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Crystallization of chiral compounds

1. Spectroscopic, thermochemical, and crystallographic investigation of homochiral and racemic glycidyl *p*-toluenesulfonate

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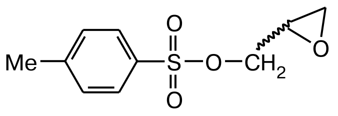
Crystalline specimens of homochiral and racemic glycidyl *p*-toluenesulfonate were studied by IR spectroscopy, differential scanning calorimetry, and X-ray diffraction analysis. The melting phase diagram of glycidyl *p*-toluenesulfonate was constructed. The stacking effect in the crystals of the racemic sulfonate is responsible for a more dense molecular packing, with the result that a heterochiral type of crystallization becomes more favorable.

Key words: glycidyl *p*-toluenesulfonate, IR spectroscopy, thermal analysis, X-ray diffraction analysis, crystallization type, chirality, crystal packing.

In the last decades, characteristic features of crystallization of chiral compounds have attracted attention of researchers in different fields.[1—6] On the one hand, an understanding of the factors responsible for a homo- or heterochiral molecular packing in the crystals of racemic compounds is directly associated with the fundamental problem of the *a priori* prediction of crystal structures.[7—9] On the other hand, the present-day practice has much need for a broad assortment of enantiopure compounds, and the quantitative characteristics of phase transitions (melting, dissolution, *etc*.) of chiral compounds serve as the basis for the rational choice of procedures for the resolution of racemic compounds into enantiomers and preparation of target products with high degrees of enantiomeric purity.[1,10,11]



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Glycidyl *p*-toluenesulfonate (**1**) in racemic and, particularly, scalemic forms finds wide application in fine organic synthesis.[12] According to the published data, the melting point of *rac*-**1** is 35.5 °C,[13] whereas the melting point of (*S*)-**1** with *ee* $\geq$ 97% is 47.5—48.5 °C.[14] For a compound with a melting point below 50 °C, the depression of the melting temperature for a racemic sample is ~12 °C due to which such a compound crystallizes as a racemic conglomerate (see Ref. 1, a nomogram in p. 81). The formation of a racemic conglomerate, *i.e.*, a mechanical mixture of crystals consisting of pure enantiomers, is the prerequisite for the resolution of racemic compounds into enantiomers with the use of the most attractive procedure, *viz*., preferential crystallization or resolution by entrainment.[1,11] Such prospects for this practically important chiral compound gave impetus to our study of the characteristic features of its crystallization in more detail.

Experimental

(*S*)-Glycidol (*ee* 91%) was prepared by enantioselective Sharpless epoxidation of allyl alcohol.[15] *p*-Toluenesulfonates of racemic and scalemic glycidols were prepared by their reactions with an equimolar amount of TsCl in toluene in the presence of Et_3N as described earlier.[16] After twofold recrystallization from hexane, the specific rotation of the sample (*R*)-**1** was $[\alpha]_D^{25}$ −17.7 (*c* = 2.5, $CHCl_3$) (for the (*S*) isomer, $[\alpha]_D^{25}$ +18.1 (*c* = 2.13, $CHCl_3$)[14]).

The IR spectra of individual single crystals and polycrystalline specimens of *rac*-**1** and (*R*)-**1** in KBr pellets were recorded on an IFS-66v (Bruker) Fourier-transform spectrometer.

The melting curves of samples of glycidyl *p*-toluenesulfonate (4—7 mg) were measured on a Setaram DSC 111 differential scanning calorimeter with the rate of heating of 2 °C min^{-1}. The changes in the temperature and heat flux were calibrated against the data for corundum, phenol, and naphthalene.

X-ray diffraction studies of single crystals of *rac*-**1** and (*R*)-**1** were carried out at the Department of X-ray Diffraction Studies of the Center of Collaborative Use of the Russian Foundation for Basic Research on the basis of the Laboratory of X-ray Diffraction Methods of the A. E. Arbuzov Institute of Organic and Physical Chemistry, the Kazan Research Center of the Russian

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Academy of Sciences. The X-ray data were collected on automated CAD-4 diffractometers (Nonius B.V.).

The crystals of *rac*-**1**, $C_{10}H_{12}O_4S$, belong to the monoclinic system. At 20 °C, $a = 7.245(2)$ Å, $b = 18.48(1)$ Å, $c = 8.249(3)$ Å, $\beta = 92.30(2)°$, $V = 1103.5(8)$ Å^3, $d_{\text{calc}} = 1.37$ g cm^{-3}, $Z = 4$, space group $P2_1/c$. The unit cell parameters and intensities of 2085 reflections, of which 904 reflections were with $I \geq 3\sigma$, were measured at 20 °C (diffractometer, graphite monochromator, λ(Mo-Kα), ω/2θ scanning technique, $\theta \leq 27°$). The intensities of three check reflections showed no decrease in the course of X-ray data collection. The absorption was ignored (μ(Mo) = 2.8 cm^{-1}).

The crystals of (*R*)-**1**, $C_{10}H_{12}O_4S$, belong to the orthorhombic system. At 20 °C, $a = 7.229(1)$ Å, $b = 8.172(2)$ Å, $c = 18.87(1)$ Å, $V = 1115(1)$ Å^3, $d_{\text{calc}} = 1.36$ g cm^{-3}, $Z = 4$, space group $P2_12_12_1$. The unit cell parameters and intensities of 3933 reflections, of which 3259 reflections were with $I \geq 3\sigma$, were measured at 20 °C (diffractometer, graphite monochromator, λ(Cu-Kα), ω/2θ scanning technique, $\theta \leq 73°$). The intensities of three check reflections showed no decrease in the course of X-ray data collection. The empirical absorption correction was applied (μ(Cu) = 24.9 cm^{-1}).

The structures were solved by direct methods using the SIR program[17] and refined first isotropically and then anisotropically. All H atoms were revealed from difference electron density syntheses. In the structure of *rac*-**1**, the contributions of the H atoms to the structure amplitudes were taken into account with fixed positional and isotropic thermal parameters. In the structure of (*R*)-**1**, the H atoms were refined isotropically. With the aim of establishing the absolute structure and absolute configuration of molecule (*R*)-**1**, the direct and inverted structures were refined taking into account anomalous scattering of all nonhydrogen atoms. The reliability factors were as follows: $R = 0.04762$, $R_w = 0.06206$ for the direct structure, and $R = 0.05638$, $R_w = 0.07868$ for the inverted structure based on 3113 reflections with $F^2 \geq 3\sigma$, 136 parameters were refined. According to the Hamilton test,[18] the direct structure corresponds to the absolute structure with the probability of 95%. The final reliability factors were as follows: $R = 0.059$, $R_w = 0.073$ based on 858 independent reflections with $F^2 \geq 3\sigma$ for the structure of *rac*-**1**, and $R = 0.043$, $R_w = 0.055$ based on 3104 reflections with $F^2 \geq 3\sigma$ for the structure of (*R*)-**1**. All calculations were carried out using the MolEN program package.[19] The molecules were drawn and the intermolecular interactions in the crystals were analyzed using the PLATON program.[20]

Results and Discussion

Generally, the type of crystallization of a racemic compound is revealed by comparing the vibrational spectra of racemic and enantiopure crystalline specimens. Substantial differences in the spectra are indicative of the formation of a racemic compound (true racemate), whereas the identity of the spectra provides evidence that the compound crystallizes as a racemic conglomerate. Unfortunately, there are presently no quantitative criteria for substantial differences in the spectra that are sufficient for the unambiguous solution of this problem.

The IR spectra of crystalline *rac*-**1** and (*R*)-**1** (polycrystalline samples in KBr pellets) are compared in Fig. 1. We also studied the spectra of individual single crystals and found that they do not differ, in principle, from the spectra of polycrystalline samples. Visual comparison of the spectra revealed no essential differences, and only computer analysis made it possible to found slight

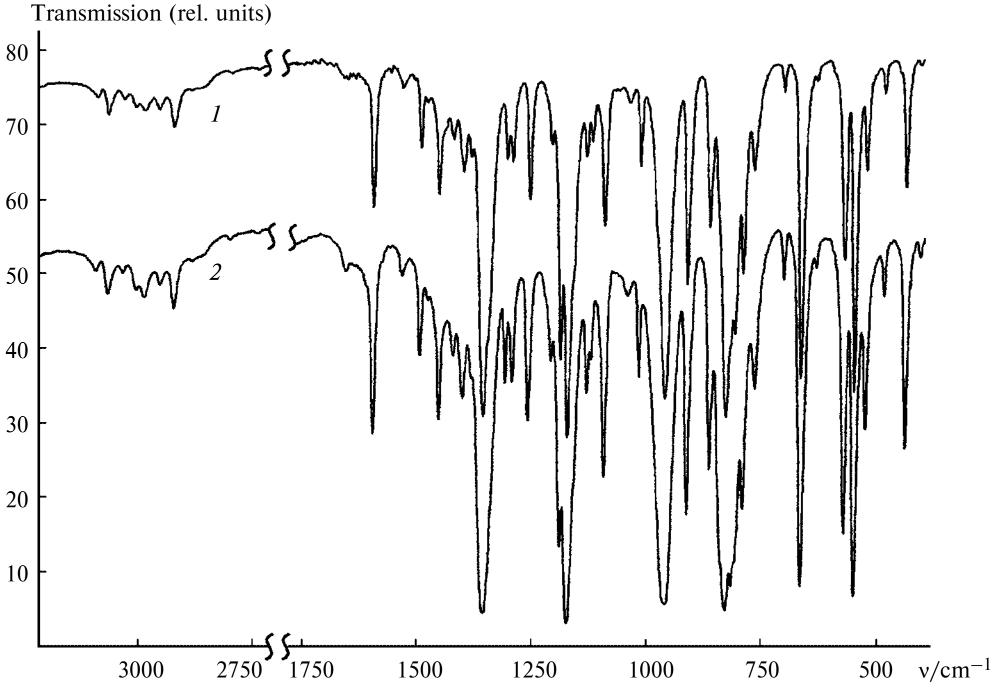

Fig. 1. IR spectra of crystalline specimens of *rac*- (*1*) and (*R*)-glycidyl *p*-toluenesulfonate (**1**) (*2*).

(1—3 cm^{-1}) differences in the frequencies of some bands and also insignificant changes in the relative integral intensities of the peaks in the ranges of 520—575, 750—900, 1100—1140, 1170—1250, and 1270—1300 cm^{-1}. Strictly speaking, the spectra of *rac*-**1** and (*R*)-**1** are not identical, but their differences are too small to be used for the unambiguous identification of the type of crystallization of glycidyl *p*-toluenesulfonate. At the same time, the obvious similarity of the IR spectra is indicative of the similarity of the molecular characteristics (bond lengths, bond angles, torsion angles, *etc.*) of glycidyl *p*-toluenesulfonate both in racemic and scalemic specimens.

Several procedures have been developed, which enable one to assign a solid sample of a racemic chiral substance to racemic compounds, racemic conglomerates, or pseudoracemates.[1,21] Some of these procedures are analogous to the procedure used in the present study and are based on comparison of not only vibrational spectra but also of other characteristics (NMR spectra, powder X-ray diffraction patterns, *etc.*) of polycrystalline racemic and enantiopure specimens. Alternative procedures are based on analysis of the properties of an individual single crystal chosen from the solid specimen with racemic composition. A specimen can be assigned to racemic conglomerates in the following cases: when a solution of this single crystal exhibits optical activity of any type, when the single crystal melts at a temperature substantially higher than the melting point of the polycrystalline sample, when dissolution of the single crystal in a liquid-crystalline nematic phase changes the character of the latter to cholesteric, *etc.* The sizes and quality of single crystals are critical for such procedures. In practice, both these characteristics are often unsatisfactory for racemic conglomerates, which form tight eutectics due to their nature.

Common to all the above-mentioned methods is the qualitative character of the information, which substantially limits the applicability of these methods. Such qualitative data allow one, in the best case, to identify the type of crystallization of a chiral compound. Studies of the quantitative thermodynamic characteristics of compounds and investigation of the molecular packings in homo- and heterochiral crystals are much more important for the understanding of the characteristic features of crystallization associated with chirality. Such data will be analyzed below.

The phase transitions attendant on crystallization of a chiral compound can be adequately described based on the quantitative characteristics of the melting of samples with different enantiomeric compositions. The temperatures (T_m) and enthalpies (ΔH_m) of melting of *rac*-**1** and (*R*)-**1** measured by the DSC method are 311.5 and 322.1 K and 20.0 and 15.3 kJ mol^{-1}, respectively. Generally, the liquidus curve of a binary melting phase diagram in the range from the individual component to the eutectic nearest in composition to this individual component is described by the simplified Schröder—Van Laar equation:[1,11]

$$\ln x = (\Delta H^A_m/R)(1/T^A_m - 1/T_m), \qquad (1)$$

where x is the mole fraction of one of the enantiomers in the mixture (the mole fraction of another enantiomer $x' = (1 - x)$); ΔH^A_m (J mol^{-1}) and T^A_m (K) are the enthalpy and temperature of melting of pure enantiomers, respectively; R is the universal gas constant (R = 8.3170 J K^{-1} mol^{-1}).

The curves *ABC* and *A′B′C* calculated for glycidyl *p*-toluenesulfonate using Eq. (1) based on the experimental data for (*R*)-**1** are shown in Fig. 2. The melting temperature of the eutectic corresponding to the hypothetical racemic conglomerate (point *C*, intersection of branches, which are mirror-symmetrical with respect to the midpoint of the diagram) is 287.4 K, which is inconsistent with the above-mentioned experimental data for racemic crystals.

The portion of the liquidus curve between the eutectics for binary mixtures forming a molecular compound with the composition 1 : 1 (a racemic compound in the case of enantiomers) is described by the Prigogine-Defay ratio[1]

$$\ln 4x(1 - x) = (2\Delta H^R_m/R)(1/T^R_m - 1/T_m), \qquad (2)$$

where ΔH^R_m (J mol^{-1}) and T^R_m (K) are the enthalpy and temperature of melting of the racemic compound, respectively.

The curve *DBEB′D′* constructed using Eq. (2) based on the experimental data for *rac*-**1** is also shown in Fig. 2. As can be seen from this plot, the theoretical melting temperature of the eutectics (points *B* and *B′* of intersections of the curves) is 306.2 K. We performed DSC mea-

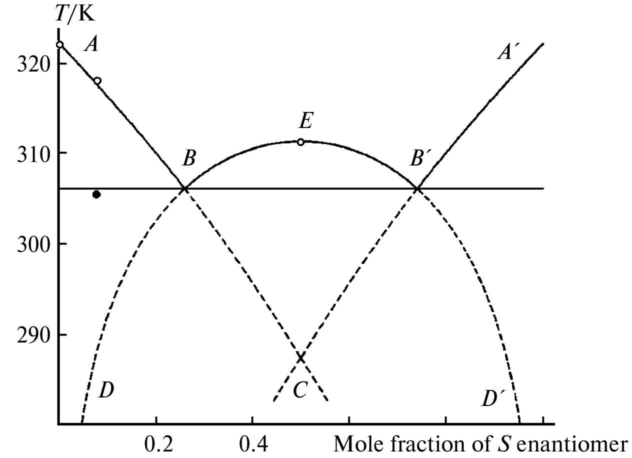

Fig. 2. Theoretical melting phase diagrams of glycidyl *p*-toluenesulfonate (**1**) calculated from the experimental data. See comments in the text.

surements of the melting of a scalemic specimen of glycidyl *p*-toluenesulfonate, which was characterized by the specific rotation $[\alpha]_D^{25}$ −16.1 (c = 2.5, $CHCl_3$), *i.e.*, by the optical purity $op \geq 16.1/(18.1/0.97) \geq 0.86$ (which corresponds to the mole fraction of enantiomer (*R*)-**1** of ~0.93). The onset of melting of this specimen, which is detected as the onset of the deviation of the experimental melting curve from the basis line, occurs at 305.6 K, and the end of melting is characterized by the temperature of 318.2 K. As can be seen from Fig. 2, both points fall well on the solidus and liquidus lines, respectively, of the calculated phase diagram (see Fig. 2, solid lines *BB´* and *ABEB´A´*).

Therefore, thermochemical data enable one to characterized melting of glycidyl *p*-toluenesulfonate by a curve with two eutectics typical of chiral compounds which form a racemic compound (true racemate) on crystallization.

Based on the X-ray diffraction data, the crystal structures of *rac*-**1** and (*R*)-**1** can be analyzed in detail. First, the fact that the crystals of *rac*-**1** belong to the achiral space group $P2_1/c$ suggests unambiguously the formation of a true racemate. It should be noted that the space groups $P2_12_12_1$ and $P2_1/c$ in which homo- and heterochiral glycidyl *p*-toluenesulfonates crystallize are the most populated chiral and, correspondingly, achiral groups for all known organic crystals.[22]

The geometric parameters (bond lengths and bond angles) of the molecules of *rac*-**1** (Fig. 3) and (*R*)-**1** are equal to within the experimental errors ((3—5)σ, Table 1). The differences in the torsion angles are also small (2—3°). Therefore, the X-ray data confirm the assumption (which has been made based on the results of IR spectroscopy) that the geometric characteristics in the crystal of *rac*-**1** are similar to those in the crystal of (*R*)-**1** (Fig. 3).

Analysis of the crystal packings of *rac*-**1** and (*R*)-**1** shows that the calculated density of the centrosymmetrical crystals of the racemate is somewhat larger than that of the chiral crystals of (*R*)-**1** (1.37 and 1.36 g cm^{-3}, respectively; the unit cell volumes are 1103.5(8) and 1115(1) $Å^3$, ΔV = 11.5 $Å^3$, the numbers of molecules per unit cell

Table 1. Selected bond lengths (d), bond angles (ω), and torsion angles (τ) in the structures of *rac*-**1** and (*R*)-**1**

Parameter	*rac*-**1**	(*R*)-**1**
Bond	d/Å	
S(1)—O(1)	1.563(5)	1.564(2)
S(1)—O(3)	1.407(5)	1.406(2)
S(1)—O(4)	1.412(5)	1.421(2)
S(1)—C(4)	1.753(6)	1.743(2)
O(1)—C(1)	1.419(8)	1.465(2)
C(2)—C(3)	1.37(1)	1.415(4)
C(7)—C(10)	1.50(1)	1.511(3)
O(2)—C(2)	1.408(9)	1.429(3)
O(2)—C(3)	1.40(1)	1.403(3)
C(1)—C(2)	1.41(1)	1.452(4)
Bond angle	ω/deg	
O(1)—S(1)—O(3)	103.5(3)	103.6(1)
O(1)—S(1)—O(4)	110.2(3)	109.0(1)
O(1)—S(1)—C(4)	103.7(3)	104.5(1)
O(3)—S(1)—O(4)	119.3(4)	119.4(1)
O(3)—S(1)—C(4)	109.9(3)	110.2(1)
O(4)—S(1)—C(4)	109.0(3)	109.0(1)
S(1)—O(1)—C(1)	120.2(4)	118.2(1)
O(2)—C(3)—C(2)	61.1(5)	60.9(2)
S(1)—C(4)—C(5)	119.3(4)	119.5(2)
C(2)—O(2)—C(3)	58.6(5)	60.0(2)
O(1)—C(1)—C(2)	112.4(6)	107.9(2)
O(2)—C(2)—C(1)	120.4(6)	116.1(2)
O(2)—C(2)—C(3)	60.3(5)	59.1(2)
C(1)—C(2)—C(3)	128.9(7)	122.1(2)
Torsion angle	τ/deg	
O(3)—S(1)—O(1)—C(1)	−175.8(5)	−173.8(2)
O(4)—S(1)—O(1)—C(1)	−47.1(5)	−45.8(2)
C(4)—S(1)—O(1)—C(1)	69.4(5)	70.7(2)
O(1)—S(1)—C(4)—C(5)	−88.3(5)	−86.1(2)
O(1)—S(1)—C(4)—C(9)	88.6(5)	91.9(2)
O(3)—S(1)—C(4)—C(5)	161.6(5)	163.2(2)
S(1)—O(1)—C(1)—C(2)	170.0(5)	170.4(2)
C(3)—O(2)—C(2)—C(1)	−120.2(9)	−113.3(3)
O(1)—C(1)—C(2)—O(2)	−75.7(8)	−80.2(2)
O(1)—C(1)—C(2)—C(3)	−150.3(8)	−148.7(2)
C(1)—C(2)—C(3)—O(2)	106.8(9)	103.3(3)
O(4)—S(1)—C(4)—C(5)	29.1(6)	30.4(2)

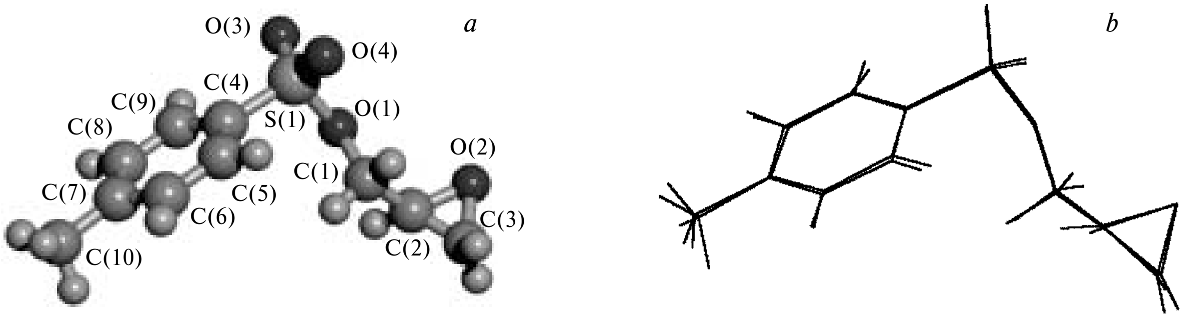

Fig. 3. Structures and atomic numbering schemes for the molecules in the crystals of glycidyl *p*-toluenesulfonates: an independent molecule of *rac*-**1** (*a*) and an arbitrary superposition of the homochiral molecules in the crystals of *rac*-**1** and (*R*)-**1** (*b*).

being equal). Formally, glycidyl *p*-toluenesulfonate follows Wallach's rule, according to which crystals of racemates have a higher density than crystals of individual enantiomers (this rule and modern analysis of its applicability were discussed in the study[7]). At the same time, the relative difference between the densities is very small (less than 1%). The difference between the packing coefficients of these crystals calculated according to Kitaigorodsky[23] is larger (67.7% for the racemate and 64.9% for (*R*)-**1**). The latter value corresponds to a very loose crystal packing, which is apparently reflected in its stability characteristics.

Analysis of intermolecular interactions in the crystals of *rac*-**1** and (*R*)-**1** demonstrated that these interactions are of the same donor-acceptor nature but the motifs of short intermolecular contacts are different. In the absence of strong intermolecular interactions, such as classical hydrogen bonds, the molecules in crystals are linked by C—H...O, C—H...π, and π—π interactions.

In the crystal of *rac*-**1**, there are no contacts corresponding to interactions of the C—H...π type. The crystals have four short C—H...O contacts involving three H atoms of the benzene ring and one H atom of the methylene group as donors and both O atoms of the sulfone group and the O atom of the epoxide ring as acceptors. The parameters of the contacts are as follows: for C(1)—H(11)...O(2′), H(11)...O(2′), 2.51(7) Å; C(1)—H(11)...O(2′) angle, 148(6)°; for C(5)—H(5)...O(4′) (*x*, 1/2 – *y*, 1/2 + *z*), H(5)...O(4′), 2.58(6) Å; C(5)—H(5)...O(4′) angle, 145.5(5)°; for C(6)—H(6)...O(3″) (*x*, *y*, 1 + *z*), H(6)...O(3″), 2.51(7) Å; C(6)—H(6)...O(4″) angle, 148(6)°; for C(8)—H(8)...O(2‴) (2 – *x*, –1/2 + *y*, 1/2 – *z*), H(8)...O(2‴), 2.63 Å; C(8)—H(8)...O(2‴) angle, 147.5(3)°. The graphs of a pattern of these short contacts, *viz.*, nonclassical hydrogen bonds, are described by the formulas[24,25] C 1,1(4)*b*, C 1,1(5)*c*, C 1,1(6)*d*, and C 1,1(9)*a* (in the order of enumeration). These interactions give rise to a bilayer hydrogen-bonded structure (Fig. 4) in which the layers are perpendicular to the *x* axis of the crystal. According to the requirements of the center of symmetry, the planar fragments related by this center, in particular, the benzene rings belonging to molecules, which have opposite configurations and form centrosymmetrical dimers, should be parallel to each other. This, in turn, is favorable for attractive dispersion interactions between these fragments with the following parameters: for the molecules related by the symmetry operation (1 – *x*, –*y*, 1 – *z*), the distance between the centers of the rings is 3.81 Å, the dihedral angle between the planes of the rings is 0°, the angle between the normal to the plane of the ring and the line between the centers of the rings is 20.1°, and the distance between the planes of the rings is 3.575 Å; for the molecules related by the symmetry operation (2 – *x*, –*y*, 1 – *z*), the distance between the centers of the rings is 4.61 Å, the dihedral angle between the planes of the rings is 0°, the angle between the normal to the plane of the ring and the line between the centers of the rings is 44.2°, and the distance between the planes of the rings is 3.305 Å. The above-mentioned characteristics are indicative of the occurrence of the stacking effect in the crystals of *rac*-**1**,[26] which gives rise to stacks of the molecules along the *x* axis of the crystal (see Fig. 4).

In the crystals of homochiral (*R*)-**1**, there are only three intermolecular interactions of the C—H...O type (Fig. 5): C(1)—H(12)...O(2‴) (1 – *x*, 1/2 + *y*, 1/2 – *z*), H(12)...O(2‴) is 2.53(3) Å, C(1)—H(12)...O(2‴) angle is 142(2)°; C(2)—H(2)...O(4′) (1 + *x*, *y*, *z*), H(2)...O(4′)

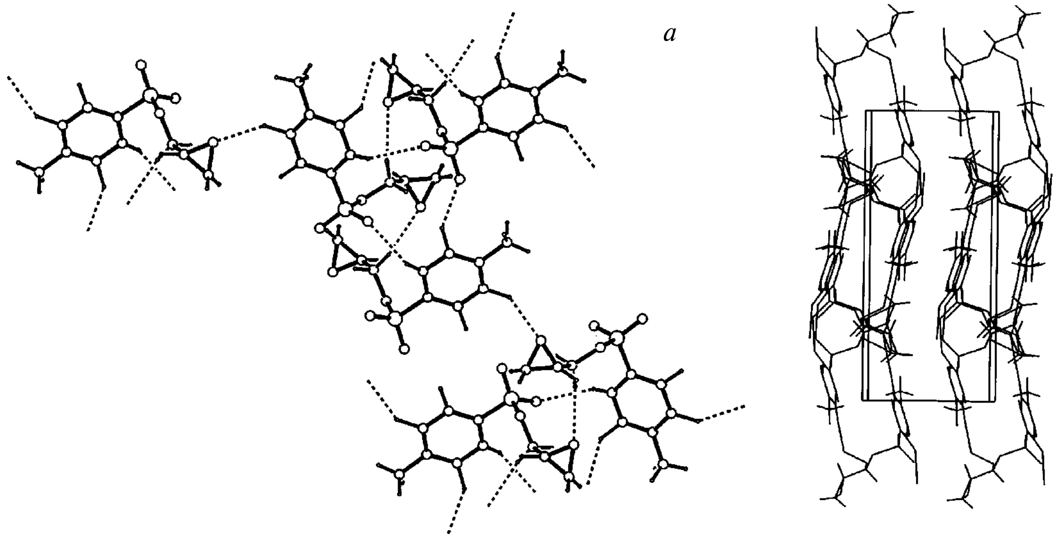

Fig. 4. Network of C—H...O hydrogen bonds (*a*, dashed lines) and molecular packing (*b*, projection along the *z* axis) in the crystal of *rac*-**1**.

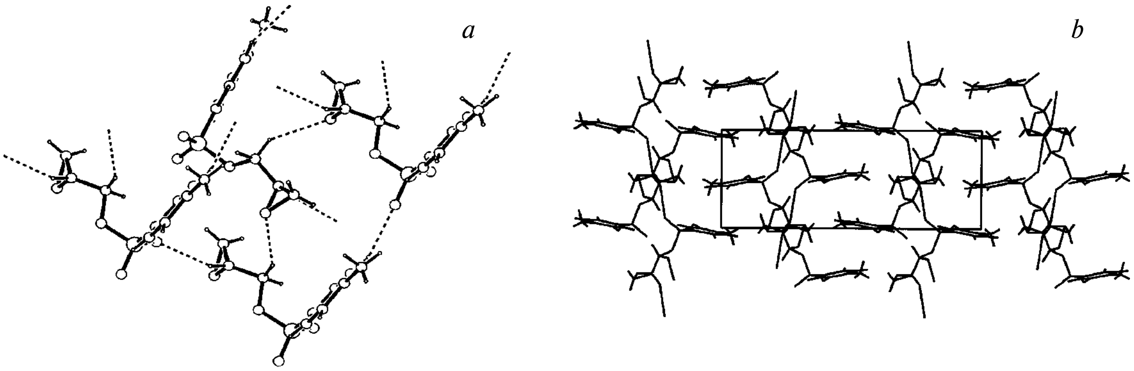

Fig. 5. Network of C—H...O hydrogen bonds (*a*, dashed lines) and molecular packing (*b*, projection along the *y* axis) in the crystal of (*R*)-**1**.

is 2.46(3) Å, C(2)—H(2)...O(4′) angle is 149(2)°; C(6)—H(6)...O(3″) (*x*, 1 + *y*, *z*), H(6)...O(3″) is 2.43(2) Å, C(6)—H(6)...O(3″) angle 149(2)°. The graphs of the pattern of these short contacts in the crystal of (*R*)-**1** are described by the formulas C 1,1(4)*b*, C 1,1(6)*c*, and C 2,2(8) > *b* > *c*. In this crystal, the molecular conformation is stabilized by intramolecular interactions of two types: C(9)—H(9)...O(3), H(9)...O(3) 2.54(3) is Å, C(9)—H(9)...O(3) angle is 114(3)°; and C(1)—H(11)...O(4), H(11)...O(4) is 2.27(3) Å, C(1)—H(11)...O(4) angle is 121(2)°. Analogous intramolecular contacts are also observed in the molecules in the racemic crystals, but the internuclear distances in the latter case are slightly larger (H...O, 2.64 and 2.75 Å) and do not satisfy the formal criterion of hydrogen bonding. Hence, we ignored these contacts. In addition to the C—H...O and π—π interactions, the crystal of (*R*)-**1** has also a short contact of the C—H...π type between one of the H atoms of the methylene group and the center of the benzene ring of the adjacent molecule (the distance is 3.24 Å).

In the crystal of (*R*)-**1**, the homochiral molecules cannot be related by a center of symmetry. Unlike *rac*-**1**, the aromatic rings of the adjacent molecules in the chiral crystal are inclined to each other, the dihedral angle between the benzene rings of the adjacent molecules is 24.1°, the distance between the centers of the rings is 4.21 Å, and the distance from the center of the ring to the plane of the adjacent ring is 3.15 Å (see Fig. 5). As a result, the crystals of (*R*)-**1** are built from inclined stacks of the molecules in which interactions between the aromatic fragments are substantially weaker than those in the crystals of *rac*-**1**.

To summarize, it can be concluded that the possibility and presence of the center of symmetry in the crystals of *rac*-**1** giving rise to additional (which are not generated by trivial translations) sets of strictly parallel aromatic fragments is favorable for the appearance of attractive dispersion interactions between the latter fragments. Combinations of C—H...O interactions giving rise to infinite layers in the crystals and π—π interactions that link these layers facilitate heterochiral crystallization, which is manifested at different levels. At the qualitative level, this is manifested in crystallization of racemic glycidyl *p*-toluenesulfonate as a true racemate rather than as a racemic conglomerate. At the quantitative level, this is reflected in a higher enthalpy of melting and a higher density of the packing of heterochiral crystals compared with the corresponding characteristics of homochiral crystals.

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References

1. J. Jaques, A. Collet, and S. H. Wilen, *Enantiomers, Racemates, and Resolutions*, Krieger Publishing Co., Malabar, FL, 1994, 447 pp.
2. Z. Bocskei, C. Kassai, K. Simon, E. Fogassy, and D. Kozma, *J. Chem. Soc., Perkin Trans. 2*, 1996, 1511.
3. K. Kinbara, Y. Hashimoto, M. Sukegawa, H. Nohira, and K. Saigo, *J. Am. Chem. Soc.*, 1996, **118**, 3441.
4. S. M. Reutzel-Edens, V. A. Russell, and L. Yu, *J. Chem. Soc., Perkin. Trans. 2*, 2000, 913.
5. G. Muller and M. Lutz, *Z. Naturforsch.*, 2001, **56B**, 871.
6. R. G. Kostyanovsky, V. R. Kostyanovsky, G. K. Kadorkina, and K. A. Lyssenko, *Mendeleev Commun.*, 2001, 1.
7. C. P. Brock, W. B. Schweizer, and J. D. Dunitz, *J. Am. Chem. Soc.*, 1991, **113**, 9811.
8. A. Gavezzotti, *Acc. Chem. Res.*, 1994, **27**, 309.
9. J. Hulliger, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 143.
10. S. H. Wilen, A. Collet, and J. Jacques, *Tetrahedron*, 1977, **33**, 2725.
11. A. Collet, J. Jacques, and M. J. Brienne, *Chem. Rev.*, 1980, **80**, 215.
12. R. M. Hanson, *Chem. Rev.*, 1991, **91**, 437.
13. *Beilst.*, EV, **17**(1), 9.

14. J. M. Klunder, T. Onami, and K.B. Sharpless, *J. Org. Chem.*, 1989, **54**, 1295.
15. Y. Gao, R. M. Hanson, J. M. Klunder, S. Y. Ko, H. Masamune, and K. B. Sharpless, *J. Am. Chem. Soc.*, 1987, **109**, 5765.
16. N. Nakabayashi, E. Masuhara, and Y. Iwakura, *Bull. Chem. Soc. Jpn.*, 1966, **39**, 413.
17. A. Altomare, G. Cascarano, C. Giacovazzo, and D. Viterbo, *Acta Crystallogr.*, *Sect. A*, 1991, **47**, 744.
18. W. C. Hamilton, *Acta Crystallogr.*, 1965, **18**, 502.
19. L. H. Straver and A. J. Schierbeek*, MolEN, Structure Determination System*, *Program Description,* Nonius B.V., Delft, 1994, **1**, 180.
20. A. L. Spek, *Acta Crystallogr.*, *Sect A*, 1990, **A46**, 34.
21. E. L. Eliel, S. H. Wilen, and L. N. Mander, *Stereochemistry of Organic Compounds*, John Wiley and Sons, New York, 1994, p. 297; E. L. Eliel, S. H. Wilen, and M. P. Doyle, *Basic Organic Stereochemistry*, Wiley-Interscience, New York, 2001, p. 197.
22. C. P. Brock and J. D. Dunitz, *Chem. Mater.*, 1994, **6**, 1118.
23. A. I. Kitaigorodsky, *Molecular Crystals and Molecules*, Academic Press, New York—London, 1973.
24. M. C. Etter, *Acc. Chem. Res.*, 1990, **23**, 120.
25. J. Bernstein, R. E. Davis, L. Simoni, and N. L. Chang, *Angew. Chem., Int. Ed. Engl.*, 1995, **34**, 1555.
26. T. Dahl, *Acta Chem. Scand.*, 1994, **48**, 95.

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