Fast and efficient synthesis of a host guest system: a mechanochemical approach†

Manuel Wilke,ab Maria Klimakow,ab Klaus Rademannb and Franziska Emmerling*a

An unusually fast and effective synthesis procedure for a host guest system consisting of a metal organic framework (MOF) and a polyoxometalate (POM) is described. The material was synthesised mechanochemically and the evolution of the structure was monitored ex and in situ using synchrotron X-ray diffraction (XRD).

Polyoxometalates (POMs) are metal oxygen cluster anions formed by early transition metals, foremost vanadium, molybdenum, and tungsten.1 Their structural variety and unusual electronic properties lead to applications in different fields such as analytical chemistry, catalysis, biochemistry, and medicine.2–5 To increase the field of applications attempts were made to stabilise and immobilise these clusters. One possibility is the encapsulation in porous coordination polymers (PCPs).6 Zubieta and co-workers described the first host guest system, where [Mo9O36]6– cluster guests are arranged between PCP chains and layers.7 Numerous structures have been characterised where the POM guests are arranged between PCP chains and layers.8 Liu et al. synthesised a series of compounds (denoted NENU-n),9 consisting of Keggin-type POMs as guest species and a Cu–BTC (BTC = 1,3,5-benzenetricarboxylate) framework (HKUST-110) as host. As an example, the authors studied the catalytic properties of [Cu12(BTC)6·H2O]21 (NENU-3a) for the hydrolysis of organic esters. The catalytic activity of NENU-3a was four times higher than for the free heteropoly acid. Furthermore NENU-3a has a high selectivity for small molecules. The structures were synthesised by heating the Keggin compound, Cu(NO3)2·2H2O, 1,3,5-benzentricarboxylic acid H3BTC, and tetramethylammonium hydroxide ([CH3]4NOH) at 180 °C in a Teflon-automated autoclave for 24 h (yield = 60–80%).9 The addition of [CH3]4NOH was necessary for deprotonation and charge compensation.

For industrial applications, it is necessary to produce catalysts in a facile and efficient way. In this context, mechanochemical syntheses have gained increasing popularity and are already used in industrial processes.11,12 Mechano-syntheses are easy to handle and produce only small amounts of waste.11,13–16

Here, we present a fast and complete mechanochemical synthesis of the host guest supra-molecule NENU-5 in a three component reaction.17 In this structure, Keggin ions [PMo12O40]6– (Fig. 1a) are encapsulated in the HKUST-1 framework. The mechanochemical synthesis of HKUST-1 was described earlier.18–21

A vibration ball mill (Pulverisette 23, FRITSCH GmbH, Germany) was used equipped with a 10 mL stainless steel vessel and two stainless steel balls (10 mm, 4 g). In the first step 229.5 mg (0.12 mmol) of the heteropoly acid H3PMo12O40·1.5H2O and 296.8 mg (1.49 mmol) copper(II) acetate monohydrate were neat milled at 30 Hz for 5 min. The heteropoly acid was synthesised according to literature.22 To the gained homogeneous mixture 208.3 mg (0.99 mmol) of H3BTC and 400 mL of ethanol were added. The reaction mixture was milled at 50 Hz for 15 min. Copper(II) acetate monohydrate (cryst. extra pure, Merck), 1,3,5-benzentricarboxylic acid (98%, Alfa Aesar) and ethanol (absolute, Merck) were purchased commercially and were used without further purification. The identification of the product was accomplished by powder XRD on a D8 diffractometer (Cu Kα1 radiation, Bruker AXS, Karlsruhe, Germany). The comparison of the obtained sample with the simulated diffraction pattern for NENU-5 proves the purity of the compound (Fig. 1c). Unlike previously reported, the use of [CH3]4NOH was not necessary for the successful synthesis. Further details are given in the ESL†. The structure of the host guest supra-molecule is depicted in Fig. 1b. Half of
the pores of the framework are filled with the Keggin-type POM.

To gain insights in the underlying formation mechanism, the reaction progress was investigated by XRD. First experiments were analyzed _ex situ_. Every 30 s the milling experiment was stopped and a small amount of the sample was drawn for XRD measurements. Fig. 2a shows the resulting diffraction patterns during the synthesis of NENU-5. These measurements include a pre-milling step of copper(II) acetate monohydrate and the POM. The pre-milling was performed at 30 Hz for 5 min. After the addition of ethanol and H3BTC the mixture was milled at 50 Hz. The first pattern was detected after the pre-milling. The reflections of copper(II) acetate monohydrate and the POM can be assigned. The next diffraction pattern (t = 0 s) shows the reaction mixture after the addition of ethanol and H3BTC before the milling was started. The pattern is already dominated by the product reflections and the reaction is almost completed. 30 s later a weak peak at 2\(\theta\) = 12.8° indicates that copper(II) acetate monohydrate is still present in a very small ratio. The reaction is completed after 60 s. In the following, the diffraction patterns show no further changes. The interval between sample drawing and measurement was 1.5 h.

The data indicate that the strong tendency of NENU-5 to self-assemble promotes a self-sustaining reaction. The short milling period of only two of three reactants is sufficient to trigger the reaction. The importance of the pre-milling step is evident from the _ex situ_ investigation of the one pot synthesis (Fig. 2b). The reaction was conducted at 50 Hz. The diffraction pattern before the milling was collected 2 h after the sample drawing (see Fig. 2b below (black)). Two very weak reflections at 5.8° and 6.7° indicate the formation of NENU-5 in a very small ratio. 90 s of milling time are required until the reaction is completed.

The milling reactions were further investigated _in situ_. The _in situ_ monitoring of mechanochemical reactions with X-ray diffraction is a recently developed and promising method. The setup used here was described earlier. A schematic representation of the used setup is shown in Fig. 3a. In brief, the respective compounds and two stainless
Four different synthesis pathways were analysed comprising two principles: either two reactants were pre-milled first and the third reactant was added later (reactions 1–3) or all reactants were milled together in a one pot synthesis (reaction 4). For reactions 1–3 two reactants were pre-milled at 30 Hz for 5 min. Afterwards 300 μL of ethanol and the third starting material were added. This reaction mixture was then milled for 25 min at 30 Hz. For the in situ investigation of reaction 4 all three starting materials and ethanol were milled together at 30 Hz for 25 min. The lower frequency was chosen to decrease the reaction time for a better detection of the intermediates.

The 2D plots of the in situ investigations of the reactions 1–3 (with pre-milling) are shown in Fig. S1–S3.† For all pre-milling steps no reaction was observed during dry milling. Only reflections of the starting materials can be detected. The POM was detected in its hydrated form with thirteen water molecules in the crystal structure. After the addition of ethanol and the third compound reflections of the POM vanished in reaction 1–3. The reactions 1–3 result in the formation of NENU-5 after 30 s of milling. During these reactions the reflections of starting materials or side products vanish at different times. In reaction 1 (pre-milling step of copper(u) acetate monohydrate and the POM), the conversion is completed after 8 min. At this point the formation of the product can be deduced from several sharp and intense reflections. The intensity increases in the next minutes. In reaction 2 (pre-milling step of copper(u) acetate monohydrate and H$_3$BTC) reflections of the framework HKUST-1 appear after addition of ethanol and before the second milling was started. The weak intensity of the reflections implicate that only a small amount of HKUST-1 is formed. The compound is stable for 60 s. Afterwards, only reflections of NENU-5 can be detected. It is unlikely that the Keggin ions fill the pores of an existing HKUST-1 framework, since the channels between the pores are too small for the Keggin ions. In milling experiments starting from powdery HKUST-1, the Keggin-type POM, and ethanol (LAG conditions) showed no conversion. For the three component reaction, we can therefore assume that in the vicinity of NENU-5 the temporarily formed HKUST-1 is destroyed and rebuilt as NENU-5. The reflections of copper(u) acetate monohydrate disappear after 6 min of milling time in reaction 2. The ones of HKUST-1 vanish 30 s later. Only a few peaks of NENU-5 with low intensity can be detected at this point. The crystallinity starts to increase after 13 min of milling. In reaction 3 (pre-milling step of H$_3$BTC and the POM) reflections of the copper starting material with low intensity persist until 11:45 min. After 8 min all reflections of NENU-5 are already detectable with a high intensity.

The analysis of reaction 1–3 indicate that the pre-milling of copper(u) acetate monohydrate is the most effective reaction regarding the speed of product formation. The reflections of copper(u) acetate monohydrate always vanish at last, comparing all starting materials. These reflections were detected for the longest time (6:45 min after the restart) in reaction 3 where copper(u) acetate monohydrate is not pre-milled. Reaction 2, where copper(u) acetate monohydrate and H$_3$BTC were pre-milled, is the fastest, based on the detection of starting materials. All reflections of the starting materials vanished 60 s after the restart. Only a few reflections of the final product are detectable at this time. Reaction 1, where copper(u) acetate monohydrate is pre-milled with the POM shows the shortest interval until a high number of intensive reflections of the final product are reached. The diffraction pattern after the addition of ethanol and H$_3$BTC but before the milling shows no reflections of the product contrary to
the respective ex situ investigation. The waiting time is obviously necessary for the self-sustaining mechanism. These results are in accordance with previous described mechanchemical self-sustaining reactions.28

Fig. 3b shows the 2D plot of the in situ investigation of the one pot synthesis (reaction 4), where all starting materials and ethanol were milled together at once. In the first measurement after 30 s only reflections of copper(u) acetate monohydrate appear (phase 1). Other starting materials cannot be observed. This is similar to reactions 1–3 after the addition of ethanol. After 60 s reflections belonging to NENU-5 appear (start of phase 2). The intensity of the reflections of copper(u) acetate monohydrate decreases and vanishes completely after 6:30 min. Our findings show that the three component reaction can be performed as one pot synthesis. The pre-milling is not necessary for the formation of the final product, but increases the reaction rate after the addition of the third compound. Based on our results we conclude that the compound shows a strong tendency to self-assembly. The Keggin ions act as template and the metal–organic framework is formed around the ions (Fig. 4).

Summarizing, we report an unexpected fast mechanchemical synthesis of a host guest system consisting of a Cu–BTC MOF and Keggin ions. The pronounced tendency of the system to self-assemble was revealed on in situ synchrotron XRD data. Ex situ studies show that the reaction is self sustaining after the dry pre-milling of two compounds of the three starting materials.

Acknowledgements

We gratefully acknowledge financial support by the Deutsche Forschungsgemeinschaft through SPP 1415 (crystalline non-equilibrium phases and polymorphs): Ra 494/15-2, and Em 198/3-2.

References


Fig. 4 Schematic representation of the formation of NENU-5 from its building units. Orange polyhedra: Cu2O-cluster, turquoise polyhedron: [PMo12O40]6−, ball-and-stick representation: 1,3,5-benzenetricarboxylic acid with red: oxygen, grey: carbon, light grey: hydrogen.