COMMUNICATION

A Polymorphic Azobenzene Cage for Energy Efficient and Highly Selective *p*-Xylene Separation

Basem Moosa¹, Lukman O. Alimi¹, Aleksander Shkurenko², Aliyah Fakim¹, Prashant M. Bhatt², Gengwu Zhang¹, Mohamed Eddaoudi² and Niveen M. Khashab^{1*}

1. Smart Hybrid Materials (SHMs) Laboratory, Advanced Membranes and Porous Materials Center, Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

2. Functional Materials Design, Discovery and Development Research Group, Advanced Membranes and Porous Materials Center, Division of Physical Sciences and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

Abstract: Developing the competency of molecular sorbents for energy-saving applications, such as C8 separations, requires efficient, stable, scalable and easily recyclable materials that can readily transition to commercial implementation. Here, we report an azobenzene-based cage for the selective separation of *p*-xylene isomer across a range of C8 isomers in both vapor and liquid states with selectivity that is higher than the reported all-organic sorbents. Interestingly, the crystal structure shows non-porous cages that are separated by *p*-xylene molecules through selective CH... π interactions between the azo bonds and the methyl hydrogens of the xylene molecules. This cage is stable in solution and can be regenerated directly under vacuum to be used in multiple cycles. We envisage that this work will promote the investigation of the azo bond as well as guest induced crystal to crystal phase transition in non-porous organic solids for pivotal energy intensive separations.

Molecular separations are critical for the production of specialty chemicals and fuels.^[1-5] C8 separation is one of the seven most valuable chemical separations that can change the world's economy.^[6] Separation techniques that do not require huge amounts of heat can lower the carbon footprint, emission and overall pollution.^[7] C8 isomers separation (specifically xylene isomers and ethylbenzene) dictates the purity of the starting materials for multiple industries including polymers, plastics, pigments and resins.^[8,9] Para-Xylene (**pX**), is the most valued among the C8 isomers for producing polymers such as polyethylene terephthalate (PET) and polyester.^[10] Conventionally, C8 isomers are separated by different energy-demanding methods including fractional crystallization^[11] and selective adsorption using inorganic and hybrid sorbents such as zeolite H-ZSM,^[12] metal organic frameworks,^[13-15] and

metallocycles.^[16] More recently, a non-porous molecular complex^[17], switching layered materials^[18] and organic non-porous adaptive crystals (NACs) have shown excellent selectivity in the separation of xylenes^[19] where the preferred guest molecules, entering these initially non-porous crystals, are accommodated by structural transformations. Although selective adsorption processes have showed superiority in molecular separations, long term stability and economic scale up of the molecular recognition entities have been the main hurdles towards the industrial translation of such platforms.

Organic cages are a class of intrinsically porous materials (IPMs) made from discrete organic molecules with accessible windows.^[20] These stable systems are easily prepared and scaled-up in addition to being solution processable,^[20,21] which allows them to be combined in a modular way to generate porous co-crystals^[22] and porous liquids.^[23] Organic cage crystals can be polymorphic^[24,25] which is a close analogy to zeolites^[26] and metal-organic frameworks (MOFs)^[27] where different crystalline polymorphs have different porosity, physical properties, and guest molecules selectivity. Here, a non-porous polymorphic azobenzene-based imine cage and its use for selective separation of *p*-xylenes from xylenes mixture and commercial C8 fractions is described. This selective separation takes place in both vapor and liquid states where the latter can potentially lower the energy bill of these separations as no heating is required (**Scheme 1**).

COMMUNICATION

Scheme 1. Packing of the **AZO-Cage** crystals in $\text{CHCl}_3/\text{n-hexane}$ and xylenes showing two polymorphs.

The non-porous organic cage was synthesized by the well-known dynamic covalent chemistry, (3+2) imine condensation reaction (**Figure S1**). The (E)-4,4'-(diazene-1,2-diyl) dibenzaldehyde was reacted with tris(2-aminoethyl) amine (TREN) in a mixture of ethanol and chloroform to form exclusively an azobenzene based imine cage (**AZO-Cage**) as an insoluble orange solid in a relatively excellent yield 72%. The synthesized cage was characterized by different techniques to confirm the structure and the self-assembly (**Figure S2 & S3**). An imine bond is seen in ^1H NMR at 8.30 ppm and it appears as a singlet peak (**Figure S2**). Two types of aromatic peaks are shown as two doublets at 7.37 and 7.44 ppm respectively representing the aromatic protons of the azobenzene moiety. At the aliphatic region, a relatively two broad singlet peaks appeared at 3.86 and 2.87 ppm that are assigned to the methylene protons of the **AZO-Cage**. ^{13}C NMR shows two peaks at the aliphatic region 57.8 and 52.5 ppm which are assigned to the cage carbons, while the five aromatic peaks representing the imine bond are seen at 161.4 ppm and 153-123 (**Figure S2**). Initially, other than being an excellent recognition unit, including the azo group in the cage was intended to control the pore cavity with light/heat. Exposing the **AZO-Cage** in solution (in CDCl_3) to UV (365 nm) for 5 mins showed minor changes (NMR) to the confirmation while a complete degradation happened after 30 min of exposure (**Figure S4**). The **AZO-Cage** was crystallized in chloroform/n-hexane solvent mixture to obtain orange rhombic prisms

of crystals **AZO-Cage 1** suitable for X-ray diffraction analysis (**Scheme 1**). The single crystal X-ray diffraction (SCXRD) study showed that the compound crystallizes in trigonal $R\bar{3}c$ space group with 1/6th of the **AZO-Cage 1** in the asymmetric unit (**Figure S5 and Table S1**). The molecular packing of **AZO-Cage 1** suggests that the cage is non-porous to the solvent (**Figure S6**). Notably, irradiation of the **AZO-Cage** in the crystalline state (**AZO-Cage 1**) did not change the original non-porous conformation or affect the stability even after long exposure times (**Figure S7**). We hypothesize that the less flexible imine bond is making this cage more rigid preventing the isomerization process.

In an attempt to investigate the porosity of the **AZO-Cage** to aromatic guest molecules, we crystallized the compound using xylene isomers (**oX**, **mX** and **pX**). The **AZO-Cage** was therefore dissolved in a boiling xylene mixture solution and then allowed to cool/evaporate for one day at room temperature to give needle-like orange crystals that selectively entrap **pX** (**AZO-Cage 2**, **Scheme 1 and Table S1**). All efforts to get single crystals from **oX** and **mX** proved abortive, which suggests that the **AZO-Cage** is selective to the **pX** isomer. The SCXRD of **AZO-Cage 2** revealed that the compound crystallizes in monoclinic $C2/c$ space group with half molecule of the cage and half of the **pX** molecule in the asymmetric unit (**Figure 1 and Figure S5**).

COMMUNICATION

Figure 1. Packing arrangements of rhombic prisms of crystals (a) along [010] and (b) along [100]. (c) Intramolecular π - π stacking and host-guest C-H $\cdots\pi$ interactions and (d) host-host C-H $\cdots\pi$ interactions between cages.

In the crystal structure, two of the three azobenzene moieties in **AZO-Cage 2** are arranged parallel to one another while the third azobenzene is perpendicular to these two forming a boat-like configuration (**Figure 1**). The crystal structure shows that the **pX** molecules lie between the cages but not inside the cage (**Figure 2**). The C-H moiety of the methyl group of the **pX** molecule participate in weak host-guest C-H $\cdots\pi$ N=N (4.130 Å) interactions with the centroid of one of the azo bonds (**Figure 2** and **Table S2**). Each cage is also connected to the neighboring cage through the aliphatic C-H $\cdots\pi$ interactions involving the C-H moiety of the **AZO-Cage 2** and the centroid of four neighboring phenyl rings sandwiching the **pX** guest molecule (**Figure 2b** and

Table S3). Moreover, the crystal structure shows some C-H $\cdots\pi$ interactions (**Figure 2** and **Table S4**) and face to face π - π intramolecular interactions. These π - π intramolecular interactions keep the two azobenzene of the cage in a parallel position to each other (**Figure S8** and **Table S5**). From the crystal structure, we can conclude that the enculturation of **pX** by the **AZO-Cage 2** is influenced or favored by the host-guest C-H $\cdots\pi$ interactions. Thermogravimetric analysis (TGA) of the **AZO-Cage 2** was also determined. The thermogram indicates a loss of solvent around 120 °C which corresponds to the loss of **pX** (**Figure S9**).

COMMUNICATION

Figure 2. a) C-H... π interactions with the azo bond. b) Packing arrangement showing the C-H... π intermolecular interactions connecting the **AZO-Cage 2**.

These promising results prompted us to investigate the vapor and liquid absorption behavior of the **AZO-Cage**. The as-synthesized **AZO-Cage 2** was activated at 70 °C under vacuum for 24 h to obtain the activated **AZO-Cage 2** (Figure S9), which is non-porous (Figure S10). The experimental PXRD patterns of the as-synthesized **AZO-Cage 1** and **AZO-Cage 2** were measured and compared to the simulated PXRD (Figure S11). Furthermore, we measured the PXRD patterns of the activated **AZO-Cage 2** and compared it to the as-synthesized **AZO-Cage 2** to confirm that there is a no phase transition as a result of the loss of the **pX** (Figure S12). Xylene selectivity towards the **AZO-Cage** was first investigated by vapor-solid sorption experiments using the empty **AZO-Cage 1** with all C-8 isomers and a mixture of 1:1:1 volumetric ratio of **oX:mX:pX** (Figure 3). Following the PXRD pattern of **AZO-Cage 1** with the above-mentioned combinations, we concluded that the final obtained PXRD pattern was that of the calculated **AZO-Cage 2** meaning that a crystal to crystal phase transition is occurring in the presence of xylene guest molecules (Figure 3 & Figure S13). The PXRD patterns for **oX**, **mX** and **pX** were very similar and so a time-dependent solid-vapor sorption study was conducted and analyzed showing that the uptake of **pX** was much faster than **oX** and **mX**. This further supports that **AZO-cage1** can selectively absorb *p*-xylene (Figure S14). It's noteworthy to state that all of these experiments were performed at 298 K, which supports that the amount of vapor produced is similar in all trials as all isomers have very close boiling points and that this selective separation can take place without any intensive energy requirement. We also noticed that the kinetics for adsorption is relatively slow which would hinder the industrial translations of these system (Figure S15). Consequently, we are currently working with engineers

to find the best conditions to increase the uptake and decrease the activation temperature to achieve an efficient separation process with the least energy footprint possible.

Figure 3. PXRD patterns showing the conversion of **AZO-Cage 1** to **AZO-Cage 2** in the presence of **pX** vapor, and the effect of **oX** vapor, **mX** vapor, **EB** and 1:1:1 mixture of **oX**, **mX**, and **pX** on **AZO-Cage 1** after 24 hrs.

Further insight into the SCXRD results showed that the **pX** isomer can best fit in between the **AZO-Cage** molecules facilitated by the interaction of the azo- π bonds and the methyl protons of **pX**, which to the best of our knowledge has not been reported thus far. Moreover, *m*-, *o*-xylene and Ethylbenzene isomers cannot fit due to the shape and symmetry of the molecules in the presence of **pX** so the interaction does not take place which was verified by DFT calculations (Figure S16) However, the vapor adsorption trials in the absence of **pX** showed that **mX**, **oX** and **EB** can be adsorbed over time and gave a new phase of PXRD patterns (Figure 3 & Figure S13). Most importantly, the same studies were done using xylene isomers in the liquid phase, where **AZO-Cage 1** was incubated in 1 ml of **pX**. This produced the final PXRD pattern of **AZO-Cage 2** taking into consideration that the cage is not soluble at all in xylenes (Figure 4). Moreover, repeating the same experiment with xylenes mixture (1:1:1 volumetric ratio of **oX:mX:pX**) showed the same **pX** selectivity in the liquid phase. Selectivity values were determined using solid-vapor and solid-liquid experiments using different combination of xylene isomers. ^1H NMR spectral measurements showed **pX** isomer selectively adsorbed with a selectivity coefficient for **pX/oX**, **pX/mX** and **pX/EB** of 15.60, 10.90 and 9.70 for the vapor C-8 isomers and 12.10, 7.30 and 6.60 for the liquid C-8 isomers, respectively (Figure S17 & S18 and Table S6). This is the highest reported selectivity for an all-organic sorbent, to the best of our knowledge.

COMMUNICATION

Since we have established that the **AZO-Cage** is selective to **pX**, we opted to confirm its performance on commercially relevant samples such as the C8 aromatic fraction obtained by conventional distillation of Pygas (from light arabia crude oil). The **AZO-Cage** was activated under vacuum at a relatively low temperature of 70 °C for 24 hr before running the incubation experiment with the C8 aromatic fraction. We also tested the recyclability of the **AZO-Cage** by putting it under vacuum at 70 °C. The PXRD patterns for the number of cycles examined show that the material is reusable and remains efficient for the separation of **pX** without decrease in performance under the conditions of the investigation (**Figure S19**). This was repeated up to five cycles without losing the adsorption or the selectivity as confirmed by Gas-Chromatography analysis (**Figure S20**). An attempt to remove **pX** from **AZO-Cage** was performed using n-hexane as a soaking solvent trying to avoid heating as an activating factor which lead to unsuccessful attempt (**Figure S21**). Finally, we tested the stability of **AZO-Cage** in 0.1 M hydrochloric acid as well as in water trying to have an adsorbent that can tolerate acidic and humid environment. Incubation of **AZO-Cage** in acidic conditions degrade the cage as most of the characteristic peaks in PXRD are disappeared, however in water the cage stays stable as it shows the PXRD peaks of **AZO-Cage 1** (**Figure S22**).

Figure 4. PXRD patterns showing the conversion of **AZO-Cage 1** to **AZO-Cage 2** in the presence of *p*-xylene vapor or liquid.

Conclusion

In this work, we have prepared a non-porous imine-based organic cage (**AZO-Cage**) that undergoes a crystal (**AZO-Cage 1**) to crystal (**AZO-Cage 2**) phase transition selectively in the presence of **pX** in the liquid and vapor phase. This preferential host-guest behavior is attributed to the interaction between the azo- π bonds and **pX** molecules in between the cage molecules that is well suited for the size, and shape of **pX** over other C8 isomers. The separation selectivity for **pX** was higher than the published organic-based sorbents and comparable to the hybrid frameworks, taking into

account the relatively mild energy demands for the recycled use of this platform. We believe that the application of non-porous organic sorbents, although relatively new, can potentially revolutionize energy intensive separations as they are quite stable (even in liquid phase), readily scalable, cost-efficient and most importantly can be tailored to target specific molecular separations, which the inorganic zeolites cannot address efficiently.

Keywords: Organic cage • host-guest interactions • C8 separations • azobenzene • intrinsically porous materials

REFERENCES

- [1] S. Horike, S. Shimomura, S. Kitagawa, *Nat Chem* **2009**, 1, 695-704.
- [2] C. Gu, N. Hosono, J. J. Zheng, Y. Sato, S. Kusaka, S. Sakaki, S. Kitagawa, *Science* **2019**, 363, 387-391.
- [3] K. J. Chen, D. G. Madden, S. Mukherjee, T. Pham, K. A. Forrest, A. Kumar, B. Space, J. Kong, Q. Y. Zhang, M. J. Zaworotko, *Science* **2019**, 366, 241-246.
- [4] P. Q. Liao, N. Y. Huang, W. X. Zhang, J. P. Zhang, X. M. Chen, *Science* **2017**, 356, 1193-1196.
- [5] D. Y. Koh, B. A. McCool, H. W. Deckman, R. P. Lively, *Science* **2016**, 353, 804-807.
- [6] D. S. Sholl, R. P. Lively, *Nature* **2016**, 533, 316-316.
- [7] E. K. McGuinness, F. Y. Zhang, Y. Ma, R. P. Lively, M. D. Losego, *Chem. Mater.* **2019**, 31, 5509-5518.
- [8] Y. X. Yang, P. Bai, X. H. Guo, *Ind. Eng. Chem. Res.* **2017**, 56, 14725-14753.
- [9] M. Minceva, A. E. Rodrigues, *Aiche J* **2007**, 53, 138-149.
- [10] M. I. Gonzalez, M. T. Kapelewski, E. D. Bloch, P. J. Milner, D. A. Reed, M. R. Hudson, J. A. Mason, G. Barin, C. M. Brown, J. R. Long, *J. Am. Chem. Soc.* **2018**, 140, 3412-3422.
- [11] A. Torres-Knoop, R. Krishna, D. Dubbeldam, *Angew. Chem. Int. Ed.* **2014**, 53, 7774-7778.
- [12] L. Alaerts, C. E. A. Kirschhock, M. Maes, M. A. van der Veen, V. Finsy, A. Depla, J. A. Martens, G. V. Baron, P. A. Jacobs, J. E. M. Denayer, D. E. De Vos, *Angew. Chem. Int. Ed.* **2007**, 46, 4293-4297.
- [13] M. Rasouli, N. Yaghobi, S. Chitsazan, M. H. Sayyar, *Microporous Mesoporous Mater.* **2012**, 150, 47-54.
- [14] J. E. Warren, C. G. Perkins, K. E. Jelfs, P. Boldrin, P. A. Chater, G. J. Miller, T. D. Manning, M. E. Briggs, K. C. Stylianou, J. B. Claridge, M. J. Rosseinsky, *Angew. Chem. Int. Ed.* **2014**, 53, 4592-4596.
- [15] F. Vermoortele, M. Maes, P. Z. Moghadam, M. J. Lennox, F. Ragon, M. Boulhout, S. Biswas, K. G. M. Laurier, I. Beurroies, R. Denoyel, M. Roeflaers, N. Stock, T. Duren, C. Serre, D. E. De Vos, *J. Am. Chem. Soc.* **2011**, 133, 18526-18529.
- [16] M. du Plessis, V. I. Nikolayenko, L. J. Barbour, *J. Am. Chem. Soc.* **2020**, 142, 4529-4533.
- [17] N. Sun, S. Q. Wang, R. Zou, W. G. Cui, A. Zhang, T. Zhang, Q. Li, Z. Z. Zhuang, Y. H. Zhang, J. Xu, M. J. Zaworotko, X. H. Bu, *Chem. Sci.* **2019**, 10, 8850-8854.
- [18] S. Q. Wang, S. Mukherjee, E. P. Kazmierczak, S. Darwish, A. Bajpai, Q. Y. Yang, M. J. Zaworotko, *Angew. Chem. Int. Ed.* **2019**, 58, 6630-6634.
- [19] K. C. Jie, M. Liu, Y. J. Zhou, M. A. Little, A. Pulido, S. Y. Chong, A. Stephenson, A. R. Hughes, F. Sakakibara, T.

COMMUNICATION

Ogoshi, F. Blanc, G. M. Day, F. H. Huang, A. I. Cooper, *J. Am. Chem. Soc.* **2018**, 140, 6921-6930.

[20] T. Tozawa, J. T. A. Jones, S. I. Swamy, S. Jiang, D. J. Adams, S. Shakespeare, R. Clowes, D. Bradshaw, T. Hasell, S. Y. Chong, C. Tang, S. Thompson, J. Parker, A. Trewin, J. Bacsá, A. M. Z. Slawin, A. Steiner, A. I. Cooper, *Nat. Mater.* **2009**, 8, 973-978.

[21] T. Hasell, A. I. Cooper, *Nat. Rev. Mater.* **2016**, 1.

[22] J. Liang, A. Nuhnen, S. Millan, H. Breitzke, V. Gvilava, G. Buntkowsky, C. Janiak, *Angew. Chem. Int. Ed.* **2020**, 59, 6068-6073.

[23] N. Giri, M. G. Del Popolo, G. Melaugh, R. L. Greenaway, K. Ratzke, T. Koschine, L. Pison, M. F. C. Gomes, A. I. Cooper, S. L. James, *Nature* **2015**, 527, 216-220.

[24] J. T. A. Jones, D. Holden, T. Mitra, T. Hasell, D. J. Adams, K. E. Jelfs, A. Trewin, D. J. Willock, G. M. Day, J. Bacsá, A. Steiner, A. I. Cooper, *Angew. Chem. Int. Ed.* **2011**, 50, 749-753.

[25] S. Bera, K. Dey, T. K. Pal, A. Halder, S. Tothadi, S. Karak, M. Addicoat, R. Banerjee, *Angew. Chem. Int. Ed.* **2019**, 58, 4243-4247.

[26] B. Moulton, M. J. Zaworotko, *Chem. Rev.* **2001**, 101, 1629-1658.

[27] Z. Akimbekov, A. D. Katsenis, G. P. Nagabhushana, G. Ayoub, M. Arhangelskis, A. J. Morris, T. Friscic, A. Navrotsky, *J. Am. Chem. Soc.* **2017**, 139, 7952-7957.

COMMUNICATION

A non-porous azobenzene-based molecular cage (**AZO-Cage**) can selectively separate *p*-xylene from vapor and liquid C8 mixture. The cage shows two polymorphs in the absence (**AZO-Cage 1**) and presence (**AZO-Cage 2**) of *p*-xylene guest molecules. This is attributed to the host-guest interaction between the azo- π bonds and *pX* molecules that are well suited in terms of size and shape over the rest of the C8 isomers to be intercalated between the cages evoking structural transformations.