Electronic Supplementary Material (ESI) for Physical Chemistry Chemical Physics.

Solid-state NMR as a probe of anion binding: molecular dynamics and associations in a [*5*]polynorbornane bisurea host complexed with terephthalate

Electronic Supplementary Information

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1. Sample synthesis and characterisation

The synthetic procedure previously described by Pfeffer and Lowe was utilised in the synthesis of the host **1** and both terephthalate guests.[1]

All reagents were obtained from commercial sources and used as provided unless otherwise stated. DMAD was distilled using a Kugelrohr short-path vacuum distillation apparatus at 85 °C / 7 mbar. The Mitsudo catalyst $RuH_2(CO)(PPh_3)_3$ was prepared as described in literature and used without additional purification.[2] A toluene solution of *t*-BuOOH was prepared as outlined by Sharpless.[3]

All microwave reactions were performed using CEM discover S-class microwave reactor in sealed 10 or 35 mL vessels.

TLC was performed on Merck TLC silica gel 60 F_{254} plates and visualised using UV light (λ = 254 nm) and/or potassium permanganate oxidising dip ($KMnO_4$, H_2O, K_2CO_3). Column chromatography was performed using silica gel 60 (230-400 mesh).

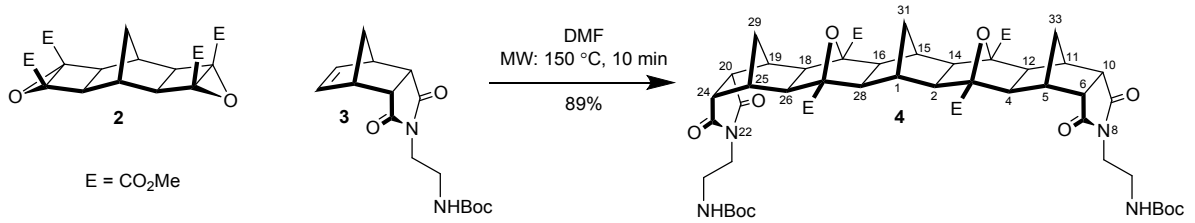
All melting points were obtained using a Stuart SMP30 melting point apparatus.

Solution state NMR were obtained from a JEOL-Ex 270 MHz, Eclipse JNM-ECP 400 MHz or a Bruker AVANCE III 500 MHZ FT-NMR spectrometer and samples were dissolved in $CDCl_3$, DMSO-d_6 or D_2O as specified. Samples are reported as: chemical shift (ppm), multiplicity (s, singlet; d, doublet; t, triplet; m, multiplet; br, broadened), *J* (coupling constant in Hz), integral, assignment. ^{13}C spectra run in D_2O were referenced to an external sample of acetone in D_2O.

High-resolution mass spectral data was collected on an Agilent Technologies LC/MSD TOF Mass spectrometer. Samples were dissolved in MeOH at a concentration of less than 0.1 mg/mL.

Compounds were named according to the IUPAC guidelines following the von Baeyer system for polycyclic compounds.[4] The relative stereodescriptors α/β are used to describe the configuration of the substituents on the ring system.

Tetramethyl(1α,2β,3α,4β,5α,6α,10α,11α,12β,13α,14β,15α,16β,17α,18β,19α,20α,24α,25α,26α,27α,28β)-8,22-(2',2''-di-*tert*-butoxycarbamatoethyl)-8,22-diaza-30,32-dioxadodecacyclo[13.13.1^{1,15}.1^{3,13}.1^{5,11}.1^{17,27}.1^{19,25}.0^{2,14}.0^{4,12}.^{6,10}.0^{16,28}.0^{18,26}.0^{20,24}]tritriacontane-7,9,21,23-tetraone-3,13,17,27-tetracarboxylate (4)



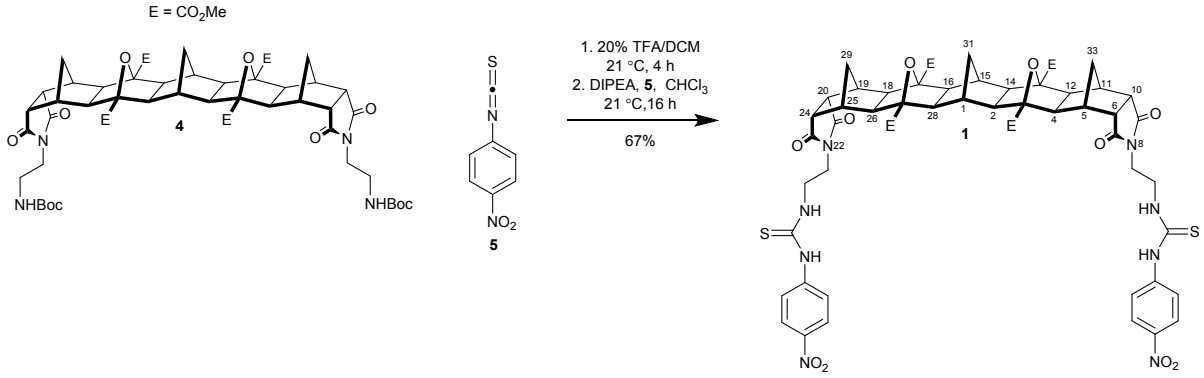
A 10 mL microwave vessel was charged with **bis epoxide (2)**[1] (134.2 mg, 0.33 mmol), **imide (3)**[1] (220.8 mg, 0.67 mmol) and DMF (1.3 mL) and the solution heated at 140 °C for 10 min. The pressure vessel was allowed to cool and the solution transferred to a round bottom flask and the solvent removed under reduced pressure. The crude powder was recrystallised using EtOAc:P.spirits to afford the title compound as a white solid (298.2 mg, 89% yield).

^{1}H NMR (400 MHz, DMSO-d_6) δ 6.62 (br s, 2H, 2 × NH), 3.76 (s, 12H, 4 × Me), 3.44 (m, 4H, 2 × CH_2N), 3.01 (m, 4H, 2 × CH_2NH), 2.98 (s, 4H, $H_{2,14,16,28}$), 2.33 (s, 4H, $H_{5,11,19,25}$), 2.25 (d, J = 9.7 Hz, 2H, $H_{29s,\ 33s}$), 2.09 (s, 4H, $H_{4,12,18,26}$), 1.87 (s, 4H, $H_{2,14,16,28}$), 1.73 (s, 2H, $H_{1,15}$), 1.58 (s, 2H, H_{31}), 1.36 (18H, 2 × *t*-Bu), 1.13 (d, J = 9.5 Hz, 2H, $H_{29a,33a}$).

^{13}C NMR (100 MHz, DMSO- d_6) δ 176.8, 168.2, 155.7, 89.3, 77.9, 53.5, 52.2, 47.7, 38.3, 37.7, 37.5, 28.14.

HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{51}H_{65}N_4O_{18}$ 1043.4108, found 1043.4135.

Tetramethyl(1α,2β,3α,4β,5α,6α,10α,11α,12β,13α,14β,15α,16β,17α,18β,19α,20α,24α,25α,26α,27α,28β)-bis-8,22-bis((2',2''-di(4'''nitrophenyl)thiourea)ethyl)-8,22-diaza-30,32-dioxadodecacyclo[13.13.1^{1,15}.1^{3,13}.1^{5,11}.1^{17,27}.1^{19,25}.0^{2,14}.0^{4,12}.^{6,10}.0^{16,28}.0^{18,26}.0^{20,24}]tritriacontane-7,9,21,23-tetraone-3,13,17,27-tetracarboxylate (1)



A solution of di-boc [5]polynorbornane **(4)** (97.2 mg, 0.10 mmol) in 20% TFA/DCM (1 mL) was stirred for 4 h. The solvent was then removed under reduced pressure followed by co-evaporation with $CHCl_3$ (2 × 5 mL) to ensure complete removal of TFA. The resulting diamine was dissolved in $CHCl_3$ (5 mL) and DIPEA (100 µL, 0.57 mmol) and 4-nitrophenylisothiocyanate (37.8 mg, 0.21 mmol) were added. The resulting reaction mixture was stirred for 16 h at 21 °C before being transferred to a separating funnel and washed with HCl (25 mL, 1 M), sat. Na_2CO_3 (25 mL) and brine (25 mL). The

organic phase was separated, dried ($MgSO_4$), filtered and the solvent removed under reduced pressure. The resulting crude bisurea product was purified using column chromatography (EtOAC R_f:0.4) to afford the title compound as a yellow powder (78.2 mg 67%).

^{1}H NMR (500 MHz, DMSO-d_6) δ 10.30 (br s, 2H, 2 × NH), 8.23 (d, J = 9.2 Hz, 4H, 2 × ArC*H*CNO_2), 8.13 (br s, 2H, 2 × NH), 7.72 (d, J = 9.1 Hz, 4H, 2 × ArC*H*CNH), 3.73 (s, 12H, 4 × Me), 3.65 – 3.69 (m, 8H, 2 × CH_2N, 2 × CH_2NH), 3.03 (s, 4H, $H_{6,10,20,24}$), 2.34 (s, 4H, $H_{5,11,19,25}$), 2.23 (d, J = 9.4 Hz, 2H, $H_{29s,\ 33s}$), 1.84 (s, 8H, $H_{2,4,12,14,16,18,26,28}$), 1.63 (s, 2H, $H_{1,15}$), 1.53 (s, 2H, H_{31}), 1.14 (d, J = 9.3 Hz, 2H, $H_{29a,33a}$).

^{13}C NMR (125 MHz, DMSO- d_6) δ 180.5, 177.1, 168.1, 145.8, 142.3, 124.7, 121.0, 89.2, 53.8, 52.2, 50.3, 47.7, 42.5, 40.3, 40.1, 37.0, 36.9, 27.7.

HRMS (ESI-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{55}H_{57}N_8O_{18}S_2$ 1181.3227, found 1181.3234.

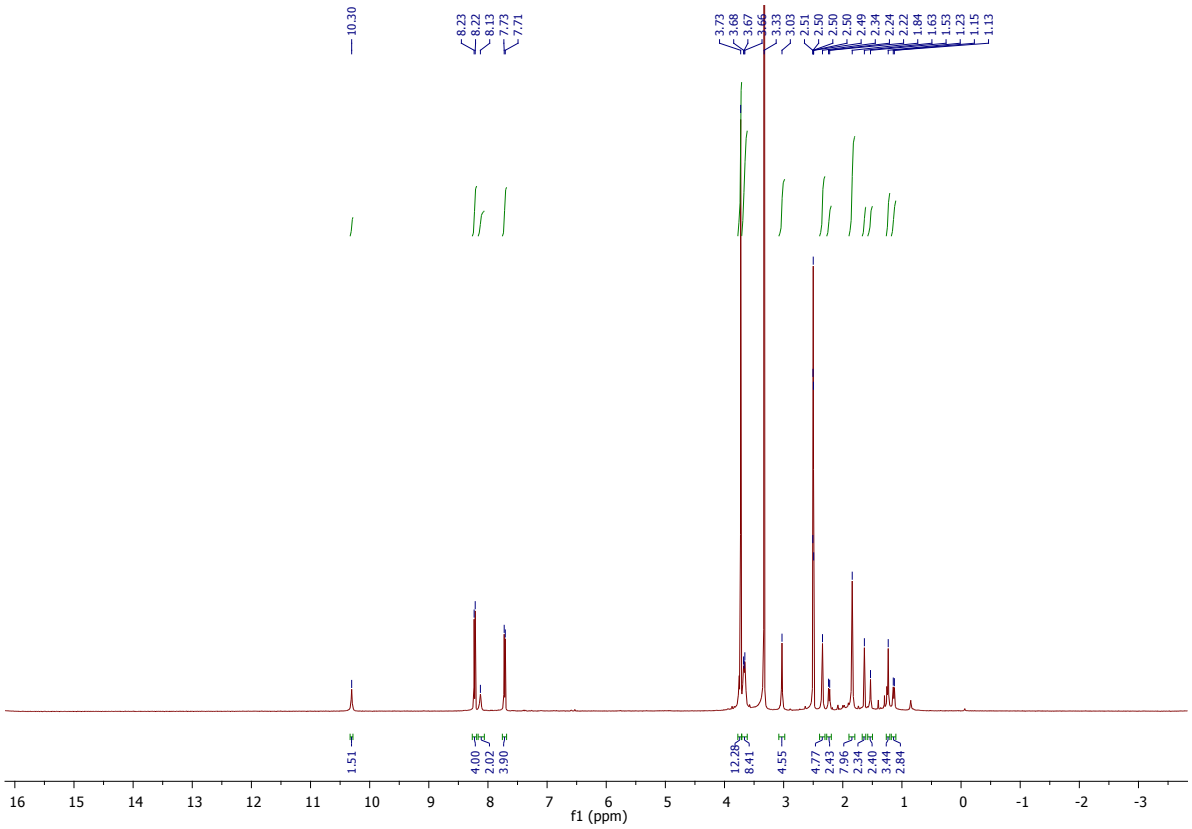
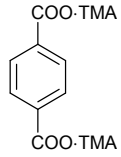


Figure S1 ^{1}H solution-state NMR spectrum of host **1**.

The dianionic guests were prepared by stirring the corresponding diacid (1.2 mmol) with tetramethylammonium hydroxide (2.4 mmol) in MeOH (2.4 mL) for 48 h. The solvent was removed under reduced pressure. The complex was stored at reduced pressure (≤ 0.7 mbar) for 48 h to ensure complete dryness.



6

Tetramethylammonium terephthalate (6)

^{1}H NMR (400 MHz, DMSO-d_6) δ 7.61 (s, 4H, 4 × Ar*H*), 3.11 (s, 24H, 8 × Me).

^{13}C NMR (100 MHz, D_2O) δ 166.8, 130.4, 120.26, 46.9.

mp >280 ° (dec)

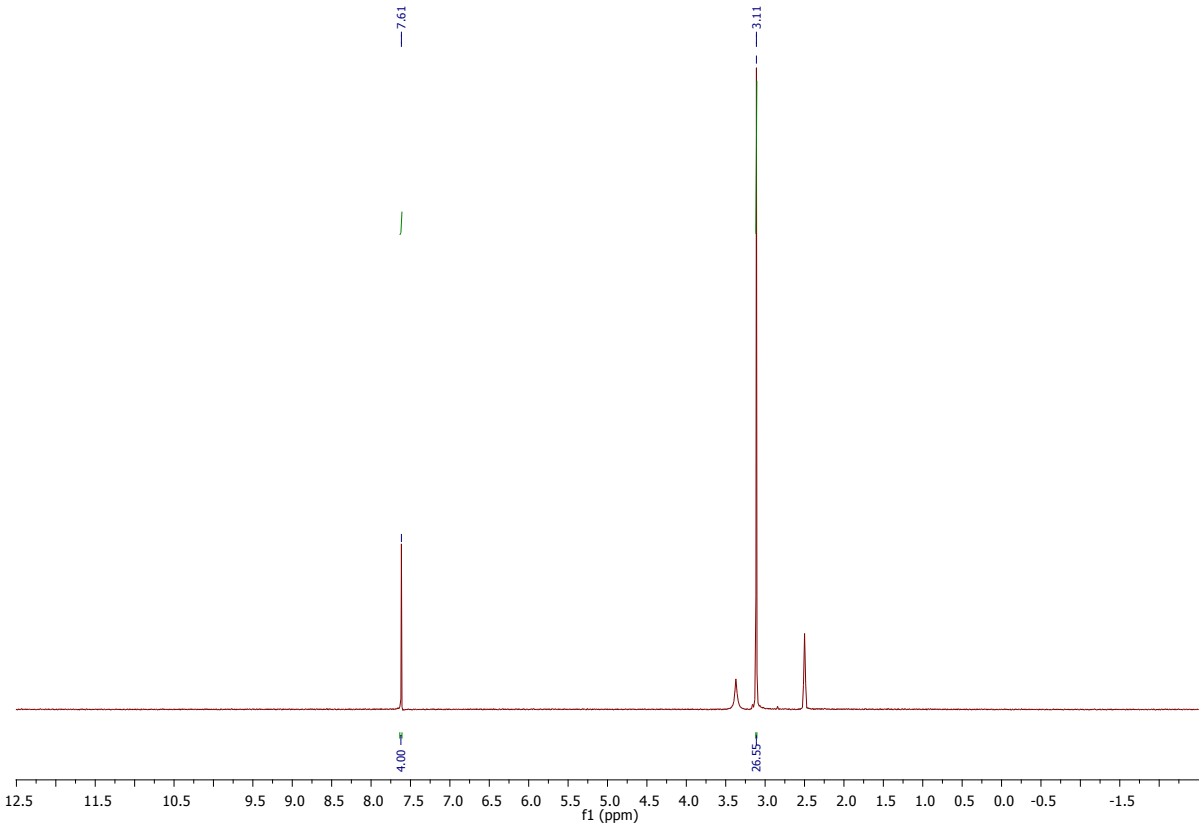
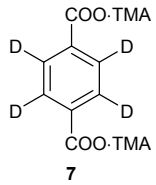


Figure S2 ^{1}H solution-state NMR spectrum of the undeuterated guest species **(6)**.



7

Tetramethylammonium terephthalate-2,3,5,6-*d*$_4$ (7)

^{1}H NMR (400 MHz, DMSO-d_6) δ 3.11 (s, 24H, 8 × Me).

^{13}C NMR (100 MHz, D_2O) δ 166.9, 130.2, 119.9, 46.9.

mp >260 °C (dec)

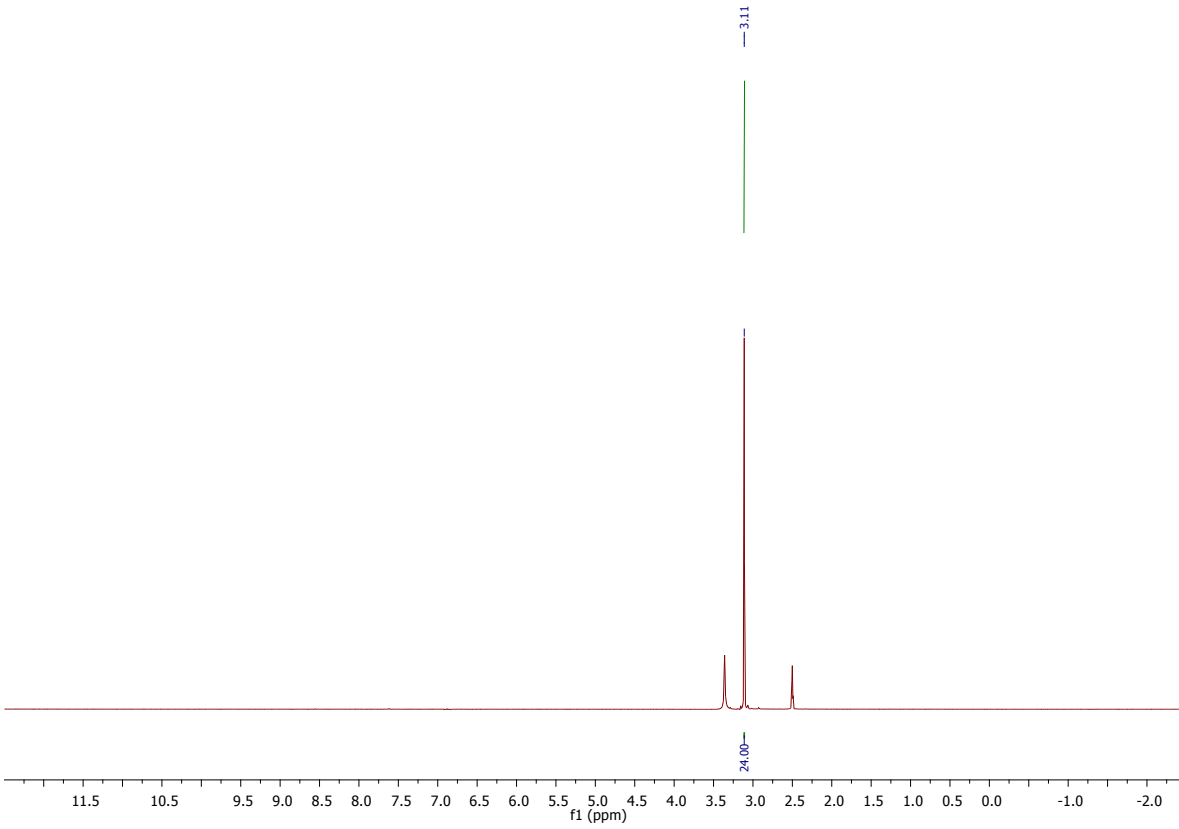


Figure S3 ^{1}H solution-state NMR spectrum of the deuterated guest species **(7)**.

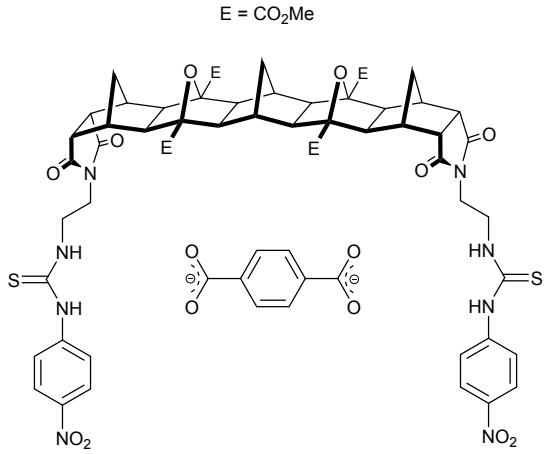


Figure S4 Complex of host **(1)** – guest **(6)**.

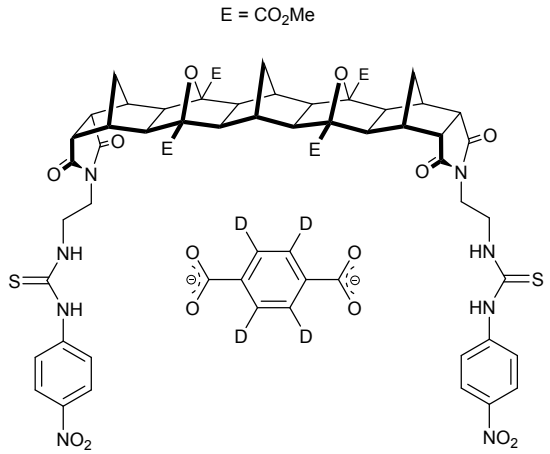


Figure S5 Complex of host **(1)** – guest **(7)**.

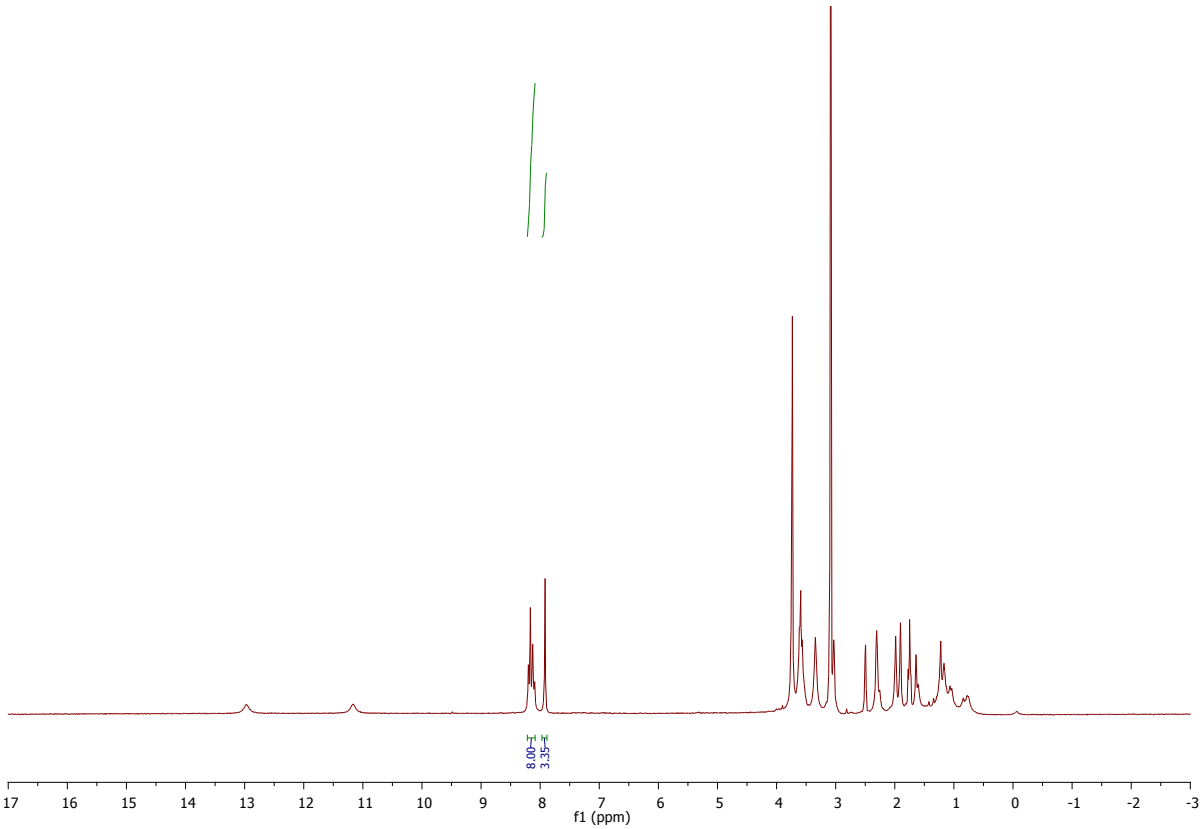


Figure S6 ^{1}H NMR spectrum of 1 host **(1)** – 1 guest **(6)**. The sample was prepared using the solid sample preparation method, then dissolved in DMSO-d_6.

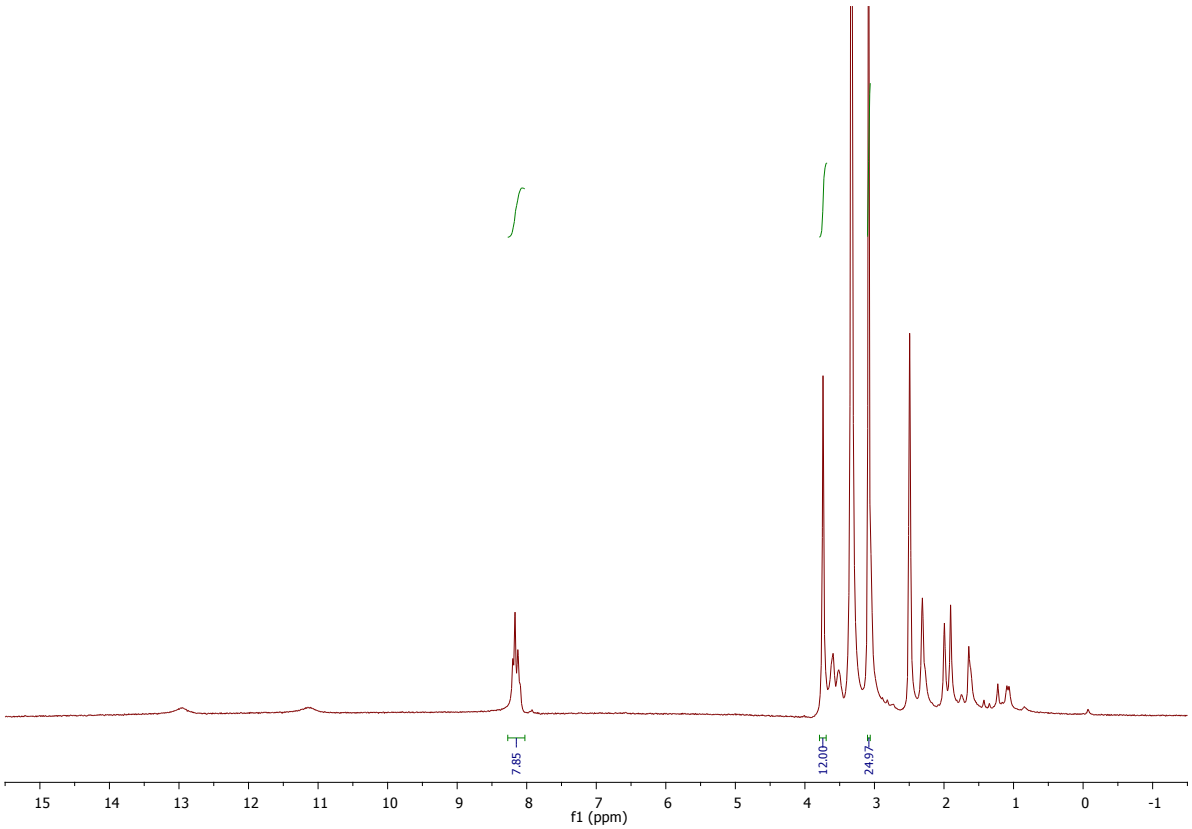


Figure S7 ^{1}H NMR spectrum of 1 host **(1)** – 1 guest **(7)**. The sample was prepared using the solid sample preparation method, then dissolved in DMSO-d_6.

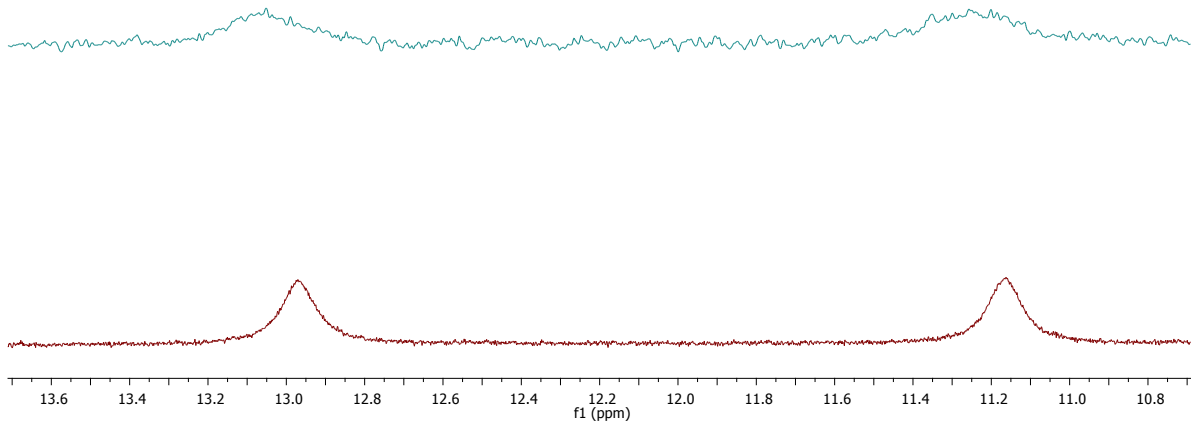


Figure S8 Comparison of thiourea ^{1}H chemical shifts. ^{1}H spectra of 1 eq. host **(1)** – 1 eq. guest **(6)** titration data 16 scans on 2.5 mM of host (top), redissolved solid 1:1 H:G material 256 scans on 10 mM of host (bottom)

2. Solution-state ^{1}H NMR titrations

The ^{1}H NMR spectroscopy titration experiments were carried out using a JEOL EX 270 MHz FT-NMR spectrometer. Stock solutions of the host (2.5 mM in DMSO-d_6) and guest (32.5 mM in host solution) were prepared. A spectrum was collected after each addition of the respective guest, and the thiourea proton chemical shifts were recorded. The data were then plotted as a titration isotherm.

Solid state samples were prepared by stirring equimolar amounts of Host and Guest in THF (5 mL) for 24 h before the solvent was removed under reduced pressure. The complex was stored at reduced pressure (≤ 0.7 mbar) for 48 h to ensure complete dryness.

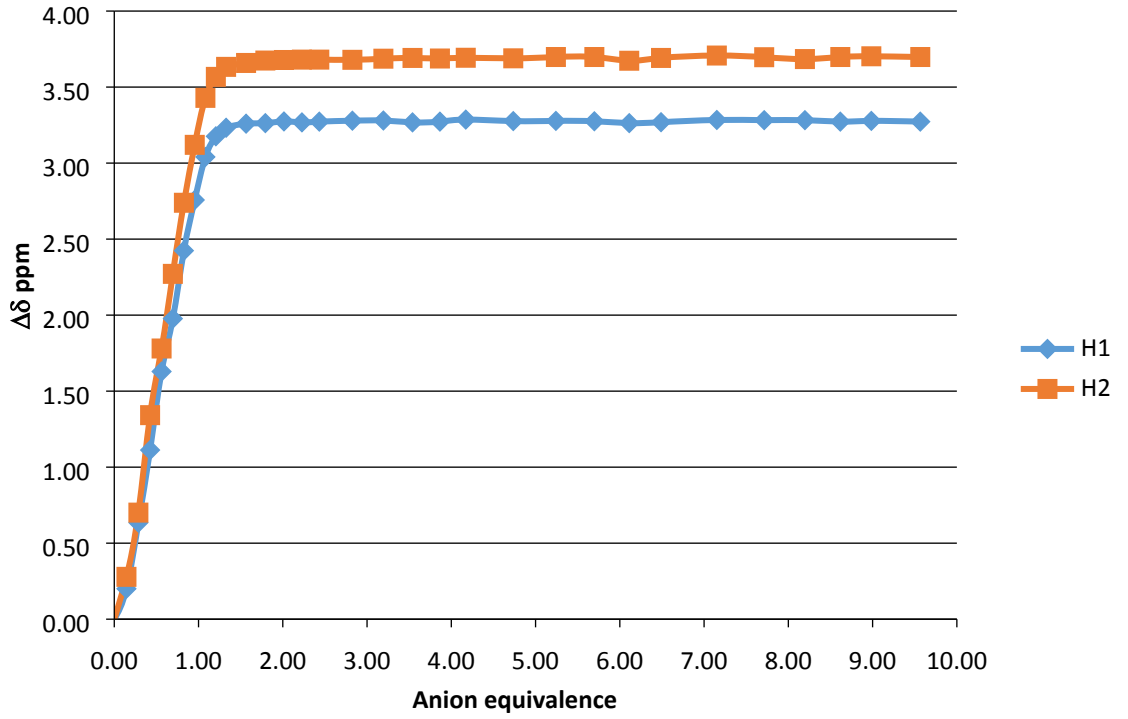


Figure S9 Titration isotherms for host **(1)** - guest **(6)**

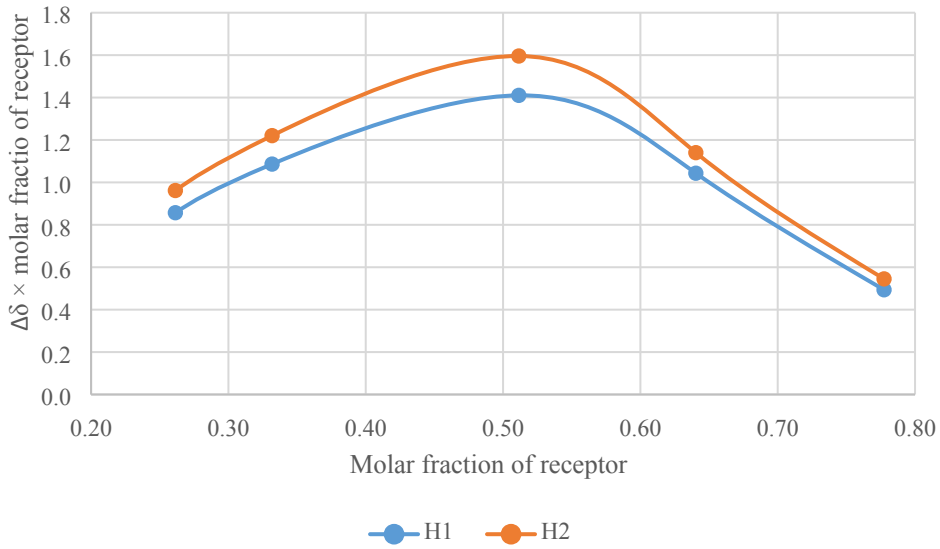


Figure S10 Job plot for host **(1)** - guest **(6)**

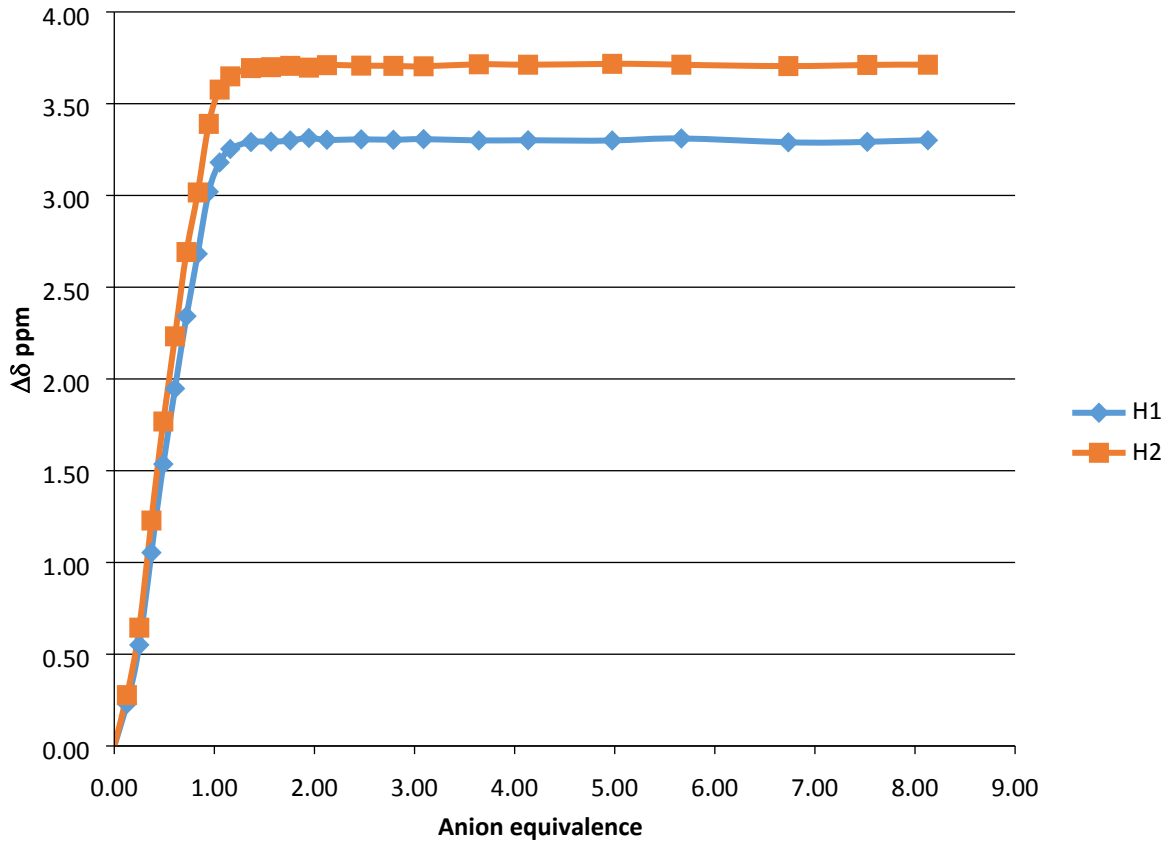


Figure S11 Titration isotherms for host **(1)** - guest **(7)**

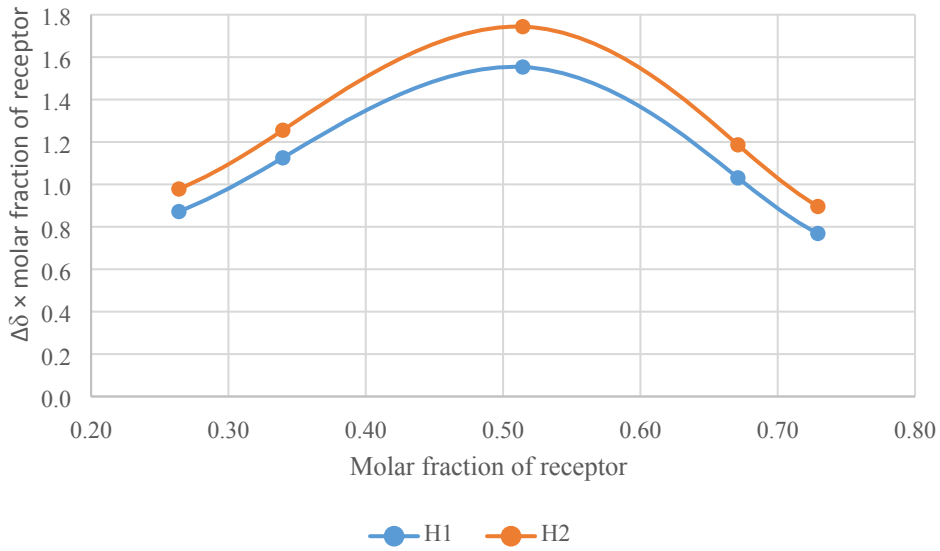


Figure S12 Job plot for host **(1)** - guest **(7)**

[1] A. J. Lowe, F. M. Pfeffer, Size matters-strong binding of the terephthalate dianion by thiourea functionalised fused [*n*]polynorbornane hosts, *Chem. Commun.*, **2008**, 1871-1873

[2] N. Ahmad, J. J. Levison, S. D. Robinson, M. F. Uttlky, E. R. Wonchoba, G. W. Parshall, Complexes of ruthenium, osmium, rhodium, and iridium containing hydride carbonyl, or nitrosyl ligands in inorganic synthesis, John Wiley & sons, Inc., **2007**, 45-64.

[3] J. Hill, B. Rossiter, K. Sharpless, Anhydrous *tert*-butyl hydroperoxide in toluene: the preferred reagent for applications requiring dry TBHP. *J org. Chem.*, **1983**, *48,* 3607-3608.

[4] G. P. Moss, Extension and revision of the von Baeyer system for naming polycyclic compounds (including bicyclic compounds), *Pure Appl. Chem.*, **1999**, *71*, 513,529.

3. X-ray powder diffraction data

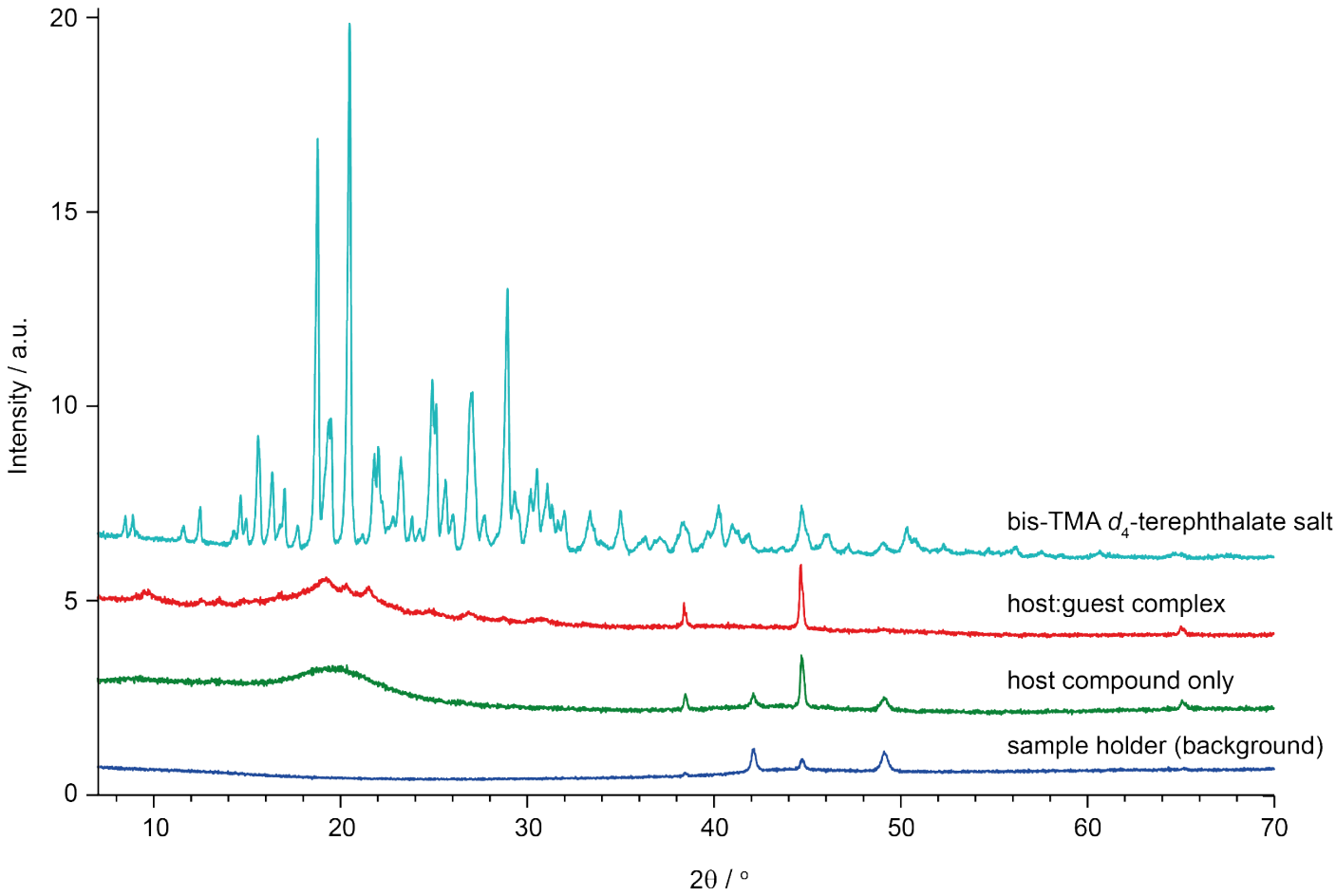


Figure S13 X-ray powder diffraction patterns obtained from the host **1** (green) and the **1**:terephthalate complex (red). The background pattern arising from the sample holder is also shown (dark blue), as is the pattern obtained from the pure bis(TMA) d_4-terephthalate salt (light blue).

4. ^{1}H-^{1}H spin diffusion spectra with short spin diffusion times

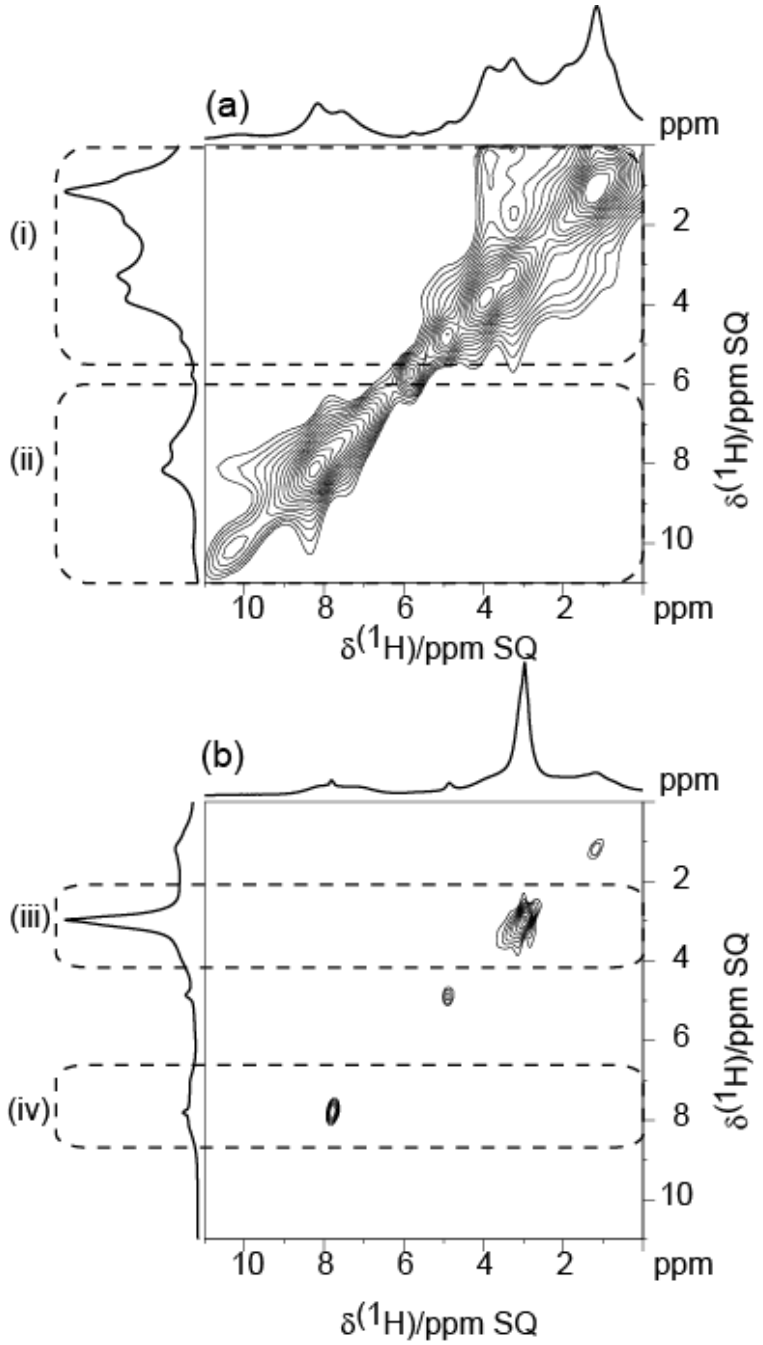


Figure S14 2D ^{1}H-^{1}H spin diffusion NMR spectra obtained (a) the neat host and (b) from the host guest complex, with a spin diffusion time (t_{sd}) of 30 μs. All the peaks are along the diagonal ridge indicating no spin diffusion contact at the short t_{sd} interval. For the complex, to observe ^{1}H-^{1}H spin diffusion from only the TMA-terephthalate to the host, a 9 ms ^{1}H-T_2 filter was inserted to suppress the signal of the host. Thus only, TMA and terephthalate signals are observed along the slope 1 diagonal in (b).

5. ^{2}H solid-state NMR spectra and simulations for the 1:terephthalate complex

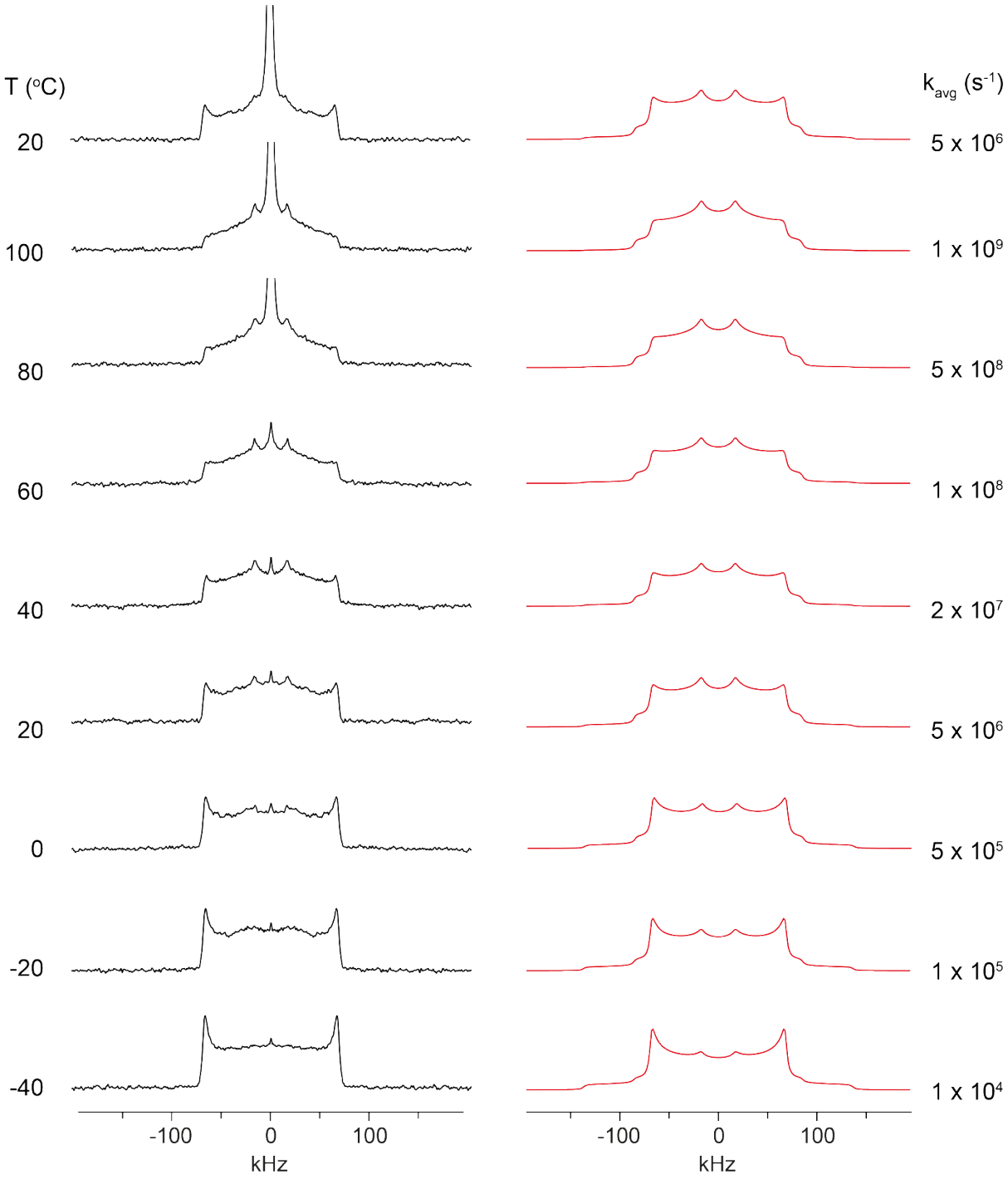


Figure S15 ^{2}H NMR spectra obtained from the **1**:terephthalate complex at select temperatures shown (black) and line shapes simulated by modelling a 180° flip of the guest molecule about its long axis at the average jump rates k_{avg} indicated (red).

6. ^{2}H solid-state NMR spectra and simulations for bis(tetramethylammonium) *d*-terephthalate

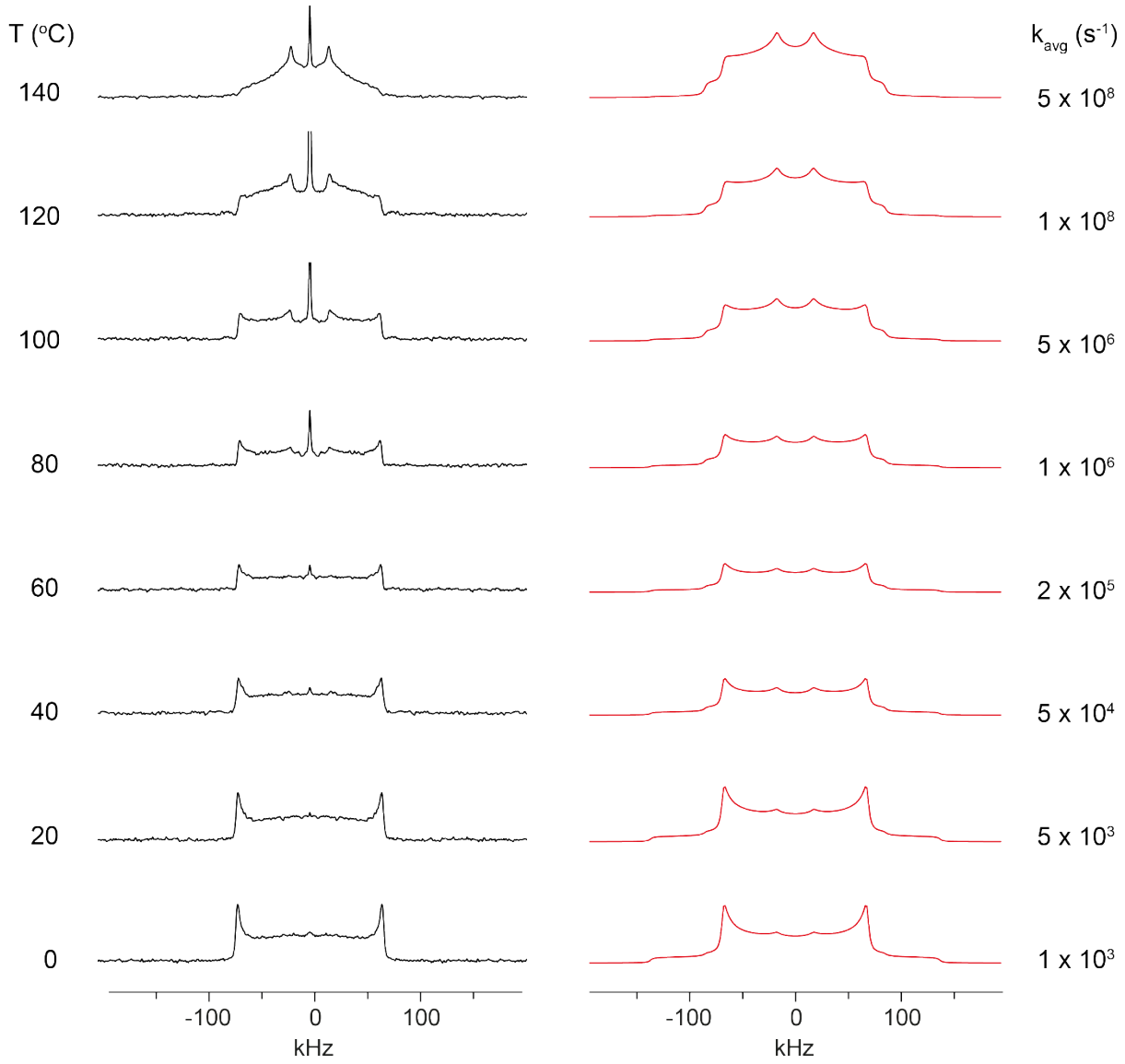


Figure S16 ^{2}H NMR spectra obtained from bis(tetramethylammonium) *d*-terephthalate at select temperatures shown (black) and line shapes simulated by modelling a 180° flip of the guest molecule about its long axis at the average jump rates k_{avg} indicated (red). In the spectrum acquired at 140 °C, the narrow component (width < 800 Hz) accounts for approximately 5% of the signal intensity, and is attributed to the presence of a hydrate phase (due to water absorption) in which the terephthalate anion is rotating rapidly and isotropically.