Post-synthetic modulation of the charge distribution in a metal–organic framework for optimal binding of carbon dioxide and sulfur dioxide†

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Modulation of pore environment is an effective strategy to optimize guest binding in porous materials. We report the post-synthetic modification of the charge distribution in a charged metal–organic framework, MFM-305-CH3, [AlOH][Li]Cl. Cyclic voltammetry shows that the methylpyridinium moiety of MFM-305 has a redox potential of -0.09 V (vs. NHE) for oxidation to the neutral form. This leads simultaneously to enhanced adsorption capacities and selectivities (two parameters that often change in opposite directions) for CO2 and SO2 in MFM-305. The host–guest binding has been comprehensively investigated by in situ synchrotron X-ray and neutron powder diffraction, inelastic neutron scattering, synchrotron infrared and 2H NMR spectroscopy and theoretical modelling to reveal the binding domains of CO2 and SO2 in these materials. CO2 and SO2 binding in MFM-305-CH3 is shown to occur via hydrogen bonding to the methyl and aromatic-CH groups, with a long range interaction to chloride for CO2. In MFM-305 the hydroxyl, pyridyl and aromatic C–H groups bind CO2 and SO2 more effectively via hydrogen bonds and dipole interactions. Post-synthetic modification via dealkylation of the as-synthesised metal–organic framework is a powerful route to the synthesis of materials incorporating active polar groups that cannot be prepared directly.

Introduction

The release of CO2 and SO2 into the atmosphere from combustion of fossil fuels causes significant environmental problems and health risks.1-4 The wholesale replacement of the carbon-based energy supply is highly challenging, not least because of the existing infrastructure.5 It is therefore vital to mitigate the emissions of these acidic gases post combustion. At present, several technologies are used to capture CO2 and SO2, such as amine scrubbing, absorption in organic solvents, ionic liquids and limestone slurry.6 However, the considerable costs and the substantial energy input required for system regeneration significantly limit their long-term application. Powerful drivers therefore exist to develop new systems showing high adsorption capacity, selectivity, storage density and excellent reversibility to sequester these gases.

Metal–organic frameworks (MOFs) constructed from metal ions and clusters bridged by organic ligands are an emerging class of porous materials showing highly crystalline structures...
and great promise for gas adsorption and storage. MOFs can exhibit very high surface areas and, more importantly, have tunable pore environments with predictable pore size and can incorporate specific functional groups. MOFs have been studied extensively as sorbents for CO$_2$ under post-combustion conditions. In contrast, adsorption of SO$_2$ in MOFs has been rarely reported due to the limited stability of coordination compounds to highly reactive and corrosive SO$_2$. Development of new stable porous materials with optimal SO$_2$ and CO$_2$ adsorption property thus remains significant challenge. Optimising the interactions between hosts and substrate molecules to enhance the storage capacity, density and selectivity is the key to overcoming these barriers. For this reason, visualisation of the host–guest interactions involved in the MOF–gas binding interactions is crucial for the design of new materials. Interrogation of adsorption mechanisms by in situ experiments as a function of gas loading can afford key insights into the preferred binding sites within pores and the interaction to the pore interior. Open metal sites and pendent functional groups (e.g. amine, hydroxyl group and nitrogen-containing aromatic rings) have been found to act as specific sites for CO$_2$ and SO$_2$ binding.

Ionic liquids are composed of cations such as ammonium, pyridinium, phosphonium and imidazolium groups, and the solubility of CO$_2$ and SO$_2$ in these systems is often high owing to strong acid–base interaction. The incorporation of functionalized organic ligands within MOFs and post synthetic modification can be used to control the number and types of functional groups within the pores. Cleavage of C–N bonds and hydrolysis of methyl viologen in alkaline solution have been observed. However, the dealkylation of pre-formed MOFs has not been reported previously, although adsorption of CO$_2$ in two imidazolium–pyridinium cation-containing MOFs has been observed. We report the synthesis of a highly unusual charged material MFM-305-CH$_3$, [Al(OH)(L)]Cl, ([H$_2$L]Cl = 3,5-dicarboxy-1-methylpyridinium chloride) incorporating cationic (methylpyridinium) and anionic (chloride) components giving the material zwitterionic features. By heating MFM-305-CH$_3$ at 180 °C, the 1-methylpyridiniumdicarboxylate ligand undergoes in situ demethylation to give the pyridine-based neutral complex MFM-305 showing the same overall framework topology. Demethylation coupled to loss of chloride anion exposes the bridging hydroxyl group in the MOF pore for hydrogen bonding to substrates, with MFM-305-CH$_3$ and MFM-305 showing distinct charge distributions and pore environments decorated with different functional groups. This provides a unique platform to investigate the precise roles of Lewis acid, Lewis base, chloride, methyl, pyridine and hydroxyl groups in the binding of guest molecules. Through in situ synchrotron X-ray diffraction, neutron diffraction, IR, $^2$H NMR and neutron spectroscopic experiments, the binding of CO$_2$ and SO$_2$ has been comprehensively investigated in these two porous materials. All experiments show that the binding domains for CO$_2$ and SO$_2$ molecules are directly affected by the tuning of surface charge distribution and functional groups. Significantly, simultaneously enhanced adsorption capacity and selectivity have been observed on going to MFM-305. We also report a unique study of structural dynamics of restricted guest molecules in MOFs as a function of temperature, showing the unprecedented mobility of CO$_2$ molecule within the pores.

## Results and discussion

### Structural analysis of MFM-305-CH$_3$

Solvent exchange of AlCl$_3$, 6H$_2$O, [H$_2$L]Cl ([H$_2$L]Cl = 3,5-dicarboxy-1-methylpyridinium chloride) in a mixture of methanol and water (v/v = 12) at 130 °C for 3 days afforded MFM-305-CH$_3$-solv, [Al(OH)(L)]Cl-solv, as a white crystalline powder in ca. 45% yield. The structure of MFM-305-CH$_3$-solv has been determined by high resolution synchrotron X-ray powder diffraction (SPXRD). MFM-305-CH$_3$-solv crystallizes in the space group $I4_1/amd$ and has an open structure comprising cis-connected, corner-sharing chains of [AlO$_4$(OH)$_2$]$_2$ bridged by dicarboxylate ligands. The Al$^{III}$ centre shows octahedral coordination defined by four carboxylate oxygen atoms from the ligand [Al-O = 2.048(8) and 1.881(3) Å; each appears twice] and two oxygen atoms from two $\mu_2$-hydroxyl groups [Al–O = 1.776(6) Å]. Adjacent Al$^{III}$ centers are linked by a $\mu_2$-hydroxyl group to form an extended chain of [AlO$_4$(OH)$_2$]$_2$ along the c axis. The ligands further bridge [AlO$_4$(OH)$_2$]$_2$ chains to give a three dimensional network with square-shaped channels filled with disordered guest solvents. The window size of the channel is approximately 4.6 × 4.6 Å taking van der Waals radii into consideration (Fig. 1 and S23†). Overall, the metal–ligand connection in MFM-305-CH$_3$-solv is comparable to that in MFM-300 (ref. 21) and CAU-MU-2.
Guest solvent molecules in the pores can be removed by heating at 110 °C under vacuum for 10 h to give the desolvated material MFM-305-CH₃, which retains the structure of the solvated material as determined by SXRD. As expected, the framework of desolvated MFM-305-CH₃ is cationic since it incorporates pyridinium moieties, and these are balanced by chloride ions that hydrogen bond to the hydroxyl groups and aromatic –CH groups on the pyridinium ring [Cl⋯H-O = 2.01(1) Å; Cl⋯H-C = 2.47(1) Å]. As a result, the μ₂-OH groups in MFM-305-CH₃ are hindered by the Cl⁻ ions and are thus not accessible to guest molecules, leaving 1-methylpyridinium and chloride ion as potential sites for guest interaction. The stability and rigidity of the framework in MFM-305-CH₃ has been confirmed by variable temperature PXRD (Fig. S5 and S6†). A change in color from white to pale yellow upon the removal of chloride (see below) is a clear indicator of the framework decomposition above 450 °C.

Structural analysis of MFM-305

TGA-MS measurements of desolvated MFM-305-CH₃ shows that the methyl and chloride groups can be removed from the pore at 150–300 °C (Fig. S3†) giving the iso-structural neutral material MFM-305. To prepare a bulk sample of MFM-305, as-synthesized MFM-305-CH₃-solv was heated at 180 °C under vacuum for 16 h to completely remove the guest solvents and CH₃OH (Fig. S4†). A change in color from white to pale yellow is observed on going from MFM-305-CH₃ to MFM-305. SXRD analysis of MFM-305 confirms that it retains the same space group I₄₁/amd, but shows a slight contraction along the a/b axis (Δ = 0.06%) and c axis (Δ = 4%) with an extended channel size of 5.6 × 5.6 Å. The total free solvent volume in MFM-305 was estimated by PLATON/SOLV to be 39.9%. The most significant change is conversion of the methylpyridinium species in MFM-305-CH₃ to a free pyridyl moiety in MFM-305 and formal loss of CH₃Cl. The bridging hydroxyl groups in MFM-305 are now exposed because of the removal of chloride (see below). Moreover, the pyridyl groups are now accessible within the pores of MFM-305, and IR spectroscopy confirms the loss of the stretching vibration of the –CH₃ group at 2988 cm⁻¹ on going from MFM-305-CH₃ to MFM-305 (Fig. S7†). The complete removal of Cl⁻ in MFM-305 has been confirmed by XPS spectroscopy (Fig. S5 and S6†). Interestingly, the post-synthetic modification leads to distinct pore environments for isostructural MFM-305-CH₃ and MFM-305, and thus provides an excellent platform to examine their capabilities of guest binding and selectivity. To the best of our knowledge, this is the first example of studying the mechanism of guest adsorption within an isostructural pair of MOFs with charged and neutral pore environments of this kind (Table 1).

| Table 1 Unit cell parameters of MFM-305-CH₃ and MFM-305 |
|----------------|----------------|
| MFM-305-CH₃    | MFM-305        |
| Formula        | All(OH)(C₆H₂NO₃)Cl | All(OH)(C₆H₆NO₃) |
| Mᵣ            | 259.6           | 209.1           |
| Space group    | I₄₁/amd         | I₄₁/amd         |
| a, b (Å)       | 21.48(6)        | 21.495(3)       |
| c (Å)          | 10.90(3)        | 10.457(2)       |
| Volume (Å³)    | 5030(30)        | 4831.6(1)       |
| BET surface area/m² g⁻¹ | 256            | 779             |
| Pore volume    | 0.181           | 0.372           |
| Pore size (HK)/Å | 5.2            | 6.2             |
| Pore volume (Cal.)/cm³ g⁻¹ | 0.209         | 0.347           |
| Pore size (Cal.)/Å | 4.6            | 5.6             |
| CO₂ uptake/mmol g⁻¹ | 2.98/2.39     | 3.55/2.65       |
| (273/298 K)    |                 |                 |
| SO₂ uptake/mmol g⁻¹ | 5.29/5.16     | 9.05/6.99       |
| (273/298 K)    |                 |                 |

Gas adsorption analysis

N₂ isotherms at 77 K for desolvated MFM-305-CH₃ and desolvated MFM-305 both show type-I profiles confirming retention of microporosity. The BET surface area and total pore volume for MFM-305-CH₃ are estimated to be 256 m² g⁻¹ and 0.181 cm³ g⁻¹, respectively, and 779 m² g⁻¹ and 0.372 cm³ g⁻¹, respectively, for MFM-305 confirming a ~2.0 fold increase in porosity upon the modification (Fig. 2a, Table S1†). Horváth–Kawazoe (HK) analysis* of the N₂ isotherm confirms a pore size distribution centered at 5.2 and 6.2 Å for MFM-305-CH₃ and MFM-305, respectively (Fig. 2b). The increase in pore size is consistent with those confirmed by X-ray structural analysis.

CO₂ isotherms at 195 K and 1.0 bar show saturated uptake capacities of 4.23 and 5.69 mmol g⁻¹ for MFM-305-CH₃ and MFM-305, respectively (Fig. S24†). The increase (ca. 33%) is much smaller than that of N₂ isotherm, consistent with the reduced kinetic diameter of CO₂ (3.30 Å) compared to N₂ (3.89 Å). At 273 K and 298 K, MFM-305-CH₃ shows CO₂ uptakes of 2.67 and 2.41 mmol g⁻¹, respectively, at 1.0 bar (Fig. 2c and d). In comparison, the values for MFM-305 were recorded as 3.55 and 3.02 mmol g⁻¹, respectively. The CO₂ uptake at 0.15 bar, which is relevant to its partial pressure in flue gas, are 0.86 mmol g⁻¹ for MFM-305-CH₃ and 1.76 mmol g⁻¹ for MFM-305. This uptake is higher than that of H₂(CuCl)₃(BTTri)₃-en (BTTri = 1,3,5-tris[1H-1,2,3-triazol-5-yl]benzene) (0.682 mmol g⁻¹)* and NH₂-MIL-101(Cr) (0.5 mmol g⁻¹),* but lower than that of MFM-300[Al] (2.64 mmol g⁻¹),* MOF-74(M) (M = Mg, Ni, Co) (5.3, 2.7, 2.7 mmol g⁻¹, respectively)* and the aminomodified MIL-101 (4.2 mmol g⁻¹)* under the same conditions.

The excellent stability of these two MOFs motivated us to measure the adsorption isotherm of SO₂. At 298 K and 1.0 bar, Mg-MOF-353 and MFM-305 show SO₂ adsorption capacities of 5.16 and 6.99 mmol g⁻¹, respectively (Fig. 2c and d). Importantly, the SO₂ uptake is fully reversible in both materials, and no loss of crystallinity or porosity was observed for the regenerated samples. At 298 K and 1.0 bar, the SO₂ uptake of MFM-305 is notably higher than that of most solid sorbents in the literature (Fig. S29,† Table S2†), and only lower than that of MFM-300(In) (8.28 mmol g⁻¹), Mg-MOF-74 (8.6 mmol g⁻¹), Ni(bdc)(ted)₆₃ (9.97 mmol g⁻¹) (H₂bdc = terephthalic acid; ted = triethylenediamine), MFM-202a (10.2 mmol g⁻¹) and SIFSIX-1-Cu (11.01 mmol g⁻¹), which have higher surface areas of 1071, 1525, 1783, 2220 and 3140 m² g⁻¹, respectively. At 303 K, MFM-305 shows an adsorption capacity...
for SO₂ of 6.70 mmol g⁻¹ at 1.0 bar, and a high uptake of 3.94 mmol g⁻¹ at 0.025 bar, comparable to the best-behaving MOFs. Using the total pore volume, the storage density of SO₂ in a given MOF system can be estimated; those for MFM-305-CH₃, SIFSIX-1-Cu-i, MFM-305 and MFM-300(In) are calculated to be 1.83, 1.70, 1.20 and 1.27 g cm⁻³, respectively at 298 K and 1.0 bar. Thus, MFM-305-CH₃ gives a notably higher storage density that is 70% of liquid density of SO₂ at 298 K (2.63 g cm⁻³), indicating the presence of efficient packing of adsorbed gas molecules within the pore.

Both MFM-305-CH₃ and MFM-305 show highly selective SO₂ uptakes. At 298 K, MFM-305-CH₃ and MFM-305 exhibit very steep adsorption profiles for SO₂ between 0 and 20 mbar, leading to an uptake of 3.59 and 3.94 mmol g⁻¹, respectively, accounting for 70% and 56% of the total uptake at 1.0 bar. In contrast, under the same conditions, MFM-305-CH₃ and MFM-305 show a much lower uptake of CO₂ (i.e., 0.15 and 0.40 mmol g⁻¹, respectively).
Moreover, the uptakes of N₂ under the same conditions are negligible (<0.01 mmol g⁻¹) in these two materials. The isosteric heat of adsorption (Qₑ) for CO₂ in MFM-305-CH₃ and MFM-305 both lie in the range of 29-34 kJ mol⁻¹; on average the Qₑ of MFM-305 is ca. 3 kJ mol⁻¹ higher than MFM-305-CH₃ (Fig. 2e). The Qₑ for adsorption of SO₂ in MFM-305 and MFM-305-CH₃ is estimated to be 39-43 kJ mol⁻¹ and 30-32 kJ mol⁻¹, respectively (Fig. 2g). MFM-305 displays a higher Qₑ value for SO₂ uptake than MFM-305-CH₃, indicating the presence of enhanced host-guest binding affinity upon the pore modification. To further evaluate their potential for gas separation, the selectivities for CO₂/N₂(SCN), SO₂/CO₂ (S₇c) and SO₂/N₂ (S₈n) at 298 K have been calculated using ideal adsorbed solution theory (IAST) over a wide range of molar compositions (i.e., 1:99 to 50:50) (Fig. 2f, h, S31 and S32†). Sigificantly, for a 5:95 mixture of SO₂/CO₂ and a 15:85 mixture of CO₂/N₂, MFM-305-CH₃ and MFM-305 both show exceptionally high IAST selectivities, and these are enhanced by the pore modification. The calculations for S₈n are subject to large uncertainties due to the extremely low uptake of N₂. The adsorptive removal of low concentration SO₂ by MFM-305 has been confirmed by breakthrough experiments in which a stream of SO₂ (2500 ppm diluted in He/N₂) was passed through a packed bed of MFM-305 under ambient conditions (Fig. 3a). As expected, He and N₂ were the first to elute through the bed, whereas SO₂ was retained selectively under dry condition (Fig. 3a). On saturation (dimensionless time > 500), SO₂ breaks through from the bed and reaches saturation gradually. The ability of MFM-305 to capture SO₂ in the presence of moisture has also been demonstrated by breakthrough experiments using a wet stream of SO₂ (Fig. 3b). In the presence of water vapor, the breakthrough of SO₂ from MFM-305 slightly reduces to 420 (dimensionless time) as a result of competitive adsorption of water. Thus, the marked differences in adsorption profiles, uptake capacities, Qₑ of SO₂, CO₂ and N₂, the corresponding IAST selectivity and the dynamic adsorption experiments indicate the potential of MFM-305-CH₃ and MFM-305 to have the potential to act as selective adsorbents for CO₂ and SO₂.

**Determination of binding domains for adsorbed CO₂ and SO₂**

We sought to determine the binding domains for CO₂ and SO₂ in the pores of MFM-305-CH₃ and MFM-305 since comparison between the binding sites within these two materials affords a direct observation of the effect of pore environment on guest binding. High resolution SXPD data were collected at 198 K for CO₂-loaded samples and at 298 K for SO₂-loaded samples at 1 bar. SXPD data enabled full structural analysis via Rietveld refinement (Fig. S8-S22†) to yield the positions, orientations and occupancies of adsorbed CO₂ and SO₂ molecules (Fig. 4 and S33†). Overall, all gas-loaded samples retain the H₄/ adamant space group and two crystallographically independent binding sites (I and II) are observed in each case.

In CO₂-loaded MFM-305-CH₃, CO₂ (occupancy = 0.32) interacts with the methyl group with a H₃CCO distance of 2.54(1) Å, indicating the formation of a weak hydrogen bond. CO₂ also forms supramolecular interactions with aromatic –CH groups on neighboring pyridinium rings [OCO-…HC = 2.87(2) Å]. Additionally, dipole interactions were observed between CO₂ and Cl⁻ [OCO-…Cl⁻ = 3.78(1) Å, ∠O-C…Cl⁻ = 99.2(8)°].

CO₂ [occupancy = 0.41] binds to the aromatic –CH group [OCO-…HC = 3.50(1) Å]. Further dipole interactions were observed between CO₂ and CO₂ [O2-…C2 = 3.87(1) Å; O2…C2 = 4.10(1) Å] in a typical T-shape arrangement.

In CO₂-loaded MFM-305, CO₂ (occupancy = 0.48) interacts with the hydroxyl group in an end-on mode [OH…CO = 3.45(3) Å]. This distance is longer than that obtained for CO₂-loaded MFM-300(AI) [2.298(4) Å] studied by PXRD at 273 K. CO₂ also interacts with the exposed pyridine nitrogen atom via a dipole interaction [OCO-N = 2.89(1) Å]. Additionally, a series of weak supramolecular contacts of CO₂ to surrounding –CH groups [OCO-…HC = 2.44(1); 2.73(1) Å] are also observed. Further dipole interactions are found between CO₂ and CO₂ with intermolecular c²-…O²/C²-…O² distances of 3.09(1)/3.14(1) Å, comparable to that observed in dry ice [3.178(1) Å]. At 298 K SO₂-loaded MFM-305-CH₃ shows the SO₂ molecule (occupancy = 0.30) binding to two adjacent methyl groups simultaneously [OSO-…HC = 2.49(3) Å]. SO₂ also forms hydrogen bonds with surrounding –CH groups [OSO-…HC = 2.54(2) Å]. SO₂ [occupancy = 0.47] lies perpendicular to SO₂ [S²…O²/S²-…O² = 3.38(2) and 3.97(3) Å] and parallel to the pyridinium ring [OSO-…HC = 3.95(1) Å]. The SO₂ intermolecular distances within MFM-305-CH₃ are comparable to that observed in the crystal structure of SO₂ (3.10 Å), confirming the very efficient packing of adsorbed SO₂ molecules leading to its high observed storage density.
In MFM-305, SO$_2^-$ (occupancy = 0.39) primarily binds to the pyridyl N-atom via a dipole interaction [O$_{\text{SO}}$–N = 2.78(1) Å] and also forms hydrogen bonds with the exposed hydroxyl group [–OH···O$_{\text{SO}}$ = 3.42(4) Å] as well as the surrounding –CH groups [–CH···O$_{\text{SO}}$ = 2.63(3) and 3.14(3) Å]. Further dipole interactions were observed between SO$_2$ molecules on sites I and II with intramolecular distance of 4.29(2) Å. Overall, these observations confirm that the methyl group and –CH$_3$ groups are the primary binding sites in MFM-305-CH$_3$ for both CO$_2$ and SO$_2$. In contrast, modulation of the pore environment in MFM-305 induces notable shifts of binding sites to the free pyridyl nitrogen center and hydroxyl group. This study offers a comprehensive understanding of the synergistic effect of functional groups on the binding of CO$_2$ and SO$_2$ in these materials.

**Analysis of host-guest binding via inelastic neutron scattering (INS)**

To directly visualise the multiple supramolecular host-guest binding modes in these systems, INS spectra of bare and CO$_2$-loaded MFM-305-CH$_3$ and MFM-305 (1 gas/Al) were collected at 5 K (Fig. 5). In addition, the structural models obtained from X-ray crystallographic studies were optimized by DFT calculations. The corresponding DFT-calculated INS spectra show good agreement with the experimental data (Fig. S35–S39†). Comparison of the INS spectra of desolvated MFM-305-CH$_3$ and MFM-305 shows (Fig. S35†) three distinct low-energy peaks at 13, 27, 36 and 19, 28, 37 meV, respectively, related to the lattice modes of MFM-305-CH$_3$ and MFM-305. The most significant change is the absence of the –CH$_3$ rotation/torsion mode at 20 meV in MFM-305, confirming full demethylation by the post-synthetic modification procedure. The groups of peaks observed at 40–85 meV and 85–200 meV in MFM-305-CH$_3$ are assigned to wagging/bending modes of the bridging hydroxyl group and of the aromatic C–H bonds, respectively. As crystallographic studies confirm above, the hydroxyl groups within MFM-305-CH$_3$ form hydrogen bonds to the chloride ion in the pores. Upon demethylation, the peaks at 40, 69 and 83 meV in MFM-305-CH$_3$ shifts to higher energies at 53, 83, 115 and 119 meV in MFM-305, consistent with the removal of the chloride ions.

Addition of CO$_2$ in MFM-305-CH$_3$ is accompanied by significant change to peaks at 13 and 27 meV, indicating stiffening of the lattice modes as a result of CO$_2$ inclusion. Large intensity changes were observed for the peaks at 20 meV, indicating the hindrance of rotation motion of –CH$_3$ groups upon CO$_2$ binding, consistent with the formation of hydrogen bonds.
as observed in the structural models. This is further accompanied by small red shifts for the peaks between 85 and 200 meV (bending modes of –CH groups). Thus, the INS result confirms that the methyl and –CH groups are the effective binding sites for CO2 in MFM-305-CH3. Addition of CO2 in MFM-305 leads to similar changes of peaks at 19, 28 and 37 meV. Significant changes to peak at 53, 83, 115 and 119 meV indicate that the bridging hydroxyl is directly involved in binding to CO2. The peaks between 120 and 200 meV also show notable changes in the C–H modes on CO2 binding. This result confirms unambiguously that the –OH group and pyridine ring are the primary binding site for CO2 in MFM-305, in excellent agreement with the crystallographic study. The combination bands of the –C–C– vibrations within MFM-305-CH3 centered at 1555 cm⁻¹ shi to 1560 cm⁻¹, and that at 1552 cm⁻¹ in MFM-305 shifts to 1566 cm⁻¹ upon CO2 loading, consistent with the formation of supplementary interactions between CO2 molecules and pyridinium or pyridyl rings (Fig. S40†). Thus, the observed changes in IR experiments gives further evidence and supports the distinct interactions between guest CO2 molecules and these two porous MOFs.

Analysis of host–CO2 binding via in situ ²H NMR spectroscopy

The –CH3 group in the 1-methylpyridinium dicarboxylate linker represents a fast stochastic rotor or natural isolated gyroscope. As such, its rotational parameters can be used to track the possible binding interaction with the guest molecules. We were interested to probe further the dynamic changes of the methyl groups on CO2 binding by synthesising MFM-305-CD3 and studying it by solid state ²H NMR spectroscopy over a wide temperature range (90–300 K). MFM-305-CD3 was obtained using the same synthetic route described above but using the deuterated ligand, 3,5-dicarboxy-1-methyl-d₃-pyridinium chloride. Two samples were used in this ²H NMR study: guest-free MFM-305-CD3 and CO2-loaded MFM-305-CD3.
Typically the $\text{–CD}_3$ group is expected to exhibit very fast uniaxial rotation and hence its dynamics can be probed by $^2\text{H}$ NMR spin-lattice ($T_1$) relaxation, which is sensitive to rapid (rate $> 10^8$ s$^{-1}$) motions.\textsuperscript{45,46} The $T_1$ relaxation curves (Fig. 6) show for both materials that the temperature dependence is characterised by two regions of monotonous decrease separated by a local minimum (marked as a and c in Fig. 6). Such behavior shows that in addition to the usual uniaxial rotations, the methyl groups perform another type of motion – a faster one, as it governs the relaxation curve notably at lower temperatures (marked b and d in Fig. 6). In CO$_2$-loaded MFM-305-CD$_3$, both modes are notably slower which is reflected in the behavior of the $T_1$ curves behavior at $\sim$180 K and $\sim$100 K. A quantitative analysis requires a model of rotation (Fig. 6d and e): considering the close contact of the $\text{–CD}_3$ group with the neighboring linker ($d \sim 3 \text{ Å}$), it is reasonable to assume that the slower (a, c) motion ($k_1, k_1$) reflects the uniaxial rotation of the $\text{–CD}_3$ group about its $C_3$ symmetry axis aligned along the $\text{–CD}_3$ bond, while the faster (b, d) motion ($k_2, k_2$) represents small angular librations of the rotating axis restricted within borders $\pm \gamma_{\text{lib}}$.

Parameters derived within such a model confirm that the rotation along $\text{–C}D_3$ axis ($E_1 = 4.2 \text{ kJ mol}^{-1}, k_{10} = 2.1 \times 10^{10}$ s$^{-1}$) reaches a rate of $k_1 \sim 10^8$ s$^{-1}$ at 100 K (a), while in the presence of the CO$_2$ it is $\sim$10 times slower with $k_{10}^\prime \sim 10^7$ s$^{-1}$ ($E_1^\prime = 4.2 \text{ kJ mol}^{-1}, k_{10}^\prime = 1.8 \times 10^9$ s$^{-1}$), and reaches $10^5$ s$^{-1}$ at 180 K (c). Hence, by interacting with CO$_2$, the pre-exponential factor of the $\text{–CD}_3$ rotation is affected. This indicates that although the interaction with CO$_2$ is not sufficient to increase the activation barrier of the rotation, the dynamic density of guests around the methyl groups is tight enough and sufficient to slow down the rotation rate by 10-fold by random collisions. Similarly, the libration mode is affected as well and the pre-exponential is faster and reaches its characteristic minimum\textsuperscript{45} below 90 K (b, d). For MFM-305-CD$_3$ its rate at 100 K is $k_2 \sim 10^{11}$ s$^{-1}$, while for CO$_2$-loaded MFM-305-CD$_3$ it is notably slower and can be resolved unambiguously ($E_2^\prime = 5.1 \text{ kJ mol}^{-1}, k_{20} = 0.65 \times 10^{13}$ s$^{-1}$) with $k_2^\prime \sim 10^{10}$ s$^{-1}$ (100 K). Notably, the amplitude of the restricted librations also sense the presence of CO$_2$ with $\gamma_{\text{lib}} \sim 5^\circ$ decreasing to $\gamma_{\text{lib}}^\prime \sim 2^\circ$. This decrease in libration angle coupled with the strong deceleration of both motional modes by $\sim$10 times in the presence of CO$_2$ evidences the interaction of CO$_2$ guests with the methyl groups within the MOF pores.

**Structural dynamics of restricted CO$_2$ molecules in the pore**

To investigate the dynamics of host–guest interaction, we sought to study the structural flexibility of restricted CO$_2$ molecules (e.g., positions, orientations and occupancies) within the pores of MFM-305-CH$_3$ and MFM-305 via variable temperature SXRD. Le Bail analysis reveals changes in lattice parameters of CO$_2$-loaded samples as a function of temperature (Fig. 7, Table S3†). As the temperature decreases from 273 K to 117 K, the lattice parameters of CO$_2$-loaded MFM-305-CH$_3$ contract along all directions ($\Delta V/V = 0.7\%$), whereas MFM-305 expands along $c$ axis ($\Delta c/c = 1.3\%$) and contracts along the $a$/$b$ axes ($\Delta a/b = 0.02\%$) as the temperature decreases from 270 K to 100 K (Fig. S41†). Throughout the temperature range studied, two independent binding sites for CO$_2$ molecules were observed in both samples. In general, the intermolecular distances of

![Fig. 6 View of the temperature dependence of $^2\text{H}$ NMR spin–lattice relaxation for $\text{–CD}_3$ groups. (a) Experimental results for guest free MFM-305-CH$_3$ (black circles) and for CO$_2$@MFM-305-CH$_3$ (1 mol per cavity) (red squares). (b and c) The simulated curve for MFM-305-CH$_3$ and CO$_2$@MFM-305-CH$_3$ based upon two relaxation mechanisms corresponding to the two dynamic states of the $\text{–CD}_3$ groups. (d and e) Representation of possible $\text{–CD}_3$ motions in MFM-305-CH$_3$ cavity.](Image)
MOF–CO₂ and CO₂–CO₂ decrease continuously as the temperature decreases (Tables S3 and S4†).

The CO₂ supply was maintained at 1.0 bar on going from room temperature to 198 K. In MFM-305-CH₃, the occupancy of CO₂ [I + II] increased from 0.60 to 0.70 from 273 K to 230 K, with CO₂ hydrogen bonding with the methyl group and the –CH groups on the pyridyl ring. The hydrogen bond distances [OC₁–O₂H₃C] decrease steadily from 3.10(2) to 2.38(2) Å from 273 K to 117 K, indicating that the strength of these hydrogen bonds is highly sensitive to temperature (Fig. 7, Table S4†). Interestingly, as the temperature decreases, we observe significant re-arrangement of restricted CO₂ molecules at site I and II. CO₂ molecules move closer to the pore surface and rotate to drive the oxygen atoms closer to the ligands to form stronger hydrogen bonds. CO₁ and CO₂ retain their T-shape arrangement, but move closer to each other. From 273 K to 117 K, the ratio [i.e. CO₂/(CO₂ + CO₂) × 100%] of the occupancy of site I decreases from 50(2)% to 40(2)% while the occupancy of site II increases from 50(2)% to 60(1)%.

The activation energy ($E_a$) of the site configuration and occupancy was calculated using the Arrhenius equation as a function of temperature. From 273 K to 117 K, $E_a$ for site I is 0.233 kJ mol⁻¹, and for site II it is −0.128 kJ mol⁻¹. The changes of site configuration and occupancy reveal that the host–guest binding is highly sensitive to temperature via intra-pore re-arrangement.

Variable temperature PXRD data were collected for MFM-305 using the same method. CO₂ forms hydrogen bonds with hydroxyl group and the –CH groups of the pyridyl ring, and the free N-center of the pyridyl ring interacts with CO₂ via dipole interactions. The hydrogen bond distance (OC₁–HO) and the distance of CO₂ to the N-center (N–O) both reduce from 4.20(3) to 3.34(4) and from 3.16(1) to 2.96(1) Å, respectively, as the temperature is lowered from 270 K to 100 K. The intermolecular distances between CO₂ and CO₁ (OC₁–OC₁′ and OC₁–OC₁″) reduce from 5.03(2) to 3.07(1) Å and 5.04(3) to 2.94(1) Å, respectively, from 270 K to 100 K (Fig. 7, Table S4†). From 270 K to 198 K, the total CO₂ occupancy increases from 0.5 to 0.92, which was retained to 100 K. From 270 K to 198 K, the ratio of CO₂ decreases from 74(1)% to 53(1)% and that of CO₂ decreases from 26(1)% to 47(1)%. Below 198 K, the ratio of CO₂ increase slightly to 57(1)% and that of CO₂ decreases to 43(1)%. CO₂ is in a cross-tunnel mode at 270 K. CO₂ molecules are...
parallel to the pyridine ring at 270 K, and rotate to be almost parallel to CO$_2$ with reducing temperature. From 270 K to 198 K, the $E_a$ of CO$_2$ and CO$_2^+$ are 2.068 and $-2.842$ kJ mol$^{-1}$, respectively, and from 198 K to 100 K, the $E_a$ values are $-0.125$ kJ mol$^{-1}$ and 0.154 kJ mol$^{-1}$ for CO$_2$ and CO$_2^+$, respectively. The $E_a$ for adsorbed CO$_2$ molecules in MFM-305 is significantly higher than that of MFM-305-CH$_3$ at 270–198 K, indicating the formation of stronger host–guest interactions in MFM-305. This study confirms that the host–guest interaction between functional groups and CO$_2$ molecules in these two MOFs follows the trend of hydroxyl/pyridyl groups: CO$_2$ > CO$_2^+$ > methyl group – methyl group. Thus, the simultaneous enhancements of adsorption capacity and host–guest binding affinity upon pore modification on going from MFM-305-CH$_3$ to MFM-305 can be fully rationalised.

The crystal structure of CO$_2$-loaded MFM-305-CH$_3$ was also determined at 7 K by neutron powder diffraction which confirms retention of the space group $I4_1/amd$. Interestingly, a completely new structure was resolved where only one binding domain for adsorbed CO$_2$ was located near the methyl group (Fig. S34†). The adsorbed CO$_2$ molecules are disordered about a 2-fold rotation axis and in a cross-tunnel mode interacting with the methyl group with a CH$_3$–OCO distance of 3.58(2) Å. CO$_2$ also binds to the pyridinium–hydrogen atoms with a CH–OCO distance at 3.08(2) Å. This result confirms the significant impact of temperature on the binding sites and orientation of adsorbed CO$_2$ molecules in MFM-305-CH$_3$.

Conclusions

We have reported here the synthesis and characterisation of porous MFM-305-CH$_3$, and its transformation via post-synthetic demethylation to give the isostructural, neutral MFM-305. The post-synthetic modification has enabled direct modulation of the pore environment, including changes in charge distribution and accessible functional groups. Significantly, MFM-305 shows simultaneously enhanced CO$_2$ and SO$_2$ uptake and CO$_2$/N$_2$ and SO$_2$/CO$_2$ selectivities over MFM-305-CH$_3$; these two factors are widely known to display a trade-off in porous materials. A comprehensive investigation of the host–guest binding using a combination of synchrotron X-ray and neutron powder diffraction, INS, $^3$H NMR and IR spectroscopy and modelling has unambiguously revealed the role of Lewis acid, Lewis base, chloride ions, methyl and hydrosulphide groups in the supramolecular binding of guest molecules within the pores of both MOFs. Considering that these two MOFs have similar pore shape and size, the distinct binding mechanisms to guest molecules between these two samples is a direct result of the charge modulation. We have also confirmed that post-synthetic modification via dealkylation of the as-synthesised metal–organic framework is a powerful route to the synthesis of materials incorporating active polar groups, in this case a free pyridyl N-donor. Thus, deprotection of the as-synthesized MOF allows the synthesis of materials that cannot as yet, in our hands, be synthesized directly.

Conflicts of interest

The authors declare no competing financial interests.

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Notes and references
