

Exploring the Solution Formation of UiO Family Hf Metal-Organic Framework clusters with *in situ* X-Ray Pair Distribution Function Analysis

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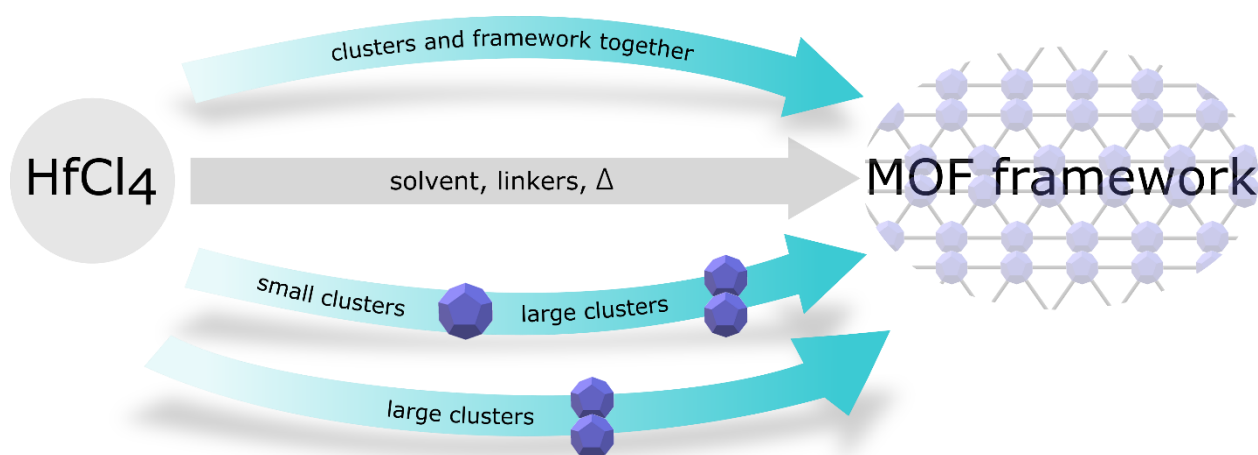
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Abstract

The structures of Zr and Hf metal-organic frameworks (MOFs) are very sensitive to small changes in synthetic conditions. One key difference affecting the structure of UiO MOF phases is the shape and nuclearity of Zr or Hf metal clusters acting as nodes in the framework; although these clusters are crucial, their evolution during MOF synthesis is not fully understood. In this paper, we explore the nature of Hf metal clusters which form in different reaction solutions, including in a mixture of DMF, formic acid and water. We show that the choice of solvent and reaction temperature in UiO MOF syntheses determines the cluster identity and hence the MOF structure. Using *in situ* X-ray pair distribution function measurements, we demonstrate that the evolution of different Hf

cluster species can be tracked during UiO MOF synthesis, from solution stages to the full crystalline framework, and use our understanding to propose a formation mechanism for the **hcp** UiO-66(Hf) MOF, in which first the metal clusters aggregate from the M_6 cluster (as in **fcu** UiO-66) to the **hcp**-characteristic M_{12} double cluster, and following this, the crystalline **hcp** framework forms. These insights pave the way towards rationally designing syntheses of as-yet unknown MOF structures, via tuning the synthesis conditions to select different cluster species.



Introduction

Metal-organic frameworks (MOFs) are of great interest for a wide variety of applications, including energy storage and carbon capture,^{1,2} and have outstanding chemical tunability.³ In order to fully exploit the potential of MOFs for real-world applications, however, we must work towards designing syntheses to obtain MOFs with new sorption or catalytic properties, particularly enabled by new or previously inaccessible structures. While to some extent this can be achieved by the use of new geometries and functionalities of organic linker, one of the key components determining the structure of a MOF is the shape and identity of the metal cluster.⁴ By increasing our understanding of the inorganic component, we can obtain control over the nuclearity of the cluster, and hence the connectivity of the MOF, which allows us to dramatically change the MOF structure.

Zirconium and hafnium are particularly favourable for the design of new MOF structures: in contrast to copper, for example, (which often forms dinuclear “paddlewheel” units⁵), there is a rich variety of known zirconium and hafnium clusters, with a wide range of nuclearities, geometries and coordination denticities.^{6–10} There are in fact over 1300 structures containing between 3 and 21 Zr or Hf ions in their molecular formula – forming either molecular clusters or being part of an extended framework (including MOFs) – in the CCDC (Cambridge Crystallographic Database) alone.^{11*}

From these structures, we can identify a wide variety of Zr and Hf metal-oxide inorganic substructures (derived by removing peripheral ligands), or “core” clusters. The metal ions have high charge density, arising from their +4 oxidation state, and so favour hard donor atoms such as oxygen, to which they coordinate strongly. Therefore, hydroxyl bridges and oxo- and hydroxo-capped clusters are predominant in the Zr and Hf “core” clusters, and clusters are often found with ligands coordinating through oxygen, such as carboxylate groups.^{12,13}

Although the most common cluster motif in Zr and Hf MOFs, e.g. in the UiO family¹⁴ **[Error! Reference source not found.]**, is the $M_6(\mu^3-O)_4(\mu^3-OH)_4$ cluster based on Zr_6O_8 octahedra,^{8,15,16} the “core” clusters range from small, low-nuclearity molecular clusters through to large structures such as infinite polymeric chains.^{17–21} Just as in other extended metal oxide structures, these metal (hydr)oxide clusters can share vertices,⁸ edges,^{16,22} faces and coordination-polyhedra.^{8,23–25} As these structures increase in nuclearity, they increasingly resemble the structure of high temperature, tetragonal ZrO_2 .²⁶

The standard method for synthesising Zr/Hf MOFs is solvothermal synthesis; the choice of solvent affects the MOF metal clusters, the degree of Zr or Hf cluster aggregation being greatly

* Cambridge Crystallographic Database, search performed July 2020

affected in particular by the presence of water in the synthesis. In aqueous, and especially aqueous acidic conditions, the distorted-square tetrameric species $[\text{M}_4(\text{OH})_8 \cdot 16\text{H}_2\text{O}]^{8+}$ is dominant.^{25,27–32} This cluster is surrounded by a structured coordination sphere of water molecules^{33,34} similar to other nanoparticles in solution.³⁵ This water coordination sphere is potentially the source of further hydroxide bridges between metal centres during condensation of the clusters.^{33,34,36–38} The degree of hydrolysis, and subsequent aggregation, can be modulated by the use of additional reagents,³⁷ such as acid,³⁹ which in some MOF syntheses is required to form the crystalline framework,^{40,41} and in others is used to control particle morphology.^{15,40,42,43} Monocarboxylic acids are often chosen for this purpose; since they can possess a wide range of metal-ligand binding strengths, a judicious choice of carboxylic acid can “block” coordination sites on the cluster to further nucleophilic attack preventing, in the case of water/hydroxides, cluster aggregation, or for linkers, the formation of multi-cluster framework species.^{13,34,44} However, while it is now clear that water and modulating ligands are critical to the identity and stability of the resultant metal clusters (from ligand-terminated molecular clusters³⁰ through to MOFs^{12,34,45–48}), the exact interplay of these factors, especially in multi-species reaction mixtures, is not well understood.

The degree of cluster aggregation is also directly affected by the temperature and duration of the synthesis. Both heating acidic aqueous zirconium solutions, for example during a solvothermal synthesis, and ageing the reaction mixture, increase the amount of bridging $\mu^2\text{-OH}$ between metal centres, and also encourages their conversion to $\mu^3\text{-O}$ and $\mu^3\text{-OH}$ groups.^{15,30,34,49} This therefore favours the formation of higher-nuclearity Zr or Hf clusters.⁵⁰

Building on this work, we recently showed that by tuning the synthesis conditions of UiO family MOFs,^{14,51–53} we can produce MOFs with distinct and different framework topologies, caused by the formation of different nuclearities of different zirconium or hafnium metal clusters.^{16,54,55}

Increasing the temperature, concentration of water and concentration of formic acid modulator allowed us to selectively produce UiO family hafnium MOFs containing larger Hf_{12} metal clusters [**hcp** (hexagonal close-packed) UiO-66(Hf), **hcp** and **hns** (hexagonal nanosheets) UiO-67(Hf)] instead of Hf_6 clusters, which form the **fcu** (face-centred cubic) topology [Figure 1].

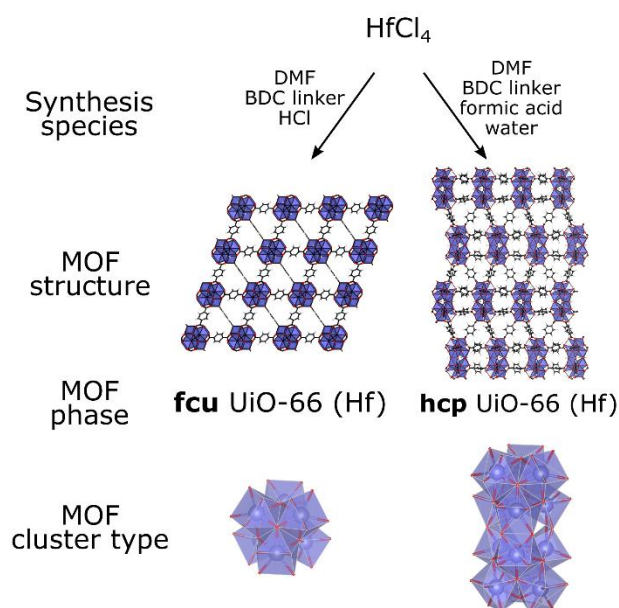


Figure 1 Differences in synthesis conditions of UiO family MOFs lead to the formation of different MOF phases.⁵⁴ A synthesis performed with HCl leads to the **fcu** MOF structure with $\text{Hf}_6(\mu^3\text{-O})_4(\mu^3\text{-OH})_4$ 'single' clusters, while a synthesis performed with formic acid and water leads to the **hcp** MOF structure with $[\text{Hf}_6(\mu^3\text{-O})_4(\mu^3\text{-OH})_4]_2(\mu^2\text{-OH})_6$ 'double' clusters: the type and nuclearity of the metal cluster affects the topology via the change in linker coordination site number and geometry. The metal-oxide coordination polyhedra are also shown. Colour scheme: Hf or Zr, blue; O, red; C, black; H, white.

Our previous work showed that, due to the similarities between the PXRD patterns of the **fcu** and **hcp** MOFs,^{16,54} it is not always immediately obvious that a MOF structure with a different cluster has formed. Despite advances in understanding,^{56–58} including studies on the effects of

different variables (including acid modulator and water) on the crystallisation of UiO-66(Zr)⁴¹ (and cerium analogues⁵⁹), a full picture of the formation routes of MOFs – in particular the pre-crystalline stages of cluster growth – is still far off. In our work on UiO family MOFs, *in situ* measurements to probe crystallisation of the **hcp** phase suggested that inorganic (i.e. largely free from organic ligands) pre-crystalline species formed at early stages in the synthesis.¹⁶ Although this inorganic, noncrystalline material is likely to be a key intermediate in the formation and crystallisation of UiO family MOFs, we were unable to determine its identity. Moreover, it is unknown when in the reaction the crucial structural differences between UiO MOF phases emerge (i.e., selectivity of the **hcp** phase over the **fcu**); it is unclear whether the different clusters form via different routes, or if they pass through common intermediates; finally, the timing of the cluster interlinking and framework growth, relative to the timing of the formation of the different clusters, has been little explored.

Studies on Zr and Hf clusters to track or solve their structures are not straightforward (especially *in situ* studies of solvothermal syntheses). Bragg diffraction cannot be used to study the critical non-crystalline species. Solution NMR is extremely challenging, as the key nuclei (¹⁷O, ⁹¹Zr, ¹⁷⁷Hf and ¹⁷⁹Hf, in the absence of organic linker species^{60,61}) all either have large quadrupolar moments (e.g. $Q(^{177}\text{Hf}) = 4.9 \text{ b}$),⁶² have low gyromagnetic ratios (e.g. $\gamma(^{179}\text{Hf}) = -0.682 \times 10^7 \text{ rad/Ts}$), or are of very low abundance (e.g. ¹⁷O = 0.038 %). While extended X-ray absorption fine structure (EXAFS) methods can identify Zr and Hf species in solution, and are sensitive to species with low abundance, this technique is limited to smaller molecular clusters such as the tetramer and single cluster,³⁰ due to multiple scattering events reducing the sensitivity required to observe longer-range coordination, such as that seen in the molecular double cluster or in the interlinked MOF.

X-ray pair distribution function (XPDF) measurements can acquire structural information on non-crystalline species and are particularly sensitive to heavier elements such as Zr and Hf due to their high electron density. In our previous work, we have shown that *ex situ* XPDF measurements are sensitive to the identity of the cluster in UiO family MOFs, and can clearly distinguish between isolated Zr atoms, Zr₆ clusters, and Zr₁₂ clusters.¹⁶ *Ex situ* XPDF measurements can detect and differentiate between tetramer and single cluster species in room temperature solutions related to UiO syntheses,⁵⁶ and have successfully been used *in situ* to track the size of interlinked cluster aggregates forming MOF crystallites in solvothermal UiO-66 syntheses,⁵⁶ as well as of metal oxido nanoclusters.⁶³ However, until now, no study has been able to follow both the cluster formation and the coordination of the MOF framework in the same *in situ* reaction.

It is imperative to further explore the *in situ* formation of Hf and Zr MOFs and their related clusters and precursors, in order to understand their behavior when combined with other species, with different identities and concentrations, which are present under solvothermal conditions. The future of MOF design lies in the rational synthesis of new desired MOF structures, with a range of connectivities and different linkers and subsequently different physical/chemical properties and topologies. In order to do this, through the deliberate design of syntheses to exploit the wide library of possible cluster species, we must improve our understanding of the mechanisms of MOF and MOF-precursor formation. In this work, we bridge the gap between *ex situ* cluster identification and *in situ* MOF crystallite growth. We focus our investigation on the UiO-66 family of MOFs, as an archetype of Zr/Hf MOFs. We perform *in situ* XPDF measurements on reactions of Hf-containing solutions, under conditions required to form both the **hcp** UiO-66(Hf) MOF and its molecular cluster precursors. We show that, alongside a careful structure search for plausible cluster models, these XPDF measurements enable us to identify critical cluster intermediates in

the materials, including the M_6 cluster found in **fcu** UiO-66(Hf) and the M_{12} double cluster found in **hcp** UiO-66(Hf). We also gain insight into the relationship between the cluster formation and the MOF framework coordination. These advances in understanding the stages of growth of UiO family MOFs, including the formation of clusters as precursors, provide routes towards the deliberate and efficient design of MOF syntheses, exploiting the wide library of possible metal cluster species for new and unrealised members of this important class of materials.

Experimental Methods

No unexpected or unusually high safety hazards were encountered in the course of this work.

Synthesis

Reaction mixtures were carried out in a 2.5 mm fused-quartz capillary, sealed with a Teflon cap before being loaded into the *in situ* cell.

An aqueous solution of $HfCl_4$ (30 wt%) was prepared through dissolution of $HfCl_4$ (Acros Organics, 99 %) in deionised water and sonication for 10 minutes.

The conditions for the synthesis of the **hcp** UiO-66(Hf) MOF were adapted from Ref. 54, with quantities reduced to account for the smaller *in situ* reaction volume. The concentrations of $HfCl_4$ and, where relevant, organic linker, were increased to improve signal to noise. The compositions of the reaction mixtures are described below.

$HfCl_4$ (4.8 mg, 0.015 mmol) and terephthalic acid (H_2BDC) (Alfa Aesar, 98 %, 2.5 mg, 0.015 mmol) were added to a capillary, followed by dry *N,N*-dimethylformamide (Sigma Aldrich, 99.85 % anhydrous DMF) (65 μ L), formic acid (Fisher, 98/100 %) (25 μ L) and water (10 μ L), then sonicated for 10 minutes. We also carried out reactions without the terephthalic acid ligand, to assess its importance in cluster formation. $HfCl_4$ (116 mg, 0.362 mmol) was sonicated for 10 minutes with dry DMF (6.5 mL), formic acid (2.5 mL) and water (1.0 mL). 0.1 mL of the resulting solution was measured into the capillary.

***In situ* measurements**

Total scattering X-ray diffraction patterns were collected at beamline i15-1 at the Diamond Light Source using an X-ray energy of 76.7 keV ($\lambda = 0.161669 \text{ \AA}$). Initial calibration measurements were performed on a silicon standard. *In situ* measurements were carried out using a heated steel sample holder with openings for the X-ray beam to pass through the sample. The capillary was positioned so that the beam passed through it close to the base, so that any solid formed during the reaction would not precipitate out of the path of the beam. Once the capillary was loaded, heating was started with a fast ramp, then scattering detection and temperature measurements proceeded at a rate of one scan per minute. Two separate thermocouples measured the temperature of the capillary and of the sample holder. The experimental setup of the hydrothermal cell is shown in Figure S1. Diffraction measurements of capillaries containing pure water and the 65:25:10 DMF : formic acid : water solvent were taken at room temperature and at 150°C for use as backgrounds. *In situ* experiments were performed at room temperature, 120°C and 150°C.

Analysis

The diffraction data were integrated using DAWN⁶⁴ and processed, with corrections applied for background, meaningful instrument intensity cutoff and polynomial smoothing using the PDFgetX3 software package⁶⁵ using the following parameters: $q_{\min} = 1 \text{ \AA}^{-1}$, $q_{\max} = 22.5 \text{ \AA}^{-1}$, $r_{\text{poly}} = 1.24 \text{ \AA}$. Structural models were quantitatively refined against XPDF data using the DiffPy-CMI software package⁶⁶. The resolution peak dampening term Q_{damp} was constrained to $Q_{\text{damp}} = 0.035 \text{ \AA}^{-1}$, this value derived from refinement against a Si standard. The $\Delta 1$ parameter, corresponding to atomic-motion-derived peak broadening in the “high temperature limit” (with a $1/r$ dependence) was set to 2 \AA following an initial refinement and the isotropic displacement parameters (U_{iso}) were derived from the reported values for Hf clusters, determined from single-crystal data, and set to 0.18 \AA^2 for H, 0.075 \AA^2 for C and 0.06 \AA^2 for O. U_{iso} for Hf was obtained from refinement of

an *ex situ* sample of **hcp** UiO-66(Hf) [Figure S2] and subsequently fixed at 0.0069 \AA^2 . Refinement of isolated cluster models and the optimised full structure model of **hcp** UiO-66(Hf) was carried out with refinement parameters set to $q_{\min} = 1 \text{ \AA}^{-1}$, $q_{\max} = 22.5 \text{ \AA}^{-1}$, $r_{\text{poly}} = 1.24 \text{ \AA}$ and $r_{\min} = 1.5 \text{ \AA}$. XPDF patterns were simulated using the DiffPy-CMI software package,⁶⁶ with the optimised parameters as detailed above. Peak tracking and analysis of processed XPDF and powder X-ray diffraction (PXRD) data was performed using the NumPy and SciPy packages.^{67,68}

Results

In order to study the *in situ* formation of UiO-66 family MOFs, we designed a series of experiments based on the conditions used in our lab syntheses of these materials, as summarised in Table 1. While UiO family MOFs are typically synthesised from zirconium salts, in this (as with our previous) work we have used hafnium chloride, due to the chemical similarity of Hf compared to Zr but greater scattering power.⁵⁴ While a variety of solvents and conditions have been used across the literature, the majority of our work has focussed on reactions in DMF with formic acid and water.^{16,54} Our XPDF experiments, therefore, used these same reagents.

We initially observed the behaviour of our HfCl_4 metal salt in water alone as a baseline, since the behaviour of ZrCl_4 in water is well-established. We then focussed on a 65:25:10 (by volume) DMF : formic acid : water mixture (referred to below as “DFW 65:25:10”) as a solvent, setting out to elucidate the behaviour of the UiO-related system throughout the reaction at different temperatures. We also investigated whether the stages and rate of cluster formation are affected by the presence of additional coordinating linkers, and explored the timing of the framework growth and crystallinity relative to the cluster formation, by performing reactions at the two different temperatures both with and without terephthalic acid (H_2BDC) linker, i.e. reactions with

the potential to form UiO-66-type structures (containing BDC, at 150 and 120°C), and molecular-cluster-only reactions (no BDC, at 150 and 120°C) [Table 1].

Table 1 Summary of experimental conditions used in the XPDF studies, listing the solvent, nature of linkers (if any) and temperatures used.

Experiment	Solvent	Linker	Temperature
1	Water	No	R.T.
2	DFW 65:25:10*	No	R.T.
3	DFW 65:25:10*	No	150°C
4	DFW 65:25:10*	BDC	150°C
5	DFW 65:25:10*	No	120°C
6	DFW 65:25:10*	BDC	120°C

*The notation “DFW 65:25:10” gives the ratio of DMF : formic acid : water

We start by detailing our approach to model the different clusters present, beginning with the aqueous solution of HfCl_4 . We then consider the effect of changing the solvent and temperature, and the effect of adding linkers, on the type and evolution of the clusters in these UiO-related systems.

Cluster models

Since there are many possible cluster structures adopted by Zr and Hf in solution, we first identified all the relevant clusters that could be present in our system via a systematic search of the Cambridge Structural Database (CSD). This search yielded over 1300 structures containing 3 to

21 Zr or Hf atoms[†] (including “infinite” structures with repeating subunits) [Figure 2 (a)]. We then discarded all structures containing heterometallic clusters and extracted the metal (hydr)oxo core clusters by stripping out the peripheral ligands, giving us more than 170 unique results. Our candidates were then reduced to 25 core clusters by considering only those feasible in typical MOF reaction conditions and within the constraints of our experimental conditions [Figure 2 (b)]. We then discarded core clusters appearing only once, those with syntheses reported to be irreproducible, and those from syntheses requiring more than a few days (i.e. with reaction times more than two orders of magnitude longer than used in our experiments) or temperatures below 0°C, and further only considered clusters reported to form in reaction mixtures containing water. The remaining 25 clusters included the classic (**fcu**) UiO M₆ single cluster and **hcp** UiO M₁₂ double cluster [shown in Figure 1].

[†] The majority of n<3 search results contained higher-nuclearity clusters, but with the molecular formula reduced to an empirical formula; very few clusters with n>21 are observed.

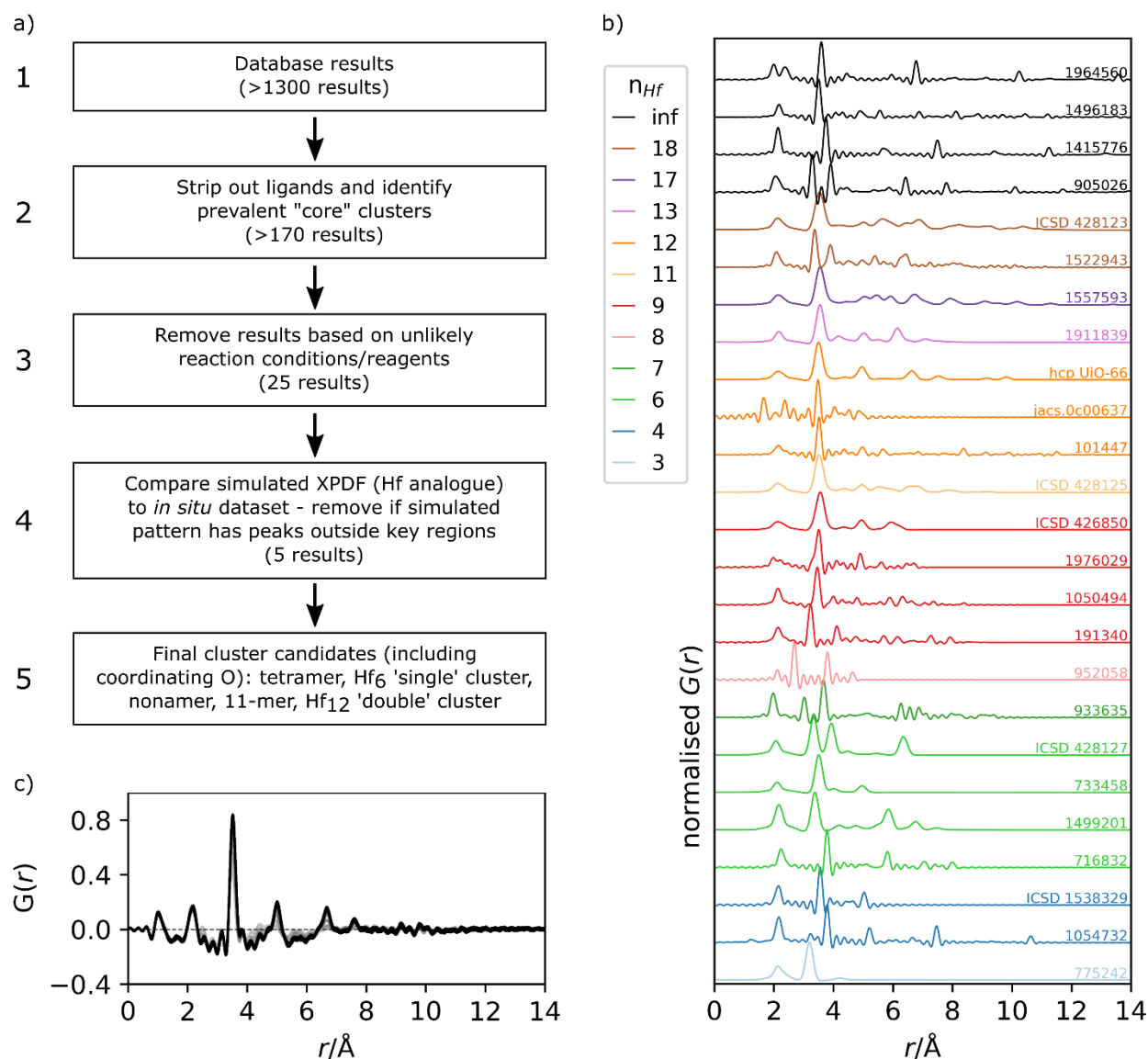


Figure 2 a) Route used to find an appropriate set of cluster candidates; b) Simulated XPDF patterns of remaining clusters at step 3 (CCDC/ICSD codes as shown), with each dataset normalised to its most intense peak; cluster datasets have been colour-coded according to the number of Hf atoms in the cluster (n_{Hf} in the legend). c) *in situ* dataset of a linker-free reaction in DFW 65:25:10 solvent at 150°C, showing regions of characteristic peaks used as boundaries for step 4. Cluster structure models were obtained from crystal structure files and edited using the VESTA programme.⁶⁹

References: $n=3$;³⁶ $n=4$;^{29,70} $n=6$;^{14,38,71,72} $n=7$;⁷³ $n=8$;¹⁰ $n=9$;^{15,23,74,75} $n=11$;⁷¹ $n=12$;^{16,23,76} $n=13$;⁷⁷ $n=17$;⁵⁰ $n=18$;^{71,78} 'infinite' structures^{18–20,79}

Initial examination of an *in situ* XPDF dataset of a linker-free reaction in DFW 65:25:10 solvent [Error! Reference source not found. (c)] revealed that low- r peaks were only experimentally observed in six regions (as illustrated in Figure 3c). We therefore used this constraint to narrow down the 25 chemically feasible core clusters to five [Figure 3], removing those core clusters with peaks outside these regions. We edited all five core cluster models to obtain the Hf (rather than Zr) analogues, in keeping with the composition of our reaction mixtures.

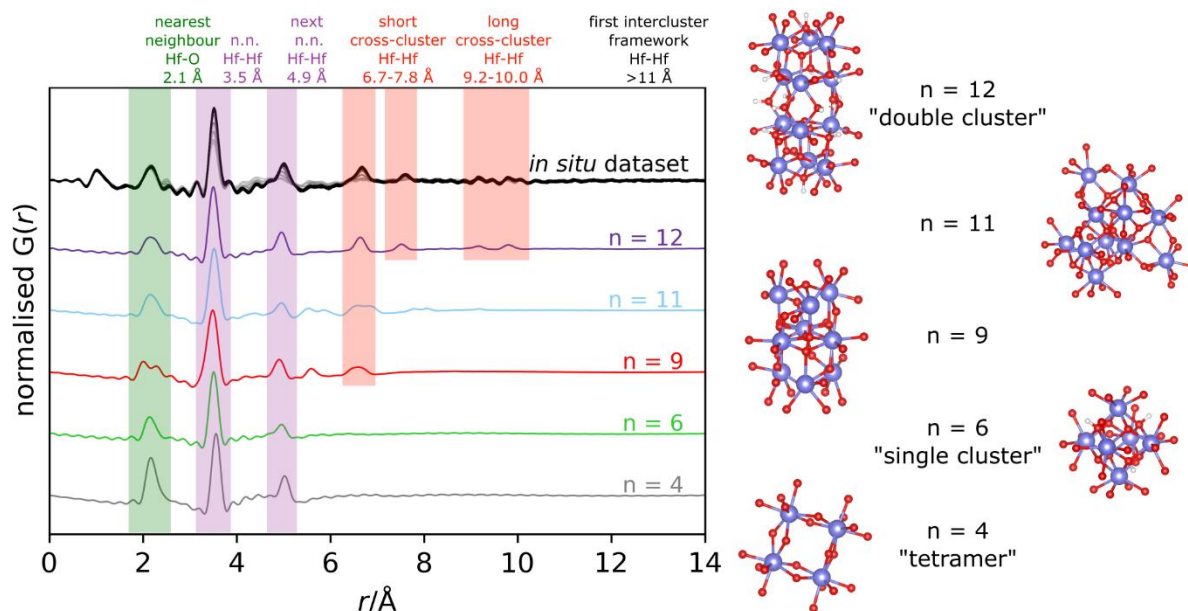


Figure 3 Final cluster options and their simulated XPDF patterns, with key peak areas highlighted, and an *in situ* dataset of a linker-free reaction at 150°C for comparison. Cluster structure colour scheme: Hf, blue; O, red; H, white. Cluster structure models were obtained from crystal structure files^{14,23,25,54,71} and edited using the VESTA programme to give the Hf analogues and remove peripheral ligands.⁶⁹

In order to obtain our cluster models, we removed peripheral ligands from the original structures. However, in our reactions, it is likely that the clusters are coordinated by a combination of carboxylate groups³⁰ (formate and/or BDC, where present in the synthesis), and water/hydroxide⁵⁴ (the tetramer is predominantly coordinated by water only).^{25,30} We therefore added coordinating oxygen atoms to the five core cluster models, to allow for the presence of non-specific peripheral ligands while avoiding chemically-unrealistic undercoordinated metal centres.

Hf behaviour in water

Due to the similarity between the calculated XPDF patterns of the five core clusters, we turned to quantitative refinement of the structures against the experimental data with Diffpy-CMI,⁶⁶ to determine the composition of our reaction mixtures. To validate our approach, we carried out a refinement, our model (“the five-cluster model”) including all five core clusters (as in Figure 3) and allowed their relative concentrations to vary, against an XPDF measurement of our “baseline” solution of aqueous HfCl_4 (30 wt%, room temperature). Our refinement converged to give a contribution from the tetramer only [Figure 4 (a)], as expected,^{25,29,32} confirming the viability of this approach, even for structurally closely-related clusters.

A significant misfit in the region around 4.5 Å was found in this initial refinement [Figure 4 (a)] that was not well fit by the isolated tetramer cluster model. This initial model did not take account of the likely structuring of water as a coordination sphere around the cluster.^{33,34} We therefore augmented our tetramer model by including an additional coordination shell of 24 water molecules, with the oxygens placed using the locations of water and chloride in the crystal structure of zirconyl chloride octahydrate [Figure S3].^{25,31} The simulated XPDF of this augmented tetramer model, “tetramer·H₂O”, shows both significant intensity at about 4.5 Å, and broader, weaker contributions at 7-9 Å, both due to non-nearest-neighbour Hf (cluster) - O (solvent) distances. Refining the tetramer·H₂O cluster model against the experimental XPDF data [Figure 4 (b)]

improved the quality of fit ($R_w(\text{tetramer}) = 0.345$ vs $R_w(\text{tetramer} \cdot \text{H}_2\text{O}) = 0.319$), with the fit particularly improved in the aforementioned region around 4.5 Å [Figure 4 (b)], suggesting that in solution there is a highly structured coordination sphere of water around the $[\text{Hf}_4(\text{OH})_8(\text{H}_2\text{O})_{16}]^{8+}$ cluster.

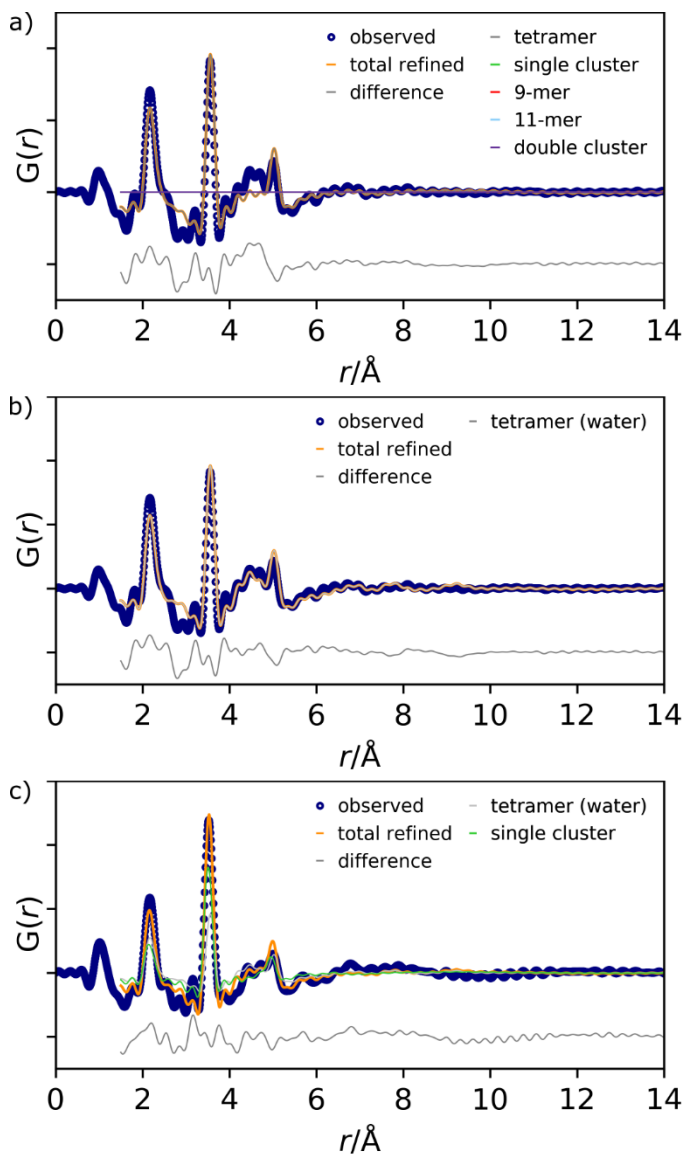


Figure 4. XPDF studies of HfCl_4 in water and in DMF : formic acid : water solvent. Refinement of a) the 5-cluster model against the XPDF dataset of HfCl_4 in water at room temperature ($R_w = 0.346$) (Scale factors of all species except the tetramer are less than 0.05% of the scale value of the

tetramer), b) the tetramer·H₂O model²⁵ against the XPDF dataset of HfCl₄ in water at room temperature ($R_w = 0.319$), and c) both the tetramer·H₂O and single cluster models, against the XPDF dataset of HfCl₄ in DFW 65:25:10 solvent at room temperature ($R_w = 0.259$).

Hf behaviour in DMF : formic acid : water solvent

Once we had confirmed the viability of our method to differentiate between structurally closely-related clusters, we set out to elucidate the behaviour of the system throughout the reaction in DFW 65:25:10 solvent, both with and without terephthalic acid (BDC) linker, and at different temperatures. In particular, we investigated the conditions which trigger a difference in cluster nuclearity, which we have previously shown to result in different UiO-66(Hf) MOF structures,^{16,54} to try and identify at what stage of the reaction these differences occur. We began with a room-temperature experiment, to compare the clusters which formed in the aqueous-only HfCl₄ solution with those found in a solution comprising DMF, formic acid and water. Compared to the XPDF of HfCl₄ in water, which contains only the tetramer cluster, the XPDF of room-temperature HfCl₄ in DFW 65:25:10 solvent (65:25:10 v/v dimethylformamide (DMF): formic acid : water) has greater intensity at 2.1 Å, implying a greater number of Hf-O nearest neighbours, and less intensity at 4.5 Å, suggesting a reduced water coordination shell [Figure 4 (c)].

Refinement of the five-cluster model against the room-temperature DFW 65:25:10 solvent dataset [Figure S4 (a)] gave the best fit with a mixture of only the tetramer and the **fcu** UiO-66 type¹⁴ hexanuclear single cluster [Figure 3], with no significant contribution from any higher-nuclearity species. A high degree of correlation was however observed between the proportions of the 11-mer and the single cluster owing to similarities between the XPDF patterns of the species. However, the correlations were reduced, and the fit improved, when the tetramer·H₂O was used instead of the tetramer in the five-cluster model [Figure S4 (b)], suggesting that, rather than extra

species being present, the refinement was using contributions from the 11-mer to fit the weak signals arising from the solvent restructuring at 7-9 Å [these signals can be seen in Figure S4 (b)]. The refinement was then repeated with the tetramer·H₂O and the single cluster only [Figure 4 (c)], showing a good fit with a 58:42 ratio of scale factors (albeit correlated), which was an improvement on that obtained from refinement of a mixture of the tetramer (without water) and the single cluster [Figure S4 (c)], again suggesting some solvent restructuring remains.

Additional refinements were performed to explore the contributions by the tetramer and single cluster separately, and the extent of solvent reorganisation [Figure S5 (a,b)]. These results overall indicated that the solvent structuring due to water is less obvious than that seen in the XPDF pattern of the tetramer·H₂O in water, even though water is in large excess compared to Hf in our sample of HfCl₄ in DFW 65:25:10 solvent (1:232:183:153 molar ratio Hf : DMF : formic acid : water).

The XPDF analysis of our DFW 65:25:10 solvent dataset corroborates that a change of solvent system, without any change in temperature, is already sufficient to cause some degree of cluster aggregation, from the tetramer to the **fcu** UiO-type single cluster. However, the double cluster was not observed in any of these studies. The single cluster species is known to be particularly stable,^{14,80} as well as being found in a wide range of syntheses and conditions,^{20,81} which suggests that changing the type and concentration of modulating acid, or the reaction time, are not sufficient alone for further cluster aggregation;^{14,20,28,30,80,81} higher temperatures may also be required to encourage the formation of higher-nuclearity clusters.^{16,54,60}

Behaviour of Hf in DMF : formic acid : water solvent at raised temperatures

We next investigated the effect of raised temperature on a solution of HfCl₄ in the same DFW 65:25:10 solvent. Since our previous work showed that **hcp** UiO-66(Hf), containing dodecanuclear metal clusters (“double cluster”), required higher synthesis temperatures compared to **fcu** UiO-66(Hf), which contains the hexanuclear single cluster,^{16,54} we studied our system at two

temperatures: 150°C, the temperature used for our lab syntheses of **hcp** UiO-66(Hf) and **hcp** UiO-67(Hf), and 120°C, at which temperature **hcp** UiO-67(Hf) did not form.¹⁶ We also investigated the effect of the presence of additional coordinating linkers by performing reactions at the two different temperatures both with and without terephthalic acid (H₂BDC) linker.

For our analysis of these four *in situ* datasets, we tracked the change in area of specific key peaks in the XPDF [Figure 5]. Based on our analysis of the room-temperature DFW 65:25:10 dataset [see Figures S4, S5], we established that the area under the peak at 3.5 Å (the nearest neighbour Hf-Hf) is larger for the hexamer than for the tetramer. In all our *in situ* reactions the area under this peak initially increases, corresponding to a reduction in the proportion of tetramer. This is further corroborated by the increase in the area under the peak at 4.9 Å at the start of the reaction, corresponding to an increase in the amount of next-nearest neighbour Hf-Hf interactions, which also indicates the formation of clusters other than the tetramer. The growth of the peaks at 3.5 and 4.9 Å indicates species of higher nuclearity than the tetramer are forming, but cannot distinguish between the growth of single cluster and the Hf₁₂ double cluster. However, these peaks generally precede the growth of the peak at 9.2 Å, which is only seen in the Hf₁₂ double cluster [Figure 3], allowing us to distinguish the appearance of the double cluster separate from the single cluster. While in our room temperature experiments the tetramer is found alongside the single cluster, the elevated-temperature data suggests that once the temperature is raised, higher nuclearity clusters are favoured (as expected³⁴) over the tetramer.

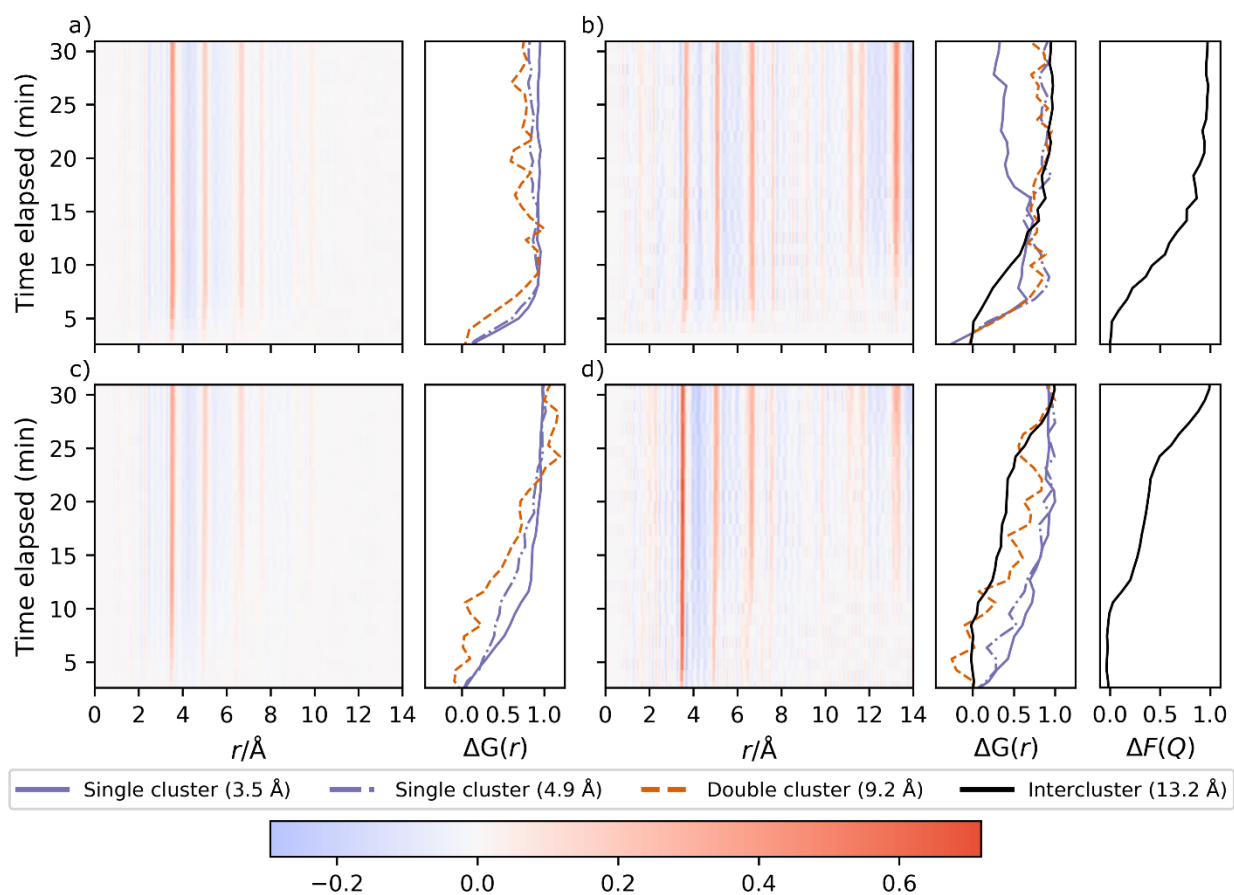


Figure 5 Colour plots showing the change in the $G(r)$ s over time at 150 and 120 °C: a) 150°C, no BDC linker; b) 150°C, with BDC linker; c) 120°C, no BDC linker; d) 120°C, with BDC linker. $\Delta G(r)_t$ is shown to the right of each plot, calculated as $[(G(r)_t - G(r)_{t=0}) / [(G(r) - G(r)_{t=0})_{\max}]]$ (experimental data may continue slightly beyond the bounds of the plots shown). The crystalline component is analysed via $F(Q)$ peak tracking, where the change in the intensity of the reflection at 3.01 \AA^{-1} is plotted as $\Delta F(Q)$. $G(r)$ intercluster and $F(Q)$ peak tracking are only shown for reactions containing BDC (that is, reactions which form a framework). (Experimental data may continue slightly beyond the bounds of the plots shown).

As a complementary analysis, we also performed refinements in the same manner as for the room temperature reactions, using the five-cluster model for refinements of each time step in the

datasets. These initial refinements [Figure S6] showed no significant contribution from the nonamer and 11-mer throughout the reactions, meaning that only the tetramer, single cluster and double cluster are present in measurable concentrations. A second analysis was then performed with only these three clusters (i.e. omitting the nonamer and 11-mer) [Figure S7]. In these refinements of the heated *in situ* reactions, we always observe the single cluster first, with the double cluster emerging at later stages; this agrees with our analysis from the peak-tracking data.

Due to the high correlation between the proportions of these remaining cluster species, the exact ratios of these species as the reactions progressed could not be confidently determined using this method. However, from the cluster proportions obtained from this refinement [Figure S7], in all of the *in situ* reactions, the growth in the concentration of the double cluster occurs alongside a reduction in the amount of single cluster, and there is no delay between the loss of single cluster and the formation of the double cluster. This suggests that the double cluster forms by the direct combination of single clusters, rather than forming directly from the tetramer (a pathway not involving the single cluster) or requiring the breakdown of single clusters into lower nuclearity clusters prior to the formation of the double cluster.

Peaks beyond 11 Å, when considered against our five-cluster model, only arise from intercluster distances in an interlinked framework [Figure 3]; in our systems, these peaks, such as that at 13.2 Å, correspond to clusters joined by BDC linkers. In the BDC-containing reactions at both temperatures-, the growth of these inter-cluster peaks occurs both following, and at a slower rate than, the intra-cluster peaks. This shows that intercluster coordination occurs following, rather than simultaneously with, the cluster formation, in keeping with our previous work which suggested that the non-crystalline precursor of the framework (i.e. the cluster material) is in large excess prior to the framework coordination and growth.¹⁶

To further understand the behaviour of the linker-containing systems (i.e. with the potential to form a crystalline MOF framework), we also examined the reciprocal-space structure factor, $F(Q)$ [Figure S8], and tracked the changes at 3.01 \AA^{-1} [shown in Figure 5 for the BDC-containing reactions as $\Delta F(Q)$] as an indication of the formation of **hcp** UiO-66(Hf), this reflection at 3.01 \AA^{-1} being indexed to the intense and characteristic {063} Bragg reflection of the crystalline **hcp** framework. The growth of this Bragg peak coincides with the growth of the framework inter-cluster peaks, including that at 13.2 \AA , in the XPDF [Figure 5], meaning that the connection of the clusters into a framework occurs simultaneously with the crystal formation, rather than first forming as an amorphous linked-cluster polymeric phase with subsequent rearrangement to become crystalline.

The changes in the $F(Q)$ data indicate that the **hcp** UiO-66(Hf) material is formed in both the BDC-150 and the BDC-120 reactions [Figure 5(b,d), Figure S8]. However, there appears to be two stages to the growth in the framework at 120°C [Figure 5 (d)], shown both by the tracked intercluster peak in $G(r)$ at 13.2 \AA , and by the changes in the 3.01 \AA^{-1} reflection in $\Delta F(Q)$. The first stage occurs once some amount of double cluster has formed, with a sudden increase in the intensity of the reflection at 3.01 \AA^{-1} at c. 11.5 minutes [Table S1] indicating rapid framework growth. But, after an initial increase in peak area, the rate of framework formation slows and plateaus around 18.9 minutes (likely limited by the amount of available double clusters, which does not reach a maximum until around 25.1 minutes, according to the $G(r)$ tracking). The second stage, with fastest framework growth at c. 26.1 minutes, occurs once the double cluster peaks in the $G(r)$ have reached their maximum (i.e. once there is significant excess of the “free” double cluster), with a higher rate, as the amount of double cluster is no longer limiting.

Discussion

The role of acid

In this paper, we have shown that in water, HfCl_4 forms the tetramer cluster $[\text{Hf}_4(\text{OH})_8 \cdot 16\text{H}_2\text{O}]^{8+}$, surrounded by a structured coordination shell of water, as expected at room temperature. With a change of solvent system to DMF : formic acid : water, we obtained a mixture of the tetramer and the single cluster (with a core of $[\text{Hf}_6(\mu^3\text{-O})_4(\mu^3\text{-OH})_4]$), with less structured solvent surrounding the clusters. This suggests that (alongside the DMF solvent) the acid is a critical species in causing the formation of the single cluster. However, in this room-temperature experiment, both the tetramer· H_2O and the single cluster coexisted in solution, even though both water and formic acid were in large excess (modulator : metal molar ratio of 183:1). This contrasts with the analysis in a previous XPDF investigation (of Zr species rather than Hf), which suggested that solutions of ZrCl_4 in either DMF/HCl (37 wt% in water) solvent (1:10.3:41.5 molar ratio metal : acid : water) or in DMF/ H_2O solvent without added acid (1:28.8 molar ratio metal : water) produced predominantly the single cluster.⁵⁶ Although the hydrolysis reactions necessary for cluster interconversion are known to be kinetically hindered,³⁹ that study employed neither heating nor ageing to overcome these kinetic limitations, so it is surprising that a mixture of single cluster and tetramer was not observed, especially given the lower concentrations of acid and water relative to metal in that study.⁵⁶

Our observation in this work of the importance of acid to the formation of the single cluster is corroborated by an EXAFS study,³⁰ which revealed that the addition of acetic acid to the tetramer in aqueous solution triggers a rearrangement via a (too short-lived to be identifiable) intermediate to form the single cluster. In the EXAFS study, a mixture of the two clusters (as we observed here) was only seen with modulator : metal ratios below 10:1, which is a far smaller ratio than in our work, despite acetic acid being less reactive than the formic acid modulator we use.³⁹ This difference is likely because the reaction solutions in the EXAFS study were aged for weeks prior

to measurement in order to obtain equilibrium, which will greatly affect the degree of cluster hydrolysis and conversion.

The role of water

This paper shows for the first time the formation of the Hf_{12} double cluster from the Hf_6 single cluster. This conversion could be achieved via the hydrolysis reactions common to these Hf and Zr species, via terminal hydroxide groups on the single clusters⁵⁴ joining clusters together to give the 12-mer, with its characteristic ‘belt’ of six μ^2 -OH groups.

The single cluster has the formula $[\text{Hf}_6\text{O}_4(\text{OH})_4]\text{L}_{24}$ and the double cluster $[\text{Hf}_{12}\text{O}_8(\text{OH})_8(\text{OH})_6]\text{L}_{36}$ (or the equivalent $[\text{Hf}_6\text{O}_4(\text{OH})_4]_2(\text{OH})_6\text{L}_{36}$), where, in our BDC-free solutions, each terminating singly-coordinating L group could either be half of one bidentate formate anion (as formate takes up two coordination sites), or the combination of one metal-bound OH and one metal-bound H_2O .⁵⁴ The cluster-joining reaction could therefore, for example, take the form of $2[\text{Hf}_6\text{O}_4(\text{OH})_4]\text{L}_{18}(\text{OH})_3(\text{H}_2\text{O})_3 \rightarrow [\text{Hf}_{12}\text{O}_8(\text{OH})_8(\text{OH})_6]\text{L}_{36} + 6\text{H}_2\text{O}$, i.e. three metal-coordinated terminating OH groups on each single cluster could form the ‘belt’ of six μ^2 -OH, releasing six metal-coordinated water molecules. The joining of clusters alone would give an entropy penalty when considering ΔG for the reaction – this release of water molecules could alleviate the entropy penalty or even make the cluster-joining entropically favourable. While this release of water may seem counterintuitive to our previous observation that water in the synthesis is required for the formation of **hcp** UiO frameworks,^{16,54} we note that this cluster joining reaction requires at least 3 L = (OH) and 3 L = (H_2O) groups on each single cluster (that is, a maximum of 18/24 L sites being coordinated by carboxylate groups); potentially, with less water in the synthesis, insufficient water is present, either in solution or as terminating groups on the clusters, to permit this cluster-joining.

These two observations in this work, of the formation conditions of the single cluster and of the double cluster, therefore help to explain why both water and formic acid are necessary in forming **hcp** UiO frameworks: formic acid is crucial for the formation of the single clusters, while water is also necessary in order for these single clusters to join to form the double clusters of the **hcp** framework.

The role of temperature

This paper also shows that the double cluster requires elevated temperatures to form. Compared with studies which did not show any interconversion between pre-synthesised single and double molecular clusters at room temperature,⁶⁰ our observation demonstrates that double clusters can form from single clusters, but that that elevated temperatures are necessary. This is in keeping with our earlier work showing that the **hcp** UiO-67(Hf) framework, containing the double cluster, requires a higher temperature to form compared to the **fcu** framework.¹⁶

In this work, we chose to examine the behaviour of our reaction mixtures at two elevated temperatures: 150°C and 120°C. By carrying out the reactions at a lower temperature, any kinetically limited processes – such as hydrolysis reactions³⁹ – should be slowed down. In both reactions carried out at 120°C, growth of all peaks, especially the intra-cluster peaks, was significantly slower than at 150°C (the 3.5, 4.9 and 9.2 Å peaks reached their maximum at 22.4, 29.5 and 26.3 minutes respectively for the no-BDC reaction at 120°C, compared to 10.1, 9.3 and 11.3 minutes for the no-BDC reaction at 150°C [Table S1]), suggesting that these cluster reactions (including the formation of the double cluster from single clusters) are indeed kinetically limited. Despite the slower transformation at lower temperatures, we observed no additional cluster species. The formation of the 9- or 11-mer would require additional μ^3 -bridging O and OH, which are disfavoured at lower temperatures³⁴ particularly once a cluster is saturated with terminating coordinating groups,⁷¹ whereas the μ^2 -OH bridging in the Hf₁₂ cluster could occur via a much more

straightforward nucleophilic attack of OH^{37} from one cluster to another. Thus at both 150°C and 120°C, the double cluster is obtained preferentially to other high-nuclearity clusters.

Elevated temperatures also thermodynamically favour processes which result in an increase in entropy. From our discussion of the role of water, the formation of the double cluster is one such process, due to the increase in entropy from the release of structured water upon cluster joining. As well as the metal-coordinated water released as single clusters join to form double clusters, there is also strong evidence for coordination shells of water – including hydrogen-bonded water – around clusters,^{54,82} some which would also be released upon cluster joining. This indicates that higher temperatures favour the formation of the double cluster for thermodynamic, as well as kinetic, reasons.

Framework growth and temperature

Perhaps surprisingly, in this work we observed that reactions at both 120 and 150°C produced the **hcp** UiO-66(Hf) framework. This contrasts with our previous work, in which we observed that **hcp** UiO-67(Hf) required a temperature of 150°C to form (and not 120°C),¹⁶ and also with literature, in which **fcu** UiO-67(Hf) is usually synthesised at lower temperatures including 120°C.^{83–85} As we have shown that, at both temperatures, the double cluster forms, the clue to this behaviour could lie in the framework formation. At both of these temperatures, the growth rates of the intra-cluster peaks do not appear to change with the presence of BDC linker in the reaction. While there is a different concentration of Hf in the linker-containing reaction mixtures, vs the molecular-cluster-only reactions, meaning they cannot be directly compared, this nevertheless suggests that the linkers do not play a critical part in initial cluster formation and become involved later in the reaction through post-cluster-formation ligand exchange (in agreement with previous research on ligand exchange^{60,86,87}).

As a result of the different binding strengths of different carboxylic acids,^{13,34} the low solubility of BDC in DMF/formic acid solutions,¹⁶ and the ratio of formic acid to BDC in these reactions being in excess of 40:1, it is not surprising that the BDC linkers may be outcompeted initially by formate (or hydroxide), and so coordinate to clusters later in the reaction. As hydroxide groups are more strongly coordinated than carboxylate groups,^{6,37} the joining of the single clusters to form the double cluster could therefore occur before the terminating ligands can exchange (in the linker-containing reactions) for dicarboxylate linkers (which would either “trap” the single cluster species or slow down the cluster conversion). Alongside our discovery that the growth of the crystalline framework occurs simultaneously with, rather than after, the linking of clusters together, this further suggests that once the clusters link up into a framework, the dicarboxylate linkers are less labile, and that dissociation (required for rearrangement) is kinetically and entropically less favourable. This would therefore mean that, despite the lower temperature used here, the successful formation and linking-up of the double cluster determines the formation of the **hcp** framework over the **fcu**.

The two-stage framework growth of **hcp** UiO-66(Hf) at 120°C described in this work may, however, shed light on our previous discovery that an *ex situ* reaction with a UiO-67(Hf) reaction mixture at 120°C resulted in a poorly crystalline material,¹⁶ rather than either the **fcu** or the **hcp** framework. If that previous *ex situ* UiO-67(Hf) reaction mixture follows a similar framework growth pattern to the two-stage pattern shown in this work, then the first stage of framework growth could occur before the cluster aggregation from single to double clusters is complete. This could involve the cluster coordination sites being ‘blocked’ against further attack by exchange of dicarboxylic acid linkers with the cluster-terminating ligands,⁴⁴ resulting in a mixture of coordinated single and double clusters, with different and less compatible coordination geometries.

This further suggests that, by adjusting the temperature of the reaction to take advantage of the different rates of cluster condensation and of framework growth, it may be possible to allow more time for the clusters to join together prior to coordination by inter-cluster linkers, and so obtain “multi-cluster” species intermediate between the double cluster and previously-observed infinite 1-D chains, all based on the M_6 single cluster unit.⁸

Alongside the previous studies, our work with formic acid corroborates that cluster formation in these UiO systems is determined by a complex interplay of temperature, ageing, concentration of metal salt and the type, concentration and pH of acid (which can act as a modulator and as directing groups^{43,71,75}). The complex processes discussed in this work motivate further exploration to enable understanding in greater detail, and hence improved exploitation. With careful control over the timing of linker addition, and consideration of the coordination-site-preferential exchange between linkers and terminating ligands known to occur with molecular double clusters⁶⁰ (particularly involving the ligands at the “narrow” ends of the cluster),¹⁶ this enhanced understanding of cluster formation in UiO systems could lead to intentional control of the framework growth, potentially providing routes to ordered mixed-linker frameworks, double-cluster-containing nanosheets such as those we previously reported,^{16,54} or as-yet-unknown “multi-cluster” MOFs.

Conclusions

In this work, we have demonstrated that XPDF data can successfully capture the pre-crystalline stages of Hf MOF formation during *in situ* solvothermal reactions, including distinguishing between different metal clusters in solution. We have used this technique to explore the response of $HfCl_4$ to different reaction temperatures and solvents, in particular those used to synthesise the **hcp** UiO-66(Hf) MOF, using a combination of refinement and peak area calculations to track subtle changes in the XPDF between different systems and over the course of *in situ* reactions. In

water the dominant cluster form is the tetramer, but in a mixture of DMF, formic acid and water, it quickly begins to convert to the hexanuclear single cluster form even at room temperature; the formic acid is likely to act as a directing group, but we were not able to identify any intermediates in the transition from tetramer to single cluster. Heating this reaction mixture results in an initial decrease in the proportion of tetramer, followed by the growth of the double cluster alongside a reduction in the amount of single clusters. This provides strong support for a mechanism for double cluster formation directly from pairs of single clusters with μ^2 -OH bridges created between them, rather than forming directly from the tetramer or requiring the single clusters to break down and reform larger clusters. No double clusters were observed at room temperature, suggesting that aggregation to form higher-nuclearity clusters is favoured by higher temperatures and the rate of double cluster formation increases with temperature. Once the double clusters form, they then undergo ligand exchange to link together in a framework, with BDC in place of terminating ligands; this framework appears to form directly as a crystalline MOF, with no evidence of a transformation from amorphous to crystalline. Via this analysis we propose a mechanism for the formation of **hcp** UiO-66(Hf) [outlined in Figure 6].

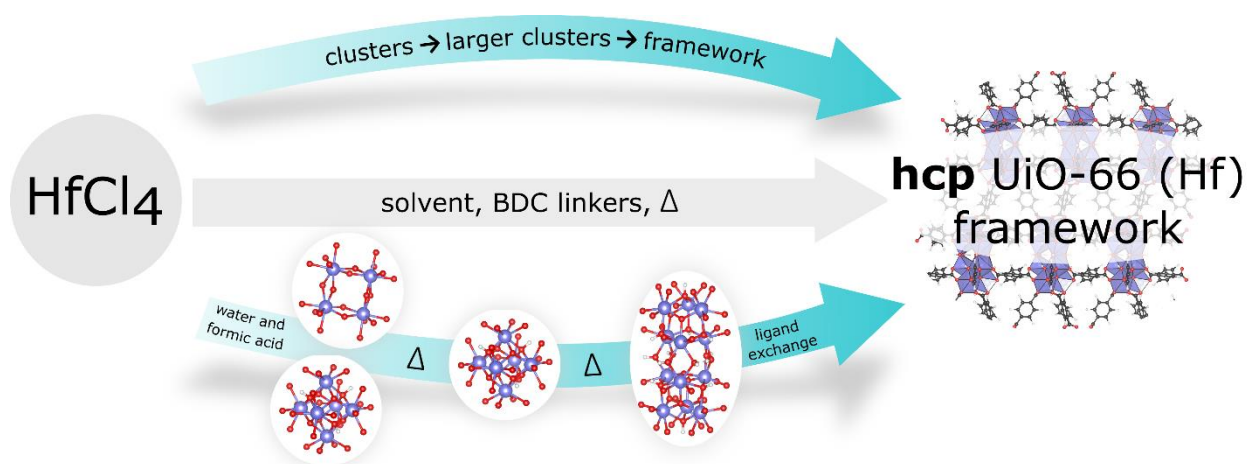


Figure 6 Summary of stages in the formation of **hcp** UiO-66(Hf) in solvothermal conditions

The insights we have presented here into the behaviour of Hf (and Zr) MOFs during their synthesis advance our understanding of the formation of these important materials. The UiO family of MOFs are particularly promising candidates for real-world applications, for example in energy storage devices,⁵² but in order to further unlock their potential, they must be able to be deliberately engineered with application-specific properties. The identity and nature of the metal clusters in the framework greatly influence these properties, and so understanding the mechanisms of their formation is key to designing and engineering new frameworks. This will open up possibilities for the synthesis of as-yet unrealised Zr and Hf MOFs with different cluster species and linkers or even mixed-cluster MOFs.

Associated Content

Supporting Information: Schematic of experimental setup, additional simulations and refinements and *in situ* $F(Q)$ data.

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Conflicts of Interest

There are no conflicts to declare.

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