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Two polymorphs of potassium trichloro[diethyl (methylsulfinylmethyl)phosphonate-κS]platinum(II) with Z' = 1 and 3 in the space group $P2_12_12_1$

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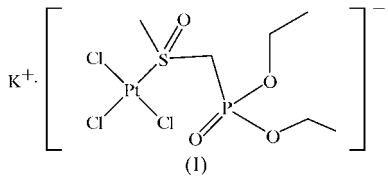
Two new polymorphs of the title compound, K[Pt$Cl_3(C_6H_{15}O_4PS)$], already known in the monoclinic form, were obtained by crystallization from acetone–*n*-pentane solutions of different composition. Both polymorphs are orthorhombic in the space group $P2_12_12_1$, with Z' = 1 (solvent ratio 1:4) and 3 (solvent ratio 1:9). In both polymorphs, electrostatic interactions link K^+ cations and $[PtCl_3(SMP)]^-$ anions [SMP is diethyl (methylsulfinylmethyl)phosphonate] in infinite chains, while adjacent chains are held together by weak C—H···Cl and C—H···O hydrogen-bond interactions.

Comment

Several compounds form different crystalline structures having the same molecular composition. This phenomenon, known as polymorphism, can stem from different possible ways of optimizing the intra- and intermolecular interactions within the crystal packing. Several drugs used in clinical medicine show this peculiar behaviour. For instance, chloramfenicol palmitate exists in three crystalline forms and phenylbutazone in as many as five different polymorphic structures. Although the mode of interaction with the biological target(s) does not change, different polymorphic structures of a given drug can show a variety of chemicophysical properties (rate of dissolution in physiological media, bioavailability, *etc*.) which can significantly influence the success of the pharmacological treatment (Aguiar *et al.*, 1967; Foppoli *et al.*, 2003; Kaliszan, 1986). It is generally accepted that, among different polymorphs, the best form is that with the greatest bioavailability, which usually coincides with the least stable crystalline form at room temperature.

Recently, we have proposed new platinum(II) compounds containing diethyl [(methylsulfinyl)methyl]phosphonate, SMP (Laforgia *et al.*, 2004), as antitumour drugs which may have a selective tropism for bone tissue (thanks to the phosphonate moiety)



(I)

and which have shown interesting MMP inhibition activity (MMP is membrane metalloproteinase; Sasanelli *et al.*, 2006). Our investigation has already led to the isolation and characterization of a monoclinic species, K[$PtCl_3$(SMP)], (I*a*) (Laforgia *et al.*, 2005). We now report the crystallographic analysis of two new orthorhombic polymorphs. The monoclinic form (space group $P2_1/a$, Z' = 1), (I*a*) was obtained from a mixture of H_2O–acetone–$CHCl_3$ (0.2:1:1). However, if acetone–pentane is used as solvent, two orthorhombic polymorphs, having the space group $P2_12_12_1$ and with Z' = 1 for (I*b*) (solvent ratio 1:4) or Z = 3 for (I*c*) (solvent ratio 1:9), are obtained.

The bond lengths in the orthorhombic polymorphs (I*b*) and (I*c*) are very similar to those found in the monoclinic polymorph (I*a*), and do not require further discussion. In contrast, the patterns of the supramolecular aggregations are very different for (I*a*), (I*b*) and (I*c*), and these will be discussed here.

The simpler orthorhombic polymorph, (I*b*) (Fig. 1), has Z' = 1 in the space group $P2_12_12_1$. Each complex anion is linked to three K^+ cations by way of the three Cl^- ligands (Cl1, Cl2, and Cl3) and the S═O and P═O oxygens of the SMP ligand (O1 and O2). Similar to the case of (Ia), the P═O oxygen interacts with only one K^+ cation. Atoms Cl1 and Cl2 interact with two K^+ cations, while atom Cl3 interacts with only one K^+ cation (Fig. 1). Each K^+ cation is trapped in an irregular seven-donor cage formed by five Cl and two O atoms

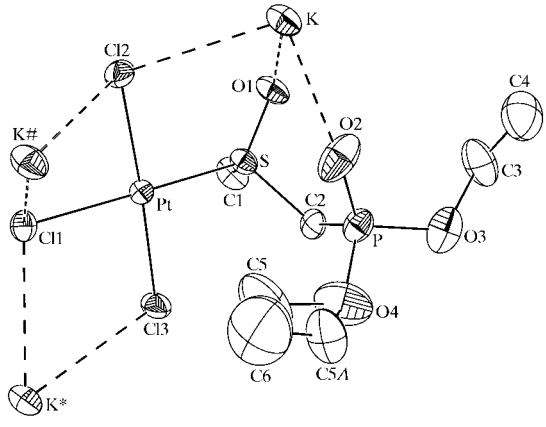


Figure 1
A view of the asymmetric unit of K[$PtCl_3$(SMP)] in polymorph (I*b*), showing the atomic numbering scheme. Displacement ellipsoids are drawn at the 30% probability level. H atoms have been omitted for clarity. Atoms labelled with an asterisk (*) or a hash (#) are at the symmetry positions ($x-1, y, z$) and ($x-\frac{1}{2}, \frac{3}{2}-y, 1-z$), respectively.

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of three different anions, namely atoms Cl2, O1, and O2 of one platinum unit (Pt), atoms Cl1 and Cl3 of the second platinum unit (Pt^{i}; symmetry code as in Table 1), and atoms Cl1 and Cl2 of the third platinum unit (Pt^{ii}); the K···O and K···Cl distances are reported in Table 1.

Electrostatic interactions link cations and anions in to an infinite chain extending along the *a* direction (Fig. 2). Adjacent chains are held together by hydrogen-bond interactions of different strengths involving Cl1 atoms of one chain and C2 atoms of an adjacent chain, and atoms O2 and O1 of one chain and atoms C3 and C1 of an adjacent chain (Table 2). A view of the crystal packing along the *a* direction is shown in Fig. 3. In this polymorph, one ethyl group (C5/C5*A* and C6) is disordered, probably because it lacks significant intermolecular interactions.

The second orthorhombic polymorph, (I*c*), has $Z' = 3$ in the space group $P2_12_12_1$. Each independent anion interacts with three K^+ cations by way of atoms Cl1, Cl2, O1 and O2 (Fig. 4). In two of the three independent anions (Pt1 and Pt1*A*), ester atom O4 is also involved in electrostatic interactions with the K^+ cations. In particular, two anions (Pt1*A* and Pt1*B*) have one K^+ cation interacting with the S═O and P═O oxygens of the SMP ligand and the Cl ligand *cis* to the sulfoxide [as observed in (I*a*) and (I*b*)], while the third anion (Pt1), having the S═O and P═O oxygens more distant [O1···O2 = 3.505 (5) Å, compared with O1*A*···O2*A* = 3.323 (5) Å and O1*B*···O2*B* = 3.235 (5) Å], has its K^+ cation interacting with the P═O oxygen of the SMP ligand and with the Cl1 and Cl2 ligands which are *cis* and *trans* to the coordinated sulfoxide (Fig. 4). In general, atom Cl1 interacts with only one cation and atom Cl2 with two cations (three in the case of Pt1). Two independent K^+ cations are trapped in an irregular eight-donor cage formed by three Cl and five O atoms of three different anions in the case of K1, and by four Cl and four O

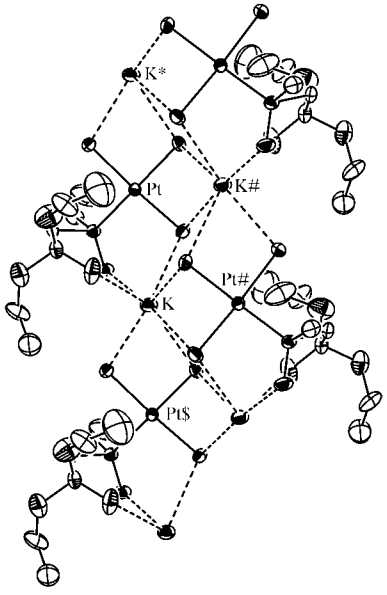

Figure 2
Chains of anions and cations extending along the *a* direction for K[PtCl$_3$(SMP)] in polymorph (I*b*). H atoms have been omitted for clarity. Atoms labelled with an asterisk (*), a dollar sign ($) or a hash (#) are at the symmetry positions $(x-1, y, z)$, $(x+1, y, z)$ and $(x-\frac{1}{2}, \frac{3}{2}-y, 1-z)$, respectively.

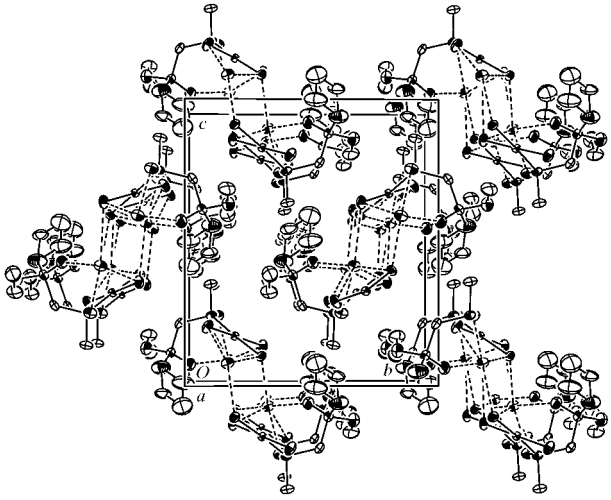

Figure 3
A view of the crystal packing along the *a* direction for K[PtCl$_3$(SMP)] in polymorph (I*b*). H atoms have been omitted for clarity.

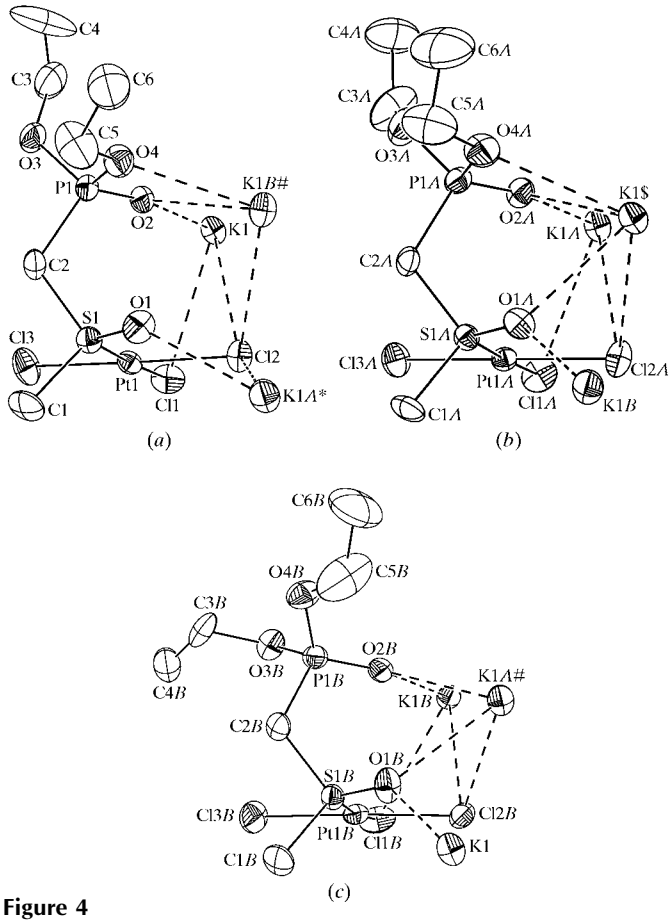

Figure 4
A view of the three independent anions and corresponding interactions with K^+ cations for K[PtCl$_3$(SMP)] in polymorph (I*c*). Displacement ellipsoids are drawn at the 30% probability level. H atoms have been omitted for clarity. Atoms labelled with an asterisk (*), a dollar sign ($) or a hash (#) are at the symmetry positions $(x, y, 1+z)$, $(\frac{3}{2}-x, 1-y, -\frac{1}{2}+z)$ and $(\frac{3}{2}-x, 1-y, \frac{1}{2}+z)$, respectively.

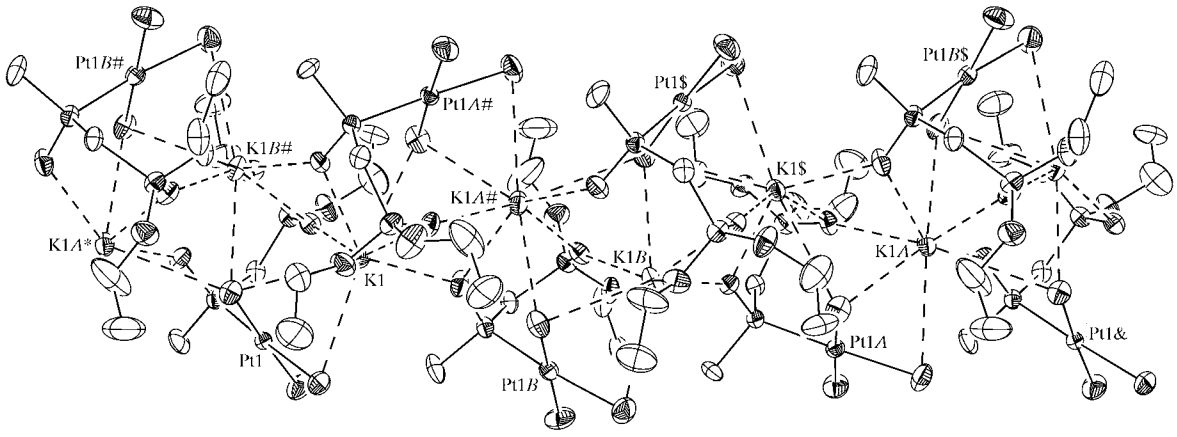

Figure 5
The chain of anions and cations extending along the *c* direction for K[$PtCl_3$(SMP)] in polymorph (I*c*). H atoms have been omitted for clarity. Atoms labelled with an asterisk (*), an ampersand (&), a dollar sign ($) or a hash (#) are at the symmetry positions $(x, y, 1 + z)$, $(x, y, z - 1)$, $(\frac{3}{2} - x, 1 - y, -\frac{1}{2} + z)$ and $(\frac{3}{2} - x, 1 - y, \frac{1}{2} + z)$, respectively.

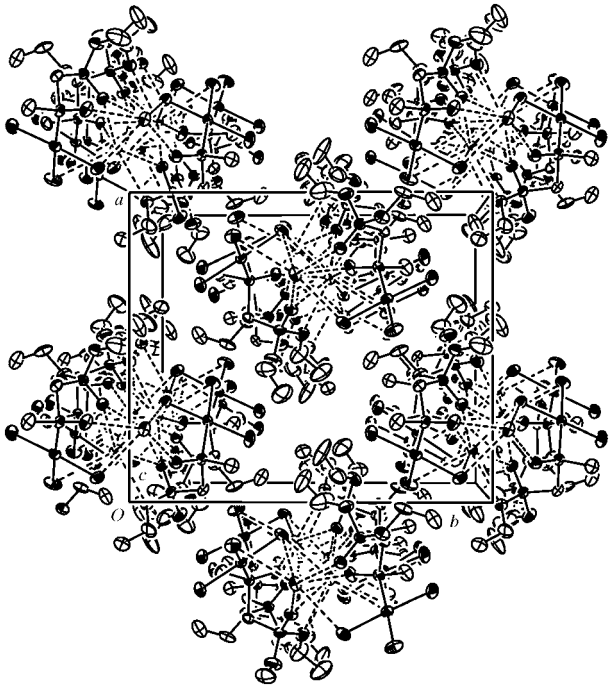

Figure 6
The crystal packing of K[$PtCl_3$(SMP)] in polymorph (I*c*). H atoms have been omitted for clarity.

atoms of three different anions in the case of K1*A*. The third cation, K1*B*, is trapped in a seven-donor cage formed by three Cl and four O atoms. The K···O and K···Cl distances for cations K1, K1*A* and K1*B* are given in Table 3.

Intra-chain hydrogen-bonding interactions of different strengths are also present. These involve Cl and O atoms on one hand (Cl1, O4*B* and O3*B*) and C atoms on the other hand (C1*B*, C1*A*, C2*A* and C5*A*). Infinite chains of anions and cations extend along the *c* direction (Fig. 5). Adjacent chains are held together by hydrogen-bond interactions involving atoms Cl1, Cl1*A*, Cl1*B* and Cl3*A* of one chain, and atoms C1, C2*B*, C3*B*, C3*A*, C3 and C5 of adjacent chains (Table 4). A view of the crystal packing along the *c* direction is shown in Fig. 6.

In conclusion, this work has shown that it is possible to isolate the complex K[$PtCl_3$(SMP)] in three different crystalline forms, one of which has already been reported (Laforgia *et al.*, 2005). The solvent of crystallization [H_2O–acetone–$CHCl_3$ (0.2:1:1) for (I*a*), and acetone–*n*-pentane in the ratios 1:4 and 1:9 for (I*b*) and (I*c*), respectively] appears to be responsible for the different crystalline packing. In all cases, strong interactions between anions and cations lead to chains extending in one direction. The chains are held together in the crystal structure by weak hydrogen-bond interactions involving Cl or O atoms of one chain and CH atoms of adjacent chains. In the case of (I*c*), there are also hydrogen bonds of this type within each chain. The P═O oxygen interacts with only one K^+ cation in (I*a*) and (I*b*) (the same K^+ cation also interacts with the S═O oxygen and with the Cl^- *cis* to the sulfoxide), and with two K^+ cations in (I*c*) (one K^+ cation also interacts with atoms Cl1 and Cl2, and the other interacts with atoms Cl2 and O1 in Pt1 and Pt1*B*, and with atoms Cl2 and O4 in Pt1*A*). Moreover, in the structures of (I*a*) and (I*b*), all three Cl atoms of the complex anion are involved in interactions with K^+ cations, while in the structure of (I*c*), one Cl atom (Cl3 of all three independent anions) does not interact with any K^+ cation. The different mode of interaction of the [$PtCl_3$-(SMP)]$^-$ anion with the cations revealed in this investigation can also provide useful information for elucidating the mechanism of the biological activity of this type of compound, particularly the inhibition of MMP activity.

Experimental

K[$PtCl_3$(SMP)] was prepared as reported by Laforgia *et al.* (2005). The polymorphs (I*b*) and (I*c*) were crystallized as follows. For the crystallization of (I*b*), K[$PtCl_3$(SMP)] (15 mg, 2.7×10^{-2} mmol) was dissolved in acetone (4 ml) and layered under *n*-pentane (16 ml). After one week at room temperature, crystals suitable for crystallographic analysis were obtained, and they were characterized by elemental analysis, IR spectroscopy and X-ray crystallography. Analysis calculated for $C_6H_{15}Cl_3KO_4PPtS$: C 13.00, H 2.73%; found: C 13.25, H 2.64%; IR (KBr pellet, cm^{-1}): 2913 (ν_{CH}), 1253 (ν_{PO}), 1049 (ν_{SO}), 1013 (ν_{POR}), 341 (ν_{PtCl}). For the crystallization of (I*c*),

K[$PtCl_3$(SMP)] (5 mg, 9 × 10^{-3} mmol) was dissolved in acetone (1 ml) and layered under *n*-pentane (9 ml). After one week at room temperature, crystals suitable for crystallographic analysis were obtained and they were characterized by elemental analysis, IR spectroscopy and X-ray crystallography. Analysis found for $C_6H_{15}Cl_3KO_4PPtS$: C 13.31, H 2.78%; IR (KBr pellet, cm^{-1}): 2913 (ν_{CH}), 1253 (ν_{PO}), 1049 (ν_{SO}), 1013 (ν_{POR}), 341 (ν_{PtCl}).

Polymorph (I*b*)

Crystal data

K[$PtCl_3(C_6H_{15}O_4PS)$]
M_r = 554.75
Orthorhombic, $P2_12_12_1$
a = 8.1697 (2) Å
b = 13.2052 (3) Å
c = 14.9286 (4) Å
V = 1610.54 (7) Å^3
Z = 4
D_x = 2.288 Mg m^{-3}
Mo $K\alpha$ radiation
μ = 9.70 mm^{-1}
T = 295 (2) K
Prism, yellow
0.50 × 0.25 × 0.14 mm

Data collection

Bruker X8 APEX CCD area-detector diffractometer
φ and ω scans
Absorption correction: multi-scan (*SADABS*; Sheldrick, 1996)
T_{min} = 0.017, T_{max} = 0.437
(expected range = 0.010–0.257)
63182 measured reflections
7591 independent reflections
4342 reflections with $I > 2\sigma(I)$
R_{int} = 0.046
θ_{max} = 36.0°

Refinement

Refinement on F^2
$R[F^2 > 2\sigma(F^2)]$ = 0.037
$wR(F^2)$ = 0.065
S = 0.87
7591 reflections
167 parameters
H-atom parameters constrained
$w = 1/[\sigma^2(F_o^2) + (0.0271P)^2]$ where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$ = 0.005
$\Delta\rho_{max}$ = 2.63 e Å^{-3}
$\Delta\rho_{min}$ = −1.30 e Å^{-3}
Extinction correction: *SHELXL97* (Sheldrick, 1997)
Extinction coefficient: 0.00146 (12)
Absolute structure: Flack (1983), with 3348 Friedel pairs
Flack parameter: 0.002 (6)

Table 1
Selected contact distances (Å) for polymorph (I*b*).

K···O1	2.829 (4)	K···Cl1^{ii}	3.139 (2)
K···Cl2	3.184 (2)	K···Cl3^{i}	3.190 (2)
K···O2	2.553 (6)	K···Cl2^{ii}	3.616 (2)
K···Cl1^{i}	3.116 (2)		

Symmetry codes: (i) $x+1, y, z$; (ii) $x+\frac{1}{2}, -y+\frac{3}{2}, -z+1$.

Table 2
Hydrogen-bond geometry (Å, °) for polymorph (I*b*).

D—H···*A*	*D*—H	H···*A*	*D*···*A*	*D*—H···*A*
C2—H2*A*···Cl1^{iii}	0.97	2.69	3.639 (6)	166
C3—H3*A*···O1^{iv}	0.97	2.95	3.726 (9)	138
C1—H1*C*···O2^{v}	0.96	2.77	3.592 (8)	144

Symmetry codes: (iii) $-x+1, y-\frac{1}{2}, -z+\frac{1}{2}$; (iv) $-x+2, y-\frac{1}{2}, -z+\frac{1}{2}$; (v) $-x+\frac{3}{2}, -y+1, z-\frac{1}{2}$.

Polymorph (I*c*)

Crystal data

K[$PtCl_3(C_6H_{15}O_4PS)$]
M_r = 554.76
Orthorhombic, $P2_12_12_1$
a = 14.2518 (3) Å
b = 16.6754 (3) Å
c = 20.8743 (3) Å
V = 4960.87 (15) Å^3
Z = 12
D_x = 2.228 Mg m^{-3}
Mo $K\alpha$ radiation
μ = 9.44 mm^{-1}
T = 295 (2) K
Acicular, yellow
1.00 × 0.07 × 0.06 mm

Data collection

Bruker X8 APEX CCD area-detector diffractometer
φ and ω scans
Absorption correction: multi-scan (*SADABS*; Sheldrick, 1996)
T_{min} = 0.121, T_{max} = 0.437
(expected range = 0.157–0.567)
169856 measured reflections
23275 independent reflections
10272 reflections with $I > 2\sigma(I)$
R_{int} = 0.031
θ_{max} = 37.6°

Refinement

Refinement on F^2
$R[F^2 > 2\sigma(F^2)]$ = 0.050
$wR(F^2)$ = 0.067
S = 0.85
23275 reflections
469 parameters
H-atom parameters constrained
$w = 1/[\sigma^2(F_o^2) + (0.0238P)^2]$ where $P = (F_o^2 + 2F_c^2)/3$
$(\Delta/\sigma)_{max}$ = 0.003
$\Delta\rho_{max}$ = 3.73 e Å^{-3}
$\Delta\rho_{min}$ = −1.50 e Å^{-3}
Absolute structure: Flack (1983), with 10077 Friedel pairs
Flack parameter: −0.008 (3)

Table 3
Selected contact distances (Å) for polymorph (I*c*).

K1···O2	2.678 (4)	K1*A*···O1^{ii}	2.748 (4)
K1···O1*B*	2.737 (3)	K1*A*···O2*B*^{iii}	2.909 (4)
K1···Cl1	3.359 (2)	K1*A*···O1*B*^{iii}	2.924 (4)
K1···Cl2	3.428 (2)	K1*A*···Cl2*B*^{iii}	3.179 (2)
K1···Cl2*A*^{i}	3.426 (2)	K1*B*···Cl1*B*	3.342 (2)
K1···O1*A*^{i}	2.823 (4)	K1*B*···Cl2*B*	3.166 (2)
K1···O2*A*^{i}	2.888 (4)	K1*B*···O1*A*	2.678 (4)
K1···O4*A*^{i}	3.013 (5)	K1*B*···O2*B*	2.787 (4)
K1*A*···Cl1*A*	3.379 (2)	K1*B*···O2^{iii}	2.868 (4)
K1*A*···Cl2*A*	3.317 (2)	K1*B*···O4^{iii}	2.934 (4)
K1*A*···O2*A*	2.771 (4)	K1*B*···Cl2^{iii}	3.263 (2)
K1*A*···Cl2^{ii}	3.504 (2)		

Symmetry codes: (i) $-x+\frac{3}{2}, -y+1, z+\frac{1}{2}$; (ii) $x, y, z-1$; (iii) $-x+\frac{3}{2}, -y+1, z-\frac{1}{2}$.

Table 4
Hydrogen-bond geometry (Å, °) for polymorph (I*c*).

D—H···*A*	*D*—H	H···*A*	*D*···*A*	*D*—H···*A*
C1*A*—H13*A*···O3*B*	0.96	2.65	3.552 (7)	157
C2*A*—H22*A*···O3*B*	0.97	2.93	3.794 (6)	148
C5*A*—H52*A*···O4*B*	0.97	2.98	3.833 (9)	147
C1—H13···Cl1*A*^{iv}	0.96	2.88	3.770 (7)	154
C3*B*—H32*B*···Cl1^{iv}	0.97	2.81	3.544 (6)	133
C3*A*—H31*A*···Cl1*A*^{v}	0.97	2.83	3.559 (8)	132
C3—H32···Cl1*B*^{iv}	0.97	2.85	3.678 (10)	144
C5—H51···Cl3*A*^{iv}	0.97	2.92	3.679 (8)	136
C1*B*—H11*B*···Cl1	0.96	2.85	3.748 (6)	155
C2*B*—H21*B*···Cl1*B*^{iv}	0.97	2.73	3.478 (5)	135

Symmetry codes: (iv) $x-\frac{1}{2}, -y+\frac{1}{2}, -z+1$; (v) $x-\frac{1}{2}, -y+\frac{1}{2}, -z$.

H atoms were placed in calculated positions, with C—H = 0.96–0.97 Å, and refined with U_{iso}(H) = 1.2 (1.5 for the methyl H atoms) times U_{eq}(parent). Four restraints were used in the refinement of the structure of (I*b*). These were associated with an ethoxy group, which was disordered over two orientations (DFIX 1.5 O4 C5 O4 C5*A* and DFIX 1.45 C5 C6 C5*A* C6). The coordinates of the disordered ethoxy group were refined with occupancies tied to sum to unity.

For both compounds, data collection: *COSMO*, *APEX2* and *BIS* (Bruker, 2004); cell refinement: *SAINT-IRIX* (Bruker, 2004); data reduction: *SAINT-IRIX*; program(s) used to solve structure: *SIR2002* (Burla *et al.*, 2003); program(s) used to refine structure: *SHELXL97* (Sheldrick, 1997); molecular graphics: *ORTEP-3 for Windows* (Farrugia, 1997); software used to prepare material for publication: *PARST97* (Nardelli, 1983, 1995) and *WinGX* (Farrugia, 1999).

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Supplementary data for this paper are available from the IUCr electronic archives (Reference: SK3018). Services for accessing these data are described at the back of the journal.

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