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Triol Crystalline Hosts Derived from Malic Acid. Synthesis, Inclusion Formation and X-ray Crystal Structures of a Free Host and its Inclusion Compound with Ethanol (1:1)

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Four new host compounds **1–3** (**a**, **b**) derived from malic acid as different optical species and having particular lateral substituents were synthesized. Their properties in crystalline inclusion formation were studied and discussed. Crystal structures of a free host compound **1** and its ethanol inclusion complex [**1**·EtOH (1:1)] have been determined by X-ray analysis [**1**: orthorhombic, $P2_12_12_1$, $a = 9.304(3)$, $b = 14.950(3)$, $c = 15.712(3)$ Å, $Dc = 1.248$ Mg·m^{-3}, $Z = 4$, $R = 0.039$ for 2474 reflexions; **1**·EtOH (1:1): triclinic, $P\bar{1}$; $a = 11.945(3)$, $b = 14.080(3)$, $c = 16.029(4)$ Å, $\alpha = 106.82(2)$, $\beta = 97.74(2)$, $\gamma = 89.93(2)°$, $D_c = 1.187$ Mg·m^3, $Z = 4$, $R = 0.096$ for 10404 data]. Spontaneous resolution occurs during crystallization in crystals of **1**. An interesting H-bonding pattern develops that probably is responsible for the inclusion formation with ethanol in the associate crystal.

INTRODUCTION

Host design based on bulky groups and making use of hydroxyl functions has proved very profitable in the formation of crystalline inclusion complexes.[1] Compounds of this type involve rigid linear or cyclic spacers and mostly they are diols having the hydroxy group incorporated into a crowded diarylhydroxymethyl residue.[2] There are also more simple hosts of this construction having only a single hydroxy site.[3] On the other hand, a systematic approach to crystalline hosts typical of a triol functionality is missing in the literature although they are promising due to the increased number of polar sites making for high guest binding capacity or stabilization of the inclusion lattice.[4] Hence we attempt to design triol host compounds from malic acid by using a common building principle.[5]

Here we describe synthesis of a respective compound series **1–3** report the crystal inclusion property and present X-ray crystal structures of the free host **1** and of its inclusion complex with ethanol (1:1).

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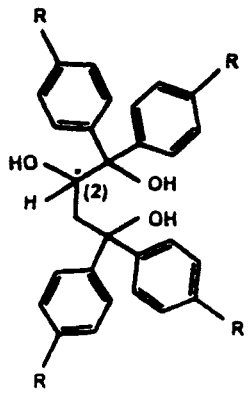
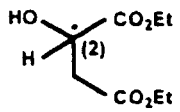


	R	
1	H	(2*R*,2*S*)
2	CH_3	(2*R*,2*S*)
3a	$C(CH_3)_3$	(2*R*,2*S*)
3b	$C(CH_3)_3$	(2*S*)



4a (2*R*,2*S*)
4b (2*S*)

RESULTS AND DISCUSSION

Synthesis

Compounds **1–3** (**a**, **b**) were obtained in moderate yields from diethyl malates **4a** or **4b** and the respective aryllithium reagent prepared from aryl bromides and lithium or n-butyllithium in dry diethyl ether.

The crystalline inclusion compounds were prepared by single recrystallization of the host from the respective guest solvent, isolation of the crystals and drying under standard conditions (see Experimental).

Inclusion Properties

In order to show the inclusion properties clearly and to learn about specific features, all potential host compounds **13** (**a**, **b**) were tested with the same variety of solvents (Table I). These include alcohols and amines of different ring sizes and shapes, dipolar aprotic compounds of different polarities, heterocycles of different ring sizes and with different numbers and types of heteroatoms, as well as aromatic and alicyclic hydrocarbons or chloroform. The ability of **1–3** (**a**, **b**) to form inclusion compounds is evident from Table I, which specifies 63 different lattice inclusions. However, these are not uniformly distributed among the individual host molecules dependent on the substituents R [H, CH_3, $C(CH_3)_3$] and the optical species (**3a**, **3b**). More properly speaking, the increasing bulk of the substituents is shown in an increasing host efficieny, and in case of host **3** the racemic species (**3a**) is much more efficiently complexed compared to the optically resolved species (**3b**).

TABLE I Host: guest ratios in the inclusion compounds

	Host[a]			
Guest compound	1	2	3a	3b
MeOH	2:1	2:1	1:1	—
EtOH	1:1	1:2	—	—
i-PrOH	1:1	2:1	1:3	b
n-BuOH	—	—	1:2	b
i-BuOH	—	—	1:2	b
t-BuOH	2:1	2:1	1:2	1:2
2-$BuNH_2$	b	b	1:3	1:1
i-$BuNH_2$	b	1:1	1:2	1:1
Et_2NH	b	1:1	1:3	b
n-Pr_2NH	b	1:3	1:2	1:1
Et_3N	1:1	1:3	1:2	b
Morpholine	b	1:1	b	1:1
Pyridine	1:2	b	1:3	—
3-Picoline	b	—	1:3	b
Cyclohexanone	b	—	1:3	—
Cyclopentanone	b	1:1	1:1	2:3
3-Me-Cyclohexanone	b	b	1:2	1:2
Dimethylformamide	b	1:1	b	1:1
Dimethyl sulfoxide	2:1	1:1	b	b
Acetonitrile	—	1:1	b	—
Propionitrile	—	—	1:3	—
Tetrahydrofuran	2:1	—	1:1	—
Dioxane	1:1	1:1	1:2	b
Toluene	2:1	1:1	—	—
Xylene	—	b	—	1:1
Cyclohexane	—	—	1:2	1:1
Chloroform	—	1:1	—	1:1

[a]Inclusion compounds were also obtained from **2** with *n*-Bu_3N (1:1) and nitroethane (1:1), from **3a** with *n*-PrOH (1:2), *i*-PentOH (1:2), 3-methylpiperidine (1:1) and 4-methylcyclohexanone (1:3), and from **3b** with β-butyrolactone (1:2). [b]Difficult to crystallize.

Considering the nature of the solvents included by **1–3** (**a**, **b**), differences are also evident in that **1**, **2**, and in particular **3a**, readily yield inclusion compounds with alcohols. Moreover, **2**, **3a** and **3b** gave amine inclusion compounds, while **1** is more suitable for the inclusion of 5- and 6-membered heterocycles and toluene which are less efficient with the other hosts. On the other hand, compounds **3a** and **3b** show the highest ability to include ketones, and **3b** is also suitable for the inclusion of the hydrocarbons xylene and cyclohexane.

Stoichiometric ratios (host:guest) found for the different inclusions range between 2:1 and 1:3 including 1:1, 2:3 and 1:2, but ratios of 1:1 and 1:2 predominate (Table I). None of the hosts exhibit one single stoichiometric ratio regardless of the guest although priorities are shown. The higher host:guest ratios 2:1 and 1:1 are those prefered of the lower bulky compounds **1** and **2** while the lower host:guest ratios 1:2 and 1:3 are more frequent for the more bulky hosts **3a** and **3b**, thus indicating that molecular bulk of the host and the degree of solvent inclusion are being connected. One may also speculate on the stoichiometric ratio of 1:3 in some of the inclusion compounds of **2** and **3a** reflecting that each of the three hydroxyl groups of the host is involved in hydrogen bonding to a guest molecule. Nevertheless, a clear relation based on the hydrogen bond donor/acceptor potencies of host and guest functional groups is difficult to see from Table I.

In view of these problems and in order to investigate the building principles of the new inclusion family, we studied the crystal structures of free host compound **1** and its solvent inclusion with EtOH [**1**·EtOH (1:1)].

X-ray Structural Study

Molecular Structures

The molecular shapes of both the host and its ethanol associate (**1** and **1**·EtOH) are presented in Figures 1 and 2. A summary of the experimental

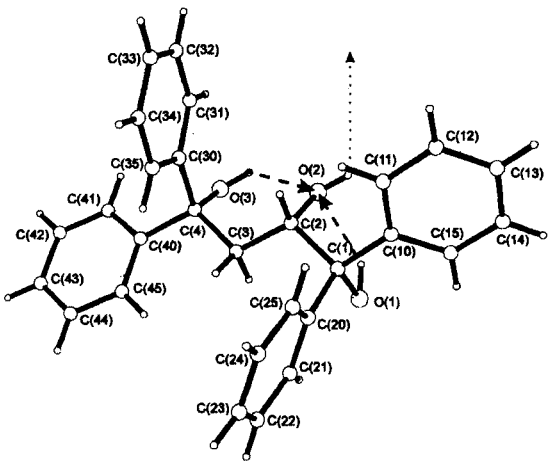


FIGURE 1 Perspective view (including atom numbering) showing the conformation of host compound **1**. Intra- and intermolecular H-bonding attachments are indicated as stroke and dotted arrows, respectively.

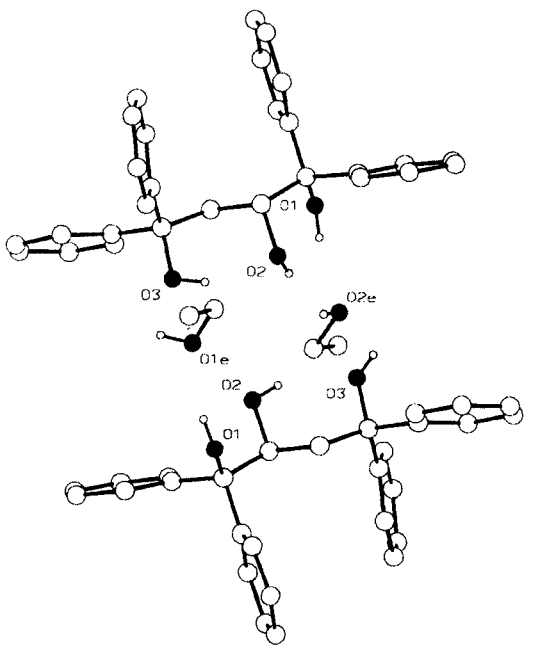


FIGURE 2 Perspective view of the asymmetric unit showing the conformation and the relative positioning of the supramolecular constituents for inclusion compound **1**·EtOH (1:1). O atoms are shaded.

TABLE II Crystal data and selected details of the refinement calculations

Compound	1	1·EtOH (1:1)
Empirical formula	$C_{28}H_{26}O_3$	$C_{30}H_{32}O_4$
Formula weight	410.49	456.56
Temperature (K)	298(2)	293(2)
Radiation, λ(Å)	CuK_α/1.5418	CuK_α/1.5418
Crystal size (mm)	0.40 × 0.40 × 0.25	0.66 × 0.45 × 0.34
Crystal system	orthorhombic	triclinic
Space group	$P2_12_12_1$	$P\bar{1}$;
a (Å)	9.304(3)	11.945(3)
b (Å)	14.950(3)	14.080(3)
c (Å)	15.712(3)	16.029(4)
α (°)	90	106.82(2)
β (°)	90	97.74(2)
γ (°)	90	89.83(2)
V (Å^3)	2185.5(9)	2555.2(11)
Z	4	4
D_c(Mg·m^{-3})	1.248	1.187
μ (cm^{-1})	6.31	6.16
Θ-range data coll. (°)	4.08–74.82	2.91–74.82
Index ranges	0 < h < 11,	−14 < h < 14,
	0 < k < 18	−17 < k < 16
	0 < l < 19	0 < l < 20
Reflections collected	2552	10893
Indep. refl. [$R_{(int)}$]	2552[0.0]	10503[0.015]
Data/restraints/params.	2474/0/284	10404/0/630
Goodness-of-fit on F^2	1.022	1.105
R indices [$I > 2\sigma(I)R_1$]	0.038	0.096
and wR^2	0.098	0.279
R_1 and wR^2 (all data)	0.045/0.106	0.117/0.308
Abs. struct. param.	0.2(3)	—
Extinction coefficient	0.0029(3)	0.0053(5)
Largest peak/hole (e·Å^{-3})	0.18/−0.14	0.37/−0.40

and crystallographic data is given in Table II, while Table III contains the final atomic coordinates for both **1** and **1**·EtOH. Relevant bonding parameters are in Tables IV and V.

It is clearly visible in the free host (Fig. 1) that the molecular structure is partly sustained by the untramolecular H-bonds from two sides to the central -OH moiety. The torsion angles in the central host skeleton indicate that the backbone conformation hardly changes upon complexation with ethanol (Figure 2 and Table IV), in spite of the intramolecular H-bonding system partly broken up by the intervening guest –OH function (Table V). Another part of the intramolecular hydrogen is also conserved in the ethanol associate (see below). Otherwise the molecular structures do not feature any unexpected bonding dimension.

Aggregate Structures

A basic difference in the packing between the parent crystal structure and the ethanol associate of **1** is the present of the center of symmetry in the crystal lattice in the complex (Figures 1, 3 and 4).

In free host compound **1** the crystal lattice is built from pure 3D-translations and two-fold screw axes maintaining endless hydrogen bonding contacts (Figure 1, Table V). The packing in structure **1** shows helical turns of molecules along the crystallographic *a* axis (endless chains) associated mainly through hydrogen bonds as indicated in Figure 1.

In the structure of the **1**·ethanol complex, it is indicated that hydrogen bonding has a complicated nature (Figure 3). This arises from hydrogen position conflicts which cannot be resolved under the present experimental circumstances better than assuming that either a crossover of H atoms takes place as a time averaged phenomenon (proton switch) or a space averaged ensemble of positions occurs, the latter assumption being the more probable. One such alternative ordered H-bonding motif model is shown in Figure 4. Thus, the center of symmetry, which is obviously violated by the alternation in the proton sites, may only exist as statistical average. Consequently the real space group of this structure must be P1. However, crystal quality did not allow for an unambiguous decision, therefore Occam's razor was used.

It is interesting to note that the packing, as reflected by the densities and the respective packing coefficients (0.67 for **1** and 0.65 for the **1**·ethanol complex) appears to be looser in the inclusion crystal than in the parent compound. This, together with the observed statistic disorder underlines that probably the Gibbs free energy changes (enthalpy from H-bonding and entropy increase from disorder) contribute to inclusion formation in this instance.

TABLE III Non-hydrogen atomic coordinates ($\times 10^4$) and equivalent isotropic displacement parameters ($A^2 \times 10^3$) for **1** and **1**·EtOH (1:1). *U(eq)* is defined as one third of the trace of the orthogonalized *Uij* tensor

Atom	x/a	y/a	z/c	U(eq)
1				
O(1)	1608(2)	7424(1)	148(1)	47(1)
O(2)	-853(2)	6508(1)	0(1)	50(1)
O(3)	-584(2)	4722(1)	-222(1)	51(1)
C(1)	796(2)	7316(1)	916(1)	36(1)
C(2)	-124(2)	6451(1)	803(1)	36(1)
C(3)	766(2)	5594(1)	803(1)	36(1)
C(4)	-111(2)	4742(1)	645(1)	36(1)
C(10)	-209(2)	8127(1)	1030(1)	42(1)
C(11)	107(3)	8926(2)	622(2)	58(1)
C(12)	-792(4)	9663(2)	707(2)	80(1)
C(13)	-2014(4)	9623(2)	1182(2)	80(1)
C(14)	-2339(4)	8837(2)	1587(2)	74(1)
C(15)	-1452(3)	8094(2)	1514(2)	56(1)
C(20)	1865(2)	7213(1)	1645(1)	40(1)
C(21)	1455(3)	7314(2)	2485(2)	55(1)
C(22)	2409(4)	7146(2)	3142(2)	73(1)
C(23)	3791(3)	6874(2)	2973(2)	71(1)
C(24)	4219(3)	6788(2)	2144(2)	72(1)
C(25)	3268(2)	6947(2)	1484(2)	54(1)
C(30)	790(2)	3893(1)	758(1)	38(1)
C(31)	246(3)	3098(2)	455(2)	65(1)
C(32)	975(4)	2297(2)	564(2)	78(1)
C(33)	2261(3)	2280(2)	973(2)	66(1)
C(34)	2825(3)	3056(2)	1271(3)	81(1)
C(35)	2099(3)	3864(2)	1156(2)	69(1)
C(40)	-1393(2)	4705(1)	1259(2)	41(1)
C(41)	-2784(3)	4646(2)	962(2)	64(1)
C(42)	-3928(3)	4645(3)	1533(3)	97(1)
C(43)	-3702(4)	4701(3)	2386(3)	92(1)
C(44)	-2330(4)	4754(2)	2690(2)	81(1)
C(45)	-1185(3)	4747(2)	2133(2)	59(1)
1·*EtOH (1:1)*				
O(1A)	1460(2)	2702(1)	10329(1)	49(1)
O(2A)	2253(2)	3657(1)	9101(1)	47(1)
O(3A)	4480(2)	4174(2)	9407(2)	62(1)
C(1A)	1650(2)	2175(2)	9454(2)	36(1)
C(2A)	2617(2)	2714(2)	9202(2)	34(1)
C(3A)	3694(2)	2861(2)	9863(2)	39(1)
C(4A)	4730(2)	3229(2)	9546(2)	43(1)
C(10A)	551(2)	2060(2)	8819(2)	38(1)
C(11A)	-443(2)	1843(2)	9097(2)	53(1)
C(12A)	-1464(2)	1713(2)	8539(2)	64(1)
C(13A)	-1499(2)	1786(2)	7708(2)	62(1)
C(14A)	-527(3)	1989(2)	7418(2)	61(1)
C(15A)	492(2)	2128(2)	7973(2)	47(1)
C(20A)	2043(2)	1142(2)	9486(2)	40(1)
C(21A)	2177(3)	421(2)	8729(2)	63(1)
C(22A)	2573(4)	-510(2)	8755(3)	80(1)
C(23A)	2794(4)	-708(3)	9544(3)	83(1)
C(24A)	2667(4)	4(3)	10282(3)	93(1)
C(25A)	2276(3)	924(2)	10274(2)	68(1)
C(30A)	5784(2)	3395(2)	10246(2)	40(1)
C(31A)	6835(2)	3423(2)	10006(2)	53(1)
C(32A)	7798(3)	3624(3)	10631(2)	66(1)
C(33A)	7729(3)	3782(2)	11488(2)	63(1)
C(34A)	6706(4)	3754(4)	11751(3)	96(2)
C(35A)	5722(4)	3562(4)	11128(3)	99(2)
C(40A)	4961(2)	2497(2)	8680(2)	58(1)
C(41A)	5053(4)	2812(4)	7949(3)	97(1)
C(42A)	5254(4)	2117(7)	7167(3)	145(3)
C(43A)	5355(5)	1126(7)	7115(4)	171(4)
C(44A)	5292(4)	855(4)	7809(4)	119(2)
C(45A)	5094(3)	1509(3)	8623(3)	75(1)
O(1EA)	954(2)	4669(2)	364(2)	75(1)
C(1E1A)	1416(5)	5309(3)	1198(3)	108(2)
C(2E1A)	889(6)	5165(5)	1881(3)	128(2)
O(1B)	3541(2)	7319(2)	4673(2)	77(1)
O(2B)	2754(2)	6349(2)	5891(2)	84(1)
O(3B)	520(2)	5827(1)	5598(1)	56(1)
C(1B)	3338(3)	7843(3)	5539(2)	66(1)
C(2B)	2392(3)	7294(3)	5810(2)	65(1)
C(3B)	1311(3)	7144(3)	5145(2)	60(1)
C(4B)	281(2)	6766(2)	5444(2)	43(1)
C(10B)	4452(3)	7952(3)	6180(2)	75(1)
C(11B)	5445(3)	8169(5)	5902(3)	116(2)
C(12B)	6464(4)	8277(6)	6458(4)	139(3)
C(13B)	6517(4)	8222(5)	7297(4)	126(2)
C(14B)	5538(4)	8027(4)	7577(3)	103(2)
C(15B)	4506(3)	7880(4)	7024(3)	83(1)
C(20B)	2963(3)	8861(3)	5519(2)	67(1)
C(21B)	2800(4)	9600(3)	6277(3)	84(1)
C(22B)	2445(4)	10509(4)	6246(3)	100(1)
C(23B)	2212(5)	10736(5)	5488(4)	126(2)
C(24B)	2355(7)	10014(5)	4711(4)	156(3)
C(25B)	2718(5)	9082(5)	4741(3)	116(2)
C(30B)	-778(2)	6600(2)	4747(2)	52(1)
C(31B)	-1837(4)	6542(6)	4987(3)	148(3)
C(32B)	-2795(4)	6318(7)	4390(4)	186(4)
C(33B)	-2716(4)	6207(4)	3499(3)	102(2)
C(34B)	-1674(3)	6230(3)	3248(2)	71(1)
C(35B)	-722(3)	6420(2)	3870(2)	57(1)
C(40B)	41(2)	7494(2)	6310(2)	41(1)
C(41B)	-85(3)	8504(2)	6403(3)	63(1)
C(42B)	-276(3)	9158(2)	7178(3)	80(1)
C(43B)	-364(3)	8838(3)	7912(3)	79(1)
C(44B)	-244(3)	7862(3)	7827(2)	75(1)
C(45B)	-47(2)	7187(2)	7044(2)	52(1)
O(1EB)	954(2)	4669(2)	364(2)	75(1)
C(1E1B)	1416(5)	5309(3)	1198(3)	108(2)
C(2E1B)	889(6)	5165(5)	1881(3)	128(2)

TABLE IV Selected torsion angles (°) of the host molecular skeletons for compounds **1** and **1**·EtOH (1:1) (**1A** and **1B** are for the two independent molecules in the latter case)

Torsion angle	1	1A	1B
O(2)-C(2)-C(1)-O(1)	-49.9(3)	-69.0(3)	66.3(4)
C(2)-C(3)-C(4)-O(3)	70.6(3)	61.0 (4)	-59.8(4)
C(3)-C(2)-C(1)-O(1)	69.7(3)	54.6 (3)	-55.7(4)
C(4)-C(3)-C(2)-O(2)	-57.3(3)	-66.5(3)	66.9(4)
C(4)-C(3)-C(2)-C(1)	-176.9(3)	169.9(4)	-170.2(5)
C(10)-C(1)-C(2)-O(2)	68.1(3)	54. 0(3)	-55.1(4)
C(10)-C(1)-C(2)-C(3)	-172.3(3)	177.6(4)	-177.1(5)
C(20)-C(1)-C(2)-O(2)	-166.7(3)	175.7(4)	-176.2(5)
C(20)-C(1)-C(2)-C(3)	-47.1(3)	-60.6(3)	61.8(4)
C(30)-C(4)-C(3)-C(2)	-173.1(3)	178.3(4)	-178.5(4)
C(40)-C(4)-C(3)-C(2)	-51.7(3)	-58.2(3)	58.4(4)

CONCLUSIONS

Triol hosts derived from malic acid such as compounds **1–3** (**a**, **b**) have proved a new source of inclusion hosts. They form crystalline inclusion compounds with a variety of uncharged organic molecules ranging from protic dipolar to apolar compounds depending on the structural parameters of the host.

Compared to previous diol hosts based on natural hydroxy acids (lactic acid,[5a,6] mandelic acid[5b] and tartaric acid[7]) the present triol hosts do not show the inclusion property enhanced as expected due to the extra hydroxy group present. Nevertheless there is some profitable high guest inclusion ratio of 1:3 (Table I). From a more detailed comparison between the other diol hosts and the present triol ones it is evident that amines, the favourite guests of the diols,[7a,b] are not as favoured guests for triol hosts. From the point of view of the stereochemistry (racemic vs. optically resolved host species) we see similar trends between diols[5–7] and triols with the racemic hosts being mostly superior. Intramolecular H-bonds are a characteristic feature common to most of the crystal structures including the previous diol hosts.[5–7] These intramolecular H-bonds, due to the vicinal arrangement of the -OH functions, are also responsible for the reduced inclusion affinity. They give, however, rise to potentially interesting switching phenomena in the system of H-bonding of the alcoholic inclusion.

Obviously, a mere extension of the number of hydroxyl groups attached to the host molecule without considering geometric parameters does not necessarily mean an improved host structure. In this nexus, structural optimization as well as the potential chiroselectivity of the system are the future challenges.

EXPERIMENTAL

Synthesis

General: Melting points (uncorrected) were determined with a hot-stage apparatus (VEB Analytik

TABLE V Bond distances (Å) and angles (°) of hydrogen bonds in **1** and **1**·EtOH (1:1). No esd's are given for the dimensions of H atoms, these being meaningless under the experimental circumstances

Compd.	Donor-H···Acceptor[a]	D···A	D-H	H···A	D-H···A
1	O(1)-H(1)···O(2)	2.678(3)	0.91	1.97	133
	O(3)-H(3')···O(2)	2.704(3)	0.82	2.09	132
	O(2)-H(2')···O(1)^{i}	2.860(2)	0.82	2.13	149
1·EtOH	O(1)-H(1a)···O(1e)^{ii}	2.82(2)	0.82	2.01	168
(1:1)	O(2)-H(2a)···O(3)	2.702(3)	0.82	2.04	138
	O(1e)-H(1e)···O(1e)^{iii}	2.707(5)	0.82	1.95	153
	O(1)-H(1b)···O(2e)	2.807(5)	0.82	1.99	173
	O(2)-H(2b)···O(2e)	2.761(5)	0.82	1.98	160
	O(3)-H(3b)···O(2)	2.712 (3)	0.82	1.97	151

[a]Symmetry operators for acceptor atom (A) transformations (*x,y,z* where not indicated otherwise):
i = 1 − *x*, 1/2 + *y*, 1 − *z* for **1**; *ii* = *x*, *y*, *z* − 1 and *iii* = −*x*, −*y* −1, −*z* for **1**·EtOH (1:1)

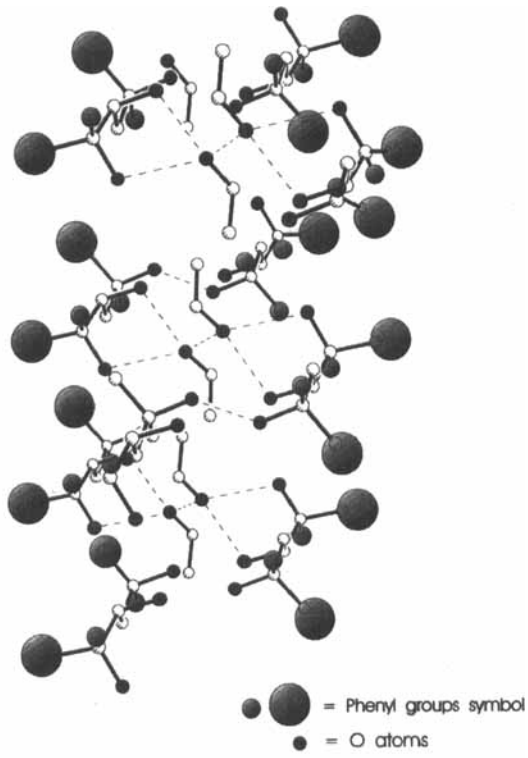


FIGURE 3 Schematics of the H-bonding in the **1**·EtOH (1:1) crystal. H atoms as well as phenyl groups are omitted for clarity, the latter being replaced by the symbols indicated.

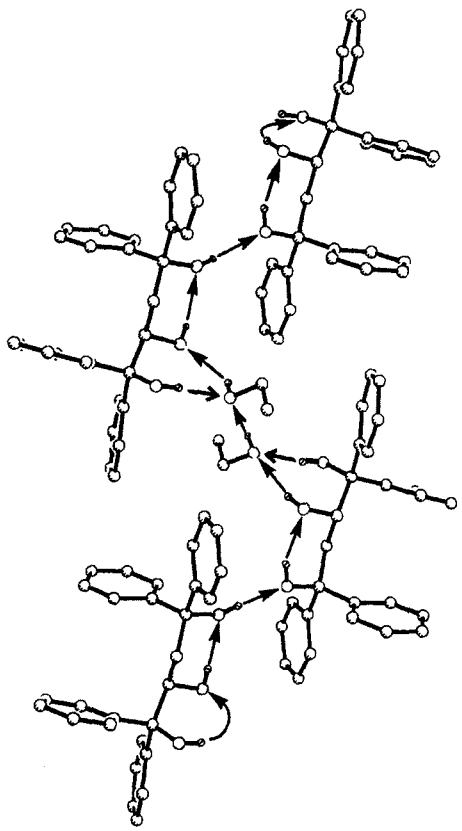


FIGURE 4 Packing motif of the **1**·EtOH (1:1) associate. One of the plausible switching states in the H-bonding scheme is marked in arrows. Non-relevant H atoms are omitted for clarity.

Dresden). IR spectra were recorded on a Nicolet FT-IR spectrometer; spectral bonds are reported in cm^{-1}. Proton and ^{13}C-NMR spectra were measured with a Bruker MSL-300 spectrometer; chemical shifts in δ down field from internal Me_4Si. Elemental analysis were carried out by the Microanalytical Laboratory of the Technical University Bergakademie Freiberg. Solvents were purified and dried in the usual manner before use.

Optically resolved (*S*) and racemic (*R,S*) diethyl malates were prepared as described in the literature.[8] Specific details are given below.

4a: colorless liquid, 85%, b.p. 143–45°C/7 Torr (lit.[9] b.p. 95–96°C/2 Torr), $n_D^{20} = 1.4349$ (lit.[10] $n_D^{20} = 1.4350$)

4b: colorless liquid, 82%, b.p. 139–41°C/4 Torr (lit.[11] 85–86°C/0.5 Torr), $n_D^{20} = 1.4360$ (lit.[11] $n_D^{20} = 1.4361$)

Host Compounds 1 and 2 (General Procedure)

To a stirred suspension of lithium (3.0 g, 0.43 mol) in dry diethyl ether (50 mL) was added dropwise during 1 h at room temperature and under argon the respective aryl bromide (0.204 mol) in dry diethyl ether (100 mL). The mixture was refluxed for 2 h, then cooled, filtered through glass wool and added dropwise to an ice-cooled solution of diethyl malate **4a** (5.32 g, 0.028 mol) in dry diethyl ether (100 mL). The mixture was refluxed for 3 h and stirred overnight. The working up was car-

ried out in the usual manner. Specific details for **1** and **2** are given below.

1: colorless solid, 11%, m.p. 162°C. IR (KBr): 3510, 3450, 3360, 3090, 3060, 3030, 2990, 2950, 1600, 1490, 1450, 720, 710. ^{1}H-NMR (300 MHz, $CDCl_3$): 2.32–2.58, m, 2H (CH_2); 4.62–4.68, d, 1H (CH); 7.15–7.46, m, 20H (Ar-H). ^{13}C-NMR (75.4 MHz, $CDCl_3$): 40.16, 73.66, 78.99, 80.09, 125.36, 125.93, 125.96, 126.24, 126.24, 126.87, 127.08, 127.22, 127.16, 128.24, 128.48, 143.24, 145.25, 145.25, 147.46. Anal. Calcd. for $C_{28}H_{26}O_3$: C, 81.95; H, 6.34. Found: C, 81.73; H, 6.17%.

2: colorless solid, 11%, m.p. 160°C. IR (KBr): 3520, 3410, 3350, 3090, 3060, 3030, 2980, 2940, 1620, 1510, 1450, 1410, 820. ^{1}H-NMR (300 MHz, $CDCl_3$): 2.06–2.52, m, 14H (CH_2, CH_3): 4.60–4.64, d, 1H (CH); 7.00–7.34, m, 16H (Ar-H). ^{13}C-NMR (75.4 MHz, $CDCl_3$): 20.87, 20.95, 21.12, 40.50, 73.78, 78.85, 79.98, 120.56, 125.40, 125.79, 125.92, 126.72, 128.86, 129.13, 136.32, 136.60, 136.75, 140.73, 142.54, 142.64, 145.12, 158.06. Anal. Calcd. for $C_{32}H_{34}O_3$: C, 82.40; H, 7.30. Found: C, 82.13; H, 7.36%.

Host Compounds 3a and 3b (General Procedure)

To a stirred solution of *p*-bromo-*tert*-butylbenzene (42.6 g, 0.20 mol) in dry diethyl ether (100 mL) was added dropwise during 1.5 h at –15°C and under argon *n*-butyllithium (1.6 M in hexane; 140 mL, 0.224 mol). After stirring the mixture for 1 h at the same temperature, diethyl malate **4a** or **4b** (5.32 g, 0.028 mol) in dry diethyl ether (100 mL) was slowly added. The mixture was refluxed for 3 h and stirred over night at room temperature. The working up was carried out in the usual manner. Specific details for **3a** and **3b** are given below.

3a: colorless solid, 16%, m.p. 255–57°C. IR (KBr): 3575, 3460, 3320, 3090, 3060, 3030, 2960, 2900, 2870, 1610, 1460, 1400, 1360, 840. ^{1}H-NMR (300 MHz, $CDCl_3$): 1.24–1.37, m, 36H (*t*-But); 2.32–2.58, m, 2H (CH_2); 4.62–4.68, d, 1H (CH); 7.15–7.46, m, 20H (Ar-H). ^{13}C-NMR (75.4 MHz, $CDCl_3$): 40.58, 74.01, 78.73, 79.95, 124.90, 125.04, 125.11, 125.37, 125.56, 125.62, 126.06, 140.29, 142.31, 142.36, 144.94, 149.40. Anal. Calcd. for $C_{44}H_{58}O_3$: C, 83.28; H, 9.15. Found: C, 82.94; H, 8.90%.

3b: colorless solid, 7%, m.p. 289–91°C. $[\alpha]_{436}$ +125.4° (c 0.33, $CHCl_3$). IR (KBr): 3560, 3460, 3350, 3090, 3060, 3030, 2970, 2900, 2870, 1670, 1510, 1450, 1460, 1405, 1360, 840. ^{1}H-NMR (300 MHz, $CDCl_3$): 1.16–1.48, m, 36H (*t*-Bu-H); 2.70–2.97, m, 2H (CH_2); 4.92–5.00, m, 1H (CH); 7.10–7.52, m, 16H (Ar-H). ^{13}C-NMR (75.4 MHz, $CDCl_3$): 31.31, 43.37, 36.96, 45.20, 86.44, 90.66, 120.54, 124.57, 124.95, 125.18, 125.37, 126.00, 127.13, 139.46, 144.57, 144.79, 148.88, 149.21, 149.35, 149.14. Anal. Calcd. for $C_{44}H_{58}O_3$: C, 83.28; H, 9.15. Found: C, 82.98; H, 9.10%.

Crystalline Inclusion Compounds

These were obtained by recrystallization of the corresponding host compound from a minimum amount of the respective guest solvent. The crystals formed were collected by suction filtration, washed with an inert solvent (hexane) and dried (0.5 h, 15 Torr, room temperature). The host-guest stoichiometric ratio was determined by ^{1}H-NMR integration. Data for each compound are given in Table I.

X-ray Data Collection, Structure Determination, and Refinement

Single crystals of **1** and **1**·EtOH (1:1) were prepared by slow evaporation of solvent from β-butyrolactone and EtOH solutions of **1**, respectively.

Preliminary examinations and data collections were performed for both crystals with CuKα radiation (λ = / 1.54184 Å) mounted on an Enraf-Nonius CAD4 computer controlled κ axis diffractometer equipped with a graphite crystal incident beam monochromator.[12] Data collection were performed in ω-2θ mode at ambient temperatures. Both models of **1** and **1**·EtOH (1:1) were

analyzed via standard crystallographic techniques (structure model by SHELXS-86,[13] refinement by SHELXL-93[14]). Pertinent crystallographic and model refinement details are summed up in Table II. All calculations were performed on an SGI Indigo workstation using the SHELX program suite[13,14] and local programs.

Supplementary Material

Lists of the structure factors, atomic coordinates and thermal components for the nonhydrogen atoms, bond lengths and bond angles involving nonhydrogen atoms, and hydrogen atom parameters are available from the authors (E.Weber).

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