The influence of water on dielectric property in cocrystal compound of [orotic acid][melamine] · H₂O†

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An organic cocrystal compound consisting of melamine, orotic acid and water molecules was synthesized under hydrothermal conditions. Investigation of its temperature- and frequency-dependent dielectric behaviors reveals that the fluctuation of hydrogen atoms of water molecules between the layers plays a key role in its dielectric anomaly.

Organic cocrystal compounds, containing at least two kinds of organic molecules, have attracted much attention in the field of crystal engineering,† pharmaceuticals,‡ and material science.§ Owing to the existence of many types of hydrogen bonds in these compounds, their structures are very flexible and easily influenced by temperature and pressure, not only facilely resulting in the occurrence of phase transition,° even charge transfer in these compounds.¶ Significantly, a series of organic ferroelectrics, such as [H-55DMBP][Hca] (Hca = chloranilic acid, H-55DMBP = 5,5'-dimethyl-2,2'-bipyridine), Phz-H2xa (Phz = phenazine, H2xa = chloranilic acid or bromanilic acid) and TTF-BA (TTF = tetrathiafulvalene, BA = p-bromanil), have been prepared by utilizing the intermolecular collective proton displacement or charge transfer in the organic cocrystal compounds.¶

The water molecule, as a proton donor and acceptor, is easily involved in the organic cocrystal system. It not only influences the stability of the organic cocrystal compounds, but also changes their pharmaceutical properties.¶ However, the influence of water molecules on the dielectric properties of organic cocrystal compounds has seldom been investigated, despite previous studies demonstrating that water in coordination polymers plays a key contribution to their dielectric properties.° Here we report the crystal structure and temperature-dependent dielectric behavior of [C₅H₄N₂O₄][C₃H₆N₆]·H₂O (I).

Compound I was synthesized‡ by the hydrothermal reaction of manganese dichloride, melamine and orotic acid in water.§ Single-crystal structure analysis at 298 K reveals that I crystallizes in P1 (no.2) space group with one melamine, one orotic acid and one water molecule in an asymmetric unit as adjacent ones through hydrogen-bonding interaction with nitrogen atoms as proton donors and carbonyl oxygen atoms as proton acceptors generating a 1D chain of (orotic acid), shown in Fig. 1a.

Each orotic acid molecule connected with two adjacent melamine molecules are hydrogen-bonded through one amino as a proton donor and imino as a proton acceptor, forming a dimer. Adjacent dimers further connected through two water molecules as proton acceptors and amino as proton donors leads to a 1D chain of (melamine)_n. Alternately connected 1D chains of (orotic acid)_n and (melamine)_n through hydrogen-bonding interaction generates a layer structure as shown in Fig. 1b. Adjacent layer structures are further extended into a 3D structure (Fig. 1c) through hydrogen-bonding interactions of the water molecules with melamine and orotic acid ligands.

Fig. 1 (a) The asymmetric unit in I; (b) Hydrogen bonds present in I; (c) The layer structure of I along [121] direction.
interaction between water molecules from one layer as proton donors and carbonyl from adjacent layers, similar to those of [(HMA\(^+\)) (HIA\(^-\))] \(\cdot\) 2H\(_2\)O (MA = melamine, H\(_3\)JA = isophthalic), [(melamine) (barbituric acid)] and [(MAH\(^+\)) (DNBA\(^-)\)] (MA = melamine, DNBA = 3, 5-dinitrobenzoic).\(^{15-17}\)

Fig. 2 shows the dielectric constant of \(\mathbf{1}\) measured at various temperatures (from 200 K to 292 K) and frequencies (from 1 kHz to 10 MHz) on the basis of its powder pellet sample. At \(f = 1\) kHz, the dielectric constant of \(\mathbf{1}\) slowly increases in the temperature range from 200 K to 240 K, then increases rapidly and reaches a maximum of 23.5 at about 265 K. Further increase in temperature results in the dielectric constant of \(\mathbf{1}\) slowly decreasing. In addition to the temperature, frequency also significantly influences the dielectric constant of \(\mathbf{1}\). As shown in Fig. 2, the dielectric peak at around 265 K decreases from 23.5 to 15.5 in amplitude with the frequency increasing from 1 kHz to 10 MHz. These results indicate that the dielectric constant of \(\mathbf{1}\) is temperature- and frequency-dependent.

To reveal the temperature- and frequency-dependent dielectric behavior of \(\mathbf{1}\), its dielectric constant was measured on single crystals along different directions at different temperatures at 1 kHz. As shown in Fig. S1 (ESI†), the dielectric constants for \(E \perp (111)\) and \((121)\) are almost temperature-independent, while that for \(E \perp (111)\) increases and reaches a maximum at around 240 K, indicating that the structure change for \(E \perp (111)\) at different temperatures contributes mainly to the dielectric anomaly. However, it shows very poor proton conductivity (less than \(8.2 \times 10^{-9} \text{ S cm}^{-1}\)), which proves that the dielectric anomaly is not associated with the proton or hydrated proton conduction.

To further demonstrate that temperature- and frequency-dependent behavior of \(\mathbf{1}\) is attributed to the structure change for \(E \perp (111)\), the single-crystal structures of \(\mathbf{1}\) were measured at around 200 K (before the dielectric peak appeared) and 265 K (around the dielectric peak) respectively. Although the frameworks of the two 3D structures at different temperatures are very similar, the hydrogen-bonding interactions in the two structures are significantly changed. As shown in Table 1, the hydrogen-bonding separations between the layers at 200 K are 3.012(2) and 2.993(2) \(\text{A}\) for O1W→O2 and O1W→O4 respectively, 0.020 and 0.013 \(\text{A}\) shorter than those of 3.032(2) and 3.006(2) \(\text{A}\) at 265 K respectively. In comparison, the change in hydrogen-bonding interaction within the layer is significantly smaller than that between the layers. Of the twelve hydrogen-bonding interactions within the layer, six of them (O2→N3; O2→N4; N4→O2; N4→O4; N5→O1; O1W→O1) almost keep a constant (the change less than 0.002 \(\text{A}\)) at different temperatures, the remaining changes between 0.004 to 0.009 \(\text{A}\). It was noted that two larger changes in hydrogen-bonding interactions within the layer (N7→O4, 0.009 \(\text{A}\) and N6→O1W, 0.008 \(\text{A}\)) at different temperatures are invariably related to water molecules in the structure (N6 and O4 atoms are directly hydrogen-bonded to O1W). Considering the fact that the E \(\perp (111)\) direction is consistent with that of hydrogen-bonding between the layers (ESI, Fig. S2†), it is reasonable to attribute the temperature-dependent dielectric behavior along the E \(\perp (111)\) direction to the change in hydrogen-bonding interactions between the layers. Owing to the hydrogen-bonding interaction between the layers involved in water molecules, the dielectric peak along the E \(\perp (111)\) direction at around 265 K is probably related to the increasing temperature resulting in the fluctuation of hydrogen atoms in water molecules between the layers (ESI, Fig. S3†), consistent with the crystal structures at different temperatures that show the hydrogen-bonding interaction within the layer is less influenced by temperature than those between the layers.

To demonstrate that it is the fluctuation of hydrogen atoms in water molecules between the layers that plays a key contribution to the dielectric behavior along the E \(\perp (111)\) direction, TG analysis and XRD patterns at different temperatures were respectively performed. The TG curve (ESI, Fig. S4†) shows that \(\mathbf{1}\) starts to lose water molecules at 190 \(\text{C}\), and finishes losing water molecules at 228 \(\text{C}\). Moreover, when the water molecule was fully lost, the framework of \(\mathbf{1}\) is retained. Consistently, XRD patterns at different temperatures (ESI, Fig. S5†) show that \(\mathbf{1}\) remains crystalline when water molecules

![Fig. 2](Image)

(a) The dielectric constant of \(\mathbf{1}\) measured at different frequencies and temperatures based on its powder pellets. (b) The dielectric constant of \(\mathbf{1}\) and dehydrated \(\mathbf{1}\) measured at 1 kHz and various temperatures based on their powder pellets.

### Table 1 The hydrogen-bonding interactions in \(\mathbf{1}\)

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<th>200 K</th>
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<th>298 K</th>
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<td>3.104(2)</td>
<td>3.106(2)</td>
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<td>2.993(2)</td>
<td>2.997(2)</td>
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<td>3.104(2)</td>
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<td>2.827(2)</td>
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<td>3.006(2)</td>
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</table>
were removed. Although it is difficult to obtain the crystal structure of the dehydrated 1 due to the split of the crystals upon heating, based on the temperature-independent dielectric behavior of the dehydrated 1 measured in the temperature range from 200 K to 292 K (Fig. 2b), it is clear that the fluctuation of hydrogen atoms in water molecules between the layers plays a key role in the dielectric anomaly of 1.

The DSC curve was also measured to understand the temperature- and frequency-dependent dielectric constant of 1. As shown in Fig. 3, a sharp endothermic peak was observed at 272 K. Although there are no exothermic peaks observed during the cooling process, owing to the endothermic peak appearing again during the second heating process, these results indicate that the phase transition for 1 is reversible but sluggish.\(^{48}\) From the DSC data, it is estimated that \(\Delta H\) is equal to 67.76 J mol\(^{-1}\), while \(\Delta S\) is estimated to be \(\Delta S = \Delta H/T_c = 0.2494 \text{ J mol}^{-1} \text{ K}^{-1}\). According to \(\Delta S = R \ln N\), it is estimated that \(N\) is equal to 1.03. This value is only slightly larger than 1, suggesting the uncomplicated ordered–disordered feature of the phase transition.\(^{59}\)

Accordingly, the dielectric peak at around 265 K is attributed to the phase transition of 1. Based on the fact that there is no significant changes in the cell parameters in the temperature range, the occurrence of a phase transition at around 265 K is due to the fluctuation of hydrogen atoms of water molecules (i.e., the phase transition is from the order–disorder of hydrogen atoms of water molecules) instead of the framework of 1.

Consistently, when the water in 1 was replaced by deuterated water, the temperature- and frequency-dependent dielectric constant for \([\text{C}_5\text{H}_4\text{N}_2\text{O}_4][\text{C}_3\text{H}_6\text{N}_6]\)\(_2\text{O}\) (namely, 1D) is distinctly different from that for 1. Meanwhile, the \(\text{D}_2\text{O}\) of 1D was introduced through using deuterated water as solvent in the preparation of 1D. The solid state \(^1\text{H}-\text{NMR}\) of 1D shown in Fig. 4 shows that some peaks obviously disappear compared with that of 1, which proved that partly hydrogen atoms were replaced by deuterium. However, only the hydrogen atoms from the water molecules and some active hydrogen atoms (such as hydrogen atoms on amino groups of melamine or carbonyl groups of orotic acid) are easily replaced by deuterium.

As shown in Fig. 5, the dielectric peak for 1D is not only sharper than that of 1, but also shifts to 274 K, significantly higher than that of 1. The clear “deuteration effect” demonstrates that it is the fluctuation of hydrogen atoms in water molecules between the layers that plays a key role in its dielectric anomaly.

In summary, we have reported the synthesis and crystal structure of an organic cocrystal compound consisting of melamine, orotic acid and water molecules. Investigation of its dielectric behavior reveals that fluctuation of hydrogen atoms in water molecules between the layers plays a key role in its dielectric anomaly.

**Acknowledgements**

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**Notes and references**

\(^1\) Preparation of 1: melamine (0.5 mmol, 0.063 g), orotic acid (0.5 mmol, 0.078 g) and manganese dichloride tetrahydrate (0.5 mmol, 0.099 g) were dissolved in 10 mL deionized water, while stirring at room temperature. When the pH value of the mixture was adjusted to about 5.0 with NaOH solution (\(\approx 1 \text{ mol L}^{-1}\)), the mixture was put into a 25 mL Teflon-lined Parr and heated to 140 °C for 2000 min, and then cooled to room temperature at a rate of 1.5 °C h\(^{-1}\). Colorless block crystals of 1 were obtained in 25% yield (based on orotic acid). IR (KBr): 3528(m), 3423(s), 3372(s), 3150(s), 2364(s), 2325(s), 1697(s), 1618(s), 1502(m), 1474(m), 1383(s), 1177(m), 1116(m), 930(m), 862(m), 775(s), 688(s), 568(s), 543(s) cm\(^{-1}\); Anal. Calc. for 1: C 32.00%, H 4.03%, N 37.32%. Found: C 31.89%, H 3.97%, N 36.93%.

\(^2\) Preparation of 1D: melamine (0.5 mmol, 0.063 g), orotic acid (0.5 mmol, 0.078 g) and manganese dichloride tetrahydrate (0.5 mmol, 0.099 g) were dissolved in 10 mL deuterated water, while stirring at room temperature. The mixture was put into a 25 mL Teflon-lined Parr and heated to 140 °C for 2000 min, and then cooled to room temperature at a rate of 1.5 °C h\(^{-1}\). Colorless block crystals of 1D were obtained in 20% yield (based on orotic acid). IR (KBr): 3400(s), 2616(w), 2568(s), 2502(s), 2364(s), 2325(s), 1692(s), 1647(s), 1613(s), 1586(s), 1485(s), 1391(s), 1312(m), 1271(m), 1197(m), 1065(w), 928(w), 773(s), 530(m), 494(m), 435(m) cm\(^{-1}\); Anal. Calc. for 1D: C 30.77%, H(D) 4.27%, N 35.90% (based on the \([\text{C}_5\text{D}_4\text{N}_2\text{O}_4][\text{C}_3\text{D}_6\text{N}_6]\)\(_2\text{O}\); Found: C 30.79%, H(D) 3.77%, N 35.86%. The water molecule in compound 1 replaced by deuterated water was demonstrated by XRD (Fig. S6), IR spectrum (Fig. S7) and \(^1\text{H}-\text{NMR}\) spectra in solid (Fig. S8) of 1D.

Single-crystal X-ray structure determination: Data collections were performed on an Oxford Gemini S Ultra CCD area detector using Mo-K\(_{\alpha}\) radiation at 200 K, 265 K and 298 K for 1. Absorption corrections were applied by using the multi-scan program. The structures were solved by...
direct methods, and non-hydrogen atoms were refined anisotropically by least-squares on $F^2$ using the SHELXTL-97 program. The hydrogen atoms of the water molecules were generated geometrically. The hydrogen atoms of the organic ligand were located from difference Fourier maps.

Crystal data for $C_2H_4N_2O_2$: $T = 200(2)K$, triclinic, $P1$, $a = 8.1869(6)$, $b = 8.3465(6)$, $c = 9.7987(8)$, $\alpha = 109.313(7)$, $\beta = 97.935(6)$, $\gamma = 99.832(6)\, ^\circ$, $V = 593.88(8)\, A^3$, $Z = 2$, $D_c = 1.679\, g\, cm^{-3}$, $M = 300.26\, \mu g$-$Kz = 0.141\, mm^{-1}$. 4246 reflections are collected, 2326 are independent ($R_{int} = 0.0163$) and 1856 are observed ($I > 2\sigma(I)$). On the basis of all these data and 234 refined parameters, $R_f(\text{obs.)}) = 0.0368$ and $wR_f$ (all data) = 0.1073.

Crystal data for $C_2H_4N_2O_2$: $T = 265(2)K$, triclinic, $P1$, $a = 8.1960(6)$, $b = 9.7987(8)$, $c = 113.233(7)$, $\beta = 97.935(6)$, $\gamma = 99.832(6)\, ^\circ$, $V = 593.88(8)\, A^3$, $Z = 2$, $D_c = 1.679\, g\, cm^{-3}$, $M = 300.26\, \mu g$-$Kz = 0.141\, mm^{-1}$. 4246 reflections are collected, 2326 are independent ($R_{int} = 0.0163$) and 1856 are observed ($I > 2\sigma(I)$). On the basis of all these data and 234 refined parameters, $R_f(\text{obs.)}) = 0.0388$ and $wR_f$ (all data) = 0.1117.

Crystal data for $C_2H_4N_2O_2$: $T = 298(2)K$, triclinic, $P1$, $a = 8.2133(6)$, $b = 8.3969(7)$, $c = 9.8069(8)$, $\alpha = 113.340(8)$, $\beta = 97.788(7)$, $\gamma = 99.804(7)\, ^\circ$, $V = 596.52(8)\, A^3$, $Z = 2$, $D_c = 1.672\, g\, cm^{-3}$, $M = 300.26\, \mu g$-$Kz = 0.140\, mm^{-1}$. 4270 reflections are collected, 2338 are independent ($R_{int} = 0.0159$) and 1856 are observed ($I > 2\sigma(I)$). On the basis of all these data and 234 refined parameters, $R_f(\text{obs.)}) = 0.0382$ and $wR_f$ (all data) = 0.1114.