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Structural, thermal, kinetic and spectroscopic characterization of a metastable polymorph of 2-(2'-hydroxyphenyl)benzothiazole

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2-(2'-hydroxyphenyl)benzothiazole (HBT) exhibits remarkable photophysical properties, in particular intense fluorescence, both in solution and in solid state. For this reason, this compound and related ones are intensely studied for a wide range of optoelectronic applications. In addition, benzothiazole derivatives are known to present polymorphism, that is, the characteristic of crystallizing in more than one crystallographic structure. Herein, following a recently published work in which the existence of a metastable polymorph of HBT was reported, we describe the determination of its crystal structure, by means of powder X-ray diffraction. The new polymorph is found to crystallize in the $P2_1$ space group, with lattice parameters $a = 17.82605$ Å, $b = 4.96006$ Å, $c = 6.00379$ Å and $\beta = 93.1630^\circ$. The experimentally determined lattice parameters are compared to those obtained by modelling the structure by density functional theory, revealing excellent agreement. In addition, the transition of the metastable polymorph to the stable one is studied both kinetically and thermodynamically, by means of non-ambient X-ray diffraction and DSC experiments, respectively. From the kinetic point of view, an activation energy of 66 ± 6 kJ mol⁻¹ is found, while from the thermodynamic one, an enthalpy of conversion of -4.5 ± 1.4 kJ mol⁻¹ is obtained, consistent with the value calculated by DFT, of -5 kJ mol⁻¹. Additionally, the two forms of HBT are characterized spectroscopically, by means of UV-visible, fluorescence and Raman spectroscopy, and the experimental spectra are compared with the computational ones, revealing very good agreement.

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1. Introduction

The compound 2-(2'-hydroxyphenyl)benzothiazole (HBT) is an intensely investigated species, owing to its peculiar optoelectronic properties.^{1–4} It is well known that this molecule shows excited-state intramolecular proton transfer (ESIPT),^{5,6} a fast (occurring in the femtosecond time scale) photochemically activated process in four states ($E \rightarrow E^* \rightarrow K^* \rightarrow K$) involving the tautomerization from enol (E) to keto (K) form in the excited state, arising from the presence in the molecule of an intramolecular hydrogen bond between a proton-donor and a proton-acceptor in close proximity. This phenomenon has attracted considerable attention^{7,8} as it leads to advantageous photophysical properties, such as broad and/or dual emission,⁹ where the short and long wavelengths are due to the excited

state enol and the excited state keto forms, respectively. For this reason, its fluorescence in both forms has been extensively studied in various solvents and in the solid state^{10,11} and has made this compound and its derivatives attractive for a broad range of applications, such as light emitting diodes,¹² fluorescent probes,¹³ laser dyes,¹⁴ molecular switches¹⁵ and chemical sensors.¹⁶

In addition to ESIPT, benzazoles,¹⁷ the class of molecules to which HBT belongs, characterized by the presence of a benzene ring fused with a five-carbon cycle containing nitrogen and at least another heteroatom, are also known to present polymorphism,^{18,19} that is, the property of existing in two or more crystallographic structures.^{20,21} Two classes of polymorphs can be identified, namely conformational and packing polymorphs: in the first case, the possibility of rotation around a single bond makes possible the existence of different conformations, leading to a different crystal packing,²² while in the second case the different polymorphs possess the same conformation.²³ The phenomenon of polymorphism has a great relevance for instance in pharmaceutical and medicinal chemistry,²⁴ since different polymorphs can have different physico-chemical properties, such as solubility and dissolution rate, in turn affecting their bioavailability. Polymorphism

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of benzimidazole and its derivatives,^{25–27} a group of substances of pharmaceutical interest, for example as anthelmintics,²⁸ has been widely reported and studied, both crystallographically and with different techniques and approaches, such as Raman and NMR spectroscopy, and quantum chemical calculations.^{27,29,30} Furthermore, several examples of benzothiazole-containing compounds showing the existence of different polymorphs have also been reported.³¹

The determination of crystal structures is usually carried out by means of single-crystal X ray diffraction, which is by far the most important technique required to perform this task. However, its biggest limitation is the strict requirement of crystals of appropriate size and quality, which are often difficult and sometimes practically impossible to obtain. This has led to substantial advancements in strategies for crystal structure determination from powder X-ray diffraction.^{32,33} Since different polymorphs possess different diffraction patterns, the latter are often used as a fingerprint to identify a particular polymorphic form, especially in pharmaceutical chemistry. However, thanks to the progress in the methods for structure determination from powder diffraction data, it is now common to employ this technique to determine the structure of new polymorphs,³⁴ especially those that are metastable or can be obtained only in particular conditions and in polycrystalline form.

In this paper, we describe the crystal structure of a metastable polymorph of HBT (indicated as Form I), whose existence has been recently discovered and reported in a previously published work.³⁵ This structure was determined by means of powder X-ray diffraction. Furthermore, new thermodynamic data for the two forms, obtained both experimentally and computationally, are presented, thus extending those reported in ref. 35 and 36 for the stable polymorph. Moreover, a kinetic study of interconversion between the two forms and their spectroscopic characterization, along with density functional theory calculation of their vibrational and electronic spectra, are reported herein.

Through a thermal treatment of the thermodynamically stable form (*i.e.* Form II), the compound is forced to crystallize into Form I; this form then slowly converts back to Form II at room temperature and over a time scale of some days. The thermal treatment consists of melting Form II and rapidly quenching it to room temperature.

2. Experimental

2-(2'-hydroxyphenyl)benzothiazole, HBT, in Form II was used as received (Merck, 99%), *i.e.* as a light green powder. The molar fraction was obtained by gas–liquid chromatography with flame ionization detector, performed on a water-free basis using an Agilent 8860 instrument equipped with a polysiloxane column. It yielded a molar fraction purity of 0.9999. Form I was prepared in a similar way to that described in ref. 35, by heating the substance in a muffle up to 423 K at 2 K min^{−1}, then removing it from the muffle and allowing it to solidify rapidly at room temperature. It was obtained as pale green crystals.

2.1. Powder X-ray diffraction

Powder X-ray diffraction patterns of Forms I and II of HBT in the 5–110° 2 θ range were obtained by using a Malvern Panalytical X'Pert Pro diffractometer (Cu K α radiation) equipped with a capillary spinner, a graded multilayer elliptical mirror, and an ultrafast RTMS X'Celerator detector. The powders, previously ground in an agate mortar, were placed in 0.5 mm borosilicate glass capillaries. The determination of the crystal structure of Form I was carried out using EXPO 2014 software.³⁷ Non-ambient measurements were performed using an Anton Paar XRK 900 reactor chamber with a factory calibrated automatic stage mover, on a Macor glass-ceramic sample holder, under He gas flow (20 cm³ min^{−1}@STP, purity 99.999%). Quantitative phase analysis for the study of the kinetics of conversion of Form I into Form II was performed with the Rietveld method, using the MAUD (Materials Analysis Using Diffraction) software.³⁸

2.2. Differential scanning calorimetry

Differential scanning calorimetry experiments on the two forms of HBT were performed with a Linseis Chip-DSC 1 instrument in aluminum crucibles with a lid placed on them, in static air, in the temperature range 298–423 K, with a heating rate of 20 K min^{−1}. About 15 mg (accurately weighed) of HBT were used for each measurement. The instrument was calibrated for temperature and enthalpy by using indium, tin, lead and zinc as standard materials.^{39,40}

2.3. UV-visible spectroscopy

UV-visible spectra of the two powders were recorded with a Shimadzu UV-2600 spectrophotometer equipped with an ISR 2600 Plus integrating sphere, with BaSO₄ as reflectance standard, in the range 220–1400 nm. Spectra of the two forms in solution (acetonitrile, 2.2 × 10^{−4} M) were also acquired with the same instrument, in the spectral range 190–900 nm, using SUPRASIL quartz cells (10 mm optical path).

2.4. Solid-state fluorescence – micro-photoluminescence (μ -PL)

μ -PL spectra were acquired at room temperature using a 405 nm laser with a power of 200 nW. The same 100× objective with NA = 0.9 was used for excitation and collection in a backscattering configuration. The laser light was filtered out using a 407 nm long-pass filter, and the emitted signal was dispersed by a spectrometer (model IsoPlane 160) equipped with a 300 grooves per mm grating and detected with a liquid nitrogen-cooled Si CCD camera (Pylon).

2.5. Raman spectroscopy

Raman spectra were recorded in the 100–3200 cm^{−1} region, with a Renishaw inVia micro-Raman spectrophotometer, equipped with a Leika DLML microscope and a CCD detector. A 514 nm laser source was employed with a 20× magnification.

2.6. Computational details

DFT-based simulations were performed with the CP2K/Quickstep package, using a hybrid Gaussian and plane wave method⁴¹

A triple quality TZVP Gaussian basis set was employed for all the atoms⁴². The Goedecker–Teter–Hutter pseudopotentials⁴³ together with a 400 Ry plane wave cutoff were used to expand the densities obtained with the Perdew–Burke–Ernzerhof (PBE)⁴⁴ exchange–correlation density functional, and van der Waals forces were taken in account with the Grimme D3 Method⁴⁵. Only the gamma point was considered in a supercell approach. Periodic boundary conditions were applied in all directions of space.

The cells were optimized starting from experimental data and considering a $1 \times 4 \times 3$ supercell for HBT Form I and $2 \times 3 \times 1$ supercell for HBT Form II to obtain two supercells containing the same number of atoms (600). Raman transitions were obtained by a frequency analysis at 298.15 K and UV-VIS spectrum is modelled by the TDDFT approach. The Raman and UV-VIS spectra are acquired only for the HBT molecule: in this case, calculations were performed adopting the M06⁴⁶ hybrid GGA functional with the standard all-electron cc-pVTZ basis set within the Gaussian16 code.⁴⁷

3. Results and discussion

3.1. X-ray diffraction and determination of the structure of Form I of HBT

Both forms of HBT have the appearance of light-green polycrystalline powders. The previously cited study carried out with DSC to investigate the thermal behaviour of this compound³⁵ highlighted the presence of a monotropic s–s transition when the sample (Form II) was rapidly cooled after melting.

To assess the difference in the crystal structure between pristine HBT (Form II) and the sample subjected to the thermal treatment described in the Experimental section (Form I), powder diffraction patterns of both samples were measured and are shown in Fig. 1, with the most intense reflections indexed.

The differences between these patterns are evident, pointing to the existence of two polymorphic forms. In particular, the pattern of the pristine sample is in good agreement with that reported in the literature⁴⁸ and available in the COD database (COD ID 7002569), while that of the quenched sample does not find correspondence with any reported crystal structure. For this reason, we decided to perform the determination of its

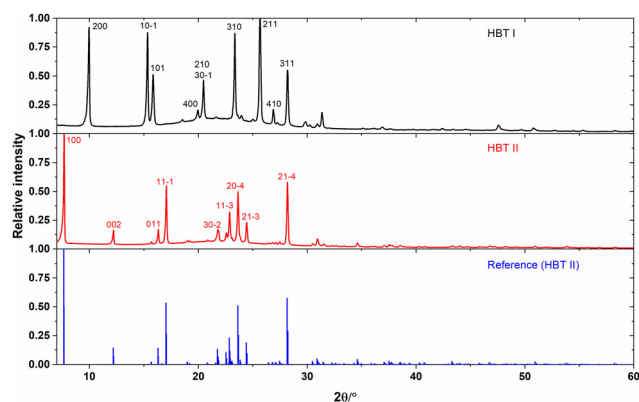


Fig. 1 Powder diffraction patterns of the two forms of HBT, along with the reference pattern for Form II (COD ID 7002569).

crystal structure from powder diffraction data. To this end, we carried out a 15-hours scan in the angular range $5\text{--}110^\circ$, with the sample placed in a spinning glass capillary, to avoid preferred orientation effects.

The determination of the crystal structure of Form I of HBT was carried out using EXPO 2014 software. The compound crystallizes in the monoclinic system, in the $P2_1$ space group, with lattice parameters $a = 17.82605 \text{ \AA}$, $b = 4.96006 \text{ \AA}$, $c = 6.00379 \text{ \AA}$ and $\beta = 93.1630^\circ$. The crystal structure of the metastable polymorph viewed along the c axis is shown in Fig. 2a, while in Fig. 2b the different stacks of molecules in the unit cell are shown more clearly and, finally, atom labelling is shown in Fig. 2c.

The molecules in the cell of Form I are stacked but laterally shifted (see Fig. 2b), so that the thiazole ring of one molecule is almost superimposed to the phenol one of the adjacent molecule in the stack, with a distance between the centroids of these two rings of $3.770 \text{ \AA}$, while the distance between the centroids of two overlaying molecules is $4.960 \text{ \AA}$; moreover, the lateral distance between the corresponding atoms of two neighbouring molecules is $7.786 \text{ \AA}$. The structure of polymorph I was refined with the Rietveld method, yielding a very good fit of the

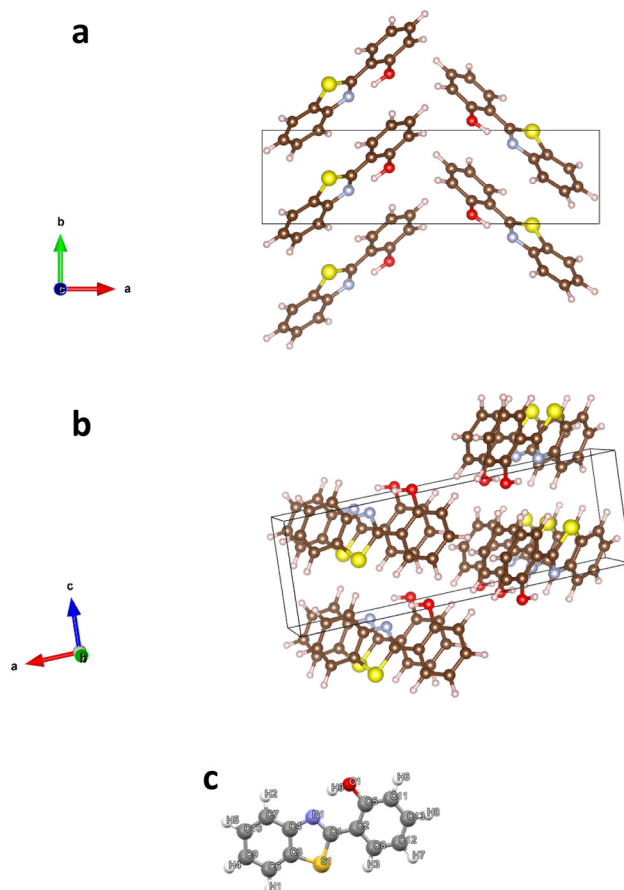


Fig. 2 View of crystal structure of HBT Form I along the c axis (a), representation of molecule stacking (b) and atom labelling (c), with carbon in grey, hydrogen in white, nitrogen in blue, sulfur in yellow and oxygen in red.

experimental pattern, with $R_{wp} = 4.52\%$. Fig. S3 shows the experimental pattern along with the calculated one and their difference.

The asymmetric unit of Form I is composed of one molecule, having an almost planar structure with a dihedral angle of 1.177° between the phenol and the thiazole ring and a strong intramolecular O–H...N hydrogen bond, as demonstrated by the short N...H distance of $1.786 \text{ \AA}$. This conformation is very similar to that of the minimum energy conformer predicted by a theoretical study.⁴⁹ Additionally, intermolecular hydrogen bond interactions take place between the oxygen and H6 and H7, bound to C11 and C12 of the phenol ring, with distances of 2.667 and $2.657 \text{ \AA}$, respectively.

In contrast, in the case of the crystal structure of Form II (Fig. S1), the dihedral angle between the phenol and the thiazole ring is 2.45° , while the N...H distance is $1.885 \text{ \AA}$, about $0.1 \text{ \AA}$ longer than in Form I, thus suggesting a weaker intramolecular hydrogen bond compared to the latter. Another evidence of the stronger intramolecular hydrogen bond taking place in Form I is the weakening of the O–H bond (due to the formation of two intermolecular hydrogen bonds by the oxygen), which has a length of $0.971 \text{ \AA}$, considerably longer than that of Form II, of $0.824 \text{ \AA}$. The stronger intramolecular hydrogen bond of Form I, along with the lower deviation from planarity of the molecule, is expected to allow an easier proton transfer. This can possibly enhance the ESIPT behaviour of this polymorph with respect to Form II, but this hypothesis needs to be backed by deeper spectroscopical experiments. However, N...H–O angle would indicate otherwise, as the shorter angle in Form I (143.74°) compared to Form II (144.19°) leads to a less efficient ESIPT. Even though, it is worth pointing out that the difference is rather small.

Regarding the number of intermolecular interactions, by an analysis of the short contacts (see Fig. S2) one can readily see that Form I has a higher number of short contacts; thus, its crystallization is dominated by these and not by thermodynamic stability. This is in line with the metastability and with the nature of the formation of the polymorph, *i.e.*, the rapid cooling of the melt. This might mean that the molecules are in a more strained state. This, however, does not necessarily lead to more intense intermolecular interactions as the stacking observed on Form II has a considerable contribution.

In order to get further insight into the differences between intermolecular interactions in the crystal structure of the two polymorphs, Hirshfeld surface analysis was also performed, by using the CrystalExplorer software.⁵⁰ Different properties were analyzed (Fig. 3a–f), namely d_{norm} , shape index and curvedness, with d_{norm} defined as:

$$d_{\text{norm}} = \frac{d_e - r_{\text{vdw}}}{r_{\text{vdw}}} + \frac{d_i - r_{\text{vdw}}}{r_{\text{vdw}}} \quad (1)$$

where d_e and d_i are, respectively, the distance from the Hirshfeld surface to the nearest nucleus outside and inside the surface, and r_{vdw} is the van der Waals radius of the atom involved. Shape index is a qualitative measure of shape, while curvedness is a function of the root-mean-square curvature of the surface. The fingerprint plots for the two forms of HBT are

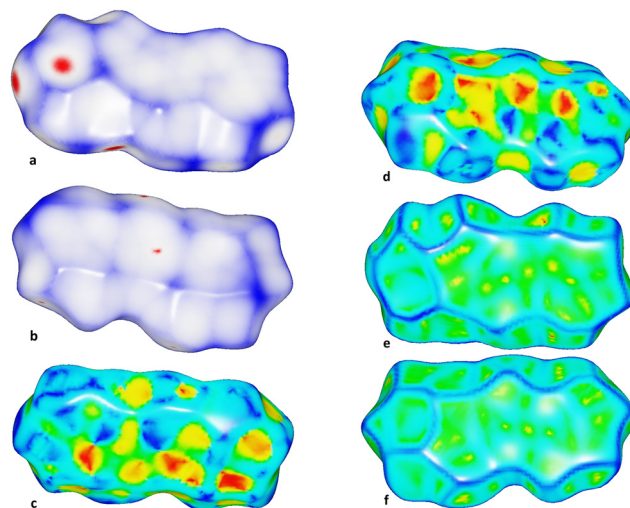


Fig. 3 Hirshfeld surfaces computed for the two polymorphs: d_{norm} of Form I (a) and II (b), shape index of Forms I (c) and II (d), and curvedness of Form I (e) and II (f).

reported in Fig. S4a and b. From these, it was possible to extract individual contributions of the various intermolecular contacts to crystal packing. In both cases, the H...H contacts dominate, with similar percentages (43.4% in Form I and 42.0% in Form II), followed by the H...C/C...H contacts, which instead show a noticeable difference in percentage, this being 22.4% for Form I and 30.2% for Form II. Another interesting difference is constituted by the percentage of C...C contacts, which is 7.8% for Form I while only 3.2% for Form II.

The ranges of d_{norm} for Forms I and II are the following: from -0.2804 to 1.0693 for the former and from -0.0155 to 1.1910 for the latter, thus meaning that in Form I there are shorter contacts than in Form II; this is also visualized in Fig. 3a and b with the presence of more intense red regions in Form I compared to Form II. As regards the shape index, the range for Form I is from -0.9975 to 0.9911 , while that of Form II is from -0.9878 to 0.9890 . In Form I (Fig. 3c), complementarity features are present between the phenol and the thiazole ring on opposite faces of the molecule (only one face is shown), while in Form II (Fig. 3d) complementary red and blue triangles are visible on the same face between the thiazole and the phenyl ring. Finally, as concerns curvedness, the range for Form I is from -3.4070 to 0.0661 , while for Form II it is from -3.7753 to 0.0994 , in both cases showing (Fig. 3e and f) mostly flat regions, corresponding to the aromatic rings.

Table 1 Experimental and computed lattice parameters of Form I and Form II of HBT

	HBT Form I ($P2_1/c$)		HBT Form II ($P2_1$)	
	Experimental	Modelled	Experimental ^a	Modelled
<i>a</i>	17.82605	17.30366	12.432	12.3978
<i>b</i>	4.96006	5.108158	5.863	5.75975
<i>c</i>	6.00379	5.952092	15.623	15.6303
β	93.163	96.36188	111.696	111.769

^a Data taken from ref. 48.

Based on the crystallographic data experimentally found, two structures of the HBT were modelled, namely Form I and Form II. Geometry inside the cells and the cell parameters extracted from the modelling are perfectly superimposable on those found experimentally (Table 1).

Moreover, it is found that Form II is more stable than Form I of about 5 kJ mol^{-1} , in very good agreement with experimental findings from DSC measurements (see Section 3.3).

3.2. Non-ambient X-ray diffraction and kinetics of conversion

A series of X-ray diffraction patterns at different temperatures (303, 308, 313 and 318 K) were acquired at constant intervals of time to study the kinetics of conversion of Form I into Form II. Unfortunately, the temperature range could not be extended, since the rate of conversion becomes too fast at temperatures higher than 318 K (it is for this reason that at this temperature only four patterns could be acquired before complete conversion). In the experiments carried out at 313 K, patterns were acquired every two hours, while those performed at different temperatures were acquired every hour.

Quantitative phase analysis based on Rietveld method was performed on all the obtained patterns to determine molar fraction of the two forms for each experimental point. The kinetic constant of conversion from Form I to Form II was obtained at each temperature, by fitting with a linear fit the data from the plot of the natural logarithm of the ratio between molar fraction of polymorph I at each time interval and its initial molar fraction *vs.* time (Fig. S5a–d), and taking the slope with opposite sign. Finally, by means of the Arrhenius plot (natural logarithm of the kinetic constant *vs.* reciprocal temperature, shown in Fig. 4), the activation energy of conversion from metastable Form I to stable Form II, was obtained, by multiplying the slope of the linear fit with opposite sign by *R* (universal gas constant). The value of $66 \pm 6 \text{ kJ mol}^{-1}$ was obtained. The reported uncertainty has been expanded to a level of confidence of 95% by using $k = 2$.

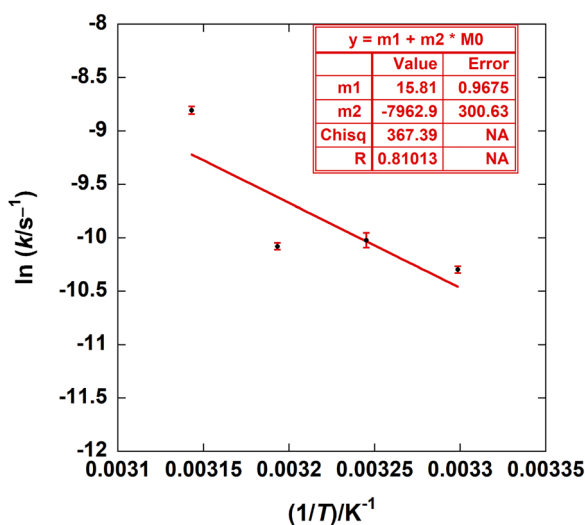


Fig. 4 Arrhenius plot for conversion of HBT Form I into HBT Form II.

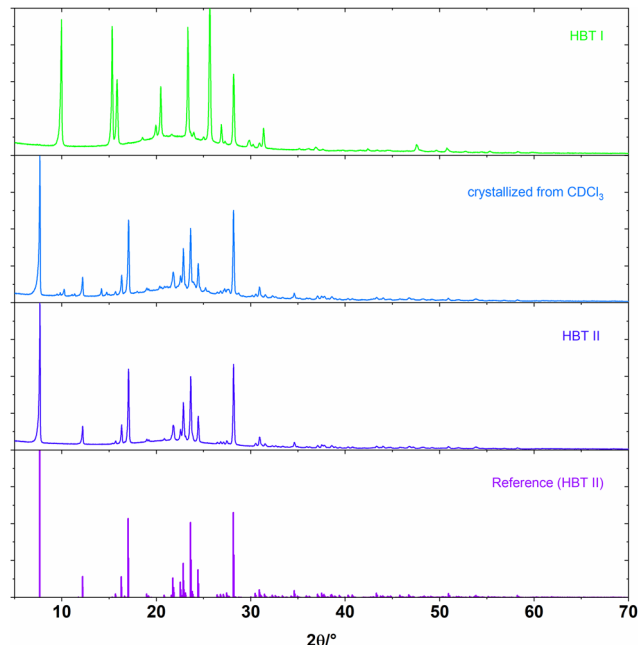


Fig. 5 Powder diffraction pattern of HBT crystallized from CDCl_3 (light blue), compared with patterns of Form I (green), Form II (indigo) and the reference pattern of Form II (purple).

Additionally, we measured the XRD pattern of the compound (initially in Form I) recrystallized from CDCl_3 in an NMR tube after being left there for almost two months at room temperature (Fig. 5) and performed quantitative phase analysis on the pattern, to determine the molar fraction of the two forms. We found that the molar fractions were 0.981 and 0.019 for Form II and Form I, respectively, pointing to a practically complete conversion of the metastable polymorph, in agreement with kinetic experiments.

3.3. Differential scanning calorimetry

The thermal behaviour of the compound has already been explored in a previous paper, and the presence of a solid–solid

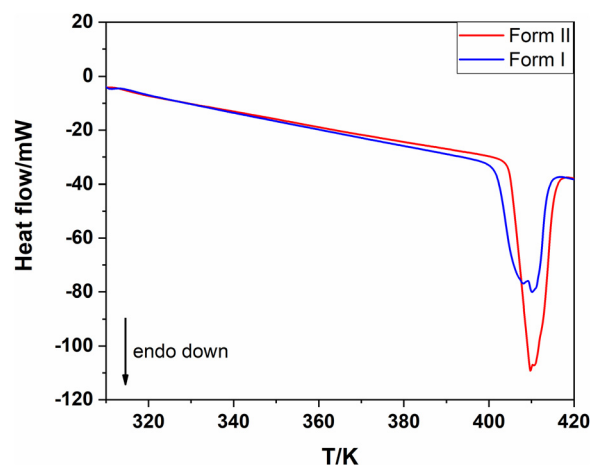


Fig. 6 DSC curves, performed at 20 K min^{-1} under static air, of Form I (blue) and II (red) of HBT, showing fusion.

phase transition has already been observed,³⁵ however, neither temperature nor enthalpy of fusion of Form I had been provided, so we performed DSC experiments to obtain this data. The DSC curves showing fusion of Form I and Form II of HBT are displayed in Fig. 6.

Three repetitions were carried out on both forms. Form I was obtained by melting Form II and allowing it to rapidly cool down to room temperature. The heating rate of 20 K min^{-1} was chosen to minimize the conversion of Form I into Form II. The obtained temperature of fusion is $401.6 \pm 0.4\text{ K}$ and $404.6 \pm 0.3\text{ K}$ for Form I and II, respectively. These values were obtained from the average of the onset values for each of the three repetitions. Furthermore, the obtained enthalpy of fusion is $19.1 \pm 0.5\text{ kJ mol}^{-1}$ for Form I and $23.6 \pm 0.9\text{ kJ mol}^{-1}$ for Form II, the latter in good agreement with the value reported in ref. 35. However, From the analysis of the DSC curves, one can see that for Form I, there are two distinct peaks. This is an indication that this is a mixture of both forms. Despite the quite high heating rate employed, the two forms are difficult to separate near the melting temperature, as, when Form I is heated, it starts to convert back to Form II. As such, the fusion enthalpy value should be considered with care.

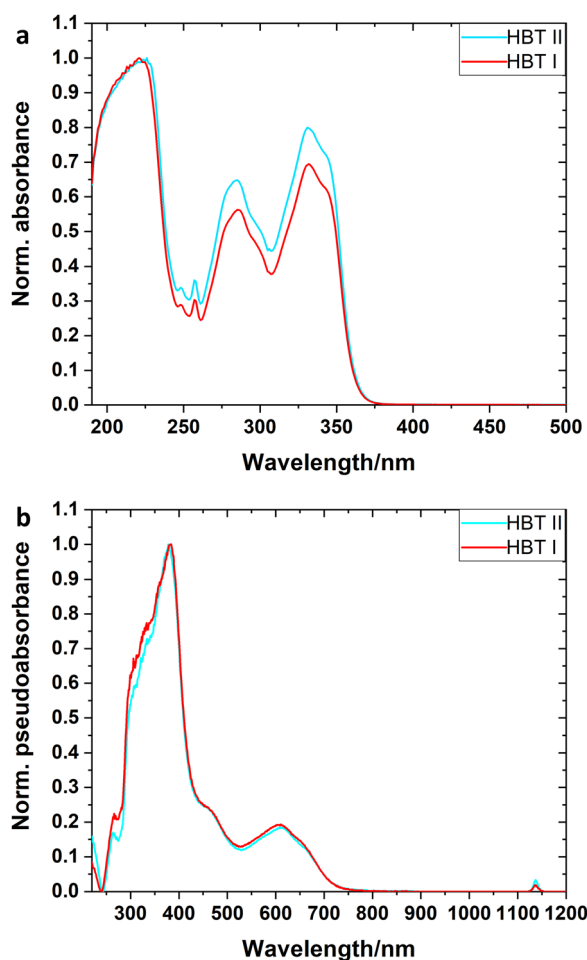


Fig. 7 UV-visible spectra of Form I and II of HBT in acetonitrile solution (a) and in solid Form (b).

From the difference between the two enthalpies of fusion, an enthalpy of transition of $-4.5 \pm 1.4\text{ kJ mol}^{-1}$ is obtained, in agreement with DFT calculations. All errors are given as standard errors.

3.4. UV-visible spectroscopy

UV-visible spectra of the two forms of HBT were measured both in acetonitrile solution ($2.2 \times 10^{-4}\text{ M}$ concentration) and in powder form, in diffuse reflectance mode, and are shown in Fig. 7a and b, respectively.

Spectra in solution of the two forms present, as expected, very similar absorption bands, associated mainly to π - π transitions, with absorption maxima at about 220 nm, 285 nm and 330 nm, although normalized absorbance is slightly higher for Form II in the case of the two latter bands. These spectra are in very good agreement with the literature.⁵¹ Moreover, the computed spectrum of the molecule, in perfect agreement with the experimental ones, is shown in Fig. S6.

As concerns pseudoabsorbance spectra, obtained from diffuse reflectance data collected on solid samples, by application of the Kubelka-Munk function, $F(R) = \frac{(1-R)^2}{2R}$, where R is reflectance, they show only minor differences between the two forms. In fact, the position of the maximum of the most intense band is at 383 nm in the case of Form I and at 378 nm for Form II, while another band shows a maximum around 610 nm for both forms, and intensities are very similar for all the bands, except for a small peak at 1137 nm, for which intensity of Form II is almost twice than that of Form I. Notably, the only previous measurement of the UV-visible spectrum of solid HBT that was found in the literature reports an absorption maximum of 340 nm.⁵²

3.5. Solid-state fluorescence- micro-photoluminescence (μ -PL)

Solid-state fluorescence of the two polymorphs at room temperature was studied by using an excitation wavelength of 405 nm. Different spectra (not shown) were acquired with variable laser power, in the range 0.05 – $10\text{ }\mu\text{W}$; however, no differences, neither in the emission wavelengths nor in the

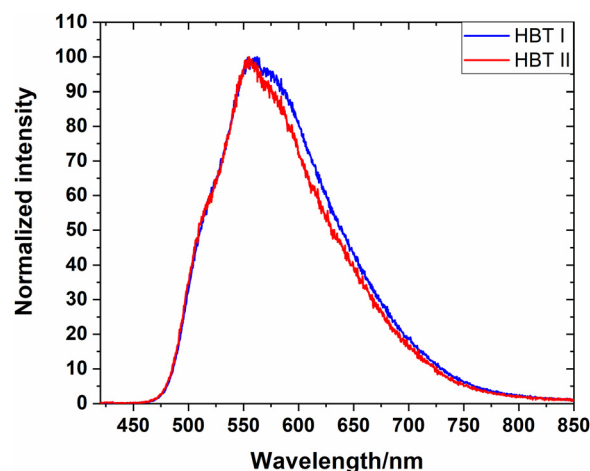


Fig. 8 Solid-state fluorescence spectra of the two forms of HBT.

relative intensities, could be observed. The spectra of both fall in the range 420–850 nm, measured using a laser power of 200 nW, and are shown in Fig. 8.

No significant differences are indeed visible between the two spectra, peaked at 555 nm, consistently with the identity of the absorption spectra in Fig. 7, meaning that the different packing of the molecules in the crystal has no appreciable influence on the interaction of HBT with light.

3.6. Raman spectroscopy

Raman spectra of the two forms in the region between 100 and 2000 cm^{-1} are displayed in Fig. 9, while the complete spectra showing also the peak at 3064 cm^{-1} for both forms are reported in Fig. S7.

The two spectra are very similar as far as the number and the position of the peaks are concerned, showing only minor differences, the most relevant of which are visible in the region between 1100 and 1200 cm^{-1} : in fact, the peak at 1172 cm^{-1} is absent in the spectrum of Form I, while the peak at 1157 cm^{-1} is barely visible in the case of Form II; moreover, the peak at 1141 cm^{-1} in the spectrum of Form II is shifted at 1135 cm^{-1} in Form I. Another visible difference is represented by the absence of the peak at 124 cm^{-1} in the spectrum of Form I. However, relative intensities display more pronounced discrepancies between the two forms, with notable differences for example as concerns the group of peaks in the region 1390–1530 cm^{-1} , having a higher relative intensity in the spectrum of Form I; moreover, the peak at 3064 cm^{-1} presents a notably higher relative intensity in the case of Form II.

Raman spectrum of HBT molecule was also modelled by means of DFT calculations, and the computed spectrum, showing very good agreement with the experimental ones of the two forms, is reported in Fig. S8. Raman modes at 1680, 1650, and 1615 cm^{-1} correspond to in-plane symmetric stretching vibrations of the two thiazole and phenol rings. The component at 1564 cm^{-1} is assigned to the stretching vibration of the C–N bond, while at 1502 cm^{-1} lies the bending mode localized on the C–O–H group.

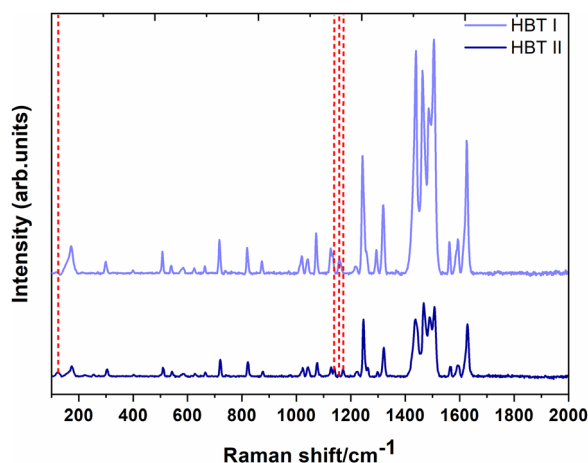


Fig. 9 Raman spectra of HBT Form I and Form II in the 100–2000 cm^{-1} region.

Finally, the bending vibrations of the C–H bonds fall in the range between 1465 and 1263 cm^{-1} .

4. Conclusions

In this work, the previously undescribed crystal structure of a metastable polymorph of HBT (form I) was determined by means of powder X-ray diffraction. The experimentally determined lattice parameters were compared to those modelled by DFT, showing very good agreement. The interconversion of the metastable form into the stable one was studied both from a kinetic point of view, through non-ambient X-ray diffraction, affording an activation energy of conversion of $66 \pm 6 \text{ kJ mol}^{-1}$, and from a thermodynamic one, by differential scanning calorimetry, yielding an enthalpy of conversion of $-4.5 \pm 1.4 \text{ kJ mol}^{-1}$. The latter value is in accordance with that obtained computationally. Finally, UV-visible (in solution and in solid form), fluorescence (in solid form) and Raman spectra (in solid form) of both polymorphs were measured, revealing only minor differences between each other. UV-visible and Raman spectra are in good agreement with those calculated for the molecule by DFT.

Author contributions

Lorenza Romagnoli – conceptualization (equal); data curation (equal); formal analysis (equal); investigation (equal); methodology (lead); visualization (main); writing – original draft (lead); writing – review and editing (equal). José Miguel Silva Ferraz – conceptualization (equal); data curation (equal); formal analysis (supporting); visualization (equal); writing – review and editing (equal); funding acquisition (equal). Nikodem Sokołowski – data curation (equal); investigation (equal); formal analysis (equal) writing – review and editing (equal). Federico Tuzi – data curation (equal); investigation (equal); formal analysis (equal) writing – review and editing (equal). Antonio Polimeni – data curation (equal); formal analysis (equal) writing – review and editing (equal); funding acquisition (lead). Alessandro Motta – data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); visualization (main); writing – review and editing (equal).

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: view of crystal structure of HBT Form II; sideways view of the short contacts of HBT Form I and II; experimental and calculated powder diffraction patterns of HBT Form I with difference plot; fingerprint plots of the Hirshfeld surfaces of HBT Form I and II; plots of the natural logarithm of the ratio of molar fraction of HBT Form I and its initial molar fraction vs

time; calculated UV-vis spectrum of HBT molecule; Raman spectra of HBT I Form and Form II in the 100–3200 cm^{-1} region; calculated Raman spectrum of HBT molecule. Supplementary information is available. See DOI: <https://doi.org/10.1039/d6cp02012g>.

CCDC 2564045 contains the supplementary crystallographic data for this paper.⁵³

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