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Polymorphism of Inclusion Complexes and Unsolvated Hosts. V. Crystal Structure of the α-Dimorph of the 1 : 2 Dianilinegossypol–DMSO Complex and a 1 : 1 : 1 Inclusion Complex Based on a Mixed Dianilinegossypol/1,4-Dioxane Host Matrix and 1,2-Dichloroethane Guest

B.T. IBRAGIMOV,* K.M. BEKETOV, S.A. TALIPOV and T.F. ARIPOV
Institute of Biorganic Chemistry, H. Abdullaev Str., 83, Tashkent, 700143, Uzbekistan.

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Abstract. Dianilinegossypol forms a 1 : 2 host–guest complex with DMSO: monoclinic, space group $P2_1/n$, a = 8.522(3), b = 18.034(4), c = 28.462(6) Å, $\beta = 94.14(2)^\circ$, V = 4362 Å^3, Z = 4, D_x = 1.26 g cm^{-3}, T = 295 K. Final R value is 0.102 for 1793 observed reflections. A 1 : 1 : 1 adduct of dianilinegossypol with 1,4-dioxane and 1,2-dichloroethane is found to be isostructural with the dianilinegossypol complex with DMSO: monoclinic, space group $P2_1/n$, a = 8.281(2), b = 19.245(3), c = 27.970(7) Å, $\beta = 95.18^\circ$, V = 4439 Å^3, Z = 4, D_x = 1.28 g cm^{-3}, T = 295 K. Final R value is 0.114 for 2458 observed reflections.

The host molecules are associated by O(4)—H $\cdots$O(3) H-bonds to infinite chains running in the direction of the c-axis The chains are incorporated into layers through 1,4-dioxane or DMSO molecules having H-bonds with dianilinegossypol molecules. Another DMSO or 1,2-dichloroethane molecule is included as a guest in the channels formed between the layers.

At 60 °C a cryptate-type inclusion complex of dianilinegossypol is formed with DMSO or 1,4-dioxane. It is isostructural with the acetone complex reported in Part IV of the present series.

Key words: Dianilinegossypol, crystal structure, host–guest complexes, H-bond, α- and β-dimorphs.

Supplementary Data relevant to this article have been deposited with the British Library as Supplementary Publication No. SUP 82219 (18 pages).

1. Introduction

Dianilinegossypol is a versatile host molecule, like gossypol itself [1]. However, there is an essential difference between the structures of the host–guest complexes of these two substances.

Up to the time of writing, crystallographic parameters of 30 dianilinegossypol inclusion complexes belonging to 10 groups of isostructural complexes have been

* Author for correspondence.

Table I. Crystal data for dianilinegossypol complexes with DMSO and 1,4-dioxane + 1,2-dichloroethane.

	DMSO (α-phase)	1,4-Dioxane + 1,2-dichlorethane
Formula	$C_{42}H_{40}O_6N_2$ $2C_2H_6OS$	$C_{42}H_{40}O_6N_2$ $C_4H_8O_2{\cdot}C_2H_4Cl_2$
Crystal system	Monoclinic	Monoclinic
Space group	$P2_1/n$	$P2_1/n$
a (Å)	8.522(3)	8.281(2)
b (Å)	18.034(4)	19.245(3)
c (Å)	28.462(6)	27.970(7)
β (°)	94.14(2)	95.18(2)
V (Å^3)	4362	4439
D_x (g/cm^3)	1.26	1.28
Z	4	4
Radiation	CuK_a	CuK_a
Absorption coefficient (mm^{-1})	1.91	1.55
Crystal size (mm)	0,04 × 0.08 × 0.09	0.06 × 0.07 × 0.1
$2\theta_{max}$ (°)	120	116
Unique data collected	5074	6106
No. of reflections with $I > 2.5\sigma\ (I)$	1793	2458
Final R indices ($I > 2.5\sigma(I)$)	R_1 = 0.102, wR_2 = 0.389	R_1 = 0.114, wR_2 = 0.376
R indices (all data)	R_1 = 0.241, wR_2 = 0.381	R_1 = 0.229, wR_2 = 0.433
Goodness-of-fit on F^2	1.08	0.96
Largest diff. peak and hole (e Å^3)	0.46, −0.37	0.56, −0.44

determined [2]. Crystal structures of the members of five groups have been solved. Only two modes of host–host association were revealed for these dianilinegossypol inclusion complexes. This contrasts with gossypol clathrates, where 22 types of host–host association modes are known [3].

It is of interest to establish how the structure of the complexes changes with different thermodynamic conditions. To this end we are investigating host–guest complex formation at different temperatures. In the case of ethylacetate [4] and acetone [5] it was shown that the structure of the clathrate changes with increasing temperature, i.e. dimorphism is characteristic of these host–guest pairs. The present paper is devoted to a further investigation of the polymorphism of the dianilinegossypol host–guest complexes with DMSO and 1,4-dioxane.

2. Experimental

Details concerning data collection and structure solution for the DMSO and the double 1,4-dioxane-1,2-dichloroethane complexes of dianilinegossypol are given in Table I.

Single crystals of the complexes were obtained by slow evaporation of the solvent from a dianilinegossypol solution in appropriate solvents at 22 and 60 °C, All crystals were light brown in colour. All measurements were carried out on a Syntex $P2_1$ diffractometer. Lattice parameters were determined by a least-squares fitting of the setting angles of 15 reflections within the 2θ range 18–26°. Two standard reflections, monitored every 100 intensity measurements during the data collection, varied by up to 3%. No corrections for extinction or absorption were applied. The structure was solved by direct methods using the program SHELXS-86 [6]. Most of the atoms of the host and guest molecules were located from the 'best' E map. The positional and anisotropic displacement parameters of the non-hydrogen atoms were refined by full-matrix least-squares method on F^2 with SHELXL-93 [7]. Hydrogen atoms of O(1), O(5), O(4) and nitrogen atoms N(1), N(2) of the dianilinegossypol–DMSO complex were located from the difference synthesis while other H-atoms were placed in idealized positions assuming a C—H distance of 0.96 Å and an O(8)—H distance of 0.85 Å. The positions of the H atoms of the O(8)—H groups were calculated assuming coplanarity with the naphthyl ring and intramolecular hydrogen bonds analogous to those observed in other inclusion compounds of dianilinegossypol. The refinement of the structure of the dianilinegossypol adduct with 1,4-dioxane and 1,2-dichloroethane with isotropic displacement parameters showed that the 1,2-dichloroethane molecules are disordered. Hydrogen atoms of O(1), O(5), O(8) and atom N(2) were located from the difference synthesis while other H-atoms were placed in idealized positions assuming a C—H distance of 0.96 Å, an O(4)—H distance of 0.85 Å and a N(1)—H bond length of 0.90 Å. The positions of H atoms of the O(4)—H and N(1)—H groups were calculated assuming coplanarity with the naphthyl ring and intramolecular hydrogen bonds analogous to those observed in other inclusion compounds of dianilinegossypol.

3. Results and Discussion

Atomic co-ordinates are listed in Table II. Hydrogen atom parameters, anisotropic thermal parameters and structure factors are in the Supplementary Material. The conformation of the molecules and their numbering scheme are shown in Figure 1.

The conformation of the dianilinegossypol molecule has been discussed in detail in previous articles of this series. Here it is worth noting the dihedral angles between naphthyl moieties is equal to 86 and 90° in the DMSO and the double 1,4-dioxane–1,2-dichloroethane complexes of dianilinegossypol, respectively. The aniline rings are inclined at 16 and 21° and 15 and 15° to the naphthyl nuclei in the double 1,4-dioxane–1,2-dichloroethane and DMSO complexes, respectively. In the complexes the isopropyl groups have an identical orientation and the hydrogen atoms at C(23) and C(28) are oriented towards atoms H(4) and H(14). Intramolecular H-bonds close five- and six-membered rings in each half of the dianilinegossypol molecule (Table III).

Table II. Atom co-ordinates ($\times 10^{-3}$ for x, $\times 10^{-4}$ for y and z) and temperature factors (Å^2 $\times$ 10^{-3}).

Atom	x	y	z	U_{eq}^{iso*}
(a) *Complex of dianilinegossypol with DMSO*				
C(1)	265(2)	3613(9)	2370(6)	31(7)
C(2)	211(2)	4013(10)	1959(6)	27(7)
C(3)	78(3)	4486(11)	1957(6)	45(8)
C(4)	O(2)	4559(10)	2354(6)	38(7)
C(5)	−53(2)	4227(11)	3181(7)	46(8)
C(6)	−14(2)	3767(12)	3573(6)	44(8)
C(7)	121(2)	3291(11)	3597(6)	35(7)
C(8)	219(2)	3294(13)	3217(6)	50(9)
C(9)	174(3)	3718(11)	2782(7)	48(9)
C(10)	43(2)	4178(10)	2775(6)	33(7)
C(11)	267(2)	3370(10)	1195(6)	27(6)
C(12)	302(2)	3930(12)	1532(6)	44(8)
C(13)	436(2)	4405(12)	1502(6)	47(9)
C(14)	534(2)	4313(8)	1116(6)	31(7)
C(15)	593(2)	3719(11)	373(6)	45(8)
C(17)	442(3)	2623(9)	97(6)	50(9)
C(16)	568(2)	3137(10)	86(7)	31(7)
C(18)	325(2)	2720(12)	447(6)	40(8)
C(19)	358(2)	3302(13)	793(6)	44(8)
C(20)	489(2)	3775(11)	764(6)	36(7)
C(21)	26(3)	4934(13)	1505(6)	66(10)
C(22)	361(2)	2902(10)	3299(6)	38(8)
C(23)	−196(3)	4751(13)	3187(6)	56(9)
C(24)	−172(3)	5263(10)	3613(7)	63(9)
C(25)	−353(3)	4351(17)	3164(9)	113(15)
C(26)	476(2)	4992(12)	1859(6)	59(9)
C(27)	184(2)	2333(11)	391(7)	46(8)
C(28)	722(3)	4243(12)	293(6)	45(8)
C(29)	884(2)	3867(11)	391(6)	47(8)
C(30)	713(2)	4582(12)	−184(7)	62(9)
O(1)	387(1)	3208(7)	2388(3)	39(4)
O(3)	143(2)	2895(9)	3965(4)	77(7)
O(4)	−103(2)	3761(7)	3939(4)	65(6)
O(5)	146(1)	2949(6)	1248(4)	38(5)
O(7)	425(1)	2073(7)	−204(4)	53(5)
O(8)	661(2)	2978(7)	−289(4)	60(6)
N(1)	410(2)	2487(11)	3684(5)	67(8)
N(2)	156(2)	1784(9)	49(5)	59(7)
C(31)	550(2)	2133(12)	3765(7)	49(9)
C(32)	669(2)	2130(15)	3480(10)	85(12)
C(33)	803(3)	1780(15)	3611(11)	93(13)
C(34)	827(3)	1387(13)	4045(12)	93(14)
C(35)	697(3)	1336(13)	4328(10)	73(11)
C(36)	558(3)	1727(11)	4197(6)	53(9)

Table II. Continued.

Atom	x	y	z	U_{eq}^{iso*}
(a) *Complex of dianilinegossypol with DMSO*				
C(37)	21(3)	1386(10)	−41(7)	46(8)
C(38)	−120(3)	1427(18)	192(10)	93(13)
C(39)	−241(4)	1013(16)	76(10)	99(14)
C(40)	−255(4)	587(16)	−304(12)	114(16)
C(41)	−116(4)	536(20)	−555(11)	135(18)
C(42)	7(3)	936(18)	−427(8)	106(43)
S(1)	693(1)	2194(4)	1839(2)	74(3)
O(9)	520(1)	2276(9)	1821(6)	82(7)
C(43)	740(3)	2363(20)	1276(9)	131(16)
C(44)	772(4)	2993(14)	2071(13)	162(19)
S(2)	117(1)	1296(4)	2077(3)	95(3)
O(10)	75(2)	2093(9)	1987(7)	115(9)
C(46)	217(4)	970(13)	1597(10)	114(44)
C(45)	288(3)	1363(14)	2499(10)	110(14)
(b) *Complex of dianilinegossypol with 1,4-dioxane and 1,2-dichloroethane*				
C(1)	265(2)	3668(6)	2405(4)	34(5)
C(2)	214(2)	4065(7)	2000(5)	33(5)
C(3)	85(2)	4510(7)	2004(5)	43(5)
C(4)	−0(2)	4529(8)	2417(4)	37(5)
C(5)	−48(2)	4179(7)	3258(4)	42(5)
C(6)	−10(2)	3737(8)	3612(5)	41(5)
C(7)	124(2)	3278(8)	3643(5)	46(5)
C(8)	236(2)	3260(7)	3255(5)	39(5)
C(9)	185(2)	3699(7)	2845(4)	34(5)
C(10)	48(2)	4143(7)	2847(5)	33(5)
C(11)	274(1)	3478(7)	1228(4)	26(4)
C(12)	313(2)	4008(7)	1567(4)	31(4)
C(13)	446(2)	4452(7)	1524(5)	39(5)
C(14)	530(2)	4357(6)	1120(4)	36(5)
C(15)	596(2)	3749(6)	374(5)	28(4)
C(16)	569(2)	3208(7)	78(4)	32(5)
C(17)	434(2)	2733(7)	109(5)	31(5)
C(18)	322(2)	2854(7)	462(4)	30(4)
C(19)	361(2)	3386(7)	821(4)	28(4)
C(20)	490(2)	3835(7)	777(4)	35(5)
C(21)	24(2)	4931(8)	1575(5)	58(6)
C(22)	381(2)	2906(8)	3321(5)	41(5)
C(23)	732(2)	4260(8)	294(5)	47(6)
C(24)	900(2)	3914(9)	395(6)	61(6)
C(25)	713(2)	4603(9)	−215(6)	57(6)
C(26)	490(2)	4992(8)	1872(5)	61(6)

Table II. Continued.

Atom	x	y	z	$U_{\text{eq}}^{\text{iso}*}$
(b) *Complex of dianilinegossypol with 1,4-dioxane and 1,2-dichloroethane* (Continued)				
C(27)	178(2)	2440(7)	430(4)	36(5)
C(28)	−181(2)	4709(8)	3281(6)	52(7)
C(29)	−349(2)	4325(11)	3234(6)	84(9)
C(30)	−163(2)	5153(9)	3732(6)	84(8)
C(31)	559(2)	2130(7)	3803(4)	44(5)
C(32)	691(2)	2187(8)	3560(6)	65(6)
C(33)	827(2)	1767(10)	3674(7)	78(7)
C(34)	821(2)	1302(9)	4054(6)	71(7)
C(35)	698(2)	1239(9)	4299(6)	67(7)
C(36)	560(2)	1644(8)	4180(5)	57(6)
C(37)	9(2)	1550(9)	11(6)	62(6)
C(38)	−128(2)	1621(8)	263(5)	57(6)
C(39)	−264(2)	1188(12)	168(8)	89(9)
C(40)	−256(3)	701(15)	−173(8)	103(11)
C(41)	−131(4)	612(13)	−424(9)	160(15)
C(42)	7(2)	1049(10)	−347(7)	96(9)
O(1)	392(1)	3216(5)	2395(3)	56(4)
O(3)	153(1)	2896(5)	4011(4)	66(4)
O(4)	−97(1)	3704(5)	4006(3)	59(4)
O(5)	151(1)	3031(5)	1289(3)	50(3)
O(7)	423(1)	2254(5)	−207(3)	53(4)
O(8)	665(1)	3055(5)	−279(3)	50(3)
N(1)	416(4)	2500(6)	3721(4)	50(4)
N(2)	150(1)	1942(6)	105(4)	50(4)
C(1)d	−221(4)	2841(13)	1548(11)	149(16)
C(2)d	−146(3)	2597(13)	2307(7)	127(11)
C(3)d	−270(4)	2030(16)	2238(10)	202(20)
C(4)d	−322(3)	2312(17)	1469(7)	133(13)
O(1)d	−73(2)	2648(13)	1898(5)	162(10)
O(2)d	−397(2)	2334(20)	1873(6)	276(20)
C(1)c	276(6)	5986(28)	2888(8)	287(37)
C(2)c	241(4)	6399(19)	3193(9)	211(18)
CL(1)	205(2)	6429(4)	2308(3)	203(6)
CL(2)	320(1)	5944(5)	3754(3)	187(5)

$^{*}U = \frac{1}{3}\sum\sum U_{ij}a_i^* a_j^* \mathbf{a}_i \cdot \mathbf{a}_j$.

Under ambient conditions dianilinegossypol with DMSO forms a 1 : 2 host–guest complex belonging to the $P2_1/n$ space group. In these complexes host molecules are associated into wavy chains in the direction of the z-axis by a pair of centrosymmetric O(4)—H $\cdots$O(7) and O(8)—H$\cdots$O(3) H-bonds (Table III). The

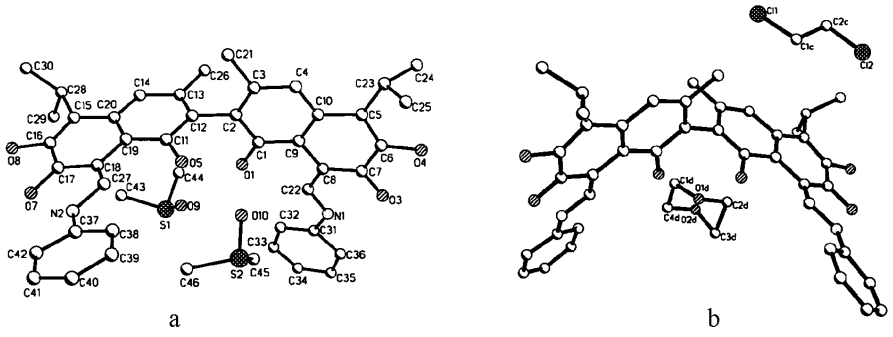

Figure 1. The conformation of the molecules and the numbering scheme in the complexes of dianilinegossypol with DMSO (a) and 1,4-dioxane + 1,2-dichloroethane (b).

Table III. Intra- and intermolecular H-bonds* in the complexes of dianilinegossypol with DMSO (a) and 1,4-dioxane + 1,2-dichloroethane (b).

Bonds	Symmetry	Donor · · · acceptor (Å) (a)	(b)
Intramolecular H-bonds			
O(4)—H · · · O(3)		2.61(3)	2.59(2)
O(8)—H · · · O(7)		2.62(2)	2.55(1)
N(1)—H · · · O(3)		2.57(3)	2.51(2)
N(2)—H · · · O(7)		2.51(3)	2.56(2)
Intermolecular H-bonds			
O(4)—H · · · O(7)	$(-0.5+x, 0.5-y, 0.5+z)$	2..86(2)	2.86(1)
O(8)—H · · · O(3)	$(0.5+x, 0.5-y, -0.5+z)$	2.64(2)	2.70(1)
O(1)—H · · · O(9)	(x, y, z)	2.64(2)	–
O(5)—H · · · O(10)	(x, y, z)	2.71(2)	–
O(1)—H · · · O(2D)	$(1+x, y, z)$	–	2.94(3)
O(5)—H · · · O(1D)	$(x, y, z$	–	2.75(2)

*As not all H-atoms at oxygen and nitrogen atoms were found from the difference synthesis and because of the low accuracy of the H-atom positions other parameters of the H-bonds are not given.

packing of such chains in the direction of the y-axis gives rise to voids between the peaks and valleys of the neighbouring host associates. The hydrophilic and hydrophobic parts of dianilinegossypol molecules correspond to the valleys and the peaks, respectively (Figure 2). The DMSO oxygen atom, which is directed to the valleys, occupies these voids in the packing of the host and guest molecules. In channels running along the direction of the x-axis two symmetrically independent guest molecules are H-bonded to the O(1)—H and O(5)—H hydroxyl groups of the host molecules, related to each other by the a-translation. Because of the specific interaction between the S atom of the first guest molecule and the O atom of the

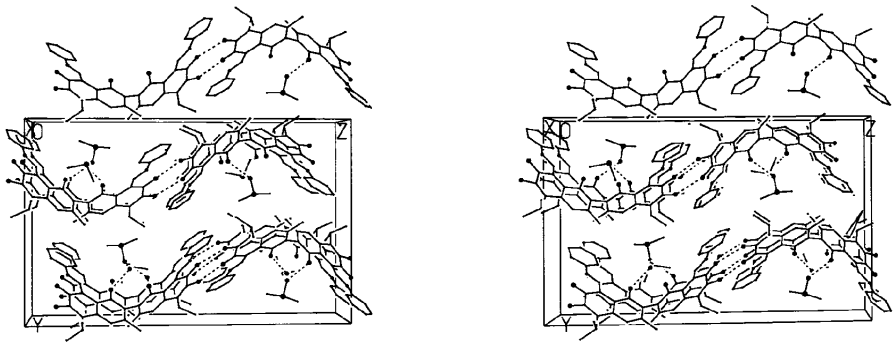

Figure 2. Stereoview of the crystal structure of the host–guest complex of dianilinegossypol with DMSO.

Table IV. Crystal data for some dimorphs of dianilinegossypol complexes with DMSO and 1,4-dioxane.

	DMSO (β-phase)	1,4-Dioxane (α-phase)	1,4-Dioxane (β-phase)
a (Å)	28.891(7)	37.713(11)	30.553(9)
b (Å)	12.105(4)	37.717(11)	11.751(6)
c (Å)	13.104(5)	20.247(5)	12.538(7)
α (°)	90	90	90
β (°)	94.21(3)	90	99.44(3)
γ (°)	90	120	90
V (Å^3)	4570	24913	4442
Space group	$C2/c$	$R\bar{3}$	$C2/c$
Host : guest	1 : 2	1 : 3	1 : 2
Z	4	27	4
D_x (g/cm^3)	1.20	1.21	1.26

second one [S(1)$\cdots$O(10) 3.25 Å], wavy chains are incorporated into layers parallel to the (010) plane.

If the temperature of the crystallization medium is raised to 60 °C, a host–guest complex with another structure is formed from a solution of dianilinegossypol in DMSO (Table IV). This β-modification is isostructural with the acetone clathrate, the structure of which has been discussed previously [5]. It is worth noting that in the case of the β-dimorph the symmetry of the crystal is raised and the intrinsic symmetry of the twofold axis of the host molecule – lost in the structure of the α-dimorph – is regained in the cryptate-type clathrate.

We have previously reported [2] that dianilinegossypol with 1,4-dioxane gives a 1 : 3 inclusion complex under ambient conditions (Table IV). The structure of this complex has been solved by Gdaniec [8].

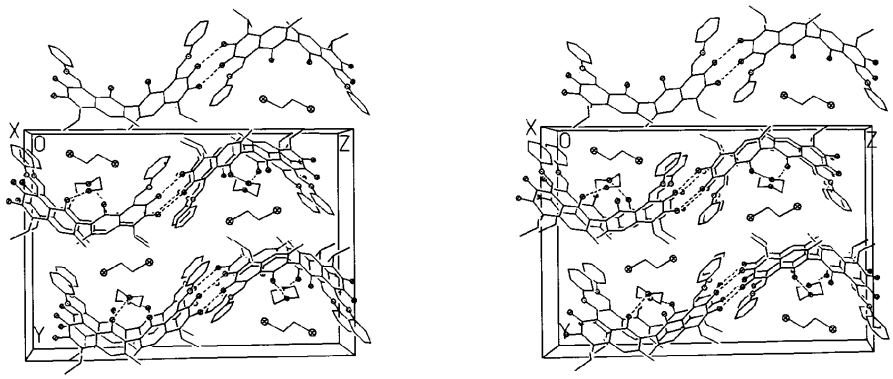

Figure 3. Stereoview of the crystal structure of the host–guest complex of dianilinegossypol with 1,4-dioxane and 1,2-dichloroethane.

If 1,2-dichloroethane is added to a solution of dianilinegossypol in 1,4-dioxane another type of host–guest complex is precipitated from solution. As will be apparent from the data in Table I, the clathrate formed is isostructural with the α-dimorph of the host–guest complex of dianilinegossypol with DMSO. This complex is found to be a 1 : 1 : 1 adduct containing dianilinegossypol, 1,4-dioxane and 1,2-dichloroethane molecules. Here one 1,4-dioxane molecule matches two DMSO molecules in the α-phase of the dianilinegossypol–DMSO complex. Each 1,4-dioxane molecule has two H-bonds *via* its two oxygen atoms as proton acceptors with the O(1)—H and O(5)—H groups of the two dianilinegossypol molecules of the neighbouring chains (Figure 3). H-bonding of the 1,4-dioxane molecules leads to the formation of layers from chains of the host molecules. However, in packing such layers, medium size voids are still retained between them. 1,2-Dichloroethane molecules are included in these channels. The structure can be considered as an intercalate on the basis of a mixed dianilinegossypol–1,4-dioxane host matrix. The same two-dimensional mixed host matrix with 1,4 dioxane is also obtained with gossypol [9] in the case where 1,4-dioxane molecules serve simultaneously as guest molecules included in the channels of the clathrate.

On increasing the crystallization temperature up to 60 °C solutions of dianilinegossypol in 1,4-dioxane give the known host–guest complex, isostructural with the $C2/c$ β-dimorph of the dianilinegossypol–DMSO complex (Table IV).

Thus host–guest complexes of dianilinegossypol with DMSO and 1,4-dioxane are both characterized by dimorphism, and transition to the same cryptate type clathrate occurs. The new type of dianilinegossypol host–guest complexes is not observed as a result of increasing the temperature.

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