Supplementary Information

Thermal Fluctuation-induced Selective CO_2 Uptake of Seemingly Nonporous *N,C*-protected Dipeptide Crystals as Elucidated by *in situ* X-ray Crystallographic Analysis

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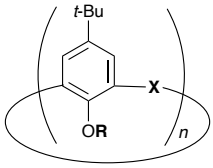
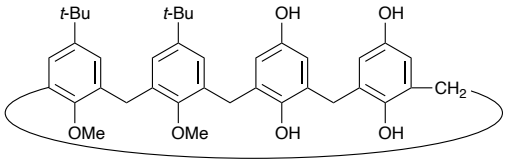
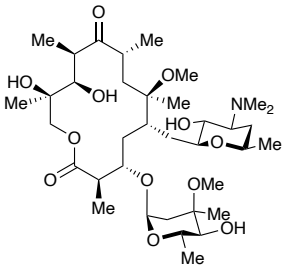
1. Molecular crystals with seemingly nonporous crystal architecture



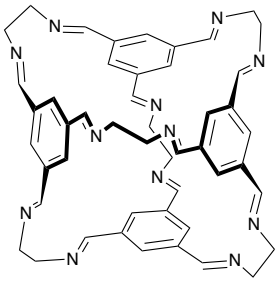
calixarene: **X** = CH_2, **R** = H, *n* = 4 or 5 (ref. 6)
thiacalixarene: **X** = S or SO_2, **R** = Me or H, *n* = 4 (ref. 11)
azacalixarene: **X** = NH, **R** = Me, *n* = 4 or 5 (ref. 14)



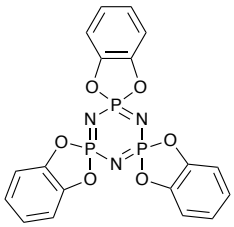
***p-tert*-butylcalix[4]dihydroquinone** (ref. 6d)



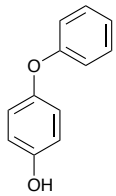
clarithromycin (ref. 7)



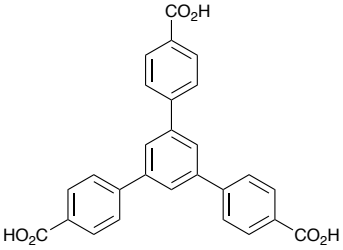
molecular cage (ref. 8)



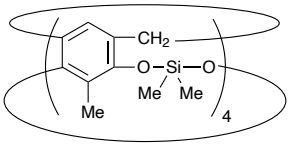
phosphazene (ref. 9)



4-phenoxyphenol (ref. 10)



1,3,5-triphenylbenzene (ref. 12)



cavitand (ref. 13)

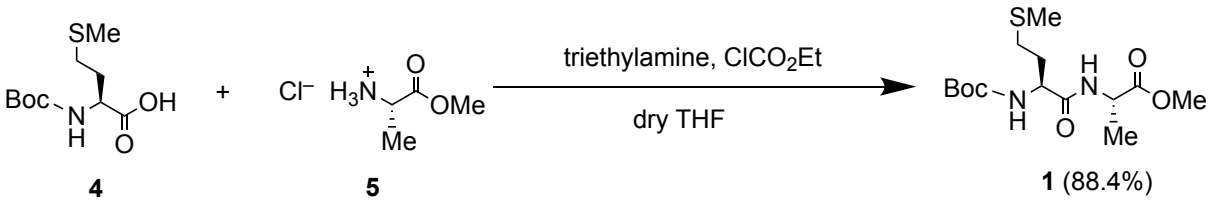
Chart S1 Chemical structures of organic compounds depositing seemingly nonporous crystals. Reference numbers are identical to those listed in the main text.

2. General methods

All reagents and solvents were purchased from commercial suppliers and used without further purification. NMR spectra were recorded on a JEOL ECX-400 NMR spectrometer. Chemical shifts were reported in δ ppm relative to tetramethylsilane (^{1}H NMR) or chloroform-d (^{13}C NMR), and signal multiplicities in ^{1}H NMR spectra are described as singlet (s), broad singlet (br), doublet (d), triplet (t), double doublet (dd) and multiplet (m). IR spectra were recorded on a Shimadzu IRSpirit-T spectrometer by using KBr tablets. Melting points were determined on a Shimadzu DSC-60. High-resolution mass spectrometry (HRMS) measurements were performed by using a Bruker micrOTOF II with ESI ionization method. Scanning electron microscope (SEM) studies were conducted on a Keyence VE-8800 instrument. Gas sorption isotherms were measured using a Shimadzu Gemini VII 2390 surface area analyzer.

3. Synthesis of *N,C*-protected dipeptides

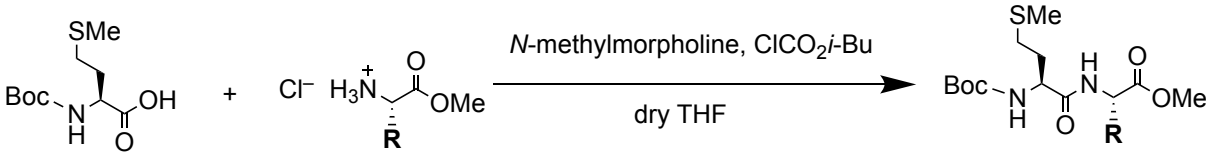
Scheme S1 Synthesis of methyl *N*-(*tert*-butoxycarbonyl)-L-methionyl-L-alaninate (**1**)



4 **5** **1** (88.4%)

To a solution of *N*-(*tert*-butoxycarbonyl)-L-methionine (**4**, 1.00 g, 4.02 mmol) in dry THF (15 mL) at −15 °C, triethylamine (2.5 mL, 18 mmol) and $ClCO_2Et$ (0.70 mL, 7.4 mmol) were added under Ar atmosphere. After stirring for 10 min, a solution of **5** (0.840 g, 6.02 mmol) in dry DMF (15 mL) was added to the reaction mixture. After 15 min, the solvent was evaporated, and the residue was dissolved in ethyl acetate. The organic layer was washed with water and brine, and dried over $MgSO_4$. The solvent was evaporated under vacuum to give a colorless oil. It was dissolved in boiling hexane, and the solution was allowed to cool to room temperature. Colorless needle crystals of **1** (1.19 g, 88.4%) were obtained by filtration. mp 87.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.70 (br, 1H, NH), 5.20 (br, 1H, NH), 4.58 (quintet, J = 7.3 Hz, 1H, NHC*H*CH_3), 4.30 (br, 1H, NHC*H*CO), 3.75 (s, 3H, OMe), 2.60 (t, J = 7.2 Hz, 2H, CH_2S), 2.12 (s, 3H, SMe), 2.10–2.03 (m, 1H, C*H*$_2$$CH_2S$), 1.99–1.90 (m, 1H, C*H*$_2$$CH_2S$), 1.48 (s, 9H, *t*-Bu), 1.42 (d, J = 7.2 Hz, 3H, CHC*H*$_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 173.0, 171.1, 155.5, 80.1, 53.1, 52.4, 48.0, 31.6, 29.9, 28.2, 18.1, 15.1; IR (KBr) ν_{max}: 3288, 3074, 2981, 1755, 1679, 1652, 1535, 1459, 1393, 1367, 1300, 1270, 1256, 1201, 1160, 1050 cm^{-1}; HRMS (ESI): Calcd for $C_{14}H_{26}N_2O_5SNa$ $[M+Na]^+$ 357.1455; found 357.1474.

Scheme S2 Synthesis of methyl *N*-(*tert*-butoxycarbonyl)-L-methionyl-L-valinate (**2**) and methyl *N*-(*tert*-butoxycarbonyl)-L-methionyl-L-leucinate (**3**)



4

6: **R** = *i*-Pr
7: **R** = *i*-Bu

2: **R** = *i*-Pr (79.5%)
3: **R** = *i*-Bu (86.5%)

To a mixture of **4** (2.36 g, 9.48 mmol) and *N*-methylmorpholine (1.1 mL, 10 mmol) in dry THF (40 mL) at −15 °C, isobutyl chloroformate (1.3 mL, 9.9 mmol) was added and then stirred for 1 h under Ar atmosphere. Aside from it, **6** (1.71 g, 10.2 mmol) was neutralized with triethylamine (3.0 mL, 22 mmol) in methanol (6 mL). After evaporation under reduced pressure, the resultant residue was suspended in dry THF (15 mL). The suspension was added to the reaction mixture, which was allowed to warm to room temperature. After stirring for 4 h, the solvent was evaporated, and the residue was dissolved in

ethyl acetate. The organic layer was washed with saturated $NaHCO_3$ solution and brine, and dried over $MgSO_4$. The solvent was removed by evaporation to give a white solid. It was dissolved in boiling hexane, and the solution was allowed to cool to room temperature. Colorless needle crystals of **2** (2.73 g, 79.5%) were obtained by filtration. mp 125.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.69 (br, 1H, NH), 5.17 (br, 1H, NH), 4.53 (dd, J = 8.0 Hz, 4.4 Hz, 1H, NHC*H*(*i*-Pr)CO), 4.31 (br, 1H, NHC*H*CO), 3.74 (s, 3H, OMe), 2.61 (t, J = 7.2 Hz, 2H, CH_2S), 2.22–2.16 (m, 1H, C*H*$(CH_3)_2$), 2.13 (s, 3H, SMe), 2.10–2.03 (m, 1H, C*H*$_2$$CH_2S$), 2.01–1.94(m, 1H, C*H*$_2$$CH_2S$), 1.45 (s, 9H, *t*-Bu), 0.93 (dd, J = 13.6 Hz, 6.8 Hz, 6H, CH(C*H*$_3$)$_2$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 172.0, 171.5, 155.5, 80.0, 57.1, 53.1, 52.1, 31.1, 31.0, 30.0, 28.2, 18.9, 17.5, 15.0; IR (KBr) ν_{max}: 3308, 3055, 2979, 1754, 1682, 1652, 1538, 1447, 1436, 1392, 1365, 1296, 1256, 1174, 1156, 1051 cm^{-1}; HRMS (ESI): Calcd for $C_{16}H_{30}N_2O_5SNa$ $[M+Na]^+$ 385.1768; found 385.1769.

Synthesis of **3** was carried out according to the above-mentioned procedure for **2** by using **4** (1.97 g, 7.90 mmol), **7** (1.44 g, 7.92 mmol), *N*-methylmorpholine (1.0 mL, 9.1 mmol), isobutyl chloroformate (1.2 mL, 8.8 mmol), and triethylamine (1.3 mL, 9.3 mmol) to give colorless needle crystals of **3** (2.57 g, 86.5%). mp 108.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.52 (br, 1H, NH), 5.15 (br, 1H, NH), 4.61 (m, 1H, NHC*H*(*i*-Bu)CO), 4.28 (br, 1H, NHC*H*CO), 3.75 (s, 3H, OMe), 2.61 (t, J = 6.8 Hz), 2.12 (s, 3H, SMe), 2.10–2.03 (m, 1H, C*H*$_2$$CH_2S$), 1.99–1.92 (m, 1H, C*H*$_2$$CH_2S$), 1.70–1.63 (m, 2H, C*H*$_2$CH), 1.60–1.54(m, 1H, CH_2C*H*), 1.45 (s, 9H, *t*-Bu), 0.93 (d, J = 6.0 Hz, 6H, CH(C*H*$_3$)$_2$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 173.0, 171.3, 155.4, 79.9, 52.9, 52.2, 50.6, 41.0, 31.4, 29.8, 28.2, 24.6, 22.7, 21.6, 15.0; IR (KBr) ν_{max}: 3338, 3280, 3074, 2972, 1759, 1682, 1659, 1549, 1520, 1445, 1392, 1366, 1296, 1266, 1253, 1157, 1045 cm^{-1}; HRMS (ESI): Calcd for $C_{17}H_{32}N_2O_5SNa$ $[M+Na]^+$ 399.1924; found 399.1925.

4. NMR spectra

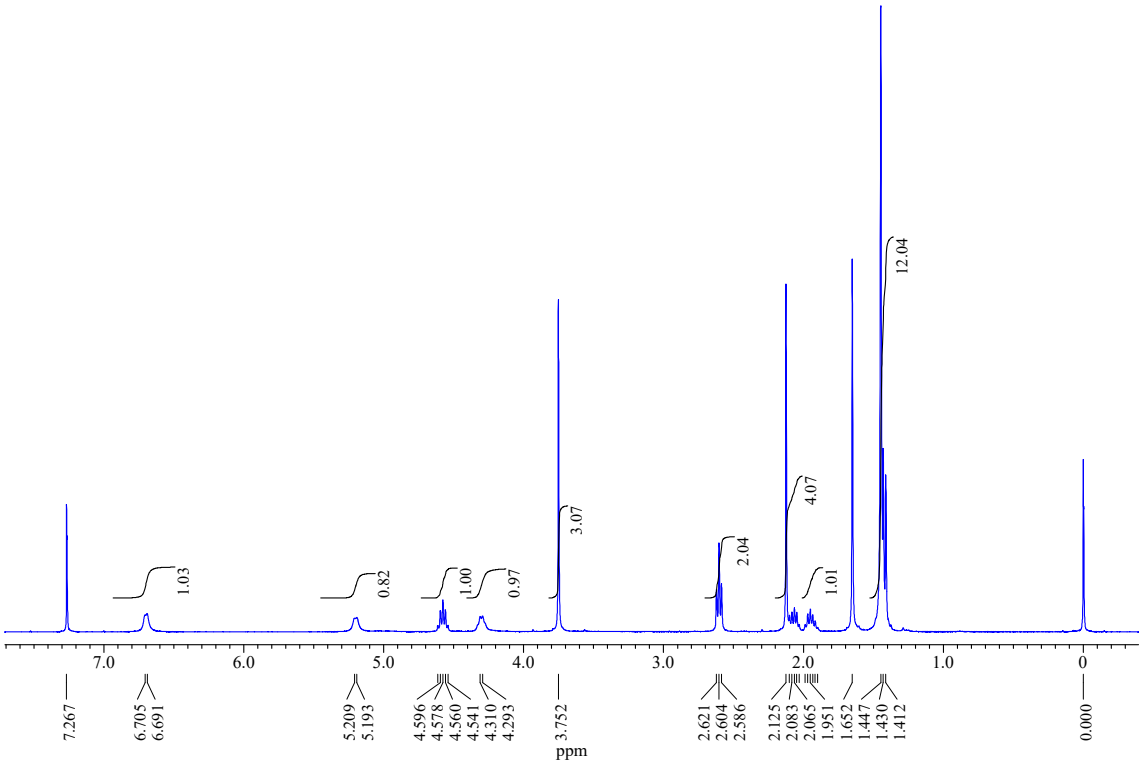


Fig. S1 ^{1}H NMR spectrum of **1** in $CDCl_3$

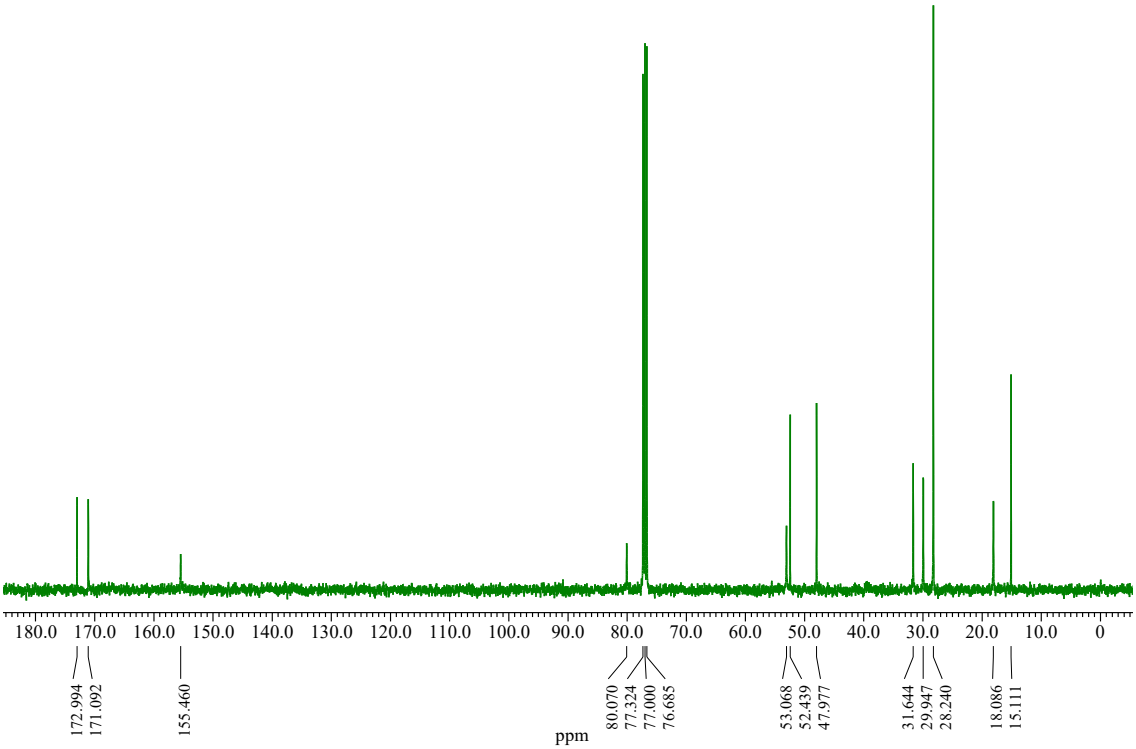


Fig. S2 ^{13}C NMR spectrum of **1** in $CDCl_3$

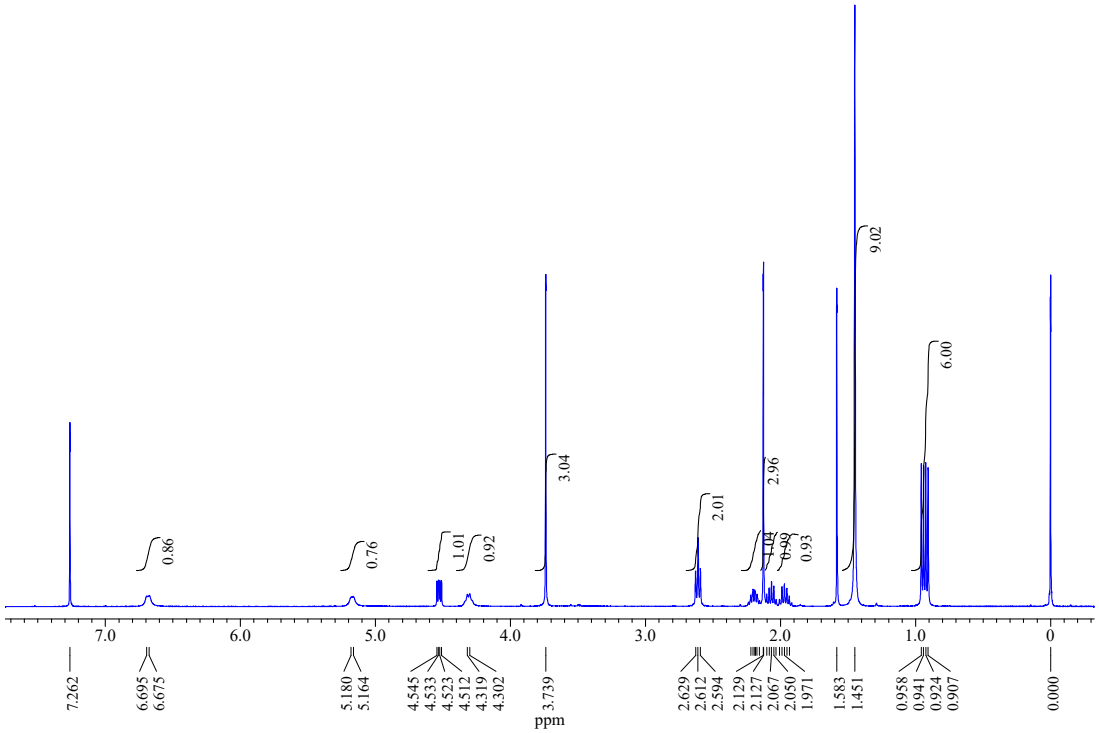


Fig. S3 ^{1}H NMR spectrum of **2** in $CDCl_3$

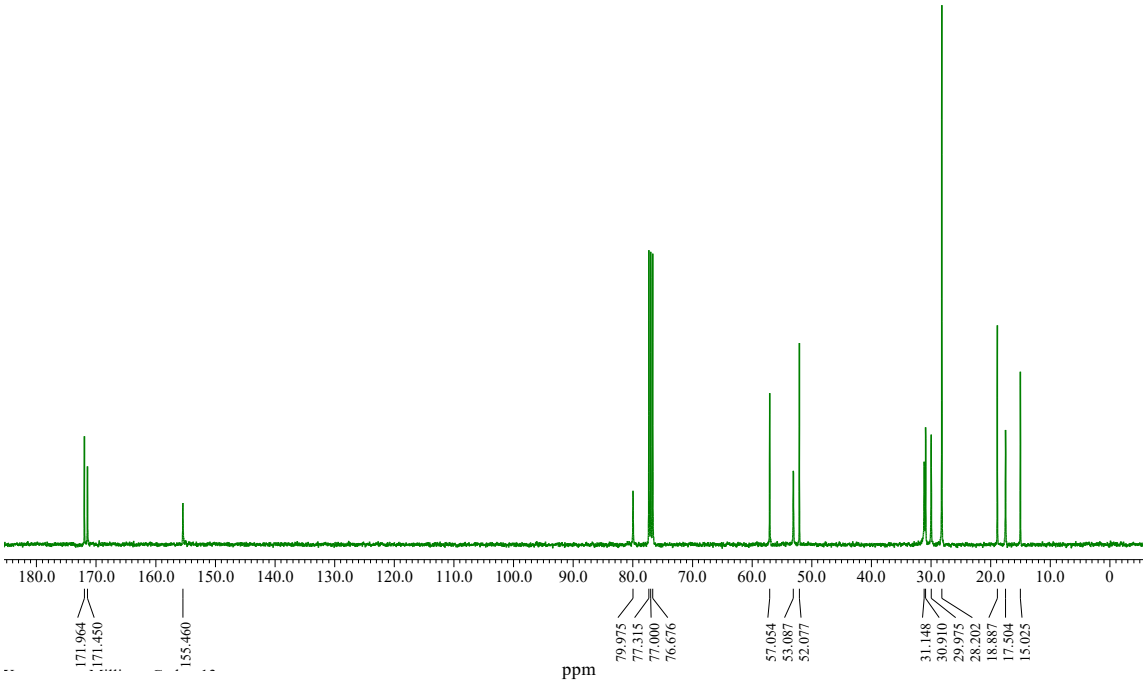


Fig. S4 ^{13}C NMR spectrum of **2** in $CDCl_3$

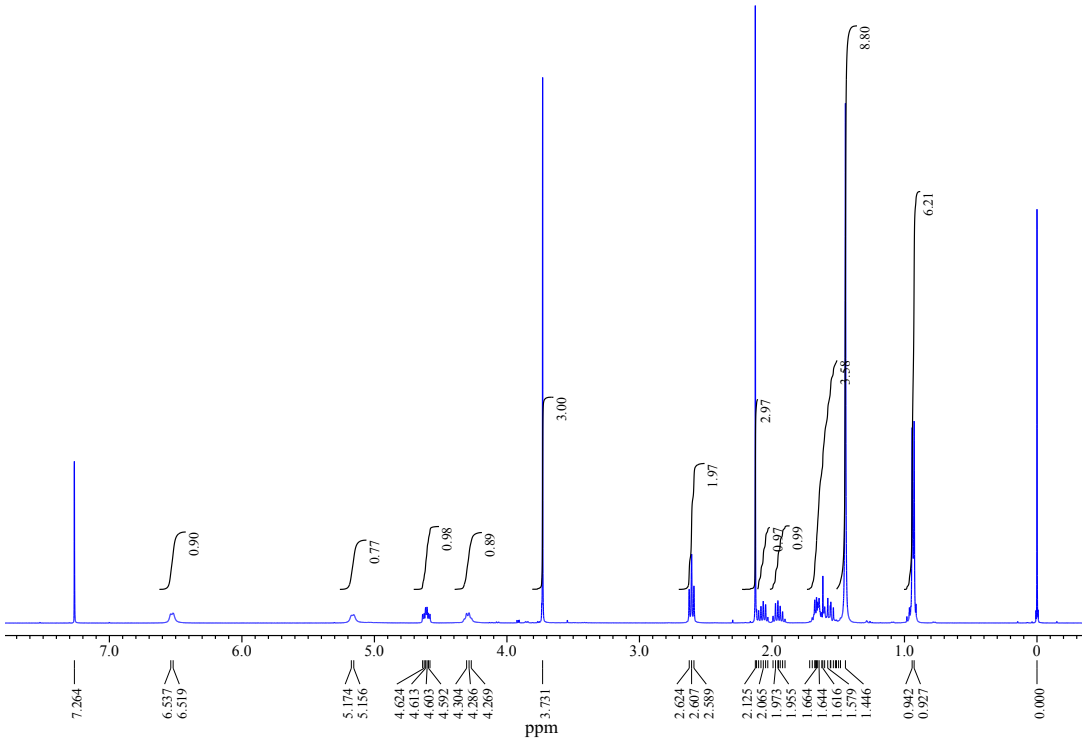


Fig. S5 ^{1}H NMR spectrum of **3** in $CDCl_3$

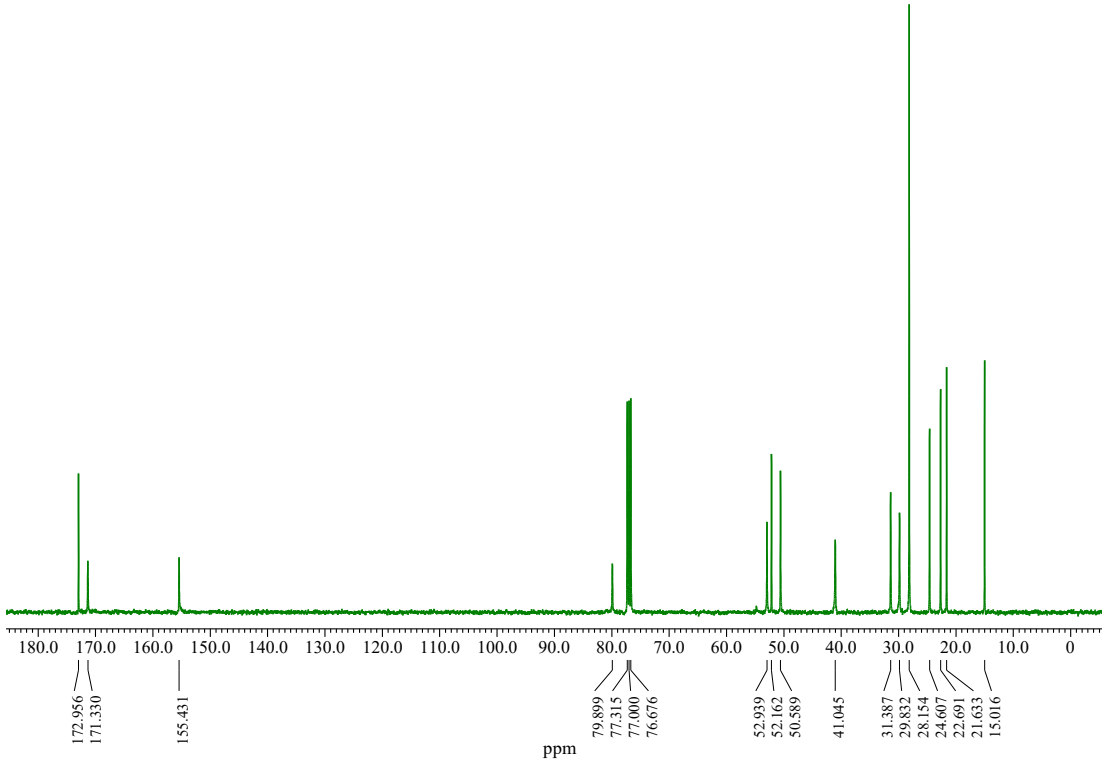


Fig. S6 ^{13}C NMR spectrum of **3** in $CDCl_3$

5. Crystallography

Single crystals of **1**–**3** were grown by cooling the boiling solutions in hexane. X-ray diffraction data of **1**–**3** were collected using a Rigaku Saturn724+ CCD area detector diffractometer [graphite-monochromated Mo Kα radiation (λ = 0.71073 Å); ω scans]. All the structures were solved by direct methods using SIR97[S1] and refined on F^2 with all data using SHELXL-2014/7.[S2] All non-hydrogen atoms were refined anisotropically, and the hydrogen atoms were refined isotropically or using the riding model. All calculations were performed using CrysAlis^{Pro} [S3] and Yadokari-XG 2009.[S4] Crystallographic data for the structures reported in the paper have been deposited with the Cambridge Crystallographic Data Centre and allocated the deposition numbers CCDC 2298630–2298633, 2342412, and 2342427. Supplementary Movies S1 and S2 for explaining the crystal structures of **1** in the absence and presence of CO_2 were prepared by using UCSF Chimera ver. 1.7.[S5]

Table S1 Crystallographic data of *N,C*-protected dipeptide crystals

Compound	**1**	**1**	**1**	**1**·0. 25 CO_2
	15 °C	–35 °C	–85 °C	–85 °C
Chemical formula	$C_{14}H_{26}N_2O_5S$	$C_{14}H_{26}N_2O_5S$	$C_{14}H_{26}N_2O_5S$	$C_{14.25}H_{26}N_2O_{5.50}S$
Formula mass	334.44	334.44	334.44	345.61
Crystal system	Hexagonal	Hexagonal	Hexagonal	Hexagonal
Space group	$P6_5$	$P6_5$	$P6_5$	$P6_5$
a / Å	11.287(1)	11.2333(9)	11.1876(8)	11.239(4)
b / Å	11.287(1)	11.2333(9)	11.1876(8)	11.239(4)
c / Å	27.130(2)	27.046(2)	26.954(2)	27.039(1)
α / °	90	90	90	90
β / °	90	90	90	90
γ / °	120	120	120	120
Unit cell volume / Å^3	2993.1(5)	2955.6(4)	2921.6(5)	2958(2)
Temperature / K	288(2)	238(2)	188(2)	188(2)
No. of formula units per cell, Z	6	6	6	6
No. of reflections measured	29458	28134	27857	9839
No. of independent reflections	6050	5962	5911	4090
R_{int}	0.0732	0.0677	0.0519	0.0390
Final R_1 values ($I > 2\sigma(I)$)	0.0859	0.0815	0.0774	0.0525
Final w$R(F^2)$ values ($I > 2\sigma(I)$)	0.1623	0.1848	0.1692	0.1424
Final R_1 values (all data)	0.2396	0.2013	0.1442	0.1010
Final w$R(F^2)$ values (all data)	0.2175	0.2460	0.1984	0.1886
S	1.0392	0.9909	1.0289	0.8476

Table S1 continued

Compound	**2**	**3**
	–85 °C	–85 °C
Chemical formula	$C_{16}H_{30}N_2O_5S$	$C_{17}H_{32}N_2O_5S$
Formula mass	362.49	376.52
Crystal system	Hexagonal	Hexagonal
Space group	$P6_5$	$P6_5$
a / Å	11.3887(8)	11.4929(7)
b / Å	11.3887(8)	11.4929(7)
c / Å	27.3424(2)	27.929(2)
α / °	90	90
β / °	90	90
γ / °	120	120
Unit cell volume / Å^3	3071.3(4)	3194.8(3)
Temperature / K	188(2)	188(2)
No. of formula units per cell, Z	6	6
No. of reflections measured	29375	30468
No. of independent reflections	5754	6393
R_{int}	0.0886	0.0614
Final R_1 values ($I > 2\sigma(I)$)	0.0754	0.0732
Final w$R(F^2)$ values ($I > 2\sigma(I)$)	0.1414	0.1499
Final R_1 values (all data)	0.1359	0.1203
Final w$R(F^2)$ values (all data)	0.1646	0.1700
S	1.0308	1.0291

Table S2 Unnormalized and normalized equivalent isotropic displacement factors (U_{eq})[a,b] of **1** at 15, –35, and –85 °C and those of **2** and **3** at –85 °C

Compound	**1**	**1**	**1**	**2**	**3**
	15 °C	–35 °C	–85 °C	–85 °C	–85 °C
C1	0.095(2) [1.7(1)]	0.084(2) [1.8(1)]	0.080(2) [2.0(1)]	0.0400(9) [1.59(5)]	0.0303(6) [1.29(4)]
C2	0.102(2) [1.8(1)]	0.089(2) [1.9(1)]	0.080(1) [2.0(1)]	0.0360(8) [1.43(5)]	0.0255(6) [1.09(3)]
C3	0.185(4) [3.3(1)]	0.162(4) [3.5(1)]	0.146(3) [3.7(1)]	0.048(1) [1.9(1)]	0.0280(6) [1.20(4)]
C4	0.065(1) [1.2(1)]	0.056(1) [1.2(1)]	0.0479(8) [1.22(3)]	0.0261(6) [1.04(3)]	0.0224(5) [0.96(3)]
C5	0.057(1) [1.0(1)]	0.0463(9) [1.00(3)]	0.0393(7) [1.00(3)]	0.0252(6) [1.00(3)]	0.0234(5) [1.00(3)]
C6	0.076(1) [1.3(1)]	0.063(1) [1.36(4)]	0.0529(9) [1.35(3)]	0.0323(7) [1.28(4)]	0.0325(7) [1.39(4)]
C7	0.098(2) [1.7(1)]	0.081(2) [1.8(1)]	0.066(1) [1.7(1)]	0.0382(8) [1.52(5)]	0.0432(8) [1.85(5)]
C8	0.154(3) [2.7(1)]	0.133(3) [2.87(9)]	0.117(2) [2.98(7)]	0.063(1) [2.5(1)]	0.076(2) [3.3(1)]
C9	0.200(5) [3.5(1)]	0.175(5) [3.8(1)]	0.163(4) [4.2(1)]	0.099(2) [3.9(1)]	0.072(2) [3.1(1)]
C10	0.073(1) [1.3(1)]	0.064(1) [1.4(1)]	0.058(1) [1.5(1)]	0.0307(7) [1.22(4)]	0.0269(6) [1.15(4)]
C11	0.129(3) [2.3(1)]	0.112(3) [2.42(8)]	0.102(2) [2.60(7)]	0.0406(9) [1.61(5)]	0.0379(8) [1.62(5)]
C12	0.179(4) [3.1(1)]	0.152(4) [3.3(1)]	0.131(3) [3.3(1)]	0.068(2) [2.7(1)]	0.117(3) [5.0(2)]
C13	0.262(7) [4.6(2)]	0.247(8) [5.3(2)]	0.252(7) [6.4(2)]	0.061(1) [2.4(1)]	0.067(1) [2.9(1)]
C14	0.301(9) [5.3(2)]	0.28(1) [6.1(3)]	0.241(7) [6.1(2)]	0.067(1) [2.7(1)]	0.119(3) [5.1(2)]
C15	—	—	—	0.067(1) [2.7(1)]	0.0288(6) [1.23(4)]
C16	—	—	—	0.087(2) [3.5(1)]	0.0433(8) [1.85(5)]
C17	—	—	—	—	0.0433(8) [1.85(5)]

[a] The U_{eq} values (Å^2) of the constituent carbon atoms were normalized by using those of the asymmetric carbon atoms (C5) of each methionine moiety as a reference. [b] Normalized U_{eq} values are shown in the square brackets.

6. Gas sorption isotherms of 1

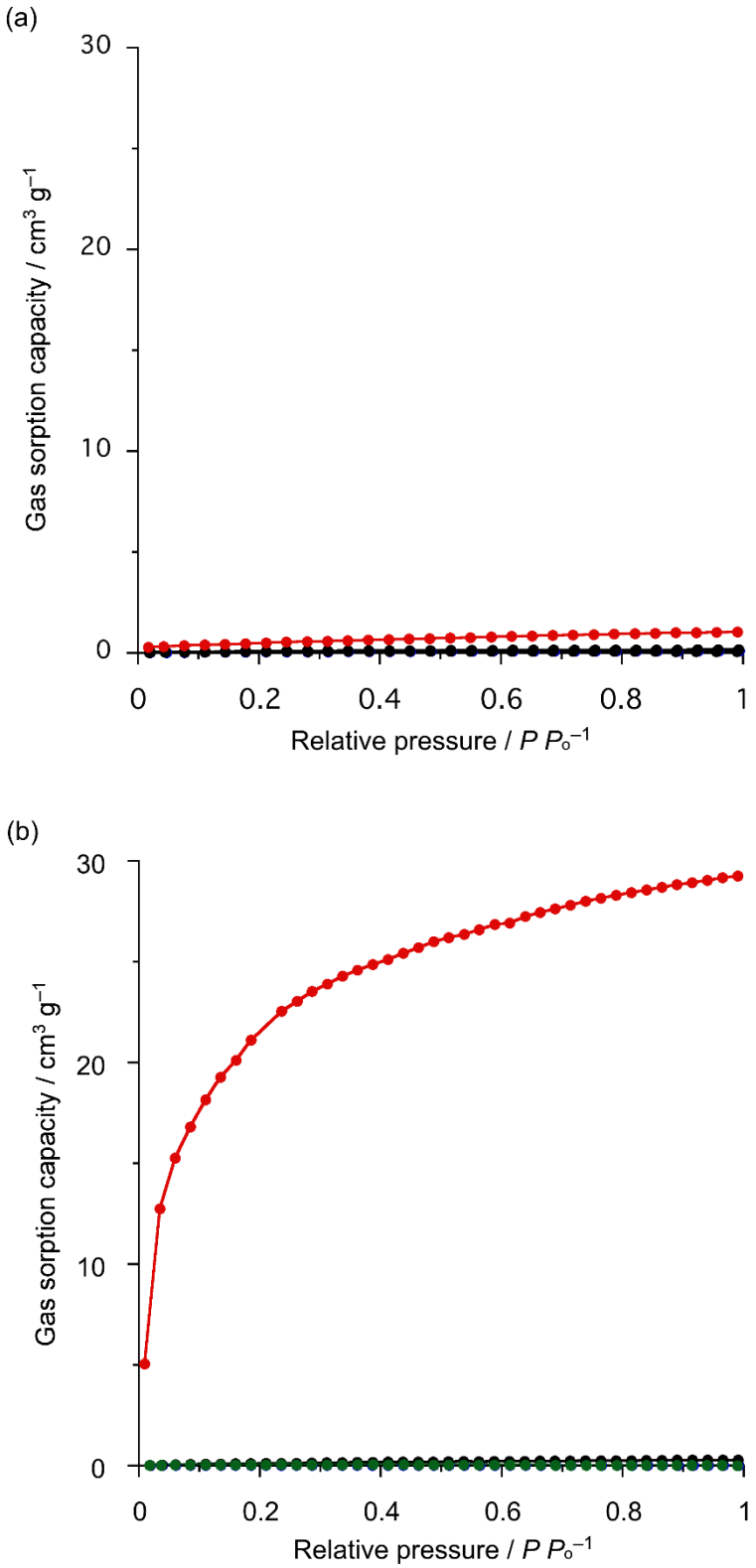


Fig. S7 Gas sorption isotherms of **1** for N_2, O_2, Ar, and CO_2 at (a] 20 ºC and (b) –78 ºC (P_o = 760 mmHg). Isotherms for N_2, O_2, Ar, and CO_2 are shown by blue, black, green, and red closed circles, respectively.

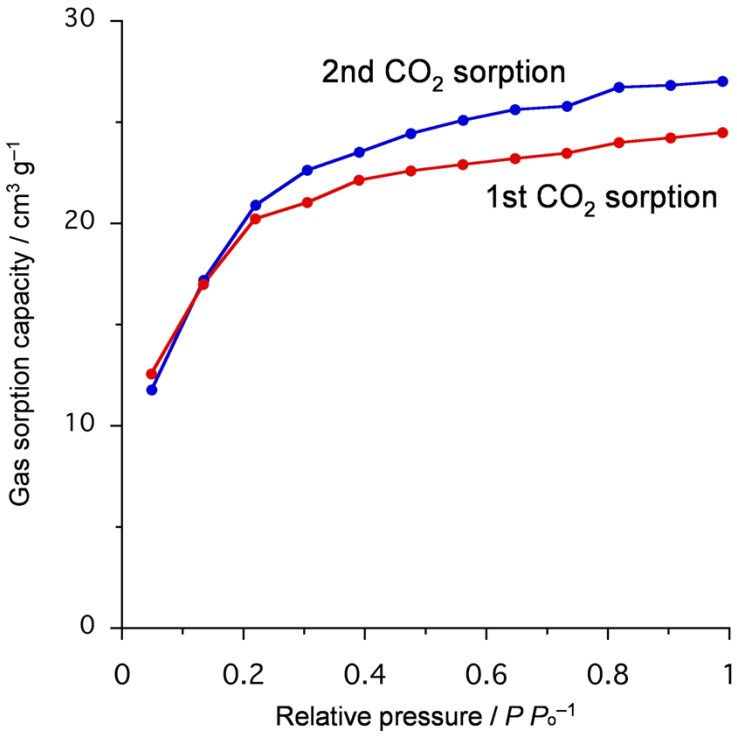


Fig. S8 First and second CO_2 sorption isotherms of **1** in two consecutive CO_2 sorption experiments at –78 °C (P_o = 760 mmHg). Single crystals of **1**, obtained from a different recrystallization batch from that applied to Figs. 4 and S7, were used to record the two consecutive CO_2 sorption isotherms.

7. SEM images of the crystals of 1 before and after CO_2 sorption experiment

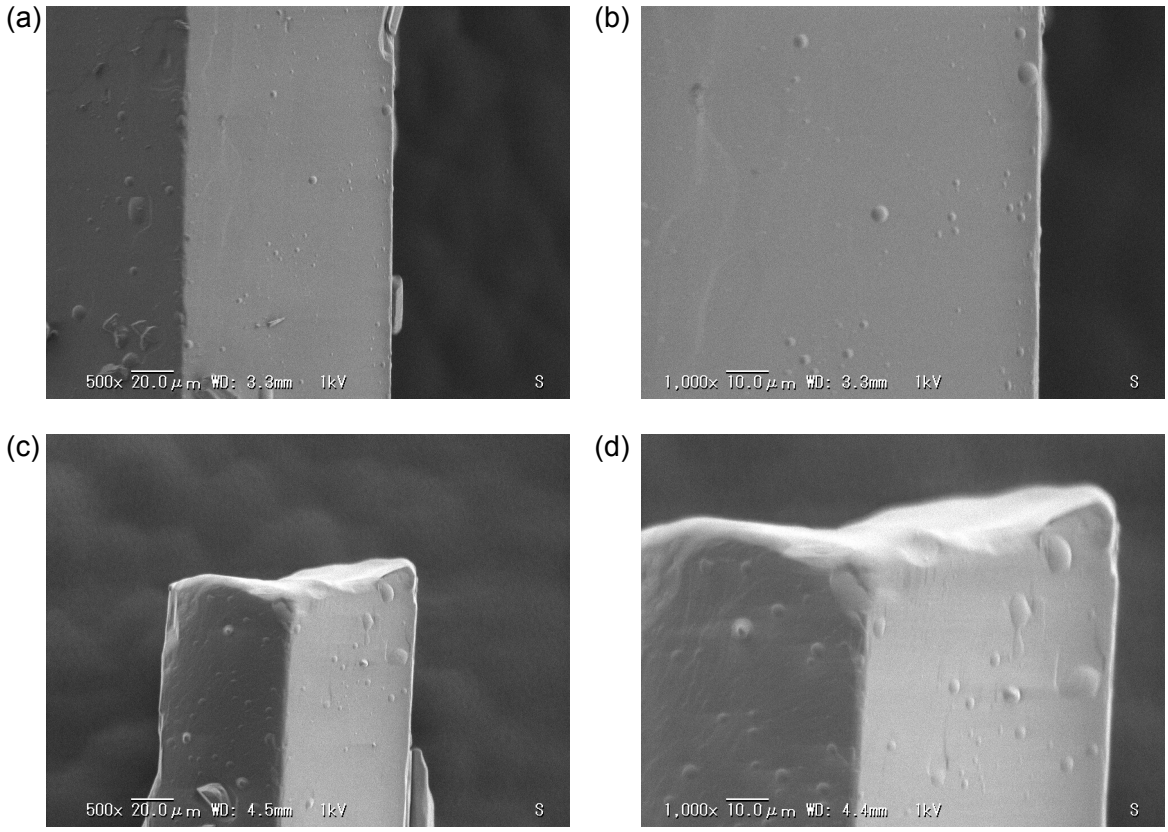


Fig. S9 SEM images of the crystals of **1** (a,b) before and (c,d) after they were subjected to CO_2 sorption experiment. Magnification: (a,c) 500x, (b,d) 1,000x.

8. Theoretical calculations

As mentioned in the main text, the main chain of **1** with a smaller occupancy is assignable to the CO_2 sorption state of **1**, and its atomic coordinates were extracted from the crystallographic data of **1**·0.25 CO_2. The atomic coordinates of hydrogen atoms were optimized under periodic boundary conditions using the fixed lattice. The DMol^3 module implemented in BIOVIA Materials Studio 2017 software was used for the optimization. The PBE functional, DND basis set, and Grimme's D2 dispersion correction were used for the calculations.

Ab initio calculations were then carried out to evaluate intermolecular interaction energies using the optimized structures. The Gaussian 16 program (Revision C.01)[S6] was used for the *ab initio* calculations. Electron correlation was corrected by the MP2 method. The aug-cc-pVDZ basis set was used for the calculations of intermolecular interaction energies. The basis set superposition error was corrected by the counterpoise method. Total intermolecular interaction energy (E_{int}) between CO_2 and each adjacent molecule of **1** was calculated at the MP2 level. The Hartree-Fock level interaction energies (E_{HF}) was also calculated.

GDMA ver. 2.2.03 program[S7] was used to calculate distributed multipole of each molecule on all atoms up to hexadecapole by using the wave functions obtained at the MP2/aug-cc-pVDZ level. Orient ver. 4.8.31 program[S8] was employed to calculate electrostatic (E_{es}) and induction energies (E_{ind}). The E_{es} was calculated as the interactions between distributed multipoles. The E_{ind} was calculated as the interactions between the polarizable sites and the electric field produced by the distributed multipole. For the calculations of E_{ind}, the following values of polarizability were used; C: 10, H: 3, N: 8, O: 6, and S: 20 a.u. The effect of electron correlation ($E_{corr} = E_{int} - E_{HF}$) is mainly the contributions of the dispersion interactions. The short-range interaction energy (E_{short}), that is comprised of exchange repulsion and charge transfer interaction, was calculated as the difference between the E_{HF} and the sum of E_{es} and E_{ind}, namely $E_{short} = E_{HF} - E_{es} - E_{ind}$.

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