Growing single crystals of small molecules by thermal recrystallization, a viable option even for minute amounts of material?†

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The growth of single crystals of small molecules by thermal recrystallization of only a few milligrams of material has been studied for carbamazepine, para-aminobenzoic acid and vitamin B₁₂. High quality single crystals could be grown for carbamazepine and para-aminobenzoic acid within just six hours. Various solvents and concentrations were tested for their influence upon the growth of crystals.

1. Introduction

In contrast to inorganic polymeric materials, for which single crystals are frequently grown by thermal recrystallization,1,2 thermal recrystallization of small molecules is described in most introductions into single crystal growth,3 however the method is rarely used in research laboratories.4–6 There is an exceptional report about the extremely slow cooling of an ethanol solution (0.5 °C per day) to achieve growth of a single crystal of an organic compound.9 Another report described a single crystal grown by cooling a 150 °C hot solution at a rate of −1.25 °C per hour.10 In many cases, it is essential that the employed crystallization methods only use few milligrams of material, as the supply of the compound of interest is limited.11

In this publication, we describe our results from attempts to grow single crystals of 3 different molecular compounds (carbamazepine, para-aminobenzoic acid and vitamin B₁₂) by thermal recrystallization using a small volume of only 0.1 ml with the help of the CrystalBreeder. The single crystals had to have sufficient quality and size in order to allow X-ray analysis on a source diffractometer equipped with a CCD detector and Microfocus Mo and Cu X-ray tubes respectively. This publication is meant to be an extension of our previous tutorial about the growth of single crystals of small molecules, which focused on isothermal methods.11

2. Experimental section

Carbamazepine (CBZ, 97%, P-monoclinic form III,12 see ESI;† we employ the nomenclature of ref. 13) was purchased from ABCR GmbH & Co. KG. Para-Aminobenzoic acid (pABA, ≥99%, α-form, see ESI14), 1-propanol (≥99%), 2-propanol (≥99.5%), 2-butanol (≥99%), tetrahydrofuran (THF, ≥99.9%), cyclohexane (≥99.5%), acetonitrile (≥99.9%) and ethyl acetate (≥99.9%) were purchased from Sigma Aldrich. All chemicals were used without further purification.

The crystallization experiments were performed with help of the CrystalBreeder (CB), a multi-reactor crystallization platform for medium-throughput solid state research. The CB shows real time turbidity information for 32 parallel vials with a working volume of only 0.1 ml. The vials are arranged in 8 blocks, which can be temperature controlled independently within a range of −15 °C to 145 °C.

UPLC-ESI-MS spectra were recorded on an Acquity Waters system equipped with a PDA detector and an autosampler using an ACQUITY UPLC BEH C18 Gravity 1.7 μm (2.1 mm × 50 mm) reverse phase column. The UPLC system was connected to a Bruker Daltonics HCT ESI-MS spectrometer. A total volume of 1 μL of a sample solution was analysed. A gradient (0 to 0.5 min 5% B, 0.5 to 2 min 30% B, 2 to 4 min 100% B, 4 to 5 min 100% B) of acetonitrile (solvent B) versus Millipore water containing 0.1% formic acid (solvent A) was applied using a flow rate of 0.3 ml min⁻¹. All solvents used were of LCMS grade.

2.1 Thermal crystallization of carbamazepine

The carbamazepine single crystals were grown by thermal crystallization in various solvents and with various concentrations always with 0.1 ml of solvent (Table 1).

For every solvent, a minimum of four different concentrations were chosen. Each sample was heated at 1 °C min⁻¹ starting from room temperature until five degrees below the
boiling point of the solvent, held at this temperature for 15 minutes, cooled at \(-0.5 \, ^\circ\text{C} \min^{-1}\) until \(-15 \, ^\circ\text{C}\) (for cyclohexane only until 0 \, ^\circ\text{C} because its melting point is at 7 \, ^\circ\text{C} and the solution should not be frozen) and held at the lowest temperature for 15 minutes (Table 2). All samples were stirred with a paddle while heating to ensure that all solids had dissolved. The stirrers were turned off during the cooling.

2.2 Thermal crystallization of \(p\)-aminobenzoic acid (\(p\)ABA)

Crystals of \(p\)-aminobenzoic acid were grown by the same method used for CBZ (Tables 3 and 4).

2.3 Thermal crystallization of vitamin B\(_{12}\)

Crystals of vitamin \(B_{12}\) were grown by the same method used for CBZ. The reported solubility of vitamin \(B_{12}\) in water is 10.2 g l\(^{-1}\),\(^{18}\) however we employed higher concentrations of 4 to 8 mg of vitamin \(B_{12}\) in 0.1 ml of water. We obtained crystals by cooling down from 95 \, ^\circ\text{C} to \(-5 \, ^\circ\text{C}\) with cooling rates of either \(-0.1\) or \(-0.05 \, ^\circ\text{C} \min^{-1}\). Unfortunately, in both cases, the obtained crystal quality was not good enough for an X-ray analysis, since the crystals were clearly not single (see Fig. S1 in the ESI\(^\dagger\)). Using smaller crystals did not help, as it is our repeated experience with crystals derived from \(B_{12}\) that they need a much bigger size to diffract decently compared with “normal” small molecules.\(^{19-26}\) Furthermore, we have previously made the experience that vitamin \(B_{12}\) and its derivates are rather delicate molecules to crystallize, that only appreciate very few crystallization conditions. Using a concentration of 20 g l\(^{-1}\) (twice the reported concentration of saturation) did not yield any \(B_{12}\) crystals. We checked by UPLC-ESI-MS whether any degradation like hydrolysis of the amide group or removal of the cyanide of the \(B_{12}\) was observed during the extended thermal treatment in an aqueous solution. As can be seen in Fig. S2 in the ESI\(^\dagger\), no deterioration of the \(B_{12}\) could be observed, when compared with \(B_{12}\) that did not undergo any thermal treatment, based upon peak purity, retention time and isotopic distribution of the mass spectra.

2.4 X-ray measurement

Crystallographic data were collected at 183(2) K on an Agilent SuperNova, dual source, single X-ray diffractometer equipped with an Atlas CCD detector with either Mo \(K\alpha\) radiation (\(\lambda = 0.7107 \, \text{Å}\)) for the monoclinic form of CBZ and \(p\)ABA or with Cu \(K\alpha\) radiation (\(\lambda = 1.54184 \, \text{Å}\)) for the rhombohedral form of CBZ. Suitable crystals were covered with oil (Infineum V8512, formerly known as Paratone N), placed on a nylon loop that is mounted on a CrystalCap Magnetic\(^\dagger\) (Hampton Research) and immediately transferred to the diffractometer. Data were corrected for Lorentz and polarisation effects as well as for absorption. The program suite CrysAlisPro was used for data collection, multi-scan absorption correction (additionally a numerical absorption correction was done for \(p\)ABA) and data reduction.\(^{27}\) Structures were solved with direct methods using \(\text{SIR97}\) (ref. 28) and were refined by full-matrix least-squares methods on \(F^2\) with SHELXL-2014.\(^{29}\) CCDC-1494536–1494538 contain the supplementary crystallographic data for this paper.

3. Results and discussion

For every solvent at least four different concentrations were chosen. The lowest concentration was at about 75\% of the solubility at room temperature and the other three concentrations were from 100 to 150/200\% of the RT solubility. Each sample was heated until five degrees below the boiling point of the solvent. Despite the small starting volume, no solvent loss from tube could be observed. However, in case of viscous solvents (like water), up to 18\% of the solvent ended up in

| Table 1 | Properties of solvents tested for the thermal recrystallization of CBZ |
|---|---|---|---|---|
| Solvent | Solubility of CBZ in that solvent | Melting point | Boiling point | Mass (in mg) of CBZ for 0.1 ml of a saturated solution |
| 1-Propanol | 18.1 g l\(^{-1}\) (25 \, ^\circ\text{C})\(^{15}\) | \(-126 \, ^\circ\text{C}\) | 97 \, ^\circ\text{C} | 1.8 |
| 2-Propanol | 9.11 g l\(^{-1}\) (25 \, ^\circ\text{C})\(^{15}\) | \(-88 \, ^\circ\text{C}\) | 82 \, ^\circ\text{C} | 0.91 |
| 2-Butanol | \(-8 \, g \, l\(^{-1}\) (25 \, ^\circ\text{C})\(^{9}\) | \(-115 \, ^\circ\text{C}\) | 99 \, ^\circ\text{C} | 0.8 |
| THF | 45.2 g l\(^{-1}\) (22.4 \, ^\circ\text{C})\(^{16}\) | \(-108 \, ^\circ\text{C}\) | 66 \, ^\circ\text{C} | 4.5 |
| Cyclohexane | 0.055 g l\(^{-1}\) (25 \, ^\circ\text{C})\(^{15}\) | 6.7 \, ^\circ\text{C} | 81 \, ^\circ\text{C} | 0.005 |

\(^{a}\) Estimated from the solubility in 2-propanol.

| Table 2 | Chosen amounts of CBZ and thermal recrystallization cycle |
|---|---|---|---|---|---|---|---|
| Solvent | Vial 1 (mg) | Vial 2 (mg) | Vial 3 (mg) | Vial 4 (mg) | Heating rate (\text{°C} \, \text{min}^{-1}) | Max temp. (\text{°C}) | Cooling rate (\text{°C} \, \text{min}^{-1}) | Lowest temp. (\text{°C}) |
| 1-Propanol | 1.5 | 2 | 2.5 | 3 | 1 | 92 | 0.5 | -15 |
| 2-Propanol | 0.5 | 1 | 1.5 | 2 | 1 | 77 | 0.5 | -15 |
| 2-Butanol | 0.5 | 1 | 1.5 | 2 | 1 | 94 | 0.5 | -15 |
| THF low conc. | 4.5 | 5 | 5.5 | 6 | 1 | 60 | 0.5 | -15 |
| THF high conc. | 6 | 6.5 | 7 | 7.5 | 1 | 60 | 0.5 | -15 |
| Cyclohexane | 0.005 | 0.01 | 0.02 | 0.05 | 1 | 76 | 0.5 | 0 |
separated drops above the original solution between the outer wall and the paddle.

3.1 Carbamazepine crystals

Carbamazepine is known to form five polymorphs and many solvates.\textsuperscript{13,30} While there are many publications about the influence of cooling rates, concentrations, solvents, seeds and stirring rates upon the (co)formation of one of these polymorphs,\textsuperscript{5,13,15,16,30–38} the focus of this work is exclusively on the formation of single crystals suitable for X-ray analysis. We have tested five different solvents at 4°C to 36°C the focus of this work is exclusively

Table 3 Properties of solvents tested for the thermal recrystallization of pABA

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Solubility of pABA at 20 °C</th>
<th>Melting point</th>
<th>Boiling point</th>
<th>Mass (in mg) of pABA for 0.1 ml solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Propanol</td>
<td>48 g l(^{-1}) (ref. 17)</td>
<td>-88°C</td>
<td>82°C</td>
<td>4.8</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>68 g l(^{-1}) (ref. 17)</td>
<td>-83°C</td>
<td>77°C</td>
<td>6.8</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>47 g l(^{-1}) (ref. 17)</td>
<td>-45°C</td>
<td>82°C</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table 4 Chosen amounts of pABA and thermal recrystallization cycle

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Vial 1 (mg)</th>
<th>Vial 2 (mg)</th>
<th>Vial 3 (mg)</th>
<th>Vial 4 (mg)</th>
<th>Max. temp. (°C)</th>
<th>Heating rate (°C min(^{-1}))</th>
<th>Lowest temp. (°C)</th>
<th>Cooling rate (°C min(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Propanol</td>
<td>4.5</td>
<td>5</td>
<td>5.5</td>
<td>6</td>
<td>77</td>
<td>1</td>
<td>-15</td>
<td>0.5</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>6.5</td>
<td>7</td>
<td>7.5</td>
<td>8</td>
<td>72</td>
<td>1</td>
<td>-15</td>
<td>0.5</td>
</tr>
<tr>
<td>Acetonitrile</td>
<td>4.5</td>
<td>5</td>
<td>5.5</td>
<td>6</td>
<td>77</td>
<td>1</td>
<td>-15</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\textbf{Fig. 1} Crystals of CBZ grown from 2-propanol in the shape of needles and prisms. The picture shows the vial together with the paddle.

3.2 p-Aminobenzoic acid crystals

\textbf{pABA} did not form any crystals in 2-propanol for all concentrations used in the experiments. In ethyl acetate, plate-like crystals of \textbf{pABA} formed (Fig. 4). In acetonitrile, the same result was obtained as in ethyl acetate: some needle crystals were formed on the bottom of the vial. Single crystals of excellent quality were obtained from ethyl acetate at concentration of 80 mg ml\(^{-1}\) (Fig. 3, right, Table 5). The exceptional quality of obtained dataset is indicated by the final difference electron density maps, where the largest peaks of residual density lie between bonded atoms and represent the bonding electrons, which are not accounted for by classical spherical atom refinement models. Sullivan obtained single crystals of
the α-form by isothermal evaporation of saturated solutions of 2-propanol, ethanol, methanol, ethyl acetate, acetonitrile, nitromethane and 1:1 methanol:toluene at room temperature and the β-form by isothermal evaporation of saturated
solutions of water.\textsuperscript{39} They had to wait up to 2 weeks for the completion of the experiments. Extensive concentration of the saturated solution at room temperature was obviously essential for crystal growth at least in the case of 2-propanol, as we could not form any crystals from 2-propanol with our thermal recrystallization method.

4. Conclusion

This study was done in order to evaluate the growth of single crystals of small molecules from minute volumes of only 0.1 ml by thermal recrystallization. For this method, it is obviously necessary that the desired molecule must change its solubility with temperature in a steady way and by a significant amount,\textsuperscript{40} additionally the molecule must be stable over the chosen temperature range. Since some molecules only slightly change their solubility as a function of temperature, it is extremely helpful to know exactly the solubility in the chosen solvents at the desired temperature, either from the literature or from own experimentation. In order to further minimize the needed amount of material, one could start with one single initial experiment per solvent at an concentration of 150\% of the saturated solution. Within only six hours using the CrystalBreeder, we were able to grow excellent quality single crystals of carbamazepine and p-aminobenzoic acid from as little as 1.5 mg of material. However, it is clear that this method is not suitable for all molecules, as shown in the case of the vitamin B\textsubscript{12}. Additionally, by comparing our results of pABA with the work of Sullivan,\textsuperscript{39} it is clear that cooling a slightly super-saturated solution will not yield in all cases crystals, unless evaporation further increases the supersaturation.

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References