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## Structure Reports

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# Di- $\mu$ -chlorido-bis[chloridobis(dimethyl sulfoxide)dioxidouranium(VI)]

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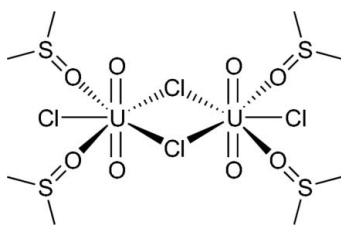
Received 20 November 2007; accepted 29 November 2007

 Key indicators: single-crystal X-ray study;  $T = 173$  K; mean  $\sigma(\text{S}-\text{C}) = 0.010$  Å;  
 $R$  factor = 0.043;  $wR$  factor = 0.111; data-to-parameter ratio = 23.7.

In the crystal structure of the title compound,  $[\text{U}_2\text{Cl}_4\text{O}_4(\text{C}_2\text{H}_6\text{OS})_4]$ , the compound has a centrosymmetric dimeric structure bridged by two chloride anions. Each  $\text{U}^{\text{VI}}$  atom is seven-coordinate in a pentagonal-bipyramidal geometry. In the equatorial plane of the uranyl unit there are two O atoms from non-adjacent dimethyl sulfoxides and three chloride ions (of which two chlorides are bridging). The compound is of interest as an anhydrous starting material of the uranyl(VI) ion.

## Related literature

For related structures, see: Berthet *et al.* (2000); Charpin *et al.* (1987); Rebizant *et al.* (1987); Wilkerson *et al.* (1999). For the synthesis, see: Calderazzo *et al.* (1997); Berthet *et al.* (2000).



## Experimental

### Crystal data

 $[\text{U}_2\text{Cl}_4\text{O}_4(\text{C}_2\text{H}_6\text{OS})_4]$   
 $M_r = 994.37$   
 Monoclinic,  $P2_1/c$ 
 $a = 9.172$  (3) Å  
 $b = 12.833$  (4) Å  
 $c = 10.691$  (2) Å

 $\beta = 97.72$  (2)°  
 $V = 1247.0$  (6) Å<sup>3</sup>  
 $Z = 2$   
 Mo  $K\alpha$  radiation

 $\mu = 13.76$  mm<sup>-1</sup>  
 $T = 173$  (2) K  
 $0.33 \times 0.21 \times 0.15$  mm

### Data collection

 Rigaku R-AXIS RAPID IP  
 diffractometer  
 Absorption correction: multi-scan  
 (Higashi, 1999)  
 $T_{\text{min}} = 0.051$ ,  $T_{\text{max}} = 0.128$ 

 10244 measured reflections  
 2849 independent reflections  
 2330 reflections with  $I > 2\sigma(I)$   
 $R_{\text{int}} = 0.084$ 

### Refinement

 $R[F^2 > 2\sigma(F^2)] = 0.043$   
 $wR(F^2) = 0.111$   
 $S = 1.10$   
 2849 reflections

 120 parameters  
 H-atom parameters constrained  
 $\Delta\rho_{\text{max}} = 2.54$  e Å<sup>-3</sup>  
 $\Delta\rho_{\text{min}} = -2.25$  e Å<sup>-3</sup>
**Table 1**

Selected interatomic distances (Å).

U1—O1	1.746 (7)	U1—Cl2	2.686 (2)
U1—O2	1.757 (6)	U1—Cl1	2.844 (2)
U1—O3	2.349 (6)	U1—Cl <sup>1</sup>	2.909 (2)
U1—O4	2.360 (6)		

 Symmetry code: (i)  $-x + 2, -y + 1, -z + 1$ .

Data collection: *PROCESS-AUTO* (Rigaku/MS, 2000-2006); cell refinement: *PROCESS-AUTO*; data reduction: *CrystalStructure* (Rigaku/MS, 2000-2006); program(s) used to solve structure: *SIR92* (Altomare *et al.* 1994); program(s) used to refine structure: *SHELXL97* (Sheldrick, 1997); molecular graphics: *ORTEPIII* (Farrugia, 1997); software used to prepare material for publication: *CrystalStructure*.

Supplementary data and figures for this paper are available from the IUCr electronic archives (Reference: XU2386).

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<sup>‡</sup> This author's last name has been changed from 'Mizuoka'.

## supporting information

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**Di- $\mu$ -chlorido-bis[chloridobis(dimethyl sulfoxide)dioxidouranium(VI)]****Koichiro Takao and Yasuhisa Ikeda****S1. Comment**

The title compound (**I**) was unexpectedly obtained from a hydrochloric acid aqueous solution containing  $U^{4+}$  and dimethyl sulfoxide (DMSO). It is reasonable to consider that **I** was formed by aerobic oxidation of  $U^{4+}$  to  $UO_2^{2+}$ .

The title compound **I** has a dimeric structure which is bridged by two  $\mu$ -Cl<sup>-</sup> between  $UO_2Cl(DMSO)_2$  fragments as shown in Fig. 1. There is an inversion center in the molecular structure of **I**. Each U atom is seven-coordinated in a pentagonal-bipyramidal geometry. Two O atoms are at the axial positions [mean  $U=O_{y1} = 1.75$  (1) Å] (Table 1). In the equatorial plane of each U, there are three Cl<sup>-</sup> ions; two of them act as  $\mu$ -Cl<sup>-</sup> to bridge the U atoms in **I** [mean  $U-Cl_{bridge} = 2.88$  (3) Å], and the remaining Cl<sup>-</sup> is placed at the position independent of the bridge formation [ $U-Cl_{non-bridge} = 2.686$  (2) Å]. The DMSO molecules in the equatorial plane coordinates to U through its O, and are non-adjacent [mean  $U-O_{DMSO} = 2.35$  (1) Å]. Deviations of Cl<sup>-</sup> and O of DMSO from the mean equatorial plane are within 0.15 Å. Interatomic distances between  $U(1)\cdots U(1)^i$  and  $\mu-Cl(1)\cdots\mu-Cl(1)^i$  [symmetry code: (i)  $-x + 2, -y + 1, -z + 1$ ] are 4.7669 (3) and 3.221 (3) Å, respectively, which indicate no interatomic interaction in each pair. These structural features of **I** are similar to that of  $[UO_2Cl(THF)_2]_2(\mu-Cl)_2$  (THF = tetrahydrofuran) reported by Charpin *et al.* (1987).

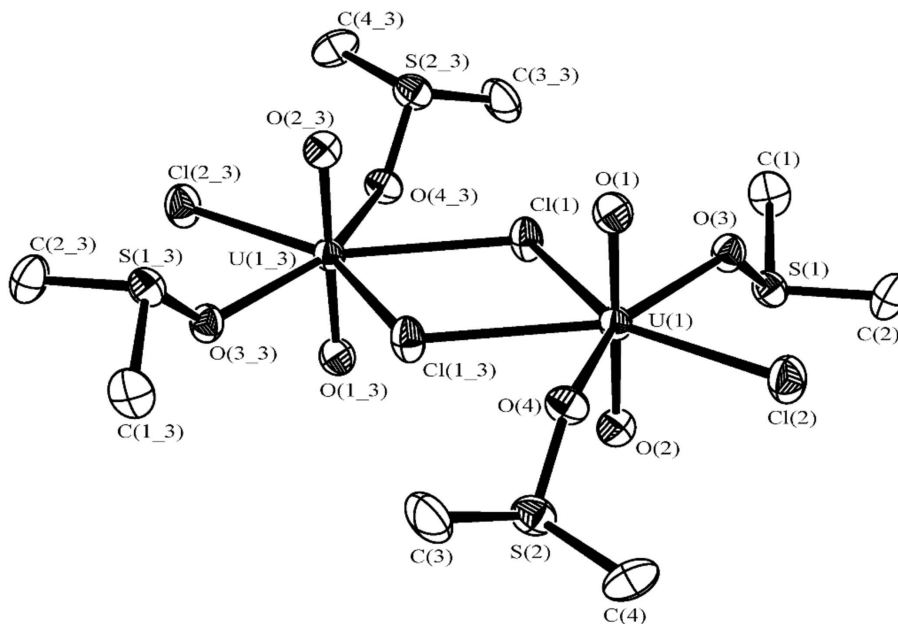
Previously, some anhydrous uranyl(VI) salts,  $UO_2Br_2(THF)_3$ ,  $UO_2Cl_2(THF)_3$ ,  $[UO_2Cl(THF)_2]_2(\mu-Cl)_2$ , and  $UO_2(CF_3SO_3)_2L_3$  ( $L = THF$ , pyridine), were reported (Rebizant *et al.* 1987, Wilkerson *et al.* 1999, Charpin *et al.* 1987, Berthet *et al.* 2000, respectively). In syntheses of water-sensitive uranyl(VI) compounds, *e.g.*, alkoxides and amides, anhydrous starting materials must be used. On the other hand, THF is not very stable, and may be decomposed by its polymerization in presence of a strong acid, *e.g.*  $CF_3SO_3H$  (Calderazzo *et al.* 1997 and Berthet *et al.* 2000). Compound **I** also has simple composition, *i.e.*, consisting only of  $UO_2^{2+}$ , Cl<sup>-</sup>, and DMSO. The use of DMSO instead of THF expands the number of choices of the anhydrous uranyl(VI) salts as the starting material.

**S2. Experimental**

Uranium(VI) trioxide was dissolved in 5 M hydrochloric acid solution. With heating and vigorous stirring, 2 molar amount of silver powder was added in the HCl aq. After 30 min, the mixture was cooled to room temperature. The insoluble residue of AgCl was removed by filtration. Small portion (*ca* 1 ml) of this filtrate was separated in a test tube. In this sample, some drops of dimethyl sulfoxide was added. The mixture was allowed to the air. After several days, yellow crystals of the title compound deposited.

**S3. Refinement**

H atoms were placed in calculated positions with  $C-H = 0.98$  Å and torsion angles were refined to fit the electron density, with  $U_{iso}(H) = 1.2U_{eq}(C)$ . The highest peak in the final difference Fourier map is 0.91 Å apart from the U atom.



**Figure 1**

Molecular structure of **I** drawn by thermal ellipsoids in 50% probability level. Asymmetric unit was expanded by the symmetry operation; (i)  $-x + 2, -y + 1, -z + 1$ . Hydrogen atoms are omitted for clarity.

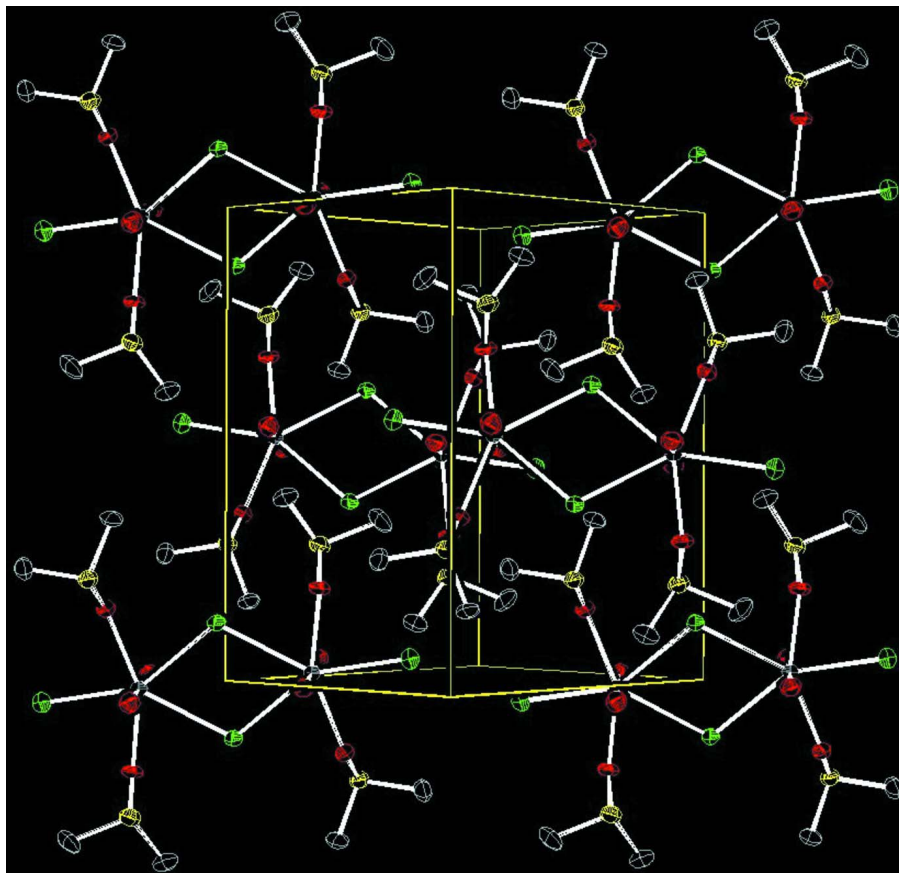


Figure 2

Packing view of **I** drawn by thermal ellipsoids in 50% probability level. Hydrogen atoms are omitted for clarity.

### Di- $\mu$ -chlorido-bis[chloridobis(dimethyl sulfoxide)dioxidouranium(VI)]

#### Crystal data

$[\text{U}_2\text{Cl}_4\text{O}_4(\text{C}_2\text{H}_6\text{OS})_4]$

$M_r = 994.37$

Monoclinic,  $P2_1/c$

Hall symbol: -P 2ybc

$a = 9.172$  (3) Å

$b = 12.833$  (4) Å

$c = 10.691$  (2) Å

$\beta = 97.72$  (2)°

$V = 1247.0$  (6) Å<sup>3</sup>

$Z = 2$

$F(000) = 904$

$D_x = 2.648$  Mg m<sup>-3</sup>

Mo  $K\alpha$  radiation,  $\lambda = 0.71075$  Å

Cell parameters from 10519 reflections

$\theta = 3.1$ – $27.5$ °

$\mu = 13.76$  mm<sup>-1</sup>

$T = 173$  K

Block, yellow

$0.33 \times 0.21 \times 0.15$  mm

#### Data collection

Rigaku R-AXIS RAPID IP  
diffractometer

Radiation source: fine-focus sealed tube

Graphite monochromator

Detector resolution: 10.00 pixels mm<sup>-1</sup>

$\omega$  scans

Absorption correction: multi-scan  
(Higashi, 1999)

$T_{\min} = 0.051$ ,  $T_{\max} = 0.128$

10244 measured reflections

2849 independent reflections

2330 reflections with  $I > 2\sigma(I)$

$R_{\text{int}} = 0.084$

$\theta_{\max} = 27.5^\circ$ ,  $\theta_{\min} = 3.2^\circ$   
 $h = -11 \rightarrow 11$

$k = -16 \rightarrow 15$   
 $l = -13 \rightarrow 13$

### Refinement

Refinement on  $F^2$   
 Least-squares matrix: full  
 $R[F^2 > 2\sigma(F^2)] = 0.043$   
 $wR(F^2) = 0.111$   
 $S = 1.10$   
 2849 reflections  
 120 parameters  
 0 restraints  
 Primary atom site location: structure-invariant  
 direct methods  
 Secondary atom site location: difference Fourier  
 map

Hydrogen site location: inferred from  
 neighbouring sites  
 H-atom parameters constrained  
 $w = 1/[\sigma^2(F_o^2) + (0.0595P)^2]$   
 where  $P = (F_o^2 + 2F_c^2)/3$   
 $(\Delta/\sigma)_{\max} = 0.001$   
 $\Delta\rho_{\max} = 2.54 \text{ e } \text{\AA}^{-3}$   
 $\Delta\rho_{\min} = -2.25 \text{ e } \text{\AA}^{-3}$   
 Extinction correction: *SHELXL*,  
 $F_c^* = kFc[1 + 0.001xFc^2\lambda^3/\sin(2\theta)]^{-1/4}$   
 Extinction coefficient: 0.0012 (2)

### Special details

**Geometry.** All e.s.d.'s (except the e.s.d. in the dihedral angle between two l.s. planes) are estimated using the full covariance matrix. The cell e.s.d.'s are taken into account individually in the estimation of e.s.d.'s in distances, angles and torsion angles; correlations between e.s.d.'s in cell parameters are only used when they are defined by crystal symmetry. An approximate (isotropic) treatment of cell e.s.d.'s is used for estimating e.s.d.'s involving l.s. planes.

**Refinement.** Refinement of  $F^2$  against ALL reflections. The weighted  $R$ -factor  $wR$  and goodness of fit  $S$  are based on  $F^2$ , conventional  $R$ -factors  $R$  are based on  $F$ , with  $F$  set to zero for negative  $F^2$ . The threshold expression of  $F^2 > 2\sigma(F^2)$  is used only for calculating  $R$ -factors(gt) etc. and is not relevant to the choice of reflections for refinement.  $R$ -factors based on  $F^2$  are statistically about twice as large as those based on  $F$ , and  $R$ -factors based on ALL data will be even larger.

### Fractional atomic coordinates and isotropic or equivalent isotropic displacement parameters ( $\text{\AA}^2$ )

	$x$	$y$	$z$	$U_{\text{iso}}^*/U_{\text{eq}}$
U1	0.78418 (3)	0.51860 (2)	0.35047 (3)	0.02280 (14)
Cl1	0.9986 (2)	0.37721 (17)	0.4687 (2)	0.0309 (5)
Cl2	0.5528 (3)	0.5489 (2)	0.1718 (2)	0.0381 (5)
S1	0.7780 (2)	0.28472 (17)	0.1748 (2)	0.0279 (5)
S2	0.8069 (3)	0.78684 (18)	0.3045 (2)	0.0319 (5)
O1	0.6738 (8)	0.4945 (5)	0.4683 (6)	0.0310 (14)
O2	0.8996 (8)	0.5398 (5)	0.2345 (6)	0.0327 (15)
O3	0.7203 (7)	0.3496 (5)	0.2783 (5)	0.0280 (13)
O4	0.7311 (7)	0.6977 (5)	0.3661 (5)	0.0296 (14)
C1	0.7963 (11)	0.1587 (7)	0.2424 (9)	0.037 (2)
H1A	0.8810	0.1575	0.3089	0.044*
H1B	0.8112	0.1077	0.1771	0.044*
H1C	0.7068	0.1412	0.2788	0.044*
C2	0.6207 (11)	0.2632 (8)	0.0621 (8)	0.038 (2)
H2A	0.5958	0.3275	0.0145	0.045*
H2B	0.5377	0.2424	0.1055	0.045*
H2C	0.6416	0.2078	0.0039	0.045*
C3	0.8216 (13)	0.8880 (8)	0.4207 (9)	0.047 (3)
H3A	0.8973	0.8694	0.4907	0.057*
H3B	0.7269	0.8965	0.4523	0.057*
H3C	0.8487	0.9534	0.3826	0.057*

C4	0.6660 (13)	0.8391 (8)	0.1913 (8)	0.044 (3)
H4A	0.6462	0.7909	0.1199	0.053*
H4B	0.6980	0.9064	0.1612	0.053*
H4C	0.5762	0.8488	0.2303	0.053*

*Atomic displacement parameters (Å<sup>2</sup>)*

	$U^{11}$	$U^{22}$	$U^{33}$	$U^{12}$	$U^{13}$	$U^{23}$
U1	0.0247 (2)	0.0179 (2)	0.0251 (2)	0.00006 (13)	0.00058 (12)	0.00017 (11)
C11	0.0314 (12)	0.0197 (11)	0.0385 (11)	0.0033 (9)	-0.0067 (8)	-0.0050 (8)
C12	0.0366 (13)	0.0324 (13)	0.0412 (13)	0.0003 (10)	-0.0095 (9)	0.0021 (10)
S1	0.0264 (12)	0.0235 (12)	0.0338 (11)	-0.0005 (9)	0.0040 (8)	-0.0015 (8)
S2	0.0318 (13)	0.0245 (12)	0.0395 (12)	0.0020 (9)	0.0052 (9)	0.0044 (9)
O1	0.036 (4)	0.025 (3)	0.032 (3)	-0.001 (3)	0.004 (3)	-0.003 (2)
O2	0.036 (4)	0.033 (4)	0.029 (3)	-0.003 (3)	0.004 (2)	0.000 (3)
O3	0.032 (4)	0.023 (3)	0.027 (3)	0.000 (3)	0.000 (2)	-0.003 (2)
O4	0.038 (4)	0.014 (3)	0.036 (3)	0.002 (3)	0.004 (2)	0.002 (2)
C1	0.038 (6)	0.020 (5)	0.051 (6)	0.010 (4)	0.001 (4)	-0.002 (4)
C2	0.043 (6)	0.037 (6)	0.030 (5)	0.008 (5)	-0.007 (4)	-0.002 (4)
C3	0.051 (7)	0.027 (6)	0.061 (7)	-0.013 (5)	-0.001 (5)	-0.001 (5)
C4	0.055 (7)	0.041 (6)	0.036 (5)	0.011 (5)	0.001 (4)	0.018 (4)

*Geometric parameters (Å, °)*

U1—O1	1.746 (7)	S2—C4	1.779 (9)
U1—O2	1.757 (6)	S2—C3	1.789 (10)
U1—O3	2.349 (6)	C1—H1A	0.9800
U1—O4	2.360 (6)	C1—H1B	0.9800
U1—C12	2.686 (2)	C1—H1C	0.9800
U1—C11	2.844 (2)	C2—H2A	0.9800
U1—C11 <sup>i</sup>	2.909 (2)	C2—H2B	0.9800
C11—U1 <sup>i</sup>	2.909 (2)	C2—H2C	0.9800
U1—U1 <sup>i</sup>	4.7669 (16)	C3—H3A	0.9800
C11—C11 <sup>i</sup>	3.221 (3)	C3—H3B	0.9800
S1—O3	1.535 (6)	C3—H3C	0.9800
S1—C1	1.770 (9)	C4—H4A	0.9800
S1—C2	1.773 (9)	C4—H4B	0.9800
S2—O4	1.533 (6)	C4—H4C	0.9800
O1—U1—O2	178.0 (3)	C4—S2—C3	100.3 (5)
O1—U1—O3	86.0 (2)	S1—O3—U1	130.0 (4)
O2—U1—O3	93.4 (2)	S2—O4—U1	125.9 (4)
O1—U1—O4	88.6 (3)	S1—C1—H1A	109.5
O2—U1—O4	92.8 (3)	S1—C1—H1B	109.5
O3—U1—O4	151.3 (2)	H1A—C1—H1B	109.5
O1—U1—C12	93.4 (2)	S1—C1—H1C	109.5
O2—U1—C12	88.2 (2)	H1A—C1—H1C	109.5
O3—U1—C12	76.21 (15)	H1B—C1—H1C	109.5

O4—U1—C12	76.03 (16)	S1—C2—H2A	109.5
O1—U1—C11	90.0 (2)	S1—C2—H2B	109.5
O2—U1—C11	88.1 (2)	H2A—C2—H2B	109.5
O3—U1—C11	71.59 (15)	S1—C2—H2C	109.5
O4—U1—C11	136.62 (15)	H2A—C2—H2C	109.5
C12—U1—C11	147.29 (7)	H2B—C2—H2C	109.5
O1—U1—C11 <sup>i</sup>	90.8 (2)	S2—C3—H3A	109.5
O2—U1—C11 <sup>i</sup>	88.5 (2)	S2—C3—H3B	109.5
O3—U1—C11 <sup>i</sup>	139.54 (15)	H3A—C3—H3B	109.5
O4—U1—C11 <sup>i</sup>	68.58 (15)	S2—C3—H3C	109.5
C12—U1—C11 <sup>i</sup>	144.24 (7)	H3A—C3—H3C	109.5
C11—U1—C11 <sup>i</sup>	68.09 (7)	H3B—C3—H3C	109.5
U1—C11—U1 <sup>i</sup>	111.91 (7)	S2—C4—H4A	109.5
O3—S1—C1	102.9 (4)	S2—C4—H4B	109.5
O3—S1—C2	104.3 (4)	H4A—C4—H4B	109.5
C1—S1—C2	99.2 (5)	S2—C4—H4C	109.5
O4—S2—C4	104.1 (5)	H4A—C4—H4C	109.5
O4—S2—C3	103.9 (4)	H4B—C4—H4C	109.5
O1—U1—C11—U1 <sup>i</sup>	-90.9 (2)	C12—U1—O3—S1	92.7 (4)
O2—U1—C11—U1 <sup>i</sup>	89.2 (2)	C11—U1—O3—S1	-81.5 (4)
O3—U1—C11—U1 <sup>i</sup>	-176.64 (17)	C11 <sup>i</sup> —U1—O3—S1	-86.3 (4)
O4—U1—C11—U1 <sup>i</sup>	-2.9 (3)	C4—S2—O4—U1	113.6 (5)
C12—U1—C11—U1 <sup>i</sup>	172.88 (11)	C3—S2—O4—U1	-141.8 (5)
C11 <sup>i</sup> —U1—C11—U1 <sup>i</sup>	0.0	O1—U1—O4—S2	169.6 (5)
C1—S1—O3—U1	138.5 (5)	O2—U1—O4—S2	-9.0 (5)
C2—S1—O3—U1	-118.4 (5)	O3—U1—O4—S2	-111.3 (5)
O1—U1—O3—S1	-172.8 (5)	C12—U1—O4—S2	-96.5 (4)
O2—U1—O3—S1	5.3 (5)	C11—U1—O4—S2	81.1 (4)
O4—U1—O3—S1	107.4 (5)	C11 <sup>i</sup> —U1—O4—S2	78.3 (4)

Symmetry code: (i)  $-x+2, -y+1, -z+1$ .