MODULAR CONSTRUCTION FOR THE PROGRAMMED ASSEMBLY OF MOLECULAR
CRYSTALS AND LIQUID CRYSTALS

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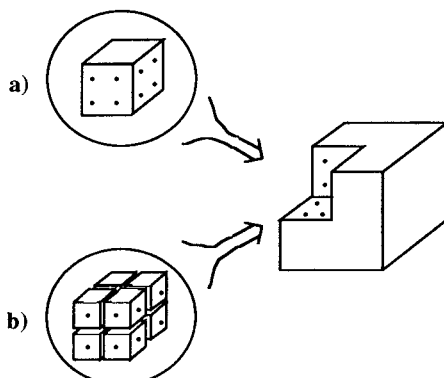Arbor, MI 48109-1055, USA

Abstract: This research aims to develop schemes for the programmed assembly of
molecular materials. The underlying premise guiding this work is that structural
information stored in the molecular constituents dictates their condensed phase
organization (i.e. through the sum of all non-covalent interactions). The challenge
then is to design molecular building blocks that encode this information in a
decipherable manner. Our approach has relied on the use of organic
nanoarchitectures, which we believe will serve as "modular units" for
programmed assembly. Large molecules of well defined constitution and
geometry offer the advantage that a high level of information can be incorporated
into a single unit. The design and synthesis of nanoscale macrocyclics and
macrobicyclics for this purpose has been achieved. Studies on the solution
aggregation of the macrocyclics have provided a unique opportunity to glimpse
some of the interactions which may influence solid state ordering. These building
blocks are being used for the rational design of novel materials such as porous
organic crystals and tubular mesophases.

INTRODUCTION

Structure gives rise to function. It is therefore of great importance that rational schemes be
devised for the programmed assembly of molecular materials. Predicting the organization of
molecules in the condensed state is a complex problem. Very often, the free energy surface
of the aggregate is dominated by entropic factors as well as abundant weak forces that are
non-specific and non-directional (e.g. van der Waals interactions). Molecular building blocks
that have predictable ordering characteristics must therefore be equipped with functional
groups that can engage in strong, selective, and directional interactions that override these

feeble, yet prevailing forces. To overcome the unfavorable entropy associated with the formation of ordered aggregates, multiple sites for specific, non-covalent interactions must be present. For less ordered states of aggregation such as liquid crystal and ordered fluid phases, building blocks must possess a highly anisotropic geometry and / or strong spatial dichotomy with respect to polarity. A general scheme that addresses the above-mentioned characteristics is

Scheme I. Self-assembly based on (a) modular constituents and (b) small-molecule constituents.

the concept of modular construction. Modular building blocks are envisioned as large molecules constructed from a conformationally well-defined skeleton. The skeleton serves to orient and position the directing functionality and to define the overall geometry of the unit. The molecular structure of the modular units can be viewed as containing the information that provides directions for assembly (Refs. 1-2). Through systematic studies, it should become possible to understand how to encode the modular units with information that leads to particular aggregate structures.

Scheme I compares the key features of the modular approach to methods of self-assembly based on small molecule constituents. Modular construction of molecular materials potentially offers a number of advantages. First, it is entropically more favorable. By using larger building blocks, there will necessarily be a smaller number of ordered constituents per unit volume. Second, the modular units can bear a high information content, while maintaining a relatively low functional group density. Finally, because of the large size of the modular units, they can more easily be endowed with functionality that modify their intrinsic molecular properties (e.g. chromophores or redox active groups).
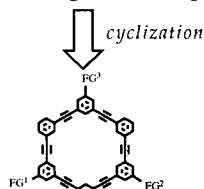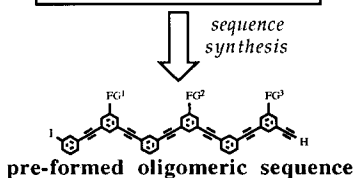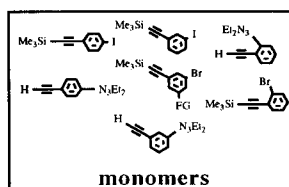
MODULAR CONSTRUCTION WITH PHENYLACETYLENE-BASED MONOMERS

To realize the modular approach, synthetic methods must be established that allow efficient, yet versatile, construction of the sophisticated modules. An interesting possibility is to use a simple set of monomers that can be catenated into an oligomeric sequences. This approach can be compared to biological systems such as peptide sequences prepared from amino acid residues (Ref. 3). Depending on the monomer chemistry, cyclization of the oligomers can generate conformationally well-defined modules. The ideal set of monomers for this
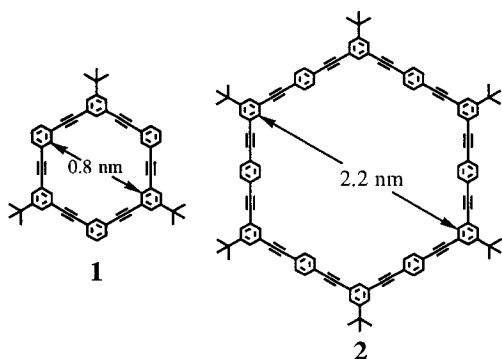
approach would spawn macrocyclic skeleton of diverse, yet simple geometries, onto which could be attached a variety of functional appendages.

With these ideas in mind, we have developed methods for synthesizing large macrocycles based on phenylacetylene repeat units, hydrocarbon examples of which are pictured in structures **1** and **2**. Scheme II illustrates the overall synthetic approach. The macrocycle is prepared by cyclization of a pre-formed oligomeric sequence. These sequences can be synthesized with precise control of chain-length, end-group functionality, and sequence order of monomers by an efficient repetitive method (Ref. 4). The oligomeric sequences have been shown to be efficiently cyclized to the corresponding site-specifically functionalized macrocycles with total command of the number, type, and location of functional groups (Ref. 5). Cyclization yields are very high considering the size of these macrocycles (>70% for hydrocarbon skeletons **1** and **2**). The geometry of the macrocycle can be widely varied by
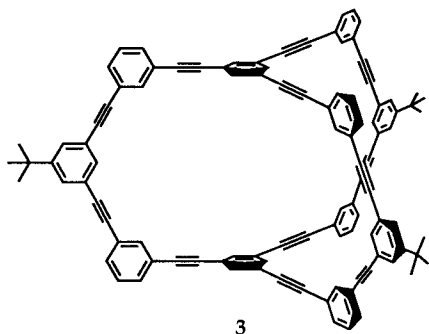
monomers

sequence synthesis

pre-formed oligomeric sequence

cyclization

site-specifically functionalized macrocycle

Scheme II. Synthesis of site-specifically functionalized phenylacetylene modules using pre-formed oligomeric sequences.

using different combinations of *ortho-*, *meta-*, and *para*-connected monomers. A sample of some of these are shown in Figure 1. These skeletons are imagined to provide a stiff, non-collapsible scaffolding that can be used to position and orient directing functionality. Besides the planar macrocycles shown in Figure 1, there are numerous skeleton based on macrobicyclic framework. The 11-monomer unit, macrobicyclic **3**, is an example that has
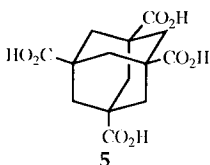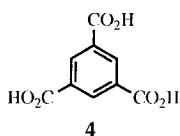
recently been prepared (Ref. 6). The plane-to-plane separation between the tri-connected aromatic rings of this D_{3h} symmetric skeleton is approximately 11.4Å. All of the skeletons in Figure 1 as well as the macrobicyclic framework represent fragments of trigonal networks whereby the aromatic rings can be pictured as network vertices and the acetylene bonds as network edges.

0.8 nm

1

2.2 nm

2

3

POROUS CRYSTAL AND POROUS LIQUID CRYSTAL PHASES - TARGETS FOR MODULAR CONSTRUCTION

Figure 1. Some planar macrocyclic skeletons resulting from combinations of *ortho-*, *meta-*, and *para*-phenylacetylene monomers.

Most molecular crystals and even liquid crystals are densely packed in the condense state. The driving force for close packing must be optimization of van der Waals forces. It is intriguing to try to imagine structures in which ordered states of high-free volume could be achieved. Such nanoporous materials could have interesting transport or absorption characteristics. The possibility of using self-assembly to achieve such structures has been recognized for some time. However, with small-molecule self-assembling constituents, very often the end result is a close-packed molecular crystal. Consider two examples. First, trimesic acid **4** might be expected to organize in a hydrogen-bonded, two-dimensional hexagonal network that reflects the symmetry of the molecule. Such a network would satisfy all of the hydrogen bond arrangements of the carboxylic acid groups in their most favorable (i.e. linear) geometry. The crystal structure of **4** reveals the presence of the expected two-dimensional network, although close-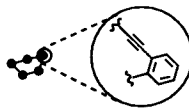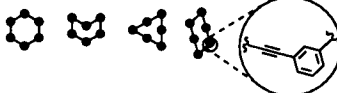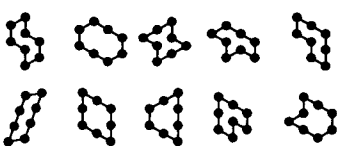packing of unit cell is still realized (Ref. 7). Close-packing, in this case, is achieved through interpenetration of the networks, so that open space left by one network is filled with molecules of other networks. In the second example, adamantane tetracarboxylic acid

CO_2H

HO_2C CO_2H

4

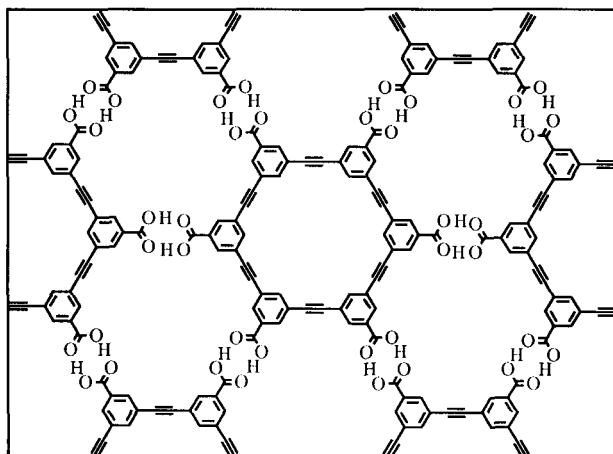CO_2H

HO_2C CO_2H

CO_2H

5

Figure 2. A possible nanoporous network using non-collapsible modular building blocks with carboxylic acid directing groups. The formation of interpenetrating networks through catenation of the macrocyclic ring would not be possible in this case.

(5), the formation of a tetrahedral lattice can be postulated from the symmetry of the self-assembling unit. By itself, this network would yield a crystal having the unusually small density of ca. 0.33 g·cm^{-3}. Instead, close-packing is achieved by interpenetration of the tetrahedral networks, giving a final crystal density of 1.66 g·cm^{-3} (Ref. 8).

Modular units which form covalently bonded macrocycles that are non-collapsible offer a possible approach to nanoporous crystals that avoids the interpenetration problem. Figure 2 illustrates this idea with a hypothetical example based on a macrocyclic hexaacid. In this case, space-filling through the formation of interpenetrating networks should be inhibited since catenation of the covalently bonded macrocyclic skeleton is not possible. We have recently prepared the hexaacid shown in this example and efforts are underway to grow crystals suitable for single-crystal structure determination. In the meantime, we have also prepared the macrocyclic hexaphenol 6 which has crystallized in a trigonal lattice having unit cell parameters of a=b=20.659Å and c=9.997Å. Preliminary refinement shows the macrocycle to be layered along the c axis with plane-to-plane spacing of 3.33Å (Ref. 9). The layers consist of two-dimensional hydrogen-bonded networks stacked in such a way as to generate large-diameter channels parallel to the c axis. The channels are filled with solvent molecules that are reasonably well ordered.

We have also sought to use the phenylacetylene macrocycles as skeleton for discotic mesogens. The idea is to capitalize on the unique geometry of the toroidal-shaped modular units such that they would self-order into liquid crystal phases. Non-collapsible macrocycles that form columnar liquid crystals are intriguing since the resulting structure creates a hallow tube. A mesophase of this
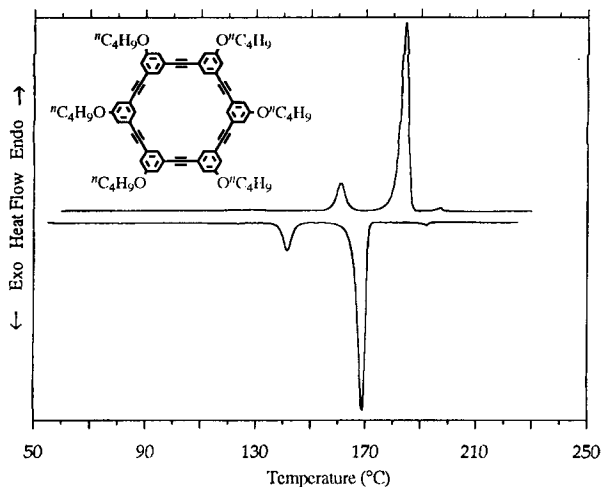

6
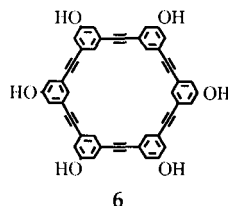
Figure 3. DSC traces of the indicated hexakis(n-heptylether) macrocycle. The upper trace was recorded during heating while the lower trace was recorded on cooling (scan rate $10°C \cdot min^{-1}$). Polarized light optical micrographs reveal a nematic phase exists between $178°C$ and $206°C$. The enthalpy associated with the nematic to isotropic transition is unusually small.

type was first suggested by Lehn et al (Ref. 10). One of the greatest challenges in trying to achieve liquid crystal phases with large, planar macrocycles is to lower transition temperatures below the decomposition point. For example, macrocycles 1 and 2 do not melt but instead undergo an irreversible reaction at temperatures exceeding $400°C$. In spite of the apparent stability of these crystalline phases, observations of solution aggregation in a number of macrocycles prompted us to continue searching for liquid crystal phases. This aggregation is believed to be driven by π-π interactions. The strength of the association is very dependent on the macrocycle geometry and substituents on the phenylene rings with planar macrocycles bearing acceptor groups being the most strongly associating (Ref. 11).

Transition temperatures for a series of hexa(phenylacetylene) macrocycles have been examined. Those compounds that associate most strongly in solution tended to have the highest melting points. This finding prompted us to investigate a series of n-alkylether derivatives of 6, none of which showed evidence for aggregating in solution, even at $-40°C$ (Ref. 12). Differential scanning calorimetry (DSC) traces of the hexakis(n-heptylether) are shown in Figure 3. The observed transitions are reversible and occur at significantly lower temperatures than the pure hydrocarbon 1. Polarized light optical microscopy reveals that above $178°C$ the compound displays a nematic phase. Isotropization occurs at $206°C$, which is well below the decomposition point. The structure of the phase between $158°C$ and $178°C$ is still under investigation at this time. These findings support the possibility that LC phases may be found for this class of compounds. The prospects of such phases, especially with regard to transport phenomena, are of great interest.

CONCLUSIONS

Modular construction is defined as self-assembly using building blocks that possess arrays of directing functional groups positioned and oriented by a well-defined skeleton. This concept has potential for the programmed assembly of molecular materials, as the examples shown here begin to demonstrate. The modular approach is well-suited to controlling aggregate structure on a size scale 0.1-10 nm which may be important in the design of assemblies that can operate on small molecule substrates (e.g. regulating transport of small molecules or ions). Our work has focused on a family of building blocks based on phenylacetylene monomers. We have shown how simple chemistry can be used to build a diverse array of molecular architectures. In fact, there is a tremendous variety of untapped architectures in the range of 1 to 10 kD. These architectures offer intriguing possibilities as modular components. As we gain deeper understanding of the non-covalent bond, and as better synthetic methods become available for preparing molecules in this size regime, the possibility of designing modular units that organize into target structures will be realized.

ACKNOWLEDGMENT

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