

# Alkylcycloarsoxanes and alkylcycloarsathianes—ambidentate macrocyclic ligands of variable metal-mediated ring size

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## Abstract

A comprehensive account of the coordination chemistry of alkylcycloarsoxanes  $(RAsO)_n$  and alkylcycloarsathianes  $(RAsS)_n$  is presented. The former ambi- and multidentate ligands are characterised by their unique ability to undergo metal-mediated ring expansion to  $n = 5, 6$  or 8. Cyclotetramers, -pentamers and hexamers of their sulphur analogues have also been stabilised as intact species in metal coordination spheres. At elevated temperatures As–S bond cleavage and metal-assisted reassembly afford novel linear and macrocyclic As–S ligands. Cyclotetramers  $(RAsO)_4$  can be employed for the self-assembly of copper(I) halide based porous lamellar and framework coordination polymers capable of hosting alkali cations or polar molecules as guests. © 1999 Elsevier Science S.A. All rights reserved.

**Keywords:** Alkylcycloarsoxanes; Alkylcycloarsathianes; Ambidentate; Macrocyclic; Ring expansion

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## 1. Introduction

Although 140 years have now passed since  $(CH_3AsO)_n$  and  $(CH_3AsS)_n$  were first reported by von Baeyer [1], it is only in recent years that their potential as ambidentate macrocyclic ligands has been recognised and explored. In his original publication “Über die Verbindungen des Arsens mit dem Methyle”, in which he prepared methylcycloarsoxane by alkaline hydrolysis of  $CH_3AsCl_2$  and methylcycloarsathiane by passing  $H_2S$  through an aqueous solution of the same compound, von Baeyer assumed that both products must be present in a monomeric form. Reports on the analogous phenyl derivatives  $(PhAsO)_n$  [2] and  $(PhAsS)_n$  [3] appeared in German journals in the period 1877–1882. Despite considerable interest in the fungicidal and bactericidal properties of cycloarsoxanes  $(RAsO)_n$  in the early 1920s [4], it was only in 1930 that Blicke and Smith [5] were able to confirm the oligomeric nature of this class of compounds. Their ebullioscopic and cryoscopic measurement suggested that cyclotetramers predominate for both  $(PhAsO)_n$  and  $(PhAsS)_n$  in  $CCl_4$  or camphor solution.

In contrast,  $^1H$ -NMR studies [6,7] have demonstrated that  $(CH_3AsO)_n$  is present as a mixture of dimeric, trimeric, tetrameric and pentameric forms in benzene or  $CCl_4$  solution. It is apparent from Fig. 1 that cyclotrimers and cyclotetramers provide the major species. Our own  $^1H$ -NMR investigations [8] have confirmed the presence of analogous dynamic reorganisation equilibria between oligomeric forms of  $(C_2H_5AsO)_n$  in chloroform. However, ebullioscopic measurements by Durand and Laurent [7] indicate that the average nuclearity  $n$  for alkylcycloarsoxanes  $(RAsO)_n$  in benzene solution decreases from 3.6 for  $R = CH_3$  to 2.9–3.1 for the longer alkyl side-chains  $R = C_2H_5$ ,  $n-C_3H_7$ ,  $n-C_4H_9$ . Preferred crystallisation of the

predominate cyclotetramers has been observed in those three cases for which an X-ray structural analysis has been performed on an organylcycloarsoxane ( $R = \text{CH}_3$  [9], Ph [10], mesityl [11]).

Analogous eight-membered ( $\text{AsS}$ )<sub>4</sub> rings have also been established for a series of organylcycloarsathianes ( $\text{RAsS}$ )<sub>n</sub>,  $R = \text{C}_2\text{H}_5$  [12], *t*-C<sub>4</sub>H<sub>9</sub> [13], Ph [14], in the solid state. Cryoscopic and ebullioscopic molecular weight measurements [15–17] suggest that cyclotrimers and cyclotetramers once again provide the major species in organic solvents. In the case of ( $\text{CH}_3\text{AsS}$ )<sub>n</sub>, it has proved possible to coprecipitate both cyclooligomers as distinct crystalline forms from a  $\text{CH}_2\text{Cl}_2$  solution [18]. Furthermore ( $\text{CH}_3\text{AsS}$ )<sub>3</sub> and ( $\text{CH}_3\text{AsS}$ )<sub>4</sub> could also be successfully separated by column chromatography with alumina as the stationary phase [18]. The presence of two major sets of resonances for the  $\text{CH}_2$  and  $\text{CH}_3$  protons of ethylcycloarsathiane in a chloroform solution (Fig. 2) is likewise in accordance with a dynamic equilibrium between the cyclotrimer and cyclotetramer [12].

Both ( $\text{RASO}$ )<sub>n</sub> and ( $\text{RAsS}$ )<sub>n</sub> are potentially ambi- and multidentate macrocyclic ligands. The presence of competing sets of alternating soft As and hard O donor atoms in the organylcycloarsoxanes and their low energy barriers to ring contraction or expansion in organic solvents suggest that this class of compounds should exhibit a rich variety of binding modes. The structural similarity of ( $\text{RASO}$ )<sub>n</sub> and ( $\text{RAsS}$ )<sub>n</sub> to ion ligating crown ethers and crown thioethers is particularly intriguing. It is, therefore, somewhat surprising to note that the first example of a metal complex of such a ligand was reported only in 1986, namely [ $\{\text{Mo}(\text{CO})_3\}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_6\}$ ], which was serendipitously assembled by Rheingold and DiMaio [19] by reacting  $\text{Mo}(\text{CO})_6$  with *cyclo*-( $\text{CH}_3\text{As}$ )<sub>5</sub> in toluene in the presence of a stoichiometric quantity of  $\text{O}_2$  in a Carius tube at 150°C. The thereby documented ability of ( $\text{CH}_3\text{AsO}$ )<sub>n</sub> to undergo metal-mediated ring expansion has been found to be characteristic for all organylcycloarsoxanes investigated in our group ( $R = \text{CH}_3$ ,  $\text{C}_2\text{H}_5$ , Ph). We have also discovered that the cyclotetramers ( $\text{CH}_3\text{AsO}$ )<sub>4</sub> and ( $\text{C}_2\text{H}_5\text{AsO}$ )<sub>4</sub> can be employed as bridging ionophoric spacer molecules for the construction of a variety of flexible lamellar and framework coordination polymers, whose cavities are capable of imbibing molecular guests. The present review

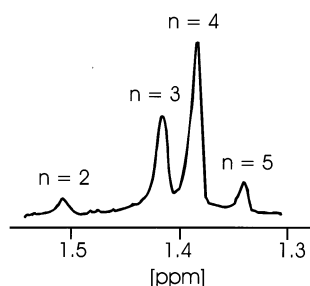


Fig. 1. <sup>1</sup>H-NMR spectrum (60 MHz) of a  $\text{CCl}_4$  solution of ( $\text{CH}_3\text{AsO}$ )<sub>n</sub> with the assignment of individual resonances to cyclic oligomers of nuclearity n [7].

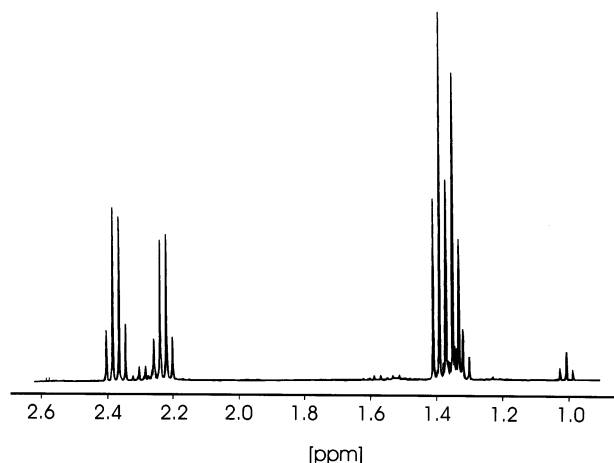


Fig. 2.  $^1\text{H}$ -NMR spectrum (400 MHz) of a  $\text{CDCl}_3$  solution of  $(\text{CH}_3\text{AsO})_n$  [12].

provides a comprehensive account of the coordination chemistry of these fascinating macrocyclic ligands.

## 2. Coordination chemistry of organylcycloarsoxanes

### 2.1. Preparation and structure of $(\text{RAsO})_n$

The preparation and properties of organylcycloarsoxanes  $(\text{RAsO})_n$  were discussed in detail by Tzschach and Heinicke in their 1978 book on arsenic heterocycles [20] and more briefly by Sowerby in a later monograph on inorganic homo- and heterocycles [21]. Several methods are available for the synthesis of these colourless solids: (a) treatment of a benzene solution of  $\text{RAsX}_2$  ( $\text{X} = \text{Cl}, \text{Br}, \text{I}$ ) with  $\text{Na}_2\text{CO}_3$  or  $\text{K}_2\text{CO}_3$  and a trace of water [22,23], (b) reduction of arsonic acids (usually with  $\text{SO}_2/\text{HCl}$ ) followed by alkaline hydrolysis [24,25], and (c) oxidation of primary arsines or cyclopolyarsines  $(\text{RAs})_n$  [26,27]. As von Baeyer mentioned in his original report on methylcycloarsoxane [1], after removal of organic solvents from the resulting cyclooligomers  $(\text{RAsO})_n$ , the presence of small quantities of impurities often leaves viscous oils, which subsequently solidify to glassy products. Although von Baeyer described the successful crystallisation of  $(\text{CH}_3\text{AsO})_n$  after purification (“würfelförmige Krystalle”), it was only in 1991 that DiMaio and Rheingold were able to structurally characterise a cyclooligomer of methylcycloarsoxane by successfully isolating  $(\text{CH}_3\text{AsO})_4$  as a crystalline solid from the aerobic oxidation of *cyclo*-( $\text{CH}_3\text{As}$ ) $_5$  in the presence of  $\text{Mn}_2(\text{CO})_{10}$ , with the latter transition metal carbonyl serving presumably as the source of a metal template [9]. This cyclotetramer exhibits the boat-chair conformation (Fig. 3) that is energetically favoured

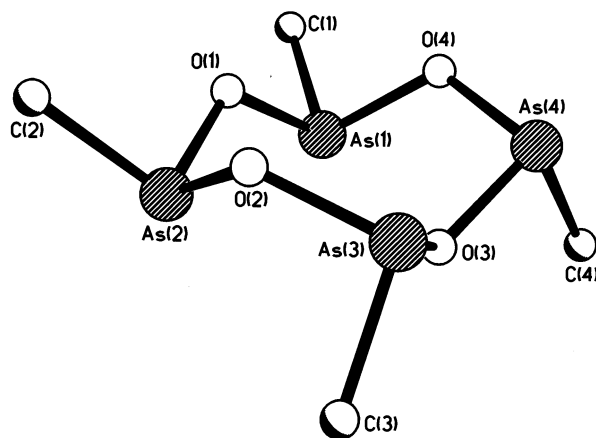


Fig. 3. Boat-chair conformation of the cyclotetramer  $(\text{CH}_3\text{AsO})_4$  in the solid state [9]. Endocyclic torsion angles beginning at As(1)–O(1) are as follows:  $-109.6$ ,  $101.4$ ,  $-89.2$ ,  $33.4$ ,  $102.3$ ,  $-109.2$ ,  $-24.7$ ,  $92.5^\circ$ .

for isolobal cyclooctane [28]. All four organyl substituents occupy equatorial sites in  $(\text{CH}_3\text{AsO})_4$  as they also do in  $(\text{PhAsO})_4$  with its analogous boat-chair conformation [10] and  $(\text{mesAsO})_4$  (mes = mesityl), which adopts the somewhat less favourable crown conformation (Fig. 4) in the solid state [11]. This implied conformational flexibility has likewise been established for bridging cyclotetramers  $(\text{RAsO})_4$  ( $\text{R} = \text{CH}_3$ ,  $\text{C}_2\text{H}_5$ ) in coordination polymers (Section 2.3), for which a third variant, the twist-chair conformation is often employed. As–O distances in the cyclotetramers fall within a narrow range ( $1.770$ – $1.819$  Å) and average to respectively  $1.792$  ( $\text{R} = \text{CH}_3$ ),  $1.796$  ( $\text{R} = \text{Ph}$ ) and  $1.790$  Å ( $\text{R} = \text{mes}$ ), values similar to that of  $1.80$  Å in the  $\text{As}_4\text{O}_6$  cage [29]. Although the endocyclic As–O–As angles in  $(\text{RAsO})_4$  are still relatively wide in comparison to an idealised tetrahedral value, it

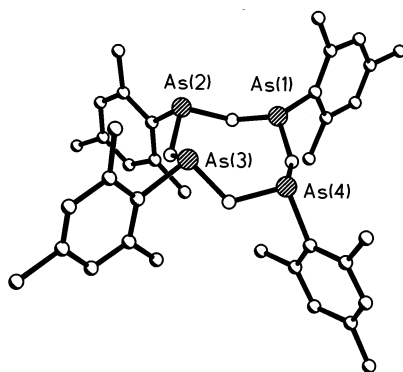


Fig. 4. Crown conformation of the cyclotetramer  $(\text{mesAsO})_4$  in the solid state [11]. Endocyclic torsion angles beginning at As(1)–O(1) are as follows:  $92.1$ ,  $-81.7$ ,  $85.8$ ,  $-112.5$ ,  $110.7$ ,  $-81.9$ ,  $75.7$ ,  $-88.5^\circ$ .

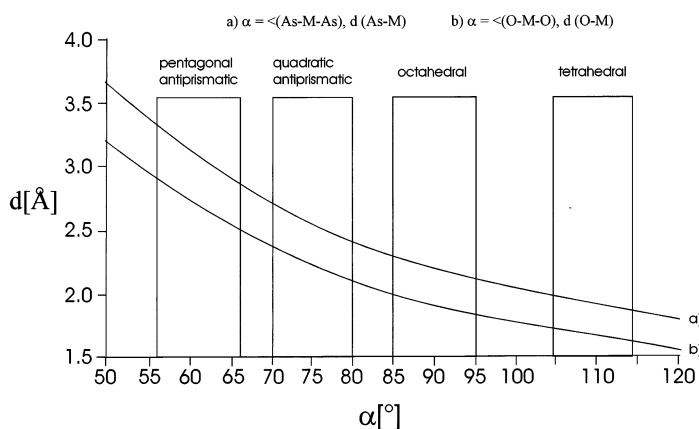


Fig. 5. Dependence of As–M–As (M = metal atom) and O–M–O angles, respectively, on (a) As–M or (b) O–M distances in four-membered chelate rings. The following typical values were employed:  $d(\text{As–O}) = 1.80 \text{ \AA}$ ,  $d(\text{As}^{\text{M}}\text{–O}) = 1.78 \text{ \AA}$ ,  $\angle(\text{As–O–As}) = 121.8^\circ$ ,  $\angle(\text{O–As–O}) = 96^\circ$  with  $\text{As}^{\text{M}}$  standing for coordinating arsenic atoms.

is interesting to note that their average sizes of  $121.7$  ( $\text{R} = \text{CH}_3$ ),  $120.2$  ( $\text{R} = \text{Ph}$ ) and  $117.3^\circ$  ( $\text{R} = \text{mes}$ ) are appreciably smaller than those of  $126$  and  $129^\circ$  in the supported arsoxane rings of  $(\text{CH}_2)_3\text{As}_4\text{O}_4(\text{CH}_2)_3$  [30] and  $\text{As}_4\text{O}_4(\text{CH}_2)_2$  [31].

## 2.2. Metal-mediated ring expansion

### 2.2.1. Conformational aspects

As discussed in Section 1,  $^1\text{H-NMR}$  investigations have indicated that the alkylcycloarsoxanes  $(\text{CH}_3\text{AsO})_n$  and  $(\text{C}_2\text{H}_5\text{AsO})_n$  are present in organic solvents as a mixture of cyclic oligomers, of which cyclotrimers and cyclotetramers predominate [7,8]. Taking the low associated energy barriers into account, metal templates should be capable of mediating ring size reorganisation to enable optimal occupation of vacant sites in the metal coordination sphere by suitable donor atoms of a cyclooligomer. The nuclearity  $n$  of the organylcycloarsoxane ligands  $(\text{RAsO})_n$  should be such as to favour the adoption of an energetically preferred conformation in the resulting metal complex. Simple geometrical considerations allow the following general predications:

1.  $\kappa^2\text{As}^1, \text{As}^2$  chelation by adjacent arsenic atoms should be possible in octahedral but not in tetrahedral transition metal coordination spheres.
2.  $\kappa^2\text{O}^1, \text{O}^2$  chelation by adjacent oxygen atoms should be possible in tetragonal and pentagonal antiprismatic alkali cation coordination spheres. Using average As–O distances and As–O–As angles for alkylcycloarsoxane complexes, Fig. 5 depicts the dependence of the As–M–As and O–M–O angles in hypothetical four membered chelate rings on the As–M or O–M distances involved. Characteristic angle ranges for tetrahedral, octahedral, tetragonal and pentagonal antiprismatic coordination spheres are indicated.  $\kappa^2\text{As}^1, \text{As}^2$  chelation can be

ruled out for a tetrahedral coordination sphere, in view of the fact that the required As–M distances would be much shorter than typical values of 2.25–2.55 Å for transition metals.

3. Cyclotetramers (RAsO)<sub>4</sub> should be expected to prefer the boat-chair or crown conformations when bridging adjacent metal atoms in the  $\mu\text{-}1\kappa\text{As}^1:2\kappa\text{As}^2$  mode but the energetically less favourable twist-chair conformation when connecting bulky metal fragments in the  $\mu\text{-}1\kappa\text{As}^1:2\kappa\text{As}^3$  coordination mode. The three ring conformations found for (RAsO)<sub>4</sub> in metal complexes are depicted in Fig. 6. It is apparent that the twist-chair conformation allows a maximisation of the distance between metal centres coordinated to opposite arsenic atoms As<sup>1</sup> and As<sup>3</sup> and is, therefore, well-suited for the construction of supramolecular structures.
4. Facial coordination of a transition metal fragment can best be achieved by the  $\kappa^3\text{As}^1, \text{As}^3, \text{As}^5$  mode of a cyclohexamer (RAsO)<sub>6</sub>. The directions of the arsenic non-bonded electron pairs are depicted in Fig. 7 for both a cyclotrimer and a cyclohexamer. Whereas the cuboctahedral conformation of (RAsO)<sub>6</sub> should be capable of coordinating a metal fragment such as M(CO)<sub>3</sub> with a minimum of conformational change, severe ring strain would clearly be introduced in the case of (RAsO)<sub>3</sub>.
5. Fourfold equatorial coordination of a transition metal can best be achieved by the  $\kappa^4\text{As}^1, \text{As}^3, \text{As}^5, \text{As}^7$  mode of a cyclooctamer (RAsO)<sub>8</sub>. Extension of the arguments presented for a facial coordination lead to the prediction that

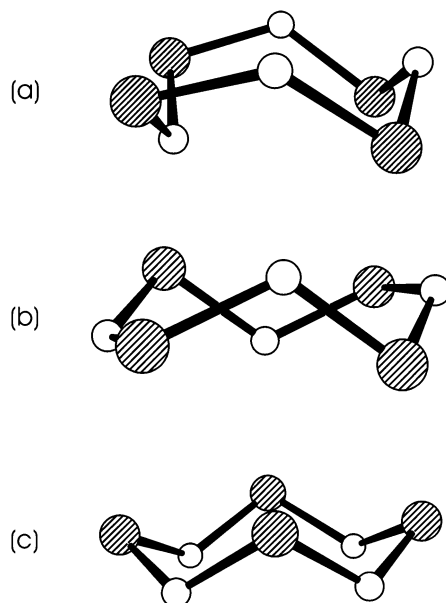


Fig. 6. (a) Boat-chair, (b) twist-chair and (c) crown conformations of the (AsO)<sub>4</sub> ring in cyclotetramers (RAsO)<sub>4</sub>.

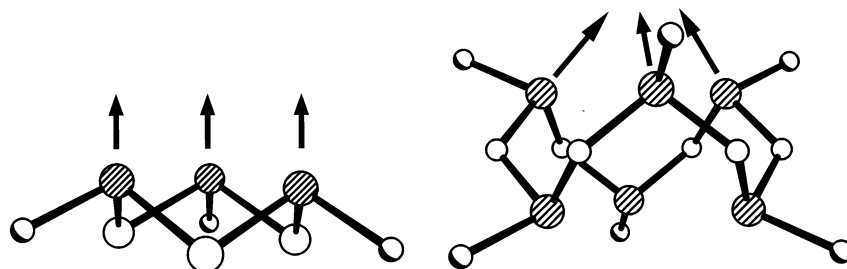


Fig. 7. Directions of lone pairs available for As–M coordination by methylcycloarsoxane: (a) as a cyclotrimer in its preferred chair conformation, (b) as a cyclohexamer with a flattened cuboctahedral conformation.

fourfold equatorial coordination should enable the stabilisation of cyclooctamers  $(\text{RAsO})_8$  previously undetected in solutions of organylcycloarsoxanes.

#### 2.2.2. $\kappa^n\text{O}$ coordination ( $n = 4, 5$ )

Both  $(\text{CH}_3\text{AsO})_n$  and  $(\text{C}_2\text{H}_5\text{AsO})_n$  are capable of acting as ionophores for alkali cations in a manner similar to classical crown ethers, and the ring size in their sandwich complexes  $[\text{M}\{\text{cyclo}-(\text{RAsO})_n\}_2]\text{SCN}$  ( $\text{M} = \text{Na}$ ,  $n = 4$ ;  $\text{M} = \text{K}$ ,  $n = 5$ ) [32,33] is clearly controlled by the radius of the central cation (Fig. 8). Although analogous complexes have not been crystallised for  $\text{Rb}^+$  or  $\text{Cs}^+$ ,  ${}^\infty[\{\text{Cs}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2\}\text{Cu}_2(\mu\text{-I})\text{I}_2]$  [34], which may be prepared by self-organisation from  $\text{CsI}$ ,  $\text{CuI}$  and  $(\text{C}_2\text{H}_5\text{AsO})_n$  in acetonitrile, contains  $[\text{Cs}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2]^+$  sandwich cations, that are linked through  $1\kappa\text{As}^1:2\kappa\text{As}^2$ -coordinated  $[\text{Cu}_2\text{I}_3]^-$  anionic units into polymeric *zweier* single chains (Fig. 9). A pentagonal antiprismatic arrangement of two cyclopentamers has also been established for  $[(\text{NH}_4)\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2][\text{Ag}(\text{SCN})_2]$  [34]. As no significant metrical differences are observed for alkali cation coordination by either  $(\text{CH}_3\text{AsO})_n$  or  $(\text{C}_2\text{H}_5\text{AsO})_n$  ( $n = 4, 5$ ) and

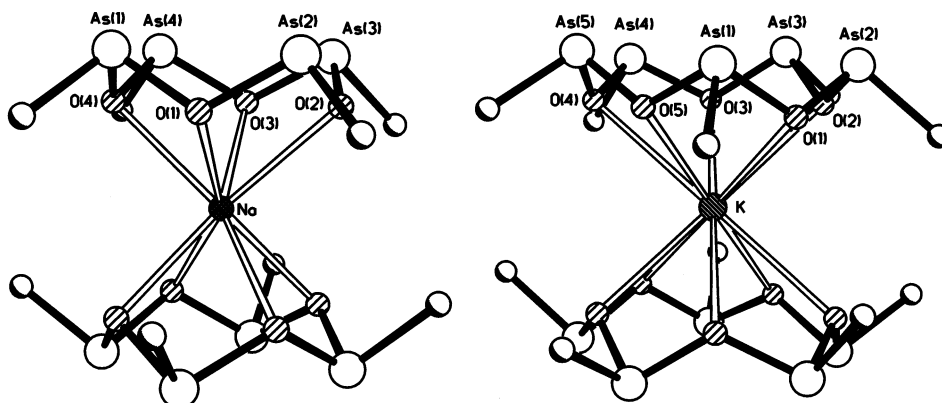


Fig. 8. Sandwich cations of  $[\text{Na}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]\text{SCN}$  and  $[\text{K}\{\text{cyclo}-(\text{CH}_3\text{AsO})_5\}_2]\text{SCN}$  [32].

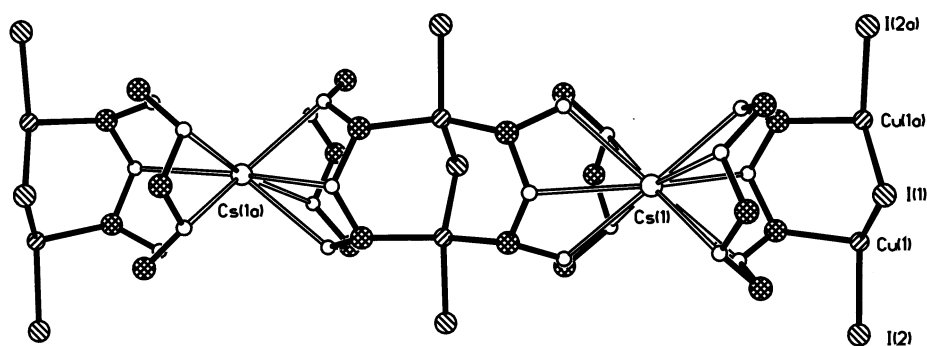


Fig. 9. Zweier single chain of  $\frac{1}{\infty}[\{\text{Cs}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2\}\text{Cu}_2(\mu\text{-I})_2]$  with pentagonal antiprismatic coordination of the participating  $\text{Cs}^+$  cations [34].

more examples are known for the latter alkylcycloarsoxane, discussion of structural details will be restricted to this cyclic ionophore. Based on the typical  $\text{O}\cdots\text{O}$  distance of 2.68 Å between adjacent oxygen atoms and tabulated values of alkali cation radii (Shannon and Prewitt [35]), Table 1 lists expected values for the distance  $\text{M}\cdots\text{Pl}$  where Pl marks the centre of the  $\text{O}_n$  plane of an undistorted crown-shaped  $\kappa^n\text{O}$  coordinating alkylcycloarsoxane. The good agreement between observed and predicted values for  $[\text{Na}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]^+$  and  $[\text{K}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2]^+$  confirms that the respective undistorted cyclooligomers provide a satisfactory pore size for the alkali cation involved. Although the results suggest that the  $\text{Cs}^+$  cation is rather too large to stabilise a cyclopentamer  $(\text{C}_2\text{H}_5\text{AsO})_5$  in an isolated sandwich cation, they also indicate that the alternative 12-fold coordination by a crown-shaped cyclohexamer would lead to a very unfavourable squashed

Table 1

Expected values for undistorted crown-shaped ethylcycloarsoxanes and averaged experimental bond length (Å) and angles (°) in sandwich cations  $[\text{M}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_n\}_2]^+$

| <i>n</i>               | Cation          | <i>d</i> (O $\cdots$ O) | <i>d</i> (M–O) [35] | <i>d</i> (M $\cdots$ Pl) | $\angle$ (O–M–Pl) | $\angle$ (O–M–O) |
|------------------------|-----------------|-------------------------|---------------------|--------------------------|-------------------|------------------|
| <i>Expected values</i> |                 |                         |                     |                          |                   |                  |
| 3                      | $\text{Li}^+$   | 2.68                    | 2.14                | 1.48                     | 46.2              | 77.5             |
| 4                      | $\text{Na}^+$   | 2.68                    | 2.56                | 1.72                     | 47.8              | 63.1             |
| 4                      | $\text{K}^+$    | 2.68                    | 2.91                | 2.20                     | 40.9              | 54.8             |
| 5                      | $\text{K}^+$    | 2.68                    | 2.99                | 1.93                     | 49.8              | 53.3             |
| 5                      | $\text{Rb}^+$   | 2.68                    | 3.00                | 1.95                     | 49.5              | 53.1             |
| 5                      | $\text{Cs}^+$   | 2.68                    | 3.21                | 2.26                     | 45.2              | 49.3             |
| 6                      | $\text{Cs}^+$   | 2.68                    | 3.28                | 1.89                     | 54.8              | 48.2             |
| <i>Observed values</i> |                 |                         |                     |                          |                   |                  |
| 4                      | $\text{Na}^+$   | 2.69                    | 2.59                | 1.76                     | 47                | 62.4             |
| 5                      | $\text{K}^+$    | 2.68                    | 2.99                | 1.92                     | 50                | 53.4             |
| 5                      | $\text{NH}_4^+$ | 2.69                    | 3.01                | 1.96                     | 49                | 53.1             |
| 5                      | $\text{Cs}^+$   | 2.69                    | 3.26                | 2.33                     | 45                | 48.5             |

hexagonal antiprismatic geometry with  $d(\text{Cs}\cdots\text{Pl})$  even shorter than in  $[\text{K}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2]^+$ . On the basis of Table 1,  $\text{Li}^+$  cations might also be expected to be capable of stabilising cyclotrimers in sandwich cations of the type  $[\text{Li}\{\text{cyclo}-(\text{RAsO})_3\}_2]^+$ .

It is interesting to compare the coordination geometries of  $[\text{Na}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]^+$  and  $[\text{K}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2]^+$  with those found in the analogous crown ether complexes  $[\text{Na}(12\text{-crown-}4)_2]\text{OH}\cdot 8\text{H}_2\text{O}$  [36] and  $[\text{K}(\text{benzo-}15\text{-crown-}5)_2]\text{I}$  [37]. On the basis of a simple ionic model, Kepert has determined an O–M–Pl angle ( $\alpha$ ) of  $59.3^\circ$  for an idealised quadratic antiprism, but typical experimental values are found to be somewhat smaller ( $57^\circ$ ) in the complexes  $\text{ML}_8$  of monodentate ligands [38].  $[\text{Na}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]^+$  exhibits a very small average  $\alpha$  angle of  $47.2^\circ$ ,  $[\text{Na}(12\text{-crown-}4)_2]^+$  a larger value of  $52.6^\circ$ . The extreme degree of elongation of the quadratic antiprism in the  $(\text{C}_2\text{H}_5\text{AsO})_4$  sandwich cation results from the shortness of the  $\text{O}\cdots\text{O}$  distance ( $2.69\text{ \AA}$ ) in the cyclotetramer in comparison to the more flexible crown ether ( $2.80\text{ \AA}$ ). The better ion ligating properties of 12-crown-4 are also confirmed by its average  $\text{Na}\cdots\text{O}$  distances, which are some  $0.10\text{ \AA}$  shorter than in  $[\text{Na}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]^+$ . A similar trend is apparent for  $[\text{K}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5\}_2]^+$  ( $\alpha = 50^\circ$ ,  $d(\text{K}\cdots\text{O}) = 2.99\text{ \AA}$ ) and in  $[\text{K}(\text{benzo-}15\text{-crown-}5)_2]^+$  ( $\alpha = 54^\circ$ ,  $d(\text{K}\cdots\text{O}) = 2.86\text{ \AA}$ ). Both  $\alpha$  values are markedly smaller than that of  $59.8^\circ$  calculated by Kepert for an idealised pentagonal antiprism and solution studies confirm the relatively poor ionophoric properties of alkylcycloarsoxanes. On redissolving  $[\text{Na}\{\text{cyclo}-(\text{RAsO})_4\}_2]\text{SCN}$  or  $[\text{K}\{\text{cyclo}-(\text{RAsO})_5\}_2]\text{SCN}$ ,  $^1\text{H-NMR}$  spectra are in accordance with a distribution of cyclooligomers ( $n = 2\text{--}5$ ) similar to that found for  $(\text{RAsO})_n$  alone [7,8,32].

### 2.2.3. $\kappa^n\text{As}$ coordination

**2.2.3.1. Cyclotetramers and cyclopentamers  $(\text{RAsO})_n$  ( $n = 4, 5$ ).** Cyclotetramers  $(\text{RAsO})_4$  and cyclopentamers  $(\text{RAsO})_5$  adopt a bridging role in all their previously characterised metal complexes. The vast majority of these are coordination polymers and will, therefore, be classified in detail in Section 2.3. Characteristic for the  $(\text{AsO})_4$  eight membered ring in alkylcycloarsoxanes ( $\text{R} = \text{CH}_3, \text{C}_2\text{H}_5$ ) is its remarkable flexibility, which allows it to bridge between two and four metal atoms. Known coordination modes for the three preferred ring conformations, boat-chair (bc), twist-chair (tc) and crown (cr) (Fig. 6) are depicted in a schematic manner in Fig. 10. Representative examples will now be considered.

**2.2.3.1.1. Twist-chair conformation (tc13, tc4).** The tc13 mode, which is particularly suitable for connecting bulky metal fragments, has been observed in both discrete and polymeric coordination compounds. For instance, two  $\text{MnCp}'(\text{CO})_2$  units ( $\text{Cp}' = \text{CH}_3\text{C}_5\text{H}_4$ ) are linked in this manner in  $[\{\text{MnCp}'(\text{CO})_2\}\{\mu\text{-cyclo}-(\text{CH}_3\text{AsO})_4\}]$ , that may be synthesised either by treatment of  $[\text{MnCp}'(\text{CO})_3]$  with  $\text{cyclo}-(\text{CH}_3\text{AsO})_5$  in the presence of air or by direct reaction of the transition metal carbonyl with  $(\text{CH}_3\text{AsO})_n$  [9]. An analogous bridging role is found in the cyclic oligomer  $[\text{cyclo}-\{\text{ReBr}(\text{CO})_3[\mu\text{-}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}]\}_4]$  (Fig. 11), prepared by reacting  $[\text{ReBr}(\text{CO})_5]$  with  $(\text{C}_2\text{H}_5\text{AsO})_n$  in refluxing toluene [34]. As–O bonds to

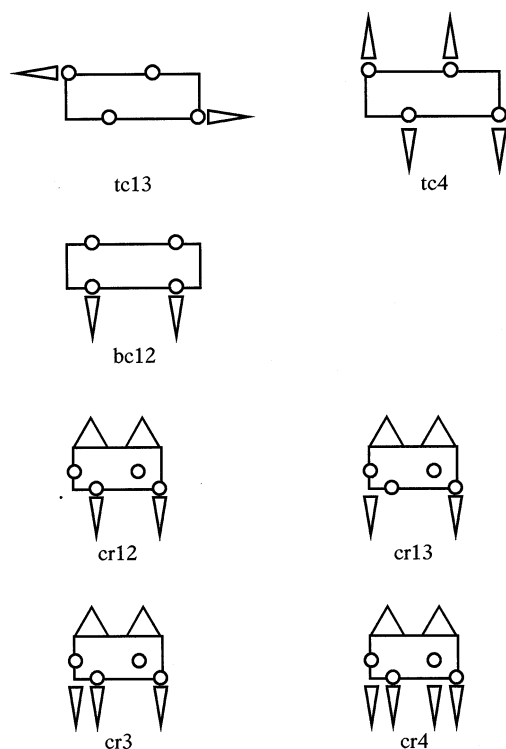


Fig. 10. Schematic representations of  $(RAsO)_4$  bridging modes: tc13 =  $\mu:1\kappa As^1:2\kappa As^3$  twist-chair; tc4 =  $\mu_4:1\kappa As^1:2\kappa As^2:3\kappa As^3:4\kappa As^4$  twist-chair; bc12 =  $\mu:1\kappa As^1:2\kappa As^2$  boat-chair; cr12 =  $\mu-1\kappa As^1:2\kappa As^2$  crown; cr13 =  $\mu-1\kappa As^1:2\kappa As^3$  crown; cr3 =  $\mu_3-1\kappa As^1:2\kappa As^2:3\kappa As^3$  crown; cr4 =  $\mu_4-1\kappa As^1:2\kappa As^2:3\kappa As^3:4\kappa As^4$  crown.

coordinated arsenic atoms in this complex exhibit an average value of 1.754(8) Å in comparison to 1.819(7) Å for non-coordinated As atoms, a change accompanied by a concomitant widening of the average O–As–O angles from 95(1) to 103(1)°. Alkylcycloarsoxanes might be expected to be relatively weak  $\pi$ -acceptors and this prognosis is confirmed in the tetrameric Re complex by the registration of an increased degree of  $\pi$ -backbonding to the CO ligands in *trans* position to the coordinated As atoms. The relevant carbonyl IR absorption bands are shifted to lower wavenumbers (2055, 1929  $\text{cm}^{-1}$ ) in comparison to  $[ReBr(CO)_5]$  (2150, 2044  $\text{cm}^{-1}$ ) [39].

Examples of the tc4 mode are found in copper halide-rich networks of the type  $[Cu_nX_n\{cyclo-(CH_3AsO)_4\}_2]$  ( $n = 3, 4, 6$ ) [40,41]. For instance infinite  $^1_\infty[CuX]$  ( $X = Br, I$ ) single chains are linked by methylcycloarsoxane ligands in a twist-chair conformation (Fig. 12) through all four As atoms into sheets  $^2_\infty[\{CuX(CuX \cdot CH_3CN)_2\}\{cyclo-(CH_3AsO)_4\}]$ .

**2.2.3.1.2. Boat-chair conformation (bc12).** Although the energetically favourable boat-chair conformation has been established for both  $(CH_3AsO)_4$  [9] and  $(PhAsO)_4$  [10] in the solid state, only one example is known for a metal complex. Two adjacent

copper atoms Cu(3) and Cu(4) in the chain coordination polymer  ${}^1_\infty[\text{Cu}_4\text{Cl}_4\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42] are bridged in the bc12 mode by an ethylcycloarsoxane tetramer of approximately  $C_s$  symmetry (Fig. 13). Interestingly this complex also contains further  $(\text{C}_2\text{H}_5\text{AsO})_4$  ligands with contrasting tc13 [As13, As1b and As24, As2a] and cr4 [As12–As42] bridging functions.

**2.2.3.1.3. Crown conformation (cr12, cr13, cr3, cr4).** Although tc13 and tc4 bridging roles are more typical for alkylcycloarsoxanes, the coordination requirements of the alkali counteranion lead to the adoption of the unusual cr12 and cr13 modes in the anionic ribbons of  $[\text{Cs}(\text{H}_2\text{O})_2][\text{Cu}_3\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]\cdot 0.5\text{CH}_3\text{OH}$  [43]. A further optimisation of the multidentate ligand properties of  $(\text{CH}_3\text{AsO})_4$  is achieved in  ${}^3_\infty[\{\text{Cs}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}\text{Cu}_3\text{I}_4\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32], in which the heterocycle now coordinates not only a  $\text{Cs}^+$  cation in a crown  $\kappa^4\text{O}$  fashion but also three I-bridged Cu(I) atoms through three of its four available As atoms in the cr3 mode. As may be seen in Fig. 14, the iodine atoms of a translation-related  $\text{Cu}_3\text{I}_4$  unit complete the 8-fold approximately cube-like coordination sphere of the alkali cation as a horseshoe part of an incomplete  $\text{Cu}_4\text{I}_4$  crown.

A crown-shaped  $\text{As}_4\text{O}_4$  ring coordinated in a cr3 or cr4 manner to three or four Cu(I) atoms has been observed as a characteristic molecular building block in the polymeric  $(\text{C}_2\text{H}_5\text{AsO})_4$  complexes,  ${}^1_\infty[\text{Cu}_4\text{Cl}_4\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42],

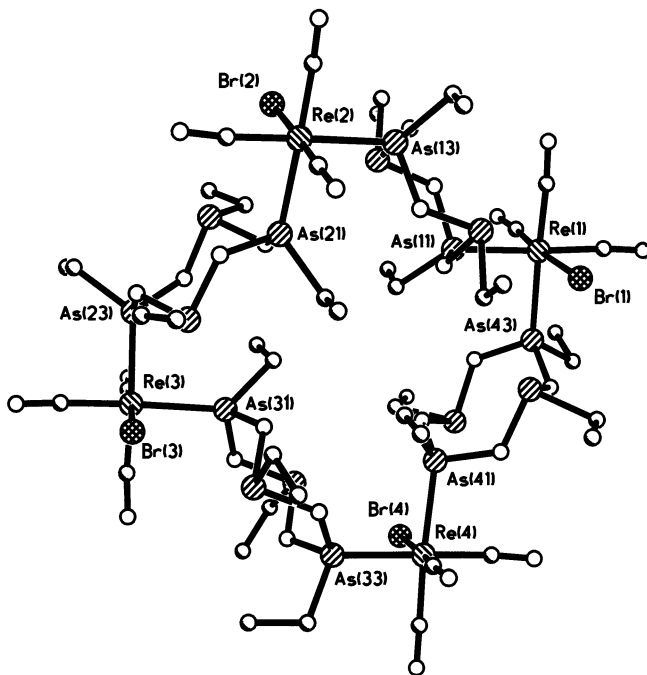


Fig. 11. Structure of the cyclic tetramer  $[\text{cyclo}\{-\{\text{ReBr}(\text{CO})_3[\mu\{-\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}\}_4]\}]$  in which individual Re atoms are linked by  $(\text{C}_2\text{H}_5\text{AsO})_4$  ligands in the tc13 mode [34].

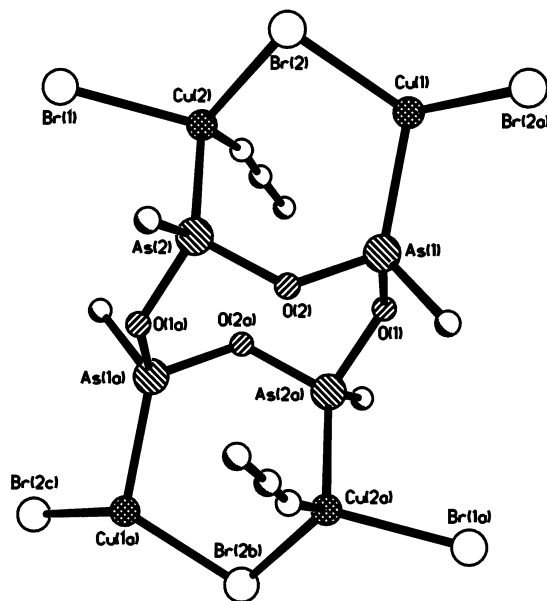


Fig. 12. tc4 bridging mode of the  $(\text{CH}_3\text{AsO})_4$  cyclotetramers in  $\frac{2}{\infty}[\{\text{CuBr}(\text{CuBr}-\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [41].

$\frac{2}{\infty}[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]$  ( $\text{X} = \text{Br}$  [42],  $\text{I}$  [34]) and  $\frac{2}{\infty}[\text{Cu}_6\text{I}_6\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42]. All these examples contain a  $\text{cr}3$  coordinated  $[\text{Cu}_3(\mu_3\text{-X})]^{2+}$  unit, that is extended by an additional  $\text{CuCl}_2$  group to afford a six-membered  $\text{Cu}_3\text{Cl}_3$  ring in the first of the coordination polymers. The  $\text{cr}4$  coordination of all four  $\text{Cu}(\text{I})$  atoms by the crown-shaped  $(\text{C}_2\text{H}_5\text{AsO})_4$  ligand [As12–As42] in this  $\text{CuCl}$  complex is depicted in Fig. 13.

The only known example of  $\kappa\text{As}$  coordination by a cyclopentamer  $(\text{RAsO})_5$  has already been mentioned in Section 2.2.2. A  $\text{Cs}^+$  counteranion is once again responsible for the stabilisation of crown-shaped heterocycles in  $\frac{1}{\infty}[\{\text{Cs}[\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5]_2\}\text{Cu}_2(\mu\text{-I})_2]$  [34], in whose anionic partial structure, two cyclopentamers  $(\text{C}_2\text{H}_5\text{AsO})_5$  are linked through a  $[\text{Cu}_2\text{I}_3]^-$  unit (Fig. 9).

**2.2.3.2. Cyclohexamers  $(\text{RAsO})_6$ .** We have followed up Rheingold and DiMaio's original report on the indirect synthesis of  $[\{\text{Mo}(\text{CO})_3\}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_6\}]$ , through treatment of  $\text{Mo}(\text{CO})_6$  with  $\text{cyclo}-(\text{CH}_3\text{As})_5$  in toluene at  $150^\circ\text{C}$  in the presence of  $\text{O}_2$  [19], by demonstrating that other cyclohexamers  $(\text{RAsO})_6$  ( $\text{R} = \text{C}_2\text{H}_5$ ,  $\text{Ph}$ ) can likewise be stabilised in the coordination sphere of facial transition metal carbonyl fragments  $\text{M}(\text{CO})_3$ . However, in contrast to  $[\{\text{Mo}(\text{CO})_3\}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_6\}]$  our series of analogous dinuclear Group 6 complexes  $[\{\text{M}(\text{CO})_3\}_2\{\text{cyclo}-(\text{RAsO})_6\}]$  ( $\text{R} = \text{C}_2\text{H}_5$ ,  $\text{M} = \text{Cr}$ ,  $\text{Mo}$ ,  $\text{W}$  [8];  $\text{R} = \text{Ph}$ ,  $\text{M} = \text{Cr}$ ,  $\text{Mo}$  [10]) were all prepared by direct reaction of  $\text{M}(\text{CO})_6$  with  $(\text{RAsO})_n$  in toluene at  $150\text{--}180^\circ\text{C}$ .  $[\{\text{Cr}(\text{CO})_3\}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$  (**1**) is depicted as a representative example of this class of compounds in Fig. 15.

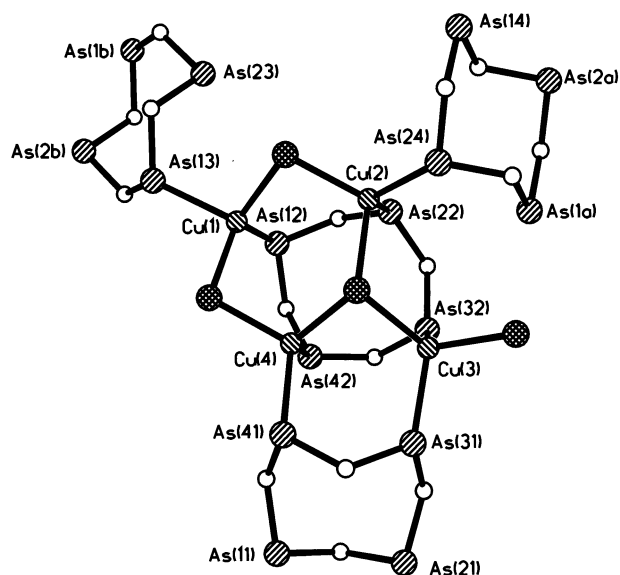


Fig. 13. The asymmetric unit of  ${}^1_{\infty}[\text{Cu}_4\text{Cl}_4\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  with the three cyclotetramers ( $\text{C}_2\text{H}_5\text{AsO}$ )<sub>4</sub> of differing bridging mode: bc12 [As31, As41], tc13 [As24, As2a and As13, As1b] and cr4 [As12–As42]. Linkage to an infinite chain is through As(1b) and As(2a) [42].

As–O distances in the hexadentate cyclohexaarsoxane ligand in this complex lie in the range 1.784(5)–1.811(5) Å with an average value of 1.80(1) Å similar to that observed in ( $\text{RAsO}$ )<sub>4</sub> ( $\text{R} = \text{CH}_3$ , 1.792 Å [10];  $\text{R} = \text{mes}$ , 1.790 Å [11]) and [ $\{\text{Mo}(\text{CO})_3\}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_6\}$ ] (1.791 Å [19]). A greater degree of flattening of

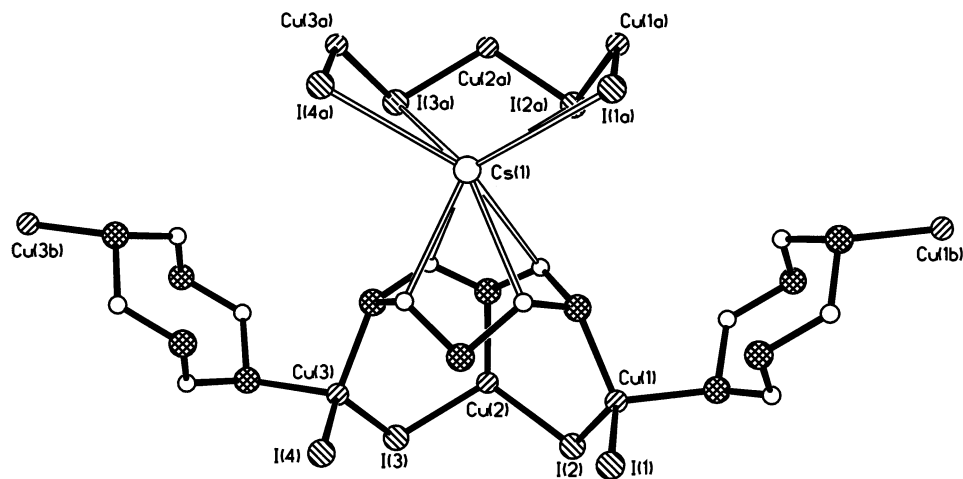


Fig. 14. Simultaneous crown  $\kappa^4\text{O}$  coordination of a  $\text{Cs}^+$  cation and  $1\kappa\text{As}^1:2\kappa\text{As}^2:3\kappa\text{As}^3$  coordination (cr3) of three Cu(I) atoms in  ${}^3_{\infty}[\{\text{Cs}[\text{cyclo}-(\text{CH}_3\text{AsO})_4]\text{Cu}_3\text{I}_4\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32].

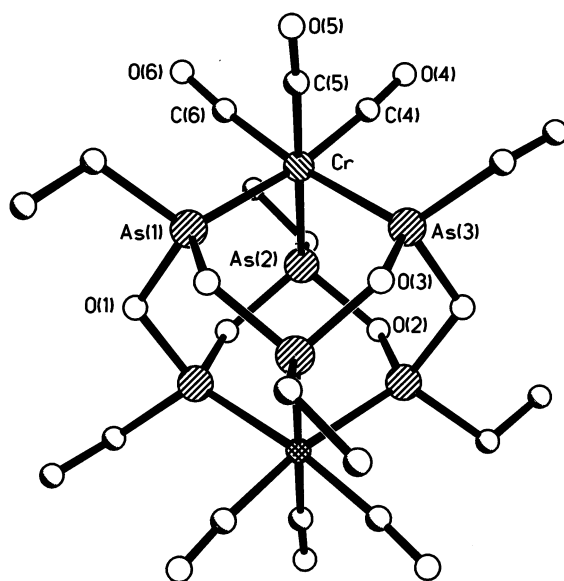


Fig. 15. Molecular structure of  $[\{\text{Cr}(\text{CO})_3\}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$  in which the twelve atoms of the  $\text{As}_6\text{O}_6$  ring form a flattened cuboctahedron [8].

the  $\text{As}_6\text{O}_6$  cuboctahedron is required to position the arsenic atoms for coordination of the smaller chromium atoms in comparison to the latter dimolybdenum complex. This is achieved by adoption of narrower As–O–As and O–As–O angles in the dichromium complex, where they lie in the respective ranges  $115.3(3)–117.5(3)^\circ$  and  $98.5(2)–99.1(2)^\circ$  in comparison to average values of  $118.9$  and  $101.0^\circ$  in  $[\{\text{Mo}(\text{CO})_3\}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_6\}]$ . In the chromium coordination sphere, C–Cr–C angles  $[84.3(4)–91.0(4)^\circ]$  are significantly narrower than As–Cr–As angles  $[94.6(1)–95.7(1)^\circ]$ . As a result of the much poorer  $\pi$ -acceptor properties of the hexaethylcyclohexaarsoxane ligand in  $[\{\text{Cr}(\text{CO})_3\}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$  in comparison to the CO ligands in  $\text{Cr}(\text{CO})_6$  [44], the Cr–C bond lengths in the first complex  $[1.857(8)–1.876(9) \text{ \AA}]$  are markedly shorter than in the hexacarbonyl, which exhibits an average value of  $1.909 \text{ \AA}$ . The increased degree of  $\pi$  backbonding to the carbonyl ligands of the alkylcycloarsoxane complex is also reflected in the observed shifts of the  $\nu(\text{CO})$  frequencies from  $2112$ ,  $2018$  and  $1986 \text{ cm}^{-1}$  in the IR spectrum of  $\text{Cr}(\text{CO})_6$  to  $1961$  and  $1898 \text{ cm}^{-1}$  in  $[\{\text{Cr}(\text{CO})_3\}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$ . CO stretching frequencies in similar ranges are also recorded for the analogous dimolybdenum ( $1970$ ,  $1920$ ,  $1904 \text{ cm}^{-1}$ ) and ditungsten ( $1962$ ,  $1908 \text{ cm}^{-1}$ ) complexes [8].

These findings prompted us to investigate the possible influence of M–As distances and As–M–As' angles of a  $\kappa^3\text{As}$  facially coordinated metal atom on the nuclearity of  $(\text{RAsO})_n$  complexes. A metal mediated ring expansion of organylcycloarsoxanes to hexameric ligands  $(\text{RAsO})_6$  was observed for a series of complexes  $[\{\text{ReBr}(\text{CO})_2\}_2\{\mu\text{-}[\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$  (2),  $[\text{RuCl}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}(\text{Ph}_3\text{P})]$  (3),

[RhCl<sub>3</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}] (**4**), [Cu<sub>2</sub>{μ-[*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>]}{(CH<sub>3</sub>)<sub>2</sub>PhP}<sub>2</sub>](CF<sub>3</sub>SO<sub>3</sub>)<sub>2</sub> (**5**) [45] and [{RuCl<sub>2</sub>(CO)}<sub>2</sub>{μ-[*cyclo*-(PhAsO)<sub>6</sub>]}] [10], despite differences in their nuclearity and metal coordination geometries. Average bond lengths and angles in **1**–**5** are summarised in Table 2.

As previously discussed in Section 2.2.3.1, reaction of ethylcycloarsoxane with [ReBr(CO)<sub>5</sub>] in refluxing toluene (110°C, 15 min) leads to substitution of only two carbonyl ligands and formation of the cyclic oligomer [*cyclo*-{ReBr(CO)<sub>3</sub>[μ-{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>4</sub>}]}<sub>4</sub>] containing tetramers (C<sub>2</sub>H<sub>5</sub>AsO)<sub>4</sub> in their typical tc13 bridging mode [34]. At the higher temperature provided by refluxing mesitylene (165°C, 6 h), a further CO ligand may be replaced to enable the metal-assisted ring expansion of ethylcycloarsoxane to its hexameric form found in the dirhenium complex **2**. This compound is also isolated at the molar [ReBr(CO)<sub>5</sub>]:(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub> ratio of 1:1 required for a mononuclear κ<sup>3</sup>As<sup>1</sup>As<sup>3</sup>As<sup>5</sup> coordinated complex. In contrast to the preferred formation of a dinuclear complex for the facial ReBr(CO)<sub>2</sub> fragment, treatment of (C<sub>2</sub>H<sub>5</sub>AsO)<sub>n</sub> with either [RuCl<sub>2</sub>(Ph<sub>3</sub>P)<sub>3</sub>] or RhCl<sub>3</sub>·3H<sub>2</sub>O allows only the isolation of the mononuclear complexes **3** and **4** (Figs. 16 and 17). The *trans* influence of the Ph<sub>3</sub>P ligand in **3** leads to a marked lengthening of the Ru1–As3 distance to 2.454(2) Å in comparison to the Ru1–As1 and Ru1–As5 distances of 2.372(2) and 2.354(2) Å. Increased strain in the As<sub>6</sub>O<sub>6</sub> ring resulting from the presence of these short Ru–As distances causes the arsoxane ring to no longer adopt the flattened cuboctahedral conformation found in the dinuclear complexes **1** and **2** [torsion angles As′–O–As–O′ ±(78.6) to ±(81.4)° in **1**, ±(76.2) to ±(79.6)° in **2**]. The solid-state conformation of **3** depicted in Fig. 16 would be incapable of coordinating a second RuCl<sub>2</sub>(Ph<sub>3</sub>P) fragment. Although the shape of the (AsO)<sub>6</sub> macrocycle in the mononuclear Rh(III) complex **4** does resemble a flattened cuboctahedron, the short Rh–As distances (2.34 Å) once again indicate a pronounced increase in ring strain, that may now be gauged from the striking difference between the average values for As′–O–As–O′ torsion angles when As is

Table 2

Average bond lengths (Å) and angles (°) in mono- and dinuclear complexes of (C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub><sup>a</sup>

| Compound       | <b>1</b>            | <b>2</b>              | <b>3</b>                              | <b>4</b>          | <b>5</b>                                |
|----------------|---------------------|-----------------------|---------------------------------------|-------------------|-----------------------------------------|
| Metal fragment | Cr(CO) <sub>3</sub> | ReBr(CO) <sub>2</sub> | RuCl <sub>2</sub> (Ph <sub>3</sub> P) | RhCl <sub>3</sub> | Cu{(CH <sub>3</sub> ) <sub>2</sub> PhP} |
| Nuclearity     | 2                   | 2                     | 1                                     | 1                 | 2                                       |
| As–M           | 2.42(1)             | 2.49(5)               | 2.39(5)                               | 2.34(1)           | 2.38(2)                                 |
| As⋯As′         | 3.57(1)             | 3.67(1)               | 3.53(4)                               | 3.57(2)           | 3.73(5)                                 |
| As(M)–O        | 1.80(1)             | 1.79(1)               | 1.77(1)                               | 1.75(1)           | 1.79(1)                                 |
| As–O           |                     |                       | 1.80(1)                               | 1.80(2)           |                                         |
| As–M–As′       | 95(1)               | 95(1)                 | 95(1)                                 | 99(1)             | 103(1)                                  |
| As–O–As′       | 116(1)              | 120(1)                | 121(3)                                | 123(1)            | 120(1)                                  |
| O–As(M)–O′     | 99(1)               | 100(2)                | 98(1)                                 | 102(2)            | 101(1)                                  |
| O–As–O′        |                     |                       | 98(1)                                 | 98(2)             |                                         |

<sup>a</sup> Compounds studied: [{Cr(CO)<sub>3</sub>}<sub>2</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}] **1** [8], [{ReBr(CO)<sub>2</sub>}<sub>2</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}] **2**, [RuCl<sub>2</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}(Ph<sub>3</sub>P)] **3**, [RhCl<sub>3</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}] **4**, [Cu<sub>2</sub>{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsO)<sub>6</sub>}-{(CH<sub>3</sub>)<sub>2</sub>PhP}<sub>2</sub>](CF<sub>3</sub>SO<sub>3</sub>)<sub>2</sub> **5** [45].

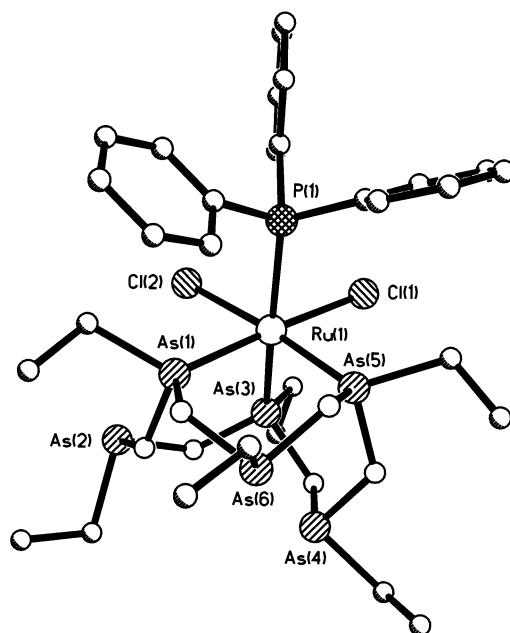


Fig. 16. Molecular structure of  $[\text{RuCl}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}(\text{Ph}_3\text{P})]$  (3) [45].

either coordinated ( $\pm 80^\circ$ ) or non-coordinated ( $\pm 72^\circ$ ). As a result, the latter atoms As2, As4 and As6 (Fig. 17) are now much further apart (average value  $3.9 \text{ \AA}$ ) than those in the Rh(III) coordination sphere (average value  $3.57 \text{ \AA}$ ). It is apparent that the energetic advantage gained by coordination of a second  $\text{RhCl}_3$  fragment must

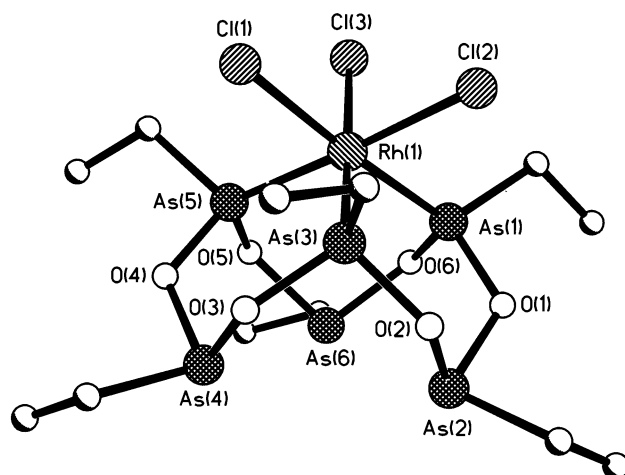


Fig. 17. Molecular structure of  $[\text{RhCl}_3\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_6\}]$  (4) [45].

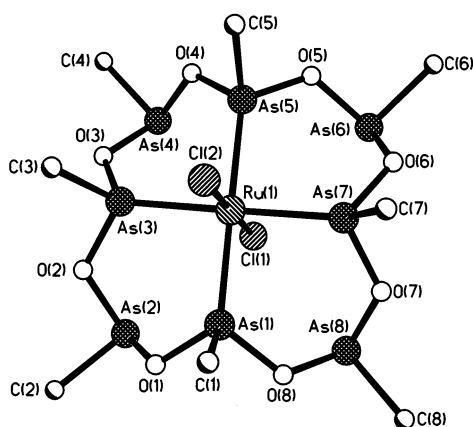


Fig. 18. Molecular structure of  $[\text{RuCl}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_8\}]$  [46].

be insufficient to compensate for the further increase in ring strain that would be necessary to reduce the former  $\text{As}\cdots\text{As}'$  distances to ca. 3.57 Å. Interestingly, the markedly larger  $\text{As}-\text{M}-\text{As}'$  angles ( $103^\circ$ ) required by a  $\text{Cu}(\text{I})$  tetrahedral coordination sphere lead to longer  $\text{As}\cdots\text{As}'$  separations (3.73 Å), thereby allowing  $(\text{C}_2\text{H}_5\text{AsO})_6$  to adopt a bridging role in the dicopper complex **5**, despite its relatively short  $\text{Cu}-\text{As}$  distance (2.38 Å).

**2.2.3.3. Cyclooctamers  $(\text{RAsO})_8$ .** Reaction of  $\text{MCl}_3 \cdot x\text{H}_2\text{O}$  ( $\text{M} = \text{Ru}, \text{Os}$ ) with  $(\text{CH}_3\text{AsO})_n$  at a molar ratio of 1:10 (for  $n = 1$ ) enables the metal-mediated ring expansion of methylcycloarsoxane to an unprecedented cyclooctamer, that is stabilised in the equatorial coordination plane of the resulting octahedral complexes  $[\text{MCl}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_8\}]$  [46]. The reduction of  $\text{M}(\text{III})$  to  $\text{M}(\text{II})$  is accompanied by ligand cleavage and oxidation to  $\text{CH}_3\text{AsO}(\text{OH})_2$ . Inspection of the  $\text{As}-\text{Ru}-\text{As}$  angles [average values  $90(1)$  and  $177.5(2)^\circ$ ] and  $\text{Ru}-\text{As}$  distances [2.400(4) Å] for the  $\text{Ru}(\text{II})$  complex shown in Fig. 18 confirm the suitability of the very flexible  $\text{As}_8\text{O}_8$  16-membered ring for its adopted coordination role.  $\text{As}-\text{O}$  distances to the coordinated arsenic atoms  $\text{As}1$ ,  $\text{As}3$ ,  $\text{As}5$  and  $\text{As}7$  are on average [1.758(8) Å] much shorter than those to the remaining non-coordinated Group 15 atoms [1.799(7) Å]. A concomitant widening of the  $\text{O}-\text{As}-\text{O}$  angles for the former atoms is apparent [ $99.7(4)$  vs.  $97.0(2)^\circ$ ]. The  $\text{As}_8\text{O}_8$  ring exhibits a double-crown conformation with a torsion angle pattern of the type  $(a, b, -b, -a)_4$ , where the absolute value of  $a$  varies between  $104.5$  and  $124.3^\circ$  and that for  $b$  between  $59.5$  and  $75.0^\circ$ .

## 2.3. Coordination polymers

### 2.3.1. Crystal engineering principles

The rational design of porous solid-state coordination networks capable of hosting guest molecules in their voids has aroused considerable current interest [47–50]. Although the majority of known examples involve tetrahedrally coordi-

nated Ag(I) or Cu(I) atoms separated by rigid organic spacer molecules (e.g. piperazine, pyrazine, 4,4'-bipyridine and 4,4'-biphenyldicarbonitril) a few encouraging reports on the employment of more flexible connecting ligands such as methylene bridged dichalcogenoethers [51] or thioether macrocycles [52–54] have appeared in the recent literature. In analogy to the porous networks of zeolites [55] or Group 14–15 chalcogenidometalates [56,57], these layers or frameworks might be expected to be capable of undergoing elastic deformations in response to different structure-directing agents or imbibed molecular guests.

The successful development of a relatively comprehensive mineralomimetic chemistry based on M–CN–M linkages [58] confirms that the rational design of solid-state coordination polymers is a feasible objective. However extension of these crystal engineering principles to the construction of coordination polymers with larger well-defined cavities is often foiled by the self-interpenetration of multiple networks, which eliminates the void space. This phenomenon is particularly typical for diamondoid networks [49] for which as many as eight or nine interweaving frameworks can be obtained [59–61]. As for organoporous hosts [62], rational crystal engineering principles must enable the systematic modification of solid-state coordination networks and control of cavity size and chemical environment, whilst retaining the supramolecular architecture and preventing lattice interpenetration. A further objective must be the ability of a particular host lattice to accommodate different types of guests by allowing the systematic introduction of molecular building blocks with tailored properties (e.g. non-linear optics, macrocyclic ionophores, chiral functional groups).

Their characteristic ability to bridge tetrahedrally coordinated metal atoms, their pronounced conformational flexibility and their confirmed ion ligating properties suggested to us that cyclotetramers of the type (RAsO)<sub>4</sub> might exhibit considerable potential as spacer molecules for the construction of porous coordination lattices with an ability to host a variety of guests (e.g. alkali cations, hydrogen bonding organic molecules). Our previous studies have concentrated on the design of neutral or negatively charged host networks but there is no apparent reason why alkylcycloarsoxanes should not also be employed for the synthesis of positively charged coordination polymers.

We have established three basic design principles for the construction of (RAsO)<sub>4</sub> (R = CH<sub>3</sub>, C<sub>2</sub>H<sub>5</sub>) bridged networks of copper(I) halides. The self-assembly of a particular supramolecular architecture from (RAsO)<sub>n</sub> and CuX (X = Cl, Br, I) is dependent on the molar ratio (RAsO)<sub>4</sub>:CuX employed, the reaction conditions, the presence of guest molecules to occupy voids, the steric requirements of the alkyl side chains and the propensity of bridging halogen atoms X to extend their coordination number from two to three.

**2.3.1.1.  $\infty[(CuX)_n\{cyclo-(RAsO)_4\}]$  ribbons, motif 1.** Two typical examples for such infinite chains are illustrated in a schematic manner in Fig. 19 for (a) a (CuX)<sub>2</sub> four-membered ring and (b) a discrete tricyclic (CuX)<sub>4</sub> molecular building block. The construction of ribbons as structural motifs has also been observed for a variety of other copper(I) halide moieties, for instance (CuX)<sub>3</sub> six-membered rings

and tricyclic  $\text{Cu}_6\text{X}_6$  units, in which a central four-membered ring is fused to two such flanking  $(\text{CuX})_3$  rings. It is apparent that in each case two  $\text{Cu(I)}$  atoms of the  $(\text{CuX})_n$  ( $n = 2, 4$ ) units in the  $^1_\infty[(\text{CuX})_n\{\text{cyclo}-(\text{RAsO})_4\}]$  chains of Fig. 19(a,b) exhibit a vacant coordination site and this can be occupied either by terminal monodentate or bridging bidentate ligands. The latter connectivity pattern generates a porous  $4^4$  net in which the bridging pillars can be either further alkylcycloarsoxanes as in the case of  $^2_\infty[(\text{CuX})_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  ( $\text{X} = \text{Cl}, \text{Br}, \text{I}$  [40]) or rigid aromatic spacer molecules as illustrated schematically in Fig. 20 for  $^2_\infty[\text{Cu}_2\text{X}_2(p\text{-H}_2\text{NC}_6\text{H}_4\text{NH}_2)\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [43].

2.3.1.2.  $^2_\infty[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{RAsO})_4\}]$  sheets, motif 2. This structural motif is depicted in schematic manner in Fig. 21. Tetradentate twist-chair shaped cyclotetramers  $(\text{RAsO})_4$  bridge parallel infinite  $^1_\infty[\text{CuX}]$  chains to afford a porous sheet in which two thirds of the  $\text{Cu(I)}$  atoms exhibit a vacant coordination position. Whereas

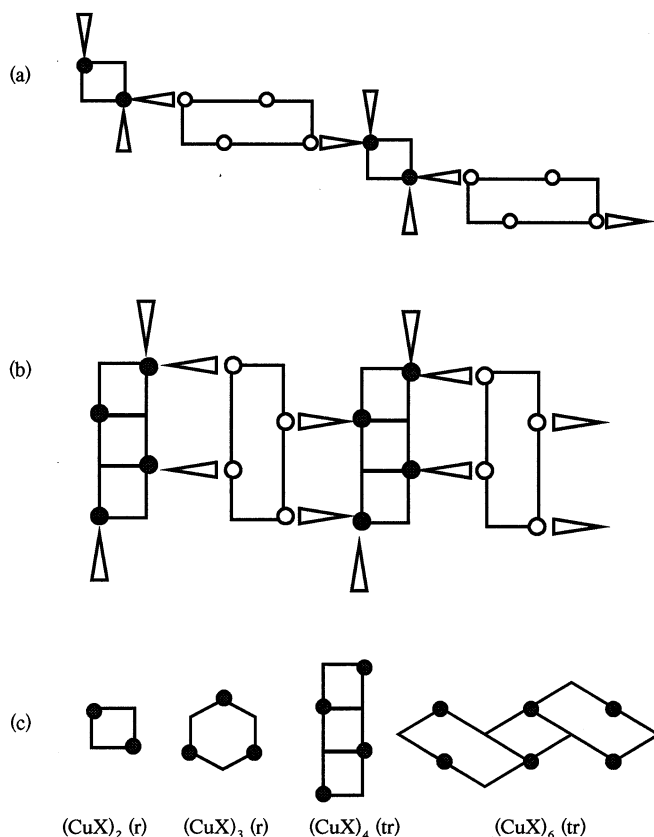


Fig. 19. Schematic representation of two types of  $^1_\infty[(\text{CuX})_n\{\text{cyclo}-(\text{RAsO})_4\}]$  ribbon (motif 1): (a)  $n = 2$ , (b)  $n = 4$ . Cartoons for various  $(\text{CuX})_n$ ,  $n = 2, 3, 4$  and  $6$  are illustrated in (c). r, ring; c, chain; tr, tricyclic unit.

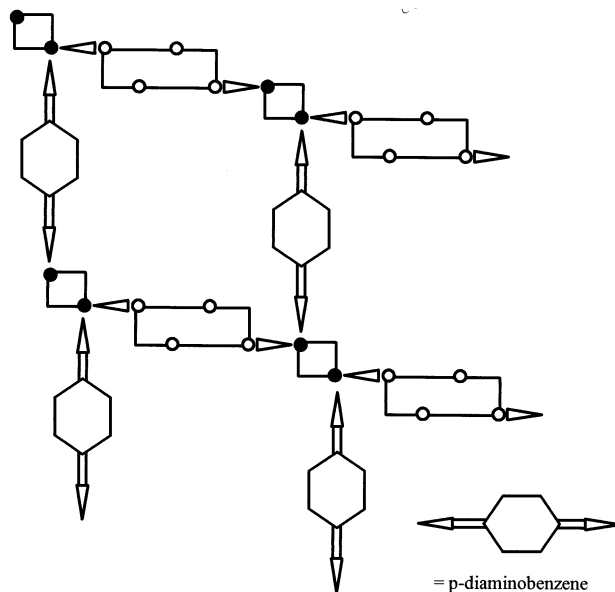


Fig. 20. Schematic representation of the  $4^4$  planar net of  ${}^2_{\infty}[\text{Cu}_2\text{I}_2(p\text{-H}_2\text{NC}_6\text{H}_4\text{NH}_2)\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [43].

occupation by a terminal ligand (e.g.  $\text{CH}_3\text{CN}$ ) preserves the dimensionality, introduction of a bridging ligand allows the construction of a 3-D framework as in  ${}^3_{\infty}[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  ( $\text{X} = \text{Cl}, \text{Br}$  [40]).

2.3.1.3.  ${}^2_{\infty}[\text{Cu}_2\text{X}_2\{\text{cyclo}-(\text{RAsO})_4\}_3]$  sheets, motif 3. This very open network (Fig. 22) has only previously been observed for a copper(I) halide-poor complex with

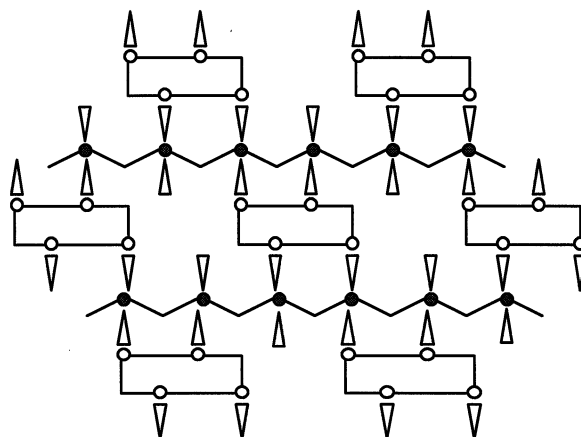


Fig. 21. Schematic representation of the  ${}^2_{\infty}[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{RAsO})_4\}]$  sheet, motif 2.

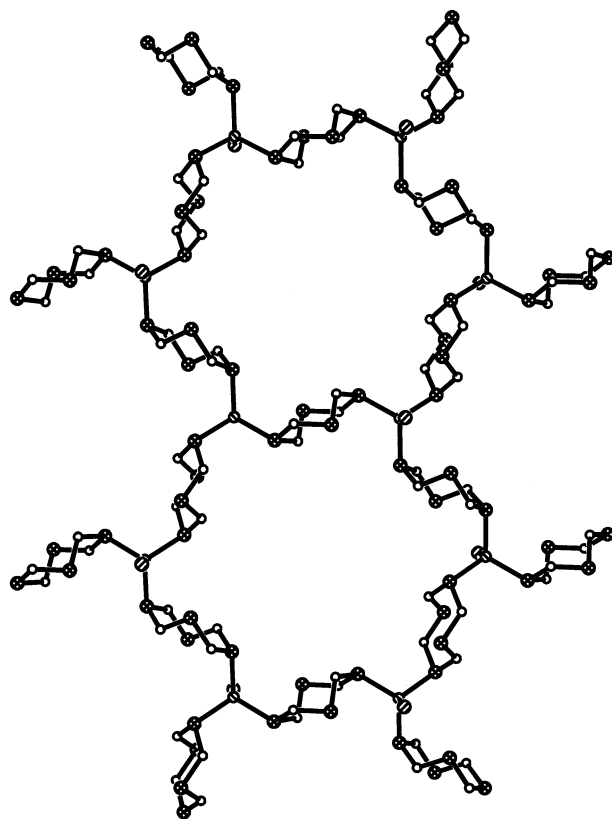


Fig. 22. The 6<sup>3</sup> net  ${}^2_{\infty}[\text{Cu}_2\text{X}_2\{\text{cyclo}-(\text{RAsO})_4\}_3]$ , motif 3, illustrated for X = Br, R = C<sub>2</sub>H<sub>5</sub> [34].

X = Br, R = C<sub>2</sub>H<sub>5</sub> [34]. The presence of either bulky side chains R (e.g. R = C<sub>2</sub>H<sub>5</sub>) or guest template molecules will be necessary to fill the voids provided by the large 36-membered pores. Replacement of terminal halides by bridging pillar ligands to neighbouring sheets could allow the construction of novel open 3-D frameworks.

We will now consider individual examples of CuX coordination polymers formed by the tetraalkylcyclotetraarsoxanes (CH<sub>3</sub>AsO)<sub>4</sub> and (C<sub>2</sub>H<sub>5</sub>AsO)<sub>4</sub>.

### 2.3.2. Bridging cyclotetramers (CH<sub>3</sub>AsO)<sub>4</sub>

${}^2_{\infty}[\text{Cu}_2\text{X}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  sheets (Cu:X:As ratio = 2:2:8, X = Cl, Br, I) may be obtained by self-organisation of CuX and (CH<sub>3</sub>AsO)<sub>n</sub> in acetonitrile over a wide range of low Cu:As starting ratios. Fig. 23 displays the layered structure of the isostructural chloride and bromide, in which  ${}^1_{\infty}[\text{Cu}_2\text{X}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  ribbons (motif 1) are bridged by bidentate (CH<sub>3</sub>AsO)<sub>4</sub> pillars to afford a porous 4<sup>4</sup> net with large 28-membered Cu<sub>6</sub>X<sub>2</sub>(As<sub>3</sub>O<sub>2</sub>)<sub>4</sub> rings of potentially ionophoric character. Translation related sheets exhibit weak secondary X⋯As interactions of 3.516 (X = Cl) and 3.567 Å (X = Br) and stack so as to generate wide channels, whose cross-section

tions are defined by the dimensions of the 28-membered rings. Although the analogous  $\mu\text{-}1\kappa\text{As}^1:2\kappa\text{As}^3\text{-(CH}_3\text{AsO)}_4$  bridged copper(I) iodide,  ${}^2_\infty[\text{Cu}_2\text{I}_2\{\text{cyclo-(CH}_3\text{AsO)}_4\}_2]$ , contains a similar  $4^4$  net it is not isotypic to the CuCl and CuBr coordination polymers. The 28-membered  $\text{Cu}_6\text{I}_2(\text{As}_3\text{O}_2)_4$  rings are now elongated in the direction of the transannular  $\text{Cu}\cdots\text{Cu}$  vectors of the  $(\text{CuI})_2$  building unit, i.e. effectively at right angles to the distortion observed for  $\text{X} = \text{Cl, Br}$  (Fig. 23). Once again, individual layers are connected through very weak interactions ( $\text{I}\cdots\text{As}$  4.101 Å), providing wide tunnels of pore size  $4.1 \times 7.2$  Å as gauged by the shortest transannular  $\text{H}\cdots\text{H}$  contacts.

When the self assembly reaction between CuI and  $(\text{CH}_3\text{AsO})_n$  is performed in  $\text{C}_6\text{H}_5\text{CN}$  instead of  $\text{CH}_3\text{CN}$ , the connectivity role of the  $(\text{CH}_3\text{AsO})_4$  pillars is taken over by terminally  $\kappa\text{N}$  coordinated solvent molecules, whose aromatic  $\pi$ -systems stack to construct a 3-D network, the component layers of which are displayed in Fig. 24 [43]. The voids generated by these stacking interactions are spacious enough ( $8.2 \times 8.2$  Å) to accommodate relatively large guest  $\text{C}_6\text{H}_5\text{CN}$  molecules. We have extended this design principle (Fig. 20) to the bridging aromatic spacer molecules  $p\text{-NH}_2\text{C}_6\text{H}_4\text{NH}_2$  [43] and  $p\text{-NH}_2\text{C}_{12}\text{H}_8\text{NH}_2$  [63]. Deep-red crystals of the layered structure  ${}^2_\infty[\text{Cu}_2\text{I}_2(p\text{-H}_2\text{NC}_6\text{H}_4\text{NH}_2)\{\text{cyclo-(CH}_3\text{AsO)}_4\}]$  may be grown by carefully underlayering a  $p\text{-H}_2\text{NC}_6\text{H}_4\text{NH}_2/(\text{CH}_3\text{AsO})_n$  solution in  $\text{CH}_3\text{CN}$  with a CuI solution in the same solvent at  $0^\circ\text{C}$ . The ordered alignment of the aromatic chromophores in this  $4^4$  net (Fig. 25) implies that its absorption of electromagnetic

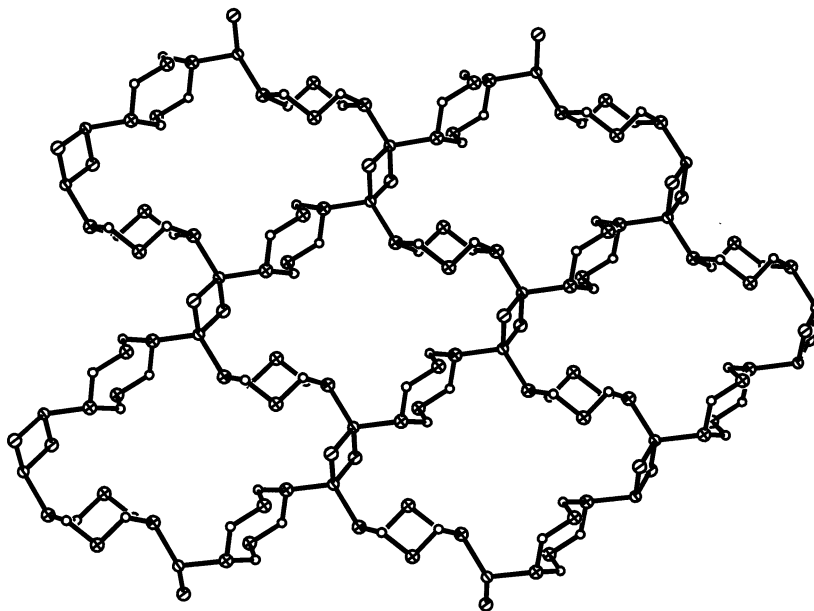


Fig. 23. Structure of  ${}^2_\infty[\text{Cu}_2\text{X}_2\{\text{cyclo-(CH}_3\text{AsO)}_4\}_2]$  ( $\text{X} = \text{Cl, Br}$ , [40]) in which  ${}^1_\infty[\text{Cu}_2\text{X}_2\{\text{cyclo-(CH}_3\text{AsO)}_4\}]$  ribbons (motif 1) are linked by  $(\text{CH}_3\text{AsO})_4$  pillars into a porous  $4^4$  net. Methyl groups have been omitted for clarity.

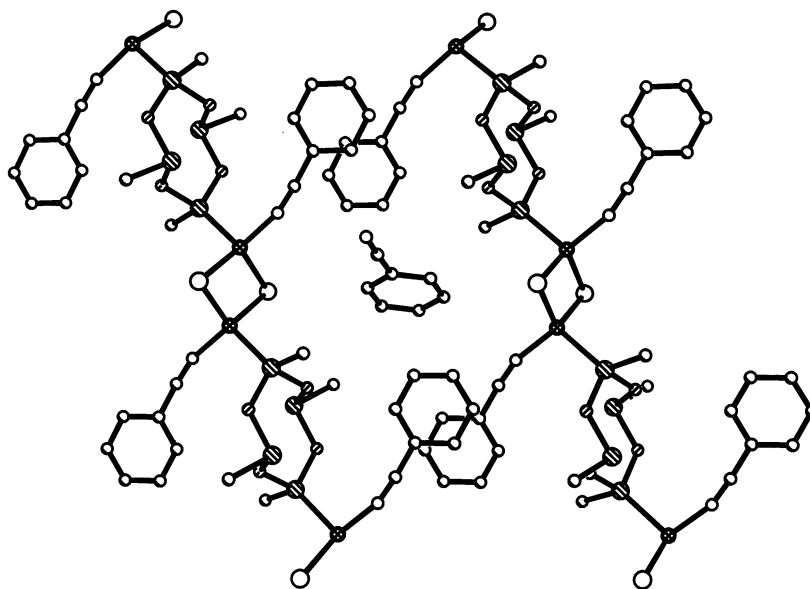


Fig. 24. Packing diagram for the  $\pi$ - $\pi$  stacked chains of  ${}^1_{\infty}[\text{Cu}_2\text{I}_2(\text{C}_6\text{H}_5\text{CN})_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$ . The resulting wide channels accommodate guest  $\text{C}_6\text{H}_5\text{CN}$  solvent molecules [43].

radiation must be anisotropic. Optical properties of zeolites with analogous imbibed parallel chromophore molecules such as *p*-nitroaniline are of considerable technological interest [64]. When *p*- $\text{H}_2\text{NC}_{12}\text{H}_8\text{NH}_2$  pillars are employed instead of *p*- $\text{H}_2\text{NC}_6\text{H}_4\text{NH}_2$ , the larger cavities accommodate disordered acetonitrile solvent molecules [65].

The ribbon motif 1 (Fig. 19a) has also been found in the CuX-rich coordination polymers  ${}^1_{\infty}[\text{Cu}_6\text{Br}_6(\text{C}_6\text{H}_5\text{CN})_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32] and  ${}^2_{\infty}[\text{Cu}_4\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  [41]. Tricyclic  $\text{Cu}_6\text{Br}_6$  building blocks are linked in the former complex into a 1-D polymer by bridging  $\kappa^4\text{As}$  coordinated cyclotetramers  $(\text{CH}_3\text{AsO})_4$ , which once again adopt the characteristic twist-chair conformation (tc4 mode). As may be seen in Fig. 26, symmetry-related  $\text{C}_6\text{H}_5\text{CN}$  molecules on opposite sides of the infinite chains are orientated away from the propagation vector of the coordination polymer and this allows their aromatic  $\pi$ -systems to stack with those of the analogous terminal solvent molecules from neighbouring chains to afford a network similar to that of  ${}^1_{\infty}[\text{Cu}_2\text{I}_2(\text{C}_6\text{H}_5\text{CN})_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  (Fig. 24).

${}^2_{\infty}[\text{Cu}_4\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  may be obtained by self-assembly from CuI and  $(\text{CH}_3\text{AsO})_n$  in acetonitrile at Cu:As starting ratios between 0.375 and 2.0. Whereas lower Cu:As ratios afford the previously described lamellar compound  ${}^2_{\infty}[\text{Cu}_2\text{I}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$ , higher Cu:As ratios lead to sole formation of  ${}^2_{\infty}[\{\text{CuI}(\text{CuI}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  with motif 2, which will be discussed subsequently. A total of 75% of the potential As coordination sites are employed in  ${}^2_{\infty}[\text{Cu}_4\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  whose sheet structure is displayed in Fig. 27. All four

As atoms of one of the independent  $(\text{CH}_3\text{AsO})_4$  ligands participate in copper binding to atoms of tricyclic  $\text{Cu}_4\text{I}_4$  building blocks, thereby providing  $^1_\infty[\text{Cu}_4\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  ribbons (motif 1) running in direction  $[010]$ .  $\mu$ - $1\kappa\text{As}^1$ : $2\kappa\text{As}^3$  coordinated  $(\text{CH}_3\text{AsO})_4$  pillars link adjacent chains to construct a porous sheet with large  $[\text{Cu}(\text{As}_2\text{O})(\text{Cu}_2\text{I})(\text{As}_2\text{O})_2]$  rings.

A higher  $\text{CuX}:\text{As}$  ratio of 0.75 is achieved in the isotypic lamellar polymers  $^2_\infty[\{\text{CuX}(\text{CuX}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  ( $\text{X} = \text{Br}, \text{I}$ ) [41] by incorporation of acetonitrile solvent molecules at the vacant coordination sites of two thirds of the  $\text{Cu}(\text{I})$  atoms of an infinite  $^1_\infty[\text{CuX}]$  single chain (structural motif 2, Fig. 21). As depicted in Fig. 12 for  $\text{X} = \text{Br}$ , adjacent copper(I) halide chains are linked through crystallographically centrosymmetric  $\kappa^4\text{As}$  coordinated  $(\text{CH}_3\text{AsO})_4$  ligands into the

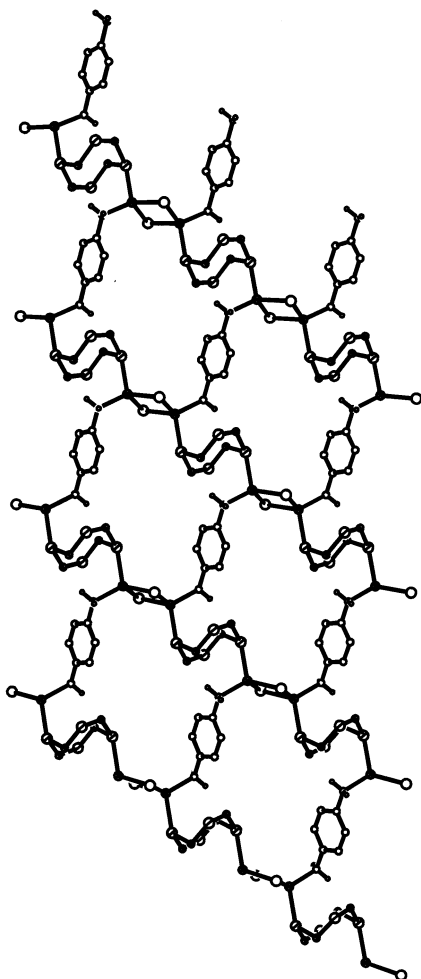


Fig. 25. Structure of the lamellar  $^2_\infty[\text{Cu}_2\text{I}_2(p\text{-H}_2\text{NC}_6\text{H}_4\text{NH}_2)\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$   $4^4$  net [43]. Methyl groups have been omitted for clarity.

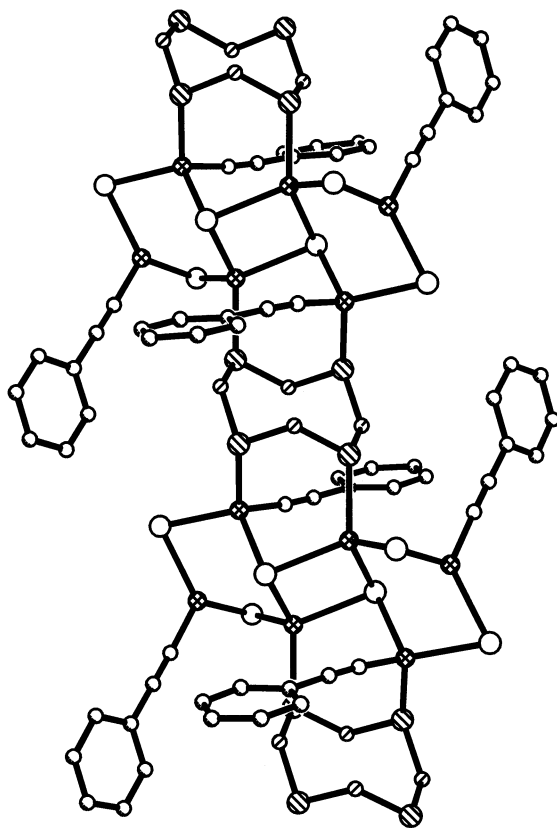


Fig. 26. Chain structure of  $^1_\infty[\text{Cu}_6\text{Br}_6(\text{C}_6\text{H}_5\text{CN})_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32]. Methyl groups have been omitted for clarity.

porous sheet structure with 16-membered  $[\text{Cu}_3\text{X}_2(\text{As}_2\text{O})_2]$  rings presented in Fig. 28. Whereas Cu(1) and Br(1) in Fig. 12 both lie on crystallographic twofold rotation axes of the monoclinic space group  $C2/c$ , the remaining atoms of the polymeric  $^1_\infty[\text{CuBr}]$  single chains, Cu(2) and Br(2), occupy general positions. A remarkable difference is apparent for the independent Cu–X–Cu chain angles in these isotypic compounds, where Cu(1)–X(1)–Cu(2) angles of  $94.8(1)^\circ$  (X = Br) and  $90.8(1)^\circ$  (X = I) within the six-membered  $[\text{Cu}_2\text{X}(\text{As}_2\text{O})]$  rings contrast with wide Cu(2)–X(1)–Cu(2)' angles of  $148.2(1)^\circ$  (X = Br) and  $143.1(1)^\circ$  (X = I).

The  $^2_\infty[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  sheets of structural motif 2 (Fig. 21) can also be identified in the unique open 3-D networks of the isotypic compounds  $^3_\infty[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  (X = Cl, Br) [40]. Opposite arsenic atoms of  $\mu$ - $1\kappa\text{As}^1:2\kappa\text{As}^3$  bridging  $(\text{CH}_3\text{AsO})_4$  ligands now occupy the vacant coordination sites of two thirds of the Cu(I) atoms of the  $^1_\infty[\text{CuX}]$  ribbons and connect neighbouring sheets to generate the porous framework structure depicted in Fig. 29. The presence of both non-coordinated and coordinated arsenic atoms in  $^3_\infty[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$

$(\text{CH}_3\text{AsO})_4\}_2]$  ( $\text{X} = \text{Cl}, \text{Br}$ ) leads to the pronounced splitting of the  $\nu(\text{As}-\text{O})$  IR absorption bands in the range  $720\text{--}760\text{ cm}^{-1}$ . Whereas the position of the  $\nu(\text{As}-\text{O})$  at respectively  $733$  ( $\text{X} = \text{Cl}$ ) and  $730\text{ cm}^{-1}$  ( $\text{X} = \text{Br}$ ) remains effectively unchanged for the non-coordinated As atoms in comparison to  $(\text{CH}_3\text{AsO})_4$  itself ( $724\text{ cm}^{-1}$ ), strengthening of the As–O bonds to the coordinated arsenic atoms causes a shift in this absorption band to higher wavenumbers for  $\text{X} = \text{Cl}$  ( $749\text{ cm}^{-1}$ ) and  $\text{X} = \text{Br}$  ( $758\text{ cm}^{-1}$ ) [40]. Analogous shifts of ca.  $20\text{--}35\text{ cm}^{-1}$  were observed in other methylcycloarsoxane complexes.

As reviewed in Section 2.2.2, alkylcycloarsoxanes coordinate alkali metal cations  $\text{M}$  in a  $\kappa''\text{O}$  fashion in sandwich complexes of the type  $[\text{M}\{\text{cyclo}-(\text{RAsO})_n\}_2]$  ( $\text{M} = \text{Na}; n = 4; \text{M} = \text{K}, \text{Cs}; n = 5$ ). The presence of immobilised cyclic ionophores in the coordination polymers previously described in this Section suggested to us that the self-assembly of negatively charged host networks from  $\text{CuX}$  and  $(\text{CH}_3\text{AsO})_n$  in solutions containing alkali metal cations should be possible. This goal was then first achieved in the layered structure of  $[\text{Cs}(\text{H}_2\text{O})_2][\text{Cu}_3\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  depicted in Figs. 30 and 31. Two water ligands were found to be

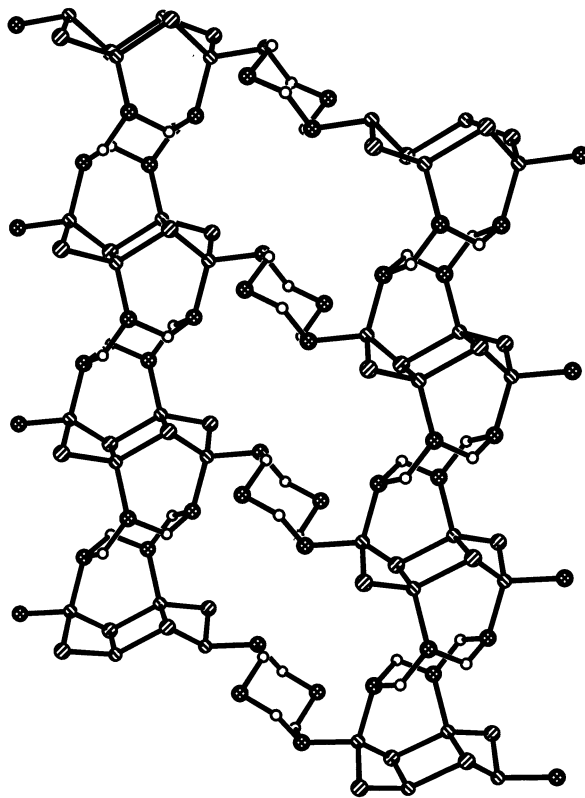


Fig. 27. Layered structure of  ${}^2_{\infty}[\text{Cu}_4\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  [41] with methyl groups omitted for the sake of clarity.

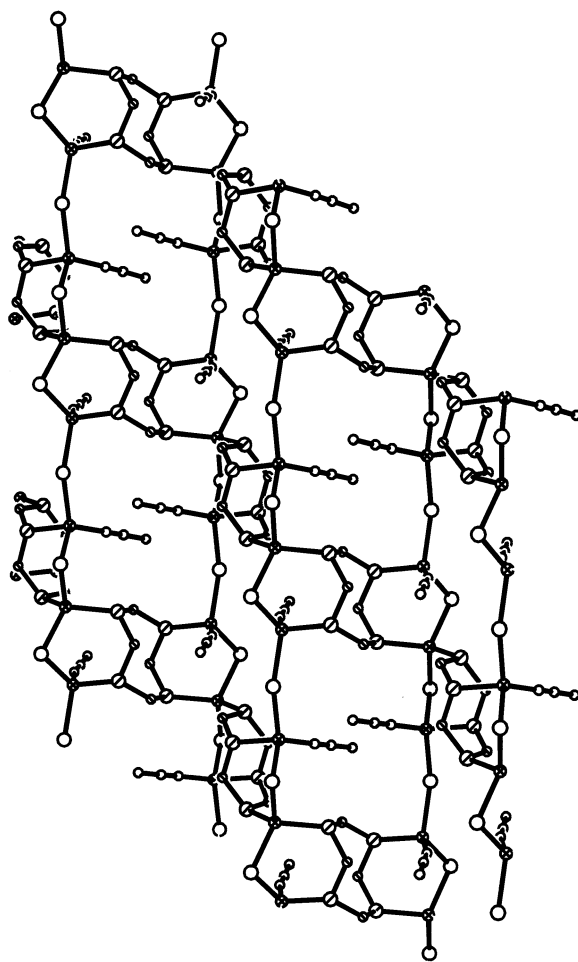


Fig. 28. The sheet structure of  $\frac{2}{\infty}[\{\text{CuBr}(\text{CuBr}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [41] with methyl groups omitted for the sake of clarity.

necessary to complete the tenfold  $\kappa^{10}\text{O}$  coordination spheres of the  $\text{Cs}^+$  cations, used to direct the self-organisation of the anionic  $\frac{1}{\infty}[\text{Cu}_3\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  chains from  $\text{CuI}$  and  $(\text{CH}_3\text{AsO})_n$  in a  $\text{CH}_3\text{CN}/\text{CH}_3\text{OH}/\text{H}_2\text{O}$  mixture [43]. Though preferred for the construction of the 1-D  $\text{CuI}$  coordination polymers in this structure, the cyclotetramers  $(\text{CH}_3\text{AsO})_4$  are clearly less well-suited for the coordination of the large  $\text{Cs}^+$  cations than would have been cyclopentamers  $(\text{CH}_3\text{AsO})_5$ , as for example the analogous  $(\text{C}_2\text{H}_5\text{AsO})_5$  ligands in  $\frac{1}{\infty}[\{\text{Cs}[\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_5]_2\}\text{Cu}_2(\mu\text{-I})\text{I}_2]$  (Fig. 9) [34]. The less favourable open sandwich structure of the  $[\text{Cs}^+\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]^+$  units and the flexible nature of the anionic ribbons suggest that exchange of the  $\text{Cs}$  cations by smaller alkali metal cations ( $\text{Na}^+$ ,  $\text{K}^+$ ) could be possible and work is in progress in this direction. Disordered

methanol molecules are located in the relatively large cavities of  $[\text{Cs}(\text{H}_2\text{O})_2][\text{Cu}_3\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$ , which exhibit an increased degree of polar character as a result of the presence of  $\text{H}_2\text{O}$  molecules in the cesium coordination sphere. A DTA trace reveals initial endothermic loss of methanol and water ( $35\text{--}120^\circ\text{C}$ ) followed by endothermic collapse of the solid-state network in a temperature range ( $122\text{--}149^\circ\text{C}$ ) similar to that recorded for other alkylcycloarsoxane-bridged  $\text{Cu}(\text{I})$  halides. These results indicate that this flexible sheet structure could be capable of imbibing a range of smaller polar molecules whilst retaining its integrity.

A second example of an anionic host network is provided by  ${}^3_\infty[\{\text{Cs}[\text{cyclo}-(\text{CH}_3\text{AsO})_4]\text{Cu}_3\text{I}_4\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32], in which  $\text{Cu}_3\text{I}_3$  units are bridged by  $(\text{CH}_3\text{AsO})_4$  in a  $\mu\text{-}1\kappa\text{As}^1\text{:}2\kappa\text{As}^3$  manner (Fig. 14) into  ${}^1_\infty[\text{Cu}_3\text{I}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  ribbons (motif 1, which themselves are linked by iodine atoms into lamellar anions (Fig. 32). As previously discussed (Section 2.2.3), a second independent cyclote-

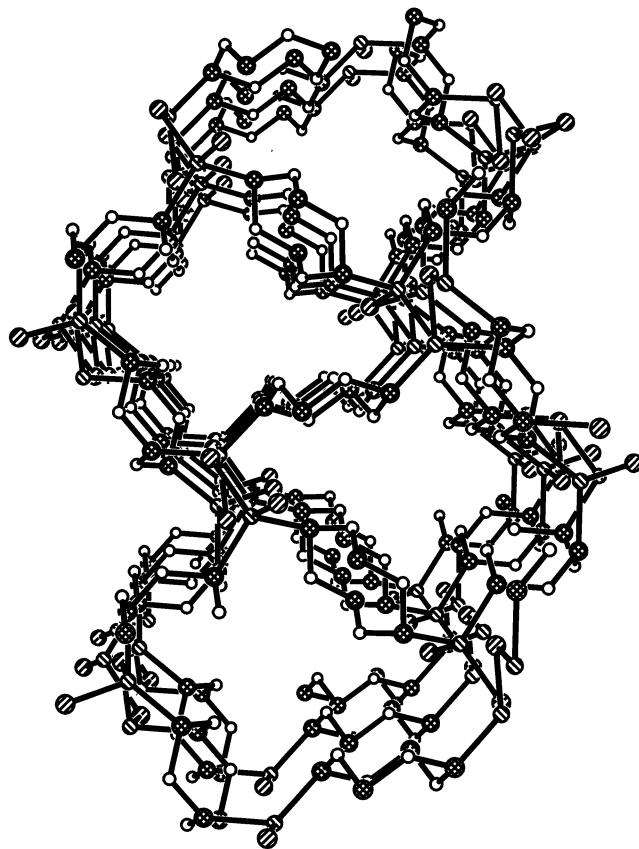


Fig. 29. The porous framework structure of  ${}^3_\infty[\text{Cu}_3\text{Br}_3\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  [40]. Methyl groups have been omitted for clarity.

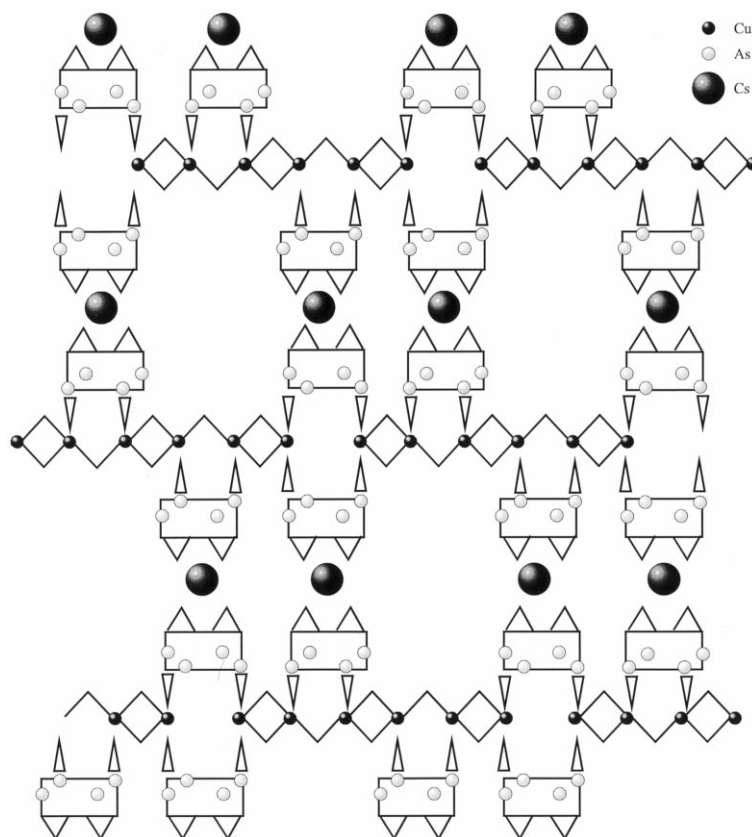


Fig. 30. A schematic diagram of the building principle of the layered structure of  $[\text{Cs}(\text{H}_2\text{O})_2][\text{Cu}_3\text{I}_4\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  [43].

tramer  $(\text{CH}_3\text{AsO})_4$  adopts a crown conformation and coordinates not only all three Cu(I) atoms of a horseshoe-like  $\text{Cu}_3\text{I}_3$  building block but also one of the  $\text{Cs}^+$  counteranions (Fig. 14), responsible for the construction of a 3-D framework.

Despite their striking diversity, all of  $(\text{CH}_3\text{AsO})_4$  bridged polymeric  $\text{CuX}$  networks listed in Table 3 can, with one exception, be assigned to either structural motif 1 or 2. The exception,  ${}^1_\infty[\{(\text{CuBr})_2(\text{CuBr}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [41], represent an intermediate product on the reaction pathway to  ${}^2_\infty[\{\text{CuBr}(\text{CuBr}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  (Fig. 21) and may be prepared in acetonitrile solution at a similar  $\text{CuBr}:(\text{CH}_3\text{AsO})_n$  molar ratio by increasing the initial rate of heating between  $20^\circ\text{C}$  and the highest reaction temperature  $100^\circ\text{C}$  from 2 to  $5^\circ\text{C h}^{-1}$ . Its chain structure is illustrated in Fig. 33 and offers an instructive insight into the self-assembly mechanisms involved in the formation of such coordination polymers. The infinite ribbons formed on initial breakdown of the  $\text{CuBr}$  structure are composed of fused chair-shaped six-membered  $\text{Cu}_3\text{Br}_3$  rings, in which individual Cu(I) atoms are coordinated by As atoms of crown-shaped

Table 3  
Copper(I) halide coordination polymers with bridging (RAsO)<sub>4</sub> cyclotetramers

| Molar ratio Cu:X:As                      | Halide X  | Motif | Dimension | CuX unit                                        | CuX type     | Terminal ligands                                 | Pillar ligands                                                           | References |
|------------------------------------------|-----------|-------|-----------|-------------------------------------------------|--------------|--------------------------------------------------|--------------------------------------------------------------------------|------------|
| <i>R</i> = CH <sub>3</sub>               |           |       |           |                                                 |              |                                                  |                                                                          |            |
| 2:2:8                                    | Cl, Br, I | 1     | 2         | (CuX) <sub>2</sub>                              | Ring         |                                                  | (CH <sub>3</sub> AsO) <sub>4</sub>                                       | [40]       |
| 3:3:8                                    | Cl, Br    | 2     | 3         | [CuX]                                           | Chain        |                                                  | (CH <sub>3</sub> AsO) <sub>4</sub>                                       | [40]       |
| 3:4:8                                    | I         | 1     | 1         | Cu <sub>6</sub> X <sub>8</sub>                  | Chain        | (CH <sub>3</sub> AsO) <sub>4</sub>               |                                                                          | [43]       |
| 2:2:4                                    | I         | 1     | 1         | (CuX) <sub>2</sub>                              | Ring         | C <sub>6</sub> H <sub>5</sub> CN                 |                                                                          | [43]       |
| 2:2:4                                    | I         | 1     | 2         | (CuX) <sub>2</sub>                              | Ring         |                                                  | <i>p</i> -NH <sub>2</sub> C <sub>6</sub> H <sub>4</sub> NH <sub>2</sub>  | [43]       |
| 2:2:4                                    | I         | 1     | 2         | (CuX) <sub>2</sub>                              | Ring         |                                                  | <i>p</i> -NH <sub>2</sub> C <sub>12</sub> H <sub>8</sub> NH <sub>2</sub> | [63]       |
| 4:4:8                                    | I         | 1     | 2         | (CuX) <sub>4</sub>                              | Tricyclic    |                                                  | (CH <sub>3</sub> AsO) <sub>4</sub>                                       | [41]       |
| 3:3:4                                    | Br, I     | 2     | 2         | <sup>1</sup> <sub>∞</sub> [CuX]                 | Chain        | CH <sub>3</sub> CN                               |                                                                          | [41]       |
| 3:4:4                                    | I         | 1     | 2         | (CuX) <sub>3</sub>                              | Chain        | (CH <sub>3</sub> AsO) <sub>4</sub>               | I                                                                        | [32]       |
| 4:4:4                                    | Br        |       | 1         | <sup>1</sup> <sub>∞</sub> [(CuX) <sub>2</sub> ] | Double chain | CH <sub>3</sub> CN                               |                                                                          | [41]       |
| 6:6:4                                    | Br        | 1     | 1         | Cu <sub>6</sub> X <sub>6</sub>                  | Tricyclic    | C <sub>6</sub> H <sub>5</sub> CN                 |                                                                          | [32]       |
| <i>R</i> = C <sub>2</sub> H <sub>5</sub> |           |       |           |                                                 |              |                                                  |                                                                          |            |
| 2:2:12                                   | Br        | 3     | 2         | CuX                                             | Monomer      |                                                  |                                                                          | [34]       |
| 4:4:12                                   | Cl        | 1     | 1         | (CuX) <sub>3</sub> CuX                          | Ring         | (C <sub>2</sub> H <sub>5</sub> AsO) <sub>4</sub> |                                                                          | [42]       |
| 3:3:8                                    | Br, I     | 1     | 2         | (CuX) <sub>2</sub>                              | Ring         | (C <sub>2</sub> H <sub>5</sub> AsO) <sub>4</sub> | (XCu) <sub>2</sub>                                                       | [34,42]    |
| 6:6:12                                   | I         |       | 2         | (CuX) <sub>2</sub> Cu                           | Ring         | (C <sub>2</sub> H <sub>5</sub> AsO) <sub>4</sub> | I                                                                        | [42]       |

(CH<sub>3</sub>AsO)<sub>4</sub> ligands. Whereas two of the crystallographically independent bromine atoms exhibit their maximal coordination of 3, the remaining two such atoms are each involved in only two Cu–Br interactions. The resulting free fourth coordination positions on two copper atoms are occupied by solvent acetonitrile molecules. Cleavage of the shared Cu–Br bonds of the fused Cu<sub>3</sub>Br<sub>3</sub> rings to afford parallel (CH<sub>3</sub>AsO)<sub>4</sub> bridged infinite  $^1_\infty$ [CuBr] ribbons and subsequent condensation of these polymeric units to layers leads to construction of  $^2_\infty$ [{CuBr(CuBr·CH<sub>3</sub>CN)<sub>2</sub>} {cyclo-(CH<sub>3</sub>AsO)<sub>4</sub>}] (motif 2) with only a limited degree of associated structural reorganisation. An alternative initial cleavage of opposite Cu–Br bonds within the individual CuBr ribbons of the original  $^1_\infty$ [Cu<sub>2</sub>Br<sub>2</sub>] double chains would generate the (CH<sub>3</sub>AsO)<sub>4</sub> linked discrete (CuBr)<sub>n</sub> units, found in the infinite  $^1_\infty$ [(CuBr)<sub>n</sub> {cyclo-(CH<sub>3</sub>AsO)<sub>4</sub>}] chains of motif 1.

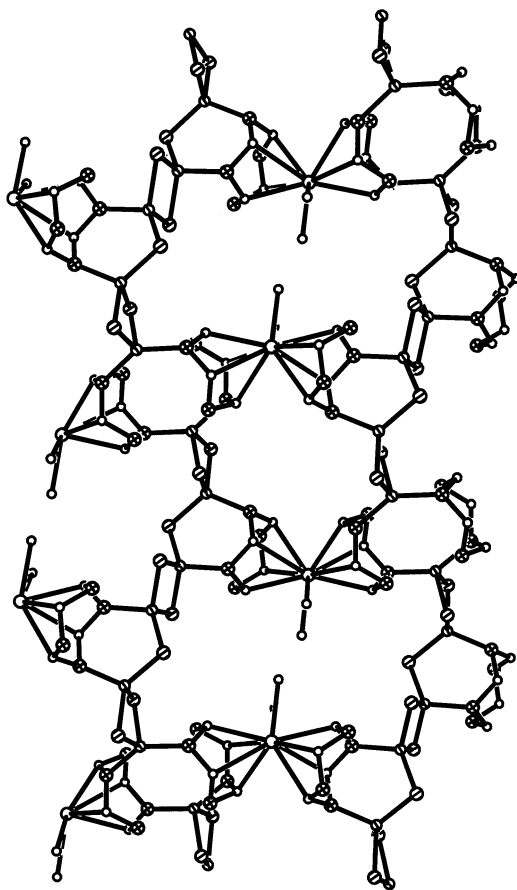


Fig. 31. Packing diagram for the anionic chains that are linked through [Cs{cyclo-(CH<sub>3</sub>AsO)<sub>4</sub>}<sub>2</sub>]<sup>+</sup> sandwiches into a porous sheet in [Cs(H<sub>2</sub>O)<sub>2</sub>][Cu<sub>3</sub>I<sub>4</sub>{cyclo-(CH<sub>3</sub>AsO)<sub>4</sub>}<sub>2</sub>] [43]. Methyl groups have been omitted for clarity.

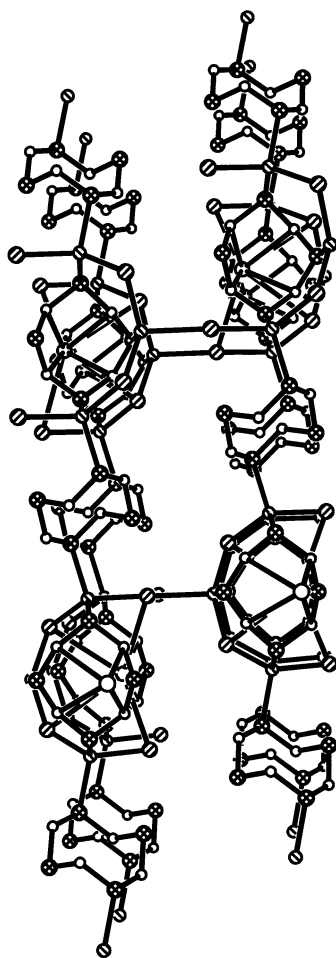


Fig. 32. The framework structure of  ${}^3_{\infty}[\{\text{Cs}[\text{cyclo}-(\text{CH}_3\text{AsO})_4]\text{Cu}_3\text{I}_4\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  [32] with methyl groups omitted for the sake of clarity.

### 2.3.3. Bridging cyclotetramers $(\text{C}_2\text{H}_5\text{AsO})_4$

The steric requirements of the hydrophobic alkyl side chains will be expected to influence the construction of  $(\text{RAsO})_4$  bridged copper(I) halides networks. It is, therefore, of interest to compare the solid-state structures for the more voluminous ethyl groups with those adapted for  $\text{R} = \text{CH}_3$ . Inspection of Table 3 indicates that far fewer coordination polymers have been characterised for the former alkyl side chain and that those that are known are all relatively CuX-poor ( $\text{CuX}:\text{As} \leq 0.5$ ).

The bulkiness of the ethyl groups allows the construction of the unique  $6^3$  nets (Fig. 22) in  ${}^2_{\infty}[\text{Cu}_2\text{Br}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  (structural motif 3) [34] in contrast to the characteristic  $4^4$  nets found in the CuX-poor complexes of the type  ${}^2_{\infty}[\text{Cu}_2\text{X}_2\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}_2]$  ( $\text{X} = \text{Cl}, \text{Br}, \text{I}$ ) (see Fig. 23) [40]. The associated

expansion of the pore size from 28 to 36 ring members on going from  $R = \text{CH}_3$  to  $R = \text{C}_2\text{H}_5$  reflects the increased steric requirements of the larger alkyl side chains, which fill the voids created by the  $\text{CuX}$  bridged arsoxane network.

Typical for  $(\text{C}_2\text{H}_5\text{AsO})_4$  coordination polymers of copper(I) halides with a  $\text{CuX}:\text{As}$  molar ratio of 0.333–0.50 is the presence of cage-like  $[\text{Cu}_3\text{X}(\text{As}_4\text{O}_4)]$  building blocks, in which three of the arsenic atoms of a crown-shaped  $(\text{AsO})_4$  ring are bridged by a  $[\text{Cu}_3(\mu_3\text{-X})]$  unit. The asymmetric unit of  ${}^1_\infty[\text{Cu}_4\text{Cl}_4\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42] with its independent crown, boat-chair and twist-chair shaped  $(\text{C}_2\text{H}_5\text{AsO})_4$  ligands (Fig. 13) was already discussed in Section 2.2.3.1. The latter heterocycles link the  $[\text{Cu}_3\text{Cl}(\text{As}_4\text{O}_4)]$  cages into the infinite chains depicted in Fig. 34 (motif 1). A similar structural motif is also present in  ${}^2_\infty[\text{Cu}_3\text{X}_3\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_2]$  ( $\text{X} = \text{Br}, \text{I}$ ) [34,42], as may be seen for  $\text{X} = \text{Br}$  in Fig. 35. However, in this case, copper(I) atoms from adjacent ribbons also participate in the shared

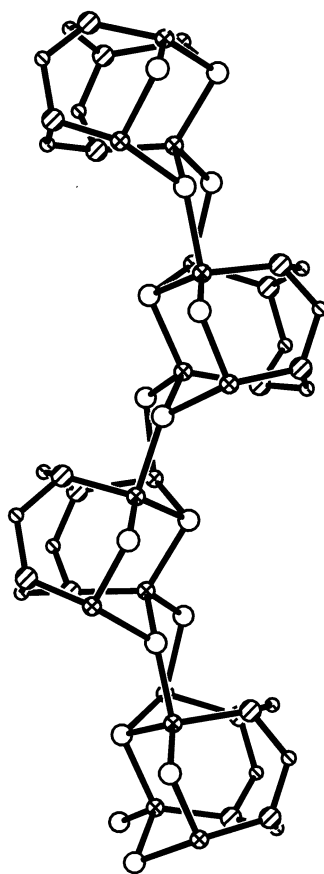


Fig. 33. The infinite chain of  ${}^1_\infty[\{(\text{CuBr})_2(\text{CuBr}\cdot\text{CH}_3\text{CN})_2\}\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  with its  $[(\text{Cu}_4\text{Br}_4)\{\text{cyclo}-(\text{CH}_3\text{AsO})_4\}]$  cages [41]. Methyl groups and coordinated acetonitrile molecules have been omitted for clarity.

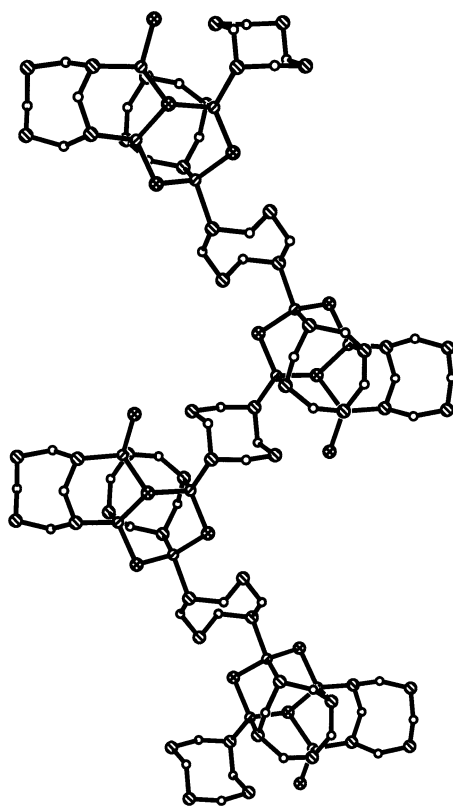


Fig. 34. The polymer chain structure of  ${}^1_{\infty}[\text{Cu}_4\text{Cl}_4\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42] in which ethyl groups have been omitted for the sake of clarity.

$(\text{CuX})_2$  rings, that function as pillars in a porous 2-D network.  $[\text{Cu}_3\text{I}(\text{As}_4\text{O}_4)]$  cages are also present in the CuX-richer complex  ${}^2_{\infty}[\text{Cu}_6\text{I}_6\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42], which once again exhibits an open lamellar structure. A central  $(\text{C}_2\text{H}_5\text{AsO})_4$  ligand joins two such cages in the  $\text{tc}4$  coordination mode to generate large  $[\text{Cu}_6\text{I}_6\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  building blocks, which corner-bridge through common iodine atoms into the  $4^4$  net illustrated in Fig. 36. The characteristic presence of relatively large oligonuclear units in the solid-state structures discussed in this Section clearly results from a screening effect of the bulky ethyl side chains.

#### 2.4. Cleavage products of $(\text{RAsO})_n$

We have studied the reaction of  $\text{K}_2\text{PtCl}_4$ ,  $\text{AgNO}_3$  or  $\text{Ag}_2\text{CO}_3$  and  $(\text{CH}_3\text{AsO})_n$  at molar ratios between 1:3:6 and 2:3:6 in acetonitrile at  $100^\circ\text{C}$  during unsuccessful attempts to stabilise the cyclooctamer  $(\text{CH}_3\text{AsO})_8$  (see Section 2.2.3.2) in the square-planar coordination sphere of Pt(II). However, two dimeric Pt(II) complexes could be isolated as red crystals in relatively low yields (13–15%) under such

conditions independent of which of the silver salts was employed [46]. To our surprise both contained novel tetradentate bridging ligands, that each result from a metal-mediated reaction between  $(\text{CH}_3\text{AsO})_n$  and acetonitrile. The structures of these products,  $[\text{Pt}_2\{\text{cyclo-}[\text{As}(\text{CH}_3)\text{OAs}\{\text{NC}(\text{O})\text{CH}_3\}\text{O}\}_2]$  and  $[\text{Pt}_2\{[\text{CH}_3\text{C}(\text{O})\text{N}]_2\text{-As}_5(\text{CH}_3)_5\text{O}_4\}_2]$  are depicted together with their respectively cyclic and acyclic anionic ligands in Figs. 37 and 38. Their Pt–As [2.387(4), 2.382(2) Å] and Pt–N distances [2.04(2), 2.03(2) Å] are very similar and both complexes contain formally trivalent arsenic atoms (As(1), As(3), As(5) and As(7) in Fig. 37, As(2) and As(4) in Fig. 38) with a trigonal bipyramidal coordination geometry, thereby providing, to our knowledge, the first examples of such an environment for As(III). These unique coordination polyhedra are completed by weak axial  $\text{O}\cdots\text{As}$  interactions between bridging ligands, e.g.  $\text{O}(32)\cdots\text{As}(5)$  and  $\text{O}(24)\cdots\text{As}(7)$  in the first complex [average distance 2.20(1) Å] and  $\text{O}(12)\cdots\text{As}(4a)$  and  $\text{O}(22)\cdots\text{As}(2a)$  in the second product [average distance 2.27(1) Å]. The opposite axial O–As bonds in the severely distorted trigonal bipyramids are, as expected, much shorter [1.83(1) and 1.82(1) Å, respectively].

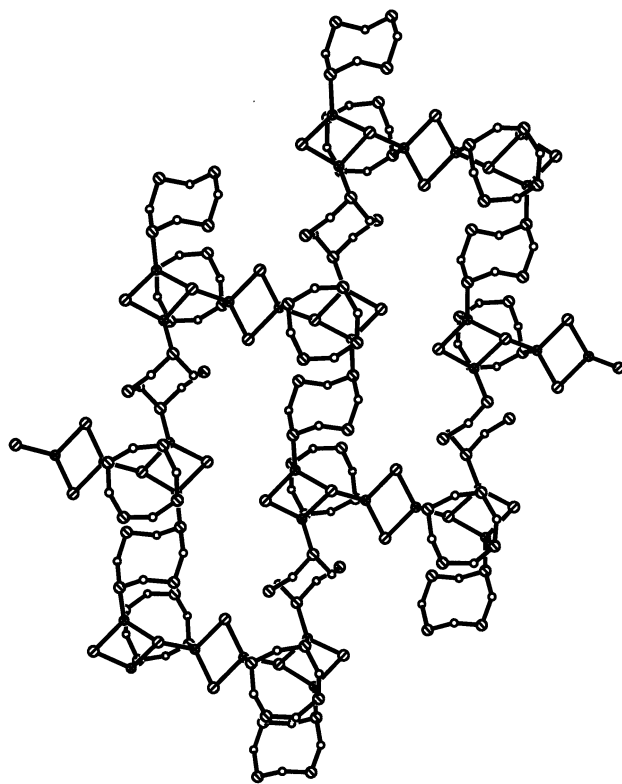


Fig. 35. The porous layer of  $2_{\infty}[\text{Cu}_3\text{Br}_3\{\text{cyclo-}(\text{C}_2\text{H}_5\text{AsO})_4\}_2]$  [42] in which  $(\text{CuBr})_2$  pillar units connect ribbons of structural motif 1. Ethyl groups have once again been omitted.

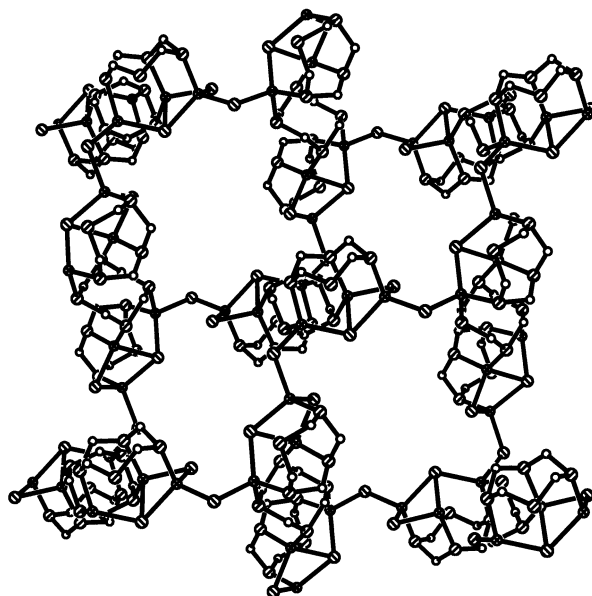


Fig. 36. The open  $4^4$  net of  ${}^2_{\infty}[\text{Cu}_6\text{I}_6\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  [42] with corner-bridged  $[\text{Cu}_6\text{I}_6\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsO})_4\}_3]$  building blocks.

As hydrolysis of alkylcycloarsoxanes is facile, solvents for these cyclic ligands must be carefully dried before use. Indeed, even the presence of water molecules of crystallisation in a starting compound can be adequate to promote the cleavage of As–C bonds. For instance,  $[\text{RhCl}_3\{\text{As}_5(\text{C}_2\text{H}_5)_2\text{O}_5(\text{OH})_2\}]$  (Fig. 39) is obtained as a minor product of the reaction between  $\text{RhCl}_3 \cdot 3\text{H}_2\text{O}$  and  $(\text{C}_2\text{H}_5\text{AsO})_n$  in acetone [66]. Interestingly this compound contains a six-membered  $(\text{AsO})_3$  ring, i.e. of a size not found in complexes of the parent cycloarsoxane.

### 3. Coordination chemistry of organylcycloarsathianes

#### 3.1. Preparation and structure of $(\text{RAsS})_n$

As summarised by Tzschach and Heinicke in their book on heterocyclic arsenic compounds [20], organylcycloarsathianes  $(\text{RAsS})_n$  are generally obtained by either (a) treatment of  $\text{RAsX}_2$  ( $\text{X} = \text{Cl}, \text{Br}$ ) with  $\text{H}_2\text{S}$  or sulphides [15], (b) oxidation of primary arsines with sulphur [67] or (c) reaction of arsines with  $\text{SOCl}_2$  [68] or  $\text{PhNSO}$  [16]. Organylcycloarsoxanes  $(\text{RAsO})_n$  can be converted to their sulphur analogues by treatment with  $\text{H}_2\text{S}$  [3,12].

Molecular weight and  $^1\text{H}$ -NMR studies indicate that cyclotrimers  $(\text{RAsS})_3$  and cyclotetramers  $(\text{RAsS})_4$  clearly predominate in organic solutions of alkylcycloarsathianes [12,15–17]. DiMaio and Rheingold [18] were successful in separating

these cyclic oligomers for  $R = CH_3$  both in solution by column chromatography with alumina and in the solid state by microscopic selection of crystals on the basis of their different morphologies. The respectively chair and crown conformations of the alternating As–S rings in  $(CH_3AsS)_3$  and  $(CH_3AsS)_4$  are depicted in Fig. 40. Whereas the average As–S distances [2.258 (1), 2.249 (5) Å] and S–As–S angles [101.4 (2), 102.5 (7)°] are similar in both cyclic oligomers, a marked widening of the average As–S–As angle from 93.8 (2) to 98.2 (7)° is apparent on going from the chair to the crown conformation. The latter structure has also been established for the tetramers  $(C_2H_5AsS)_4$  [12],  $(t-C_4H_9AsS)_4$  [13] and  $(PhAsS)_4$  [14] in the solid state.

### 3.2. Coordination properties of $(C_2H_5AsS)_4$

Both S and As are potential soft donor atoms for transition and coinage metals M in their lower oxidation states. Employing average metrical parameters from the solid state structures of  $(CH_3AsS)_4$  and  $(C_2H_5AsS)_4$ , Fig. 41 illustrates the dependence of As–M–As and S–M–S angles in hypothetical four-membered chelate

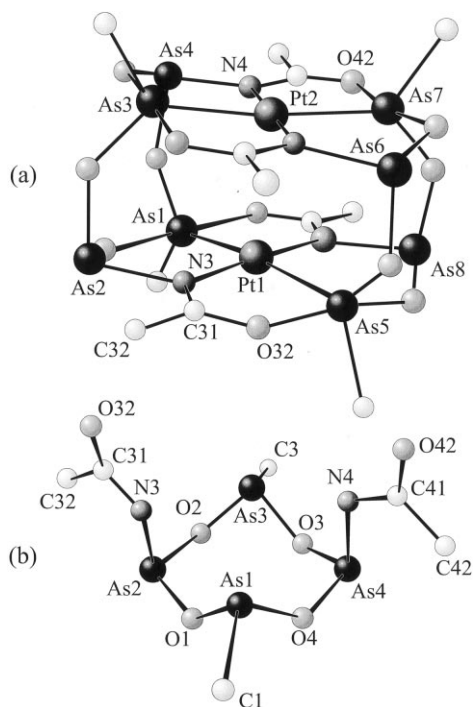
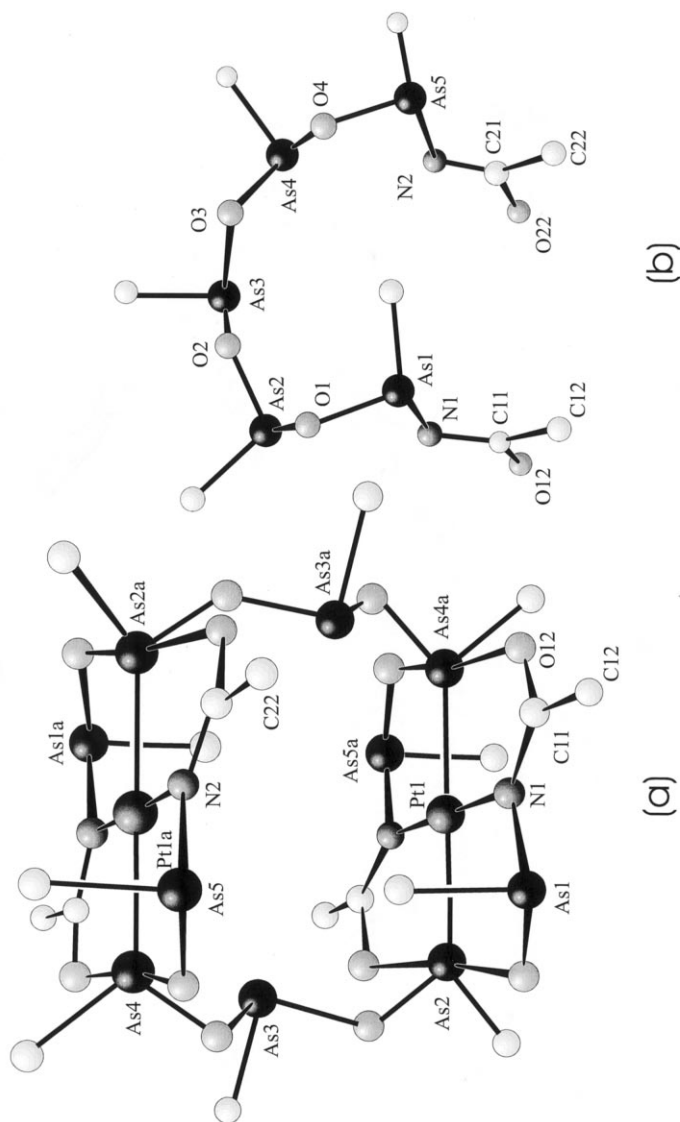


Fig. 37. (a) Molecular structure of  $[Pt_2\{cyclo-[As(CH_3)OAs\{NC(O)CH_3\}O]_2\}_2]$  prepared by reaction of  $K_2PtCl_4$ ,  $AgNO_3$  and  $(CH_3AsO)_n$  in acetonitrile at 100°C. (b) Structure of the cyclic ligand  $[cyclo-\{As(CH_3)OAs\{NC(O)CH_3\}O\}_2]^{2-}$  formed by the reaction of  $(CH_3AsO)_n$  with  $CH_3CN$  under these conditions [46].



(b)

(a)

Fig. 38. (a) Molecular structure of  $[\text{Pt}_2\{[\text{CH}_3\text{C}(\text{O})\text{N}]_2\text{As}_5(\text{CH}_3)_5\text{O}_4\}_2]$ , the product of the reaction between  $\text{K}_3\text{PtCl}_4$ ,  $\text{Ag}_2\text{CO}_3$  and  $(\text{CH}_3\text{AsO})_n$  in  $\text{CH}_3\text{CN}$  at  $100^\circ\text{C}$ . (b) Structure of the acyclic ligand  $[\{\text{CH}_3\text{C}(\text{O})\text{N}\}_2\text{As}_5(\text{CH}_3)_5\text{O}_4\}]^{2-}$  formed under such conditions [46].

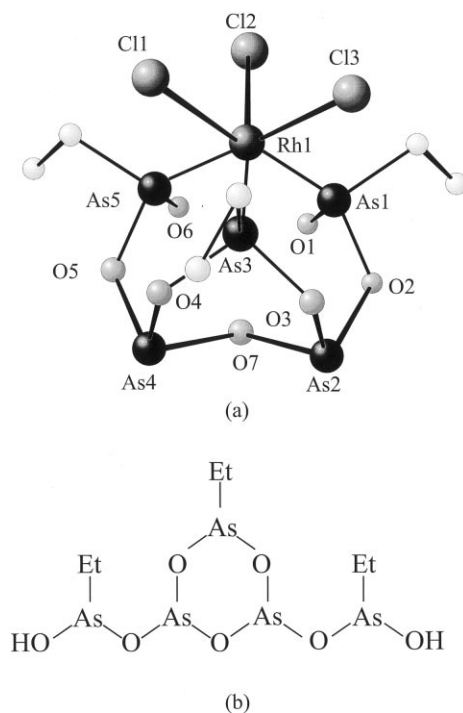


Fig. 39. (a) Molecular structure of  $[\text{RhCl}_3\{\text{As}_5(\text{C}_2\text{H}_5)_2\text{O}_5(\text{OH})_2\}]$ , a minor product of the reaction of  $\text{RhCl}_3 \cdot 3\text{H}_2\text{O}$  and  $(\text{C}_2\text{H}_5\text{AsO})_n$  in acetone. (b) Structure of the cyclic ligand  $[\text{As}_5(\text{C}_2\text{H}_5)_2\text{O}_5(\text{OH})_2]$  formed by hydrolysis of  $(\text{C}_2\text{H}_5\text{AsO})_n$  under these conditions [66].

rings on  $d(\text{As}-\text{M})$  or  $d(\text{S}-\text{M})$ . For typical  $\text{As}-\text{M}$  or  $\text{S}-\text{M}$  distances in the range 2.20–2.55 Å, both  $\kappa^2\text{As}^1$ ,  $\text{As}^2$  and  $\kappa^2\text{S}^1$ ,  $\text{S}^2$  chelation in octahedral metal coordination spheres should be possible for the preferred crown conformation of tetrameric alkylcycloarsathianes. In contrast, Fig. 41 indicates that severe narrowing of the  $\text{As}-\text{M}-\text{As}$  or  $\text{S}-\text{M}-\text{S}$  angles from the ideal tetrahedral value would be required to allow the adoption of this binding mode by a  $\text{Cu}(\text{I})$  or  $\text{Ag}(\text{I})$  atom with a coordination number of 4.  $\kappa^2\text{As}^1$ ,  $\text{As}^3$  or  $\kappa^2\text{S}^1$ ,  $\text{S}^3$  chelation by opposite  $\text{As}/\text{S}$  atoms in the eight-membered  $(\text{AsS})_4$  ring of tetrameric alkylcycloarsathianes will, therefore, be expected in a tetrahedral metal coordination sphere.

Our recent structural studies on complexes of  $(\text{C}_2\text{H}_5\text{AsS})_4$  have confirmed these prognostications. For instance, the  $\text{Cu}(\text{I})$  atom in  $[\text{Cu}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}_2]\text{CF}_3\text{SO}_3$  [69] is indeed coordinated in the predicted  $\kappa^2\text{S}^1$ ,  $\text{S}^3$  fashion by two tetrameric ethylcycloarsathiane ligands, both of which exhibit a boat-chair conformation (Fig. 42a). The  $\text{Cu}-\text{S}$  distances in the complex cation lie in the range 2.283(6)–2.340(6) Å and the endocyclic  $\text{S}-\text{Cu}-\text{S}$  angles of 112.6(2) and 114.4(2)° are close to the ideal tetrahedral value. When only the shorter  $\text{Ag}-\text{S}1$  and  $\text{Ag}-\text{S}3$  distances of 2.767(5) and 2.716(7) Å are taken into account, a similar  $\kappa^2\text{S}^1$ ,  $\text{S}^3$  chelation mode can be discerned for the  $(\text{C}_2\text{H}_5\text{AsS})_4$  ligands in  $[\text{Ag}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}_2]\text{CF}_3\text{SO}_3$  [12], the

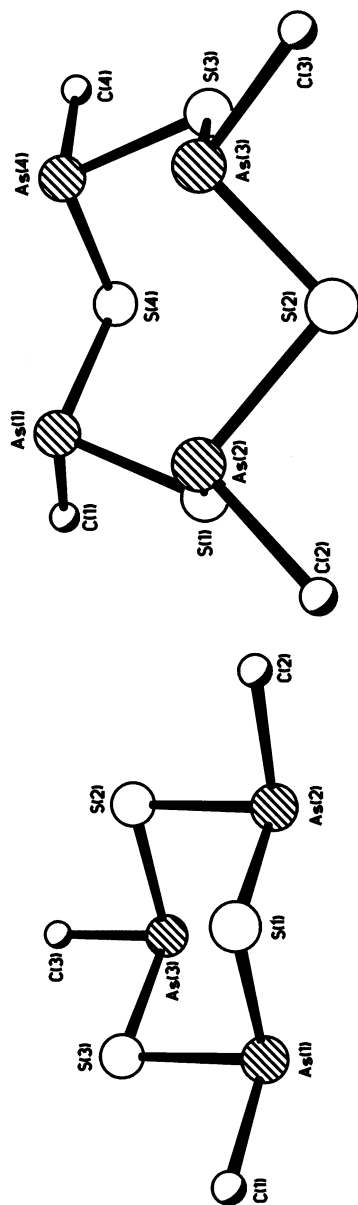


Fig. 40. Chair conformation of  $(\text{CH}_3\text{AsS})_3$  and crown conformation of  $(\text{CH}_3\text{AsS})_4$  in the solid state [18].

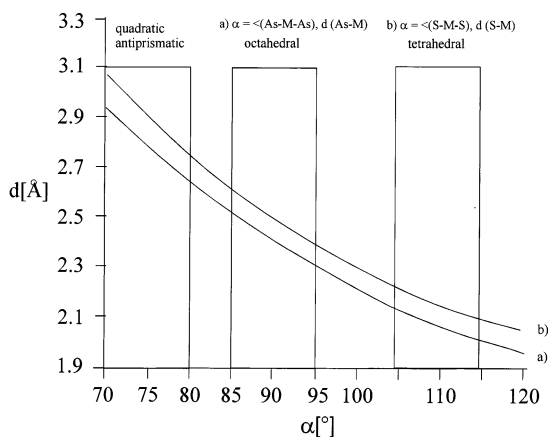


Fig. 41. Dependence of As–M–As (M = metal atom) and S–M–S angles, respectively, on (a) As–M or (b) S–M distances in four-membered chelate rings. The following average values from  $(\text{CH}_3\text{AsS})_4$  [18] and  $(\text{C}_2\text{H}_5\text{AsS})_4$  [12] were employed:  $d(\text{As–S}) = 2.25 \text{ \AA}$ ,  $\angle(\text{As–S–As}) = 97.4^\circ$ ,  $\angle(\text{S–As–S}) = 102.9^\circ$ .

complex cation of which displays crystallographic  $C_2$  symmetry (Fig. 42b). However, the remaining sulphur atoms S2 and S4 of the crown shaped heterocycle also participate in the coordination sphere of the Ag(I) cation through longer Ag–S interactions of 3.328(9) and 3.218(6) Å. Whereas the As atoms in the  $(\text{AsS})_4$  ring are close to being coplanar ( $\pm 0.043 \text{ \AA}$ ), larger deviations of  $\pm 0.132 \text{ \AA}$  from a best least-squares plane are necessary for the four sulphur atoms in order to accommodate the alternating short and long As–S bonds. It is instructive to compare the coordination geometry of the silver cations in  $[\text{Ag}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}_2]\text{CF}_3\text{SO}_3$  with

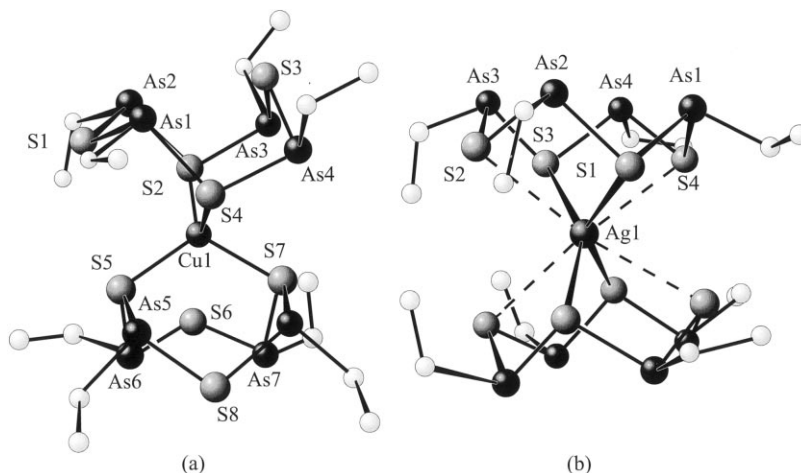


Fig. 42. Molecular structures of the cations of (a)  $[\text{Cu}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}_2]\text{CF}_3\text{SO}_3$  [69] and (b)  $[\text{Ag}\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}_2]\text{CF}_3\text{SO}_3$  [12].

that of an idealised quadratic antiprism. If one defines the centres of the  $S_4$  planes of the cycloarsathiane rings as respectively Pl and Pl', then the observed torsion angles S–Pl–Pl'–S' exhibit alternating average values of  $41.6(5)$  and  $-48.4(4)^\circ$ , i.e. in comparison to the expected value of  $45^\circ$  for a quadratic antiprism, the coordination polyhedron in the complex cation displays an 8% distortion towards a cube. All four independent S–Ag–Pl angles lie in the narrow range  $52.7$ – $56.0^\circ$  and are, therefore, relatively close to the characteristic  $\alpha$  value of  $57^\circ$  found in transition metal complexes  $ML_8$  [38]. A more pronounced longitudinal distortion is observed in the ethylcycloarsoxane complex  $[Na\{cyclo-(C_2H_5AsO)_4\}_2]^+$ , with its average  $\alpha$  value of only  $47.2^\circ$  [32].

Both of the above complexes contain the tetrameric ligand  $(C_2H_5AsS)_4$ , as do  $[cyclo-(C_2H_5AsS)_4] \cdot 2SbBr_3$  [12] and  $[RuCl_2\{cyclo-(C_2H_5AsS)_4\}(Ph_3P)]$  [70]. Despite its presence in solution [12], no examples are known in which the competitive cyclotrimer  $(C_2H_5AsS)_3$  is stabilised in the coordination sphere of a metal atom. Interestingly  $[9]aneS_3$  has been found to be capable of enforcing an elongated octahedral geometry with average chelating S–Ag–S' angles of  $80^\circ$  on the Ag(I) cation in  $[Ag([9]aneS_3)_2]^+$  [71]. An analogous facial  $\kappa^3S$  coordination mode has also been established for this macrocyclic thioether in  $[9]aneS_3 \cdot SbI_3$  [72], whose chelating S–Ag–S' angles in the range  $74.0$ – $74.8^\circ$  are even narrower than those in  $[Ag([9]aneS_3)_2]^+$ . In contrast, only one of the four potential S donor atoms in  $(C_2H_5AsS)_4$  is involved in antimony coordination in polymeric  $[cyclo-(C_2H_5AsS)_4] \cdot 2SbBr_3$  [12]. An explanation for the reluctance of  $(C_2H_5AsS)_3$  to participate in complex formation may be sought in the shortness of its intramolecular S...S distances, which would lead to unfavourably small S–Ag–S or S–Sb–S angles of bite in hypothetical compounds such as  $[Ag\{cyclo-(C_2H_5AsS)_3\}_2] CF_3SO_3$  or  $[cyclo-(C_2H_5AsS)_3] \cdot SbBr_3$ .

The molecular structure of  $[RuCl_2\{cyclo-(C_2H_5AsS)_4\}(Ph_3P)]$  [70] is depicted in Fig. 43. This OC-6-43 stereoisomer, in which  $(C_2H_5AsS)_4$  exhibits a facial  $\kappa^3As$  coordination mode, may be isolated as a red crystalline product by covering an equimolar  $[RuCl_2(Ph_3P)_3]/(C_2H_5AsS)_n$  ( $n = 4$ ) reaction mixture in  $CH_2Cl_2$  with hexane at room temperature. However a  $^{31}P$ -NMR spectrum of the reaction solution after 12 h contains no less than 11 resonances in the range  $\delta = 18.91$ – $64.06$ , thereby indicating the presence of further geometrical or linkage isomers [e.g.  $\kappa^3As^1$ ,  $S^2$ ,  $As^4$  or  $\kappa^3As^1$ ,  $As^2$ ,  $S^3$ ]. The isolated complex (Fig. 43) confirms that  $\kappa^2As^1$ ,  $As^2$  four-membered chelate rings are possible for  $(C_2H_5AsS)_4$  in an octahedral coordination sphere.

### 3.3. Metal-assisted assembly of chain and macrocyclic As–S ligands

DiMaio and Rheingold isolated the molybdenum carbonyl complex  $[Mo(CO)_3\{(CH_3)_6As_6S_3\}]$ , with a nine-membered partially sulphurated arsenic ring, as a by-product of the reaction between  $(CH_3As)_5$  and  $S_8$  in the presence of toluene at  $125^\circ C$  [18].  $Mo(CO)_6$  mediation apparently facilitates the formation of a mixture of the cyclic oligomers  $(CH_3AsS)_3$  and  $(CH_3AsS)_4$  as the major products of this reaction. The same authors also reported the preparation of a novel

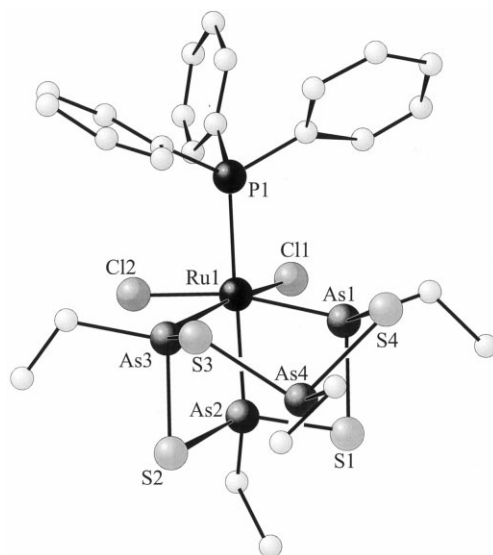


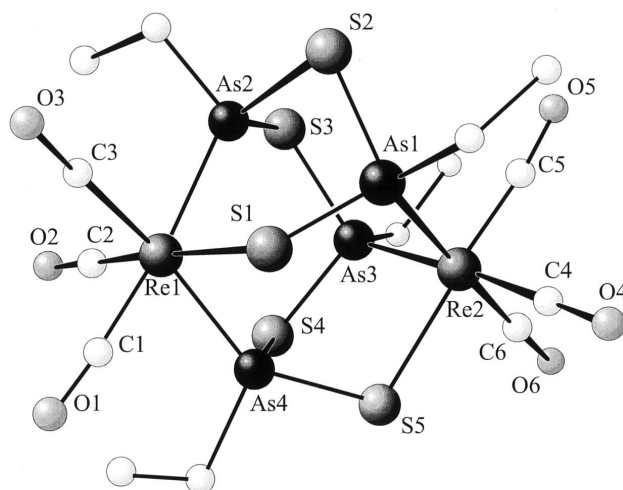
Fig. 43. Molecular structure of  $[\text{RuCl}_2\{\text{cyclo}-(\text{C}_2\text{H}_5\text{AsS})_4\}(\text{Ph}_3\text{P})]$  [70].

tripledecker sandwich  $[(\text{CpMo})_2(\mu\text{-As}_3)(\mu\text{-AsS})]$  by treating  $[\{\text{MoCp}(\text{CO})_3\}_2]$  with  $(\text{CH}_3\text{AsS})_n$  in toluene in a Carius tube at the same temperature [18]. However, no evidence was found for the formation of coordinated intact  $(\text{CH}_3\text{AsS})_n$  with either the  $\text{Mo}(\text{CO})_3$  or  $\text{MoCp}$  fragment, suggesting that a metal-assisted ring expansion may well be less facile for cycloarsathianes than for cycloarsoxanes and that As–S bond cleavage followed by reassembly into new ligands in the coordination sphere of transition metals can be expected at elevated temperature.

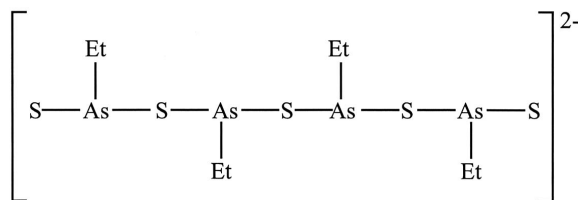
A further example of such a metal-mediated reassembly process is provided by the reaction of  $[\text{ReBr}(\text{CO})_5]$  with  $(\text{C}_2\text{H}_5\text{AsS})_n$  in toluene at reflux, which leads to the formation of the novel chain anion  $[(\text{C}_2\text{H}_5)_4\text{As}_4\text{S}_5]^{2-}$  as a bridging hexadentate ligand in the dinuclear complex  $[\{\text{Re}(\text{CO})_3\}_2\{\mu\text{-(C}_2\text{H}_5)_4\text{As}_4\text{S}_5\}]$  [70]. A possible reaction mechanism would involve an initial bidentate coordination of each of the Re atoms by alternating As atoms of an intact cyclotetramer  $(\text{C}_2\text{H}_5\text{AsS})_4$ , followed by nucleophilic attack of  $\text{S}^{2-}$  on As(1) or As(4) in Fig. 44. The driving force for the formation of this dirhenium compound is presumably provided by the stability of the resulting Re–S(thiolate) bonds. Kekia and Rheingold have very recently prepared the metallacycle complexes  $[\text{Cp}_2\text{M}(\text{–SCH}_3\text{AsSCH}_3\text{AsS–})]$  ( $\text{M} = \text{Ti}, \text{Zr}, \text{Hf}$ ) and  $[\text{Cp}_2\text{Zr}(\text{–SCH}_3\text{AsS–})]$  with analogous though shorter chain anions by reacting the sodium-reduced form of methylcycloarsathiane with Group 4 metallocene dichlorides [73].

Metal-mediated assembly of novel macrocyclic As–S ligands has been studied in our research group [70]. Reaction of  $\text{MCl}_3$  ( $\text{M} = \text{Ru}, \text{Os}$ ) with  $(\text{C}_2\text{H}_5\text{AsS})_n$  in toluene in a Carius tube at respectively 105°C (24 h) and 140°C (70 h) leads to formation of  $[\text{M}\{\text{cyclo}-(\text{C}_2\text{H}_5)_6\text{As}_8\text{S}_{10}\}]$ , whose 16-membered hexadentate As–S

ring system is depicted in Fig. 45. Bond angles in the range  $80.5(2)$ – $101.2(1)^\circ$  are observed for the distorted octahedral coordination sphere of the central osmium atom in  $[\text{Os}\{\text{cyclo}-(\text{C}_2\text{H}_5)_6\text{As}_8\text{S}_{10}\}]$ . The reduction of M(III) to M(II) ( $\text{M} = \text{Ru}, \text{Os}$ ) required for the preparation of these isostructural complexes poses the question as to the nature of the accompanying oxidation. It seems reasonable to assume that S–S bond formation will be involved and this hypothesis is, at least, partially substantiated by the isolation of a second Ru(II) complex,  $[\text{Ru}\{\text{cyclo}-(\text{C}_2\text{H}_5)_4\text{As}_6\text{S}_{10}\}]$  (Fig. 46) by employment of a longer reaction time (70 h) at higher temperature ( $140^\circ\text{C}$ ). An analogous Os(II) complex could not be isolated, even at considerably higher temperature ( $200^\circ\text{C}$ ). The novel 14-membered ring of the hexadentate ligand  $[(\text{C}_2\text{H}_5)_4\text{As}_6\text{S}_{10}]^{2-}$  exhibits crystallographic  $C_{2h}$  symmetry and contains two S–S bonds. The thiolate sulphur atoms S1/S1a are now sited *trans* to one another and the novel macrocycle is effectively perfectly dimensioned for octahedral coordination of Ru(II), as evidenced by the similar Ru–As and Ru–S



(a)



(b)

Fig. 44. Molecular structure of  $[\{\text{Re}(\text{CO})_3\}_2\{\mu-(\text{C}_2\text{H}_5)_4\text{As}_4\text{S}_5\}]$  [70].

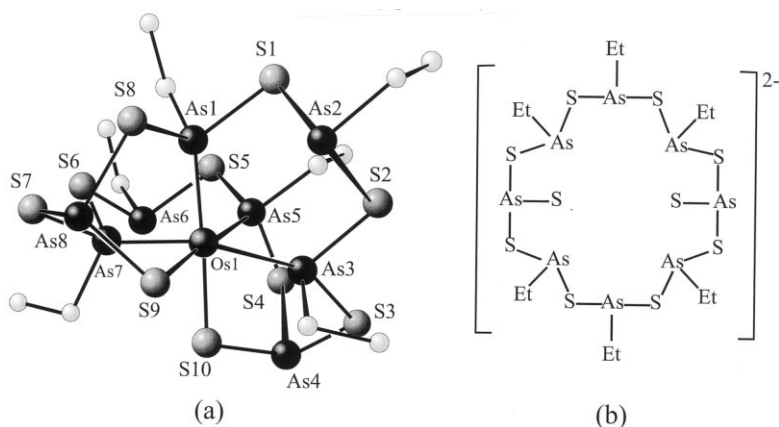


Fig. 45. (a) Molecular structure of [Os{*cyclo*-(C<sub>2</sub>H<sub>5</sub>)<sub>6</sub>As<sub>8</sub>S<sub>10</sub>}] prepared by reaction of OsCl<sub>3</sub> and (C<sub>2</sub>H<sub>5</sub>AsS)<sub>*n*</sub> in toluene for 70 h at 140°C. (b) Structure of the macrocyclic ligand [(C<sub>2</sub>H<sub>5</sub>)<sub>6</sub>As<sub>8</sub>S<sub>10</sub>]<sup>2-</sup> formed under these conditions [70].

distances [2.391(2), 2.378(6) Å] and the very minor deviations [88.7(1)–91.3(1)°] from the ideal octahedral angle. This finding is in accordance with the assumed increased thermodynamic stability of [Ru{*cyclo*-(C<sub>2</sub>H<sub>5</sub>)<sub>4</sub>As<sub>6</sub>S<sub>10</sub>}] in comparison to [Ru{*cyclo*-(C<sub>2</sub>H<sub>5</sub>)<sub>6</sub>As<sub>8</sub>S<sub>10</sub>}], which can be presumed to be an intermediate product on the reaction pathway to the former complex.

#### 4. Summary and outlook

Alkylcycloarsoxanes (RAsO)<sub>*n*</sub> (R = CH<sub>3</sub>, C<sub>2</sub>H<sub>5</sub>) are multidentate ligands capable of coordinating either hard or soft metal fragments in respectively in  $\kappa^n O$  or  $\kappa As-\kappa^4 As$  modes. They are characterised by their unique ability to undergo metal-mediated ring expansion to *n* = 4, 5, 6 or 8 and by their remarkable conformational flexibility. Furthermore, our recent studies presented in this review article indicate that their cyclotetramers (RAsO)<sub>4</sub> exhibit considerable potential as  $\kappa^2 As^1$ ,  $As^3$  linking macrocycles for the construction of novel multifunctional coordination networks with an ability to host a variety of guests such as alkali cations or polar organic molecules (e.g. CH<sub>3</sub>OH, CH<sub>3</sub>CN, C<sub>6</sub>H<sub>5</sub>CN). The combination of these ion ligating (AsO)<sub>4</sub> heterocycles and rigid aromatic ligands as spacers between metal coordination polyhedra in flexible porous sheet or framework polymers is particularly promising.

Intact tetrameric alkylcycloarsathianes (RAsS)<sub>4</sub> can be stabilised in the coordination sphere of coinage or transition metals under mild conditions and should be capable of enforcing unusual coordination geometries, e.g. the quadratic antiprismatic environment of the silver(I) cations in [Ag{*cyclo*-(C<sub>2</sub>H<sub>5</sub>AsS)<sub>4</sub>}<sub>2</sub>]<sup>+</sup>. At elevated

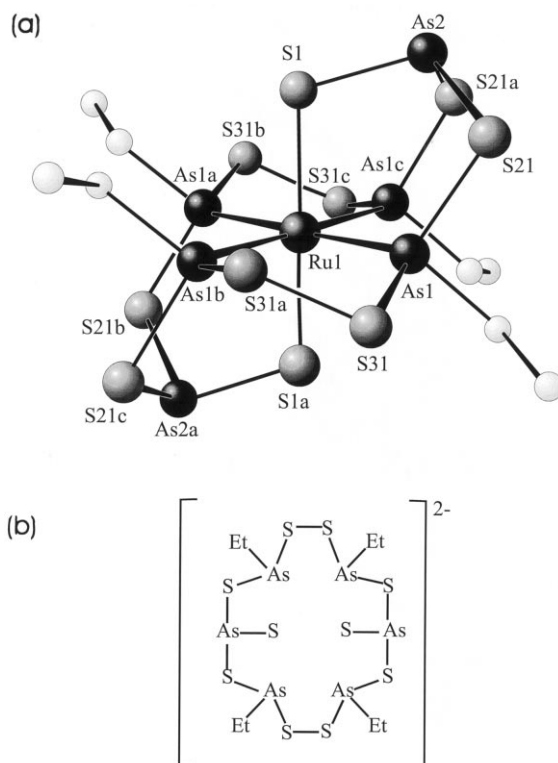


Fig. 46. (a) Molecular structure of [Ru{cyclo-(C<sub>2</sub>H<sub>5</sub>)<sub>4</sub>As<sub>6</sub>S<sub>10</sub>}] prepared by reaction of RuCl<sub>3</sub> and (C<sub>2</sub>H<sub>5</sub>AsS)<sub>n</sub> for 70 h at 140°C. (b) Structure of the macrocyclic ligand [(C<sub>2</sub>H<sub>5</sub>)<sub>4</sub>As<sub>6</sub>S<sub>10</sub>]<sup>2-</sup> assembled in the octahedral Ru(II) coordination sphere [70].

temperatures, As–S bond cleavage and metal-assisted reassembly can afford novel chainlike and macrocyclic ligands that are tailored for the coordination of the structure directing metal atom.

After submission of this article, Keki and Rheingold [74] have reported the preparation of [Cr{cyclo-(CH<sub>3</sub>AsS)<sub>4</sub>}(CO)<sub>5</sub>], [Cr{cyclo-(CH<sub>3</sub>AsS)<sub>5</sub>}(CO)<sub>3</sub>] and [W{cyclo-(CH<sub>3</sub>AsS)<sub>6</sub>}(CO)<sub>3</sub>] by photolysis of (CH<sub>3</sub>AsS)<sub>n</sub> with Group 6 carbonyls M(CO)<sub>6</sub> [M = Cr, W] in THF.

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The authors would particularly like to express their thanks to Dr. Thomas Häusler whose pioneering studies (1992–1995) on the coordination properties of (C<sub>2</sub>H<sub>5</sub>AsO)<sub>n</sub> and (C<sub>2</sub>H<sub>5</sub>AsS)<sub>n</sub> are discussed in detail in this review article.

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