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PAPER

When two symmetrically independent molecules must be different: "Crystallization-induced diastereomerization" of chiral β-hydroxy sulfone on the basis of natural (−)-β-pinene†‡

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According to X-ray data homochiral pinanyl sulfone crystallizes as an asymmetric dimer formed by pairwise H-bonds involving stereochemically different oxygen atoms of sulfonyl groups of molecules A and B. Thus *pro-R* atom is invoked for construction of relevant H-bond in the molecule A, but in the case of the molecule B only *pro-S* atom is involved. Newly formed chiral sulfur atoms take opposite chirality in molecules A and B, while the configuration of the pinane skeleton remains unchanged. Such stereochemical transformation is called "**crystallization-induced diastereomerization**". The stability of the asymmetric dimer found in the crystal, evaluated within the framework of DFT (B3LYP, 6-31G (d,p)), as well as studied by IR spectroscopy in solution.

Introduction

The phenomenon of $Z' > 1$ crystal structures formation is extensively studied for the last few years.[1-8] The origins of this phenomenon are still largely unclear, though there were various reasons put forward to explain it. Thus, Desiraju[2] have recently suggested that some high Z' structures may be metastable relics of fast growing crystal nuclei. There have been a range of particularly significant studies in the past year alone.

Anderson[3] have shown that the tendency toward high Z' structures can be increased by introducing competition between strongly directional hydrogen-bonded motifs and other packing forces (*e.g.*, π-stacking), which can frustrate the molecules causing arrangements with large values of Z'.

The incidence of $Z' > 1$ is known to be higher in chiral space groups than for the centrosymmetric space group. Structures with more than one independent molecule often show some pseudosymmetry where pairs of independent molecules are related by approximate -1, 2, or 2_1 operations. Chiral molecules cannot be related to each other by some of the more common symmetry operations, consequently they often exhibit pseudosymmetry.

Anderson[6] supposed that the likelihood of a chiral molecule forming a pseudo-centrosymmetric arrangement is greatly enhanced if the molecule is already predisposed to pack in a centrosymmetric manner, for example, if it contains a strongly directional supramolecular synthon with a preference for centrosymmetry. This idea has previously been represented generally as the "shape mimicry" concept by Whitesell and Davis.[9] It would therefore be expected that these species would still show a strong preference to form the centrosymmetric dimer,

but that the packing of the molecules would necessarily have to adapt to allow formation of this dimer because of the absence of a crystallographic inversion center. Hence there should be a strong tendency for the compound to crystallize with more than one molecule in the asymmetric unit.
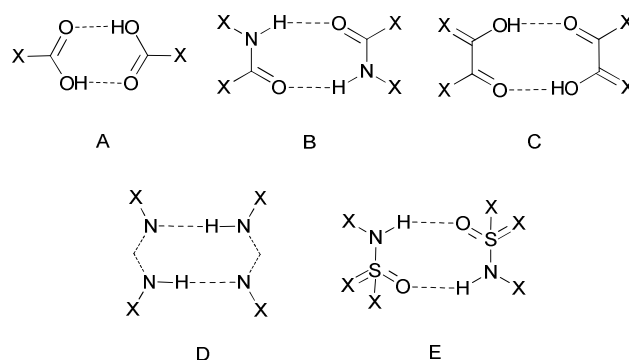
Fig. 1 The centrosymmetric hydrogen bond motifs,[6] X = any non-hydrogen atom. Dashed line indicates hydrogen bond.

As of now, there are totally 5 strongly directional supramolecular synthons with a preference for centrosymmetry described, among which there are carboxylic acid dimers, amide dimers, and some others (Fig. 1).[6] For all the five synthons, a rather large number of chiral structures is distinguished, which crystallize with more than one independent molecule. At the same time, for all the five synthons, there are chiral structures that crystallize with one independent molecule – this is possible, in case the dimer is situated on a 2-fold rotation axes.

Regarding differences between independent molecules in crystal, in most cases the molecules A and B are in the pseudo-

symmetric relations and, consequently, their difference is geometrically insignificant. So, in the common volume of publications on the issue *Z' > 1* the statement of J. Steed is widely known: "*The second independent molecule is not significantly different from the first*".[1] The significantly lesser amount of *Z'* = 2 structures, which are presented in literature, are characterized by distinctions in kind between molecules A and B, which can consist of either conformation, or (which is more uncommon) – of configuration of one or several stereogenic centers of molecule – these are cases of co-crystallization of diastereomers.[10-17]
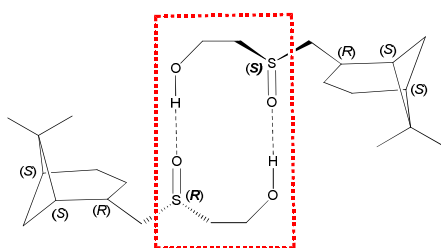
Fig. 2 The H-bonded dimer, formed by diastereomeric pinanyl sulfoxides.[17] Dashed lines indicate hydrogen bonds, red color shows the supramolecular synthon F.

Previously, we have discovered and studied the stable co-crystallization of diastereomeric (by sulfur atom) pinanyl sulfoxides.[17] These compounds are crystallized as H-bonded dimers, constructed by forming a new centrosymmetrical stereogenic sulfur-containing synthon F (Fig. 2).

In this paper we present an unexpected *Z'* = 2 crystallization type of homochiral pinanyl sulfone, associated with formation of similar supramolecular synthon.

We analyze the reasons of inclusion of an "additional" molecule into cell, and answer the question – what the second independent molecule does significantly differ from the first one with.

Results and discussion

In the previous publication we have described the phenomenon of stable co-crystallization of diastereomeric pinanyl sulfoxides **2a** and **2b**, obtained by the oxidation of sulfide **1** by the use of *m*-chloroperbenzoic acid (Scheme 1).[17] As a minor product in this reaction the corresponding sulfone **3** is formed, which can be as well easily prepared from the sulfide **1** according to the known method using hydrogen peroxide in combination with acetic acid.
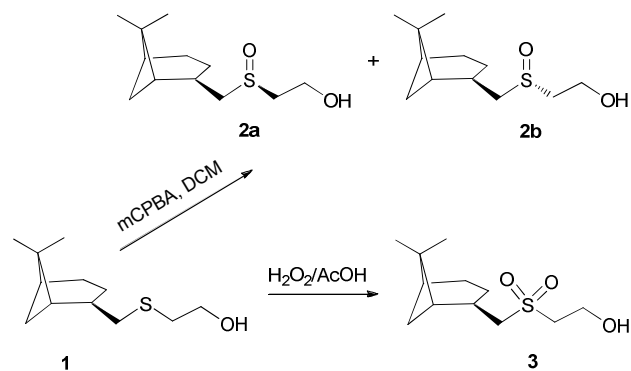
Scheme 1 Preparation of compounds **2** and **3**.
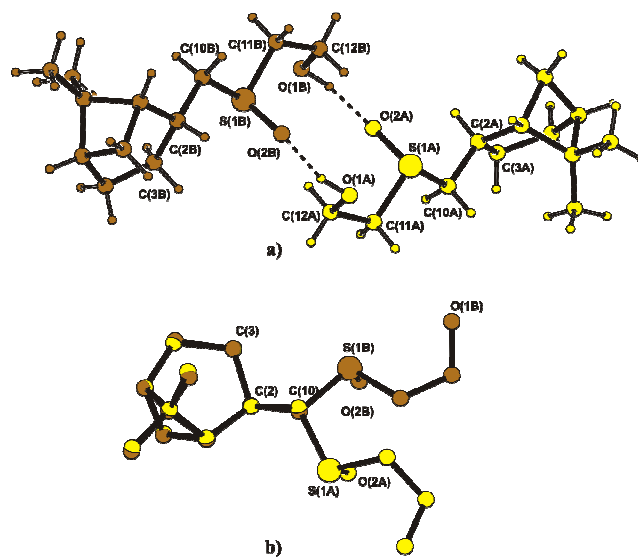
Fig. 3 a) The hydrogen-bonded dimer of **2a+2b**; b) Overlap of molecules A and B in crystal of **2**.

Crystal structures

For the co-crystal of diastereomeric pinanyl sulfoxides **2a** and **2b** we have found two modifications – triclinic and monoclinic, wherein in both cases the compound is presented by the hydrogen-bonded dimer (Fig. 3).

For the diastereomeric molecules **2a** and **2b** the different conformations along the bond C^2-C^{10} were observed: *trans* conformation around C^{10}-S^1 and C^2-C^3 bonds takes place for isomeric molecule **2a** bearing R_S configuration of stereogenic sulfur atom, at the same time C^2-C^1 bond of bicyclic skeleton adopt *trans* orientation relative to C^{10}-S^1 bond in **2b** with S_S configuration of heteroatom. Oxygen atoms of the both sulfinyl groups are placed far away from the carbocyclic fragment to avoid unfavorable steric contacts (see Table S1‡).

Thus, in the co-crystals of diastereomeric sulfoxides two independent molecules A and B have significantly different conformations, which is generally typical for isomeric molecules.

Surprisingly, we have found a similar H-bonded dimer, formed by independent molecules A and B, differing in conformation along the key bond C^2-C^{10} in the crystal of pinanyl sulfone **3**, where all sulfone molecules are identical in stereochemical aspect. What is the reason of inclusion of an "extra" molecule into unit cell in this case can?

In order to answer these questions we will examine the structure of dimer **3** (Fig. 4). These situation resembles that in the parent sulfoxides **2**, featuring in the presence of S=O…H-O interactions in 12-membered cycle. Conformation around C^2-C^{10} bond for molecules A and B is differs again as in sulfoxide **2**. It is obvious the tendency of oxygen atoms invoked in H-bonding (more encumbered) to occupy *transoid* position relative to *gem*-dimethyl fragment of pinane skeleton. *Gauche*-form of -$S^1C^{11}C^{12}O^1$- fragment in **3** similar to **2** was also established while *gauche* conformation around S^1-C^{11} bond is typical for sulfone molecule only. In dimer **3** H-bonds between sulfone molecules are not identical: O^{1A}-H^{1A}…O^{3B} bond is significantly shorter than that of O^{1B}-H^{1B}…O^{2A} (Table 1). Most probably S^{1B}=O^{3B} bond appeared to be some enlarged in comparison with S^{1B}=O^{2B} and

S^{1A}=O^{2A} as a result. Analogous situation was established for O^{1A}-C^{12A} and O^{1B}-C^{12B} bonds (Table S1‡).
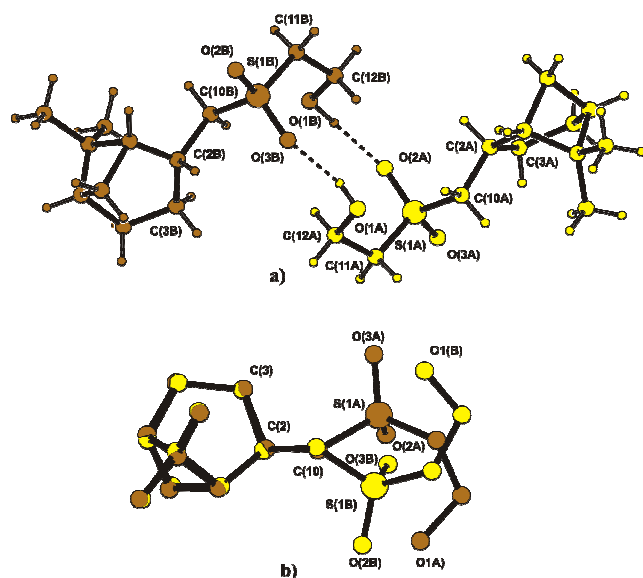

Fig. 4 a) The hydrogen-bonded dimer of **3**; b) Overlap of molecules A and B in crystal of **3**.

Table 1 Hydrogen bonds in crystal of **3**

Bond	D-H, Å	H…A, Å	D…A, Å	∠D-H…A, °
O^{1A}-H^{1A}…O^{3B}	0.90(6)	1.91(5)	2.781(5)	165(5)
O^{1B}-H^{1B}…O^{2A}	0.99(3)	1.85(3)	2.826(5)	169(2)

Stereochemical representation seems to be somewhat delicate and deserves a special comment. Sulfur atom in sulfone **3** is not stereogenic as in isomeric sulfoxides **2**. Molecules of isolated sulfone **3** are stereochemically homogeneous (homochiral) bearing three stereogenic carbons C^1, C^2 and C^5 incorporated into a pinane moiety and acyclic achiral fragment HOCH$_2$CH$_2$SO$_2$- as a substituent. Crystal phase analysis of the molecule under consideration prompted us to propose that the geminal oxygen atoms of both sulfone groups incorporating in cyclic dimer molecule may be refer to as heterotopic (as C in XABC$_2$). Consequently the descriptors *pro-R* and *pro-S* can be used. Thus O^2 *pro-R* atom is invoked for construction of relevant H-bond in molecule A, but in the case of the molecule B only *pro-S* O^3 atom is involved. There is a reason to believe that 12-membered cycles both **2** and **3** are formed by the –SO(O)$_{n=0,1}$CH$_2$CH$_2$OH moieties having opposite configuration. If this is the case we have encountered with the heterochiral dimer **3** whose sulfur atoms one should refer to as stereogenic.

Fundamental difference between **2** and **3** is based on the stereochemistry of a β-hydroxy sulfoxide (sulfone) involved in the dimerization process. In the first case optically active diastereomeric sulfoxides **2a** and **2b** serve as a starting material. Dimer **3** is formed from two identical molecules of sulfone and there diastereomerization takes place at the stage of the 12-membered H-bonded cycle building (Scheme 2).
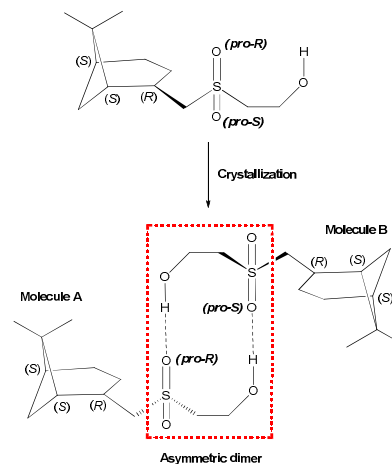
Scheme 2 Crystallization-induced diastereomerization of pinanyl sulfone **3**. Red color shows the supramolecular synthon F.

It should be noted that the dimer of sulfone **3**, due to its stereochemical features, is not simply homochiral, but also fully asymmetric. Since placing on the 2-fold rotation axis, which is the only possibility of placing in the crystal without including an additional molecule into unit cell available to the typical homochiral dimers, is not available for it, it invariably forms a Z' ≥ 2 crystal. Despite the features of crystallization of homochiral dimers have attracted attention previously (see Introduction), associates of this type were not described in literature before.

At the same time to search *via* CSD[18] allowed finding similar asymmetric dimers of five chiral sulfonamides (refcodes ATOVIO, AXAGOV, CAZFEP, NAKNAO, NISBIB). Crystals of these compounds contain centrosymmetrical synthon E (see Introduction). The scheme of formation of such dimers is similar **3**: two crystallographically independent molecules involved stereochemically nonequivalent oxygen atoms of sulfone group in hydrogen binding. Notable is that in the 5 above mentioned cases the crystallographically independent molecules are in crystals in different conformations, which is typical for different diastereomeric forms.

We suggest to use a new term "**crystallization-induced diastereomerization**" for description of stereochemical process leading to formation of sulfone dimers **3**, and of the five above mentioned sulfones (by contrast with the conventional term of the modern literature CIDT – "crystallization-induced diastereomeric transformation" – for designation of the inverse process – the crystallization of compound of equilibrating diastereomers in only diastereomeric form).[19]

In addition of asymmetric homochiral dimers research we have attempted to obtain such associate on the basis of camphanyl sulfone prepared from (+)-camphene – in other words, we have attempted to replace the chiral fragment while keeping the centrosymmetric synthon. However, due to synthetic difficulties,[20] we obtained a racemic camphanyl sulfone, which in crystal forms a common centrosymmetric dimer (containing synthon F as well, see Fig. 5).
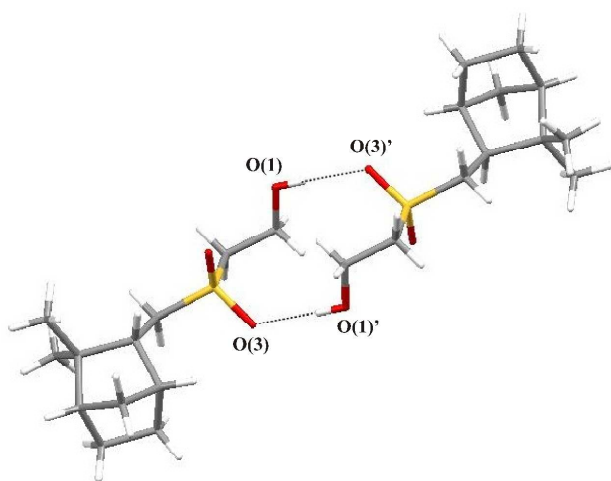
Fig. 5 Centrosymmetric dimer of camphanyl sulfone, our previously work,[20] space group *P*-1, *Z'* = 1.

We also took an interest, how stable the fully asymmetric
5 dimer is which we have found in the pinanyl sulfone crystal.

DFT calculations

We have calculated a dimer and various types of monomers within DFT (B3LYP, 6-31G (d,p)).

The geometry of dimer is reproduced quite well within
10 quantum chemistry (Fig. 6). It can be noted that nonequivalence of H-bonds remains in the gas phase as well (because of the asymmetric structure of dimer): distance $O^{1A}...O^{3B}$ is 2.79 Å, distance $O^{1B}...O^{2A}$ is 2.81 Å.
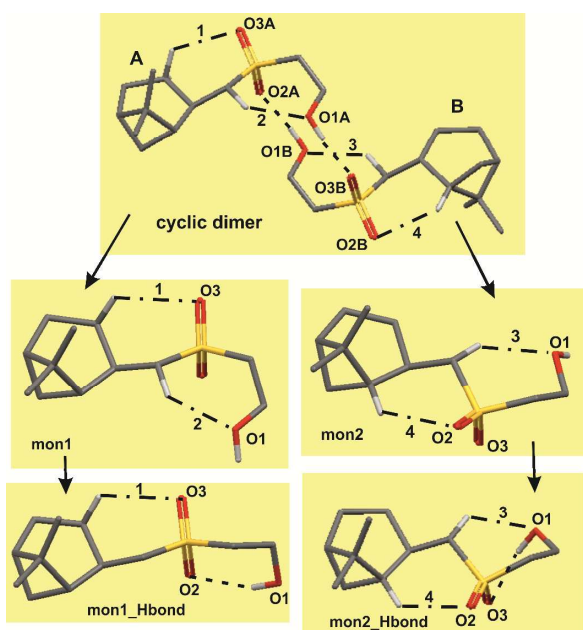
Fig. 6 The optimized geometry of dimer **3** (top) and stable conformations
of monomer (bottom), O-H…O-interactions are marked with dotted lines,
C-H…O-interactions are marked with chain lines, numbers 1-4 mean the
C-H…O-interactions observed both in a cyclic dimer and in monomers.
20 Only the hydrogen atoms involved in O-H…O and C-H…O interactions
are shown.

Regarding monomers, for the molecule of sulfone we have optimized four various forms (Fig. 6). According to calculations, the conformations of molecules A and B, observed in crystals, are
25 stable in isolated state as well – these are the forms **mon1** and **mon2**. These two forms are stabilized by two C-H…O-interactions (1 and 2 for **mon1**, 3 and 4 for **mon2** on Fig. 6), the same interactions are typical for the optimized conformation of dimer **3** (parameters of C-H…O interactions given in Table S2‡).
30 Furthermore it is possible to transform the structures **mon1** and **mon2** to two diastereomeric forms of monomer, which are stabilized by intramolecular classical hydrogen bond by means of either O^2-atom (**mon1_Hbond**), or O^3atom (**mon2_Hbond**). Intramolecular H-bonds in monomeric structures are
35 characterized by weaker parameters as compared with those in the **cyclic dimer**, so distance $O^1...O^2$ is 2.87 Å in **mon1_Hbond** and distance $O^1...O^3$ is 2.91 Å in **mon2_Hbond**. The energy characteristics of dimer and monomer forms are compared in the Table 2. It is notable, that the forms **mon1** and **mon2** are not at a
40 big disadvantage in energy compared to monomers **mon1_Hbond** and **mon2_Hbond**. This suggests that the former coexist in solution with the latter. It does facilitate the dimerization significantly, because in forms **mon1** and **mon2** the molecules of sulfone are conformationally pre-organized for the
45 formation of cyclic asymmetric dimer.

Table 2 The relative Gibbs free energies of pinanyl sulfone monomers versus the most stable conformation and dimerization energy, kcal/mol

|	Cyclic dimer[a]	mon1	mon2	mon1_Hbond	mon2_Hbond
ΔG_{298}, kcal/mol	−2.66	0.92	1.40	0	0.49

[a] ΔG_{298}dim = Gdim−Gmon1−Gmon2.

IR study

50 To find out whether the dimers found in crystal can exist also in solution of sulfone, IR spectra of sulfone **3** in crystals and in CCl$_4$ solutions were studied.

The vibrational frequencies and IR intensities computed by B3LYP/6-31G (d,p) method for OH stretching bands ν(OH) of
55 different forms of associates are compared with their be in good agreement.

In the IR spectrum of sulfone **3** crystalline phase the symmetrical contour centered at 3472 cm^{-1} (ν(OH)$_{ass}$) is observed (Fig. S1‡).
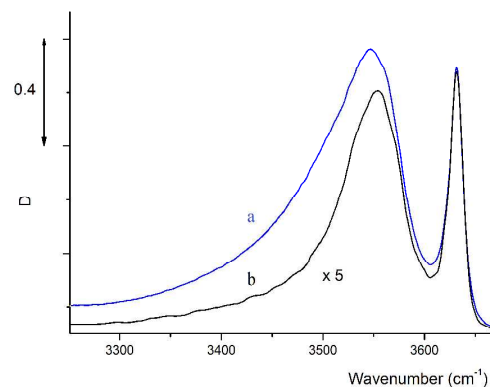
60 **Fig. 7** The ν(OH)$_{ass}$ contour in the IR spectra of sulfone **3** in CCl$_4$ solutions at a concentration 10^{-2} mol/L (a) and 10^{-3} mol/L (b).

For estimation by IR spectroscopy of the dimer **3** stability, behavior of pinanyl sulfone was studied in CCl$_4$ solutions at a concentration of 10^{-2} mol/L and 10^{-3} mol/L (see Fig. 7).
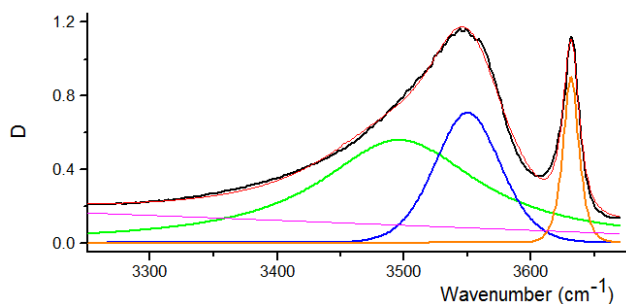
Fig. 8 Hydroxyl absorption curve fitting procedure for a 10^{-2} mol/L CCl$_4$ solution of sulfone **3**.

A curve fitting procedure can be applied to calculate quantitatively the area of each individual component representing Gaussian-Lorentz function. Fig. 8 shows the result of fitting procedure for a spectrum of sulfone in CCl$_4$ solutions at a concentration of 10^{-2} mol/L, which was obtained using OPUS software.

Dilution from 10^{-2} to 10^{-3} mol/L causes a decrease of its half-width and shift of maximum to a high frequency region as a result of the complex associates to be partially destroyed.

IR spectrum of CCl$_4$ solution at a concentration of 10^{-2} mol/L also exhibits the band of free OH vibration (ν(OH)$_{free}$) at 3631 cm^{-1}, and a broad band in the 3200–3600 cm^{-1} range originated from associated OH groups, ν(OH)$_{ass}$.

Comparison of a solid state spectrum for dimer **3** with those of solutions demonstrates, as expected, more complicated pictures due to the appearance of associates with different hydrogen bond energies. Along with the cyclic dimer possessing two intermolecular hydrogen bonds and monomer bearing no hydrogen bond and having free OH group can expect two associates in addition: linear dimer (or more high-associated structures) formed by one intermolecular hydrogen bond and monomer with intramolecular hydrogen bond. Experimental contour centered at 3631 cm^{-1} may be attributed to ν(OH)$_{free}$ of monomers forms **mon1** and **mon 2**.[18]

Hydroxyl absorption curves (10^{-2} and 10^{-3} mol/L) was also subjected to deconvolution. It appears that cyclic dimer still persist in 10^{-2} mol/L CCl$_4$ solution [ν$_{OH}$ (dimer) 3496 cm^{-1}] along with a new band at 3550 cm^{-1}, whereas the band that has been adopted to linear dimer with intermolecular hydrogen bond was found to be disappeared. 10^{-3} mol/L spectrum of **3** displays both components again though the drop in intensity of the low frequency band takes place as a result of the cyclic dimer diminishing.

The hydroxyl absorption at 3550 cm^{-1} seems to be originated either from linear dimer or monomer with intramolecular H–bond. This band may be attributed to linear dimer based on good agreement with calculation data (see Table S3‡).

Thus, we have established, that the non-typical asymmetric dimer, detected by X-ray crystallography in the crystal phase, exists in solutions of various concentration as well as the other associates.
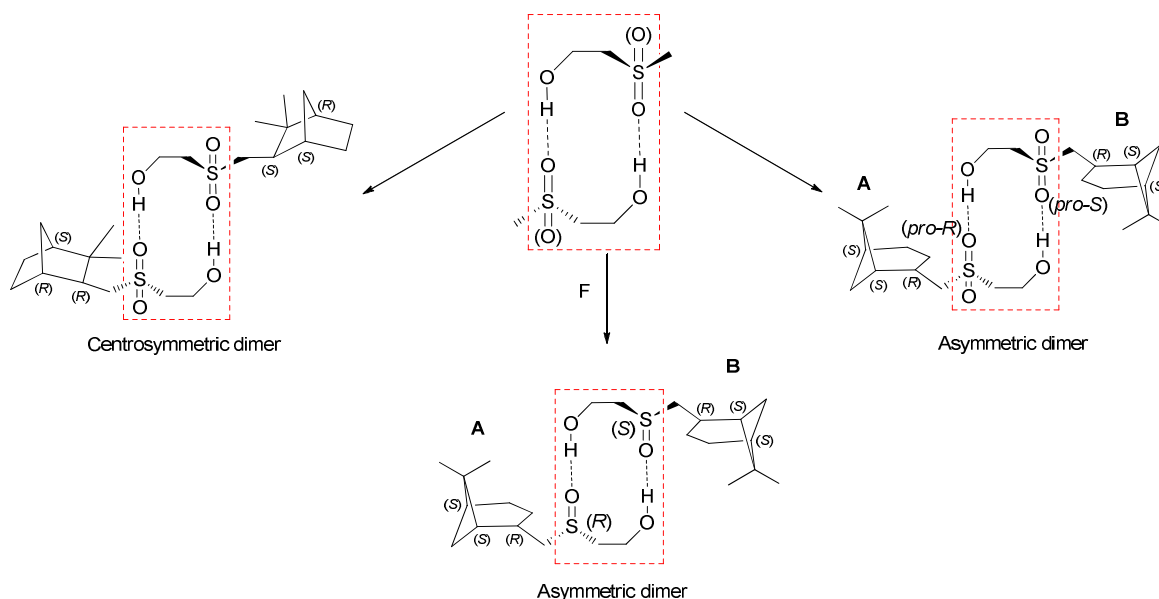
Scheme 3 New centrosymmetric stereogenic sulfur-containing synthon F in chiral and racemic crystals.

Conclusions

For the first time, the stereochemical transformation accompanying crystallization of homochiral pinanyl sulfone, and also some chiral sulfonamides are found and studied. We suggest to use a new term – "**crystallization-induced diastereomerization**" – to designate this phenomenon. From the viewpoint of the crystal engineering, this phenomenon is interesting in that it invariably results in a $Z' = 2$ structure, in which molecules A and B are essentially different in their conformations as they represent two diastereomeric forms.

From the supramolecular chemistry's point of view, we can speak of the finding of a new robust and reproducible synthon F

(Scheme 3). Tendency to form such a synthon is caused by the fragment structure, most critical for its hydrogen bonding. Namely, the chirality of a sulfoxide sulfur atom (or the prochirality of the sulfone sulfur atom), combined with the fixed *gauche*-conformation of -SO(O)-CH$_2$-CH$_2$-OH fragment, determines the specific spatial organization of the group in general, for which the formation of a cyclic dimer with a group of the contrary configuration is preferable. The "finished" -SO(O)-CH$_2$-CH$_2$-OH groups complying with this condition contain the isomeric molecules of sulfoxides. For sulfone, the problem of choosing geometrically corresponding fragments is solved by involving stereochemically different (diastereotopic) oxygen atoms from two different molecules into interaction.

From the stereochemical point of view, an "*enantiophilic*" fragment was discovered – a β-hydroxy sulfoxide (sulfone) group, capable of recognizing its mirror image both in an explicit state (a racemic camphanyl sulfone) and in a concealed state (the diastereomeric pair of sulfoxides and a homochiral pinanyl sulfone).

Experimental

General

For isolation and purification of the reaction products the method of adsorption chromatography on silica gel L (100/160 μ) was applied. As eluents a methylene chloride–acetone mixtures were used. The reaction progress and the quality of the separation of reaction mixtures were monitored by TLC on Silufol plates, developers I$_2$ and ethanol–sulfuric acid–anisaldehyde mixture (90 : 5 : 5). To remove water and purify the solvents we used known techniques described in literature.[21]

NMR spectra were obtained on a Bruker Avance instrument (Germany) with the operating frequencies 400.13 and 100.61 MHz for ^{1}H and ^{13}C nuclei respectively, internal reference TMS.

Melting points of substances were determined on a Koeffler apparatus and were uncorrected.

The infrared spectra were recorded on a FTIR Bruker Vector 22 spectrometer (400−4000 cm^{-1}). The interferograms were collected with a resolution of 2 cm^{-1}, 128 scans, and Fourier transformed using a Blackman-Harris apodization function. We have analyzed the spectra of the solid (crystals) samples and solutions in CCl$_4$. For registration of the spectra of solutions CaF$_2$ cells were used with different spacers (0.1−50.0 mm) to achieve the best signal/noise ratio. Concentrations of compounds were varied from 0.01 to 0.2 M.

Gaussian curve-fitting

Spectra data were processed with the OPUS-7.0 software (Bruker Optik GmbH) using spectra averaging, baseline correction and peak picking techniques. The curve-fitting was performed to acquire single Gaussian-Lorentz function components of overlapped bands.

X-Ray diffraction‡

The X-ray diffraction data for the crystals of **3** were collected on a Smart Apex II automatic diffractometer (Bruker, Germany) using graphite monochromated radiation MoK$_α$ ($λ$ 0.71073), T = 293 K. Details of crystal data, data collection, and refinement are given in Table 3. The structures were solved by direct method

using the SHELXS^{22} program and refined by full-matrix least-squares using SHELXL97^{23} program. All the non-hydrogen atoms were refined with anisotropic atomic displacement parameters. H(C) atoms were constrained as riding atoms, with C-H set to 0.95 Å. The hydroxyl H atoms were located from a difference Fourier map and refined isotropically in the final stages of refinement. All figures were made using the program PLATON.^{24} Crystallographic data (excluding structure factors) for the structure **3** reported in this paper has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 970674. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

Table 3 Crystallographical data and parameters of X-ray diffraction experiment

Compound reference	**3**
Chemical formula	C$_{12}$H$_{22}$O$_3$S
Formula Mass	246.36
Crystal system	Monoclinic
a/Å	13.982(3)
b/Å	6.474(2)
c/Å	15.002(4)
$β$/°	100.430(3)
Unit cell volume/Å^3	1335.4(5)
Temperature/K	296(2)
Space group	$P2_1$
No. of formula units per unit cell, Z	4
Absorption coefficient, $μ$/mm^{-1}	0.234
No. of reflections measured	11312
No. of independent reflections	5957
R_{int}	0.0524
Final R_1 values ($I > 2σ(I)$)	0.0601
Final $wR(F^2)$ values ($I > 2σ(I)$)	0.1446
Final R_1 values (all data)	0.1310
Final $wR(F^2)$ values (all data)	0.1743
Flack parameter	0.0(1)

DFT calculations

Geometry optimizations and vibrational frequencies were carried out at basic DFT level using B3LYP$^{25, 26}$ 6-31G (d,p) basis set available in Gaussian-03 package.^{27} These values were corrected using scale factor 0.9613 [DFT]^{28} and the corrected frequencies and proposed assignments were summarized in Table 2 along with the observed values. These values indicate that there is a close agreement between the calculated values and observed values.

Experimental procedure and spectral characterization of synthesized compound

The oxidation of sulfide **1** with peracetic acid:^{29} to a solution of sulfide **1** (20 mmol) in 15 mL of glacial acetic acid, 27% hydrogen peroxide (48 mmol) was added dropwise. The reaction mixture was kept at room temperature for 24 h, then diluted with water and extracted with ether. The ether extract was washed with saturated aqueous K$_2$CO$_3$, water until neutral, dried with MgSO$_4$. Crystalline mass was filtered off, the residue was concentrated in a vacuum and the compound was purified by column chromatography. Sulfone **3** is transparent thin plate, recrystallized from a mixture of petroleum ether and ethyl acetate (1 : 1).

2-({[(1*S*,2*R*,5*S*)-6,6-Dimethylbicyclo[3.1.1]hept-2-yl]methyl}sulfonyl)ethanol (3). Yield 81%; mp 68.5−69 °C; ^{1}H NMR (CDCl$_3$): $δ$ 1.05 (s, 3H, H-9), 1.24 (s, 3H, H-8), 1.07 (m,

1H, H-7), 1.72 (m, 1H, H-3), 1.72 (m, 1H, H-3), 1.88−2.08 (m, 4H, H-1, H-2, 2H-4), 2.42 (m, 1H, H-5), 2.61 (br s, 1H, OH), 3.18−3.31 (m, 2H, H-10), 3.21 (m, 2H, $SO_2C\underline{H}_2$), 4.16 (m, 2H, $C\underline{H}_2OH$); ^{13}C NMR (CDCl$_3$): δ 22.85 (C-3), 23.81 (C-9), 26.57 (C-4), 28.29 (C-8), 33.25 (C-7), 35.04 (C-5), 39.11 (C-6), 41.34 (C-1), 47.45 (C-2), 56.40 (C-10), 57.11 ($\underline{C}H_2OH$), 62.78 ($SO_2\underline{C}H_2$).

Acknowledgements

Notes and references

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† Dedicated to the memory of Professor Evgenii Naumovich Klimovitskii, with whom we developed the original ideas and which are expanded here.
‡ Electronic Supplementary Information (ESI) available: Selected geometrical parameters of the compounds studied by X-ray structural analysis (Table S1), DFT calculations (Table S2), experimental and calculated frequencies of the ν(OH) IR bands (Table S3) and IR spectrum (Fig. S1). CCDC reference number 970674. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b000000x/

1 J. W. Steed, *CrystEngComm*, 2003, **5**, 169−179.
2 G. R. Desiraju, *CrystEngComm*, 2007, **9**, 91−92.
3 K. M. Anderson, A. E. Goeta, K. S. B. Hancock and J. W. Steed, *Chem. Commun.*, 2006, 2138−2140.
4 K. M. Anderson and J. W. Steed, *CrystEngComm*, 2007, **9**, 328−330.
5 A. A. Bredikhin, R. M. Eliseenkova, Z. A. Bredikhina, A. B. Dobrynin and R. G. Kostyanovsky, *Chirality*, 2009, **21**, 637−641.
6 K. M. Anderson, K. Afarinkia, H.-w. Yu, A. E. Goeta and J. W. Steed, *Cryst. Growth Des.*, 2006, **6**, 2109−2113.
7 K. M. Anderson, M. R. Probert, C. N. Whiteley, A. M. Rowland, A. E. Goeta and J. W. Steed, *Cryst. Growth Des.*, 2009, **9**, 1082−1087.
8 Y. V. Nelyubina, M. Y. Antipin, I. A. Cherepanov and K. A. Lyssenko, *CrystEngComm*, 2010, **12**, 77−81.
9 J. K. Whitesell, R. E. Davis, M. S. Wong and N. L. Chang, *J. Am. Chem. Soc.*, 1994, **116**, 523−527.
10 E. Vedejs, R. W. Chapman, S. Lin, M. Müller and D. R. Powell, *J. Am. Chem. Soc.*, 2000, **122**, 3047−3052.
11 K. Kinbara and K. Saigo, in *Topics in Stereochemistry*, John Wiley & Sons, Inc., 2003, pp. 207−265.
12 M. Walker, E. Pohl, R. Herbst-Irmer, M. Gerlitz, J. Rohr and G. M. Sheldrick, *Acta Crystallogr., Sect. B: Struct. Sci.*, 1999, **55**, 607−616.
13 R. G. Kostyanovsky, O. N. Krutius, I. A. Bronzova, D. A. Lenev, K. A. Lyssenko and B. B. Averkiev, *Mendeleev Commun.*, 2001, **11**, 6−8.
14 L. V. Saloutina, A. Y. Zapevalov, M. I. Kodess, K. A. Lyssenko, M. Y. Antipin, V. I. Saloutin and O. N. Chupakhin, *J. Fluor. Chem.*, 2003, **120**, 41−47.
15 A. Linden, M. G. Gunduz, R. Simsek and C. Safak, *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.*, 2006, **62**, o227−o230.
16 V. Alfonsov, A. Bredikhin, Z. Bredikhina, R. Eliseenkova, O. Kataeva, I. Litvinov and M. Pudovik, *Struct. Chem.*, 2008, **19**, 873−878.
17 V. A. Startseva, L. E. Nikitina, O. A. Lodochnikova, A. E. Klimovitskii, A. V. Aref'ev, N. P. Artemova, A. V. Bodrov, R. Z. Musin and E. N. Klimovitskii, *Phosphorus, Sulfur, Silicon, Relat. Elem.*, 2013, DOI: 10.1080/10426507.2013.843003.
18 *Cambridge Structural Database System* (CSD; version 1.12), Cambridge Crystallographic Data Centre, Cambridge, 2009.
19 K. M. J. Brands and A. J. Davies, *Chem. Rev.*, 2006, **106**, 2711-2733.
20 A. V. Bodrov, L. E. Nikitina, V. A. Startseva, O. A. Lodochnikova, R. Z. Musin and O. I. Gnezdilov, *Russ. J. Gen. Chem.*, 2013, **83**, 80−86.
21 L. F. Tietze and T. Eicher, *Reaktionen und Synthesen im organisch-chemischen Praktikum und Forschungslaboratorium*, Georg Thieme Verlag, Stuttgart, New York, 1991.
22 G. Sheldrick, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 2008, **64**, 112−122.
23 G. M. Sheldrick, *SHELXL-97: Program for Crystal Structure Refinement*, University of Göttingen, Germany, 1997.
24 A. Spek, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 1990, **46**, c34.
25 A. D. Becke, *Phys. Rev. A*, 1988, **38**, 3098−3100.
26 C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B*, 1988, **37**, 785−789.
27 M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez and J. A. Pople, *Gaussian 03, Revision B.01*, Gaussian, Inc., Pittsburgh, PA, 2003.
28 D. C. Young, in *Computational Chemistry*, John Wiley & Sons, Inc., 2002, pp. 42−48.
29 C. R. Johnson and D. McCants, *J. Am. Chem. Soc.*, 1965, **87**, 1109−1114.