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Molecular beads on a charged molecular string: α,ω-alkyldiammonium complexes of cucurbit[6]uril in the gas phase

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Abstract

Complexes of α,ω-alkyldiammonium cations [$H_3N^+(CH_2)_nNH_3^+$, $n = 2$–10] with the cyclic, hollow ligand cucurbit[6]uril (CB6) were characterized in the gas phase using Fourier transform ion cyclotron resonance mass spectrometry with energy resolved sustained off-resonance irradiation (SORI) collision induced dissociation, in combination with HF/6-31G* and B3LYP/6-31G* computational methods. All the complexes have the diammonium cation threaded through the cavity of CB6. The modeled supramolecular geometries, the SORI energies required for dissociation of the complexes and for appearance of singly protonated diamine product ions, and the branching ratios for the various dissociation channels all suggest that the optimum α,ω-alkyldiammonium chain length for binding CB6 in the gas phase occurs for $n = 4$. This contrasts with observed complex stability constants in aqueous formic acid, which are maximum for $n = 6$, reflecting solvent stabilization of the ammonium groups that is not possible in the gas phase. At the B3LYP/6-31G* level of theory, the binding energy for the $n = 4$ complex with respect to dissociation to singly protonated butanediamine and protonated CB6 is 204 kJ mol^{-1}. The $n = 6$ complex exhibits especially low dissociation thresholds, perhaps reflecting compression of the diammonium cation upon complexation with CB6, forming a loaded "molecular spring."

Keywords: SORI; Alkyldiamine; Cucurbituril

1. Introduction

Molecular nanotechnology [1], the development and application of devices of nanometer size built from single molecules or supramolecular assemblies of a few molecules, is one of the most promising new areas of 21st century research. Most researchers in the nanotechnology area have taken the approach of making existing devices smaller (for example, decreasing the size of transistors used in microchips) or of carrying out existing processes on a smaller scale (for instance, using shorter wavelength radiation to scale down photolithography). Another approach, one favored by nature, is to redesign the devices using the smallest possible components, atoms and molecules. The feasibility of this approach is demonstrated in biology; biological systems use extensive molecule-based "nanotechnology," with DNA acting as a molecular information storage device and various proteins serving as molecular machines.

With the push to design and synthesize artificial nanodevices comes an urgent need to develop techniques for characterizing them. Most current methods focus on imaging the nanodevices, usually on surfaces, with high (preferably atomic) resolution. While imaging techniques are powerful, they suffer from limitations in their ability to chemically characterize the materials being imaged. In addition to imaging, techniques typically used to characterize nanomaterials and supramolecular assemblies include NMR, UV-vis and IR spectroscopy, thermogravimetry, X-ray crystallography, and electrospray mass spectrometry (ESI-MS) [2,3]. If the molecules of interest contain paramagnetic atoms or undergo rapid exchange/equilibration among multiple structures, NMR will be of only limited value. In addition, it is often difficult to obtain crystals of sufficient quality for X-ray structure determination. ESI-MS is primarily used only for detection of the molecular ion corresponding to a supramolecular structure, but seldom is it used for structural characterization beyond this. Of these methods, all but ESI-MS require relatively large amounts of material, and all (including ESI-MS as it is usually practiced) are strongly influenced by the presence of solvent

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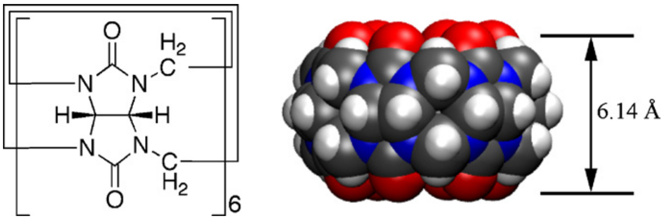

Fig. 1. Structural and space filling models of cucurbit[6]uril, CB6.

or other matrix materials. Thus, an urgent need exists for new analytical methods.

Cucurbiturils [4] are pumpkin-shaped cyclic polymers of glycoluril with hollow interior cavities that are promising as components of supramolecular devices. As shown in Fig. 1, carbonyl oxygen atoms line the portals of the cucurbituril and form ideal binding sites for positive ions, while the interior cavities can contain neutral molecules of proper size. Cucurbiturils composed of *n* glycoluril units are named cucurbit[*n*]urils, CB*n* hereafter.

CB6 has been known for over 100 years, and has been extensively characterized in condensed media beginning in the 1980s [4]. CB6 is of the proper size to form complexes with α,ω-alkyldiammonium cations in solution. In condensed media, these complexes have rotaxane structures, where the diammonium chain is threaded through the cucurbituril. Despite its low solubility in most solvents, CB6 and its complexes are straightforward to study using ESI-MS, and provide a good test bed for new mass spectrometric methods for characterizing supramolecular assemblies.

We recently used complexes of 1,4-diaminobutane with CB6 to demonstrate that ESI-MS sample introduction, combined with tandem mass spectrometry, can be used to distinguish between threaded, rotaxane structures and non-threaded conformations [5]. Both the reactivity of these complexes with neutral amines and their collision induced dissociation (CID) behavior are distinct. Threaded structures react with propylamine via slow addition, whereas non-threaded structures react via rapid amine exchange. Threaded complexes are relatively difficult to dissociate collisionally and tend to do so via covalent cleavages, whereas non-threaded structures tend to dissociate via disruption of the non-covalent interactions between the assembled molecules.

In this paper we explore the collisional dissociation behavior of α,ω-alkyldiammonium ion $[H_3N^+(CH_2)_nNH_3{}^+, n=2\text{–}10]$ complexes of CB6 in much greater detail, using sustained off-resonance irradiation (SORI) CID techniques [6], which have recently been reviewed [7]. We apply SORI in an energy-resolved manner to characterize fragmentation as a function of energy and the relative binding strengths of the various complexes, with an eye toward determining the intrinsic optimum alkyldiammonium chain length for binding CB6.

With the increasing availability of more powerful computers, even supramolecular complexes consisting of more than 80 heavy atoms, such as those described here, are within the reach of reasonably accurate computational methods. Computational chemistry, which excels at the description of isolated molecules in the gas phase, is an ideal complement to the gas phase experiments described in this paper, and we employ computational methods extensively to supplement and illuminate our experimental studies.

2. Experimental

2.1. Instrument

All experiments were carried out using a Bruker model APEX 47e FT-ICR mass spectrometer controlled by a MIDAS data system [8] and equipped with a microelectrospray source modified from an Analytica design, with a heated metal capillary drying tube based on the design of Eyler [9].

2.2. Materials

CB6 and *n*-alkyldiamines ($n=2\text{–}10$) were purchased from Sigma Chemical Co. (St. Louis, MO) and used without further purification. CB6 was dissolved in 88% formic acid (Fisher Scientific, New Jersey), diluted to about 1 mM in 50:50 methanol/water, and mixed with about 2 mM *n*-alkyldiamine. The samples were electrosprayed at a typical flow rate of 10 μL/h.

2.3. SORI–CID experiments

Stored waveform inverse Fourier transform [10] techniques were used to isolate target peaks. Sustained off-resonance irradiation–collision-induced dissociation (SORI–CID) [6] experiments were performed by irradiating 1 kHz below the resonant frequency of the ion of interest. Collision gas (air) was introduced using a Freiser-type pulsed leak valve [11], which maintains a constant pressure during the SORI excitation. SORI events involved pulsing the background pressure in the trapping cell up to 10^{-5} mbar and applying the off-resonance irradiation for 5 s. The amplitude of the SORI RF pulse was varied programmatically through a range of values from less than the threshold for dissociation to several times the threshold value. Ten scans were averaged for each SORI amplitude.

2.4. Threshold data analysis

Data analysis was performed with a modified version of the MIDAS Analysis software package [8] that was capable of extracting peak amplitudes from a set of spectra that differ in one or more experimental parameters (in this case, SORI amplitude). The software generated tables of peak intensities as a function of SORI excitation voltage.

Meaningful comparison of SORI data for different molecular systems requires a relationship between SORI amplitude and the amount of energy supplied to the molecular system by the SORI process. Because SORI supplies energy to the parent ion via a series of low energy collisions, both the average collision energy and the total number of collisions contribute to the total energy available, E_{SORI} [12]. E_{SORI} is the product of the number of collisions the parent ion undergoes, n_{coll}, and the average