2H NMR Reveals Liquid State-Like Dynamics of Arene Guests Inside Hexameric Pyrogallol[4]arene Capsules in the Solid State

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^{2}H NMR Reveals Liquid State-Like Dynamics of Arene Guests Inside Hexameric Pyrogallol[4]arene Capsules in the Solid State.†

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The dynamics of guests in molecular encapsulation complexes have been studied extensively in solution, but the corresponding behavior of those guests when the capsules are present in the solid state are not as well understood. Here we report on comparative solution ^{1}H and solid-state ^{2}H NMR measurements of encapsulation complexes of fluorene(-d_2), fluoranthene(-d_{10}), and pyrene-(-d_{10}) in pyrogallol[4]arene hexamers assembled in the solid state by ball milling. In solution, the ^{1}H spectra show that these rigid guests tumble and exchange positions quickly within the capsules' interiors, with the exception of pyrene, which has slower tumbling and positional exchange. Static solid-state ^{2}H NMR using the deuterated guests shows that, when the capsules are in the solid state, their guests retain the liquid state-like dynamics observed for the capsules in solution. When the pyrogallol[4]arene hexamers' pendant decyl groups were substituted with propyl groups, guest dynamics in the solid state were slowed. We propose that these pendant alkyl groups form an interdigitated and dynamic waxy domain surrounding the capsules in the solid state, and that the greater mobility of the decyl groups is translated across the walls of the host, resulting in more rapid guest dynamics in the capsules' interiors.

Introduction

Since the spontaneous formation of molecular encapsulation complexes was first reported, chemists have sought to understand how confinement within host molecules influences the motions, conformations, equilibria, and reactivity of guests.[1–6] Numerous examples have been studied using capsules stabilized by hydrogen bonding, metal–ligand interactions, or ion pairing, and these hosts' interiors have been shown to stabilize reactive intermediates, offer unique forms of isomerism, accelerate reactivity, and change the outcomes of chemical reactions.[7–15] Guest exchange is regulated by a variety of mechanisms, including host conformational changes, temporary metal–ligand dissociation, and partial or complete capsule disassembly.[16,17] Despite the wealth of past research on host and guest dynamics in solution, comparatively little is known about the motions of guest molecules when those same capsules are present in the solid state. Guests are often disordered in the cavities of host molecules observed in crystal structures, and solid state NMR has been used in only a handful of studies on guest dynamics in discrete encapsulation complexes.[18–20] Given the extraordinary guest dynamics inside pyrogallol[4]arene hexamers in solution,[21–23] we wondered how the solid state would change guest dynamics inside these hexamers. To what extent would the solid state's rigidity translate across the host's walls?

Pyrogallol[4]arene hexamers $\mathbf{1}_6$ are self-assembled capsules that enclose approximately 1.3 nm^3 in the form of a roughly spherical cavity (Figure 1).[24] After they were first characterized in the solid state by Atwood, a number of groups have studied their encapsulation complexes in solution, including applications in catalysis.[25–27] Our lab has shown that a variety of arenes can be encapsulated by cooling molten mixtures of pyrogallol[4]arene and guest.[21,22] The resulting encapsulation complexes can be dissolved and studied in solution, but most are not thermodynamically stable. Guest exchange for solvent occurs over time, but often with $\Delta G^{\ddagger} > 23$ kcal/mol and an imperceptibly slow rate at ambient temperature.[22,28] Guests encapsulated in these hexamers are generally dynamic in the capsules' interiors on the ^{1}H NMR timescale, although Cohen has shown evidence for distinct guest sites tied to attractive interactions between guests and the host's alcohol groups.[19,23,29] Solid-state ^{13}C NMR has been used by Cohen *et al.* to identify guest encapsulation in pyrogallol[4]arene hexamers in the solid state, and our lab has applied this method to the study of solid-state, mechanically induced hexamer assembly with guest inclusion by ball milling, extending the scope of molecular encapsulation.[19,20] Using this assembly method and static solid-state ^{2}H NMR, we show here that liquid state-like guest dynamics in the capsules' interiors

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† This paper is dedicated to Prof. Julius Rebek on the occasion of his 75th birthday.
‡ These authors have contributed equally to this work and should be regarded as joint first authors.
Electronic Supplementary Information (ESI) available: additional figures, all relevant NMR spectra, DSC traces, and synthetic details. See DOI: 10.1039/x0xx00000x

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are retained when those capsules are present in the solid state (Figure 1).

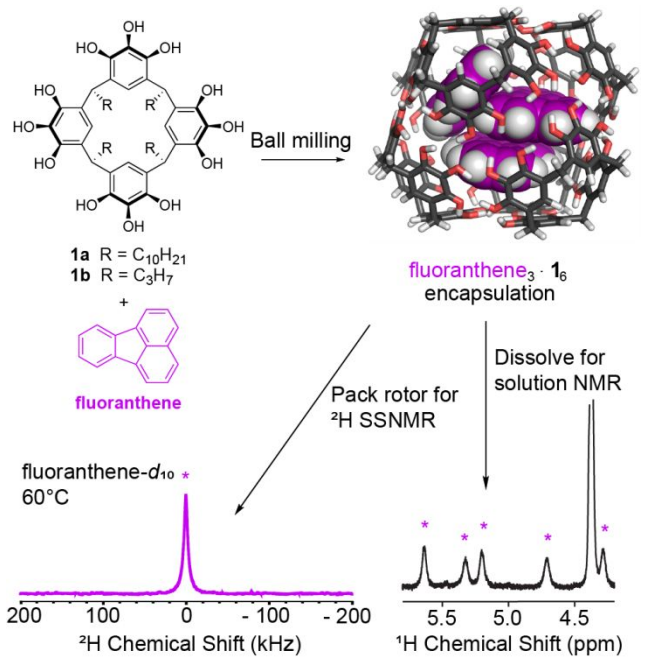


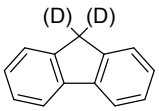
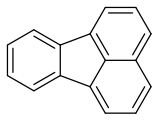
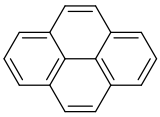
Figure 1. Mechanical forces from ball milling induce the self-assembly of pyrogallol[4]arene hexamers **1a**$_6$ and **1b**$_6$ with guest inclusion. These assemblies, once formed in the solid state, can be dissolved in nonpolar organic solvents for study in solution or can be characterized by static solid-state NMR. * indicates signals for encapsulated guests. Decyl/propyl groups of **1a/b** have been truncated from the molecular model for clarity.

Methods

Capsule Assembly and Guest Loading. Capsules loaded with fluorene(-d_2), fluoranthene(-d_{10}), and pyrene(-d_{10}) were prepared in the solid state by ball milling stoichiometric mixtures of pyrogallol[4]arene **1a** or **1b** with each respective guest (for stoichiometry, see Table 1). A stoichiometric mixture of **1a** or **1b** and guest totalling approximately 550 mg was placed in a 5 mL steel chamber along with a 7 mm steel ball. Samples were milled using a Retsch MM400 ball mill running at 30 Hz for 2 minutes at room temperature (23 °C), removed from the chamber and mixed to prevent clumping, and returned to the chamber for 28 minutes of additional milling at 30 Hz. The resulting solids were heated in vials on a hot plate at 70 °C for 30 minutes and cooled prior to solution or solid-state NMR measurements. To confirm the success of milling-induced encapsulation, samples of 5–10 mg of each milled mixture were removed, dissolved in $CDCl_3$, and immediately measured by ^{1}H NMR to confirm percent guest encapsulation (Table 1).

Solid-State Studies by Differential Scanning Calorimetry. Following encapsulation complex preparation by ball milling, and with variable-temperature NMR measurements planned, we performed differential scanning calorimetry (DSC) studies on the milled powders of host and guest (these samples were *not* heated as described above) to assess any possible heat-induced changes in the solid state. Aluminum pans containing powdered samples after ball milling were hermetically sealed and subjected to five heat-cool cycles between 30 and 70 °C using a TA Instruments Q2000 differential scanning calorimeter (TA Instruments, New Castle, DE; Figure S12).

Table 1. Structures of guest molecules and capsule loading capacity.

Guest	vdW volume / A^3	Max # encap.[a]	Packing coefficient[b]	Avg. loading[c]
 fluorene(-d_2)	180	4	0.55	83% (29%)
 fluoranthene	202	3	0.47	56% (55%)
 pyrene	198	3	0.46	70% (36%)

[a] Maximum number of each guest that can be encapsulated inside a pyrogallol[4]arene hexamer.[20,22] [b] The ratio of the total van der Waals volume of the guests to the vdW volume of the cavity of the host. [c] The experimentally determined (^{1}H NMR after dissolution) average number of guest molecules encapsulated in **1a**$_6$ as a percent of the maximum, following solid-state capsule preparation as in the Methods. The percent of average guest loading in the **1b**$_6$ hexamer is given in parentheses.

Static Solid-State ^{2}H NMR Measurements. Static ^{2}H NMR experiments were performed on a 600 MHz Bruker Avance III HD NMR spectrometer equipped with a broad band 4mm probe. Samples were packed into plastic inserts with a sample mass between 25 and 27 mg. A quadrupolar echo sequence with composite pulses ($90°_x$ $180°_{-x}$ $90°_x$ $135°_{-x}$ $45°_x$ - τ - $90°_y$ $180°_{-y}$ $90°_y$ $135°_{-y}$ $45°_y$ - $\tau/2$ - acquisition) was applied to accumulate ^{2}H NMR signals. 8192 scans were collected for each spectrum using a recycle delay of 0.25 s unless otherwise stated. The short recycle delay allows detection of only those deuteriums that relax faster than our recycle delay of 0.25 s, which are those that experience relatively fast tumbling dynamics, similar to what is observed in the liquid state. This T1-weighted filter was chosen to remove signals from less dynamics guests, including those that are not encapsulated.

Results and Discussion

Pyrogallol[4]arene hexamer synthesis and encapsulation complex formation. Our past studies have shown that ball milling of

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pyrogallol[4]arene **1a** or **1b** with guest can lead to incomplete encapsulation, including the presence of semi-formed encapsulation complexes.[20] These milled mixtures will equilibrate, in the solid state, over time to increase the extent of guest encapsulation.[30] Gentle heating accelerates the equilibration. To better understand how the variable temperatures used in our solid-state NMR measurements would impact on encapsulation, we performed DSC measurements on mixtures of host and guest immediately after ball milling without prior heating. For all pairings of fluorene, fluoranthene, or pyrene with **1a** or **1b**, we recorded DSC data across a temperature range of 30–70 °C using freshly milled samples. In all cases, the first scan differed from subsequent scans, which were identical within experimental error (Figure S12). Consistent with past observations, milling was efficient but imperfect at assembling the host–guest encapsulation complexes in the solid state. A brief heating at 70 °C is sufficient to reach equilibrium, and solution NMR of dissolved samples shows an increase in the % guest encapsulation when the solid state has been equilibrated (final results are shown in Figure 2 and Table 1). Based on this result, we heated all milled samples at 70 °C for 30 minutes prior to performing the solution and solid-state ^{2}H NMR measurements of guest dynamics, as discussed below.

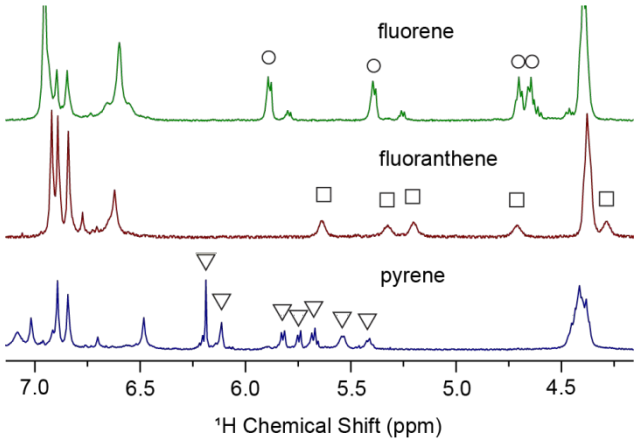

Figure 2. Solution ^{1}H NMR spectra of guest encapsulation complexes of fluorene, fluoranthene, and pyrene in $\mathbf{1a}_6$ as prepared by ball milling, heating, and subsequent dissolution in $CDCl_3$ (500 MHz, 298 K). ○, □, and ▽ denote the signals for the encapsulated guests; the pyrene spectrum shows a mixture of two forms of the capsule that differ in the arrangement of the hydrogen bonds.[22] See Figure S13 for the full spectra.

Solution ^{1}H NMR analysis of guest dynamics. Guest dynamics inside pyrogallol[4]arene hexamers can be studied in solution by observing the ^{1}H NMR spectra of encapsulation complexes. When four molecules of fluorene or three molecules of fluoranthene are encapsulated in $\mathbf{1a}_6$ or $\mathbf{1b}_6$, the NMR spectra of the guests are slightly broadened and shifted upfield (Figure 2; spectra of encapsulation complexes of $\mathbf{1b}_6$ are very similar and can be seen in the Figure S14; full spectra, with resonances for free guests between 7.2 and 8.2 ppm except for the fluorene methylene at 3.9 ppm, are shown in Figures S13 and S15). The hexamers are chiral but racemic, owing to the clockwise or counterclockwise arrangement of their hydrogen bonds, as evidenced by the fact that there are three alcohol resonances in the ^{1}H spectra and six distinct aryl C resonances in the ^{13}C NMR (for ^{1}H NMR, see Figure S13). This observation is true when the capsules are filled with fluorene, fluoranthene, $CDCl_3$, or other solvents.[22] In our opinion, the most striking feature of these NMR spectra is that all encapsulated guest molecules give rise to the same set of NMR signals. Molecular modelling shows that three fluoranthene molecules that can fit within the hexamer in a stacked or a slipped arrangement (Figures 1 and S2). In both cases, the three fluoranthenes are clearly not in the same environment. Nonetheless, the fact that they all exhibit the same ^{1}H NMR resonances at 298 K indicates that these guests tumble rapidly within the capsule *and the central fluoranthene exchanges places with those on the top and bottom*. Clearly, these guest dynamics require significant distortion of the capsule, likely with temporary rupture of at least some of its hydrogen bonds. Perhaps most striking is the fact that fluoranthene encapsulation is not thermodynamically stable in $CDCl_3$; if the capsule opens sufficiently, then the fluoranthene guests will be exchanged completely for guest solvent. The capsule exhibits a remarkable degree of plasticity in allowing these guest dynamics, but without opening sufficiently to allow guest exchange.

Pyrene is a structural isomer of fluoranthene with a shape that is comparatively wider in the middle and more tapered at the ends. As can be seen in molecular modelling (Figure 1 and S1–S3), its shape is a better match than fluoranthene to the interior of the pyrogallol[4]arene hexamer. The rate of guest exchange of pyrene for solvent is slower than that of fluoranthene, and the ^{1}H NMR spectrum shows reduced symmetry, indicative of slow tumbling of a stack of three pyrene molecules in the capsules' interiors on the NMR timescale.

Fluorene is likely arranged in the capsule with three molecules stacked and a fourth beside the stack and oriented roughly perpendicularly to the others (Figure S1). We observe dynamics similar to those of fluoranthene—slightly faster, as indicated by the sharper ^{1}H NMR resonances—with all guests experiencing on average the same environment on the NMR timescale. Although this encapsulation complex has the highest packing coefficient, it is likely that the smaller size of this guest and the impossibility of arranging four in a neat stack to complement the capsule's shape (c.f. pyrene) contribute to these fastest guest dynamics.

Static solid-state ^{2}H NMR analysis of guest dynamics. Solid-state ^{2}H NMR is an established method for studying guest and ligand dynamics in metal–organic frameworks and related systems.[31–37] Here, we applied it to discrete molecular encapsulation complexes in the solid state.[18,38] Using the same procedures for encapsulation complex synthesis by ball milling as discussed above for protio-guests, we prepared encapsulation complexes using fluorene-d_2, fluoranthene-d_{10}, and pyrene-d_{10} and recorded their static solid-state ^{2}H NMR spectra at temperatures from 273–333 K. Control static solid-

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state ^{2}H spectra recorded for the pure deuterated fluorene-d_2 and fluoranthene-d_{10} guest molecules showed very weak Pake pattern signals (Figure S10), characteristic of little rotational motion of these molecules, as expected of arenes in the solid state. For pyrene-d_{10} however, we were able to observe a narrow Pake pattern and large isotropic component, indicating that pyrene retains high levels of motion as a powder—likely a spinning motion—even with a fast recycle delay meant to record motions occuring on the liquid-like timescale. After the milling with **1a**$_6$ and **1b**$_6$, the trend of its dynamics follows those of fluorene-d_2 and fluoranthene-d_{10}, as discussed below.

The dynamics of all three guest molecules are much different when they are present in the interiors of the pyrogallol[4]arene hexamers in the solid state. The static solid-state ^{2}H spectra for each guest, encapsulated in either **1a**$_6$ or **1b**$_6$, show intense signals centered near 0 kHz, indicative of guest isotropicity, or rapid tumbling (Figure 3). Greater signal intensity and a narrower line width are both indicative of faster guest motion within the interior of the host. Two relationships between host and guest structure are immediately apparent. First, the rapidity of guest motions in the capsules' interiors decreases from fluorene to fluoranthene to pyrene, mirroring the trend in relative dynamics of these guests when the capsules are in $CDCl_3$ solution. Second, guest dynamics are faster in decyl pyrogallol[4]arene **1a**$_6$ in the solid state as compared with propyl pyrogallol[4]arene **1b**$_6$. To explain this observation, we propose a model that treats pyrogallol[4]arene capsules in the solid state as relatively rigid and ordered, but surrounded by a relatively flexible, mobile, and likely disordered domain made up of the interdigitated alkyl groups of neighboring capsules. Alkyl chains in waxy solids are mobile, and one would expect that alkyl domain mobility is greater in the solid state for decyl pyrogallol[4]arene than for propyl.[§] We propose that the enhanced guest mobility observed in the decyl pyrogallol[4]arene hexamers in the solid state as compared with the propyl is the result of greater alkyl domain dynamics, translated across the walls of the host, and manifest in the greater dynamic motions of guests in the capsules' interiors. Guest motion in the inner space of pyrogallol[4]arene hexamers in the solid state is similar to that observed in solution, but slower, and regulated by the relative rigidity of the solid state exterior to the capsules.

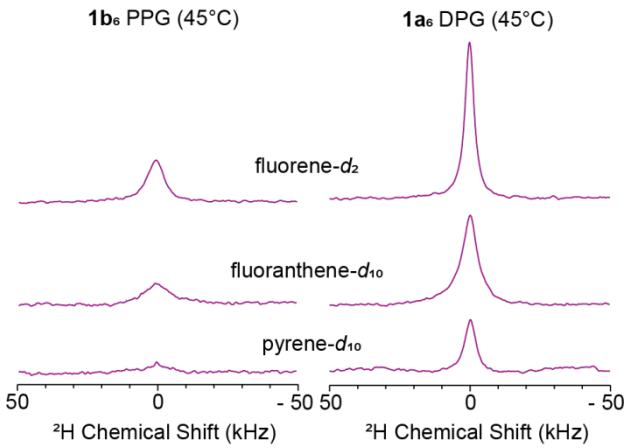

Figure 3. Comparative static solid-state ^{2}H NMR spectra of the encapsulation complexes of fluorene-d_2, fluoranthene-d_{10}, and pyrene-d_{10} in propyl pyrogallol[4]arene hexamer (PPG) 1**b**$_6$ and decyl pyrogallol[4]arene hexamer (DPG) 1**a**$_6$. Spectra are normalized using the same number of scans (8192) and the same vertical display.

To further support this interpretation, we measured the static solid-state ^{2}H NMR spectrum of all of these encapsulation complexes across a temperature range from 0 to 60 °C (data for fluorene-d_2 is shown in Figure 4; data for the other two guests are in the SI). As expected, the spectra show sharper signals and more intense signals at higher temperatures. It is possible to freeze out the motions of the guests, as indicated by the disappearance of the isotropic guest signal near 0 kHz, especially in the propyl pyrogallol[4]arene hexamer **1b**$_6$. The motions of fluoranthene-d_{10}, and pyrene-d_{10} inside **1b**$_6$ become slow at temperatures below 30 °C (Figure S9).

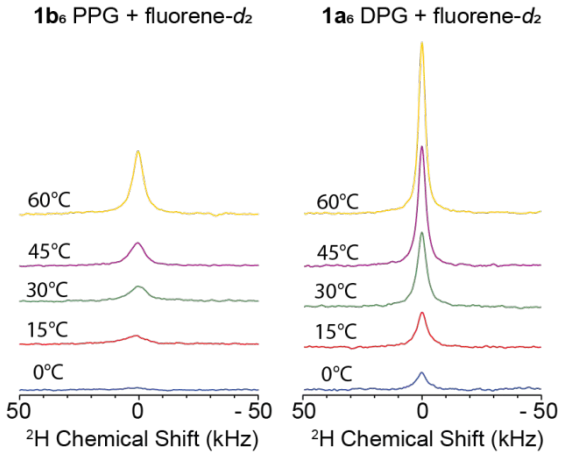

Figure 4. Comparative static solid-state ^{2}H NMR spectra of fluorene-d_2 encapsulated in propyl pyrogallol[4]arene **1b**$_6$, and fluorene-d_2 encapsulated in decyl pyrogallol[4]arene **1a**$_6$. Spectra are normalized using the same number of scans (8192) and the same vertical display.

Conclusions

Ball milling and gentle heating of mixtures of decyl pyrogallol[4]arene **1a** or propyl pyrogallol[4]arene **1b** with

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fluorene(-d_2), fluoranthene(-d_{10}), or pyrene(-d_{10}) results in the formation of pyrogallol[4]arene hexamers in the solid state with guest encapsulation. When these mixtures are dissolved in $CDCl_3$ and studied using solution ^{1}H NMR, the guests are observed to tumble and exchange position rapidly within each host, although pyrene's dynamics are somewhat slower. When the same solid-state, mechanical synthesis is performed using deuterated analogues of the guests and static solid-state ^{2}H NMR is used to measure dynamics, we observe the same trend of guest mobility: fluorene > fluoranthene > pyrene. In all cases, static ^{2}H NMR indicates a substantial degree of guest isotropicity that derives from tumbling and positional exchange in the capsules; the pure guests alone are much less dynamic in the solid state. The environment inside the pyrogallol[4]arene hexamers is remarkably similar in the solid state and solution, with the guests retaining their liquid state-like dynamic motions. By increasing the overall rigidity of the solid state—swapping the hosts' external decyl groups for propyl groups—the dynamics of the guests are slowed. These results show that molecular encapsulation can offer nanoscale, homogeneously structured, liquid state-like molecular environments regularly interspersed throughout the solid state. The relative rigidity of the solid state translates across the walls of the hosts, influencing the dynamics of the guests.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Notes and references

§ To probe the exterior dynamics, we performed capsule assembly by ball milling in the presence of 5α-2,4-($^2H_4$)-cholestan-3-one, which is too large to be encapsulated and does not appreciably alter the kinetics and yield of encapsulation complex formation using any of our three guests and **1a** or **1b**. Static solid-state ^{2}H NMR spectra shows that 5α-2,4-($^2H_4$)-cholestan-3-one is in a highly rigid environment and largely motionless outside the capsules, but we were not able to resolve clear differences between samples containing **1a** and **1b**. A smaller yet still rigid exterior probe would likely be needed, but such molecules typically compete to occupy the capsules or interfere with capsule assembly. Separately, we measured powder x-ray diffraction data of milled mixtures of **1a** with fluorene and fluoranthene and **1b** with the same guests (see details in the SI and figures S16 and S17). While difference in the spectra are apparent, general inferences on differences in the crystallinity and solid state dynamics of the samples could not readily be drawn.

1 F. Hof, S. L. Craig, C. Nuckolls and J. Rebek, *Angew. Chem. Int. Ed.*, 2002, **41**, 1488–1508.
2 J. S. Mugridge, G. Szigethy, R. G. Bergman and K. N. Raymond, *J. Am. Chem. Soc.*, 2010, **132**, 16256–16264.
3 J. S. Mugridge, A. Zahl, R. van Eldik, R. G. Bergman and K. N. Raymond, *J. Am. Chem. Soc.*, 2013, **135**, 4299–4306.
4 B. W. Purse, S. M. Butterfield, P. Ballester, A. Shivanyuk and J. Rebek, *J. Org. Chem.*, 2008, **73**, 6480–6488.
5 S. Löffler, J. Lübben, A. Wuttke, R. A. Mata, M. John, B. Dittrich and G. H. Clever, *Chem. Sci.*, 2016, **7**, 4676–4684.
6 Y. Yu and J. Rebek, *Acc. Chem. Res.*, 2018, **51**, 3031–3040.
7 S. H. A. M. Leenders, R. Gramage-Doria, B. de Bruin and J. N. H. Reek, *Chem. Soc. Rev.*, 2015, **44**, 433–448.
8 J.-N. Rebilly, B. Colasson, O. Bistri, D. Over and O. Reinaud, *Chem. Soc. Rev.*, 2015, **44**, 467–489.
9 K. I. Assaf and W. M. Nau, *Chem. Soc. Rev.*, 2015, **44**, 394–418.
10 L. Avram and Y. Cohen, *Chem. Soc. Rev.*, 2015, **44**, 586–602.
11 J. H. Jordan and B. C. Gibb, *Chem. Soc. Rev.*, 2015, **44**, 547–585.
12 S. Zarra, D. M. Wood, D. A. Roberts and J. R. Nitschke, *Chem. Soc. Rev.*, 2015, **44**, 419–432.
13 R. J. Hooley and J. Rebek Jr, *Chem. Biol.*, 2009, **16**, 255–264.
14 Y. Inokuma, M. Kawano and M. Fujita, *Nat. Chem.*, 2011, **3**, 349–358.
15 Q. Zhang, L. Catti and K. Tiefenbacher, *Acc. Chem. Res.*, 2018, **51**, 2107–2114.
16 L. C. Palmer and J. Rebek Jr, *Org. Biomol. Chem.*, 2004, **2**, 3051–3059.
17 A. V Davis and K. N. Raymond, *J. Am. Chem. Soc.*, 2005, **127**, 7912–7919.
18 C. Moon, G. Brunklaus, D. Sebastiani, Y. Rudzevich, V. Böhmer and H. W. Spiess, *Phys. Chem. Chem. Phys.*, 2009, **11**, 9241–9249.
19 L. Avram, A. Goldbourt and Y. Cohen, *Angew. Chem. Int. Ed.*, 2016, **55**, 904–907.
20 S. N. Journey, K. L. Teppang, C. A. Garcia, S. A. Brim, D. Onofrei, J. B. Addison, G. P. Holland and B. W. Purse, *Chem. Sci.*, 2017, **8**, 7737–7745.
21 M. Kvasnica, J. C. Chapin and B. W. Purse, *Angew. Chem. Int. Ed.*, 2011, **50**, 2244–2248.
22 J. C. Chapin, M. Kvasnica and B. W. Purse, *J. Am. Chem. Soc.*, 2012, **134**, 15000–15009.
23 L. Avram and Y. Cohen, *Org. Lett.*, 2006, **8**, 219–222.
24 S. Negin and G. W. Gokel, in *Organic Nanoreactors From Molecular to Supramolecular Organic Compounds*, ed. S. Sadjadi, Academic Press, Boston, 2016, pp. 235–256.
25 L. R. MacGillivray and J. L. Atwood, *Nature*, 1997, **389**, 469–472.
26 L. Catti, Q. Zhang and K. Tiefenbacher, *Chem. – Eur. J.*, 2016, **22**, 9060–9066.
27 L. Avram and Y. Cohen, *J. Am. Chem. Soc.*, 2004, **126**, 11556–11563.
28 J. C. Chapin and B. W. Purse, *Supramol. Chem.*, 2014, **26**, 517–520.
29 V. Guralnik, L. Avram and Y. Cohen, *Org. Lett.*, 2014, **16**, 5592–5595.

Please do not adjust margins

30 M. J. Cliffe, C. Mottillo, R. S. Stein, D.-K. Bučar and T. Friščić, *Chem. Sci.*, 2012, **3**, 2495.
31 C. Serre, D. I. Kolokolov, H. Jobic, A. G. Stepanov, V. Guillerm, G. Férey and T. Devic, *Angew. Chem. Int. Ed.*, 2010, **49**, 4791–4794.
32 D. I. Kolokolov, A. G. Stepanov, V. Guillerm, C. Serre, B. Frick and H. Jobic, *J. Phys. Chem. C*, 2012, **116**, 12131–12136.
33 T.-C. Ong, V. K. Michaelis, M. Dincă, R. G. Griffin, A. F. Cozzolino and N. B. Shustova, *J. Am. Chem. Soc.*, 2012, **134**, 15061–15070.
34 D. I. Kolokolov, S. S. Arzumanov, A. G. Stepanov and H. Jobic, *J. Phys. Chem. C*, 2007, **111**, 4393–4403.
35 Z. T. Lalowicz, A. Birczyński and A. Krzyziak, *J. Phys. Chem. C*, 2017, **121**, 26472–26482.
36 S. L. Gould, D. Tranchemontagne, O. M. Yaghi and M. A. Garcia-Garibay, *J. Am. Chem. Soc.*, 2008, **130**, 3246–3247.
37 A. R. Hughes, N. J. Brownbill, R. C. Lalek, M. E. Briggs, A. G. Slater, A. I. Cooper and F. Blanc, *Chem. - Eur. J.*, 2017, **23**, 17217–17221.
38 M. G. Usha and R. J. Wittebort, *J. Am. Chem. Soc.*, 1992, **114**, 1541–1548.

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