Stereochemistry of Cyclic Organophosphorus Compounds. Part 13.[1] Stereoisomerism in Bis-(4-methyl-2-thioxo-1,3,2-dioxaphosphorinan-2-yl) Oxide. Synthesis of Diastereoisomers and their Solution and Solid State Conformations

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Bis-(4-methyl-2-thioxo-1,3,2-dioxaphosphorinan-2-yl) oxide (4) has been found to exist in six diastereoisomeric forms [*cis-trans-*, *trans-trans-*, and *cis-cis-*(4a) and -(4b)] differing both in configuration at the phosphorus atoms and in the relative positions of the methyl groups on C(4) on the two 1,3,2-dioxaphosphorinan rings A and B. All diastereoisomers of (4) have been characterised by ^{1}H n.m.r., ^{31}P n.m.r., and i.r. spectroscopy. Single-crystal *X*-ray analysis of the *trans-trans-*(4a) isomer revealed that one 1,3,2-dioxaphosphorinan ring adopts a strongly flattened chair conformation with an axial methyl group on C(4); an *X*-ray analysis of the *cis-cis-*(4a) isomer shows it to have a conformation with both sulphur atoms and both methyl groups in equatorial positions relative to the 1,3,2-dioxaphosphorinan rings. The conformation of all diastereoisomers of (4) in solution is discussed and the stereochemistry of bis-(4-methyl-1,3,2-dioxaphosphorinan-2-yl) oxide (5) is briefly considered.

The discovery of cyclic organophosphorus systems in biologically active substances as well as their participation in a number of important biological processes stimulated extensive research concerning the synthesis and stereochemistry of heterocyclic organophosphorus compounds. Among these, 1,3,2-dioxaphosphorinan systems have attracted special attention. The stereochemical aspects of this class of compounds are exhaustively discussed by Maryanoff *et al.*[2] in an excellent review.

Until now, however, studies on compounds containing two 1,3,2-dioxaphosphorinan units in one molecule have been rare. Recent determinations of the crystal and molecular structures of bis-(5,5-dimethyl-2-oxo-1,3,2-dioxaphosphorinan-2-yl) oxide (1a)[3] and the corresponding sulphide (1b),[4] in which there are no chiral centres at phosphorus or carbon, revealed that the phosphoryl groups in both chair-like 1,3,2-dioxaphosphorinan rings of (1a and b) are equatorial whereas the bridging oxygen and sulphur atoms are axial. Thus, the configuration at phosphorus in both six-membered rings of (1a and b) is determined by the well established conformational preferences of the phosphorus substituents in these systems.

As a consequence of our previous studies on cyclic *cis-* and *trans-*thioacids (2)[5] and on the stereochemistry of nucleophilic substitution at phosphorus in cyclic, diastereoisomeric thiophosphoryl halogenides (3)[6,7] our attention was directed toward the bicyclic dithiopyrophosphate, bis-(4-methyl-2-thioxo-1,3,2-dioxaphosphorinan-2-yl) oxide (4).

Although dithiopyrophosphate (4) was obtained by Arbuzov[8] by the addition of sulphur to pyrophosphite (5), its stereochemistry was not discussed. It is noteworthy that, in contrast to the achiral compounds (1a and b), dithiopyrophosphate (4) has four chiral centres and should exist in a number of diastereoisomeric forms. In this paper we report the syntheses of the diastereoisomers of (4) and the elucidation of their conformation by n.m.r. spectra and *X*-ray crystallography. A brief discussion of the stereochemistry of the bicyclic pyrophosphite (5) is also given.

Results and Discussion

In view of the fact that phosphorylation of the phosphorus monothioacid anion occurs exclusively at the oxygen atom[9] we decided to prepare the diastereoisomeric forms of (4) by condensing the readily available tetramethylammonium salts of the *cis-* and *trans-*thioacids (2)[5] with the cyclic chloride (3a)[6,†] or bromide (3b)[6] having the appropriate configuration at chiral phosphorus.

However, before presenting the experimental results obtained it seems desirable to define first the number of diastereoisomers of (4). This may be conveniently done using the Cahn–Ingold–Prelog *R* and *S* notation for the absolute configuration at the chiral phosphorus and C(4) carbon atoms in (4) and basing discussion on the mode of synthesis.‡ For this reason it is convenient to specify the enantiomeric forms of the starting thioacids (2) and halogenides (3) as shown in Scheme 1.

For the sake of simplicity let us assume in this preliminary discussion that both 1,3,2-dioxaphosphorinan rings in (4) adopt a chair conformation and that the methyl groups on C(4) are equatorially situated.

Scheme 2 shows the six possible diastereoisomers of (4) and the mode of their synthesis. Thus, in the (4a) series *c*A (or *t*A) condenses with *c*H* or *t*H*, whereas in series (4b) they do so with *c*H or *t*H. With regard to the notation used in Scheme 2 three comments should be made. The first is that ring A comes from the acid and ring B from the halide. Secondly, the suffix is attached to *c*H or *t*H to indicate the inversion at phosphorus that should take place on condensation as a consequence of nucleophilic attack by the thioacid anion.[6] Finally, only one enantiomer of a racemic pair is shown for each isomer depic-

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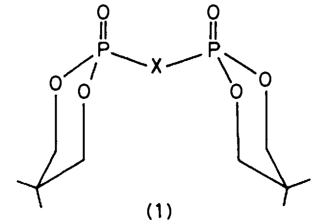
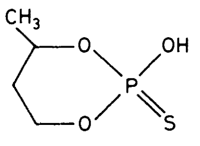
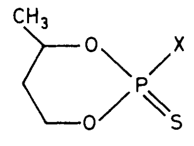
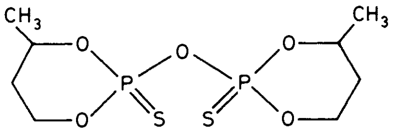
† *cis*-2-Chloro-4-methyl-2-thioxo-1,3,2-dioxaphosphorinan (3a) having 80% diastereoisomeric purity was obtained from the reaction between *cis*-thioacid (2) and phosphorus pentachloride. The reaction afforded also dithiopyrophosphate *cis-trans-*(4a + b) (M. Mikolajczyk and B. Ziemnicka, unpublished results).

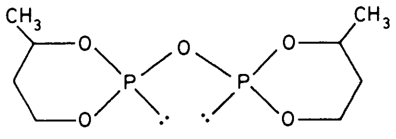
‡ We thank a referee for this suggestion.

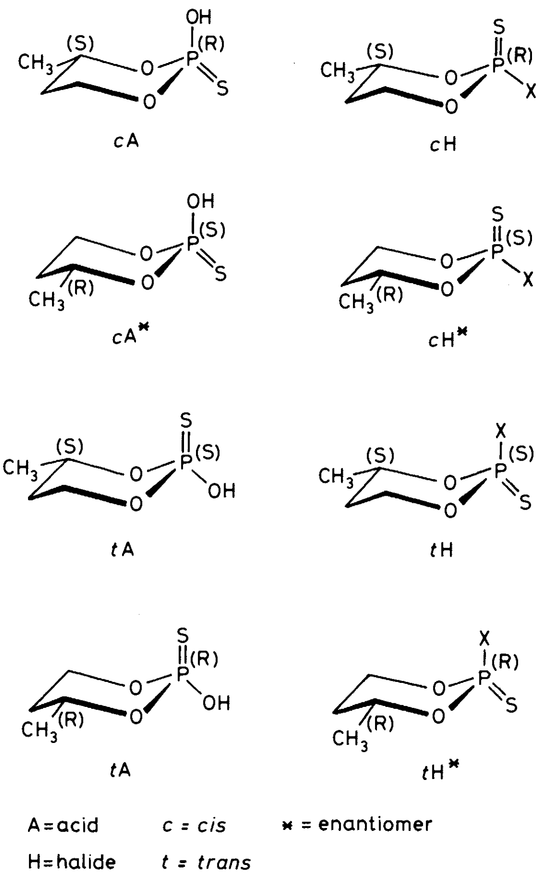

(1)
a; X = O
b; X = S


(2)


(3) a; X = Cl
b; X = Br
c; X = F


(4)


(5)



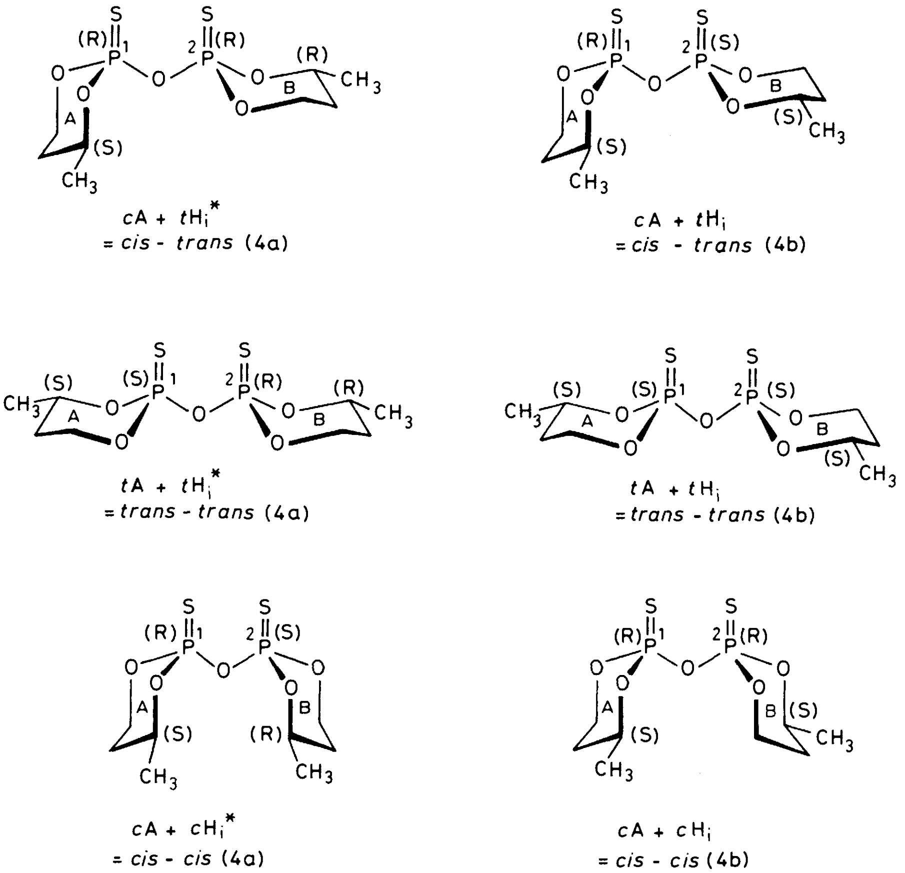
Scheme 1. Enantiomeric forms of starting materials and nomenclature

ted in Scheme 2 except of *trans-trans*-(4a) and *cis-cis*-(4a) which are achiral molecules. It is interesting that in the two *cis-trans*-isomers of (4) one thiophosphoryl group is axial and the other equatorial, whereas in each of the four more symmetrical isomers both thiophosphoryl sulphur atoms occupy either axial or equatorial positions. In conclusion, the bicyclic dithiopyrophosphate (4) which at first sight could exist in eight enantiomeric forms, in fact occurs only in six, *i.e.* two *cis-cis*, two *trans-trans*, and only two distinct *cis-trans* forms. Since the racemic thioacids (2) and halogenides (3) were used in the present study, it is obvious that the racemic or *meso* forms of (4) will be generated on condensation.

With the above discussion in mind we condensed the tetramethylammonium salt of the *cis*-thioacid (2) with *trans*-bromide (3b) in acetonitrile. The reaction afforded a solid dithiopyrophosphate (4), m.p. 80—84°. There is no doubt that, while the configuration at P(1) in *cis*-(2) remains unchanged during condensation, the configuration at P(2) in *trans*-(3b) should be inverted in accord with our previous observations.[6] Hence, the condensation under consideration should result in the formation of a mixture of the unsymmetrical *cis-trans* dithiopyrophosphates (4a and b) in both of which P(1) and P(2) are nonequivalent. Evidence for this assignment was provided by their ^{31}P and ^{1}H n.m.r. spectra.

The ^{31}P{^{1}H} n.m.r. spectrum shows a typical AB system (see Figure 1) indicating the presence of two non-equivalent phosphorus nuclei P(1) and P(2) absorbing at δ_P 45.7 and 50.0 p.p.m. ($J_{P(1)-P(2)}$ 34.5 Hz), respectively. Moreover, each arm of the AB signal is split into a doublet due to the presence of two unsymmetrical dithiopyrophosphates (4a and b). It should be noted, however, that the difference in their ^{31}P n.m.r. chemical shifts is very small. Much better support for the view that the product obtained is indeed a mixture of *cis-trans*-(4a and b) was provided by the ^{1}H n.m.r. spectra. Theoretically, all four methyl groups in either *cis-trans*-(4a or b) are chemically nonequivalent and should show different chemical shifts in the ^{1}H n.m.r. spectrum. Taking into account that the resonance signal of the methyl protons in 1,3,2-dioxaphosphorinan rings consists of four lines due to splitting by the methine proton at C(4) and phosphorus, 16 lines were expected to appear in the methyl region of the ^{1}H n.m.r. spectrum of a mixture of *cis-trans*-(4a and b). This was found to be the case (see Figure 1). Interestingly, the signals for two methyl groups at δ 0.90 and 0.87 are split by phosphorus with $^{4}J_{P-CH_3}$ 2.75 Hz whereas the other two at δ 1.05 and 1.04 couple to phosphorus with $^{4}J_{P-CH_3}$ 0.88 Hz. Extensive investigations [10-13] of 2-oxo- or 2-thioxo-1,3,2-dioxaphosphorinan systems have shown that the protons of the equatorial methyl group on C(4) couple to phosphorus more strongly when the thiophosphoryl sulphur is equatorial. Therefore, it is reasonable to assume that the coupling constants of 2.75 and 0.88 Hz correspond to coupling with P(1) and P(2) respectively, in *cis-trans*-(4a and b). The i.r. spectrum measured in KBr discs of the dithiopyrophosphate *cis-trans*-(4a and b) obtained as shown above reveals four sharp bands at 681, 695, 745, and 750 cm^{-1} [14] in the region characteristic of the thiophosphoryl P=S group.

Next, the tetramethylammonium salt of the *trans*-thioacid (2) was condensed with *trans*-bromide (3b). This reaction resulted in the formation of a crystalline dithiopyrophosphate (4), m.p. 45—60°. Based on the results discussed above



cA + tHi* = *cis* - *trans* (4a)

cA + tHi = *cis* - *trans* (4b)

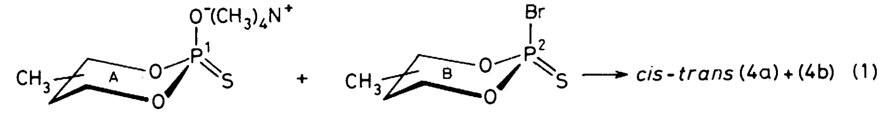
tA + tHi* = *trans* - *trans* (4a)

tA + tHi = *trans* - *trans* (4b)

cA + cHi* = *cis* - *cis* (4a)

cA + cHi = *cis* - *cis* (4b)

Scheme 2. Diastereoisomeric forms of (4)



(±) - *cis* - (2) (±) - *trans* - (3b)

it was obvious that the product of the reaction (2) is a mixture of two symmetrical dithiopyrophosphates, *trans-trans*-(4a and b). Accordingly, its $^{31}P\{^1H\}$ n.m.r. spectrum showed two singlets of equal intensity at δ_P 48.1 and 48.3 p.p.m.

By fractional crystallisation of *trans-trans*-(4a and b) from benzene–cyclohexane we were able to isolate one pure isomer, m.p. 91—92.5°, δ_P 48.3 p.p.m. The methyl protons on C(4) of the isolated isomer appeared in the ^1H n.m.r. spectrum at δ 1.04 and were split by phosphorus with a coupling constant $^4J_{P-CH_3}$ of 0.80 Hz. Its i.r. (KBr) spectrum revealed four bands in the P=S absorption region at 635, 650, 735, and 740 cm^{-1}.

Finally, the reaction between the tetramethylammonium salt of the *cis*-thioacid (2) and *cis*-chloride (3a) [1] was carried out in order to obtain a mixture of the symmetrical dithiopyrophosphates *cis-cis*-(4a and b). The product of this condensation, m.p. 120—130°, consisted of the two expected diastereoisomers. In this case, however, they were formed in unequal amounts as evidenced by the $^{31}P\{^1H\}$ n.m.r. spectrum (Figure 1) which exhibited two singlets at δ_P 46.5 and 46.8 in the ratio 19 : 81, respectively. Since the *cis*-chloride (3a) used for the reaction was only 80% diastereoisomerically pure the $^{31}P\{^1H\}$ n.m.r. spectrum also revealed the presence of the *cis-trans*-(4a + b) mixture.

Two crystallisations of the mixture of *cis-cis*-(4a and b) from benzene–cyclohexane afforded the major diastereoisomer in the pure state, m.p. 159—162°, δ_P 46.8 p.p.m. Its ^1H n.m.r. spectrum showed a typical signal for the 4-methyl protons at δ 0.87 ($^4J_{P-CH_3}$ 1.13 Hz). In the i.r. spectrum (KBr) two bands at 705 and 755 cm^{-1} were found in the region for the thiophosphoryl group.

It is generally accepted [10,13] that for 1,3,2-dioxaphosphorinan rings having methyl substituents on C(4) or C(6) a coupling constant value $^4J_{P-CH_3}$ of 2—3 Hz indicates an equatorial methyl group, while a lower value (0.5—1.5 Hz) indicates an axial methyl or a mixture of conformational isomers with axial and equatorial methyl groups. In this regard the low values of $^4J_{P-CH_3}$ found for the majority of diastereoisomeric dithiopyrophosphates (4) are rather surprising. The data suggest that in addition to the conformations shown in Scheme 1 the diastereoisomers of (4) may also adopt conformations in solution in which the methyl groups on C(4) are axial. Alternatively, the decrease in the values of $^4J_{P-CH_3}$ observed for diastereoisomeric (4) may be a consequence of unfavourable interactions between two bulky 1,3,2-dioxaphosphorinan rings leading to substantial deformation and deviation of one or both from an ideal chair conformation.

To gain more detailed insight into the structure and conformation of diastereoisomeric (4), *X*-ray analyses of the pure

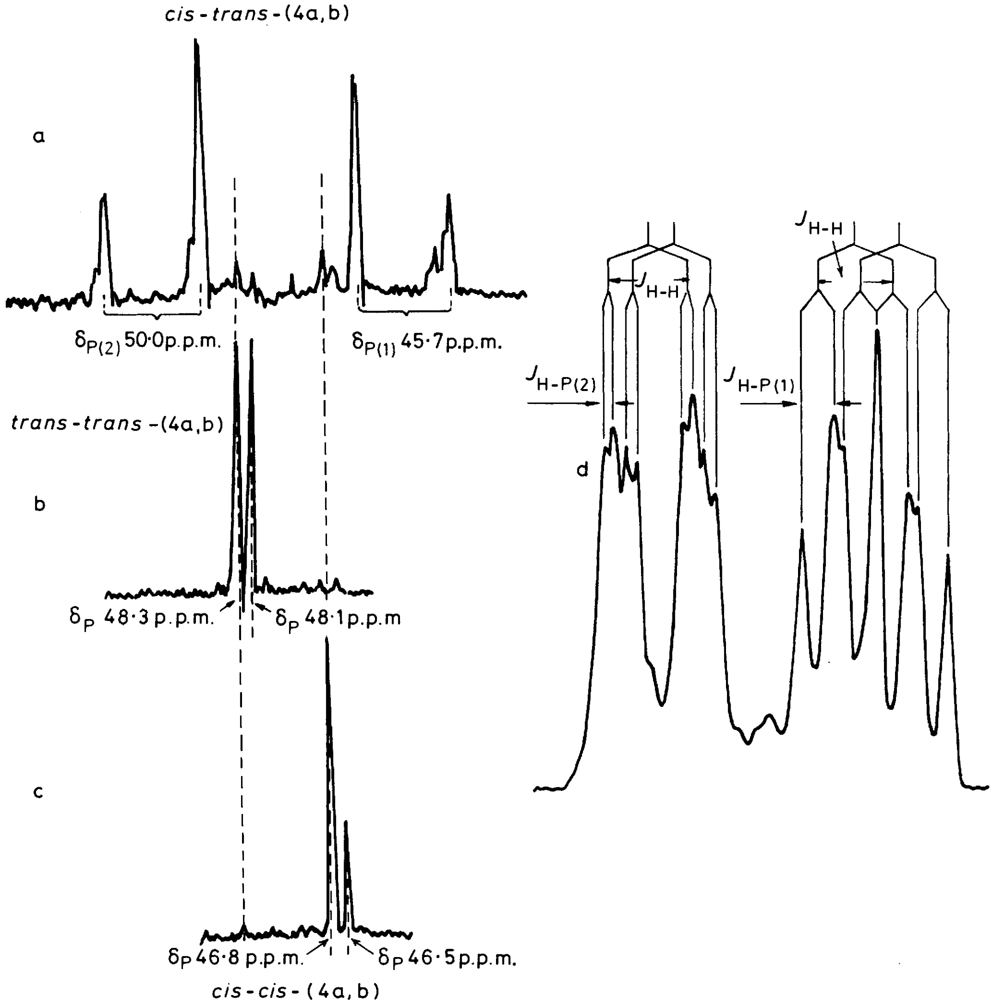
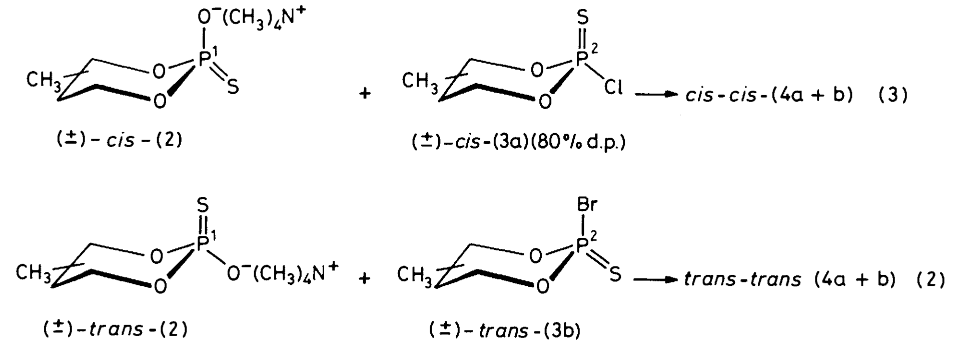


Figure 1. ^{31}P and ^{1}H n.m.r. spectra of diastereoisomeric dithiopyrophosphates (4): a, ^{31}P n.m.r. signal for *cis-trans*-(4a + b); b, ^{31}P n.m.r. signal for *trans-trans*-(4a + b); c, ^{31}P n.m.r. signal for *cis-cis*-(4a + b); d, expanded resonance signal in ^{1}H n.m.r. spectrum of the methyl protons in *cis-trans*-(4a + b)



diastereoisomers *trans-trans*-(4), m.p. 91—92.5°, and *cis-cis*-(4), m.p. 159—162°, were carried out. Determination of their structures revealed from the relative positions of the two methyl groups in the six-membered rings that both compounds were in fact in the (4a) series of Scheme 1.

X-*Ray Crystal Structures of Dithiopyrophosphates* trans-trans′-(4a) *and* cis-cis-(4a).—Three-dimensional views of single molecules of *trans-trans*-(4), m.p. 91—92.5°, and *cis-cis*-(4), m.p. 159—162°, and the atom numbering are shown in Figures 2 and 3, respectively. Figures 4 and 5 show stereoviews of the packing arrangements in their unit cells. The atomic fractional co-ordinates for non-hydrogen atoms in both compounds are listed in Table 1 and for hydrogen in Table 2. Tables 3 and 4 contain bond distances and angles.

Figure 2 reveals two most important structural features of the molecule of *trans-trans*-(4). The first is that it belongs to the (4a) series. Secondly, the substitution patterns of the dioxaphosphorinan rings A and B are different. Whereas the thiophosphoryl sulphur atom and the methyl group on C(4) in

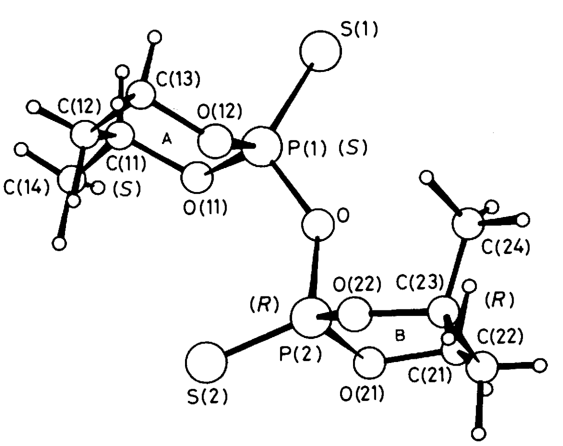


Figure 2. There-dimensional view of one of the enantiomeric molecules of *trans-trans'*-(4a) with atom numbering

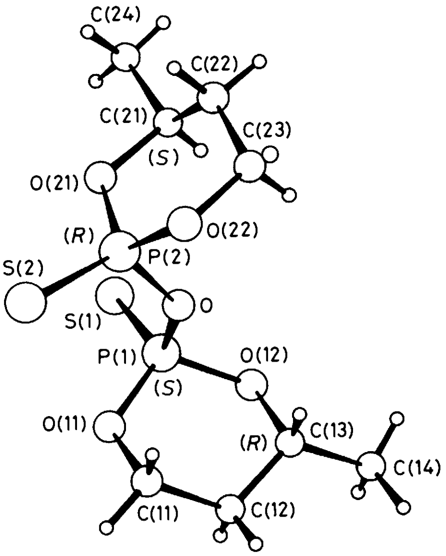


Figure 3. Three-dimensional view of one of the enantiomeric molecules of *cis-cis*-(4a) with atom numbering

ring A are, as expected, axial and equatorial, in ring B the double-bonded sulphur atom is equatorial and the methyl group on C(4) is axial. This is due to a conformational flip of ring B into its alternative chair form which reverses the axial–equatorial character of the P=S and $C-CH_3$ bonds. In this way the two rings A and B became non-equivalent and this conformer of *trans-trans*-(4a) is called *trans-trans'*-(4a) (see later). For this reason, although the diastereoisomer *trans-trans*-(4a) is chiral, Figure 2 shows only one of the enantiomeric molecules present in the crystal state.

Figure 3 clearly illustrates that the molecule of *cis-cis*-(4) investigated is also in the (4a) series. However, in this case both dioxaphosphorinan rings A and B adopt the expected chair-like conformation with the thiophosphoryl sulphur and methyl groups in equatorial positions.

Further details of the geometries of the two diastereoisomers of (4) are given in Table 5.

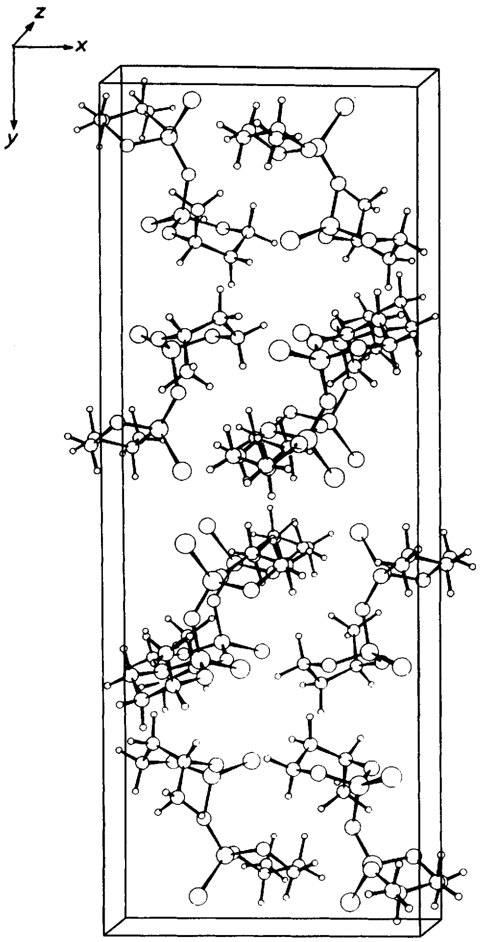


Figure 4. Packing of the molecules of *trans-trans'*-(4a) in the unit cell

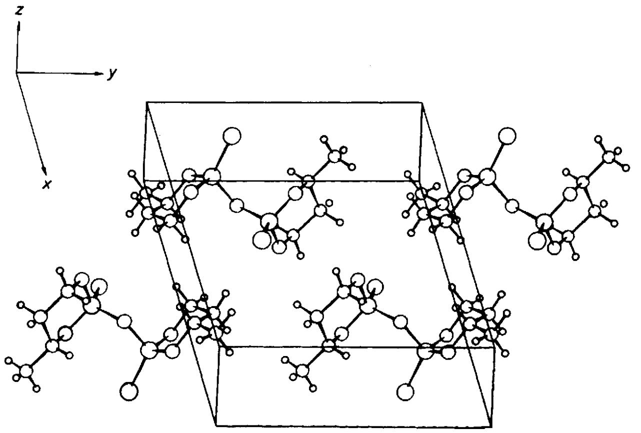


Figure 5. Packing of the molecules of *cis-cis*-(4a) in the unit cell

The substituent orientation in the six-membered ring may be described by the angle between the substituent vector and the best least-squares plane through the atoms O(11)O(12)C(11)C(13) or O(21)O(22)C(21)C(23). The corresponding values (°) are as follows:

	trans-trans'-(4a)		*cis-cis*-(4a)	
	Ring A	Ring B	Ring A	Ring B
P=S	−87.0	18.8	−9.8	13.1
$C-CH_3$	28.6	−63.7	−28.2	26.1

Table 1. Fractional positional parameters (× 10^4) for non-hydrogen atoms

	x	*y*	*z*
(a) *trans-trans'*-(4a)			
P(1)	1 494(1)	838(0)	−8(1)
S(1)	2 283(1)	375(0)	−1 058(1)
O(11)	1 382(2)	827(1)	2 043(3)
O(12)	237(2)	928(1)	−695(3)
C(11)	455(3)	565(1)	2 811(5)
C(12)	−687(3)	684(1)	2 008(6)
C(13)	−659(4)	644(1)	26(5)
C(14)	530(5)	636(2)	4 757(6)
O	2 136(2)	1 273(1)	−343(4)
P(2)	1 902(1)	1 766(0)	−33(1)
S(2)	760(1)	1 907(0)	1 656(2)
O(21)	3 153(3)	1 918(1)	430(4)
O(22)	1 631(2)	1 931(1)	−1 916(4)
C(21)	4 045(4)	1 932(1)	−939(6)
C(22)	3 600(4)	2 190(1)	−2 475(6)
C(23)	2 542(4)	2 002(1)	−3 297(6)
C(24)	2 693(5)	1 604(2)	−4 318(7)
(b) *cis-cis*-(4a)			
P(1)	2 181(1)	1 842(1)	7 293(1)
S(1)	1 058(1)	2 844(1)	8 986(2)
O(11)	3 232(2)	783(2)	8 590(3)
O(12)	1 490(2)	1 211(2)	5 300(3)
C(11)	4 015(3)	−144(3)	7 351(6)
C(12)	3 156(4)	−710(3)	5 641(6)
C(13)	2 260(3)	235(3)	4 074(5)
C(14)	1 314(5)	−269(5)	2 448(8)
O	2 987(2)	2 548(2)	6 111(3)
P(2)	3 915(1)	3 471(1)	6 393(1)
S(2)	5 363(1)	2 809(1)	9 104(1)
O(21)	2 999(2)	4 660(2)	7 686(3)
O(22)	4 266(2)	3 774(2)	4 791(3)
C(21)	1 982(3)	5 410(3)	6 054(5)
C(22)	2 589(3)	5 704(3)	4 258(5)
C(23)	3 272(3)	4 561(3)	3 192(4)
C(24)	1 359(5)	6 515(4)	7 288(8)

Table 2. Hydrogen atom positional parameters (× 10^4) with isotropic temperature factors (10^3 Å)

	x	*y*	*z*	*U*
(a) *trans-trans'*-(4a)				
H(111)	552	230	2 569	50
H(121)	−851	1 014	2 461	56
H(122)	−1 389	528	2 392	56
H(131)	−1 355	757	−350	52
H(132)	−443	354	−543	52
H(141)	1 256	601	5 178	75
H(142)	299	958	5 087	75
H(143)	−25	439	5 303	75
H(211)	4 825	2 068	−410	63
H(212)	4 230	1 612	−1 378	63
H(221)	3 587	2 523	−2 090	58
H(222)	4 241	2 232	−3 330	58
H(241)	1 918	1 394	−4 488	71
H(242)	2 975	1 690	−5 626	71
H(243)	3 354	1 417	−3 695	71
H(231)	2 120	2 232	−4 034	55
(b) *cis-cis*-(4a)				
H(111)	4 592(31)	248(31)	6 738(56)	70(10)
H(112)	4 676(35)	−807(34)	8 386(62)	90(11)
H(121)	2 680(34)	−1 077(32)	6 329(59)	76(11)
H(122)	3 689(42)	−1 288(39)	4 791(73)	112(15)
H(131)	2 699(30)	645(29)	3 420(50)	62(9)
H(141)	805(44)	434(42)	1 744(76)	111(16)
H(142)	795(43)	−645(39)	3 255(74)	110(15)
H(143)	1 849(40)	−979(39)	1 444(70)	104(13)
H(211)	1 430(27)	4 942(25)	5 580(46)	47(7)
H(221)	3 260(31)	6 230(28)	4 854(50)	65(9)
H(222)	1 926(33)	6 215(30)	3 133(57)	79(10)
H(231)	3 796(32)	4 700(31)	2 257(58)	73(10)
H(232)	2 675(34)	4 067(31)	2 571(57)	79(11)
H(241)	795(44)	7 010(40)	6 347(73)	103(14)
H(242)	1 024(40)	6 196(38)	8 462(77)	105(14)
H(243)	1 978(47)	6 969(43)	7 881(78)	116(17)

The conformation of the 1,3,2-dioxaphosphorinan ring is described by torsion angles shown in Figure 6 together with the asymmetry parameters.[14] On the other hand, Table 6 gives the distances of the atoms from the planes through four atoms of the ring. Based on these data all four rings may be classified as deformed chairs.

The general shape of a ring may also be characterised by two dihedral angles. They are defined by the angle between the best least-squares planes passing through the four central atoms of the ring and the O,P,O plane (α) or the plane of the remaining carbon atoms (β). The calculated values (°) of the angles α and β are as follows:

	trans-trans'-(4a)		*cis-cis*-(4a)	
	Ring A	Ring B	Ring A	Ring B
α	43.5	26.1	36.8	33.6
β	53.3	52.6	52.9	53.1

These data show clearly that the conformations of the 1,3,2-dioxaphosphorinan rings are distorted compared with cyclohexane, three of them being substantially flattened at the phosphorus end. Similar ring deformations were observed for the anhydrides (1a and b).[3,4] The flattening that occurs in ring B in *trans-trans'*-(4a) is a consequence of the repulsive interactions between the bridging oxygen atom (O) and the methyl group, C(24)H_3, in the axial position. The distance O · · · C(24) (3.272 Å) shows them to be in close contact. Interestingly, the other contacts between S(2) and O(11) and O(12) are 3.52 and 3.63 Å, respectively. Similar interactions do not occur in the *cis-cis*-(4a) molecule because of a different dihedral angle, S(1)–P(1) · · · P(2)–S(2) (see Figure 7). The angle between the planes S(1)P(1)O and S(2)P(2)O in *trans-trans'*-(4a) is 165.3°, and in *cis-cis*-(4a) 80.6°.

A comparison of selected bond lengths and angles is given in Table 7. It should be noted that the P(1)OP(2) angle in *trans-trans'*-(4a) (138.2°) is distinctly larger than that in *cis-cis*-(4a) (133.3°) and those found in $K_4P_3O_9NH_2$ (132°) [15] and the cyclic pyrophosphate (1a) [3] (131.8°) because of the non-bonded interactions between S(2) and the underside of ring A.

The axial thiophosphoryl bond (1.907 Å) is slightly longer than the equatorial one (1.899 Å) in *trans-trans'*-(4a). In *cis-cis*-(4a) the lengths of the thiophosphoryl bonds are 1.891 and 1.893 Å. These distances lie within the range (1.85—1.96 Å) typical of substituted thiophosphates.[16]

The average P–O bond for both structures (1.567 and 1.562 Å, respectively) is similar to the previously observed value, 1.57 Å.[17-19] The P–O ring bonds for the ring with an axial sulphur are significantly longer than those in rings with an equatorial sulphur.

Conformation of Diastereoisomeric Dithiopyrophosphates (4) in Solution.—We discuss briefly the conformation of diastereoisomeric dithiopyrophosphates (4) in solution based on the n.m.r. and i.r. data presented above as well as emphasizing some differences between the crystalline and solution state

Table 3. Bond lengths (Å) in dithiopyrophosphates (4)

(a) *trans-trans′*-(4a)

S(2)–P(2)	1.899(2)	C(11)–C(14)	1.503(6)
O–P(2)	1.605(3)	C(21)–H(211)	1.08(5)
O(21)–P(2)	1.564(3)	C(21)–H(212)	1.09(4)
O(22)–P(2)	1.559(3)	C(22)–H(221)	1.10(4)
O–P(1)	1.588(3)	C(22)–H(222)	1.00(5)
S(1)–P(1)	1.907(1)	C(23)–H(231)	1.04(4)
O(11)–P(1)	1.570(2)	C(24)–H(241)	1.13(5)
O(12)–P(1)	1.572(3)	C(24)–H(242)	1.08(6)
C(21)–O(21)	1.470(6)	C(24)–H(243)	1.08(5)
C(23)–O(22)	1.508(5)	C(13)–H(131)	0.93(4)
C(22)–C(21)	1.518(7)	C(13)–H(132)	1.05(4)
C(22)–C(23)	1.499(6)	C(12)–H(121)	1.12(4)
C(24)–C(23)	1.495(7)	C(12)–H(122)	1.00(4)
C(11)–O(11)	1.478(4)	C(11)–H(111)	1.09(4)
C(13)–O(12)	1.480(5)	C(14)–H(141)	0.91(5)
C(13)–C(12)	1.517(6)	C(14)–H(142)	1.09(6)
C(11)–C(12)	1.504(5)	C(14)–H(143)	1.00(6)

(b) *cis-cis*-(4a)

S(1)–P(1)	1.891(1)	O(11)–P(1)	1.569(2)
O(12)–P(1)	1.563(2)	O–P(1)	1.608(2)
C(11)–O(11)	1.463(4)	C(13)–O(12)	1.481(3)
C(12)–C(11)	1.505(5)	C(13)–C(12)	1.510(4)
C(14)–C(13)	1.500(4)	P(2)–O	1.617(2)
S(2)–P(2)	1.893(1)	O(21)–P(2)	1.557(2)
O(22)–P(2)	1.559(2)	C(21)–O(21)	1.480(3)
C(23)–O(22)	1.474(3)	C(22)–C(21)	1.498(4)
C(24)–C(21)	1.508(5)	C(23)–C(22)	1.504(4)
H(111)–C(11)	0.99(3)	H(112)–C(11)	1.05(4)
H(121)–C(12)	0.91(4)	H(122)–C(12)	0.97(5)
H(131)–C(13)	0.90(3)	H(141)–C(14)	0.92(5)
H(142)–C(14)	1.00(5)	H(143)–C(14)	1.11(5)
H(211)–C(21)	0.89(3)	H(221)–C(22)	1.05(3)
H(222)–C(22)	1.00(3)	H(231)–C(23)	0.94(4)
H(232)–C(23)	0.97(4)	H(241)–C(24)	0.87(5)
H(242)–C(24)	1.00(5)	H(243)–C(24)	0.95(5)

conformations especially for *trans-trans*-(4a). For the sake of brevity only the diastereoisomers (4a) are taken into consideration as the conclusions drawn are also valid for series (4b).

For the unsymmetrical diastereoisomer *cis-trans*-(4a) the four different conformations in Scheme 3 may be considered to exist in solution, but the observations of a rather high coupling constant value, $^4J_{P\text{-}CH_3}$ 2.75 Hz, which is characteristic of a 1,3,2-dioxaphosphorinan ring with both methyl and thiophosphoryl sulphur group in equatorial positions,[2,10] limits the discussion to two of them, *cis-trans*- and *cis-trans′*-(4a).*

The presence of the conformer *cis-trans′*-(4a) with an axial methyl group in ring B could explain why the second coupling constant value for the unsymmetrical isomer, $^4J_{P\text{-}CH_3}$ 0.88 Hz, is very low. However, this may be due to flattening of ring B which diminishes the distinction between axial and equatorial sites on phosphorus. Moreover, in the *cis-trans′*-(4a) conformation the non-equivalence of the phosphorus atoms is slight and the difference between their chemical shifts is likely to be small. Therefore, we believe that the predominant, if not exclusive, conformation of this isomer in solution is *cis-trans*-(4a). In accord with this, four bands observed in the i.r. spectrum (measured in $CHCl_3$ solution) in the region typical for the thiophosphoryl group can be most reasonably assigned to axial and equatorial P=S bonds.

For the second diastereoisomer (4a) having the *trans-trans*-configuration at both phosphorus atoms three conformations should be taken into account, *trans-trans*-, *trans-trans′*-, and *trans′-trans′*-(4a) (Scheme 4). As mentioned earlier isomer (4a) exists exclusively in the solid state in the *trans-trans′*-conformation. This conformer is probably more stable in comparison with the other conformers because it alone contains one 1,3,2-dioxaphosphorinan ring (B) in which the thiophosphoryl sulphur and bridging oxygen atoms occupy positions agreeing with their conformational preferences. This effect and perhaps the better stabilization of this conformer induced by crystal packing are stronger than the equatorial preference of the methyl group on C(4). However, if the *trans-trans′*-conformer of (4a) were present exclusively in solution we should observe an AB signal in the ^{31}P n.m.r. spectrum as a result of the non-equivalent phosphorus atoms P(1) and P(2), but this is not observed. The ^{31}P n.m.r. spectrum of the symmetrical *trans-trans*-isomer shows one singlet which remains unchanged to −80°. Moreover, it should also be noted that only one signal for the methyl protons on C(4) which $^4J_{P\text{-}CH_3}$ 0.80 Hz appears in the ^1H n.m.r. spectrum, and it does not change when the temperature is decreased to −80°. On the other hand, the i.r. spectrum (measured in $CHCl_3$ solution) of this isomer shows four bands for the P=S grouping as in the case of the unsymmetrical isomer *cis-trans*-(4a). All these observations lead to the conclusion that the symmetrical *trans-trans*-isomer exists in solution as a mixture of the above shown conformers and the energy for conformer interconversion is probably quite low.

The diastereoisomer (4a) with the *cis-cis*-configuration can adopt in solution three different conformations, *cis-cis*-, *cis-cis′*-, and *cis′-cis′*-(4a) as shown in Scheme 5. Among these *cis-cis*-(4a) is expected to be the most stable conformation since both its methyl groups are equatorial, both its P=S groups are in energetically favourable equatorial positions, and the exocyclic oxygen atom occupies the preferred axial position. All the spectral data (one singlet in the $^{31}P\{^1H\}$ n.m.r. spectrum, one signal for methyl protons in ^1H n.m.r. spectrum, only two P=S bands at higher frequencies in the i.r. spectrum) strongly support the view that this isomer exists in solution in the *cis-cis*-conformation which is also the exclusive conformation observed in the solid state.

^{31}P *N.m.r. Spectral Observations on the Stereochemistry of Bis*-(4-*methyl*-1,3,2-*dioxaphosphorinan*-2-*yl*) *Oxide* (5).—As previously mentioned, Arbuzov[8] obtained dithiopyrophosphate (4), m.p. 130—135°, *via* sulphur addition to bis-(4-methyl-1,3,2-dioxaphosphorinan-2-yl) oxide (5). This fact prompted us to study this reaction by means of ^{31}P n.m.r. spectroscopy in the hope of obtaining some information on the structure of (4) as well as on the stereochemistry of pyrophosphite (5). It is interesting to note that pyrophosphite (5) like dithiopyrophosphate (4), should exist in six diastereoisomeric forms differing in configuration at both phosphorus atoms and in the relationship between methyl groups in the dioxaphosphorinan rings.

With this in mind we treated *cis*-2-oxo-4-methyl-1,3,2-dioxaphosphorinan (6)[5] with *trans*-2-chloro-4-methyl-1,3,2-dioxaphosphorinan (7)[20] in the presence of triethylamine in benzene solution at 0—5°. The $^{31}P\{^1H\}$ n.m.r. spectrum of the crude condensation product showed an AB signal with δ_P 118 [P(1)] and 116 [P(2)] p.p.m. ($^2J_{P(1)\text{-}P(2)}$ 90 Hz). This product on treatment with sulphur gave a mixture of dithiopyrophosphates *cis-trans*-(4a and b). Since sulphur addition proceeds undoubtedly with retention of configuration at both phosphorus atoms,[21] the pyrophosphite (5) obtained in this way has two electron pairs, one in an axial and the other in an

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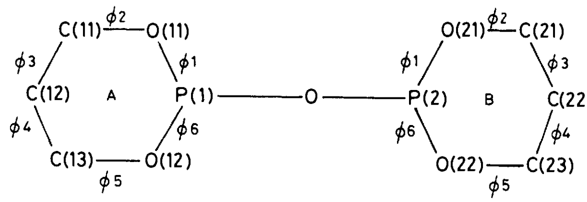
* A prime attached to the relevant half of the name shows that the 1,3,2-dioxaphosphorinan ring had flipped conformationally into its alternative chair form.

Table 4. Bond angles (°) in dithiopyrophosphates (4)

(a) *trans-trans'*-(4a)			
O–P(2)–S(2)	116.5(1)	H(211)–C(21)–O(21)	110(4)
O(21)–P(2)–S(2)	114.8(1)	H(212)–C(21)–O(21)	109(3)
O(21)–P(2)–O	100.2(2)	H(212)–C(21)–H(211)	109(4)
O(22)–P(2)–S(2)	113.9(1)	H(211)–C(21)–C(22)	111(4)
O(22)–P(2)–O	103.0(1)	H(212)–C(21)–C(22)	109(4)
O(22)–P(2)–O(21)	106.9(2)	H(221)–C(22)–C(21)	109(4)
P(1)–O–P(2)	138.2(2)	H(221)–C(22)–C(23)	119(4)
C(21)–O(21)–P(2)	120.0(3)	H(222)–C(22)–C(21)	109(4)
C(23)–O(22)–P(2)	123.5(2)	H(222)–C(22)–C(23)	113(4)
C(22)–C(21)–O(21)	109.1(4)	H(222)–C(22)–H(221)	93(3)
C(23)–C(22)–C(21)	112.6(4)	H(231)–C(23)–O(22)	99(3)
C(22)–C(23)–O(22)	109.8(3)	H(231)–C(23)–C(22)	109(4)
C(24)–C(23)–O(22)	108.6(4)	H(231)–C(23)–C(24)	112(4)
C(24)–C(23)–C(22)	117.2(4)	H(243)–C(24)–C(23)	109(4)
S(1)–P(1)–O	112.3(1)	H(242)–C(24)–C(23)	108(4)
O(11)–P(1)–S(1)	116.1(1)	H(242)–C(24)–H(243)	109(5)
O(12)–P(1)–O	102.8(1)	H(241)–C(24)–C(23)	118(4)
O(12)–P(1)–S(1)	116.3(1)	H(241)–C(24)–H(243)	107(5)
O(12)–P(1)–O(11)	105.0(1)	H(241)–C(24)–H(242)	107(5)
O(11)–P(1)–O	102.7(1)	H(131)–C(13)–O(12)	105(3)
C(11)–O(11)–P(1)	117.9(2)	H(131)–C(13)–C(12)	105(4)
C(13)–O(12)–P(1)	114.5(2)	H(132)–C(13)–O(12)	102(3)
C(12)–C(13)–O(12)	109.6(3)	H(132)–C(13)–C(12)	119(4)
C(11)–C(12)–C(13)	111.4(3)	H(132)–C(13)–H(131)	115(4)
C(12)–C(11)–O(11)	109.6(3)	H(121)–C(12)–C(13)	113(3)
C(14)–C(11)–O(11)	105.4(3)	H(121)–C(12)–C(11)	105(3)
C(14)–C(11)–C(12)	114.5(4)	H(122)–C(12)–C(13)	106(4)
H(142)–C(14)–C(11)	111(4)	H(122)–C(12)–C(11)	118(4)
H(141)–C(14)–C(11)	113(4)	H(122)–C(12)–H(121)	104(4)
H(141)–C(14)–H(142)	105(5)	H(111)–C(11)–O(11)	114(3)
H(143)–C(14)–C(11)	107(4)	H(111)–C(11)–C(12)	106(3)
H(143)–C(14)–H(142)	110(5)	H(111)–C(11)–C(14)	108(4)
H(143)–C(14)–H(141)	112(5)		
(b) *cis-cis*-(4a)			
O(11)–P(1)–S(1)	114.1(1)	O(12)–P(1)–S(1)	114.4(1)
O(12)–P(1)–O(11)	106.5(1)	O–P(1)–S(1)	115.9(1)
O–P(1)–O(11)	104.1(1)	O–P(1)–O(12)	100.4(1)
C(11)–O(11)–P(1)	117.6(2)	C(13)–O(12)–P(1)	119.7(2)
C(12)–C(11)–O(11)	109.9(3)	C(13)–C(12)–C(11)	112.6(3)
C(12)–C(13)–O(12)	109.1(3)	C(14)–C(13)–O(12)	106.3(3)
C(14)–C(13)–C(12)	114.5(3)	P(2)–O–P(1)	133.3(1)
S(2)–P(2)–O	115.2(1)	O(21)–P(2)–O	104.5(1)
O(21)–P(2)–S(2)	114.3(1)	O(22)–P(2)–O	100.6(1)
O(22)–P(2)–S(2)	113.8(1)	O(22)–P(2)–O(21)	107.1(1)
C(21)–O(21)–P(2)	119.7(2)	C(23)–O(22)–P(2)	119.2(2)
C(22)–C(21)–O(21)	108.5(2)	C(24)–C(21)–O(21)	105.0(3)
C(24)–C(21)–C(22)	115.1(3)	C(23)–C(22)–C(21)	112.5(2)
C(22)–C(23)–O(22)	110.8(2)	H(111)–C(11)–O(11)	109(2)
H(111)–C(11)–C(12)	113(2)	H(112)–C(11)–O(11)	111(2)
H(112)–C(11)–C(12)	113(2)	H(112)–C(11)–H(111)	102(3)
H(121)–C(12)–C(11)	108(2)	H(121)–C(12)–C(13)	109(2)
H(122)–C(12)–C(11)	109(3)	H(122)–C(13)–C(13)	106(3)
H(122)–C(12)–H(121)	113(3)	H(131)–C(13)–C(12)	104(2)
H(131)–C(13)–C(112)	111(2)	H(131)–C(14)–C(14)	111(2)
H(142)–C(14)–C(13)	102(3)	H(142)–C(14)–C(13)	108(3)
H(142)–C(14)–H(141)	110(4)	H(143)–C(14)–C(13)	109(2)
H(143)–C(14)–H(141)	117(4)	H(143)–C(21)–H(142)	110(3)
H(211)–C(21)–O(21)	106(2)	H(211)–C(22)–C(22)	111(2)
H(211)–C(21)–C(24)	111(2)	H(221)–C(21)–C(21)	110(2)
H(221)–C(22)–C(23)	108(2)	H(222)–C(22)–C(21)	110(2)
H(222)–C(22)–C(23)	109(2)	H(222)–C(22)–H(221)	107(2)
H(231)–C(23)–O(22)	99(2)	H(231)–C(23)–C(22)	115(2)
H(232)–C(23)–O(22)	107(2)	H(232)–C(23)–C(22)	111(2)
H(232)–C(23)–C(22)	111(2)	H(232)–C(23)–H(231)	114(3)
H(241)–C(24)–C(21)	107(3)	H(242)–C(24)–C(21)	107(3)
H(242)–C(24)–H(241)	117(4)	H(243)–C(24)–C(21)	110(3)
H(243)–C(24)–H(241)	105(4)	H(243)–C(24)–H(242)	111(4)

Table 5. The geometry of 1,3,2-dioxaphosphorinan rings in *trans-trans'*-(4a) and *cis-cis*-(4a)

Plane 1		Angles (°) between planes 1 and 2 *trans-trans'*-(4a)	 *cis-cis*-(4a)
O(11)O(12)C(11)C(13)	P(1)O(11)O(12)	43.5	36.8
	C(11)C(12)C(13)	53.3	52.9
	O(22)O(21)C(21)C(23)	31.5	26.9
	P(1)S(1)O	89.2	88.0
	P(2)S(2)O	88.5	67.4
	P(1)OP(2)	83.7	78.5
O(21)O(22)C(21)C(23)	P(2)O(21)O(22)	26.1	33.6
	C(21)C(22)C(23)	52.6	53.1
	P(1)S(1)O	86.4	66.7
	P(2)S(2)O	86.5	88.0
	P(1)OP(2)	89.3	80.7
P(1)OP(2)	P(1)S(1)O	7.9	53.1
	P(2)S(2)O	19.6	59.2
P(1)S(1)O	P(2)S(2)O	14.7	80.6



	trans-trans'-(4a)		*cis-cis*-(4a)	
	ring A	ring B	ring A	ring B
φ_1	49.2	−36.4	43.9	40.8
φ_2	−53.6	53.8	−54.4	−52.5
φ_3	56.4	−61.7	59.4	58.7
φ_4	−60.4	53.8	−56.3	−57.5
φ_5	59.5	−39.8	49.9	48.1
φ_6	−51.4	29.3	−42.2	−38.1
S(1)−P(1)−O−P(2)		172.1	53.1	
P(1)−O−P(2)−S(2)		19.6	59.2	

$$\Delta C_s = \sqrt{\frac{\sum_{i=1}^{m} (\varphi_i + \varphi_i')^2}{m}}$$

$$\Delta C_2 = \sqrt{\frac{\sum_{i=1}^{m} (\varphi_i - \varphi_i')^2}{m}}$$

		trans-trans'-(4a)		*cis-cis*-(4a)		
		ring A		ring B	ring A	ring B
ΔC_s	C(11)	3.9	C(21)	12.6	12.2	14.7
	C(12)	4.3	C(22)	10.1	3.3	3.1
	C(13)	8.1	C(23)	22.7	8.9	11.8
ΔC_2	P(1)−O(12)	2.7	P(2)−O(22)	2.4	10.9	12.6
	P(1)−O(11)	8.7	P(2)−O(22)	23.2	4.5	6.3
	O(12)−C(13)	8.2	O(22)−C(23)	24.9	14.8	18.7
	$\lvert\varphi\rvert$ =	55.1		45.8	51.0	49.3

Figure 6. Torsion angles (°) and asymmetry parameters of 1,3,2-dioxaphosphorinan rings in *trans-trans'*- and *cis-cis*-(4a)

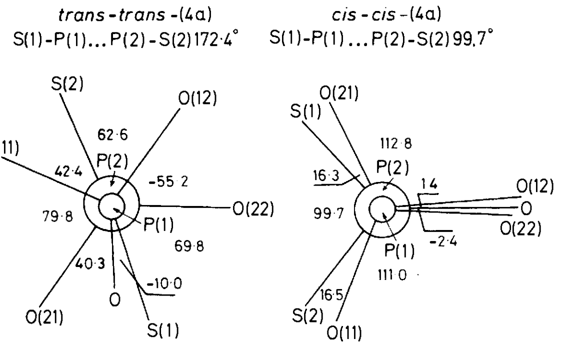


Figure 7. Newman projections around P(1) · · · P(2), showing the relevant torsion angles (°)

equatorial position, *i.e.* it is a mixture of *trans-cis*-(5a and b) isomers.

Distillation of this pyrophosphite resulted in the formation of a new diastereoisomeric pyrophosphite (5) which showed in the $^{31}P\{^1H\}$n.m.r. spectrum only one signal at δ_P 115.3 p.p.m. Addition of elemental sulphur to the distilled (5) gave mainly the dithiopyrophosphate *cis-cis*-(4a), δ_P 46.8 p.p.m. In the ^{31}P n.m.r. spectrum of this product a signal at δ_P 46.5 p.p.m. was also observed but its intensity was very low. Hence, it possesses the symmetrical *trans-trans*-structure, in which both electron pairs lie in equatorial positions. Moreover, it is reasonable to assume that the dithiopyrophosphate (4) obtained by Arbuzov was mainly a mixture of the *cis-cis*-(4a and b) isomers.

The experiments described above indicate that *trans-trans*-(5) is thermodynamically more stable than the *trans-cis*-(5)

Table 6. Distances of the atoms from the planes (Å)

Atoms	*trans-trans'*-(4a)			*cis-cis*-(4a)		
	1	2	3	4	5	6
O(11)	* −0.022	0.585	* −0.035	* −0.015	−0.558	* 0.042
O(12)	* 0.022	* −0.015	0.645	* 0.014	* 0.055	−0.521
P(1)	−0.660	* 0.014	* 0.033	0.562	* −0.052	* −0.039
C(11)	* 0.022	* −0.014	−0.640	* 0.015	* 0.054	0.648
C(12)	0.683	* 0.015	* 0.036	−0.668	* −0.057	* −0.044
C(13)	* −0.022	−0.690	* −0.034	* −0.014	0.622	* 0.041
C(14)	0.741	0.077	−0.498	−0.724	0.446	0.726
S(1)	−2.564	−1.595	−1.565	0.238	−1.080	1.069
O(21)	* −0.064	0.500	* 0.045	* −0.055	0.521	* 0.013
O(22)	0.386	* 0.105	* 0.044	0.490	* −0.069	* 0.013
P(2)	* 0.057	* 0.098	−0.429	* 0.051	* 0.064	−0.512
C(21)	−0.658	* −0.100	* −0.045	−0.644	* −0.067	* −0.013
C(22)	* 0.066	* 0.107	0.667	* 0.056	* 0.072	0.667
C(23)	* −0.060	−0.558	* 0.044	* −0.052	−0.605	* 0.013
C(24)	−1.399	−2.048	−1.296	−0.494	0.669	0.649
S(2)	1.256	1.279	0.183	1.040	1.153	−0.082

* Atoms included in the calculations of the planes.

Table 7. Comparison of selected bond lengths and angles in 1,3,2-dioxaphosphorinan rings of *trans-trans'*-(4a) and *cis-cis*-(4a)

Bond lengths	(Å)	B (eq)	A (eq)	B (eq)
P=S	1.907(1)	1.889(2)	1.891(1)	1.893(1)
P–O (bridge)	1.588(3)	1.605(3)	1.608(2)	1.617(2)
P–O (ring)	1.570(2) 1.572(3)	1.564(3) 1.559(3)	1.563(2) 1.569(2)	1.557(2) 1.559(2)
Bond angles (°)	(Å)	B (eq)	A (eq)	B (eq)
O_r–P–O_r	105.0(1)	106.9(2)	106.5(1)	107.1(1)
O_r–P–O_b	102.8(1) 102.7(1)	100.2(2) 103.0(1)	104.1(1) 100.4(1)	104.5(1) 100.6(1)
S=P–O_b	112.3(1)	116.5(1)	115.9(1)	115.2(1)
S=P–O_r	116.1(1) 116.3(1)	114.8(1) 113.9(1)	114.4(1) 114.1(1)	114.3(1) 113.8(1)
C–O_r–CP	117.9(2) 114.5(2)	120.0(3) 123.5(2)	117.6(2) 119.7(2)	119.7(2) 119.2(2)

O_r = Endocyclic oxygen atom. O_b = exocyclic oxygen atom.

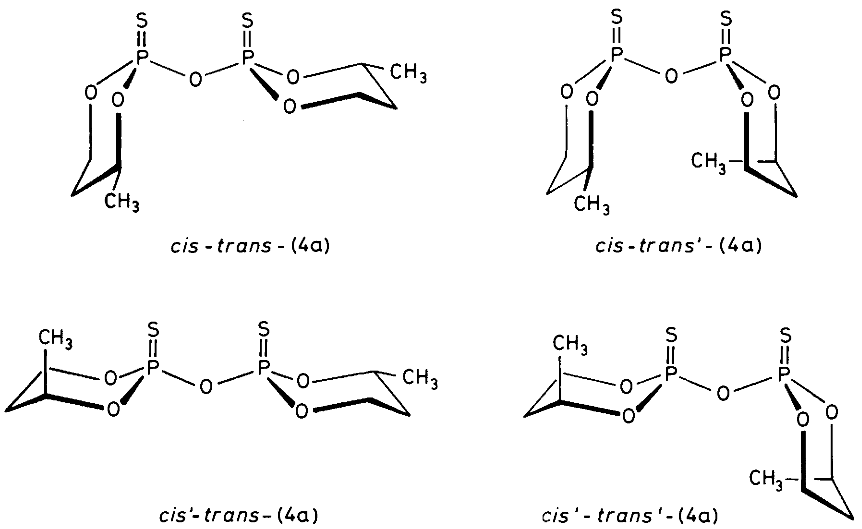
isomer. This, in turn, should be more stable than the pyrophosphite *cis-cis*-(5) which would have both lone pairs in axial positions. This isomer is probably formed as an initial product of the condensation depicted in Scheme 6 if one assumes that nucleophilic substitution at phosphorus in *trans*-(7) occurs with inversion of configuration. It would, however, undergo very fast isomerisation at phosphorus under the given reaction conditions to give *trans-cis*-(5). Therefore, one can conclude that the stability order of diastereoisomeric pyrophosphites (5) is in good agreement with the conformational preferences of the lone pair electrons in 1,3,2-dioxaphosphorinan systems.

Experimental

B.p.s and m.p.s are uncorrected. Solvents and reactants were reagent grade. ^{1}H N.m.r. spectra were obtained with a Bruker HX-90 spectrometer with tetramethylsilane as internal standard. ^{31}P N.m.r. spectra were recorded with a JEOL INM-C-60 HL spectrometer with 85% phosphoric acid as external standard. I.r. spectra were measured with UR-10 spectrometer using KBr discs or in CHCl$_3$ solution.

Synthesis of cis-trans-*Bis-*(4-*methyl*-2-*thioxo*-1,3,2-*dioxaphosphorinan*-2-*yl*) *Oxide* (4a *and* b).—To a solution of the racemic tetramethylammonium salt of *cis*-thioacid (2)[5] (1.21 g, 0.005 mol) in acetronitrile (25 ml) a solution of the racemic *trans*-bromide-(3b)[6] (1.16 g, 0.005 mol) in acetonitrile (5 ml) was added at room temperature. The mixture was stirred at 45° for 5 h. Tetramethylammonium bromide was filtered off. The filtrate was evaporated to give crude condensation product (1.3 g, 97%), m.p. 62—66°. Its crystallization from n-propanol–cyclohexane gave pure *cis-trans*-(4) which consisted of two isomers (4a and b) (1g) in equal amounts, m.p. 80—84°, δ_H (C$_6$D$_6$) 0.87 (dd, CH$_3$), 0.90 (dd, CH$_3$, $^3J_{CH_3\text{-}H}$ 6.25, $^4J_{CH_3\text{-}P(1)}$ 2.75 Hz), 1.04 (dd, CH$_3$), 1.05 (dd, CH$_3$, $^3J_{CH_3\text{-}H}$ 6.25, $^4J_{CH_3\text{-}P(2)}$ 0.88 Hz), δ_P (benzene) 45.7 [P(1)] and 50.0 [P(2)] p.p.m. (AB, $^2J_{P(1)\text{-}P(2)}$ 34.5 Hz), $\nu_{max.}$ (KBr) 681, 695, 745, 750 (P=S), and 950 cm^{-1} (P–O–P) (Found: C, 30.25; H, 5.1; P, 19.15. Calc. for C$_8$H$_{16}$O$_5$P$_2$S$_2$: C, 30.2; H, 5.05; P, 19.45%).

Synthesis of trans-trans-*Bis-*(4-*methyl*-2-*thioxo*-1,3,2-*dioxaphosphorinan*-2-*yl*) *Oxide* (4a *and* b).—Tetramethylammonium salt of the racemic *trans*-thioacid (2)[5] (1.21 g, 0.005 mol) was dissolved in acetonitrile (40 ml) and treated with a solution of the racemic *trans*-bromide (3b)[6] (1.16 g, 0.005 mol) in acetonitrile (5 ml). After 5 h stirring at 45° the mixture was cooled to room temperature and tetramethylammonium bromide was filtered off. To the filtrate cyclohexane (5 ml) was



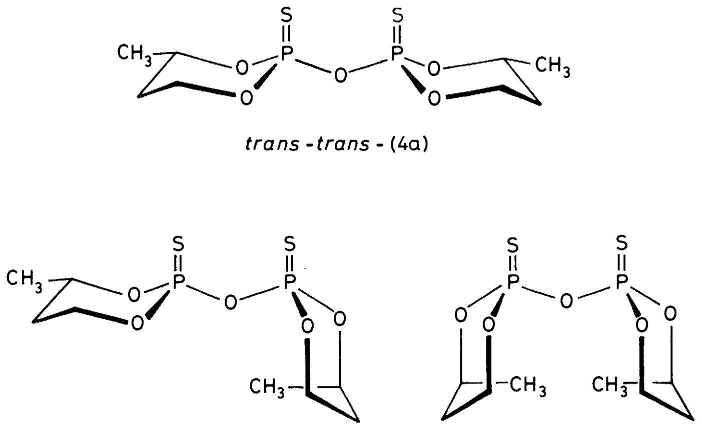
cis-*trans*-(4a)

cis-*trans'*-(4a)

cis'-*trans*-(4a)

cis'-*trans'*-(4a)

Scheme 3. Conformations of *cis-trans*-(4a)

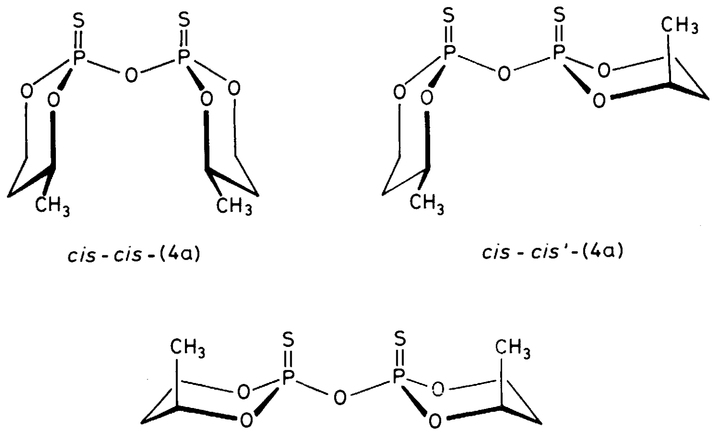


trans-*trans*-(4a)

trans-*trans'*-(4a)

trans'-*trans'*-(4a)

Scheme 4. Conformations of *trans-trans*-(4a)

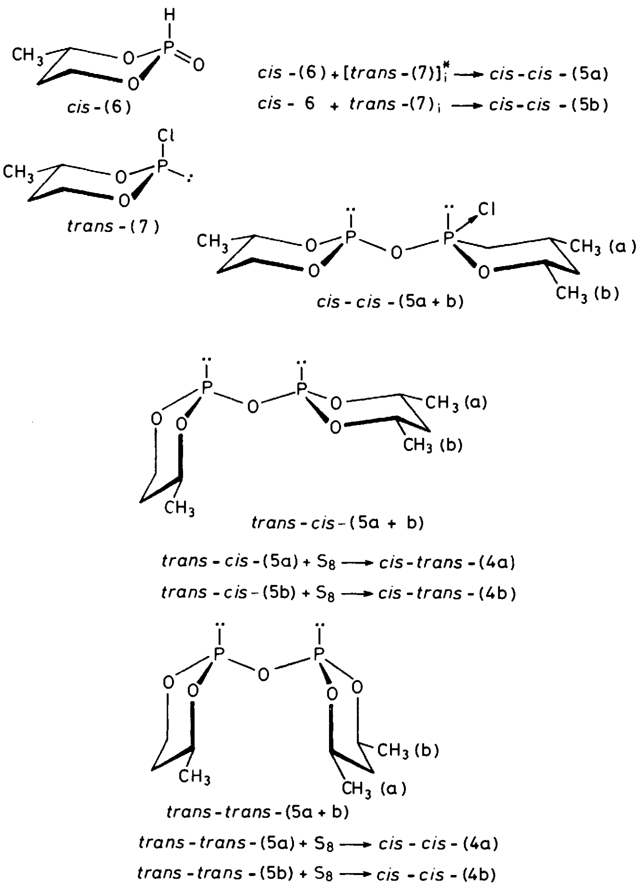


cis-*cis*-(4a)

cis-*cis'*-(4a)

cis'-*cis'*-(4a)

Scheme 5. Conformations of *cis-cis*-(4a)



Scheme 6. Diastereoisomers of (5)

added. The resulting solution was left for crystallization for a few days at 0°. The isolated condensation product, *trans-trans*-(4) (1.1 g. 82%), m.p. 45—60°, was found to consist of two isomers (4a and b) as shown by the ^{31}P n.m.r. spectrum (two singlets at δ_P 48.1 and 48.3 p.p.m.). After three crystallizations of these products from benzene–cyclohexane one pure isomer, *trans-trans*-(4a) was obtained, m.p. 91—92.5°, δ_H (C_6D_6) 1.04 (dd, CH_3, $^3J_{CH-H}$ 6.25, $^4J_{CH_3-P}$ 0.80 Hz), δ_P (C_6H_6) 48.3(s), $\nu_{max.}$ (KBr) 635, 650, 735, 740, (P=S), and 950 cm^{-1} (P–O–P) (Found: C, 30.3; H, 5.05; P, 19.55%).

Synthesis of cis-cis-*Bis*-(4-*methyl*-2-*thioxo*-1,3,2-*dioxaphosphorinan*-2-*yl Oxide* (4a *and* b).—A solution of the racemic tetramethylammonium salt of *cis*-thioacid (2)[5] (1.04 g, 0.0043 mol) in acetonitrile (30 ml) was treated with the racemic *cis*-chloride (3a) (0.8 g, 0.0043 mol, 80% d.p.) at room temperature. The mixture was stirred for 5 h at 45°. Then, tetramethylammonium chloride was filtered off and acetonitrile evaporated. The residue was dissolved in benzene (200 ml). The benzene solution was washed with water, dried ($MgSO_4$), and evaporated to give a mixture of *cis-cis*-(4a) and *cis-cis*-(4b) (1 g, 73%), in a ratio of 81 : 10 (^{31}P n.m.r. assay, δ_P 46.8 and 46.5 p.p.m., respectively), m.p. 120—130°. The condensation product was contaminated with some amount of the *cis-trans*-(4a + b) isomer. Crystallization of this product from benzene–cyclohexane gave the major diastereoisomer *cis-cis*-(4a), m.p. 159—162°, δ_H (C_6H_6) 0.87 (dd, CH_3, $^3J_{CH_3-H}$ 6.25, $^4J_{CH_3-P}$ 1.13 Hz), δ_P (C_6H_6) 46.8(s); $\nu_{max.}$ (KBr) 705, 755 (P=S), and 950 cm^{-1} (P–O–P) (Found: C, 30.2; H, 5.05; P, 19.2%).

Synthesis of and Sulphur Addition to Bis-(4-*methyl*-1,3,2-*dioxaphosphorinan*-2-*yl*) *Oxide* (5).—To a solution of *cis*-4-methyl-2-oxo-1,3,2-dioxaphosphorinan (6)[5] (4.08 g, 0.03 mol) in benzene (80 ml) triethylamine (3.02 g, 0.03 mol) and then *trans*-2-chloro-4-methyl-1,3,2-dioxaphosphorinan (7)[22] (4.64 g, 0.03 mol) were added at 0—5°. After stirring the mixture for 0.5 h at 5° triethylamine hydrochloride was filtered off and benzene evaporated. The crude reaction product gave two ^{31}P resonances in a ratio of 11 : 89. The first appeared as a singlet at δ_P 115.3 p.p.m. The second signal was a typical AB system with δ 116.0 [P(1)] and 118 [P(2)] p.p.m. ($^2J_{P(1)P(2)}$ 90 Hz) and can be ascribed to the unsymmetrical pyrophosphite *trans-cis*-(5). After addition of sulphur to the crude product the ^{31}P n.m.r. showed an AB system typical for the dithiopyrophosphate *cis-trans*-(4a + b). Distillation of the crude reaction product gave pyrophosphite (5) (3.4 g, 42%), b.p. 102—104° at 0.6 mmHg, n_D^{20} 1.4560, δ_P 115.3 p.p.m. This product was contaminated with other phosphorus-containing compounds. Addition of elemental sulphur to the distilled product at 50° gave mainly dithiopyrophosphonate with δ_P 46.8 p.p.m. together with a small amount of its isomer with δ_p 46.5 p.p.m.

X-*Ray Structure Determination of* trans-trans'-(4a) *and* cis-cis-(4a).—Single crystals of the title compounds were grown from benzene–cyclohexane. The crystal data for both dithiopyrophosphates are as follows:

trans-trans'-(4a)	*cis-cis*-(4a)
$C_8H_{16}O_5P_2S_2$	$C_8H_{16}O_5P_2S_2$
Mol. wt. 318.3	Mol. wt. 318.3
Orthorhombic	Triclinic
Space group *Pbca* (No. 61)	Space group $P\bar{1}$ (No. 2)
$Z = 8$	$Z = 2$
$F(000) = 1\,328$	$F(000) = 332$
$a = 11.572(1)$ Å	$a = 10.889(15)$ Å
$b = 31.741(1)$	$b = 11.150(15)$
$c = 7.625(1)$	$c = 6.286(6)$
	$\alpha = 92.96(7)°$
	$\beta = 100.82(6)$
	$\gamma = 75.92(5)$
$D_m = 1.505$ g cm^{-3}	$D_m = 1\,460$ g cm^{-3}
$D_c = 1.518$ g cm^{-3}	$D_c = 1.462$ g cm^{-3}
$U = 2\,800.71$ Å^3	$U = 727.03$ Å^3
Cu-K_α radiation	Mo-K_α radiation

The space groups and cell dimensions were derived from Weissenberg photographs, and the cell dimensions refined from diffractometer data. The intensity data for *trans-trans'*-(4a) were collected on a STOE automated four-circle diffractometer using Ni-filtered Cu-K_α radiation. The intensities of 1 970 reflections (out of a total of 2 173 in the range recorded) with $F > 4\sigma(F)$ were classified as observed and used for structure refinement. Intensity data for *cis-cis*-(4a) were collected on a Syntex $P2_1$ diffractometer (Mo-K_α radiation). Intensity measurements were carried out in the θ–2θ mode ($3.5 < 2\theta < 60°$) with graphite-monochromated Mo-K_α radiation. After application of the acceptance criterion, $F > 4\sigma(F)$, 3 083 unique reflections were retained for use in structural analysis. Both structures investigated were solved and refined with SHELX 76. The structure of *trans-trans'*-(4a) was solved by an automatic centrosymmetric direct method while the structure of *cis-cis*-(4a) was solved by weighted multi-solution tangent refinement. Both structures were refined by blocked full-matrix least squares with anisotropic temperature factors for all non-hydrogen atoms. All hydrogen atoms were located from difference syntheses and their positional parameters were freely refined with individual isotropic temperature factors. The terminal value ($R_w = \Sigma w^{\frac{1}{2}}\Delta/\Sigma w^{\frac{1}{2}}|F_o|$) = 0.080 and 0.048 and R = 0.058 and 0.046 for *trans-trans'*-(4a) and *cis-cis*-

(4a), respectively, were obtained. The weights were given by $w = k/[\sigma^2(F_o) + gF_o^2]$ where k and g were refined.

Anisotropic temperature factors and structure factors are in Supplementary Publication No. SUP 2348 (19 pp.).

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