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Porous organic cages for sulfur hexafluoride separation

Tom Hasell, Marcin Miklitz,† Andrew Stephenson, Marc A. Little, Samantha Y. Chong, Rob Clowes, Linjiang Chen, Daniel Holden, Gareth A. Tribello,† Kim E. Jelfs,‡ and Andrew I. Cooper*  
Department of Chemistry and Centre for Materials Discovery, University of Liverpool, Crown St., Liverpool L69 7ZD, UK.  
† Department of Chemistry, Imperial College London, South Kensington, London, SW7 2AZ, U.K.  
‡ Atomistic Simulation Centre, Department of Physics and Astronomy, Queen’s University Belfast, University Road, Belfast, BT7 1NN, U.K.  
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INTRODUCTION  
Sulfur hexafluoride (SF6) is a much more potent greenhouse gas than CO2, with an estimated atmospheric lifetime of 800–3200 years.1,2 The Intergovernmental Panel on Climate Change found SF6 to be the most potent greenhouse gas that it evaluated, with a global warming potential 23,900 times higher than CO2.3 Nonetheless, SF6 has valuable and widespread industrial uses. For example, SF6 or SF6/N2 mixtures are often used to insulate electrical equipment.4 SF6 is also a good thermo-acoustic insulator for windows, a contrast agent in medical applications, and a plasma etchant in the semiconductor industry.5 There is much current interest in finding effective materials for the separation of SF6 from gas mixtures to prevent its release into the atmosphere and to allow economically viable capture and re-use.6 Pressure swing adsorption / desorption processes using a suitable porous material offer considerable energy savings over liquefaction, but this requires high selectivity for SF6 adsorption over N2 adsorption.7 Various porous solids have been tested for SF6 adsorption or separation such as carbons,8,9 zeolites,10–13 metal-organic frameworks (MOFs),14 and pillared clays.14 Until now, the most selective of these materials have been zeolite 13X12 and a series of isostructural MOFs with a high density of unsaturated metal sites.8 The success of these materials was attributed to their pore diameters (10 and 11 Å, respectively), which were identified by Monte Carlo simulations as close to ideal. All microporous solids tested for SF6 separation so far have been insoluble, extended networks or macromolecules. Nitschke et al demonstrated that a metal-organic capsule could capture and release SF6 in solution, but such molecular separation of SF6 by a cage molecule has not yet been shown in the gas phase. However, there is also growing interest in porous molecular cages.15-20 These cages contain an internal void that is accessible via well-defined windows, and the rigid structure of the cages prevents collapse, thus providing porosity for guest molecules. Porous organic cages have been synthesized from imines,15-17 boronic esters,18 and by direct carbon-carbon bond forming reactions.19 Apparent Brunauer–Emmett–Teller (BET) surface areas for nitrogen as high as 3758 m2 g−1 have been achieved.20 Since these cages are discrete molecules, as opposed to frameworks, they are soluble in common organic solvents and can be processed into support materials and precipitated or crystallized into the solid state as required. We previously reported a class of [4+6] cycloimine cage compounds that show gas uptakes and physicochemical stabilities that are remarkable for molecular organic crystals.21-30 The gas sorption properties of these cages depends both on their molecular structure, and on their crystal packing, and many of these cages can exist as multiple polymorphs.21,31,32,33 These cages are excellent candidates for the molecular separation of noble gases,34 chiral molecules,35 and hydrocarbon isomers.36,37 In this study, a series of these organic cages (Fig. 1) was investigated for their potential in the separation of SF6. One cage, CC3, shows remarkably high SF6 selectivity, and this is related to the flexible nature of the molecular cage crystal.
Figure 1. a) Synthesis and structure of cages CC1, CC2, CC5, and CC13. b) Simplified structural representations of the packing and porosity of these cages as derived from single crystal structures. CC2α exhibits one dimensional pore channels (yellow) in addition to internal cage cavities (orange), which may also be accessible depending on the size of the guest. CC3α has a 3D diamodoid pore network (yellow). CC13β packs with the same diamodoid pore network as CC3α (running through the inside of the cages, shown in yellow), but with an additional, narrower interpenetrating diamodoid pore network between the cages (cyan). CC5α packs in the same window-to-window fashion, but the cages and hence the pore channels (yellow) are larger.

METHODS
Materials and synthesis: 1,3,5-Triformylbenzene (TFB) was purchased from Manchester Organics, UK and used as received. 2-Methyl-1,2-propanediamine was purchased from TCI Europe and used as received. All other chemicals were purchased from Sigma-Aldrich and used as received. All cages were synthesized as described previously.31,33,40,41

Gas Sorption Analysis: Powder samples were degassed offline at 100 °C for 15 h under dynamic vacuum (10⁻⁵ bar) before analysis, followed by degassing on the analysis port under vacuum, also at 100 °C. Isotherms were measured using a micromeritics 3flex surface characterisation analyser, equipped with a Cold-Edge Technologies liquid helium cryostat chiller unit for temperature control.

Single crystal diffraction data: Evacuated prism shaped single crystals of CC3α were exposed to dry SF₆ at 1 bar pressure. The crystals of were transferred to a sample vial and after 28 hour a single crystal collection was recorded.

Single crystal X-ray data for CC3·(SF₆)²·(H₂O)₃ was measured at beamline I19, Diamond Light Source, Didcot, UK using silicon double crystal monochromated synchrotron radiation (λ = 0.6889 Å, Kappa 4-circle goniometer, Rigaku Saturn72+ detector).42 Empirical absorption corrections, using equivalent reflections, were applied by the program SADABS.43 The structure was solved by SHELXD,44 and refined by full-matrix least squares on [F²] by SHELXL,44 interfaced through the programme OLEX2.45 Absolute configuration was determined using a priori knowledge of the cage chirality. For full refinement details, see SI. Supplementary single crystal XRD data, including structure factors, is available free of charge from the Cambridge Crystallographic Data Centre (CCDC) via www.ccdc.cam.ac.uk/data_request/cif.

Crystal data for CC3·(SF₆)²·(H₂O)₃, CCDC number CCDC 1437443: Formula C₁₄₄H₁₇₄F₁₅N₂₄O₃·2.5SF₆·3H₂O; M = 2654.40 g mol⁻¹; triclinic space group P1, colourless prism shaped crystal; a = 17.385(5), b = 17.425(6), c = 17.479(6) Å; α = 60.384(3), β = 60.308(3), γ = 60.168(3)°; V = 3768(2) Å³; ρ = 1.170 g cm⁻³; μ = 0.108 mm⁻¹; F (000) = 1405; crystal size = 0.13 × 0.07 × 0.07 mm²; T = 100(0) K; 52288 reflections measured (1.376 < θ < 25.503°), 28131 unique (Rint = 0.0448), 22028 (I > 2σ(I)); R₁ = 0.0894 for observed and R₁ = 0.1091 for all reflections; wR₂ = 0.2549 for all reflections; max/min difference electron
density = 0.801 and -0.923 e Å⁻³; data/restraints/parameters = 28131/363/1786; GOF = 1.037. Flack parameter 0.14(4). The structure was refined with the TWINLAW [100 001 010] and BANF refined to 0.227(2).

**Laboratory X-ray powder diffraction**: Powder X-ray diffraction (PXRD) data were collected in transmission mode on loose powder samples held on thin Mylar film in aluminium well plates on a Panalytical XPert PRO MPD equipped with a high throughput screening (HTS) XYZ stage. X-ray focusing mirror and PIxcel detector, using Cu Kα radiation. Data were measured over the range 4-50° in ~0.013° steps over 60 minutes.

**In situ PXRD gas-loading**: In situ powder diffraction data under an SF₆ atmosphere were collected at beamline I11 at Diamond Light Source using the low pressure capillary gas cell.⁴⁶ A finely ground sample of CC13β was packed in a 0.7 mm diameter borosilicate capillary and mounted on the low-pressure capillary gas cell. Samples were activated by heating to 350 K using an Oxford Cryostream Plus under dynamic vacuum (approximately 10⁻⁵ bar). Data were collected using the Mythen-II position sensitive detector (PSD)⁴⁶ at 230 K. An initial powder diffraction profile of guest-free CC13β was collected under dynamic vacuum. The sample was rocked through ±15° in θ to improve powder averaging. Gas was dosed into the system, initially to 2.7 bar and then 3 bar. Samples were allowed to equilibrate at both pressures for approximately 45 minutes after gas was dosed into the cell. PXRD data were collected during this time to monitor equilibration. The sample was then evacuated at 373 K under dynamic vacuum and the powder profile collected to confirm removal of the guest from the pore structure.

**Metadynamics simulations**: A 100 ns well-tempered metadynamics simulation was performed with DL_POLY2.2⁴⁷ and PLUMED2.⁴⁸ The OPLS-AA force field parameters,⁴⁹ and the Leapfrog Verlet algorithm⁵⁰ with a timestep of 0.5 fs was used. The Nose-Hoover thermostat⁵¹ was used to keep the temperature fixed at 300 K and no interactions were applied between periodic images in a cubic system with cell length 39 Å. A timestep of 0.5 fs with sampling step of 1 ps was chosen and full molecular motion was allowed throughout the simulation. The collective variable along which the metadynamics bias was accumulated measured the distance between the center of mass of the fully flexible CC3 and the sulfur atom of the SF₆. Gaussian hills with a width of 0.15 nm and an initial height of 1.2 kJ mol⁻¹ were added every 500 MD steps and the so-called well-tempered factor was set equal to 10. The free energy surface was calculated using the ‘sum hills’ utility of PLUMED2 with the minimum shifted to zero. An additional well-tempered metadynamics simulation using two collective variables (the distance and a torsion angle) was performed to analyze the mechanism further, see SI for further details.

**Breakthrough experiments**: Breakthrough curves were measured for a fixed bed of CC3α or zeolite 13X at 298 K using a 90:10 (v/v) N₂/SF₆ gas mixture. The breakthrough curves were measured using an automated breakthrough analyser (manufactured by Hiden Isochema, Warrington, U.K.). CC3α was made into small pellets (500–700 μm), which were packed into an adsorption bed for the breakthrough experiment. The materials were activated in situ by heating to appropriate activation temperatures and flowing helium through the column. Desorption of N₂/SF₆ was performed by flowing helium through the bed at the same flow rate as the breakthrough experiment. The effluents were measured by an inline mass spectrometer. Further details are in the SI.

**RESULTS AND DISCUSSION**

Gas adsorption analyses revealed that all four cages were porous to SF₆, but with marked differences in terms of adsorption capacities that relate to their structures (Fig. 2a–f). It is interesting that SF₆ is adsorbed by the smaller cages at all: from a simple static representation of their crystal structures, SF₆ would not be expected to be able to diffuse through the pore channels of CC2α, CC3α and CC13β. However, these organic crystals are somewhat flexible.⁵² They are comprised of discrete molecules held together by weak intermolecular dispersion forces, rather than covalently bonded frameworks, and this has been shown previously to allow “porosity without pores”.⁵³⁻⁵⁵ Hence CC2α, CC3α and CC13β can adsorb SF₆ despite the fact that this gas is larger than the static window diameter in the cages. The kinetic diameter of SF₆ is 5.5 Å,⁵⁶ and thus one might not expect it to diffuse into the smaller imine cages (CC2, CC3, CC13) since their window diameters are ~3.6 Å.⁵² Indeed, previous unbiased MD simulations for CC3α demonstrated that SF₆ did not escape the cage cavity in which it was originally positioned over a 10 ns simulation using a forcefield tailored to describe the flexibility in imine cages.⁵² Hence, to analyse the SF₆ diffusion mechanism for these smaller cages and to calculate the energetic barrier to this event, we carried out well-tempered metadynamics simulations of SF₆ and a single CC3 molecule (see Supporting Information for full simulation details). To understand the diffusion mechanism, we can think of the SF₆ molecule as two connected triangular faces, rather than a sphere that describes the widest possible diameter. As can be seen in Figure 3 and Movie S1, SF₆ exits the cage by first aligning its outermost triangular face with the triangular cage window. There is then a rotation of ~60° (Fig. 3a–d) such that the second face can align with the cage window and thus pass through. The barrier to the SF₆ diffusion through the flexible cage window is calculated to be at most 40 kJ mol⁻¹, and the configurations near the saddle point have the center of the SF₆ traversing the window. While crystal packing effects would likely influence this barrier to a small extent, it is of similar magnitude to that previously calculated for the allowed para-xylene diffusion in the same host system.⁵⁷ It is therefore reasonable that the SF₆ diffuses, albeit slowly, in this system. A comparison of a single empty CC3 window diameter distribution with the measured window diameter during the SF₆ passage (Fig. 3e) reveals the cooperative character of the mechanism. Clearly, the cage window size increases when the SF₆ is inside the window.
Figure 2. Gas sorption isotherms for the uptake of SF₆ in the various cages; adsorption curves shown as filled symbols, desorption curves as unfilled symbols. a) CC2α, b) CC3α, c) CC5α, and d) CC13β. e) This plot shows the uptake expressed in terms of the number of SF₆ molecules per cage molecule at 230 K. f) Heat of adsorption of SF₆ for the various cages.

Figure 3. a) The free energy surface for a single SF₆ molecule diffusing through the window of a single CC3 cage as a function of the distance between the centers of mass of CC3 and SF₆. b) The 2D free energy as a function of the distance used for (a) and the angle of rotation as shown in part (c). c) CC3 and SF₆ configurations corresponding to the positions marked 1 (left) and 2 (right) on the plots. Structure 1 corresponds to the global minimum orientation with SF₆ in the CC3 cavity and structure 2 represents the structure at highest point of the free energy surface, when SF₆ is placed exactly in the center of the window. The angle used for the y-axis in panel (b) is indicated on these configurations. This angle is small when the SF₆ begins to escape from the cage and increases as the SF₆ reaches position 2. d) Stick and spacefill representations of the SF₆ molecule. The three fluorine atoms that diffuse through the window first are colored red. e) Comparison of the pore envelope of the CC3 window, for an empty cage (black), for CC3 with SF₆ occupying the cage cavity (green) and for cage where SF₆ is positioned in the window (red).
CC3α shows the highest affinity for SF₆ of the four cages tested, and a steep type 1 isotherm that saturates at low pressures (Fig. 2b). This is manifested in the highest heat of adsorption of ~35–40 kJ mol⁻¹ (Fig. 2f). The saturation uptake corresponds to around 2.9 SF₆ molecules per CC3 cage (Fig. 2e). This is consistent with one SF₆ molecule in the internal cage cavity, plus one SF₆ molecule shared in each of the four window-window sites surrounding every cage, equating to a maximum theoretical loading of 3 SF₆ molecules per CC3 cage. CC2α shows the lowest SF₆ uptake and the lowest heat of adsorption (Figs. 2a, 2f). The 1D pore channels in CC2α, which run between the hexagonally-arrayed cages, are wide enough to accommodate SF₆. The uptake of 1.4 SF₆ molecules per cage (Fig. 2e) confirms that these 1D channels must be at least partially occupied. CC5α displays the highest SF₆ adsorption capacity, of 10.2 SF₆ per cage, in line with its larger internal void size and its higher surface area and pore volume. However, the heat of adsorption is much lower than for CC3α, and hence CC5α adsorbs less SF₆ at lower pressures. CC13β gives a lower heat of adsorption than CC3α, despite having a similar pore structure. The difference between the high temperature (298 K) and low temperature (230 K) SF₆ uptakes for CC13β is significant. At 230 K, CC13β adsors around 6 SF₆ molecules per cage – that is, twice as much gas as CC3α. This can be rationalized only if the SF₆ molecules are located in the intercage sites, of which there are three per CC13 (Fig. 1b; blue nodes), as well as in the cage cavities and the window-window sites. While these intercage sites were shown previously to be accessible to nitrogen, the size of the nodes relative to SF₆ suggested to us that significant rearrangement would be required to accommodate this larger gas. To explore this, the adsorption of SF₆ in CC13β was monitored by PXRD (Fig. 4). The PXRD pattern changes significantly as the structure is loaded with SF₆, losing intensity in the high angle range. This is consistent with the preservation of the long-range packing of the cage modules, but a more disordered local structure, which could allow the large SF₆ guest to diffuse through the crystal. This re-organization of the CC13 allows the incorporation of such a large quantity of SF₆ (6 per cage), which cannot not be rationalized by the original empty structure. It is remarkable that the crystallinity is restored completely to its initial state after removal of the SF₆, even after multiple cycles (Fig. S1). This behavior is allowed by the relatively weak dispersion forces between the cages, which enable reorganization in response to guests.

The SF₆ isotherms for CC3α suggested excellent potential for SF₆ separation from nitrogen, and therefore the nitrogen isotherms were measured at equivalent temperatures (Fig. S2) to allow the calculation of ideal adsorbed solution theory (IAST) predicted selectivity (Figs. 5, and S3). The industrially relevant composition for separation of an SF₆/N₂ mixture is SF₆/N₂ = 10%/90%. At 1 bar pressure CC3α gives a selectivity of 178 at 273 K, and 74 at 298 K. This surpasses the most promising candidate material previously reported, UiO-66-Zr (selectivity = 74, at 1 bar, 293 K) and other similar framework materials such as Zn-MOF-74 (selectivity = 46, at 1 bar, 298 K), Ca-A zeolite (28 at 1 bar, 298 K), and zeolite-13X (44 at 1 bar, 298 K). The total capacity of CC3α for SF₆ is higher than many of the frameworks reported (e.g., UiO-66-Zr is ~1.5 mmol, at 293 K and 1 bar), but lower than the highest (Mg-MOF-74 = 6.42 mmol/g at 1 bar, 298 K).

A crystallographic study allowed for the location of SF₆ in CC3α to be accurately determined (Figs. 6, and S4). Well-ordered SF₆ molecules were located, with full site occupancies, in the intrinsic CC3 cavities (Fig S4). CC3 provides an ideal fit for SF₆ in terms of both size and geometry of the cage cavity (Fig. 6), which explains the high heat of adsorption that we observe. The ordering of SF₆ molecules in the CC3 cavities transforms the crystallographic symmetry from F432, as determined for the empty CC3α host, to P1, but this does not alter the crystal packing of the CC3 molecules.

**Figure 4.** Powder X-ray diffraction data for in situ SF₆ loading of CC13β at 230 K. Under excess pressures of SF₆, the CC13β structure becomes more disordered at short range, indicated by loss of high angle diffraction intensity. The original profile is totally regained after guest removal by vacuum.

**Figure 5.** IAST selectivity plots for SF₆ over N₂ for CC3α at SF₆/N₂ ratios of 50:50 and 10:90 at a) 273 K and b) 298 K.

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**Figure 6.** (a) Resolved position of SF₆ in the CC3 cavity determined from the single crystal structure; (b) space filling representation as viewed through a cage window.
IAST calculations are useful to suggest selectivity in a separation of two or more gases for an adsorptive separation process, but IAST does not accurately represent a gas mixture flowing through a packed bed of material.\[40\] In particular, IAST calculations say little about separation kinetics since the calculations are derived from single-component gas sorption isotherms that are collected at thermodynamic equilibrium. Therefore, breakthrough experiments were carried out to establish the practical potential of CC3α for N₂/SF₆ separations, and in particular to demonstrate that the SF₆ diffusion kinetics are sufficiently fast for real separations. All breakthrough experiments were performed at 298 K with a 90:10 (v/v) N₂/SF₆ mixture. The breakthrough curves and desorption curves for N₂ and SF₆ flowing through a bed of CC3α are shown in Figure 7. Nitrogen breaks through the column within 1 minute, whereas SF₆ does not start to break through until after 6.5 minutes and does not completely break through until approximately 20 minutes. The large difference in breakthrough time between N₂ and SF₆ reflects the much higher affinity of CC3α towards SF₆. The breakthrough curve for N₂ shows the characteristic ‘roll-up’ as the concentration at the outlet is temporarily higher than at the inlet as the SF₆ is preferentially adsorbed and displaces the N₂. The desorption was performed by flowing helium through the column under the same conditions as for breakthrough. N₂ is desorbed quickly from the column, with 97% of the gas being desorbed within the first minute. As expected, SF₆ is desorbed more slowly, with full desorption taking about 20 minutes, approximately the same time as for full breakthrough.

Breakthrough and desorption curves for CC3α and zeolite 13X at three different gas flow rates are compared in Figures S5 and S6. In each case, the desorption of SF₆ from CC3 takes approximately the same time as the full breakthrough. However, for zeolite 13X with a 25 ml minute⁻¹ flow rate, SF₆ desorption takes twice as long as it does to breakthrough (Figure S6). The more rapid desorption efficiency of CC3α therefore gives it a potential advantage over zeolite 13X as a material for N₂/SF₆ separation.\[40\]

**Figure 7.** N₂/SF₆ (90:10) breakthrough curve for CC3α at 298 K. The total flow rate was 25 ml min⁻¹ and the pressure was 1 bar. Desorption was performed by flowing helium through the bed at the same flow rate and pressure.

**SUMMARY**

Intrinsically porous molecules, as opposed to framework or network materials, have been investigated for SF₆ uptake separation. Despite the pore limiting diameters in CC3 being considerably narrower\[40,52\] than the 11 Å recommended as the optimum pore size by simulation,\[60\] this cage showes unprecedented selectivity for SF₆ over N₂. Our simulations suggest this may be a result of the flexibility of the CC3 molecular crystal, which allows SF₆ to diffuse by cooperative effects, before the structure relaxes back to produce a closer, near-ideal interaction with the SF₆ guest. This hypothesis is further supported by research reported by Camp and Scholl while this manuscript was being written.\[40\] In that study, transition state theory methods were used to simulate the diffusion of various gases in CC3, and it was found for SF₆ that no diffusion would be expected in a static system, while diffusion should be possible if the flexibility of the host is taken into account. The IAST selectivity of CC3 for an industrially relevant mixture of 10:90 SF₆:N₂ at 298 K and 1 bar is higher than other reported materials. Breakthrough experiments confirmed that CC3 is effective for separation of N₂ and SF₆. Also, desorption curves show that SF₆ is more efficiently desorbed from CC3 than from zeolite 13X. Flexibility in MOFs has been found to provide higher gas capacities.\[52\] Similarly, the flexibility of molecular crystals, such as CC3, allows for a stronger gas binding with SF₆ which gives these materials potential for practical gas separations under flow.

**ASSOCIATED CONTENT**

Crystallographic details, analysis equipment and conditions, and further characterization details. This material is available free of charge via the Internet at http://pubs.acs.org.

**AUTHOR INFORMATION**

**Corresponding Author**  
* aicooper@liv.ac.uk

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**ABBREVIATIONS**

CCX, referring to a ‘covalent cage’ of a series published by the Cooper group, X being the order of publishing, see cited references. PXRD, powder x-ray diffraction. BET, Brunauer–Emmett–Teller. PSD, position sensitive detector. IAST, ideal adsorbed solution theory.

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