

Inclusion of molecular iodine into channels of the organic zeolite-like gossypol

Samat A. Talipov · Bakhtiyar T. Ibragimov ·
Fatkhulla Kh. Tadjimukhamedov · Zavkibek G. Tiljakov ·
Alexander J. Blake · Tino Hertzsch · Jürg Hulliger

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Abstract Gossypol has been obtained in the zeolite-like form by desolvation of the 1:1 unstable solvate with dichloromethane. It demonstrates a high potential for an uptake of molecular iodine from the environment. In a case of single crystals a stable inclusion compound (gossypol)₈·I₂, preserving the crystal structure of the zeolite-like form, has been prepared. The iodine molecules occupy large cavities of the channels and are inclined as confirmed by the absence of a strong dichroism. The iodine molecules can be removed with the help of vacuum giving back to the zeolite-like form.

Keywords Gossypol · Inclusion compound · Iodine · Organic zeolite · Polymorph · Sorption

Introduction

Gossypol, a phenolic pigment extracted from cotton seeds [1], demonstrates a diversity of biological activities such as antiviral, antiparasitic, immunosuppressive, antitumor and contraceptive properties [2]. Unique ability as a host compound to form crystalline inclusion compounds with many organic solvents [3] makes gossypol an interesting object of solid supramolecular chemistry. The structures of nearly 50 gossypol clathrates have been solved [4]. Another specific feature of solid state chemistry of gossypol is its unique polymorphism: polymorphs P1 and P2 are obtained by crystallization from solutions, while guest-free modifications P3-P7 are formed by desolvation of the unstable channel type inclusion complexes [5].

The diversity of polymorphic forms of gossypol leads to different melting points. The values of melting points lie in range 178–214 °C. Over this temperature the gossypol molecule loses two water molecules and turns to anhydrogossypol [6]. Gossypol has also a remarkable antioxidant property—small amounts added to oils have been used for the stabilization of foods [7]. A number of other technical applications of gossypol have been reported [8–11].

Gossypol forms three different host-guest complexes with dichloromethane. An unstable monosolvate, the α -form, crystallizes at room temperature [12, 13]. Increasing the temperature up to 30 °C leads to the precipitation of the β -form, a stable 1:1 host-guest complex. Further raising the temperature to 36 °C results in crystallization of the γ -form, a stable semisolvate. The crystal structures of these pseudopolymorphs are known (β -form) [14] or isomorphous with previously reported structures [15].

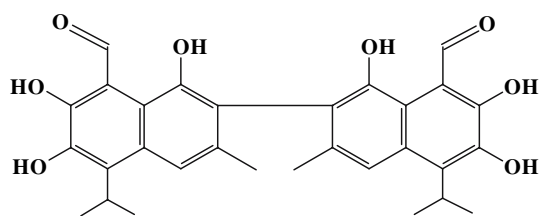
The most interesting modification of the gossypol dichloromethane clathrate is the α -form including guest molecules into channels. The inclusion complex shows

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S. A. Talipov (✉) · B. T. Ibragimov ·
F. Kh. Tadjimukhamedov · Z. G. Tiljakov
Institute of Bioorganic Chemistry, H. Abdullaev str. 83,
Tashkent 100125, Uzbekistan
e-mail: ckystal@uzsci.net

T. Hertzsch · J. Hulliger
Department of Chemistry and Biochemistry, University of
Berne, Freiestrasse 3, Berne 3012, Switzerland

A. J. Blake
School of Chemistry, The University of Nottingham,
Nottingham NG7 2RD, UK



Constitution of gossypol molecule.

desolvation, giving rise to the guest-free modification P3 in the form of an organic channel-type zeolite. Removal of the solvent molecules does not affect the crystal structure of the host: channels are retained, although they show a slight contraction (4%).

Here, we present results on the sorption of molecular iodine by the gossypol P3 polymorph. Recently, sorption of I_2 by other organic zeolite-like inclusion compound, tris(*o*-phenylenedioxy)cyclotriphosphazine [16] and a new coordination polymer with removable iodine in an eclipsed 2-D open-channel structure [17] were reported.

Experimental

Gossypol is produced in the Experimental Plant of the Institute of Bioorganic Chemistry of the Academy of Sciences of Uzbekistan from by-products of the cottonseed industry. Crystals of the α -form gossypol dichloromethane clathrate were obtained by solvent evaporation from solutions in dichloromethane at room temperature. Keeping of these crystals for 2 h at 50 °C gave rise to the guest-free product in the zeolite-like form (Table 1). Iodine was provided by the following two ways: (i) from the gas phase at 0 °C for 6 h or at room temperature for 48 h; (ii) by suspending gossypol crystals in aqueous solutions of iodine for 3 days at room temperature. Single crystals were prepared by sorption of iodine molecules from the gas phase at ambient conditions and were used for both the X-ray structure determination and for TG-DSC experiments. In order to obtain microcrystalline P3 polymorph, 100 mg of gossypol was dissolved in 4 mL of dichloromethane and the solution was kept at ambient conditions until precipi-

tation started. Then the solution was put into the ultrasonic bath ('Bandeline Sonorex') for 3 h at room temperature with simultaneous evaporation of dichloromethane. Ultrasonic activation prevents forming of large crystals of P3 polymorph and reducing them to fine particles. Thus microcrystalline P3 polymorph with particle size of 10–30 μm was obtained.

The thermal characterization of crystals was performed on a TG-DSC METTLER TOLEDO STAR^c system using an open aluminium crucible and samples with the weight of about 4–5 mg. A linear heating rate of 5 K/min was applied using a nitrogen flow of 1 L/h. Variable temperature powder-XRD patterns were recorded on a powder diffractometer Stadi P (Stoe) equipped with a variable temperature capillary set up and a linear position sensitive detector using CuK_α radiation and a monochromator (Germanium 111). Further on, the sorption of iodine into channels of the organic zeolite was investigated for crystalline powders obtained by the ultrasonic method. The increase of weight was measured by Mettler AE163 balance.

In order to show that the material can be converted back into the zeolite-like form, the crystalline powders have been exposed by iodine vapour and kept under vacuum condition at room temperature for 12 h. Whereupon XRD patterns of these samples were recorded by powder diffractometer Stadi P (Stoe).

Unit cell parameters were determined on Bruker SMART APEX CCD diffractometer equipped with an Oxford Cryosystems open-flow cryostat [18]. Data collection included the hemisphere of the reciprocal space by a combination of three sets of exposures with φ angles of 0, 90 or 180° and each exposure of 40 s covered 0.3° in ω . The 'crystal to detector' distance was 6 cm and the detector swing angle was –30°. Coverage of the unique set was over 99% complete. The crystal decay was investigated by repeating fifty initial frames at the end of data collection and also by analyzing the duplicate reflections and it was found to be negligible. The structure was solved by direct methods (SHELXS97 [19]) and refined by full-matrix least squares (SHELXL97 [20]). Molecular graphics utilized are XP in SHELXTL-Plus [21]. Crystal data and structure determination details are given in Table 2.

Table 1 Crystal data in space group $C2/c$ for the isomorphous clathrates of gossypol with dichloromethane, dibromomethane, molecular iodine and the P3 polymorph

Guest	H:G	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	β (°)	<i>V</i> (Å ³)	<i>D</i> _{calc} (g/cm ³)
CH ₂ Cl ₂	1:1	21.320(4)	19.129(6)	15.765(2)	113.05(2)	5916	1.36
CH ₂ Br ₂	1:1	21.439(9)	19.087(8)	16.049(8)	113.68(4)	6015	1.53
I ₂	8:1	21.119(7)	19.305(7)	15.274(5)	112.674(6)	5746	1.27
P3	–	21.208(8)	19.079(4)	15.267(2)	113.19(2)	5678	1.21

Table 2 The characteristics of gossypol/iodine crystal, data collection and structure determination

Empirical formula	$C_{30}H_{30}O_8 \cdot 0.125I_2$
Formula weight	550.27
Crystal system	Monoclinic
Space group	$C2/c$
T (°C)	−20
a [Å]	21.119(7)
b [Å]	19.305(7)
c [Å]	15.274(5)
β [°]	112.674(6)
V [Å ³]	5746
Z	8
$D(\text{calc})$ [g/cm ³]	1.27
Radiation	Mo- K_α
$F(000)$	2298
$\mu(\text{Mo-}K_\alpha)$ (mm ^{−1})	0.356
Crystal size (mm)	0.4 × 0.4 × 0.2
Crystal colour, shape	Dark red block
θ -range (°)	1.48–25.00
Index range (merged data)	$h(-25/21)$, $k(0/22)$, $l(0/18)$
Reflections collected	7069
Independent reflections	5630
Data/restraints/parameters	4896/0/391
Goodness-of-fit on F^2	1.17
R	0.086
R_w	0.175
ΔF extrema (e/Å ³)	+0.27, −0.29

Results and discussion

Previously, we have reported that P3 polymorph can easily absorb ammonia, methylamine and methanol [22],

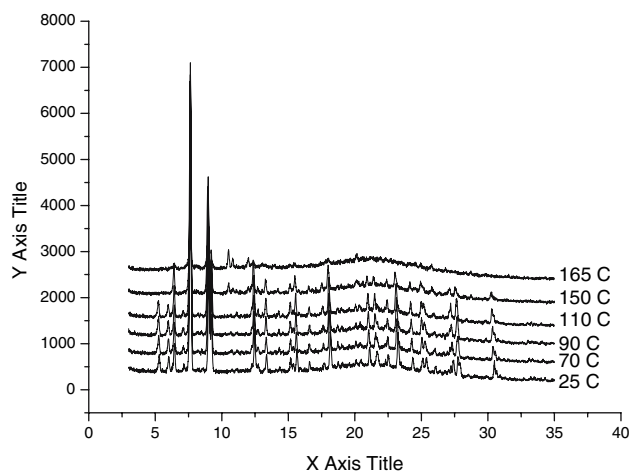


Fig. 1 The thermal stability of the gossypol zeolite: Temperature dependent XRD patterns, showing the existence of the channel type structure up to about 110 °C

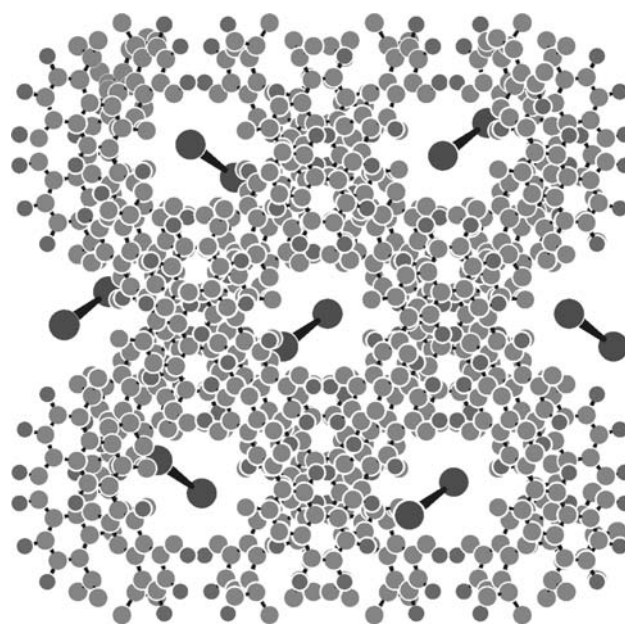


Fig. 2 The structure of the gossypol inclusion complex with iodine. View along the channel axis (101). I_2 molecules are inclined as confirmed by the absence of a significant dichroism

although the reversibility of the process has not been studied so far. Results, however, support a zeolitic behaviour for the porous structure of gossypol. To investigate the thermal stability of empty channels, powder-XRD patterns were recorded at different temperatures (Fig. 1): Up to 110 °C the empty channel-type structure is retained. Increasing the temperature up to about 165 °C resulted, however, in an unknown polymorph.

Sorption experiments performed in a gas phase or in water showed that the P3 zeolite-like form of gossypol can take up molecular iodine. Initially yellow gossypol crystals became brownish while absorbing I_2 . A single

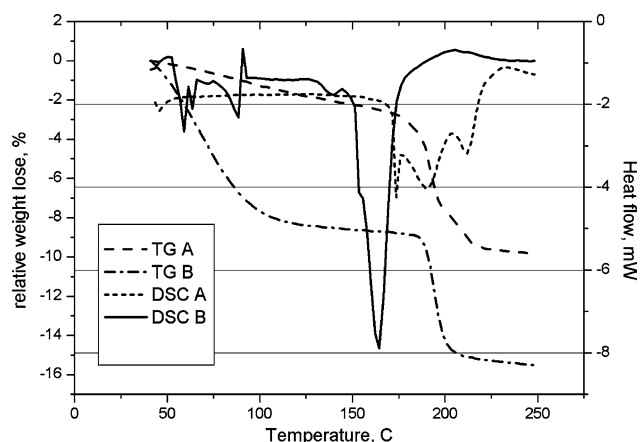
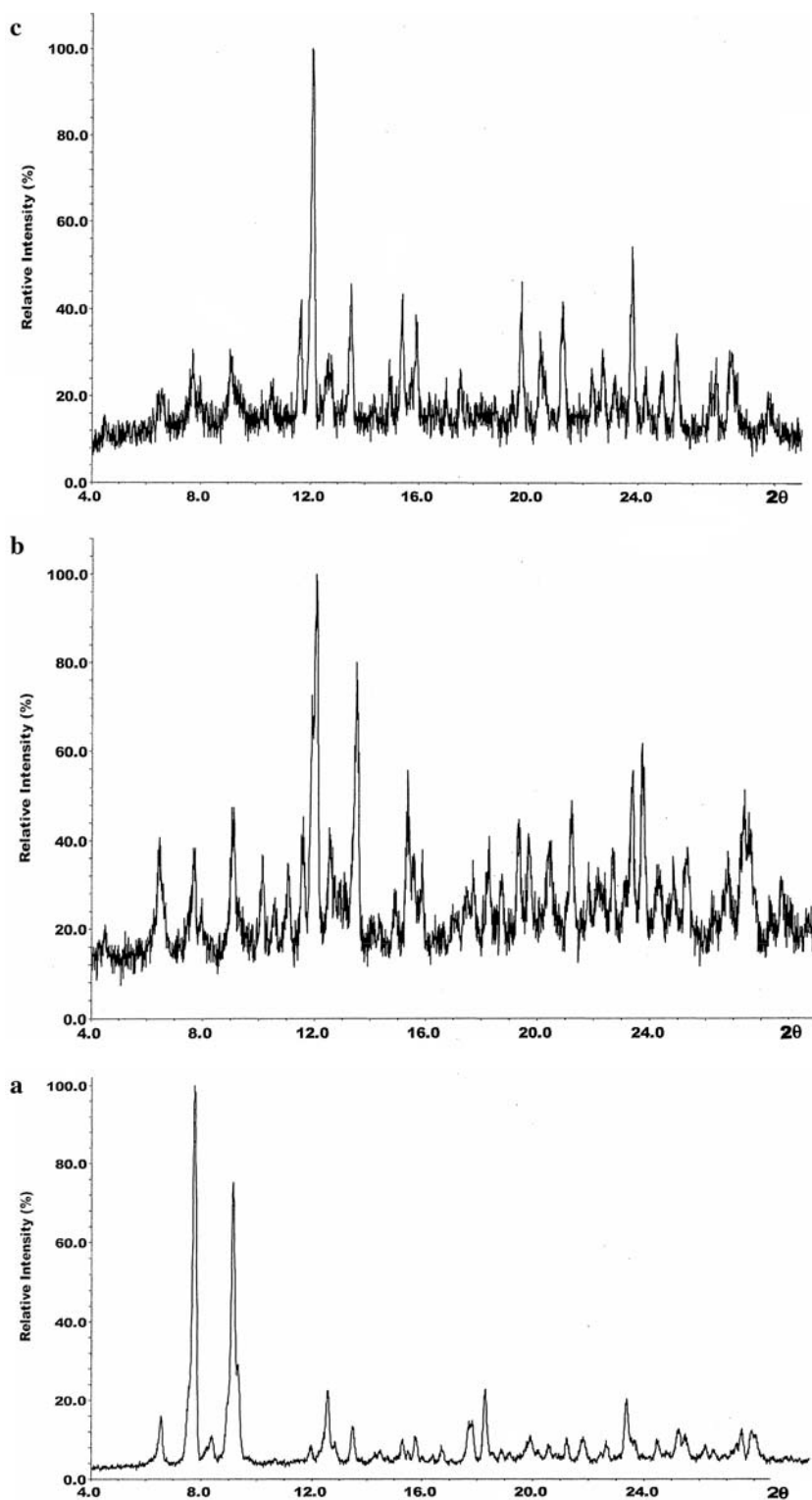


Fig. 3 TG-DSC curves of the gossypol zeolite (A); and of the gossypol inclusion complex with iodine (B)

Fig. 4 XRD patterns: (a) the guest-free zeolite form of gossypol (P3 polymorph); (b) iodine sorption at 4 °C; (c) iodine sorption at 50 °C



crystal-to-single crystal transformation of P3 to P3-iodine was confirmed by single crystal X-ray diffraction. The crystal structure of the complex is isomorphic with the structure of the dichloromethane clathrate where hydrogen-bonded columns of gossypol molecules are packed

with the help of van der Waals forces into a porous architecture [12, 13]. In the complex, iodine molecules enter the extended cavities of the channels within the zeolitic structure (Fig. 2), occupying 1/8 of the possible sites.

The TG-curve of the guest-free zeolite-like form shows one step process which corresponds to the loss of two water molecules by each gossypol molecule and formation of anhydrogossypol (Fig. 3). Calculations of TG-data are in good agreement with the theoretical percentage 6.9% of water loss (7% calculated from TG). The single endothermic peak (~180 °C) on the DSC-curve of P3 (Fig. 3) is related to melting of the sample, but the loss of water molecules takes place in the extended temperature range 190–210 °C.

The TG-curve of iodine sorption product demonstrates a two step process (Fig. 3). The first step is related to the loss of iodine (~10%) in temperature range 30–110 °C which agrees with the composition obtained by refinement of the X-ray diffraction data (I₂:Gp 1:8). while the second one is related to the water loss being in a good agreement with the theoretical percentage of mass loss. The temperature range of the water loss is identical with one of P3. The DSC-curve shows some endothermic processes in temperature range 30–110 °C which correspond to the loss of iodine (Fig. 3).

Solution NMR bears no indication that gossypol is reacting with I₂ in solution or in the solid state. The experiments on molecular iodine sorption were performed by an interaction of fine P3 polymorph powders with iodine vapours at 4 °C and 50 °C. The sorption capacity values were 44 mg of I₂ per 100 mg of P3 polymorph and 29 mg per 100 mg at 50 °C and 4 °C, respectively. This corresponds to a molar ratio of Gp:I₂ equal to 1:0.9 and 1:0.6. The crystallinity of the sample is deteriorated by increasing of the sorption temperature and becomes amorphous at ~80 °C (Fig. 4). A demonstration of reversibility of the sorption process is the fact that material can be converted back into the zeolite-like form (under vacuum and at room temperature for 12 h).

Conclusions

The stoichiometry of gossypol zeolite-like inclusion compound with molecular iodine varies in a wide range. The host-guest ratio of the obtained product depends on the size of crystallites of the initial zeolite-like form (the dispersity) and the absorption temperature. The higher sorption temperature the higher an amount of absorbed molecules but the lesser crystallinity of the product: Sorption at ~80 °C gives rise to amorphous product but at 50 °C the inclusion compound with 90% site occupation is formed. At the temperature of 4 °C nearly 60% of whole sites may be occupied giving rise to well-defined crystalline product. The least amount of included molecules is found in relatively large single crystals (12%). Inclusion compounds can be obtained by taking up I₂ either from the gas phase or

from water solution. Molecular iodine occupies the extended cavities of the channels thus being inclined to the channel axis. As a matter of fact, iodine molecules show no dense packing along channels as found for tris(*o*-phenylenedioxy)-cyclotriphosphazine [16]. However, the iodine molecules can be removed with the help of vacuum giving back to the zeolite-like form.

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