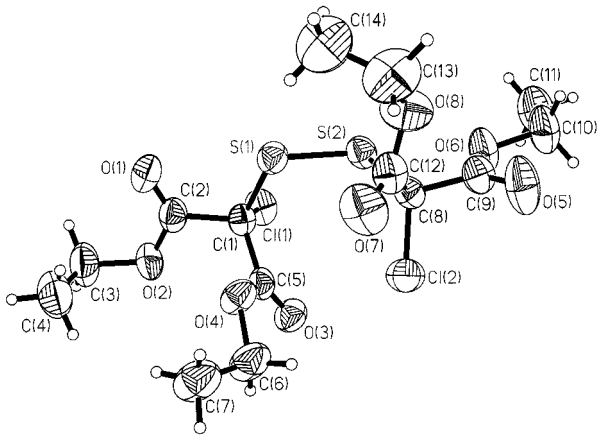
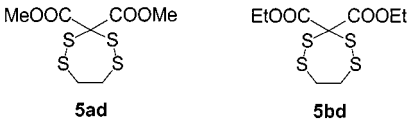
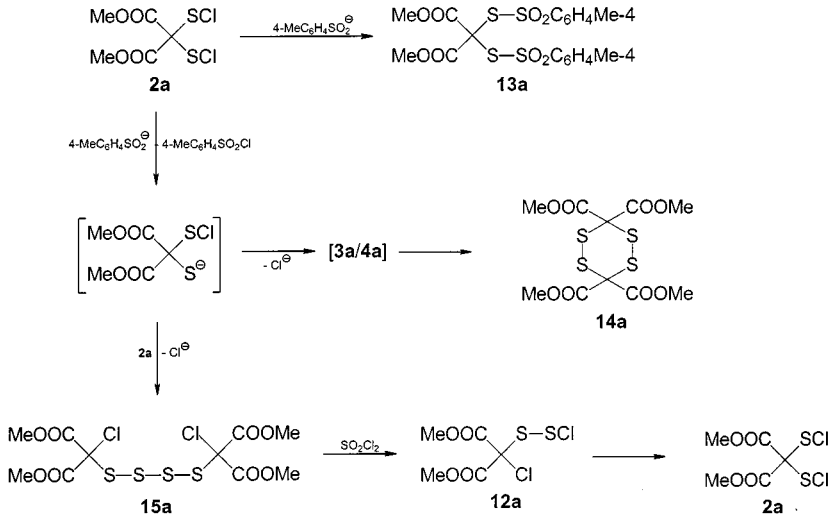


Figure 2. The molecular structure of **16b** with 50% probability ellipsoids



5ad **5bd**

The geminal disulfenyl dichlorides **2** were converted into compounds **5** with thioacetic acid (R = COMe, series **a**), thiobenzoic acid (R = COPh, series **b**), thiophenol (R = Ph, series **c**), and 1,2-ethanedithiol (R, R = CH_2CH_2, series **d**). The 1,2,4,5-tetrathiepanes **5ad** and **5bd** were subjected to single-crystal X-ray structure analyses. The structure of **5ad** is shown in Figure 3. The characteristic torsion angles C(1)−S(1)−S(2)−C(2) and C(1)−S(4)−S(3)−C(3) are 96.1(2)° and 99.0(2)°, respectively; in agreement with the corresponding values found for **16b**. The angle between the two planes C(1)−S(1)−S(2) and C(1)−S(4)−S(3) is 70.06(8)°. As expected, the 1,2,4,5-tetrathiepane ring appears unstrained in both compounds, with full staggering



Scheme 1

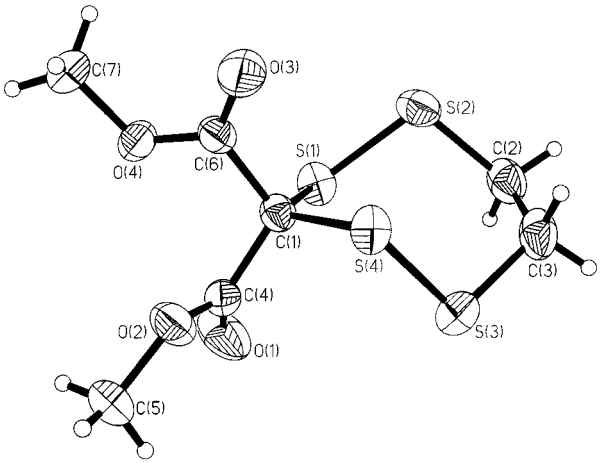


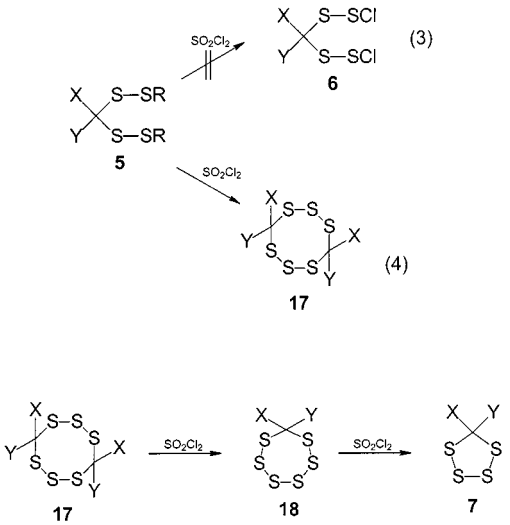
Figure 3. The molecular structure of **5ad** with 50% probability ellipsoids

of the C-6 and C-7 methylene groups [designated C(2) and C(3) in the Figures]. In both cases the two carbonyl groups C(4)−O(1) and C(6)−O(3) are roughly antiperiplanar, again as expected in the absence of significant intermolecular forces.

Compounds **5ad** and **5bd** dissolve in concentrated sulfuric acid to give a characteristic green color. No radical species can be observed by ESR in these solutions, and upon dilution with water the starting material is recovered unchanged.

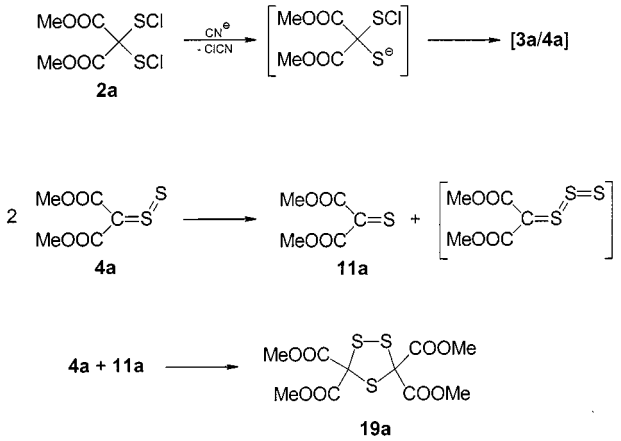
The chlorination of the bis(disulfide) **5aa** with chlorine or sulfuryl chloride took an unexpected course.

The predicted corresponding bis(thiosulfenyl chloride) **6a** was not formed, but mixtures of the corresponding heterocycles **17a**, **18a**, and **7a** were obtained instead [Equations (3) and (4); Scheme 2].



Scheme 2

The formation of **17a** (tentatively identified as tetramethyl 1,2,3,5,6,7-hexathiocane-4,4,8,8-tetracarboxylate) would be in keeping with a two-step dimerization of the



Scheme 3

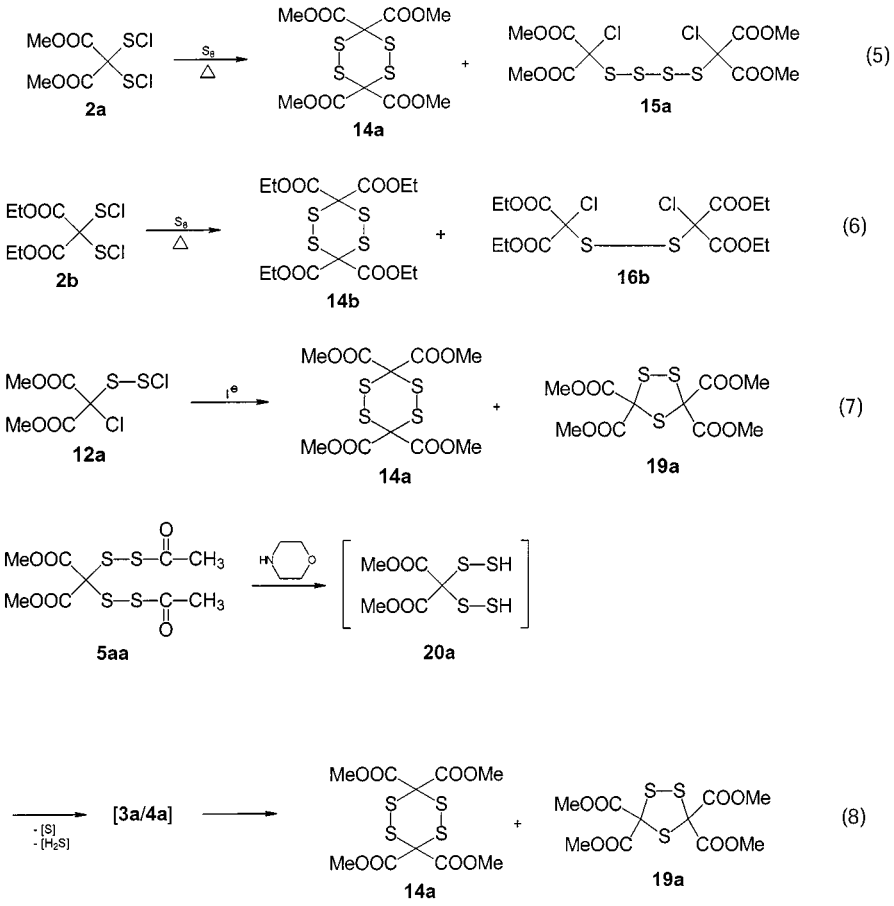
corresponding thione *S*-disulfide (cf. Scheme 3), formed in a thus far obscure manner. Hence, we assume that **17** is the primary reaction product, while **18** is formed by further chlorination of **17** (probably with concomitant formation of dimethyl 2,2-dichloropropanedioate) and **7** by further chlorination of **18** (cf. Scheme 2). With excess bromine or iodine, **5aa** forms mainly **7a**.

In the hope of obtaining sulfur-rich heterocycles like **18a** in a more straightforward manner, **2a** was treated with bis(tetrabutylammonium) hexasulfide, but the resulting crude product was virtually identical to the crude product obtained from **5aa** and sulfuryl chloride (vide supra).

When heated in admixture with **2**, sulfur behaves as a dechlorination reagent. Again, the subtle difference between the behavior of **2a** [forming (in order of elution) **14a** and **15a**; Equation (5)] and **2b** [forming (in order of elution) **14b** and **16b**; Equation (6)] is striking.

The pyrolyses of **2**, **5**, and **13a**, all leading to the corresponding 1,2,4,5-tetrathiane **14**, are a clear indication of the intermediacy of the corresponding compounds **3/4**. However, the most convincing evidence of the suitability of **2** as **3/4** precursors came from the observation that, upon reaction with cyanide, **2a** does not form the substitution product **8**, but rather a reduction product, the 1,2,4-trithiolane **19a** (the corresponding reaction with thiocyanate leads to the 1,2,4,5-tetrathiane **14a**). We are confident that this ring closure requires the concomitant formation of the thione **11a** (most probably by disproportionation of **4a**) and the thiosulfine **4a,** and that these then combine to form **19a** (cf. Scheme 3).

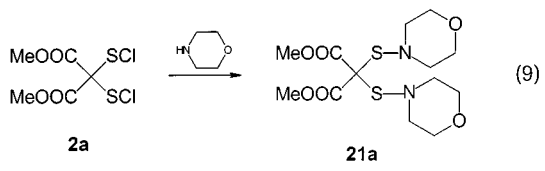
We believe that the rationale for the varying behavior of nucleophiles towards **2** − i.e. either substitution (corresponding to nucleophilic attack on the sulfenyl chloride sulfur) or reduction (corresponding to nucleophilic attack on the sulfenyl chloride chlorine) − lies in their HSAB features. Hence, relatively soft nucleophiles such as thiols attack the relatively soft sulfur atom, while relatively hard nucleophiles such as cyanide appear to attack the relatively hard chlorine atom. Sulfinate anions would then constitute a borderline case, with competing attacks at both sulfur and chlorine atoms. Admittedly, the reaction of thiocyanate with **2a** does not readily fit into this scheme.



For good measure, the reduction of the α-chloro-substituted thiosulfenyl chloride **12a** with iodide or triphenylphosphane to form the 1,2,4,5-tetrathiane **14a** and the 1,2,4-trithiolane **19a** shows that such a system is also a convenient precursor for **3/4** [cf. Equation (7)].

A most surprising experiment showed further that even treatment of a *gem*-bis(disulfide) such as **5aa** with morpholine leads to the same result as the preceding reactions; i.e. concomitant formation of **14a** and **19a**. The primary reaction product, conceivably the *gem*-bis(disulfanyl) compound **20a**, could probably suffer subsequent loss of hydrogen sulfide and of sulfur to yield **4a**, which in turn would form the observed end products [cf. Equation (8)].

The substitution of **2a** with morpholine was straightforward and led to the formation of the bis(sulfenamide) **21a** [cf. Equation (9)].



Experimental Section

Commercial chemicals and solvents were used as received, except for sulfur dichloride, which was distilled immediately prior to use. Bis(2,2,2-trichloroethyl) propanedioate (**1c**),[11] *N*,*N*′-di-*tert*-butylpropanediamide (**1g**),[12] and 2,2-bis(chlorothio)propanedianilide (**2f**)[2,6] were prepared according to literature procedures. The electrochemical reductions were performed in a three-compartment H cell at constant potential by means of a home-built potentiostat. − The stationary phase in column chromatography was Merck silica gel 60, particle size 0.040−0.063 mm. TLC was carried out with Merck silica gel 60 on aluminum foil. The eluent for TLC was hexane/ether (1:1) and for column chromatography petroleum ether (b.p. 40−60 °C)/ether (10:1) unless otherwise indicated. − All NMR spectra were recorded in $CDCl_3$ solution, ^1H NMR spectra at 300 or 500 MHz, ^{13}C NMR spectra at 75.45 or 125.76 MHz with a Bruker AC250 or Bruker AM500 apparatus. − IR spectra of solids were recorded with KBr wafers, those of liquids neat between NaCl windows with a Perkin−Elmer 1600 Series FTIR spectrometer. − The mass spectra were obtained with a VG (Mass lab) Trio-2 mass spectrometer with direct inlet. − The elemental analyses were carried out by the Microanalytical Laboratory of the Department of Physical Chemistry, University of Vienna, A-1090 Vienna, Austria.

Bis(2,2,2-tribromoethyl) Propanedioate (1d): This compound was prepared according to a general procedure[13] from propanedioic acid and 2,2,2-tribromoethanol. A mixture of propanedioic acid (0.7 g, 9.6 mmol), *N*,*N*′-dicyclohexylcarbodiimide (2.1 g, 10.2 mmol), and 2,2,2-tribromoethanol (5.4 g, 19.2 mmol) in dichloromethane (50 mL) was stirred overnight at room temperature, after which TLC showed that the starting materials had been consumed. The reaction mixture was filtered by suction and the solid washed with ethyl acetate. The dichloromethane and ethyl

acetate solutions were combined and concentrated in vacuo. The residue was column chromatographed (eluent ethyl acetate/hexane, 3:1). Yield 3.20 g (53%) **1d** as pale yellow crystals, m.p. 68.5−69.5 °C. − IR: $\tilde{\nu}$ = 2984, 2894 (aliphatic CH), 1740 (C=O), 1368, 1255, 1028, 896, 858, 560 cm^{-1}. − ^1H NMR: δ = 3.75 (s, 2 H, CH_2), 5.05 (s, 4 H, 2 CH_2). − ^{13}C NMR: δ = 34.3 (CH_2), 40.9 (2 CH_2), 77.5 (2 CBr_3), 163.9 (2 CO). − MS (EI); *m/z* (%): 628 (0.2) [M], 548 (2.5) [M − HBr], 349 (12) [$C_5H_4Br_3O_3$], 87 (100%) [$C_3H_3O_3$]. − MS (CI, ammonia); *m/z* (%): 629 (very weak) [MH^+]. − $C_7H_6Br_6O_4$ (633.5): calcd. C 13.27, H 0.95; found C 13.58, H 1.20.

Dimethyl 2-Chloro-2-(chlorodithio)propanedioate (12a): Sulfuryl chloride (1.0 mL, 10 mmol) was added dropwise to a stirred solution of tetramethyl 1,5-dichloro-2,3,4-trithiapentane-1,1,5,5-tetracarboxylate[7] (4.3 g, 10 mmol) in tetrachloromethane (30 mL). After 3 h, the reaction was complete as judged by TLC. After concentration in vacuo, the residue was column-chromatographed to yield a first fraction of 1.24 g (43%) **9a**[7] and a second fraction of 1.41 g (53%) **12a**. The thiosulfenyl chloride **12a** is a yellow oil, b.p. 93−97 °C/0.5 Torr. − IR: $\tilde{\nu}$ = 2961 (aliph. CH), 1733 (C=O), 1433, 1237, 1005, 955, 841, 769, 624, 523 cm^{-1}. − ^1H NMR: δ = 3.93 (s). − ^{13}C NMR: δ = 54.7 (2 CH_3), 96.0 (C-2), 164.0 (2 C=O). − MS (EI); *m/z* (%): 264 (2.5) [M], 232 (10) [$C_5H_6Cl_2O_4S$], 229 (4) [$C_5H_6ClO_4S_2$], 173 (15) [$C_3H_3Cl_2O_2S$], 162 (10) [$C_5H_6O_4S$], 153 (18), 138 (23) [$C_3H_3ClO_2S$], 109 (25), 103 (25) [$C_3H_3O_2S$], 79 (32) [CClS], 59 (100) [$C_2H_3O_2$]. − $C_5H_6Cl_2O_4S_2$ (265.1): calcd. C 22.65, H 2.28, S 24.19; found C 22.58, H 2.60, S 24.01.

Dimethyl 2,2-Bis(chlorothio)propanedioate (2a): Dimethyl propanedioate (1.7 mL, 15 mmol) and freshly distilled sulfur dichloride (6.8 mL, 90 mmol) were dissolved in benzene (20 mL). The mixture was heated at reflux until TLC showed that the reaction was complete (42 h). After concentration to dryness, the last traces of benzene and sulfur dichloride were removed under high vacuum. A yellow precipitate of **2a** was obtained by trituration with ether/petroleum ether with cooling. Yield 3.80 g (95%) of crude product, m.p. 65−68 °C, which was recrystallized from ether to give yellow crystals of **2a**, m.p. 69.5−70.5 °C, yield 3.50 g (88%). − IR: $\tilde{\nu}$ = 2961 (aliph. CH), 1733 (C=O), 1433, 1237, 1005, 955, 841, 769, 624, 523 cm^{-1}. − ^1H NMR: δ = 3.90 (s). − ^{13}C NMR: δ = 54.8 (2 CH_3), C-2 not observed, 164.2 (2 C=O). − MS (EI); *m/z* (%): 264 (10) [M], 197 (35) [$C_5H_6ClO_4S$], 194 (8) [$C_5H_6O_4S_2$], 169 (3), 162 (5) [$C_5H_6O_4S$], 111 (15), 103 (40) [$C_3H_3O_2S$], 59 (100) [$C_2H_3O_2$]. − $C_5H_6Cl_2O_4S_2$ (265.1): calcd. C 22.65, H 2.28, S 24.19; found C 23.04, H 2.30, S 24.26. A single-crystal X-ray structure determination was performed (cf. Figure 1 and Table 2).

Rearrangement of 12a to 2a: Dimethyl 2-chloro-2-(chlorodithio)-propanedioate (**12a**) (2.7 g, 10 mmol) was dissolved in benzene (20 mL). This mixture was heated at reflux for 28 h and then concentrated to dryness. The yellow residue was triturated with ether/petroleum ether with cooling. The crude solid (2.42 g, 93%) thus obtained melted at 63−68 °C. Recrystallization from ether gave yellow crystals of **2a** (vide supra), m.p. 69.5−71.0 °C, yield 2.29 g (88%).

Reaction of Bis(2,2,2-trichloroethyl) Propanedioate (1c) with SCl_2: **1c**[11] (5.4 g, 15 mmol) and freshly distilled sulfur dichloride (6.8 mL, 90 mmol) were mixed in benzene (20 mL). This mixture was heated at reflux until TLC showed that the reaction was complete (46 h), then concentrated to dryness, and remaining traces of benzene and sulfur dichloride were removed under high vacuum to give 6.80 g of a viscous yellow oil. According to TLC, this oil contained at least six components, but all attempts at chromatographic separation failed. The Lassaigne test showed the presence of sulfur and chlorine.

Reaction of Bis(2,2,2-tribromoethyl) Propanedioate (1d) with SCl_2: **1d** (9.4 g, 15 mmol) and freshly distilled sulfur dichloride (6.8 mL, 90 mmol) were mixed in benzene (20 mL). The mixture was heated at reflux until TLC showed that the reaction was complete (40 h), then concentrated to dryness, and remaining traces of benzene and sulfur dichloride were removed under high vacuum to give a highly viscous yellow oil (yield 5.70 g). According to TLC, this oil contained at least five components, but all attempts at chromatographic separation failed. The Lassaigne test showed the presence of sulfur and halogen.

Derivatization of 2 with Mercapto Compounds: A general procedure[14] was followed. A geminal disulfenyl dichloride (10 mmol) and a mercapto compound (thioacetic acid, series **a**, thiobenzoic acid, series **b**, thiophenol, series **c**, or 1,2-ethanedithiol, series **d**) (20 equivalents) were dissolved in tetrachloromethane (50 mL) and heated at 50−60 °C until TLC showed that the reaction was complete (3 h). After evaporation of the solvent, the corresponding

Table 2. Crystal data for compounds **2a**, **5ad**, **5bd**, and **16b**, the structures of which have been determined by X-ray crystallography

Crystal data[a]	**2a**	**5ad**	**5bd**	**16b**
Formula	$C_5H_6C_{12}O_4S_2$	$C_7H_{10}O_4S_4$	$C_9H_{14}O_4S_4$	$C_{14}H_{20}C_{12}O_8S_2$
M	26512	23839	31444	45132
M.p. [°C]	69.5−70.5	120.5−121.5	79.5−80.0	51.5−52.0
Crystal system	orthorhombic	triclinic	triclinic	monoclinic
Space group	$Pna2_1$	$P\bar{1}$	$P\bar{1}$	$P2_1/n$
a [Å]	12.0351(3)	6.4762(2)	9.2825(4)	9.3667(3)
b [Å]	7.7587(2)	7.2387(2)	11.6340(5)	9.0708(3)
c [Å]	10.7084(3)	13.5734(3)	14.0935(7)	24.5864(7)
α [°]	−	80.528(2)	103.422(2)	−
β [°]	−	88.6320(10)	92.105(2)	92.9110(10)
γ [°]	−	70.0270(10)	90.904(2)	−
V [Å^3]	998.63(5)	589.53(3)	1478.96(12)	2086.25(11)
Z	4	2	4	4
Total number of unique refl.	2480	2621	5723	2983
[$I > 2\sigma(I)$]	2364	2112	3445	2465
Θ-range [°]	3.13−29.46	1.52−29.57	1.49−26.00	1.66−23.22
R (obs. data)	275	398	958	419
*wR*2 (all data)	659	985	2174	1083

[a] Data were collected at 296 K with a SMART diffractometer using Mo-K_α radiation. The crystal-to-detector-distance was 4.5 cm. The structures were solved by direct methods (SHELXTL) and refined with a full-matrix least-squares technique. All hydrogen atoms were at calculated positions using a riding model with C−H = 0.96−0.97 Å and fixed thermal parameters [*U*(H) = 1.2 times *U* for attached C].

bis(disulfides) **5** were obtained upon separation by column chromatography.

Dimethyl 2,2-Bis(acetyldithio)propanedioate (5aa): Colorless crystals, 3.15 g (91%), m.p. 74.5−75.0 °C. − IR: $\tilde{\nu}$ = 2995 (aliphatic CH), 1732 (C=O), 1720 (C=O), 1435, 1273, 1107, 940, 838, 766, 695 cm^{-1}. − ^1H NMR: δ = 2.45 (s, 6 H, 2 CH_3CO), 3.85 (s, 6 H, 2 CH_3). − ^{13}C NMR: δ = 29.1 (2 CH_3CO), 54.3 (2 CH_3O), C-2 signal not observed, 164.8 (2 COO), 191.8 (2 COS). − MS (CI); *m/z* (%): 362 (100) [M + NH_4^+], 345 (20) [M + H^+]. − $C_9H_{12}O_6S_4$ (344.5): calcd. C 31.38, H 3.51, S 37.24; found C 31.36, H 3.29, S 37.86.

Dimethyl 2,2-Bis(benzoyldithio)propanedioate (5ab): Colorless crystals, 4.10 g (87%), m.p. 86.5−87.0 °C. − IR: $\tilde{\nu}$ = 3054 (aromatic CH), 2951 (aliph. CH), 1739, 1717 (2 C=O), 1599, 1580, 1446, 1435, 1336, 1272, 1264 cm^{-1}. − ^1H NMR: δ = 3.85 (s, 6 H, 2 CH_3), 7.45−8.00 (m, 10 H, Ar−H). − ^{13}C NMR: δ = 54.4 (2 CH_3), C-2 signal not observed, 128.1, 129.0 (C-2, C-2, C-6, C-6), 134.4 (C-3, C-3, C-5, C-5), 135.2 (C-4, C-4), 164.9 (2 COO), 187.7 (2 COS). − MS (CI); *m/z* (%): 486 (0.7) [M + NH_4^+], 469 (0.2) [M + H^+], 105 (100) [C_7H_5O]. − $C_{19}H_{16}O_6S_4$ (468.6): calcd. C 48.70, H 3.44, S 27.37; found C 48.78, H 3.46, S 27.29.

Dimethyl 2,2-Bis(phenyldithio)propanedioate (5ac): Colorless crystals, 2.80 g (68%), m.p. 71.5−72.0 °C. − IR: $\tilde{\nu}$ = 3035 (aromatic CH), 2252 (aliph. CH), 1728 (C=O), 1576, 1475, 1437, 1229, 1068, 1020, 952, 832, 764, 738, 687, 627, 470 cm^{-1}. − ^1H NMR: δ = 3.25 (s, 6 H, 2 CH_3), 7.3−7.6 (m, 10 H, ArH). − ^{13}C NMR: δ = 53.3 (2 CH_3), C-2 signal not observed, 127.7, 128.9 (C-2, C-2, C-6, C-6), 129.4 (C-3, C-3, C-5, C-5), 135.4 (C-4, C-4), 165.1 (2 CO). − MS (EI); *m/z* (%): 412 (0.9) [M], 353 (0.6) [$C_{15}H_{13}O_2S_4$], 306 (0.3) [$C_{14}H_{10}O_2S_3$], 271 (48) [$C_{11}H_{11}O_4S_2$], 250 (30) [$C_{12}H_{10}S_3$], 218 (18) [$C_{12}H_{10}S_2$], 211 (38) [$C_9H_7O_2S_2$], 141 (78) [$C_6H_5S_2$], 109 (100) [C_6H_5S], 103 (16) [$C_3H_3O_2S$], 77 (44) [C_6H_5], 59 (49) [$C_2H_3O_2$]. − $C_{17}H_{16}O_4S_4$ (412.6): calcd. C 49.49, H, 3.91, S 31.09; found C 50.00, H 4.03, S 30.01.

Diethyl 2,2-Bis(acetyldithio)propanedioate (5ba): Colorless crystals, 3.20 g (86%), m.p. 73.5−74.0 °C. − IR: $\tilde{\nu}$ = 2990 (aliphatic CH), 1732 (C=O), 1720 (C=O), 1391, 1223, 1113, 1042, 944, 859, 596 cm^{-1}. − ^1H NMR: δ = 1.30 (t, ^3J = 7.0 Hz, 6 H, 2 CH_3CH_2), 2.45 (s, 6 H, 2 CH_3CO), 4.25 (q, ^3J = 7.0 Hz, 4 H, 2 CH_3CH_2). − ^{13}C NMR: δ = 13.9 (2 CH_3), 29.1 (2 CH_3), 63.8 (2 CH_2), C-2 signal not observed, 164.4 (2 COO), 192.0 (2 COS). − MS (CI); *m/z* (%): 390 (72) [M + NH_4^+], 373 (12) [M + H^+], 320 (42) [$C_7H_{10}O_5S_4$+NH_4^+], 318 (100) [$C_8H_{12}O_4S_4$ + NH_4^+]. − $C_{11}H_{16}O_6S_4$ (372.5): calcd. C 35.47, H 4.33, S 34.43; found C 35.52, H 4.31, S 34.75.

Reactions of 2 with 1,2-Ethanedithiol: A 250-mL three-necked flask, equipped with a reflux condenser and magnetic stirring bar, was charged with tetrachloromethane (20 mL) and brought to reflux. Compound **2a** or **2b** (10 mmol) in tetrachloromethane (5 mL) and 1,2-ethanedithiol (0.7 mL, 10 mmol) in tetrachloromethane (5 mL) were simultaneously added dropwise over 25 min; at the end of the addition the heating continued at reflux until TLC showed that the reaction was complete (9 h). After concentration in vacuo, the residue was column-chromatographed.

Dimethyl 1,2,4,5-Tetrathiepane-3,3-dicarboxylate (5ad): Colorless crystals, 2.40 g (84%), m.p. 120.5−121.5 °C. − IR: $\tilde{\nu}$ = 2990 (aliphatic CH), 1724 (C=O), 1435, 1398, 1254, 1020, 951, 917, 838, 760 cm^{-1}. − ^1H NMR: δ = 3.25 (d, ^3J = 11.0 Hz, 2 H, 2 CH_aH_b), 3.35 (d, ^3J = 11.0 Hz, 2 H, 2 CH_aH_b), 3.85 (s, 6 H, 2 CH_3). − ^{13}C NMR: δ = 44.1 (C-6, C-7), 54.2 (2 CH_3), C-3 signal not observed, 166.9 (2 CO). − MS (EI); *m/z* (%): 286 (1) [M], 255 (0.9) [$C_6H_7O_3S_4$], 227 (1.3) [$C_5H_7O_2S_4$], 124 (100) [$C_2H_4S_3$], 103 (8) [$C_3H_3O_2S$], 59 (45) [$C_2H_3O_2$]. − $C_7H_{10}O_4S_4$ (286.4): calcd. C 29.36, H 3.52, S 44.78; found C 29.49, H 3.34, S 45.14. − A single-crystal X-ray structure determination was performed (cf. Figure 2 and Table 2).

Diethyl 1,2,4,5-Tetrathiepane-3,3-dicarboxylate (5bd): Colorless crystals, 2.30 g (73%), m.p. 79.5−80.0 °C. − IR: $\tilde{\nu}$ = 2979 (aliphatic CH), 1735 (C=O), 1445, 1392, 1366, 1248, 1092, 1030, 916, 857, 830, 815, 759, 627, 530 cm^{-1}. − ^1H NMR: δ = 1.30 (t, 6 H, ^3J = 7.0 Hz, 2 CH_3), 3.25 (d, ^3J = 11.0 Hz, 2 H, 2 CH_aH_b), 3.38 (d, ^3J = 11.0 Hz, 2 H, 2 CH_aH_b), 4.30 (q, ^3J = 7.0 Hz, 4 H, 2 CH_2). − ^{13}C NMR: δ = 13.9 (2 CH_3), 44.0 (C-6, C-7), 63.4 (2 CH_2O), 77.7 (C-3), 166.5 (2 C=O). − MS (EI); *m/z* (%): 314 (1) [M], 269 (0.8) [$C_7H_9O_3S_4$], 241 (1.3) [$C_6H_9O_2S_4$], 124 (100) [$C_2H_4S_3$]. − $C_9H_{14}O_4S_4$ (314.5): calcd. C 34.38, H 4.49, S 40.79; found C 34.57, H 4.29, S 41.29. − A single-crystal X-ray structure determination was performed (see Table 2).

Reduction of Geminal Disulfenyl Dichlorides

1. With Sodium *p*-Toluenesulfinate: A general procedure[15] was followed. A two-phase mixture of sodium *p*-toluenesulfinate dihydrate (4.3 g, 20 mmol), **2a** (2.7 g, 10 mmol), tetrabutylammonium hydrogen sulfate (0.20 g), water (25 mL), and benzene (25 mL) was stirred at room temperature until TLC showed that the reaction was complete (12 h). The benzene phase was washed three times with water and dried with anhydrous calcium chloride. After concentration in vacuo, the residue was column-chromatographed. The following products (in order of elution) were obtained: **13a** (yield 2.00 g, 40%), **14a** (yield 0.60 g, 31%), **15a** (yield 0.30 g, 13%).

Dimethyl 2,2-Bis(*p*-tolylsulfonylthio)propanedioate (13a): Colorless crystals, m.p. 154.5−155.0 °C. − IR: $\tilde{\nu}$ = 3030 (aromatic CH), 2990 (aliphatic CH), 1737 (C=O), 1653, 1593, 1559, 1491, 1436, 1377, 1308 cm^{-1}. − ^1H NMR: δ = 2.50 (s, 6 H, 2 CH_3Ar), 3.80 (s, 6 H, 2 CH_3O), 7.29 (d, ^3J = 8.0 Hz, 2 H, 2 × 2 H, Ar−H), 7.59 (d, ^3J = 8.0 Hz, 2 H, 2 × 2 H, Ar−H). − ^{13}C NMR: δ = 21.7 (2 CH_3Ar), 55.0 (2 CH_3O), C-2 signal not observed, 128.2 (C-3, C-3, C-5, C-5), 129.5 (C-2, C-2, C-6, C-6), 140.7 (C-4, C-4), 145.6 (C-1, C-1), 163.3 (2 C=O). − MS (EI); *m/z* (%): 504 (0.08) [M], 349 (1.4) [$C_{12}H_{13}O_6S_3$], 278 (4), 194 (5) [$C_5H_6O_4S_2$], 162 (13) [$C_5H_6O_4S$], 155 (52) [$C_7H_7O_2S$], 139 (38) [C_7H_7OS], 123 (7) [C_7H_7S], 103 (21) [$C_3H_3O_2S$], 91 (100) [C_7H_7], 59 (55) [$C_2H_3O_2$]. − $C_{19}H_{20}O_8S_4$ (504.6): calcd. C 45.22, H 3.99, S 25.42; found C 45.25, H 3.77, S 25.44.

Tetramethyl 1,2,4,5-Tetrathiane-3,3,6,6-tetracarboxylate (14a): Colorless crystals, m.p. 165.0−166.0 °C. Recrystallization from ether/petroleum ether (1:1) gave 0.60 g (31%) **14a**, m.p. 166.0−166.5 °C. − IR: $\tilde{\nu}$ = 2960 (aliphatic CH), 1738 (C=O), 1432, 1244, 1042, 1005, 910, 800, 660, 580 cm^{-1}. − ^1H NMR: δ = 3.85 (s). − ^{13}C NMR: δ = 54.4 (4 CH_3), 96.0 (C-3, C-6),166.3 (4 CO). − MS (EI); *m/z* (%): 388 (1.6) [M], 356 (0.4) [$C_{10}H_{12}O_8S_3$], 324 (15) [$C_{10}H_{12}O_8S_2$], 226 (38) [$C_5H_6O_4S_3$], 167 (30) [$C_3H_3O_2S_3$], 162 (19) [$C_5H_6O_4S$], 118 (15), 103 (48) [$C_3H_3O_2S$], 59 (100) [$C_2H_3O_2$]. − $C_{10}H_{12}O_8S_4$ (388.5): calcd. C 30.92, H 3.11, S 33.02; found C 31.33, H 3.02, S 32.73.

Tetramethyl 1,6-Dichloro-2,3,4,5-tetrathiahexane-1,1,4,4-tetracarboxylate (15a): Yellow crystals, m.p. 92.5−94.0 °C. − IR: $\tilde{\nu}$ = 2957, 2846 (aliphatic CH), 1756 (C=O), 1435, 1245, 1007, 947, 906, 846, 751, 706, 654 cm^{-1}. − ^1H NMR: δ = 3.85 (s). − ^{13}C NMR: δ = 54.7 (4 CH_3), 96.0 (C-1, C-4), 164.0 (4 C=O). − MS (EI); *m/z* (%): 458 (0.2) [M], 426 (4) [$C_{10}H_{12}Cl_2O_8S_3$], 394 (20) [$C_{10}H_{12}Cl_2O_8S_2$], 335 (9) [$C_8H_9Cl_2O_6S_2$], 330 (2) [$C_{10}H_{12}Cl_2O_8$], 261 (8), 229 (14), 197 (10), 180 (9), 162 (12), 153 (22), 137 (43), 109 (28), 103 (20),

79 (16), 59 (100) [$C_2H_3O_2$]. − $C_{10}H_{12}Cl_2O_8S_4$ (459.4): calcd. C 26.15, H 2.60, Cl 15.44; found C 26.60, H 2.50, Cl 14.97. − Several attempts to grow crystals of **15a** suitable for X-ray analysis were unsuccessful. − Chlorination of **15a**: At room temperature, sulfuryl chloride (1.0 mL, 10 mmol) was added dropwise to a stirred solution of **15a** (4.59 g, 10 mmol) in dioxane (30 mL). The mixture was stirred until TLC showed that the reaction was complete (3 h). After concentration in vacuo, the residue was column-chromatographed. The eluted product was identified as **2a** (2.54 g, 96%).

2. With Potassium Iodide: A solution of **2a** or **2b** (10 mmol) in acetonitrile (50 mL) was treated with potassium iodide (3.3 g, 20 mmol) with stirring at room temperature until TLC showed that the reaction was complete (2 h). The reaction mixture was then decolorized with aqueous sodium thiosulfate. The product was extracted with benzene, washed with water three times, and dried with anhydrous calcium chloride. After concentration in vacuo, the residue was column-chromatographed. The following products (in order of elution) were obtained: from **2a**: **14a** (yield 1.30 g, 67%), **15a** (yield 0.65 g, 28%); from **2b**: **14b** (yield 1.20 g, 54%), **16b** (yield 0.70 g, 31%).

Tetraethyl 1,2,4,5-Tetrathiane-3,3,6,6-tetracarboxylate (14b): Colorless crystals, m.p. 56.5−57.5 °C (ref.[6] m.p. 56 °C). − IR: $\tilde{\nu}$ = 2995 (aliphatic CH), 1732 (C=O), 1391, 1246, 1223, 113, 1042, 944, 859, 857, 596 cm^{-1}. − ^1H NMR: δ = 1.30 (t, ^3J = 7.0 Hz, 12 H, 4 CH_3), 4.30 (q, ^3J = 7.0 Hz, 8 H, 4 CH_2). − ^{13}C NMR: δ = 13.7 (4 CH_3), 63.8 (4 CH_2), 96.0 (C-3, C-6), 167.1 (4 C=O). − MS (CI); *m/z* (%): 462 (10) [M + NH_4^+], 208 (100).

Tetraethyl 1,4-Dichloro-2,3-dithiabutane-1,1,4,4-tetracarboxylate (16b): Colorless crystals, m.p. 51.5−52.0 °C. − IR: $\tilde{\nu}$ = 2983 (aliphatic CH), 1739 (C=O), 1246, 857, 670, 650, 580, 520 cm^{-1}. − ^1H NMR: δ = 1.30 (t, ^3J = 7.0 Hz, 12 H, 4 CH_3), 4.35 (q, ^3J = 7.0 Hz, 8 H, 4 CH_2). − ^{13}C NMR ($CDCl_3$): δ = 13.7 (4 CH_3), 63.8 (4 CH_2), 96.0 (C-1, C-4), 167.1 (4 C=O). − MS (CI); *m/z* (%): 468 (100) [M + NH_4^+], 450 (18) [M]. − $C_{14}H_{20}Cl_2O_8S_2$ (451.3): calcd. C 37.26, H 4.47, S 14.21; found C 37.98, H 4.48, S 14.52. − A single-crystal X-ray structure determination was performed (cf. Figure 3 and Table 2).

3. With Further Reducing Agents: Reduction of **2a** with triphenylphosphane, sodium azide, and tin(II) chloride led to concomitant formation of **14a** and **15a**, while only reduction with magnesium turnings in ether led exclusively to the formation of **14a** in 80% yield. The corresponding reductions of **2b** yielded **14b**[6] and **16b** (vide supra).

4. Electrochemical Reduction of 2: Compound **2a** (1.0 g, 3.8 mmol) was reduced in an H cell at a platinum net electrode in 30 mL of an argon-deaerated 0.1 M solution of tetrabutylammonium tetrafluoroborate in *N,N*-dimethylformamide.[16] A graphite electrode was used as anode. The potential was fixed at 0 V vs. Ag/AgI, 0.1 M I^- in DMF, and the temperature of the cell kept at ambient level (22 °C) by means of a water bath. After the consumption of 1469 C (n = 4) the current stopped and the catholyte solution was poured into water (1000 mL) and extracted with ether (250 mL). The ether phase was washed twice with water (100 mL) and finally dried with anhydrous magnesium sulfate. Filtration and subsequent evaporation of the ether yielded 0.65 g (89%) of **14a**. In contrast with the chemical reduction procedures, no chromatographic purification of **14a** was required.

When **2b** (1.0 g, 3.4 mmol) was reduced as above the yield of pure **14b** was 0.60 g (79%). Current consumption 1330 C, calculated for a 4-electron process 1322 C.

Reaction of 2 with Sulfur: Compound **2** (10 mmol) and elemental sulfur (0.32 g, 10 mmol) were fused together at 220 °C under a reflux condenser until TLC showed that the reaction was complete (6 h). The crude reaction product was column chromatographed. From **2a** was obtained **14a** (yield 76%) and **15a** (yield 17%), while **2b** formed **14b** (yield 47%) and **16b** (yield 34%).

Pyrolysis of 2: Compound **2** (10 mmol) was dissolved in 20 mL of sulfolane and this mixture heated at 220 °C under a reflux condenser until TLC showed that the reaction was complete (3.5 h). The reaction mixture was then poured into a large volume of water, extracted three times with ether, and the ether extract dried with anhydrous calcium chloride. After concentration in vacuo, the residue was column-chromatographed. Compound **2a** gave 78% **14a**, while **2b** gave 63% **14b**.

Under the same pyrolytic conditions the following compounds also gave the corresponding compound **14** as the only isolated product (yields in% in parentheses): **5aa** (61), **5ab** (48), **5ac** (45), **5ad** (47), **5ba** (58), **5bd** (49), **13a** (33).

Reaction of 5aa with Chlorine: Compound **5aa** (3.4 g, 10 mmol) was dissolved in tetrachloromethane (100 mL). Chlorine gas was then passed through the stirred solution until TLC showed that the reaction was complete (25 min). Evaporation in vacuo led to a crude product that contained at least four compounds by TLC, and which decomposed upon attempted chromatography. Crude yield: 1.90 g of a yellow oil (vide infra).

Reaction of 5aa with Sulfuryl Chloride

a) With Two Equivalents of SO_2Cl_2: Sulfuryl chloride (2.0 mL, 20 mmol) was added dropwise to a stirred solution of **5aa** (3.4 g, 10 mmol) in tetrachloromethane (30 mL) at room temperature. The reaction mixture was stirred until TLC showed that the reaction was complete (3 h). Concentration in vacuo gave 1.75 g of a yellow oil that contained at least four compounds by TLC. Attempted isolation of these compounds by column chromatography was unsuccessful. According to MS, tetramethyl 1,2,3,5,6,7-hexathiocane-4,4,8,8-tetracarboxylate (**17a**), dimethyl hexathiepane-7,7-dicarboxylate (**18a**), and tetramethyl ethenetetracarboxylate were present in the product mixture. − IR: $\tilde{\nu}$ = 2958, 2846 (aliphatic CH), 1732 (C=O), 1435, 1257, 1028, 948, 849, 803, 763, 703 cm^{-1}. − ^1H NMR: δ = 3.85 (s), 3.87 (s), 3.89 (s), 3.91 (s). − ^{13}C NMR: δ = 53.6, 54.4, 54.7, 54.8 (CH_3), C-4, C-8 signals not observed, 165.1, 166.3 (2 C=O). − MS (CI); *m/z* (%): 470 (3) [M(**17a**) + NH_4^+], 438 (12) [470 − S], 406 (13) [470 − 2 S], 374 (8) [470 − 3 S], 340 (80) [M(**18a**) + NH_4^+], 323 (4), 308 (18) [340-S], 290 (5), 278 (88) [M(tetramethyl ethenetetracarboxylate) + NH_4^+], 258 (38), 214 (10), 194 (20), 180 (100), 163 (17), 150 (38). − No useful elemental analyses could be obtained.

b) With Excess SO_2Cl_2 at Room Temperature: Sulfuryl chloride (4.0 mL, 40 mmol) was added dropwise to a stirred solution of **5aa** (3.4 g, 10 mmol) in tetrachloromethane (30 mL) at room temperature. The reaction was stirred until TLC showed that the reaction was complete (5 h). Concentration in vacuo led to a crude product that contained at least two compounds by TLC, and which decomposed upon attempted chromatography. Crude yield: 2.00 g (93%) of a yellow oil. The heaviest component appeared to be dimethyl hexathiepane-7,7-dicarboxylate (**18a**) (MS, vide infra). − IR: $\tilde{\nu}$ = 2955 (aliphatic CH), 1748 (C=O), 1433, 1353, 1248, 1108, 1036, 947, 837, 799 cm^{-1}. − ^1H NMR: δ = 3.95 (s). − ^{13}C NMR: δ = 54.7, 54.8, 54.9, 55.0 (CH_3), C-7 signal not observed, 163.6, 163.5, 163.9 (C=O). − MS (EI); *m/z* (%): 322 (4) [M], 290 (12) [$C_5H_6O_4S_5$], 258 (58) [$C_5H_6O_4S_4$], 194 (56) [$C_5H_6O_4S_2$], 162 (40)

$[C_5H_6O_4S]$, 103 (100) $[C_3H_3O_2S]$, 64 (60) $[S_2]$, 59 (73) $[C_2H_3O_2]$. − No useful elemental analyses could be obtained.

c) With Excess SO_2Cl_2 at Elevated Temperature: Sulfuryl chloride (4.0 mL, 40 mmol) was added dropwise to a stirred solution of **5aa** (3.4 g, 10 mmol) in tetrachloromethane (30 mL) at 50 °C. The reaction was stirred until TLC showed that the reaction was complete (2 h). Concentration in vacuo led to a product which, according to TLC, contained only one compound. Its ^{13}C-NMR spectrum contained some minor supernumerary lines, however. Crude yield: 2.20 g (85%) of dimethyl tetrathiolane-5,5-dicarboxylate (**7a**). − IR: $\tilde{\nu}$ = 2986 (aliphatic CH), 1754 (C=O), 1433, 1235, 1036, 948, 845, 8001, 762, 688 cm^{-1}. − ^{1}H NMR: δ = 3.95 (s). − ^{13}C NMR: δ = 54.75, 54.77, 55.0 (CH_3), C-5 signal not observed, 164.2 (C=O). − MS (EI); *m/z* (%): 258 (12) [M], 194 (30) $[C_5H_6O_4S_2]$, 162 (28) $[C_5H_6O_4S]$, 103 (50) $[C_3H_3O_2S]$, 64 (67) $[S_2]$, 59 (100) $[C_2H_3O_2]$. − No useful elemental analyses could be obtained.

Reaction of 5aa with One Equivalent of Bromine or Iodine: Bromine or iodine (20 mmol) was added in small portions to a stirred solution of **5aa** (3.4 g, 10 mmol) in tetrachloromethane (30 mL) at room temperature. After completion of the addition, the reaction mixture was stirred until TLC showed that the reaction was complete (2 h). The tetrachloromethane phase was washed with water (3 times), dried with anhydrous magnesium sulfate, and concentrated in vacuo to give a crude product that contained at least four compounds by TLC, and which decomposed upon attempted chromatography. Crude yield 1.40 g (78%) (with Br_2) and 1.30 g (73%) (with I_2), respectively, of a yellow oil with the composition of tetramethyl 1,2,3,5,6,7-tetrathiocane-4,4,8,8-tetracarboxylate (**17a**) (vide supra for details).

Reaction of 5aa with Excess Bromine or Iodine: Bromine or iodine (40 mmol) was added in small portions to a stirred solution of **5aa** (3.4 g, 10 mmol) in tetrachloromethane (30 mL) at room temperature. After completion of the addition, the reaction was stirred until TLC showed that the reaction was complete (2 h). The tetrachloromethane phase was washed with water (3 times), dried with anhydrous magnesium sulfate, and concentrated in vacuo to afford a pure product, which contained only one compound by TLC. Crude yield: 1.75 g (68%) (with Br_2) or 1.60 g (62%) (with I_2) of tetramethyl 1,2,3,5,6,7-tetrathiocane-4,4,8,8-tetracarboxylate (**17a**) as a yellow oil (vide supra for details).

Reaction of 2a with Bis(tetrabutylammonium) Hexasulfide: A solution of **2a** (2.7 g, 10 mmol) in acetonitrile (50 mL) was treated with bis(tetrabutylammonium) hexasulfide (6.8 g, 10 mmol), dissolved in acetonitrile (50 mL). The mixture was heated at reflux until TLC showed that the reaction was complete (2 h). Concentration in vacuo led to a crude product that contained at least four compounds by TLC, and which decomposed upon attempted chromatography. Yield: 1.70 g of a yellow oil with the overall composition of tetramethyl 1,2,3,5,6,7-tetrathiocane-4,4,8,8-tetracarboxylate (**17a**) (vide supra for details).

Reaction of 2a with Cyanide: A general procedure[17] was followed. A 250-mL three-necked flask, fitted with a reflux condenser, two dropping funnels, and a magnetic stirring bar, was charged with trichloromethane (8 mL) and ethanol (32 mL). A solution of **2a** (2.7 g, 10 mmol) in ethanol (10 mL) and a solution of potassium cyanide (1.3 g, 20 mmol) in ethanol (10 mL) and water (10 mL) were simultaneously added dropwise. Subsequently, the reaction mixture was stirred for another 1 h, after which TLC showed that the reaction was complete. Concentration in vacuo led to 1.25 g (70%) of crude tetramethyl 1,2,4-trithiolane-3,3,5,5-tetracarboxylate (**19a**), which was column-chromatographed to yield 1.15 g (65%) of colorless crystals of **19a**, m.p. 53.5−57.0 °C. A final recrystallization from ether/petroleum ether (1:1) gave 0.95 g (53%) of pure **19a**, m.p. 58.5−59.5 °C, mentioned in ref.[18] without physical data. − IR: $\tilde{\nu}$ = 2960 (aliphatic CH), 1732 (C=O), 1432, 1224, 1042, 1010, 940, 860, 680, 540 cm^{-1}. − ^{1}H NMR: δ = 3.95 (s). − ^{13}C NMR: δ = 54.5 (2 CH_3), C-3, C-5 signal not observed, 166.4 (2 CO). − MS (EI); *m/z* (%): 356 (18) [M], 324 (12) $[C_{10}H_{12}O_8S_2]$, 297 (40) $[C_8H_9O_6S_3]$, 292 (16) $[C_{10}H_{12}O_8S]$, 235 (20), 233 (42) $[C_8H_9O_6S]$, 226 (17) $[C_5H_6O_4S_3]$, 103 (50) $[C_3H_3O_2S]$, 59 (100) $[C_2H_3O_2]$. − $C_{10}H_{12}O_8S_3$ (356.4): calcd. C 33.70, H 3.39, S 26.99; found C 33.16, H 3.53, S 26.80.

Reaction of 2a with Thiocyanate: When the above procedure was repeated with potassium thiocyanate (1.9 g, 20 mmol) instead of potassium cyanide, we obtained **14a** in 77% yield.

Reduction of 12a

1. With Potassium Iodide: A solution of **12a** (2.7 g, 10 mmol) in acetonitrile (50 mL) was treated with potassium iodide (1.66 g, 10 mmol) with stirring at room temperature until TLC showed that the reaction was complete (1 h). The reaction mixture was decolorized with aqueous sodium thiosulfate. The product was extracted with benzene, washed three times with water, and dried with anhydrous calcium chloride. After concentration in vacuo, the residue was column-chromatographed. The elution of the column first gave **19a** (yield 0.50 g, 28%), m.p. 57.5−58.0 °C (vide supra), and then **14a** (yield 0.85 g, 44%), m.p. 164.5−165.5 °C (vide supra).

2. With Triphenylphosphane: A general procedure[19] was followed. To a solution of triphenylphosphane (2.6 g, 10 mmol) in toluene (50 mL), maintained at 5−10 °C, was added a solution of **12a** (2.7 g, 10 mmol) in toluene (50 mL). The resulting mixture was stirred until TLC showed that the reaction was complete (2 h), and then concentrated to dryness. The residue was triturated with absolute ether (20 mL) and water (0.1 mL), and stirred for 5 min until the evolution of hydrogen chloride had ceased. After concentration in vacuo, the residue was column-chromatographed. The first fraction consisted of **19a** (yield 0.65 g, 37%), m.p. 58.5−59.0 °C (vide supra), and the second of **14a** (yield 0.95 g, 49%), m.p. 162.5−163.5 °C (vide supra).

Dimethyl 2,2-Bis(4-morpholinothio)propanedioate (21a): Compound **2a** (2.7 g, 10 mmol) in dichloromethane (20 mL) was stirred well at 0−5 °C, and a solution of morpholine (4.0 mL, 40 mmol) in dichloromethane (20 mL) was added dropwise over 10 min. The reaction mixture was stirred further at room temperature until TLC showed that the reaction was complete (3 h). The reaction mixture was filtered and the filtrate washed with water and dried with anhydrous calcium chloride. Concentration in vacuo led to 2.50 g (68%) of a crude oily product, which was column-chromatographed. This yielded 2.20 g (60%) of **21a**, colorless crystals, m.p. 123.5−124.0 °C. − IR: $\tilde{\nu}$ = 2954 (aliphatic CH), 1729 (C=O), 1453, 1251, 1114, 1045, 1018, 990, 935, 871 cm^{-1}. − ^{1}H NMR: δ = 2.88 (t, ^3J = 5.0 Hz, 4 H, 2 CH_2N), 2.93 (t, ^3J = 5.0 Hz, 4 H, 2 CH_2N), 3.69 (t, ^3J = 5.0 Hz, 4 H, 2 CH_2O), 3.78 (t, ^3J = 5.0 Hz, 4 H, 2 CH_2O), 3.80 (s, 6 H, 2 CH_3). − ^{13}C NMR: δ = 49.2, 52.7 (2 × 2 C, CH_2N), 67.1, 67.4 (2 × 2 C, CH_2O), 56.1 (2 CH_3), 85.7 (C-2), 165.6 (2 CO). − MS (CI); *m/z* (%): 367 (3) [M + H^+], 216 (100). − $C_{13}H_{22}N_2O_6S_2$ (366.5): calcd. C 42.61, H 6.05, N 7.65, S 17.50; found C 42.92, H 6.05, N 7.63, S 17.30.

Reaction of 5aa with Morpholine: Compound **5aa** (3.4 g, 10 mmol) in dichloromethane (20 mL), was stirred well at 0−5 °C, and a solution of morpholine (4.0 mL, 40 mmol) in dichloromethane (20 mL) was added dropwise over 10 min. The reaction mixture was stirred further at room temperature until TLC showed that the

reaction was complete (2 h). The reaction mixture was filtered and the filtrate washed with water and dried with anhydrous calcium chloride. After concentration in vacuo, the residue was column-chromatographed. The first fraction consisted of **19a** (0.50 g, 28%) (vide supra), the second of **14a** (0.65 g, 34%) (vide supra).

Reaction of 5ba with Morpholine: Treatment of **5ba** as above yielded **14b** (1.40 g, 63%), m.p. 55.0−57.0 °C (ref.[6] m.p. 56 °C) (vide supra).

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[1] K. N. Koch, A. Senning, *Phosphorus Sulfur Silicon* **1997**, *120/121*, 337−338; for a review see K. N. Koch, A. Senning, *Sulfur Rep.* **1998**, *20*, 419−431.
[2] K. N. Koch, Cand. scient. thesis, Aarhus University, **1996**.
[3] J. Fabian, A. Senning, *Sulfur Rep.* **1998**, *21*, 1−42; for more recent work see: M. I. Hegab, F. M. E. Abdel-Megeid, F. A. Gad, S. A. Shiba, I. Søtofte, J. Møller, A. Senning, *Acta Chem. Scand.* **1998**, *53*, 133−141; F. A. G. El-Essawy, S. M. Yassin, I. A. El-Sakka, A. F. Khattab, I. Søtofte, J. Ø. Madsen, A. Senning, *J. Org. Chem.* **1998**, *64*, 9840 −9845; A. Ishii, T. Nakaniwa, K. Umezawa, J. Nakayama, *Tetrahedron* **1999**, *55*, 10341−10350; K. Shimada, K. Kodaki, S. Aoyagi, Y. Takikawa, C. Kabuto, *Chem. Lett.* **1999**, 695−698.
[4] A. Ishii, J. Yinan, Y. Sugihara, J. Nakayama, *Chem. Commun.* **1996**, 2681−2862; Y.-N. Jin, A. Ishii, Y. Sugihara, J. Nakayama, *Heterocycles* **1997**, *44*, 255−259; Y.-N. Jin, A. Ishii, Y. Sugihara, J. Nakayama, *Tetrahedron Lett.* **1998**, *39*, 3525−3528.
[5] For instance, J. Lermontoff, *Ber. Dtsch. Chem. Ges.* **1874**, *7*, 1282−1287; Kinkai Kagaku Co., Ltd, *Jpn. Kokai Tokkyo Koho* JP 60,072,858, **1985** (*Chem. Abstr.* **1985**, *103*, 123029); P. Werle, M. Trageser, W. Pahling (Degussa A.-G.), *Ger. Offen.* DE 4,306,556, **1994** (*Chem. Abstr.* **1994**, *121*, 300482).
[6] R. M. Bannister C. W. Rees, *J. Chem. Soc., Perkin Trans. 1* **1990**, 509−514.
[7] M. A. Hawata, A. E.-H. Ismail, J. Ø. Madsen, I. Søtofte, A. Senning, manuscript in preparation.
[8] I. El-Sayed, V. K. Belsky, V. E. Zavodnik, K. A. Jørgensen, A. Senning, *J. Chem. Soc., Perkin Trans. 1* **1994**, 1251−1252 (Erratum: *J. Chem. Soc., Perkin Trans. 1* **1994**, 3051).
[9] For a review of the electrochemistry of organosulfur compounds, see: O. Hammerich, V. D. Parker, *Sulfur Rep.* **1981**, *1*, 317−396.
[10] N. W. Alcock, M. Pennington, *Acta Crystallogr., Sect. C* **1990**, *46*, 18−21.
[11] L. Töke, Gy. Kalaus, Cs. Szantay, *Acta Chem. Acad. Sci. Hung.* **1968**, *55*, 237−245 (*Chem. Abstr.* **1968**, *69*, 35905).
[12] F. R. Benson, J. J. Ritter, *J. Am. Chem. Soc.* **1949**, *71*, 4128−4129.
[13] V. V. Mozhaev, C. L. Budde, J. O. Rich, A. Ya. Usyantinsky, P. C. Michels, Yu. L. Khmelnitsky, D. S. Clark, J. S. Dordick, *Tetrahedron* **1998**, *54*, 3971−3982.
[14] A. Senning, H. C. Hansen, M. F. Abdel-Megeed, W. Mazurkiewicz, B. Jensen, *Tetrahedron* **1986**, *42*, 739−746; cf. ref.[3]
[15] S. Holm, J. A. Boerma, N. H. Nilsson, A. Senning, *Chem. Ber.* **1976**, *109*, 1096−1099.
[16] H. Lund, M. M. Baizer, *Organic Electrochemistry*, 3rd ed., Marcel Dekker, New York, **1991**, chapter 6.
[17] I. Crossland, *Acta Chem. Scand.* **1977**, *B31*, 890−894.
[18] K. Oka, A. Dobashi, S. Hara, *Tetrahedron Lett.* **1980**, *21*, 3579−3582.
[19] D. J. Martin, C. C. Greco, *J. Org. Chem.* **1968**, *33*, 2357−2361.

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