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# Tandem synthesis of ε-caprolactam from cyclohexanone by an acidified metal-organic framework

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**Abstract:** Tandem synthesis of ε-caprolactam, one of the largest scaled commercial chemicals, is highly desired from the viewpoint of cost, energy, and environment. However, relevant studies have remained largely underexplored. Herein, by using a one-pot strategy, we encapsulated phosphotungstic acid (PTA) into a chromium terephthalate metal-organic framework (MOF), MIL-101, for the efficient tandem conversion of cyclohexanone to ε-caprolactam. The highly dispersed PTA in the MOF matrix showed a high yield of ε-caprolactam through a tandem oximation-Beckmann rearrangement reaction at 100 °C for 12 h. Moreover, MIL-101-PTA was recycled three times, with only a slight loss in their catalytic performance. This represents the first report using acidified MOF for a tandem oximation-Beckmann rearrangement reaction to the best of our knowledge.

## Introduction

ε-Caprolactam (CPL), the monomer of nylon-6, is one of the largest scaled commercial products. Based on recent research, the annual production of CPL increases at a rate of 3% each year since 2017 and is predicted to reach around 6.5 million tons by the end of 2023.[1] Among the developed methods for the synthesis of CPL, one traditional synthetic route is to start from phenol substrates through phenol hydrogenation to form cyclohexanone,[2] cyclohexanone-hydroxylamine condensation to produce the cyclohexanone oxime,[3] and Beckmann rearrangement to transform the oxime intermediate into the CPL.[4] Conventionally, the step of Beckmann rearrangement is carried out in fuming sulfuric acid (a.k.a., oleum) that serves as both catalyst and solvent.[5] However, oleum causes severe environmental and safety concerns. Moreover, a massive waste of ammonium sulfate is produced from the neutralization of oleum in the production of CPL. To circumvent these drawbacks, solid acids have emerged as alternative candidates to oleum, and a variety of heterogeneous catalysts have been developed to realize the liquid-phase Beckmann rearrangement at low temperatures, such as zeolites,[6] ionic liquid anchored on metal oxide,[7] acidified carbon,[8] etc. Among them, Polyoxometalates (POMs) have been proved as effective catalysts for the transformation of oxime to yield CPL.[9] However, the low surface area of POMs (1-10 $m^2/g$) severely restricted the activity, thus restraining their scale-up applications.

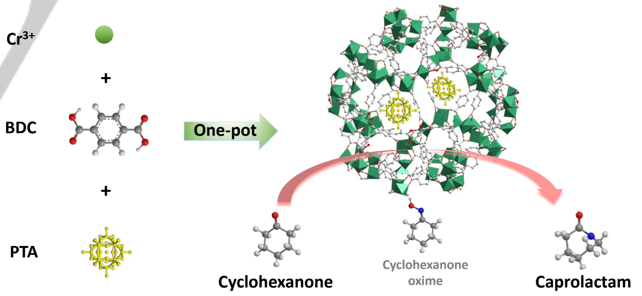

**Figure 1.** Synthetic scheme of MIL-101-PTA and one-pot tandem synthesis of CPL through a tandem oximation-Beckmann rearrangement reaction.

Metal-organic frameworks (MOFs), a class of crystalline porous materials constructed by assembling metal ions/clusters and organic ligands, have emerged as auspicious platforms for heterogeneous catalysis.[10] MOFs have high porosity and structural tunability that allows precise integration of various active sites in their pores, including solid acid,[11] metal complexes,[12] nanoparticles,[13] and others,[14] allowing for the flexible design of multifunctional catalysts for tandem catalysis. Inspired by this, we encapsulate phosphotungstic acid (PTA) in a robust and high-surface-area MOF matrix to afford an acidified MOF catalyst. In essence, the chromium terephthalate MOF, MIL-101 (MIL for Matérial Institut Lavoisier), is rationally selected to support PTA (termed MIL-101-PTA) for the following considerations (Figure 1): i) MIL-101 features high chemical and thermal stability, which is critical for heterogeneous catalysis; ii) the high surface areas and uniform mesopores of MIL-101 allows for the well-dispersive and homogenous distribution of PTA; iii) the nanoconfinement effects endowed by MIL-101 could lead to the synergistic interplay between PTA and surrounded frameworks, thus resulting in enhanced properties through cooperative catalysis.[15] With these in mind, we firstly apply MIL-101-PTA as acidic catalysts in a tandem oximation-Beckmann rearrangement reaction that directly transforms cyclohexanone to CPL in one pot (Figure 1). Remarkably, the acidified MOF displays a high yield of ε-caprolactam (89%) and could be recycled three times with only a slight loss in their catalytic performance. We further encapsulate Pd nanoparticles in the MIL-101-PTA. The resultant multifunctional catalyst shows a high yield of ε-caprolactam in sequential tandem catalysis that combines phenol hydrogenation, oximation, and Beckmann rearrangement, despite significant Pd leaching after the first run. The failure of recyclability of Pd loaded catalysts has been the biggest challenge in reported efforts to develop multifunctional catalysts for this transformation,[16] which will be the target for our future studies.

## Results and Discussion

PTA was immobilized into MIL-101 following a one-pot encapsulation method to yield the hybrid acidified MOFs, MIL-101-PTA.[17] The Powder X-ray diffraction (PXRD) patterns of MIL-101 and MIL-101-PTA match the simulated pattern,[18] indicating that the presence of PTA did not interfere with the formation of MIL-101 framework (Figure 2a). It is known that there are two types of cages in MIL-101, with the diameter of 29 and 34 Å. The window size of the smaller cage is 12 Å that is slightly smaller than the diameter of PTA molecule. Therefore, PTA leaching problem can be largely suppressed by the size restriction of the cage window. Another common problem encountered by the loading of PTA is that some carrier materials, such as $SiO_2$ and $Al_2O_3$, have strong interactions with PTA, which could lead to the loss of the acidity of PTA or even partially decomposition forming lacunary species.[19] To test the acidity of the PTA encapsulated in MIL-101, the amount of acidic proton was quantified by acid-base titration.[20] As shown in Table S1, the proton amount increases with the PTA loading and agrees with the corresponding theoretical value.

A comparison of the spectra obtained by diffuse reflectance infrared Fourier-transform spectroscopy (DRIFTS) of MIL-101 and MIL-101-PTA confirms the presence of PTA in MIL-101-PTA (Figure 2b). The three major characteristic absorption peaks of PTA at 1078, 978, and 886 cm$^{-1}$ are assignable to the vibrations of P–O, terminal W=O, and edge-sharing W–O–W, respectively (grey-shaded areas in Figure 2b).[11a] Moreover, these bands are absent in the spectra of the pristine MIL-101. It is evidenced that the band at 886 cm$^{-1}$ will disappear when lacunary structures are formed. Therefore, the presence of this band for MIL-101-PTA indicates that the kegging structure is preserved during the MOF synthesis and encapsulation process. It is noteworthy that there is a 10 cm$^{-1}$ blueshift for the characteristic band of edge-sharing W–O–W (886 cm$^{-1}$) and around 5 cm$^{-1}$ redshift for the band of terminal W=O vibration in PTA, represented by the blue and red arrows in Figure 2b, presumably due to the interaction between MOF and PTA.[21]

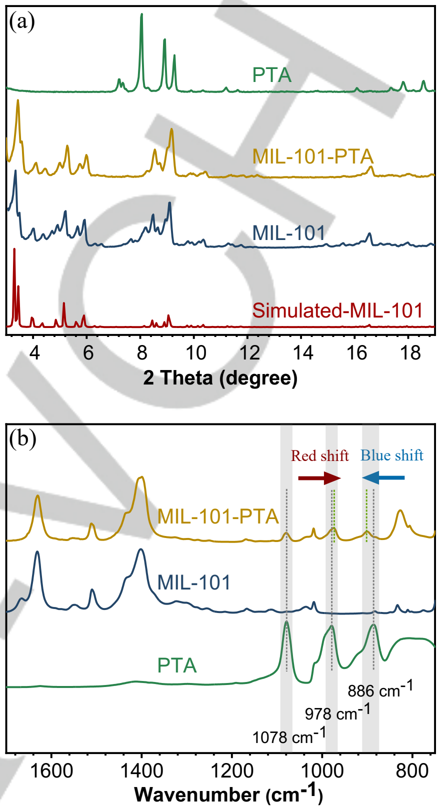

**Figure 2.** (a) PXRD patterns of PTA, MIL-101, MIL-101-PTA, and simulated MIL-101. (b) DRIFTS spectra of PTA, MIL-101, and MIL-101-PTA. The grey-shaded regions represent the characteristic vibrational bands of PTA. The red (blue) arrow indicates the red (blue) shift of the vibration band of PTA after the encapsulation in MIL-101.

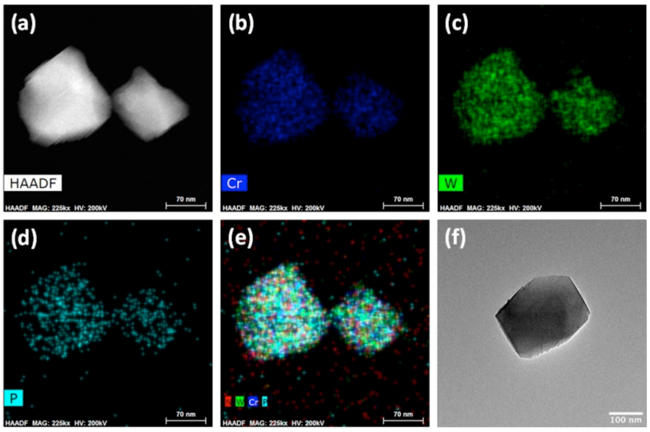

**Figure 3.** (a) HAADF-STEM image of MIL-101-PTA. EDS elemental mapping analysis of (b) Cr, (c) W, (d) P, and (e) the composite. (f) TEM image of MIL-101-PTA.

High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) and energy-dispersive X-ray spectroscopy (EDS) elemental mapping of MIL-101-PTA (Figure

3) show the well-mixed Chromium (Cr), Phosphorus (P), and Tungsten (W) signals in MIL-101-PTA, which unambiguously indicates the homogeneous and uniform distribution of PTA throughout the MIL-101 framework. The smooth and uniform surface of MIL-101-PTA (Figure 3a) also implies the well-dispersed PTA in the MOF since dark, and small dots are observed if PTA molecules aggregate on the surface of the MOF, especially when using wetness impregnation method to load PTA on MIL-101.[22] The loading of W from PTA is determined by inductively coupled plasma-mass spectroscopy (ICP–MS) at around 17% (Table S1). Nitrogen physisorption isotherms of MIL-101 and MIL-101-PTA also confirm the presence of PTA inside the pores (Figure 4). The Brunauer–Emmett–Teller (BET) surface area drops from 2840 to 1630 m$^3$/g, and the pore volume of MIL-101 also decreases from 1.38 to 0.90 cm$^3$/g after the encapsulation of PTA (Figure 4a, Figure 4b, and Table S2).

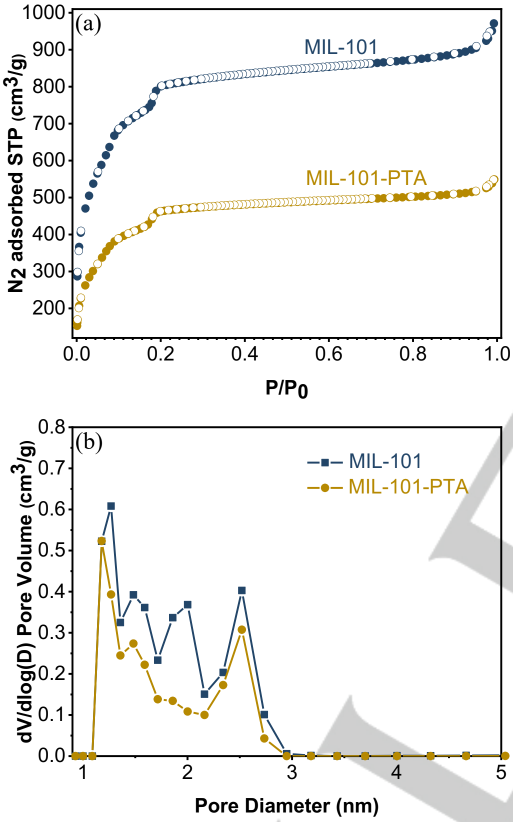

**Figure 4.** (a) Nitrogen sorption isotherms of MIL-101 and MIL-101-PTA. (b) Pore size distributions of MIL-101, MIL-101-PTA.

With the thorough characterizations of MIL-101-PTA in hand, we set to optimize conditions for the tandem synthesis of ε-caprolactam through an oximation-Beckmann rearrangement reaction (Table 1). We find that the dielectric constant or polarity of the solvents plays a critical role in catalysis activity. When dichloroethane (DCE) is solely used as the solvent (entry 1), no selectivity to the CPL is observed, and the products are mainly oxime (88%) and 2-chlorocyclohexanone. To increase the selectivity to CPL, various polar aprotic organic additives are added along with DCE. The addition of dimethylformamide (DMF), dimethylacetamide (DMAC), or dimethyl sulfoxide (DMSO) (entries 2-4) shows no improvement in CPL selectivity, probably due to the weak basicity of the solvent competing with the adsorption of reactant that poisons the active acid sites.[6c] Other solvents such as dioxane and nitrobenzene (entries 5, 6) do not improve the selectivity. To our delight, when acetonitrile (MeCN) is added to DCE in a 1:1 ratio, a high CPL yield (89%) and cyclohexanone conversion (94%) are observed (entry 7). By varying the ratio between MeCN and DCE, we find that a larger ratio of MeCN/DCE leads to a higher selectivity towards CPL (entries 7-9). Given that the proton transfer from nitrogen to oxygen during the process of forming O-protonated oxime is the rate-determining step, we speculate the MeCN is prone to stabilize the charged intermediate during the Beckmann arrangement to lower its' activation energy.[23] We also find that it is crucial to use an anhydrous solvent in the reaction. Adding 1% of water to the reaction solvent decreases the conversion to 84% and selectivity to 34% by facilitating the hydrolysis of cyclohexanone oxime to cyclohexanone. The conversion and selectivity decrease more when 10% of water is added to the reaction (entries 10, 11). The reaction temperature (Figure 5) is also investigated to show the highest cyclohexanone conversion of 94% with a CPL yield of 89% at 100 °C. In a nutshell, the optimal reaction condition (entry 7, Table 1) for the tandem synthesis of CPL catalyzed by MIL-101-PTA is 100 °C in a binary mixture of DCE/MeCN (1:1) as solvent.

**Table 1.** Optimal reaction conditions screening in the oximation-Beckmann rearrangement. [a]

| Entry | Additive | Add./DCE | Conv. (%) | Yield. (%) | |
|---|---|---|---|---|---|
| | | | | Oxime | CPL |
| 1 | - | - | 99 | 88 | 2 |
| 2 | DMSO | 1:1 | 77 | 65 | 0 |
| 3 | DMAC | 1:1 | 87 | 82 | 0 |
| 4 | DMF | 1:1 | 96 | 77 | 0 |
| 5 | Dioxane | 1:1 | 99 | 77 | 2 |
| 6 | Nitrobenzene | 1:1 | 69 | 55 | 0 |
| 7 | MeCN | 1:1 | 94 | 3 | 89 |
| 8 | MeCN | 3:7 | 96 | 10 | 79 |
| 9 | MeCN | 1:9 | 95 | 42 | 41 |
| 10 | MeCN, 1%water | 1:1 | 84 | 45 | 29 |
| 11 | MeCN, 10%water | 1:1 | 44 | 26 | 4 |
| 12[b] | MeCN | 1:1 | 63 | 11 | 42 |
| 13[c] | MeCN | 1:1 | 75 | 8 | 64 |

[a] Reaction condition: MIL-101-PTA (20 mg, 7 nmol PTA), cyclohexanone (0.25 mmol), hydroxylamine hydrochloride (0.375 mmol), internal standard (n-decane, 20 μL), solvent (1 mL, DCE and additive), 100 °C, 12 h stirring at 600 rpm. [b] No catalyst was added. [c] MIL-101 was used as the catalyst.

Considering the oximation-Beckmann rearrangement is catalyzed solely by the acid sites, PTA plays a significant role in ensuring the tandem transformation of cyclohexanone to CPL. As expected, MIL-101-PTA shows a higher yield (89%, entry 7) of

CPL compared to that catalyzed by MIL-101 (65%, entry 13). The Brønsted acid sites of PTA boost the catalyst activity in Beckmann rearrangement since the protonation of the nitrogen in the oxime group is proved as the initial step. However, the hydroxylamine hydrochloric acid ($NH_2OH·HCl$) also possesses acid sites. Therefore, we perform a blank experiment in which the MIL-101 or MIL-101-PTA is not added (entry 12). Interestingly, a 42% yield (entry 12) of CPL is achieved without any catalyst, suggesting that the hydrochloric acid in $NH_2OH•HCl$ also serves as a catalyst (Figure S1).[24] Compared with the blank experiment, reaction catalyzed by MIL-101 exhibited an increased yield of CPL. Previous study demonstrates that Lewis acid can also catalyze Beckmann rearrangement.[25] The increased production of CPL by MIL-101 was likely attributed to the Lewis acidic Cr sites. By changing the loading of PTA in the MOF, we synthesized MIL-101-0.5PTA and MIL-101-2PTA and tested their catalytic properties (Figure S2). Overall, we observed an increased yield of CPL as we increased the loading of PTA in the catalyst from MIL-101 to MIL-101-PTA, and the yield of CPL stopped growing for MIL-101-2PTA, probably due to the high yield of CPL. To differentiate the performance of these two catalysts, we ran the reaction at 80 °C. MIL-101-2PTA exhibits a higher yield of CPL (20%) than MIL-101-PTA (12%). We also test the oximation solely with our catalyst and compare the result with reaction catalyzed with MIL-101 and no catalyst (Figure S3). Since oximation is a relatively mild reaction and can proceed even without the aid of the catalyst. We conducted the reaction at 25 °C to maximize the catalytic difference between the reactions with and without catalyst. These results illustrate that MIL-101-PTA also facilitates the oximation with 70% yield in 1 min compared with MIL-101 (56%) and no catalyst (6%). The above results indicate that even though both Lewis and Bronsted acids can facilitate oximation-Beckmann rearrangement reaction, Bronsted acid performs better than Lewis acid in catalyzing the reaction. We recycle the MIL-101-PTA catalyst in oximation-Beckmann reaction three times. Compared with fresh catalyst, MIL-101-PTA exhibits ca. 25% decrease in the yield in the third run (Figure S4). By comparing the DRIFTS spectra of recycled MIL-101-PTA with the fresh catalyst, it is evident that the characteristic bands of the PTA are at the same positions, which proves that the PTA molecules are still in the Keggin structure (Figure S5). However, the PXRD analysis reveals that the crystallinity of the recycled catalyst is gradually lost during each cycle (Figure S6). The surface area and pore size/volume of the recycled MOF catalyst also decrease after three reaction cycles (Figure S7-S8). Therefore, the reduced activity of the catalyst could stem from the partial collapse of the MOF structure.

To account for the crystallinity loss of recycled MOFs, we did a series of control experiments. First, we evaluated the stability of MIL-101 after recycling for different times. The decreasing peak intensity of the recycled MOF samples indicates that the crystallinity of MIL-101 gradually lost during each cycle (Figure S9), which is similar to what we observed in MIL-101-PTA (Figure S6). The similar stability performances of MIL-101 and MIL-101-PTA indicate that the collapse of the MOF structure during cycling is not due to the encapsulation of PTA in the MOF matrix. To study the role of HCl in the collapse of MOF structures, we conducted a recycle test by using hydroxylamine aqueous solution instead of hydroxylamine hydrochloride salt in the reaction. After recycling three times, the PXRD pattern of the recycled MOF catalyst barely changes compared with the pristine MOF (Figure S10), implying HCl plays a major role in destroying MOF primary structure during the reaction. However, hydroxylamine aqueous solution is not preferred for the reaction because the presence of $H_2O$ leads to the backward reaction of oxime to cyclohexanone.

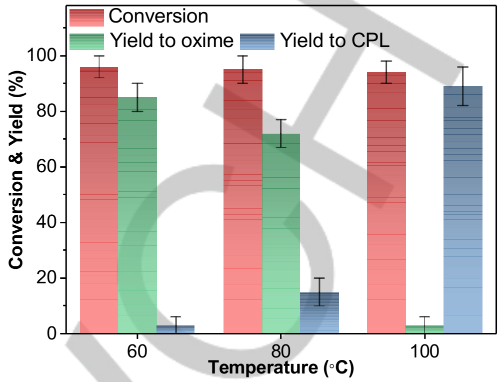

**Figure 5.** Temperature effect on oximation-Beckmann rearrangement. (Reaction condition: MIL-101-PTA (20 mg, 7nmol PTA), cyclohexanone (0.25 mmol), hydroxylamine hydrochloride (0.375 mmol), n-decane (20 μL), DCE (0.5 mL), MeCN (0.5 mL). The reaction was performed at different temperatures for 12 h under stirring at 600 rpm).

Encouraged by the successful one-pot synthesis of CPL from cyclohexanone, we sought to add one more step to the tandem reaction with selective phenol hydrogenation to cyclohexanone. The whole tandem catalysis then combines phenol hydrogenation, oximation, and Beckmann rearrangement in one pot. To achieve phenol hydrogenation in the initial step, we loaded Pd precursor into the MOF and reduced it to Pd nanoparticles in MIL-101-PTA (termed Pd-MIL-101-PTA, Figure S11-13). The loading of Pd in Pd-MIL-101-PTA is 4.9 wt.% measured by ICP-MS (Table S3). Pd nanoparticles have been proved as highly selective catalysts in the hydrogenation of phenol to cyclohexanone.[2,26] We first run the phenol hydrogenation over Pd-MIL-101-PTA in DCE under 20 bar hydrogen at 60 °C, followed by the subsequent addition of MeCN and hydroxylamine hydrochloride to conduct oximation-Beckmann arrangement. As shown in Table S4, a remarkable yield of CPL (92%) is achieved after 6 h of phenol hydrogenation and 12 h of oximation-Beckmann rearrangement. However, Pd-MIL-101-PTA cannot be recycled in such sequential tandem catalysis since the recovered catalyst becomes inactive towards phenol hydrogenation in the second run. Such a problem was also encountered by Ju Yeon Shin *et al.*, where $Pd/Sc(OTf)_3$/ionic liquid system was employed as the catalyst for the tandem synthesis of CPL from phenol.[16] To account for such "quenched" activity, we perform ICP-MS (Table S3) analysis of the used catalyst and find that 40% of Pd leaches from the MOF support after the first round of tandem catalysis, which could be induced by the strong acidic condition and chloride ions which facilitate the dissolving of Pd by coordination.[27] Currently, more endeavors are ongoing to resolve the Pd leaching issue.

The core problem of the tandem reaction starting from phenol is that the required reaction condition for oximation-Beckmann rearrangement is quite harsh, which is under strong acidic and high-temperature.[16, 28] Pd nanoparticles cannot survive under these conditions, most likely due to etching by the acid and poisoning by the solvent such as $CH_3CN$, resulting in the lost activity of Pd in recycled catalysts for phenol hydrogenation.

## Conclusion

In conclusion, we have developed acidified MOFs, MIL-101-PTA, by encapsulating phosphotungstic acid (PTA) into MIL-101 for the one-pot transformation of cyclohexanone to ε-caprolactam. The resultant MIL-101-PTA shows uniformly dispersed PTA throughout the MOF matrix and high yield of ε-caprolactam in the tandem oximation-Beckmann rearrangement. MIL-101-PTA can be recycled three times with a slight loss in their catalytic performance. Moreover, a new multifunctional MOF catalyst is developed by encapsulating Pd nanoparticles in MIL-101-PTA and shows a high yield of ε-caprolactam in sequential tandem catalysis that combines phenol hydrogenation, oximation, and Beckmann rearrangement in one pot, despite significant Pd leaching after the first run. This work opens up new avenues to the synthesis of ε-caprolactam via tandem catalysis by multifunctional acidified MOFs and uncovers the great potential of using MOFs in the efficient synthesis of fine chemicals.

## Experimental Section

**Synthesis of MIL-101.** MIL-101 was synthesized following the hydrothermal method reported in previous literature.[17] Typically, a mixture of $Cr(NO_3)_3 \bullet 9H_2O$ (2.00 g, 5.00 mmol) and terephthalic acid (0.832 g, 5.00 mmol) in 20 mL deionized water was stirred at room temperature for 20 min. The mixture was transferred to a 100 mL autoclave and was heated to 220 °C and maintained for 18 h. After cooling to room temperature, the solid was collected by centrifugation and thoroughly washed with water (three times) and methanol (three times). Then the materials were activated by heating at 150 °C for 12 h under vacuum.

**Synthesis of MIL-101-PTA, MIL-101-0.5PTA, and MIL-101-2PTA**. MIL-101-PTA was synthesized following a one-pot encapsulation method.[29] A mixture of $Cr(NO_3)_3\cdot 9H_2O$ (2.00 g, 5.00 mmol), terephthalic acid (0.832 g, 5.00 mmol), and phosphotungstic acid hydrate (1.00 g, 0.345 mmol) in 20 mL deionized water was stirred at room temperature for 20 min. Then the mixture was transferred to a 100 mL autoclave and was heated to 220 °C and maintained for 18 h. The washing and activation procedures are the same as the synthesis of MIL-101. 0.5 g phosphotungstic acid hydrate was used for MIL-101-0.5PTA, and 2 g phosphotungstic acid hydrate was used for MIL-101-2PTA.

**Synthesis of Pd-MIL-101-PTA.** 200 mg of MIL-101-PTA was dispersed in 2 mL chloroform and sonicated for 20 min to achieve a homogeneous suspension. Afterward, 2 mL chloroform solution containing 29.5 mg $Pd(acac)_2$ was added dropwise in the MOFs suspension. After stirring for 24 h at ambient temperature, the mixture was vacuum dried and reduced at 200 °C for 2 h under 10% $H_2$/Ar at a flow rate of 50 mL/min to afford Pd-MIL-101-PTA.

**Characterization**. Powder X-ray diffraction (PXRD) patterns were obtained using a STOE Stadi P powder diffractometer and a Bruker D8 Advance Twin diffractometer with Cu Kα radiation (40 kV, 40 mA, λ = 0.1541 nm). Surface area and pore size distribution analysis of the catalysts were performed by nitrogen sorption isotherms at 77 K using Micromeritics 3Flex surface characterization analyzer. All the samples were degassed under vacuum at 150 °C for 12 h before analysis. Transmission electron microscopy (TEM) images were acquired with a Tecnai G2 F20 electron microscope. High-angle annular dark-field scanning TEM (HAADF-STEM) and elemental mapping analysis were conducted using a Titan Themis 300 probe corrected TEM equipped with an energy-dispersive X-ray spectroscopy (EDS) detector (Oxford INCAEDS). Inductively coupled plasma-mass spectroscopy (ICP–MS) (X Series II, Thermo Scientific) was used to determine the metal loading of Pd and W in the samples. All samples were completely digested in aqua regia and diluted by 2 wt.% $HNO_3$ to appropriate concentrations for the elemental measurement. The acidity of the catalysts was measured by acid-base titration.[20] 250 mg catalyst were suspended in 10 g saturated NaCl solution and stirred at room temperature for 24 h. The solid was collected by centrifuge and washed with 20 g deionized water. All of the filtrates were titrated with 0.01 M NaOH solution.

**Reaction conditions for oximation-Beckmann rearrangement reaction**. Cyclohexanone (0.25 mmol, 26 µL), hydroxylamine hydrochloride (0.375 mmol, 26.1 mg), n-decane (20 µL) and catalyst (20 mg) were added in a binary mixture of acetonitrile and DCE (1 mL, *v:v* =1:1). The reaction was performed at 100 °C for 12 h with stirring in the autoclave under 40 bar nitrogen in a 300 mL high-pressure vessel.

**Reaction conditions for oximation reaction.** Cyclohexanone (0.75 mmol, 78 µL), hydroxylamine (1.125 mmol, 74.4 µL, 50 wt. % in water), n-decane (20 µL) and catalyst (20 mg) were added in a binary mixture of acetonitrile and DCE (1 mL, v:v =1:1). The reaction was performed at 25 °C for 1 min with stirring in 6-dram vial.

**Reaction conditions for the one-pot sequential synthesis of CPL from phenol.** Phenol (0.250 mmol, 23.5 mg), n-decane (20 µL) and catalyst (20 mg) were added in 0.5 mL 1,2-dichloroethane (DCE) solution in a 6-dram vial. The reaction was stirred under 20 bar $H_2$ at 60 °C for 6 h. After release the hydrogen pressure, acetonitrile (0.5 mL) and hydroxylamine hydrochloride (0.375 mmol, 26.1 mg) were added to the reaction vial. The reaction mixture was stirred at 100 °C for 12 h under 40 bar nitrogen. The reaction was carried out in a 300 mL high-pressure vessel.

For all the reactions, the reactants/products were quantified by gas chromatography (Hewlett Packard 5890 II) equipped with an FID detector and an HP-5 column (30 m × 0.32 mm × 0.25 µm) and gas chromatography-mass spectrometer (Agilent 6890N/5975 GC-MS) equipped with an HP-5ms capillary column (30 m × 0.32 mm × 0.25 µm).

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**Keywords:** Metal-organic frameworks (MOFs) • Tandem reaction • ε-caprolactam • phosphotungstic acid

[1] W. M. Strategy, "The Global Caprolactam Market", can be found under https://www.researchandmarkets.com/research/3wdpsg/caprolactam?w=5, **2020**.

[2] a) H. Liu, T. Jiang, B. Han, S. Liang, Y. Zhou, *Science* **2009**, *326*, 1250-1252; b) Y. Wang, J. Yao, H. Li, D. Su, M. Antonietti, *J. Am. Chem. Soc.* **2011**, *133*, 2362-2365.

[3] a) S. Zhao, W. Xie, J. Yang, Y. Liu, Y. Zhang, B. Xu, J. G. Jiang, M. He, P. Wu, *Appl. Catal. A-Gen.* **2011**, *394*, 1-8; b) L. Dal Pozzo, G. Fornasari, T. Monti, *Catal. Commun.* **2002**, *3*, 369-375.

[4] a) G. P. Heitmann, G. Dahlhoff, W. F. Hölderich, *J. Catal.* **1999**, *186*, 12-19; b) W. C. Li, A. H. Lu, R. Palkovits, W. Schmidt, B. Spliethoff, F. Schüth, *J. Am. Chem. Soc.* **2005**, *127*, 12595-12600.

[5] a) K. You, L. Mao, L. Chen, D. Yin, P. Liu, H. Luo, *Catal. Commun.* **2008**, *9*, 2136-2139; b) N. T. Zuidhof, M. H. J. M. de Croon, J. C. Schouten, J. T. Tinge, *Chem. Eng. Technol.* **2012**, *35*, 1257-1261.

[6] a) C. Ngamcharussrivichai, P. Wu, T. Tatsumi, *J. Catal.* **2005**, *235*, 139-149; b) C. Ngamcharussrivichai, P. Wu, T. Tatsumi, *Catal. Commun.* **2007**, *8*, 135-138; c) X. Wang, C. C. Chen, S. Y. Chen, Y. Mou, S. Cheng, *Appl. Catal. A-Gen.* **2005**, *281*, 47-54; d) A. Erigoni, S. H. Newland, G. Paul, L. Marchese, R. Raja, E. Gianotti, *ChemCatChem* **2016**, *8*, 3161-3169; e) T. D. Conesa, R. Mokaya, Z. Yang, R. Luque, J. M. Campelo, A. A. Romero, *J. Catal.* **2007**, *252*, 1-10.

[7] H. Annath, S. Chapman, G. F. Donnelly, P. C. Marr, A. C. Marr, R. Raja,

10.1002/cctc.202100425

*ACS Sustain. Chem. Eng.* **2018**, *6*, 16797-16805.

[8] G. Wen, B. Wang, C. Wang, J. Wang, Z. Tian, R. Schlögl, D. S. Su, *Angew. Chem. Int. Ed.* **2017**, *56*, 600-604.

[9] a) D. Mao, Z. Long, Y. Zhou, J. Li, X. Wang, J. Wang, *RSC Adv.* **2014**, *4*, 15635-15641; b) X. Zhang, D. Mao, Y. Leng, Y. Zhou, J. Wang, *Catal. Lett.* **2013**, *143*, 193-199.

[10] a) J. Lee, O. K. Farha, J. Roberts, K. A. Scheidt, S. T. Nguyen, J. T. Hupp, *Chem. Soc. Rev.* **2009**, *38*, 1450-1459; b) G. Li, S. Zhao, Y. Zhang, Z. Tang, *Adv. Mater.* **2018**, *30*, e1800702; c) L. Jiao, Y. Wang, H. L. Jiang, Q. Xu, *Adv. Mater.* **2018**, *30*, 1703663.

[11] a) Z. J. Lin, H. Q. Zheng, J. Chen, W. E. Zhuang, Y. X. Lin, J. W. Su, Y. B. Huang, R. Cao, *Inorg. Chem.* **2018**, *57*, 13009-13019; b) K. Sabyrov, J. Jiang, O. M. Yaghi, G. A. Somorjai, *J. Am. Chem. Soc.* **2017**, *139*, 12382-12385.

[12] X. Li, R. Van Zeeland, R. V. Maligal-Ganesh, Y. Pei, G. Power, L. Stanley, W. Huang, *ACS Catal.* **2016**, *6*, 6324-6328.

[13] a) X. Li, T. W. Goh, L. Li, C. Xiao, Z. Guo, X. C. Zeng, W. Huang, *ACS Catal.* **2016**, *6*, 3461-3468; b) X. Li, B. Zhang, R. Van Zeeland, L. Tang, Y. Pei, Z. Qi, T. W. Goh, L. M. Stanley, W. Huang, *Catal. Lett.* **2018**, *148*, 940-945; c) M. Zhao, K. Yuan, Y. Wang, G. Li, J. Guo, L. Gu, W. Hu, H. Zhao, Z. Tang, *Nature* **2016**, *539*, 76-80; d) Q. Yang, Q. Xu, H. L. Jiang, *Chem. Soc. Rev.* **2017**, *46*, 4774-4808; e) S. Zhao, Y. Wang, J. Dong, C. T. He, H. Yin, P. An, K. Zhao, X. Zhang, C. Gao, L. Zhang, J. Lv, J. Wang, J. Zhang, A. M. Khattak, N. A. Khan, Z. Wei, J. Zhang, S. Liu, H. Zhao, Z. Tang, *Nat. Energy* **2016**, *1*, 16184; f) W. Zhang, G. Lu, C. Cui, Y. Liu, S. Li, W. Yan, C. Xing, Y. R. Chi, Y. Yang, F. Huo, *Adv. Mater.* **2014**, *26*, 4056-4060; g) B. Yuan, Y. Pan, Y. Li, B. Yin, H. Jiang, *Angew. Chem. Int. Ed. Engl.* **2010**, *49*, 4054-4058.

[14] a) W. Zhao, G. Li, Z. Tang, *Nano Today* **2019**, *27*, 178-197; b) Z. Xu, J. Zhang, T. Pan, H. Li, F. Huo, B. Zheng, W. Zhang, *Chem. Mater.* **2020**, *32*, 3553-3560.

[15] X. Li, B. Zhang, L. Tang, T. W. Goh, S. Qi, A. Volkov, Y. Pei, Z. Qi, C. K. Tsung, L. Stanley, W. Huang, *Angew. Chem. Int. Ed.* **2017**, *56*, 16371-16375.

[16] J. Y. Shin, D. J. Jung, S. G. Lee, *ACS Catal.* **2013**, *3*, 525-528.

[17] L. Bromberg, Y. Diao, H. Wu, S. A. Speakman, T. A. Hatton, *Chem. Mater.* **2012**, *24*, 1664-1675.

[18] G. Férey, C. Mellot-Draznieks, C. Serre, F. Millange, J. Dutour, S. Surblé, I. Margiolaki, *Science* **2005**, *309*, 2040-2042.

[19] I. V. Kozhevnikov, K. R. Kloetstra, A. Sinnema, H. W. Zandbergen, H. van Bekkum, *J. Mol. Catal. A-Chem.* **1996**, *114*, 287-298.

[20] a) S. Y. Chen, T. Yokoi, C. Y. Tang, L. Y. Jang, T. Tatsumi, J. C. C. Chan, S. Cheng, *Green Chem.* **2011**, *13*, 2920-2930; b) Y. Zang, J. Shi, F. Zhang, Y. Zhong, W. Zhu, *Catal. Sci. Technol.* **2013**, *3*, 2044-2049.

[21] Y. Zhang, J. Wan, Y. Wang, Y. Ma, *RSC Adv.* **2015**, *5*, 97589-97597.

[22] Q. Deng, G. K. Nie, L. Pan, J. J. Zou, X. W. Zhang, L. Wang, *Green Chem.* **2015**, *17*, 4473-4481.

[23] P. Teesdale-Spittle, *Appl. Organomet. Chem.* **1993**, *7*, 293-293.

[24] E. Rancan, F. Aricò, G. Quartarone, L. Ronchin, P. Tundo, A. Vavasori, *Catal. Commun.* **2014**, *54*, 11-16.

[25] a) P. Gupta, S. Paul, *Catal. Today* **2014**, *236*, 153-170; b) A. Zicmanis, S. Katkevica, P. Mekss, *Catal. Commun.* **2009**, *10*, 614-619.

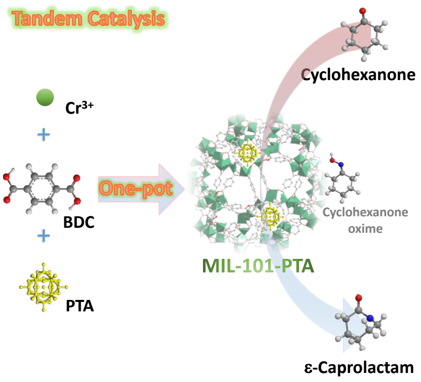
[26] a) H. Liu, T. Jiang, B. Han, S. Liang, Y. Zhou, *Science* **2009**, *326*, 1250-1252; b) H. Liu, Y. Li, R. Luque, H. Jiang, *Adv. Synth. Catal.* **2011**, *353*, 3107-3113.

[27] Y. Ding, H. Zheng, J. Li, S. Zhang, B. Liu, C. Ekberg, *Materials* **2019**, *12*, 1205.

[28] a) F. Aricò, G. Quartarone, E. Rancan, L. Ronchin, P. Tundo, A. Vavasori, *Catal. Commun.* **2014**, *49*, 47-51; b) L. Yu, L. Guo, W. Hu, Z. Zhang, Y. Bai, J. Ye, H. Wang, L. Li, *Catal. Commun.* **2019**, *123*, 119-123; c) J. Zhang, Y. Lu, K. Wang, G. Luo, *Ind. Eng. Chem. Res.* **2013**, *52*, 6377-6381; d) Z. Li, Q. Yang, X. Qi, Y. Xu, D. Zhang, Y. Wang, X. Zhao, *Chem. Commun.* **2015**, *51*, 1930-1932.

[29] J. Juan-Alcañiz, E. V. Ramos-Fernandez, U. Lafont, J. Gascon, F. Kapteijn, *J. Catal.* **2010**, *269*, 229-241.

## Entry for the Table of Contents



Using a one-pot strategy, we encapsulate phosphotungstic acid (PTA) inside a Cr-based metal-organic framework (MOF) matrix to afford MIL-101-PTA catalysts. The acidified MOFs catalyze the tandem oximation-Beckmann rearrangement reaction that directly transforms cyclohexanone to ε-caprolactam. The acidified MOF displays a high yield of ε-caprolactam (89%) and can be recycled three times with a slight loss in their catalytic performance.