Determining Structures of Shape-persistent Macrocycles in Solution Using High-angle X-ray Scattering

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Introduction

The synthesis of shape-persistent macrocycles with defined 3-dimensional nanoscale molecular architectures is a milestone achievement in supramolecular chemistry. Synthetic capabilities have advanced to the point where specific architectures and ensuing host-guest, dynamical, and adaptive properties can be designed. However, validation of design targets and synthetic strategies are significantly hindered by the lack of suitable methods for resolving static and dynamic supramolecular configurations in liquids and other functionally relevant disordered media.

We have investigated opportunities for characterization of shape-persistent macrocycle structure in solution using wide-angle scattering by performing initial characterization studies on a cyclic diphenylethyne-linked porphyrin assembly **1**, and its corresponding host-guest complex, **(1+2)** [1-5], illustrated in Fig. 1. We demonstrate the ability to accurately characterize the shape of macrocycles **1** and **(1+2)** in aromatic hydrocarbon solvents using high-angle x-ray scattering techniques. Experimental scattering patterns measured to 6 Å resolution are shown to resolve individual porphyrin pair distance correlations and to identify molecular thermal factors or configuration dispersion though measurement of the angle-dependent attenuation of the wide-angle scattering features. This work establishes the general applicable opportunity of using wide-angle scattering data for structural characterization of shape-persistent macrocycles in liquids.
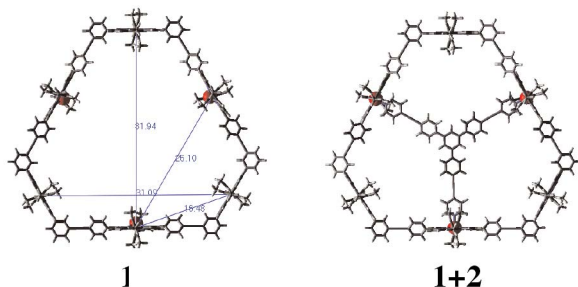

FIG. 1. *Energy minimized model structures for host (1) and host-guest (1+2) porphyrin heximer assemblies.*

Materials and Methods

The shape-persistent cyclic hexameric architecture (*cyclo*-Zn_3Fb_3U-*p/m*) that comprises three free base (Fb) porphyrins and three zinc porphyrins linked at the *meso*-positions via diphenylethyne units was prepared as described previously [2, 5]. X-ray scattering measurements were carried out using the undulator beam-line 12-ID at the Advanced Photon Source (APS), Argonne National Laboratory. The x-ray scattering instrument utilized a double-crystal Si(111) monochromator and a two-dimensional mosiac charge-coupled device (CCD) detector for detection [6]. The x-ray wavelength was set at $\lambda = 1.0$ Å and the sample-to-detector distances were adjusted to achieve scattering measured across the range of momentum transfer 0.02 Å^{-1} < q < 0.8 Å^{-1}, where $q = (4\pi /\lambda)sin\theta$, and λ is the x-ray wavelength and 2θ is the scattering angle.

Results

X-ray scattering patterns calculated for the energy-minimized model **1** is shown in Fig. 2, along with the experimental data for assembly **1** measured in toluene solution. The scattered intensities are plotted with arbitrary offset as a function of scattering vector, q, which is related to the scattering angle 2θ by the relation $q = (4\pi /\lambda)sin\theta$, where λ is the x-ray wavelength. The scattering pattern for the model structure was calculated to $q = 3$ Å^{-1}, which corresponds to a spatial resolution, $d = 2\pi/q$, of 2.1 Å. In the low-resolution scattering region below $q = 0.1$ Å^{-1}, the variation in electron density across the molecular assembly cannot be resolved and the calculated scattering fits the Guinier relationship [7], $I(q) = I(0)exp(-q^2R_g^2/3)$, that approximates scattering from a spherical particle with uniform electron density having a radius of gyration, R_g, of 17.0 Å. In the region beyond $q = 0,1$ Å^{-1}, the calculated scattering shows a strong oscillatory pattern that reflects the interference produced by x-ray scattering from spatially resolved portions of the molecular assembly. Calculations show that characteristic features of this interference pattern, including the oscillatory beat pattern, amplitude, and damping are sensitively dependent upon the atomic structure, configurational dispersion and dynamics, electron density contrast with the solvent, and solvent packing around the assembly. Each of these features is significant for understanding the photochemistry of these assemblies in liquids.
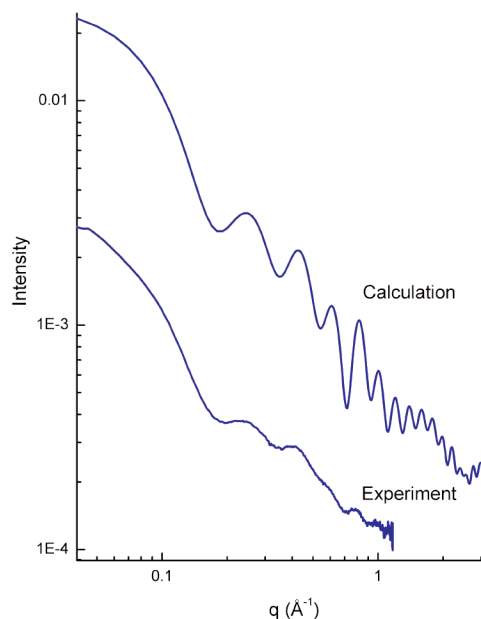
*FIG. 2. Calculated and experimental scattering for assembly **1**.*

*FIG. 3. Calculated and experimental scattering patterns for the multiporphyrin host and host-guest assemblies **1** and **1+2**.*

The results of an experimental measurement of high-angle x-ray scattering for compound **1** are shown plotted in the lower trace in Fig. 3, measured to a spatial resolution 6 Å in toluene solution. The experimental scattering data generally parallel those calculated from the model compound, showing a transition between small-angle and high-resolution interference scattering near $q = 0.1$ Å^{-1}. The high-angle oscillatory interference pattern measured experimentally is similar to that calculated from the model structure but with significant amplitude attenuation. The measurement of the experimental scattering pattern to higher spatial resolution in these experiments was mainly restricted by the experimental geometry, where the high-angle scattering rings are only partially captured by the corners of the mosaic detector. Preliminary experiments with shorter sample-to-detector distances show that precise measurement of even these damped scattering patterns can be measured with excellent signal-to-noise to 2 Å spatial resolution.

A comparison of the calculated and experimental scattering for the heximer porphyrin host assembly **1** and the host-guest assembly **1+2** is shown in Fig. 3, measured to a spatial resolution of 7.8 Å. Model calculations show characteristic changes in high-angle scattering produced by inclusion of the guest molecule. Experimental results again show characteristic changes that generally parallel those predicted based on the design models. But experimental results differ from model calculations both in terms of the amplitudes of the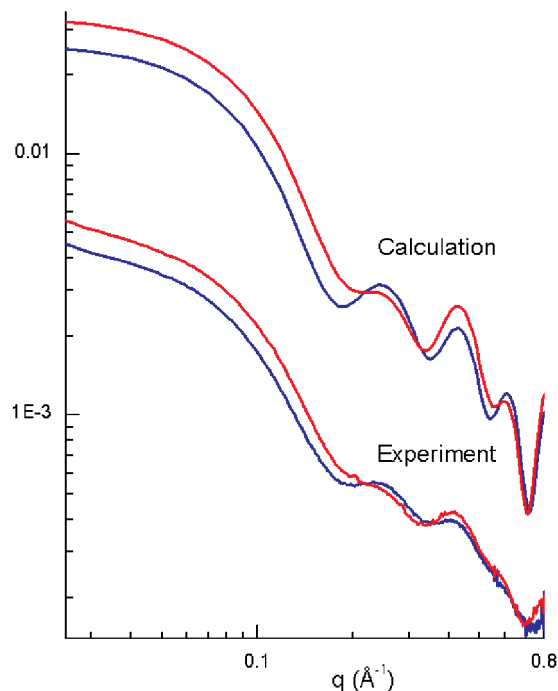 oscillatory interference pattern and in details of the peak positions and lineshapes. Atomic pair distance-distribution analysis using indirect inverse Fourier transform techniques allows detailed comparisons to be made between the structure and conformational dispersion measured for the multiporphyrin assemblies in solution with targeted design models.

Discussion

These experiments demonstrated the ability to use *in situ* high-angle x-ray scattering for the characterization of structure and conformational dispersion of shape-persistent macrocycles in liquids. Scattering measurements were made to a spatial resolution of 6 Å for a cyclic, diphenylethyne-linked hexameric porphyrin assembly and a host-guest assembly formed by the inclusion of a tripryidyl guest molecule. These measurements were found to resolve three geometrically distinct sets of atom pair distance correlations that are shown to correspond to nearest neighbor, next-to-nearest neighbor, and opposing porphyrin pair positions in the hexameric wheel assembly. The positions and broadening of the measured porphyrin pair distance correlations demonstrate that the porphyrin assembly exists in distribution of conformers centered on dimensions close to those obtained from energy-minimized model structures. Conformational dispersion in the wheel assembly was approximated through rigid-body

motions of the porphyrin groups and shown to involve approximately 20° variance in porphyrin orientation and 2 Å variance in radial position. Inclusion of the triprydyl guest molecule was found to expand the overall diameter of the assembly by 0.6 Å and decrease the configurational dispersion by about half. These results provide experimental validation of the synthetic design target and provide new information on the configuration dispersion of the assemblies critical for understanding their photophysical function. The high-angle scattering approach is generally applicable and can be extended at least up to 2 Å spatial resolution to achieve a more detailed picture of structure, modes of configurational dispersion, and solvent association with molecular assemblies in liquids.

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