cules in subsequent layers are rotated by 180° with respect to each other. This leads to an efficient packing of the molecules. The dipole moment of $ReF_7$ is small (*17*), and antiferroelectric ordering is likely to play only a minor role.

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9. Twenty-four grams of $ReF_7$ (nominal purity 98%), supplied by Fluorochem Ltd. (Glossop, United Kingdom), was sublimed in vacuo into a 15-mm diameter quartz glass ampoule and sealed. The vacuum line was flamed out and pretreated with $ReF_7$ vapor to avoid decomposition of the $ReF_7$ during sublimation. Catalytic traces of water on the surface of the glass result in the formation of impurities such as $ReOF_5$ and $SiF_4$ (*7*). Ideally the sample should have been checked for soluble solid-state impurities such as $ReOF_5$, for example, by Raman spectroscopy where the Re–O bond gives rise to a strong band at 992 $cm^{-1}$. However, the absence of other by-products such as $SF_4$ indicated a pure sample. $ReF_7$ is a deep yellow solid. The ampoule, held in a thin-walled vanadium tube, was transferred to a liquid-helium flow cryostat, and powder neutron diffraction patterns were collected as a function of temperature on the position-sensitive multidetector diffractometer D1B at the Institut Laue Langevin, Grenoble. High-resolution powder neutron diffraction patterns were subsequently collected of $ReF_7$ at both 1.5 K and 151 K with $\lambda$ = 2.99 Å and $\lambda$ = 1.594 Å (both nominal) on the diffractometers D1A and D2B, respectively. On warming slowly, a transition to the cubic high-temperature phase was observed at 153 K.
10. The D1A diffraction pattern of $ReF_7$ at 151 K taken with nominal $\lambda$ = 2.99 Å was indexed using the $2\theta$ positions of 21 reflections with the program FZON (*11*) as C-centered monoclinic with $a$ = 5.619 Å, $b$ = 8.608 Å, $c$ = 9.228 Å, $\beta$ = 93.90°, and $M_{20}$ = 19.0. Integrated $F^2$ values were extracted from the shorter wavelength data measured on D2B with the program PAWHKL (*12*). The values of $F^2$ were used as input to direct methods program SHELXS (*13*), which found the five atoms required to define a complete $ReF_7$ molecule in space group *C2/c*. The structure was refined by the method of Rietveld with the program PROFIL (*18*).
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# Encapsulation of Methane and Other Small Molecules in a Self-Assembling Superstructure

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**Physical inclusion of small molecules in larger structural lattices is well known in the crystalline state and is a common feature of the chemistry of zeolites. In the liquid state, a variety of synthetic macrocyclic molecules are available to complex and contain smaller guest species. An alternative strategy for binding is explored: assembly of cavity-forming structures from smaller subunits. Encapsulation of small guest molecules such as methane can be achieved with a synthetic structure that assembles reversibly through hydrogen bonding.**

Studies of molecular recognition phenomena have led to increasingly sophisticated compounds—cryptands (*1*), cryptophanes (*2*), and carcerands (*3*)—for binding ions and small molecules. These covalently bound structures feature macrocyclic shapes with openings of various sizes that permit entrance and exit of the guest. Free and complexed species are separated by energy barriers related to the ease of passage of the guest through the openings. Reversible assembly of the host around the guest is a frequent lesson taught by biological chemistry; weak intermolecular forces are used and viral capsids are the paradigm example. The economic appeal of using multiple copies of a single, self-complementary structure for guest inclusion led us to explore this means for binding small molecules.

We recently introduced the structure **1** (Fig. 1) and gave evidence of its self-association into a dimeric assembly in solution (*4*). The molecule is prepared in a single operation from commonly available materials and is easily isolated. The structure features an array of hydrogen bonding sites along its periphery and a skeletal curvature that positions these sites in a self-complementary manner. The dimer is held together by eight hydrogen bonds along the seam of a roughly spherical structure that resembles a tennis ball.

The inner dimensions, as defined by molecular modeling (*5*), indicate a cavity of 50 to 55 $Å^3$ and suggest that suitable smaller molecules of complementary shape and symmetry can fit within. In solvents such as chloroform-*d* ($CDCl_3$) which compete weakly for hydrogen bonds, two forms of the dimer are present, as evidenced by proton nuclear magnetic resonance (NMR) spectroscopy at 500 MHz. One form is "empty" (*6*), whereas the other is most likely occupied by solvent. The exchange between these two forms is slow on the NMR time scale; separate signals are seen for the resonances of the N–H and one of the benzylic protons. As the temperature is lowered, the occupied form increases in concentration at the expense of the empty one. By using a number of guests in $CDCl_3$, it is possible to probe the dimer's capacity for small molecules of appropriate size with NMR titrations. For example, as $CH_2Cl_2$ is added, signals for a third dimeric species appear in the N–H and benzylic regions of the spectra. In favorable cases using guests such as methane ($CH_4$), ethane ($CH_3CH_3$), and ethylene ($H_2C{=}CH_2$), sig-

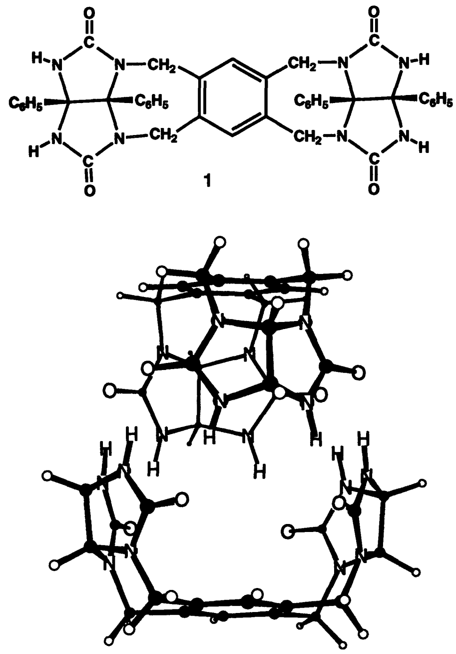

**Fig. 1.** Monomeric **1** and energy-minimized structure of the dimer (MacroModel 3.5× with AMBER* force field and GB/SA chloroform solvation). Phenyl groups have been omitted for clarity.

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nals of the encapsulated guest can be directly observed. This is shown for $CH_4$ in Fig. 2. The corresponding differences in chemical shift between free and bound versions of the other guest species are >1 ppm.

The ratio of the empty and variously occupied assemblies can be determined by integration of the signals as a function of temperature. This procedure allows equilibrium constants and thermodynamic parameters to be assessed (Fig. 3 and Table 1). The following trends emerge from the data: (i) The inclusion of all guests involves a large entropic cost. Limiting the translational freedom of the small molecule to the confines of the dimer's interior is compensated by enthalpic factors, presumably van der Waal's contacts with the concave inner surface. (ii) Exchange of all guests in and out of the assembly is slow on the NMR time scale. Stochastic dynamics calculations (*7*) suggest that most of the eight hydrogen bonds of the dimer must be broken to provide a suitable opening for entrance and exit. The container, rather than guest size, determines the dynamics of the exchange process in this series. (iii) Correlations of guest volume with the inclusion constant $K_{inc}$ suggest that the volume of the cavity presented by the dimer is indeed ~50 Å$^3$. This figure is based on the estimate that an optimal host is ~20% larger than the guest and is justified by the largest binding constant, that observed for $CH_4$.

In a recent and perspicacious study of inclusion of $CH_4$ and other one-carbon species in a cryptophane, Collet and co-workers (*8*) suggested that the occupancy factor ρ (the ratio of guest to host volumes) can be related to macroscopic states of matter. For the cases at hand, $CH_4$ inclusion within the dimer ($\rho > 0.5$) would then translate into a supercritical fluid, and $H_2C{=}CH_2$ ($\rho > 0.7$) into a densely packed crystal. For the larger guests such as $CH_2Cl_2$ ($\rho \approx 1$) and $CDCl_3$ (ρ apparently >1), these descriptors can no longer be appropriate. Instead, dynamics simulations show that encapsulation of the larger (but not smaller) guests requires lengthening and weakening of the hydrogen bonds of the dimer with an ultimate increase in cavity volume. Assemblies, gathered by weak intermolecular forces, will generally share this feature of adjustable size and ambiguous occupancy factors.

There are nonetheless enigmatic behaviors of the dimer. No evidence of binding of $CH_3F$ or $CF_4$ (using $^1H$ or $^{19}F$ NMR spectroscopy) could be obtained, despite the good fit expected. This feature may be related to the much admired properties of Teflon. Unexpectedly, the highly soluble tetrabutylammonium borohydride ($Bu_4N^+$ $BH_4^-$) destroyed the dimer. Even so, reversible assembly as a means of encapsulating molecules in solution shows considerable promise, and several molecular systems with likely cavities have been devised elsewhere (*9*). We have also identified a number of other self-complementary structural modules (*10*) and their properties will be reported in due course.

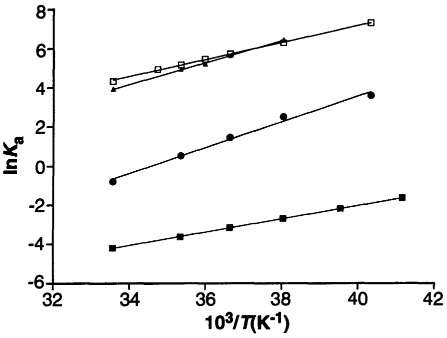

**Fig. 3.** Plots of ln$K_a$ (association constant) against 1/*T* (reciprocal temperature) for **1** in $CDCl_3$ with addition of various guests over the temperature range from 243 to 298 K: (■) $CDCl_3$; (●) $CH_2Cl_2$; (□) $CH_4$; and (▲) $H_2C{=}CH_2$. All values of $K_a$ were corrected for $CDCl_3$ encapsulation.

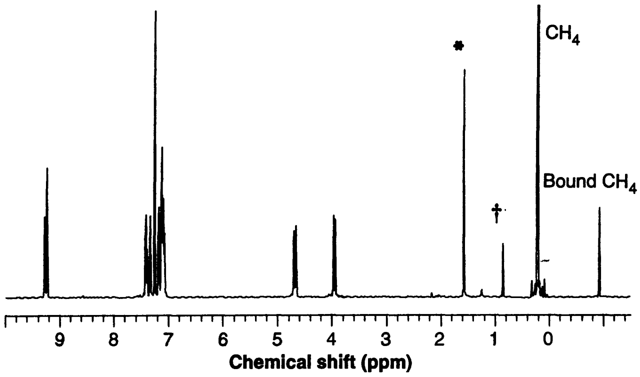

**Fig. 2.** A 500-MHz $^1H$ NMR spectrum of **1** in $CDCl_3$ with $CH_4$ added at 298 K showing slow exchange of $CH_4$ encapsulation. The resonances for free and bound $CH_4$ are at 0.23 and −0.91 ppm, respectively (Δδ = 1.14 ppm). Signals for residual water (*) and ethane (†; commercial-grade methane contains 7 to 10% ethane) are labeled. Separate resonances for the N–H protons corresponding to the "empty" and methane-filled dimer are observed (~9.2 ppm).

**Table 1.** Inclusion of guest species in the cavity of the dimer **1**. The guest volume was calculated according to (*11*). Abbreviations: $K_{inc}$, inclusion constant; Δ*H*, enthalpy; Δ*S*, entropy; and e.u., entropy units.

| Guest | $K_{inc}$ ($M^{-1}$) at 273 K | *T* range (K) | Δ*H* (kcal/mol) | Δ*S* (e.u.) | Guest volume (Å$^3$) |
|---|---|---|---|---|---|
| $CHCl_3$ | 0.04 | 243–298 | −7 | −31 | 73 |
| $CH_2Cl_2$ | 4 | 248–298 | −13 | −45 | 58 |
| $H_2C{=}CH_2$ | 280 | 263–298 | −11 | −30 | 40 |
| $CH_4$ | 300 | 248–298 | −9 | −20 | 28 |

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6. We cannot exclude occupation by dissolved gases such as $N_2$ or even water in the "empty" form of the dimer.
7. Performed at 300 K with constrained bond lengths (SHAKE) and a 1.5-fs timestep. After a 15-ps induction period, structures were sampled and NH–O hydrogen bond lengths were measured every 15 fs for 240 ps.
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