of peptide side chains and that the synthesis of peptidomimetics can provide information about the conformation of the natural ligands.

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Supplementary Material Available: Listings of complete spectral data for **1a–d** and **3–11** and tables of experimental details, positional parameters, and thermal parameters for the X-ray analysis of **6** (14 pages). Ordering information is given on any current masthead page.

Aggregation of Hexa(phenylacetylene) Macrocycles in Solution: A Model System for Studying π–π Interactions[†]

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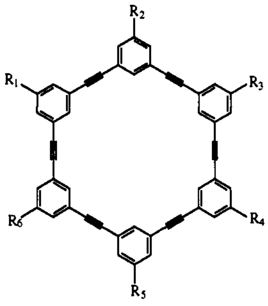
π-Stacking interactions between aromatic rings have received a great deal of attention[1] due to their importance in such diverse areas as molecular recognition,[2] stereocontrol of organic reactions,[3] structure of biological molecules,[4] and solid-state packing of organic molecules.[5] Specific details on the nature of these interactions, especially regarding the contributions of various noncovalent bonding forces, remain unclear. Although substituents on the π-systems are known to strongly influence stacking tendencies, these effects cannot always be explained in terms of simply donor–acceptor interactions.[1g] Here we would like to report on the self-association of phenylacetylene macrocycles (PAMs) in solution. These compounds should be useful as models for quantitatively studying substituent effects on π–π interactions. Moreover, depending on the geometry of the aggregate, self-association of toroidal-shaped macrocycles represents the initiation of a noncovalently bound molecular channel. Thus, a better understanding of these interactions may be useful for designing novel, tubular mesophases,[6] porous organic solids, and molecular monolayers for controlling transport properties at surfaces.[7]

Table I. Thermodynamic Data for Dimerization of **1–5** in Chloroform-*d*

compd	K_{assoc} (M^{-1})[a]	ΔG (kcal mol^{-1})[a]	ΔH (kcal mol^{-1})	ΔS (cal mol^{-1} K^{-1})
1	60	−2.4	−5.0 ± 0.2	−9.2 ± 0.8
2	18	−1.7	−5.6 ± 0.3	−13.6 ± 1.0
3	26	−1.9	−5.1 ± 0.3	−10.8 ± 1.0
4	*b*	*b*	*b*	*b*
5	*b*	*b*	*b*	*b*

[a] At 293 K. [b] No evidence for dimerization was observed.



1: $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = COO^nBu$
2: $R_1 = R_3 = R_5 = COO^nBu$, $R_2 = R_4 = R_6 = O^nBu$
3: $R_1 = R_2 = R_3 = COO^nBu$, $R_4 = R_5 = R_6 = O^nBu$
4: $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = O^nBu$
5: $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = CH_2O^nBu$

Using our previously reported synthetic methods,[8] we have synthesized compounds **1–5**.[9] It was found that the chemical shifts (δ) of the aromatic protons of **1** depended strongly on concentration. At ambient temperature, the chemical shifts (in $CDCl_3$) of the two aromatic protons of **1** varied from 8.12 to 7.23 ppm and from 7.81 to 6.79 ppm, respectively, as the concentration changed from 0.83 to 106 mM. This indicates that PAM **1** self-associates in solution.[10,11] If we assume that monomer–dimer equilibrium is the predominant process of this self-association,[12] ^1H NMR measurements at different concentrations can be used to determine the dimerization constant, K_{assoc}, using a reported procedure.[13] By this method, K_{assoc} was found to be 60 M^{-1} at 20 °C, which is of the same order as porphyrin dimerization in $CDCl_3$.[14] Since **1** has no functionality to engage in hydrogen bonding, we believe that the observed behavior results from π-stacking interactions. This idea is supported by the observation that only the protons directly attached to the aromatics show significant concentration-dependent chemical shifts. It is also consistent with the fact that we observed no evidence for self-association in benzene-d_6.[15] We suspect that the well-defined,

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[†] Nanoarchitectures. 3. Part 2: see ref 8b.

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rigidly held planar geometry of PAMs promotes cooperative, π–π interactions among several pairs of aromatic rings in neighboring molecules. Consequently, weak interactions between a single pair of aromatic rings that may be difficult to observe in small molecules are amplified by the PAM molecular architecture.[16] Because our synthetic chemistry allows aromatic functionalities to be varied easily, PAMs should provide a unique opportunity to study substituent effects on π-stacking interactions.

K_{assoc} was also found to vary significantly with temperature. According to van't Hoff analyses, $\Delta H = -5.0 \pm 0.2$ kcal mol^{-1} and $\Delta S = -9.2 \pm 0.8$ cal mol^{-1} K^{-1}. Surprisingly, PAM **2**, with alternating alkoxyl and ester groups, was found to have a smaller dimerization constant than **1** at 20 °C ($K_{\mathrm{assoc}} = 18$ M^{-1}). Further studies give $\Delta H = -5.6 \pm 0.3$ kcal mol^{-1} and $\Delta S = -13.6 \pm 1.0$ cal mol^{-1} K^{-1} for the self-association of **2**. These results suggest that donor–acceptor interactions between alkoxyl and ester groups slightly favor π-stacking enthalpically, but disfavor π-stacking entropically relative to **1**. Overall, the entropy effect dominates near ambient temperature, resulting in a decrease in K_{assoc} for **2**. The difference in ΔS might also indicate that the dimer pair of **2** is more highly ordered than that of **1**. For **3**, which has segregated alkoxyl and ester groups, it was found that $K_{\mathrm{assoc}} = 26$ M^{-1}, $\Delta H = -5.1 \pm 0.3$ kcal mol^{-1}, and $\Delta S = -10.8 \pm 1.0$ cal mol^{-1} K^{-1}. It is interesting to note that ΔS for dimerization of **1**, **2**, and **3** does not correlate with their symmetry, but may be rationalized by considerations of the shape of electrostatic potential surface of the dimer pair. Preliminary calculations based on the Hunter–Sanders model[18] suggest a face-to-face geometry with a 30° rotational off-set around the principal axis for the dimer of **1**.

No evidence of self-association was observed for **4** or **5**. The chemical shifts of the aromatic protons of these PAMs remain essentially constant with concentration and temperature. This clearly shows that aromatic substituents have a strong influence on the π-stacking interaction. We have also attempted to study the heteroassociation of **1** and **4** as well as **1** and **5** by NMR titration. We were unable to obtain accurate values of these heteroassociation constants because of the strong self-association of **1**. Qualitatively, however, the heteroassociation appears not to dominate over self-association of **1**. All of these data are consistent with the model developed by Hunter and Sanders.[18] Their model predicts that π–π interactions between two π-deficient aromatic systems can be more favorable than those between a π-deficient and π-rich system or two π-rich systems.

In conclusion, we have demonstrated that PAMs are valuable models for studying the influence of chemical structure on π–π interactions. We hope to use this information to design modular building blocks that can engage in specific noncovalent bonding for the rational construction of molecular materials.

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Supplementary Material Available: Listings of characterization data of compounds **1–5**, graphs and tables of variable-temperature ^{1}H NMR data,[17] and data analysis (17 pages). Ordering information is given on any current masthead page.

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(16) The well-defined geometry seems essential for observing aggregation of these PAMs. This is supported by the fact that the open-chain oligomeric precursors to these macrocycles do not self-associate under the same conditions. Molecular modeling shows that hexa(PAM)s prefer to adopt a planar geometry. This is another example of Cram's preorganization.

(17) Variable-temperature ^{1}H NMR was done on a Bruker AM-360 equipped with a Eurotherm temperature controller. The temperature was calibrated with 4% methanol in methanol-d_4. All NMR spectra were taken in $\mathrm{CDCl_3}$ with the residual solvent peak as the reference. $\mathrm{CDCl_3}$ was assumed to expand linearly with temperature and have the same expansion coefficient as $\mathrm{CHCl_3}$: *International Critical Tables of Numerical Data: Physics, Chemistry and Technology*; Washburn, E. W., Ed.; MacGraw-Hill: New York, 1928; Vol. III, p 27.

Direct Electron Transfer Involving Free-Solute Ferrocene in Fluid Electrolyte on an Oxocuprate (Bi(Pb) 2223) Electrode in the Superconducting State

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High critical temperatures T_c invite the probing of the electronic spectra of superconducting oxocuprates by electrochemical study of charge transfer at the superconductor/electrolyte interface. Hitherto solid electrolytes[1,2] or frozen aqueous glasses[3,4] have been employed, the latter involving irresolvably complex proton reductions[3] or poorly-resolved $\mathrm{Fe^{II/III}}$ processes.[4] Electron transfer effected between a superconducting electrode and free electroactive species in a fluid solution offers a wider choice of systems and more intimate electrode/electrolyte contact.[5] R. W. Murray et al.,[4–9] having developed low-temperature electrolytes and oxocuprate microelectrodes (on which low currents i minimize large iR potential drops through high electrolyte resistances R at ~100 K), now employ silver-coated oxocuprate macroelectrodes[10] (with proximity-effect Ag superconduction) bearing surface-bound electroactive species.

Following experimental advances i–v, we can now report free-solute ferrocene electrochemistry in fluid electrolyte at 102–104 K (i.e., $<T_c$) on superconducting Bi(Pb) 2223 oxocuprate itself ($\mathrm{Pb_{0.34}Bi_{1.84}Sr_{1.91}Ca_{2.03}Cu_{3.06}O_{\mathit{x}}}$), T_c being established as 105 K by four-probe resistivity measurements.

(i) A new $<T_c$ solvent (cf. ref 5), of mixed chloroethane/tetrahydrofuran plus $\mathrm{LiBF_4}$ background electrolyte, remains a supercooled glass retaining sufficient fluidity to allow significant diffusion at the electrode for >10 min.

(ii) Epoxy-embedded microelectrode fabrication from a wholly encapsulated sample[8] has been improved using partial encapsulation, thus. A ~5-mm-long wedge-shaped fragment, cut from a pressed oxocuprate pellet, is attached to copper wire at its rear edge with Ag paint and sanded to a point with fine emery paper. By standing this construction on its tip in a cylindrical PTFE mold subsequently filled with a cryorobust resin, only the extremity is exposed to provide the electrode surface.

(iii) A four-electrode resistance probe used as the electrical connection to the oxocuprate allows observation of the normal-to-superconducting transition prior to experimentation, and its reverse afterward. Thermal equilibrium at $<T_c$ (demonstrated by steady thermocouple and sample resistance readings) is rapidly restored (<10 min) after electrolyte injection (item v below), thermal perturbations being minimized by the large thermal mass of the cell.

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