Experimental Evidence for a General Model of Modulated MOF Nanoparticle Growth

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Abstract: Nanoparticles of metal-organic frameworks (nanoMOFs) boast superior properties compared to their bulk analogs, yet little is known about how common synthetic parameters dictate particle sizes. Here, we provide experimental evidence for the “seesaw” model of nanoMOF growth. Solution acidity, ligand excess, and reactant concentrations are decoupled and shown to form the key independent determinants of nanoMOF sizes, thereby validating the proposal that nanoMOFs arise from coupled equilibria involving ligand deprotonation and metal-ligand complexation. By achieving the first demonstration of a seesaw relationship between nanoMOF sizes and ligand excess, these results provide further proof of the model, as they required deliberate manipulation of relationships outlined by the model. Exploring the relative impacts of these parameters reveals that ligand excess has the greatest ability to decrease sizes, although low acidity and high concentrations can exhibit similar effects. As a complement to existing models of polymer formation and crystal growth, the seesaw model therefore offers a powerful tool for reliable control over nanoMOF sizes.

Keywords: Metal-organic frameworks, nanoparticles, crystal growth

Introduction

Precise size control can yield distinct functional behavior from materials with seemingly similar compositions. Achieving control at the nanoscale, in particular, has uncovered remarkable size-dependent properties, such as the luminescence of quantum dots and the distinct catalytic activities of metal nanoparticles.¹ ² Recent reports suggest that the rich structural and compositional diversity of bulk metal-organic frameworks (MOFs) produces enhanced functional properties when realized on the nanoscale.³ For example, advanced MOF-based gas separation technologies use nanoparticulate MOFs (nanoMOFs) dispersed into mixed matrix membranes (MMMs) to achieve enhanced efficiencies over bulk phases. Remarkably, MMMs that employ
nanoMOFs have been shown to surpass the Robeson limit—an intrinsic trade-off between selectivity and permeability in separation membranes. While the gas separation performance of nanoMOFs has attracted industrial interest, their improved activities as atomically defined catalysts and drug delivery agents has opened emerging areas of research. Despite advances in nanoMOF applications, accurate models are still needed to probe fundamental mechanistic details and reliably control particle sizes.

Scheme 1

Several models exist to describe nanocrystal nucleation and growth, including the classic La Mer model, the Watzky-Finke model, and various statistical models, yet recent evidence challenges their applicability to MOF growth. Whereas the LaMer model describes distinct stages of burst nucleation induced by supersaturated monomer concentrations, followed by diffusion-limited particle growth, nanoMOFs form at dilute concentrations, and in-situ studies reveal continuous nucleation and growth of MOF particles. Models based on monomer addition also do not apply to MOFs, as mechanistic studies suggest MOF formation involves transiently metastable “primary” phases, aggregative growth, and other non-classical events. Although these existing models can be modified to account for non-classical events, nanoMOF research requires a general model based on the acid-base and coordination chemistry of MOFs to reliably predict and control particle sizes.
Previously, we proposed a novel “seesaw” model of nanoMOF growth based on a metadata analysis of existing literature. This model specifically explained why the use of modulators—typically monotopic analogs of MOF linkers—causes particle sizes to increase in certain cases, but decrease in others. These trends could be explained by modulators functioning as capping ligands at low concentrations and as acids at high concentrations (Scheme 1). More broadly, we proposed that MOF nanoparticles result from excess ligand depleting local concentrations of metal ions and kinetically trapping particle growth. Additionally, the model proposes that this trapping processes depends on the competition between coupled equilibria associated with ligand deprotonation and metal-ligand complexation. A seesaw-shaped relationship between nanoMOF sizes and modulator equivalents was therefore posited to exist as consequence of the dual ligand-acid role of modulators (Scheme 1). Herein, we provide experimental evidence for the seesaw model by demonstrating that solution acidity, ligand excess, and concentration form independent parameters that can be used to achieve the first demonstration of a seesaw relationship and reproducibly control nanoparticle sizes of two iconic MOF materials, Zn(mIm)$_2$ (ZIF-8) and Cu$_2$BTC$_3$ (HKUST-1). Prior this report, the seesaw trend was never directly probed, but a seesaw relationship was observed in a previous study on MIL-125 modulated with p-toluic acid, and in UiO-66 modulated with either benzoic acid or p-toluic acid. With the results presented here, the seesaw trend appears in at least four compositionally distinct MOF systems, suggesting that the mechanistic model outlined here is universal to all modulated MOF syntheses.

**Scheme 2**

\[
\begin{align*}
L + H & \rightleftharpoons L^- + H^+ & \text{Eq. 1} \\
\text{Mod} + H & \rightleftharpoons \text{Mod}^- + H^+ & \text{Eq. 2} \\
L + M & \rightleftharpoons L^- + M^+ & \text{Eq. 3} \\
M + \text{Mod} & \rightleftharpoons M + \text{Mod}^- & \text{Eq. 4}
\end{align*}
\]
Results and Analysis

Scheme 2 outlines the four key equilibria expressions that form the basis of the seesaw model: linker deprotonation (Eq. 1), modulator deprotonation (Eq. 2), metal-linker complexation (Eq. 3), and metal-modulator complexation (Eq. 4). According to our model, the competition of these coupled reactions creates conditions that either produce bulk or nanocrystalline MOFs. For example, if these coupled equilibria maintain stoichiometric ratios of metal ions and linkers, then the reaction proceeds to form bulk MOF crystals. If, on the other hand, the coupled equilibria cause depletion of local metal ion concentrations, then excess ligand overwhelms particle surfaces, trapping MOFs as nanoparticles. Coupled equilibria can be studied by several mathematical formalisms. Herein, we simplify the system of equations using assumptions similar to the well-known Initial-Change-Equilibrium (ICE) table method (Table S19).

The ICE table approach overs a method for predicting relative amounts of product components, such as metal-linker versus metal-modulator species, given the initial reaction conditions. We propose that changes to initial concentrations of the protonated linker \([\text{LH}]\), protonated modulator \([\text{ModH}]\), deprotonated modulator \([\text{Mod}^-]\), and metal ion species \([\text{M}^+]\), respectively, can be determined by assuming that changes to concentrations relating to metal-ligand complexation (Eq. 3 and Eq. 4) do not impact the concentrations of the protonated linkers or modulators. This assumption rests on the fact that stability constants of metal-carboxylates are typically three to four orders of magnitude smaller than the \(K_a\) values for carboxylic acids employed in MOF syntheses. For simplicity, we treat ligands as monoprotic acids and consider only individual metal-ligand bonds rather than the entire coordination sphere. We propose that this analysis can be used to predict whether synthetic conditions produce nanoMOFs by 1) knowing equilibrium constants for the metal ions and carboxylic acids, 2) knowing the initial reactant
concentrations, and 3) by assuming that nanoparticles arise from reaction conditions that develop excess concentrations of deprotonated linkers \([L^-]\) relative to the concentration of uncoordinated metal ions \([M^+]\). In other words, reactant concentrations and equilibrium constants could be chosen such that \([L^-] + [\text{Mod}^-] > [M^+]\) in the distribution of chemical species at equilibrium.

![Graph showing nanoparticle sizes as a function of excess modulator equivalents.](image)

**Figure 1: ZIF-8 nanoparticle sizes as a function of excess modulator equivalents.** a) Particle sizes versus excess linker equivalents of 2-methylimidazole (Hmim). Above 18-20 equivalents, formation of ZIF-8 was not observed. b) Particle sizes resulting from increasing HCl equivalents with respect to zinc nitrate. Blue circles denote samples synthesized with 14 equivalents of Hmim compared to zinc nitrate. Details of the synthetic conditions can be found in S1 and Tables S16-S18.

Powerful predictions can be made about the outcome of MOF syntheses by using the ICE table analysis. Because proton concentration and excess capping ligands form the key independent determinants of nanoMOF sizes in the seesaw model, we considered several limiting scenarios that explore the impact of linkers and modulators when functioning as acids or as capping agents (additional details in SI section S2). The results of these scenarios suggest that nanoparticles should always result from cases that employ excess linker and no modulator, and cases that use deprotonated modulators only as Brønsted bases or capping ligands. When modulators function solely as acids, they decrease the availability of \(L^-\), which may inhibit kinetic trapping of nanoMOFs. The outcome depends on the particular equilibrium constants and initial reactant concentrations, however. The most complex scenario, which also appears most frequently in the
literature, involves modulators functioning as both acids and capping ligands. Nevertheless, nanoMOF sizes should be tunable through careful manipulation of acid and ligand binding strengths if indeed nanoMOF growth depends on these two independent parameters.

With these predictions in hand, we sought experimental evidence for the seesaw model and the independent tunability of nanoMOF sizes through acid and ligand addition. Figure 1a plots nanoparticle sizes of ZIF-8 (Zn(mIm)₂, mIm = 2-methylimidazolate) as a function of added HmIm ranging from 4 to 14 equivalents per Zn²⁺, where conditions above 2 equivalents represent linker in excess. According to the ICE table analysis (Case 1, SI), addition of only HmIm without modulator should causes depletion of [M⁺], resulting in kinetic trapping of smaller nanoMOF sizes. Indeed, up to a reactant stoichiometry of 16-18 Hmim equivalents per metal, ZIF-8 particle sizes continue to decrease. Above this linker excess, product is simply not observed. These results resemble a previous report by Cravillon et al. that showed excess linker up to eight linker equivalents leads to progressively smaller ZIF-8 nanoparticles, but the data presented here show that ZIF-8 sizes decrease even further. We note that particle sizes isolated here are much larger than those reported by Cravillon et al., which we attribute to the lack of control over local concentrations of reactants when added together, which we expect has a large impact on kinetic trapping of particles.

Figure 1B plots the size dependence of ZIF-8 particles versus number of HCl equivalents with respect to Zn²⁺ at a fixed linker excess of 14 equivalents. As a non-coordinating species, HCl acts only a strong acid. Therefore, HCl addition allowed us to test the hypothesis that nanoMOF sizes increase with higher proportions of protonated linkers incapable of trapping nanoparticles, as detailed in Case 2 of the Supporting Information. Indeed, the data show ZIF-8 nanoparticle sizes predictably increase with additions up to 0.7 HCl equivalents per Zn²⁺ ion. (Fig. 1B). These results
demonstrate that protons and capping ligands form independent parameters that control nanoMOF sizes.

As sources of both protons and ligands, modulators complicate synthetic control of nanoMOFs. The dual role of modulators acting as sources of protons and ligands can nevertheless be separated and demonstrated to control the equilibria that govern particle sizes. Previously, we proposed that the dual role of modulators could give rise to a seesaw relationship between particle sizes and modulator equivalents where sizes decrease with increasing equivalents and then increase as proton activities become sufficiently high to inhibit linker deprotonation. For proof of the seesaw relationship, we targeted the iconic MOF Cu$_3$BTC$_2$ (BTC = 1,3,5-benzenetricarboxylate) because many modulated nanoMOF reports have focused on this material. These reports have shown that increasing equivalents of carboxylic acid modulators increases particle sizes, whereas Cu$_3$BTC$_2$ sizes decrease with increased amounts of deprotonated carboxylate modulators.$^{23,24,25,26}$ Hypothesizing that these trends reflect the dual role of modulators acting as acids versus ligands, we investigated the impact of adding benzoate versus benzoic acid to the synthesis of Cu$_3$BTC$_2$. Although literature reports often use SEM or light scattering methods to determine sizes of MOF nanoparticles, sizes in this study are reported from Scherrer analysis because SEM images of Cu$_3$BTC$_2$ products in alkaline conditions (Figure S6) revealed severe aggregation of particles, which is also prevalent in literature reports.$^{23,27,28}$ The few discernable particles were smaller than the Scherrer sizes, but they did not give an accurate and statistically significant representation of the nanoMOF batch. Therefore, all particle sizes reported here are derived using the Scherrer equation. Interestingly, MOF product could not be isolated from the synthesis with benzoic acid by mixing the reagents at room temperature, whereas particle sizes strictly decreased by adding additional equivalents of sodium benzoate (Fig. S2). Increasing
sodium benzoate also leads to extra peaks in the PXRD patterns, likely arising from fast reaction kinetics causing benzoate ligands to trap within the MOF structure. These results validate the prediction from the ICE table analysis that deprotonated modulators acting as either ligands or bases lead to MOF nanoparticles, also consistent with previous studies.24

Figure 2: Dependence of Cu₃BTC₂ particle sizes on modulator equivalents and benzoic acid content. A) Dependence of size on modulator equivalents with varying benzoic acid content. Syntheses were performed with a linker:metal:modulator ratio of 3:1:21, where modulator corresponds to the sum of benzoic acid and sodium benzoate. The metal concentration was held constant (1 mM). The dotted line at 7 equivalents shows the data used again in panel B. Details of the synthetic conditions can be found in section S1.3 and tables S5-S7. B) Cu₃BTC₂ particle sizes versus benzoic acid content of modulator mixtures at constant modulator equivalents. Two trials at low concentration were completed, and we present the data as the average of the two. Reactant concentrations are defined with respect to the linker (L). Details of the synthetic conditions can be found in section S1.3 and Tables S1-S3.

To observe a seesaw dependence between Cu₃BTC₂ sizes and modulator equivalents, we employed a buffer mixture of benzoate and benzoic acid to balance the opposing trends observed when adding only acid or ligand. Hypothesizing that particle stability depends on achieving ligand-rich surfaces, we employed excess linker stoichiometries. Figure 2A plots Cu₃BTC₂ nanoparticle sizes versus equivalents of modulator mixtures with benzoic acid (BA) contents of 33%, 50%, or 66%. Indeed, seesaw curves appear in all three cases with similar qualitative features: a steep decrease from 1 to ~10 equivalents, a flat region, and a gradual increase in sizes from 20 to 40 equivalents. Additionally, the most acidic modulator mixture produced sizes that were overall largest, whereas the least acidic mixture gave the smallest sizes. Interestingly, the
least acidic modulator mixture (33% BA) results in the steepest downward slope, which, according to the seesaw model, reflects more favorable linker deprotonation or metal ion complexation. Rather than exhibit minimum sizes around a narrow range of modulator equivalents, all data sets show a broad flat region that we attribute to the modulator mixture functioning as a buffer: the benzoic acid-benzoate pair accepts protons from the excess linkers so that sizes increase only when the proton activity exceeds the buffer capacity of the modulator mixture. Although modulators have induced changes to MOF structures and introduced defects, PXRD patterns exhibit peaks associated only with the Cu$_3$BTC$_2$ phase (Fig. S3), and particle morphologies show either a typical octahedral geometry or aggregated spherical shapes (Fig. S7). These results therefore validate the seesaw model we had previously proposed: by using conjugate acid/base mixtures, nanoMOF sizes decrease with additional capping ligand until proton activities inhibit ligand from trapping metal ions, allowing for bulk MOF growth.

To further decouple the independent roles of acidity and ligand complexation, we explored the size dependence of Cu$_3$BTC$_2$ nanoparticles as a function of benzoic acid content in the modulator mixture at fixed modulator equivalents. Figure 2B plots Cu$_3$BTC$_2$ particle sizes versus benzoic acid content of modulator mixtures for three different reactant concentrations. According to the seesaw model, larger particle sizes should result from increased proton activities. Indeed, without adding additional modulator equivalents, particle sizes increase in reactions where BA contents exceed 50%. Interestingly, higher reactant concentrations lead overall to smaller sizes except at BA contents near 100%, where sizes converge to ~1 micron. Within the context of the seesaw model, the decreased sizes with higher reactant concentrations result from efficient metal ion depletion and kinetic trapping of particles, likely due to the excess linker employed in these reactions. The experiments in Figures 2A and 2B, hence, explore a cross section of the same multi-
dimensional reaction space. Therefore, datasets that intersect in this reaction space could be analyzed for reproducibility. Figure 2B includes three data points from Figure 2A for comparison against the 3-mM dataset, which employs the same reaction conditions, showing excellent reproducibility. We attribute the slight increase in particle sizes at low BA contents and low concentration to the benzoate out-competing the MOF linker. Increasing the BA could decrease particle sizes by keeping benzoate partially protonated. Although previous reports have used modulators in combination with manipulation of pH,\textsuperscript{24,30} this report is the first to systematically manipulate particle sizes with a buffer.

![Figure 3](image_url)

**Figure 3: Cu\textsubscript{3}BTC\textsubscript{2} particle sizes resulting from variable reactant concentrations and total modulator equivalents.** Panels a, b, and c show dependence of particle sizes on concentration at three different modulator:linker ratios. Syntheses were performed with a linker:metal:modulator ratio of 3:1:21, with a 50\% benzoic acid modulator mixture. Synthetic conditions can be found in Tables S12-S14.

Concentration acts as a third key determinant of nanoMOF sizes because it controls the impact of the other two parameters, acidity and ligand excess. Building on the concentration dependence exhibited in Figure 2B for modulator acidity, we explored the impact of concentration in relation to modulator equivalents. Figure 3 plots the concentration dependence of Cu\textsubscript{3}BTC\textsubscript{2} sizes using a 50\% benzoic acid modulator mixture at three different equivalents of modulator. At both 0.7 and 7 equivalents of modulator, sizes decrease with increasing concentration. The effect
of concentration on size is most pronounced at 7 modulator equivalents, spanning the size range of 200-800 nm, with the largest difference occurring between linker concentration of 3 and 5 mM (Fig. 3B), and little if any difference at 13.14 modulator equivalents (Fig. 3C).

Discussion

These results demonstrate that MOF nanoparticle sizes can be tuned through independent control over solution acidity, ligand excess, and concentration, although certain parameters have greater impacts than others. For example, the data in Figure 3 show that while increased concentrations cause Cu$_3$BTC$_2$ particle sizes to decrease over a range of linker concentrations from 5 to 20 mM, increasing the modular equivalents produces a greater overall decrease in particle sizes. In terms of the seesaw model, these results suggest that equilibria shift less in response to concentration changes compared to changes in stoichiometry. Furthermore, equilibria become so shifted by excess modulator that they become nearly insensitive to concentration changes, as indicated by Figure 3C. On the other hand, Figure 2B shows that changes to BA content have minor impact on particle sizes in comparison to the effect of reagent concentration, until BA contents exceed 50%, which we propose corresponds to a critical decrease in the buffer capacity of the modulator mixture. Once the buffer mixture no longer absorbs excess protons, we expect that the conditions favor exchange of surface capping ligands for linkers that allow continued bulk growth, as has been observed in post-synthetic MOF linker exchange$^{31}$ and in reports on metal-linker stability in ZIF-8.$^{32}$ These results, taken to the extreme limit, explain why additional acid aids in the synthesis of large single crystals.$^{33}$ Interestingly, data in Figure 2A indicate that modulator excess and BA content can produce similar absolute changes to particle sizes. For example, varying modulator equivalents between 0 and 40 for a modulator mixture with 66% BA causes sizes to differ by ~800 nm, whereas varying BA contents between reactions at fixed
modulator equivalents also alters sizes by ~800 nm. The impact of changing any of these parameters appears strikingly nonlinear. Just as reducing BA content from 50% to 33% leads to small overall changes in sizes, doubling linker concentrations from 7.5 mM to 15 mM in Figure 2B has diminishing effects. Such nonlinearity complicates predictions about nanoparticle sizes, but its existence lends further proof for the seesaw model, which relies on nonlinear relationships between coupled equilibria.

Overall, these results suggest that ligand excess, of either linker or modulator, exerts the greatest impact on nanoMOF sizes in general. Whereas excess linker generates nanoparticles of ZIF-67, ZIF-7, and ZIF-71, cases for carboxylate MOFs are rare.\textsuperscript{34-36} While excess trimesic acid increases grain sizes of Cu\textsubscript{3}BTC\textsubscript{2} particles, in NU-1000, another carboxylate MOF, particle sizes decrease as excess linker is used.\textsuperscript{37,38} In the report of NU-1000 particles, a strong base is added as well, which likely counters any increase in [H\textsuperscript{+}]. We attribute this difference to the fact that ZIF linkers contain just single protic sites, whereas multi-topic carboxylates contain several, which, according to the seesaw model, increase solution acidity and hinder the ability of ligands to trap metal ions. Additionally, the greater strength of zinc-imidazolate bonds should facilitate rapid trapping by excess linker, whereas metal-carboxylate bonds are more dynamic and, hence, less effective at terminating particle growth. Therefore, the synthesis of carboxylate-based MOF nanoparticles depends strongly on modulator excess. Although solution acidity and reactant concentration influence the kinetic trapping of MOF nanoparticles, achieving small nanoMOF sizes ultimately relies on the presence of excess ligands.

According to the seesaw model, dilute local concentrations of metal ions overwhelmed by excess ligand leads to kinetic trapping of small particle sizes. This prediction helps explain previous reports that dilution yields smaller ZIF-8 nanoparticles,\textsuperscript{39} but at first seems in conflict
with the concentration studies presented here. Although Figures 2B and 3 both show Cu$_3$BTC$_2$ particle sizes decreasing with increased concentrations, this apparent discrepancy can be explained in terms of the specific chemistry of these two types of MOFs. Whereas ZIFs feature strong metal-linker bonds that rapidly form bulk crystals under concentrated conditions, carboxylate-based MOFs exhibit slower growth kinetics that tend to form large single crystals through slow and dynamic exchange of ligands.$^{40}$ Increasing the local concentration of linker therefore improves kinetic trapping of carboxylate MOF nanoparticles by shifting the weak metal-linker equilibrium towards complexation.

These results also highlight the complex role played by ligands in trapping metal ions as molecular complexes, preventing their incorporation into growing MOF particles. For example, Figure 1 shows that extreme excess of linker equivalents suppresses ZIF-8 formation. We propose that under these conditions, imidazolate molecules coordinatively saturate Zn$^{2+}$ ions and the metal-linker binding equilibrium shifts far toward complexation, inhibiting the dynamic ligand dissociation needed for monomer attachment and growth. Indeed, a previously reported in-situ study of ZIF-8 growth under excess linker conditions suggested particle growth proceeds by linker dissociation from zinc-imidazolate oligomers.$^{41}$ Similarly, excess benzoate appears to inhibit Cu$_3$BTC$_2$ formation by trapping Cu$^{2+}$ ions as benzoate complexes. This hypothesis could explain why particle sizes at first decrease with added BA content in Figure 2B at 3 mM linker concentration. By increasing the solution acidity, the modulator mixture becomes less competitive with trimesate for Cu$^{2+}$ ions and Cu$_3$BTC$_2$ forms more rapidly, whereas benzoate-only conditions make particle growth reliant on the slow release of Cu$^{2+}$ ions, leading to larger particles. Another explanation for the larger sizes under benzoate-rich conditions is the tendency of deprotonated modulators to induce aggregation.$^{23,27}$ In fact, previous reports have shown that pH adjustment can
manipulate the assembly and aggregation of MOF-525 particles\textsuperscript{42,43} and that strongly acidic modulators improve the colloidal stability of UiO-66.\textsuperscript{38}

More generally, the seesaw model serves as a complement to well-established models of bulk crystal growth and polymer formation. Whereas successful growth of ionic crystals and condensation polymers depends on maintaining stoichiometric mixtures of reactants, the seesaw model proposes that MOF nanoparticle sizes minimize from maximally imbalanced local concentrations of reactants. For many classes of polymers, molecular weights decrease considerably under conditions of imbalanced monomer stoichiometries, producing oligomers instead of long polymer chains. Interestingly, molecular weights can also be controlled by terminating chain growth with the addition of monofunctional monomers, akin to MOF modulators.\textsuperscript{44} For ionic solids, the rate of crystal growth maximizes when the relative ratios of monomers diffusing to crystal surfaces matches the stoichiometry of the bulk lattice.\textsuperscript{45} Models of ionic crystal growth state that rates of monomer attachment relates directly to $n_{\text{site}} \times t_m \times J$, where $n_{\text{site}}$ represents the density of available binding surface sites, $t_m$ is the lifetime of monomer units, and $J$ is the flux of the monomer to the growing crystal.\textsuperscript{45} In terms of the seesaw model, therefore, small nanoMOF sizes result from rapid depletion of metal ion concentrations and overwhelming particle surfaces with excess ligand. For MOFs, the relevant diffusing species may be metal ions, linkers, or even entire clusters, given in-situ studies that suggest Cu\textsubscript{2}BTC\textsubscript{3} grows by increments of individual Cu\textsubscript{2}BTC\textsubscript{4} paddlewheel units.\textsuperscript{46} Interestingly, typical representations of this model of ionic crystal growth plot growth rate versus solution stoichiometry, with maximum growth centered at balanced ratios in an “upside down seesaw” curve.\textsuperscript{47} Scheme 1, therefore, illustrates the complementary relationship of the seesaw model to common models of bulk crystal and polymer growth, where sizes minimize at maximally unbalanced stoichiometries, and vice versa.
Lastly, we propose that the steep downward slope observed in “region I” of the seesaw curve can be interpreted in terms of classical collision theory. In collision theory, the probability of no collision taking place between particles as a function of time, $P(t)$, equals $\exp(-t/\tau)$, where $\tau$ represents the average time between collisions.\(^{48}\) Similarly, we propose that the probability of MOF nanoparticles not being kinetically trapped by excess ligand decreases exponentially as more modulator enters the reaction mixture. In other words, the probability of particles colliding with capping ligand increases with higher available equivalents of excess ligand. This model helps explain why slopes in Figure 2A become shallower with higher acidic content—the probability of successful particle trapping diminishes as the modulator becomes more acidified. Therefore, we anticipate that temperature, concentration, and other factors expected to impact collision probability play decisive roles in the mechanism of MOF nanoparticle growth.

**Conclusion**

In conclusion, we offer experimental proof of the seesaw model of nanoMOF growth by demonstrating for the first time the existence of a seesaw relationship between nanoMOF sizes and modulator excess through deliberate manipulation of key parameters in the model. Specifically, we show that MOF nanoparticle sizes can be tuned through independent control over solution acidity, ligand excess, and reactant concentrations. Demonstrating that these three parameters control nanoMOF sizes supports the key claim of the model that nanoMOFs result from kinetic trapping of nanoparticles determined by competition between coupled equilibria involving metal-ligand complexation and ligand acid-based chemistry. The relative impact of these parameters on nanoparticle sizes was explored, with ligand excess showing the greatest overall impact. Sizes generally decease with lower acidity, greater ligand excess, and, for dynamic metal-linker bonds, higher concentrations. Importantly, particle sizes showed excellent reproducibility.
when approaching similar reaction conditions from different directions on the multi-dimensional reaction space defined by these three parameters. Although the seesaw model represents a novel perspective for understanding MOF growth in general, we show that it complements well-established models of bulk polymer and crystal growth. Taken together, these results demonstrate that the seesaw model offers a powerful tool for advancing the synthesis and basic understanding of this emerging class of materials.
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