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Jacopo Perego, Andrea Daolio, Charl Bezuidenhout, Sergio Piva, Giacomo Prando, et al.. Solid State Machinery of Multiple Dynamic Elements in a Metal–Organic Framework. *Angewandte Chemie International Edition*, 2024, 63 (10), 10.1002/anie.202317094 . hal-04754231

HAL Id: hal-04754231

<https://hal.science/hal-04754231v1>

Submitted on 25 Oct 2024

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RESEARCH ARTICLE

Solid State Machinery of Multiple Dynamic Elements in a Metal-Organic Framework

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Supporting information for this article is given via a link at the end of the document.

Abstract: Engineering coordinated rotational motion in porous architectures enables the fabrication of molecular machines in solids. A flexible two-fold interpenetrated pillared Metal-Organic Framework precisely organizes fast mobile elements such as bicyclopentane (BCP) (10^7 Hz regime at 85 K), two distinct pyridyl rotors and *E*-azo group involved in pedal-like motion. Reciprocal sliding of the two sub-networks, switched by chemical stimuli, modulated the sizes of the channels and finally the overall dynamical machinery. Actually, iodine-vapor adsorption drives a dramatic structural rearrangement, displacing the two distinct subnets in a concerted piston-like motion. Unconventionally, BCP mobility increases, exploring ultra-fast dynamics (10^7 Hz) at temperatures as low as 44 K, while the pyridyl rotors diverge into a faster and slower dynamical regime by symmetry lowering. Indeed, one pillar ring gained greater rotary freedom as carried by the azo-group in a crank-like motion. A peculiar behavior was stimulated by pressurized CO_2 , which regulates BCP dynamics upon incremental site occupation. The rotary dynamics is intrinsically coupled to the framework flexibility as demonstrated by complementary experimental evidence (multinuclear solid-state NMR down to very low temperatures, synchrotron radiation XRD, gas sorption) and computational modelling, which helps elucidate the highly sophisticated rotor-structure interplay.

Introduction

The study of dynamics in solids is presently a topical issue, since the design and fabrication of smart materials with integrated molecular rotors, motors and switches offers unprecedented opportunities to express innovative properties in response to either chemical or physical stimuli.^[1] Relevant examples comprise commutation of light into mechanical work, tunable dielectric and

optical properties, the switch of ferroelectricity and on-command gas capture.^[2]

Porous materials have been shown as a robust platform providing the necessary free space for dynamics to occur.^[3] Self-assembly of appropriate organic modules into Metal-Organic Frameworks (MOFs) provides a versatile strategy to design highly porous 3D crystalline materials with excess free volume wherein limited interference among the dynamogenic moieties can be realized.^[4] Among the variety of organic linkers suitable for the assembly of MOFs, fast molecular rotors can be designed and integrated within the backbone of the network considering a few criteria to promote their mobility, including a limited interference among rotors and a low-density scaffold. Additionally, conformational softness to rotation, which is not compatible with extended electronic conjugation and steric hindrance about the mobile elements, is a fundamental feature: these requisites are widely satisfied by aliphatic ligands, which are less common in the realm of MOFs.

Engineering a proper symmetry mismatch of the molecular rotor and the supporting nodes has been a novel principle recently achieved in this family, yielding benchmark rotation with virtually absent energy barrier and frustrated-symmetry rotors.^[4a] Specifically, bicyclopentane dicarboxylate ligands (BCP) are optimal candidates as rotors in the frameworks, since they maintain high-frequency motion even in the low temperature limit with the negligible energy of a few calories per mole.^[5] The overall frameworks can be intrinsically endowed with dynamics or flexibility which derive from the geometry of metal nodes or structural phase transitions, showing breathing effects in response to chemical or physical stimuli.^[6,7]

Pillared MOFs represent a well-known family which may exhibit reversible dynamic flexibility of the framework when solicited by guest atoms, molecules or simply temperature.^[8] Furthermore,

pillared MOFs, being composed by two organized molecular struts, offer the opportunity to design interdigitated networks comprising juxtaposed dynamic elements to fabricate cooperative rotary motion in engineered and elaborated architectures.^[5a]

Herein, we show the construction of a pillared MOF, named FTR-P2 (belonging to the family of Frustrated Trigonal Rotors), which encompasses multiple co-assembled moving parts, yet integrated into a dynamic machinery, and is governed in turn by the guest-stimulated flexibility of the entire structure. FTR-P2 comprises platforms of BCP dicarboxylate and metal nodes, sustained by azo pyridyl pillars, thus generating four rotating elements: BCP, two distinct pyridyl rings and an azo group. It forms an interpenetrated architecture of two independent networks which undergo reciprocal sliding, switching between two stable states according to the presence or absence of guests which may be loaded in the pores. In the free-pore high symmetry structure, each network is precisely centered in the middle of mutual voids, containing extremely mobile BCP rotors operating at 3.3×10^7 Hz at 85 K and azo groups with fast mobility of 3.6 kHz at 150 K. Strikingly, bulky guests, such as iodine, dramatically re-structure the framework by reducing symmetry and fuel reciprocal network sliding in a piston-like enlargement of a pore, which promotes BCP rotors to faster mobile regimes of 3.3×10^7 Hz even down to 44 K. Moreover, the guest-induced piston-like movement induces a circular motion of one pyridyl ring driven by the attached azo group, which behaves as a crank. Contrarily, smaller CO₂ molecules sorbed by the MOF maintain the high symmetry structure and interact with BCP modulating their rotation speed, as observed by in situ synchrotron radiation PXRD of the CO₂-loaded framework up to 10 bar. The dynamics of the molecular rotors, their trajectories and energy barriers were determined by a combined approach, which includes single crystal and synchrotron radiation powder X-ray diffraction, ¹³C CP

MAS down 100 K, ¹H T₁ relaxation times down to 4 K and DFT/MM modelling. Collectively, this work aimed to demonstrate how unconventional integration of rotors (mobile elements) and structural softness can govern a reversible stimulated switch of solid-state molecular motion at surprisingly low temperatures.

Results and Discussion

Pillared FTR-P2 was synthesized by self-assembly two distinct ligands (BCP = bicyclo[1.1.1]pentane-1,3-dicarboxylate and azpy = 4,4'-1,2-diazenediylbispyridine) and Zn ions under solvothermal conditions (75 °C, DMF/MeOH 1:4 mixture) (see Section S2). The synthesis produces dichromic crystals suitable for single crystal X-ray diffraction analysis, which were activated under high vacuum at 120 °C to remove solvent guest-molecules and provide open porosity, while maintaining crystallinity as demonstrated by single crystal and synchrotron source powder XRD patterns (Table S1, Figure S16). The infrared spectrum showed a band assigned to the asymmetric CO₂ stretching vibration of the carboxylate group at 1621 cm⁻¹, which is shifted to lower values of 43 cm⁻¹ due to the coordination to the Zn ions with respect to the C=O stretching of the carboxylic acid of BCP ligand (Figure S4). Solution ¹H NMR of digested samples were consistent with a 2:1 ratio between BCP and the bipyridyl ligands (Figure S8). TGA runs displayed sudden weight loss at 300 °C, associated to the thermal degradation of BCP and azpy ligands, confirming the stability of the crystals up to those temperatures (Figure S6). Additionally, ¹³C and ¹H MAS NMR spectra confirmed the purity of the samples and the absence of residual solvent molecules after activation (Figure S17 and S20a).

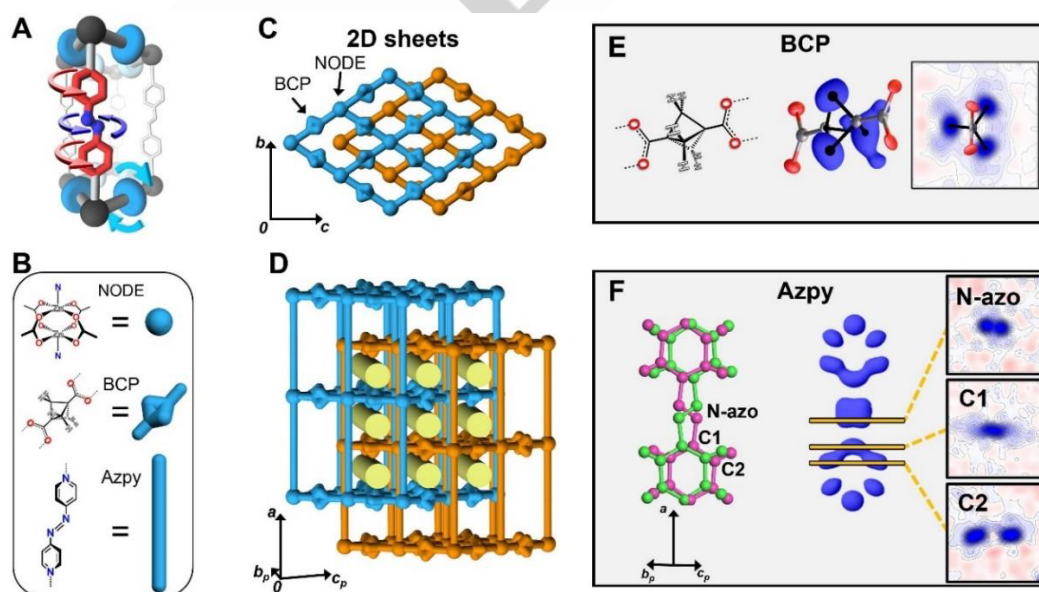


Figure 1. Crystal structure of FTR-P2. A) A single rhombus cube showing the metal node (black sphere) and the connectivity of the ligands, azo group in blue, azpy pyridyl groups in red and the BCP in cyan. B) Zn-paddlewheel node, molecular structures of BCP and azpy linkers. C) 2D layers made by BCP dicarboxylate linkers and Zn nodes forming rhombic shapes. D) The two centre-interpenetrated networks form channel-like cavities shown in yellow. E) The electron density associated with the CH₂ groups of the BCP rotor. F) *Left* - The disorder of the azpy linker with carbons C1 and C2 is highlighted. *Right* - The electron density of azpy linker (from SC-XRD data collected at 200 K) with 2D contours of C1, C2 and the azo nitrogen.

1 Single Crystal XRD of FTR-P2 revealed a two-fold
2 interpenetrated framework, wherein one network sits in the
3 center of the other (Figure 1). The two ligands, BCP and azpy,
4 play a well-diversified role in the architecture, constituting
5 layers and pillars, respectively. BCP molecules were organized
6 as layers in a rhombohedral motif by coordination to Zn ions in
7 a paddle-wheel fashion, while azobipyridyl pillars sustained the
8 layers. The resulting 2-fold interpenetrated 3D framework has
9 a **pcu** topology^[9] and orthorhombic unit-cell, with space group
10 *Cmce* (Figure 1C and 1D). In FTR-P2 structure the pyridyl rings
11 are equivalent by symmetry, and each forms two short
12 hydrogen bonds with the oxygens of the second network nodes,
13 strengthening the layer and pillar 3D architecture (Figure S11)).
14 Both ligands exhibited the signature of dynamic disorder as
15 confirmed by solid-state NMR: first, the three methylene
16 groups of the bicyclopentane ligand showed circularly
17 elongated electron density, which was compatible with a fast
18 rotation on a plane perpendicular to the BCP main molecular
19 axis (Figure 1E). Diffuse electron density was also manifested
20 in pillar azo-groups, associated with pyridyl rings swinging on
21 a common plane, indicative of a pedal-like motion (Figure
22 1F).^[10] The interpenetrated framework displays 1D corrugated
23 channels running parallel to the *b*-axes, ca. 10% of the crystal
24 volume, with cross-sections ranging from 6.0 x 2.9 Å² to 3.8 x
25 3.8 Å². No residual electron density was observed inside the
26 channels. The open porosity of the framework was
27 demonstrated by CO₂ adsorption isotherms at 195 K up to 1
28 bar (Figure S9). FTR-P2 displayed a maximum adsorbed
29 amount of about 3.2 mmol/g (ca. 8 molecules per unit cell).
30 Interestingly, FTR-P2 adsorbs neither N₂ and Ar at 77 K nor N₂
31 at 298 K, due the molecular sieving effects of the small pores
32 (Figure S10). As a consequence of the above-mentioned pore
33 selectivity of activated FTR-P2 with small and selective pores,
34 the structure should prevent the bulky molecular iodine
35 diffusing-in. However, contrary to the expectations, the crystals
36 visibly absorb I₂ without fracturing, thus yielding crystals
37 suitable for SC-XRD. I₂ inclusion, about 4 molecules per unit
38 cell as quantified from TGA (Figure S7), enables a remarkable
39 channel expansion, driven by the displacement of the
40 interpenetrated networks, as revealed by the SC-XRD of the
41 black I₂-loaded crystals (Figure 2A). The reciprocal sliding of
42 the two networks along the pillar direction of 2.45 Å thereby
43 transforms the centered interpenetrated architecture to a new
44 off-centered one, expanding one channel while virtually closing
45 the adjacent one, resembling a piston movement which pushes
46 layers apart by I₂ action (Figure 2A). The structural resolution
47 of the FTR-P2-I₂ and the localization of I₂ was obtained by
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combining *ab initio* calculations with fitting of experimental SC-
XRD data (Figure S14 and S15). The I₂ molecules can be
entirely removed by thermal treatment at 180°C, as directly
followed by thermal gravimetry (Figure S21). The empty
structure was fully restored as shown by PXRD pattern and ¹³C
CP MAS NMR, demonstrating the reversibility of the piston
movement and the cyclability of the phenomenon (Figure S24,
S25 and S27).

Following iodine insertion, the β -angle changes from 90° to 97°,
thereby changing the crystal system from orthorhombic (*Cmce*)
to monoclinic (*C2/m*, Figure 2A). Unlike the empty structure,
the coordination of the two BCP carboxylate moieties with the
Zn ions and the main BCP axis are aligned (Figure S12). In this
off-centred phase, the two rings of the pillaring ligand are no
longer equivalent: one ring (A) is exposed to the channels while
the other (B) sits in the plane of the 2D layers. Ring B is placed
at the centre of the rhombus and is close to the metal nodes,
forming multiple C-H...O hydrogen bonds with the carboxylate
oxygens, which pin its position inside the 2D layer (Figure 2D).
In contrast, ring A gains freedom and explores multiple
configurations reflected in four electron density maxima
associated with carbons C2 and C3 distributed along an arch
(Figure 2D). The Na of azo group, on which the ring A is pivoted,
is off-plane with respect to ring B and shows electron density
delocalized on two distinct positions separated by 1.2 Å. The
motion of the azo group between these two sites consequently
induces a crank-like motion of the pivoting ring A, as modelled
by MM calculations (Figure S65).

Interestingly, the I₂ molecules confined inside the channels are
localized in two distinct crystallographic environments,
denoted I₂-A and I₂-B (Figure 2B) and disordered over multiple
equivalent positions in each environment (Figure S15). The
axes of I₂-B molecules are in the most confining part of the
channels and approximately are mainly aligned along the *c*
axis (slightly tilted towards *a* axis) whilst I₂-A molecules lie
along the *b* axis. Both I₂ arrangements form intermolecular
interactions with the aromatic ring A (Figure S15B). Out of four
I₂ molecules per unit cell, two sit in I₂-A site and two in I₂-B site,
in agreement with thermogravimetry and PXRD pattern (Figure
S21 and S25, respectively).

Surprisingly, even with I₂ molecules occupying the framework
channels, the electron density of the BCP ligand is more
spread out than that of the empty structure, describing a
toroidal shape. This diffuse density indicates a major disorder
of the rotor, thus suggesting increased dynamics, instead of
the commonly described hindering action of guest
molecules.^[11]

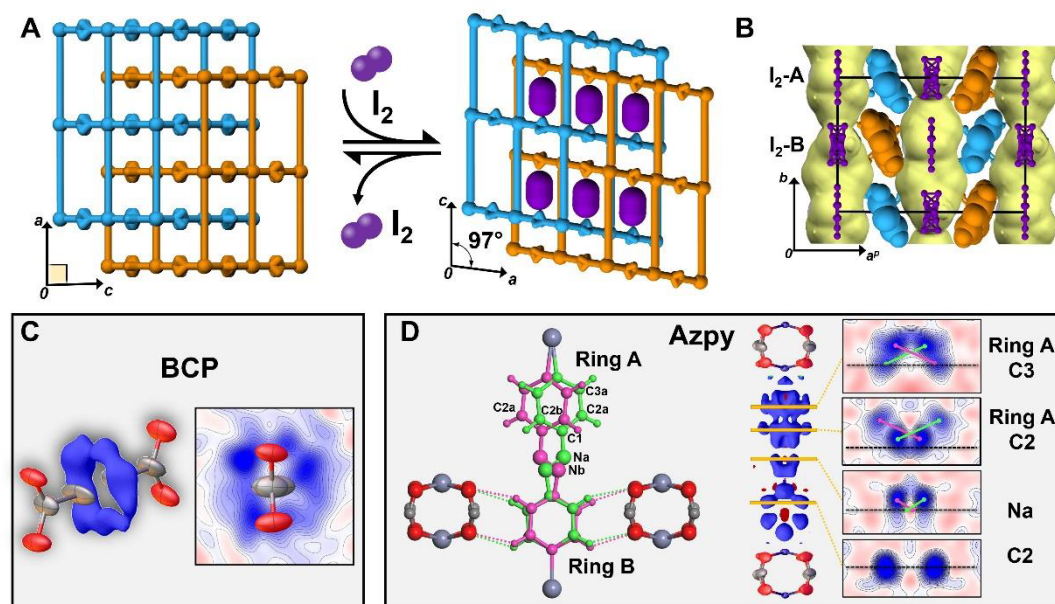


Figure 2. A) The reversible structural transformation of FTR-P2 upon inclusion of I_2 . As viewed along the b axis with the α -angle highlighted. B) FTR-P2- I_2 structure as viewed along the c -axis, highlighting the channels (light yellow) and the highly disordered I_2 molecules (iodine: violet). C) Diffused electron density with a toroidal shape about the main BCP axis shows increased BCP rotor dynamics. D) *Left* - The disorder of the azpy linker with atoms C1 and C2A, C2B, C3A, Na and Nb for Ring A highlighted. Ring B is shown to form interactions with the carboxylate oxygens. *Right* - The electron density of azpy linker (from SC-XRD data collected at 200 K) with 2D contours of C2 Ring B and C2 and C3 of Ring A and the azo nitrogen Na.

High resolution ^{13}C MAS NMR is a method of choice to understand the environment explored by each carbon atom within the observation time-scale. Variable temperature experiments under magic angle spinning and cross polarization were performed on FTR-P2 and FTR-P2- I_2 from room temperature to 100 K at ^{13}C NMR frequencies of 75 MHz and 100 MHz (Figure 3 and Figure S29 and S31). The first prominent observation is a single methylene signal for BCP rotors, detected at any acquisition temperature for both the samples, indicating the fast motional exchange about its rotational axis.

Regarding the pillars, the high symmetry of the unit cell of FTR-P2 entails the equivalence of the homologous carbons in the two pillar rings. Signal multiplicity is significantly modulated by temperature: indeed, on lowering the temperature, we observe a broadening of the C2 resonance and two distinct signals appearing at about 136 K, suggesting two non-equivalent environments for C2 carbons that are affected by the dihedral angle $\theta = \text{C2-C1-N=N}$ (Figure 3B). The chemical shifts of C2 carbons depend on their arrangement with respect to the azo group (syn or anti). The C2 in the syn conformation ($\theta \approx 11^\circ$) is shifted to higher frequencies compared to the C2 carbon in the anti conformation ($\theta \approx 169^\circ$).^[12] Above 150 K a coalescence signal due to the averaging of C2 chemical shifts is observed unveiling fast pedal-like motion of the azo-group with $k_{\text{exch}} > 3630$ Hz. This finding agrees with the diffused electron density

of the nitrogens in the SC-XRD (Figure 1F). FTR-P2 scan computed with Molecular Mechanics for a 360° rotation of the azo moiety confirmed the occurrence of pedal-like motion (Figure S60).^[10] The high symmetry of the crystal structure at room temperature is confirmed by the presence of only two signals in the ^{15}N MAS NMR spectra, which are assigned to the pyridyl nitrogens and azo group (Figure S32). Additionally, the observation of a marked motional broadening^[12] of the ^{13}C MAS NMR signals in the 270 - 280 K range (Figure S30) reveals the fast reorientation of pyridyl rings in the 10^5 Hz regime with respect to the framework, consistent with the energy barrier estimated by theoretical calculations (Figure S61).

For FTR-P2- I_2 , a completely different behavior is observed for the azpy ligands. The reciprocal sliding of the two interpenetrated networks from FTR-P2 by I_2 absorption, as determined by SC-XRD, is mirrored in the dramatic changes of ^{13}C MAS NMR spectra, owing to the distinct environments of each aromatic ring. Additionally, on going from the empty to the I_2 -containing framework, the piston-like sliding imprints its remarkable effect on the dynamics of each aromatic ring. The symmetry change is apparent in the splittings of all three signals of the azpy pillar (as also confirmed by ^{15}N MAS NMR, see Figure S32). Focussing on the C2 carbon signal, a complex modulation with temperature is observed: we can discriminate two families of signals pertaining to the two rings (Figure 3C red and blue colors).

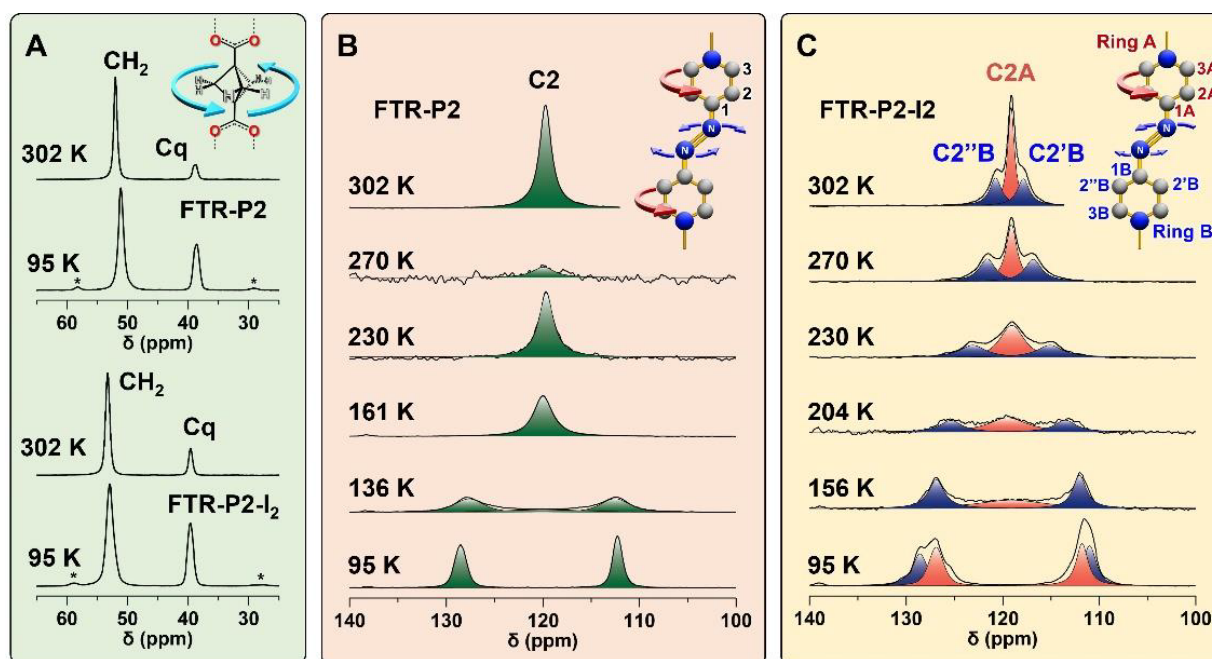


Figure 3. ^{13}C $\{^1\text{H}\}$ CP MAS spectra collected at variable temperatures, 7.04 T, 8.0 kHz and a contact time of 2 ms for 302–230 K temperature range, (12.5 kHz for 302 K), 9.40 T, 10 kHz and a contact time of 6 ms for lower temperatures. A) BCP CH_2 and C_q signals of FTR-P2 (top) and FTR-P2- I_2 (bottom), B) Azy C2 signal of FTR-P2, and C) Azy C2 signals of FTR-P2- I_2 . All the spectra of B) and C) were scaled to match the intensity of the BCP carboxylate peaks. Full spectra are reported in Figures S29 and S31.

A couple of resonances (Figure 3C: marked by red) undergoes coalescence on increasing the temperature from 95 K to 150 K. A different behavior was observed for the second couple of signals (Figure 3C: marked by blue), whose chemical shift difference decreases progressively on increasing the temperature in the 95–302 K range. Indeed, molecular mechanics and PW-DFT calculations predict an asymmetric potential for the reorientation of the azo group by 180° , with an energy difference of 2 kcal/mol (Figure S65).^[13] On the contrary in the empty system, the azo group reorients between two energetically and structurally equivalent sites. At 95 K, carbon $\text{C}2'\text{B}$ is substantially in the *syn* conformation with respect to Na ($\angle = \text{Na-Nb-C1-C}2'\text{B}$). However, the azo group reorientation upon increasing temperature leads carbon $\text{C}2'\text{B}$ to explore *anti* conformation according to Boltzmann distribution (Figure S67). These changes in population distribution for $\text{C}2'\text{B}$ result in the observed peak shifting to higher frequencies from $\delta = 111.7$ to 117.8 ppm upon increasing temperature (Figure 3C: blue signals). The same mechanism applies to carbon $\text{C}2''\text{B}$ but in reverse, moving the peak to lower frequencies upon increasing temperature (from $\delta = 127.0$ to 120.7 ppm). This mechanism of motion is ascribed to the azo group since ring B is embedded in the 2D layer, and its reorientation requires a high energy barrier, as shown by long ^{13}C T_1 relaxation times in the solid regime (Table S13). On the contrary, the mechanism of ring A reorientation is more complex and involves both the azo group and the pyridyl ring with reorientation phenomena of comparable activation energies, yielding two equivalent arrangements for the $\text{C}2'\text{A}$ and $\text{C}2''\text{A}$ carbons and thus the coalescence of their signals (Figure 3C: red set of signals).

The dynamics of BCP molecular rotors was demonstrated by spin-lattice relaxation times (T_1) as a function of temperature. Notably, ^{13}C NMR spin-lattice relaxation times of BCP in both FTR-P2 and FTR-P2- I_2 from room temperature to 200 K evidence that the relaxation behavior happens in the extreme narrowing regime ($\omega_0 \tau \ll 1$), typical of liquids. This result shows the BCP moiety is highly dynamic with rotational frequencies higher than the observation frequencies of 75 MHz and 100 MHz, corresponding to the ^{13}C Larmor frequencies (Figure 4). Interestingly, the presence of I_2 in the channels did not hamper the dynamics of BCP rotors but lowered the energy barrier slightly by 0.3 kcal/mol compared to the empty framework (Figure 4A-inset).

An in-depth study of the motional behavior was provided by ^1H T_1 relaxation times of both the samples collected over a wide temperature range down to 4 K (Figure 4A). The relaxation rate profile of FTR-P2 fitted by Kubo-Tomita equation^[14] is in full agreement with a progressive slowdown of dynamics on decreasing temperature, still exploring the high-frequency regimes of about 10^7 Hz (33.8 MHz) at 85 K and $7 \cdot 10^5$ Hz at 45 K. The activation energy for rotation was 1.2 kcal/mol and the attempt frequencies of about $4.7 \cdot 10^{11}$ Hz ($\tau_0 = 2.1 \cdot 10^{-12}$ s) for BCP, consistent with independent rotors of rotating inertial masses of 42 (BCP, theoretical $\tau_0 = 2.45 \cdot 10^{-12}$ s).^[15] The same energy barrier was also determined by ^{13}C T_1 relaxation times (Figure S36). The NMR measurements performed even with the application of different thermal ramps were fully reproducible, showing the robustness of the material. 2D DFT potential energy scans, using M062X/6-311+G(d) level of theory, were used to calculate the energy for rotation of BCP

rotors as arranged in the crystal structure (rotors R1 and R2). Two lowest energy rotation pathways could be extracted, which also pass through the global minimum of the system, thus proving that single rotor rotations are effective even in the porous framework (Figure 4C). Additionally, the calculated energy barriers are 1.03 and 1.26 kcal/mol, which are congruent with the experimental value of 1.2 kcal/mol (Figure 4B).

After the iodine-induced piston-like sliding of the framework, the profile of the ^1H NMR relaxation rates showed a distinct broadening. The overall dependence of the relaxation rate on the temperature is consistent with the sum of multiple Kubo-Tomita contributions whose maxima are markedly shifted to lower temperatures centered at 44, 61, 74 and 87 K, indicating the augmented mobility with lower energy barriers of 0.6, 0.8, 1.0 and 1.2 kcal/mol (the attempt frequency = $3 \cdot 10^{12}$ s). For the I_2 -loaded structure (Figure 4A), 2D DFT potential energy scans were performed considering four unique rotors (R1, R2, R3 and R4) and their nearest iodine molecules as positioned in the FTR-P2- I_2 crystal structure (Figure 4D). The lowest energy pathways, yielded by the 2D energy scans, unveiled the

occurrence of single rotor rotation even in the presence of the bulky I_2 molecules in the pores. Specifically, two rotational pathways for R1 with barriers of 0.6 and 0.87 kcal/mol (P1 and P2) and two rotational pathways for R2 of 1.2 and 1.4 kcal/mol (P3 and P4) were estimated and agree with the experimental barriers measured by ^1H and ^{13}C T_1 NMR. The average energy of R1 rotations is 0.4 kcal/mol lower with respect to R2 due to the much weaker rotor-iodine interactions of R1 (0.36 kcal/mol maximum) compared to R2 (1.0 kcal/mol maximum) (Figure 4E). The stronger interactions between R3/R4 and the iodine molecules increase their rotational barriers to above 2 kcal/mol, with average energies more than 2 kcal/mol higher than R1. Thus, the guest intervention did not entail rotor hampering, as it would conventionally be predicted because of the guest steric encumbrance and intermolecular interactions; instead, iodine molecules pushed the network sliding, liberating the dynamics of both BCP and the channel-exposed ring A rotor.

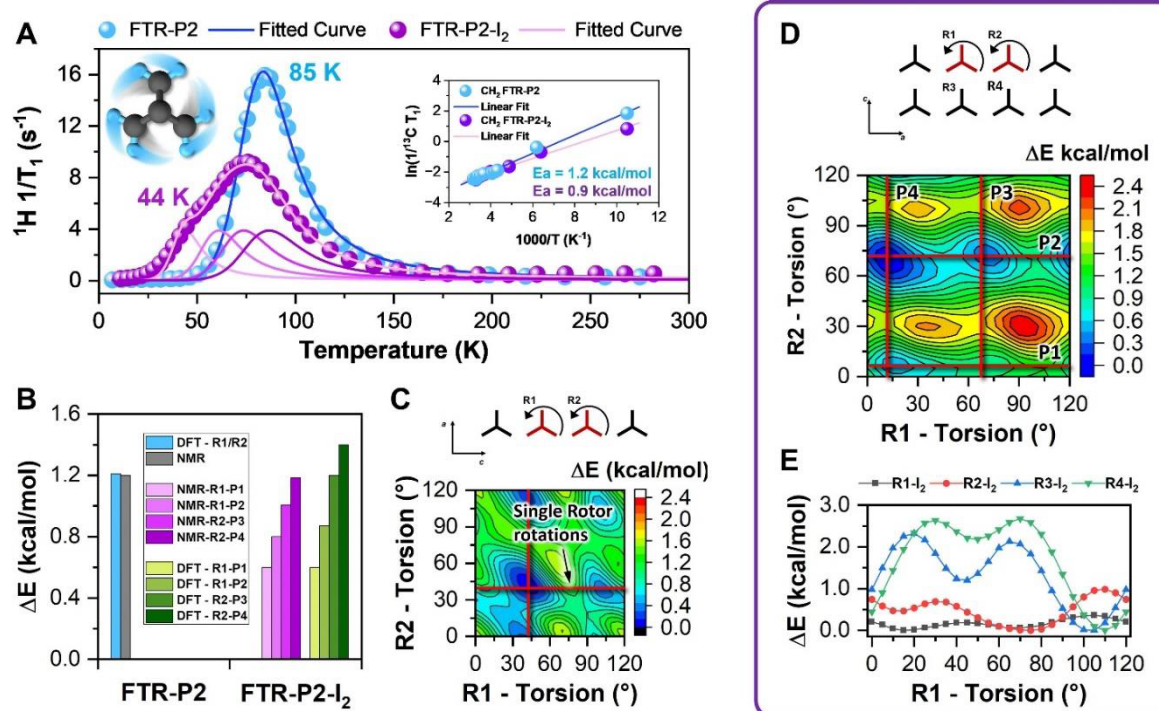


Figure 4. A) ^1H relaxation rates as a function of temperature for FTR-P2 (blue circles) and FTR-P2- I_2 (purple circles). The fitted Kubo-Tomita functions are shown in solid lines. In the inset, variable temperature ^{13}C T_1 relaxation times of CH_2 collected at 75 and 100 MHz for both FTR-P2 (blue circles) and FTR-P2- I_2 (purple circles). B) The bar chart shows the comparison between the NMR determined rotational barriers and the DFT computed barriers (for FTR-P2: grey and blue bar, respectively). In the case of the FTR-P2- I_2 , multiple rotational barriers were found, two for R1 and two for R2. C) FTR-P2 2D scans calculated by DFT. *Top* – computational model and schematic representation of the 2D scan computational model. *Bottom* – The potential energy map for the 2-D scan of rotors R1 and R2 is shown. The red lines indicate the lowest energy rotations passing through the minima of the system. D) FTR-P2- I_2 2D scans calculated by DFT. *Top* – Schematic representation of the 2D scan computational model, the interacting azpy pillars and iodine molecules have been omitted for clarity. *Bottom* – The potential energy map for the 2-D scan of rotors R1 and R2 is shown. The red lines (P1, P2, P3 and P4) indicate the lowest energy rotations passing through the minima of the system. E) Potential energy scans for the interaction between the unique rotors and the iodine molecules.

The empty FTR-P2 adsorbs efficiently CO_2 between 253 K - 298 K up to 1 bar (Figure 5), and thus, we explored the

dynamics of the framework in response to CO_2 as an alternative guest. An enthalpy of adsorption at low coverage of

30 kJ/mol was estimated by microcalorimetry coupled with adsorption analyzer for the simultaneous acquisition of gas adsorption enthalpy and gas loading (Figure S78). Contrarily, nitrogen could not enter the small pores of the structure: the very distinct sorption behavior of CO₂ vs N₂ suggests that FTR-P2 is suitable for gas separation. Under operative conditions of gas-mixture streams with 15% and 5% CO₂ over N₂, at 298 K,

CO₂ was completely separated from the mixture whilst N₂ passed through the column and was collected with a purity of more than 99% for 5.0 min g⁻¹ and 6.4 min g⁻¹, respectively, as assessed by breakthrough adsorption experiments (Figure S82).

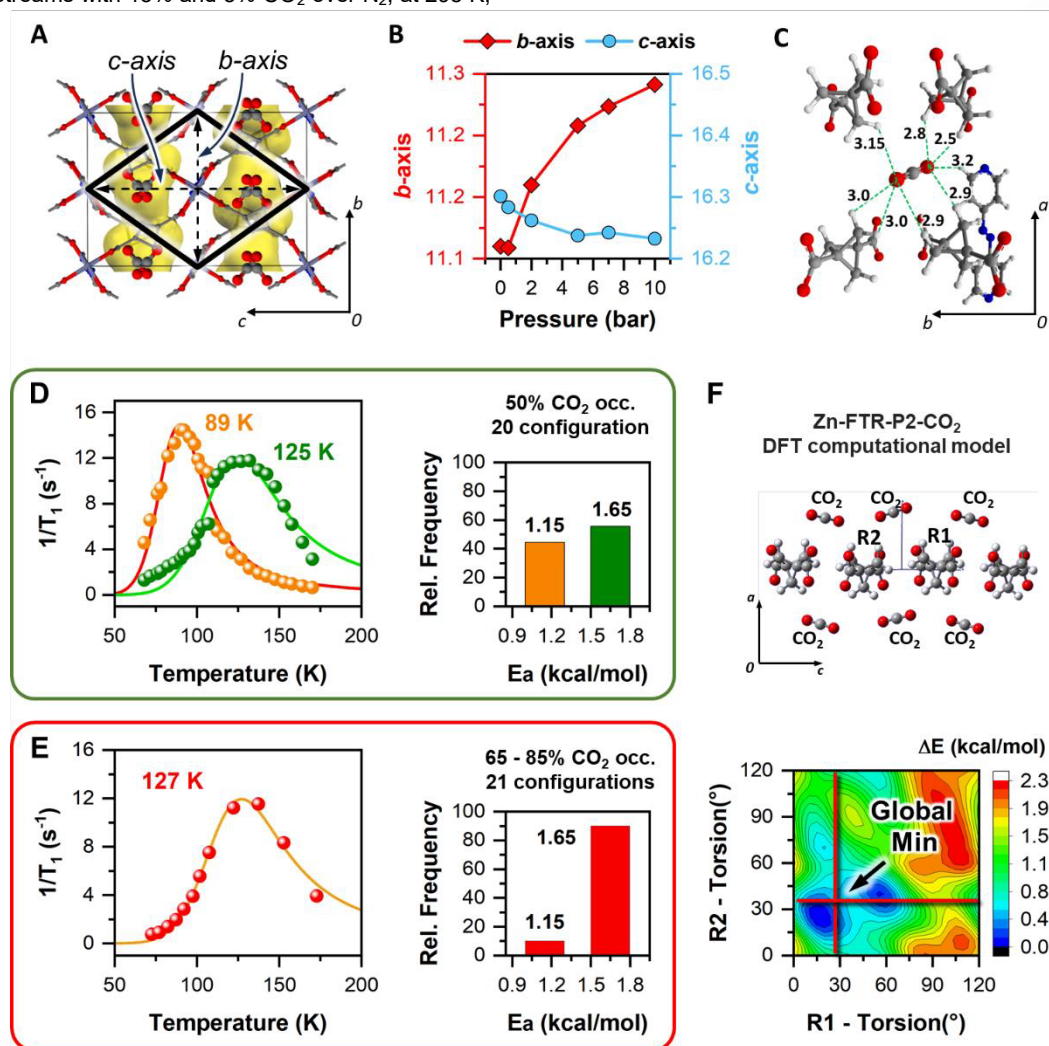


Figure 5. A) The structure for FTR-P2-CO₂-10bar obtained by Rietveld refinement against data collected using synchrotron radiation under 10 bars of CO₂ gas and room temperature (293 K) viewed down (1 0 0) with the channels shown in yellow and the CO₂ molecules in ball-and-stick representation. The rhombus of the carboxylate network is shown with the diagonal indicated using double-sided arrows as well as their corresponding cell axes. B) The *b*- and *c*-axes (the diagonals of the rhombus) plotted versus CO₂ gas pressure. C) The interactions between the CO₂ molecule and MOF as shown in green dashed lines. The interactions are mostly between CO₂ and the hydrogens of the BCP CH₂ groups. The distances are indicated in Å. D) ¹H T₁ NMR relaxation times of FTR-P2-CO₂ collected at variable temperature and frequency of 33.77 MHz. *Top* – 50% loading of CO₂ in FTR-P2. *Bottom* – Fully loaded CO₂ FTR-P2. The data were fitted by Kubo-Tomita function. E) The histogram relative frequency plots for the BCP rotational barriers calculated by DFT considering the possible configurations of CO₂ over the various sites. *Top* – 50% CO₂ loading (the two relaxation rates are quantified from the double-exponential shape of the recovery law). *Bottom* – 65 – 85% CO₂ occupancy. The histograms are centred around two energy barrier values, 1.15 and 1.65 kcal/mol, with almost equal distribution up to 50% CO₂ and mainly distributed on 1.65 kcal/mol for the 65 – 85% CO₂ loading. F) FTR-P2-CO₂ 2D scans and relative activation energies. *Top* – the view along (0 1 0) to highlight the arrangement of the CO₂ molecules with respect to the BCP rotors. *Bottom* – The potential energy map for the DFT 2-D scan of rotors R1 and R2 considering 50% CO₂ is shown as an example. The red line shows the lowest energy rotations, single rotor rotations, passing through the global minimum of the system. Energy barriers were extracted for different CO₂ occupancies and configurations. All these rotational barriers were then analyzed statistically using a histogram with a bin width of 0.4 kcal/mol.

CO₂ molecules, with their small size (kinetic diameter of 3.3 Å) and its quadrupolar nature, could enter the pores of the empty

structure and did not slide the networks with respect to each other (as for I₂ capture), which was demonstrated by

1 synchrotron radiation powder XRD under CO₂ gas pressure up
2 to 10 bar at room temperature (Figure S85 and Table S31).
3 The crystal structure was refined with a high symmetry *Cmca*
4 space group. The maximum CO₂ occupancy at 10 bars, as
5 estimated by Rietveld refinement, is of 6 MPU, corresponding
6 to 75% of the maximum loading of 8 MPU determined by the
7 CO₂ adsorption isotherm at 195 K. The crystal structures show
8 that the *b*-axis increases upon increased CO₂ loading. The
9 stretching of the *b*-axis slightly moves the sorption sites apart
10 along the channel direction for optimal CO₂-CO₂ interactions
11 and inclusion of CO₂ into the pores. The CO₂ molecules are
12 tilted with respect to the channel direction and ca. parallel to
13 the *bc* plane, thus avoiding repulsion between the oxygen
14 atoms of vicinal CO₂ molecules. The CO₂ molecules are off-
15 centered with respect to the channel axis and disordered over
16 two symmetry-equivalent positions. Importantly, CO₂
17 molecules install effective C-H...O interactions between BCP
18 molecular rotors and CO₂ oxygens.

19 The highly efficient CO₂ capture reduced mobility as shown by
20 the ¹H 1/T₁ maximum of Kubo-Tomita curve which is shifted to
21 higher temperatures for BCP molecular rotors compared to the
22 empty structure. The FTR-P2 sample fully loaded with CO₂
23 showed a peak maximum shifted up to 127 K, evidence of CO₂
24 interactions with the BCP rotors. Thus, the energy barrier
25 increased from 1.1 to 1.5 kcal/mol while the attempt frequency
26 1.5×10^{11} Hz ($\tau_0 = 6.5 \times 10^{-12}$ s) fell in the typical single rotor
27 rotation range.

28 DFT calculations for estimating the BCP rotational barrier upon
29 increasing CO₂ loading in FTR-P2 resulted in considering
30 several CO₂ configurations. The CO₂ configurations about the
31 rotors generate two main dynamics associated with the two
32 unique R1 and R2 rotors (Figure 5F) with rotational barriers
33 concentrated around two values, 1.15 and 1.65 kcal/mol.
34 Loadings up to 50% produce an almost equal distribution for
35 the two rotational barriers, resulting in a recovery of the nuclear
36 magnetization with markedly double-exponential character
37 (Figure S2). In comparison, for loading between 65% and 85%,
38 the 1.65 kcal/mol rotational barrier prevails, in agreement with
39 the energy barriers measured by the simulation of ¹H T₁
40 relaxation times. These results show a strong correlation
41 between the multiple intermolecular interactions between the
42 CO₂ oxygen atoms and the BCP hydrogen atoms and the
43 dynamics of the BCP rotor.

44 Conclusion

45 The design and fabrication of a dynamic machinery that
46 comprises several mobile elements of diverse nature and
47 symmetry were accomplished successfully in a pillared Metal
48 Organic Framework. Multiple molecular rotating elements,
49 such as bicyclopentane, pyridyl, and trans azo-groups, were
50 integrated into a flexible framework, which guides an intriguing
51 concerted dynamics of the individual components. As the
52 result of the open porosity, both structure and rotary motion
53 were fine-tuned and even enhanced, in response to stimuli, as
54 diffused CO₂ or I₂ vapors. Indeed, the dynamic MOF undergoes

a piston-like displacement of the framework, propelled by the
55 guest absorption.

56 These fully-dynamical solids promote intrinsic motility at low
57 temperatures where the molecular motions of most materials
58 are frozen. The BCP, pyridyl and azo groups are known to
59 manifest their mobility individually, however, integration in a
60 common tunable framework generates additional diversified
61 local environments, thus exploring unprecedented motional
62 mechanisms and interactions.

63 This example highlights the degree of control over dynamics
64 and symmetry obtainable by the design of "rotors -in-a-scaffold"
65 combined with a crystal architecture endowed with reciprocally
66 sliding networks. The soft, low-activation-energy landscape of
67 these prototypal materials stimulates a dynamical yet
68 structurally stable playground for enabling sophisticated
69 responsive machines in solids. This exquisite interplay of
70 framework and local dynamics will be helpful for the
71 construction of switchable ferroelectric materials, switches and
72 actuators. Moreover, the reversible uptake/release of I₂
73 molecules promises access to applications of capture of
74 radioactive I₂ and material recyclability.

75 Acknowledgements

76 Ministry of University (MUR) for PRIN 2020EZ8EPB
77 (SHERPA) and Lombardy Region for "Enhancing
78 Photosynthesis" grant (2021-2023) are acknowledged for the
79 financial support. The authors also acknowledge the Horizon
80 Europe project PANACEA " Pan-European Solid-State NMR
81 Infrastructure for Chemistry-Enabling Access", (H2020, Grant
82 N.101008500_Göteborg) and Arthur Pinon for technical
83 support. We would like to thank the European Synchrotron
84 Radiation Facility (ESRF) in Grenoble (France) for the access
85 to the ID22 beamline (Project HC-5193) and Giorgia
86 Confalonieri for technical support. D.J.K. acknowledges the
87 ERC-selected PhotoPeroNMR project funded by UKRI Horizon
88 Europe guarantee (EP/Y01376X/1).

89 Supporting Information

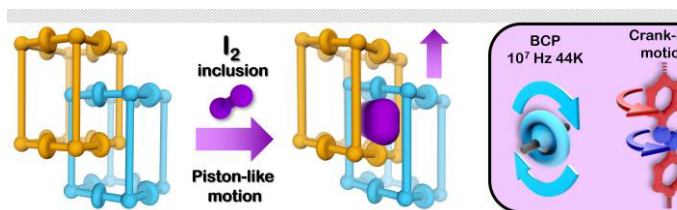
90 The raw NMR data are available on Zenodo [link to be added
91 at proof stage].

92 **Keywords:** Crystal Engineering • Metal Organic Frameworks
93 • Molecular Dynamics • Molecular Rotor • Solid State NMR

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Entry for the Table of Contents



The flexible framework sliding governs the overall dynamical machinery. Moving elements, bicyclopentane, bipyridyls and azo groups, rotate with modulated dynamics in response to chemical stimuli such as I₂ vapors and pressurized CO₂ diffused into a pillared MOF.