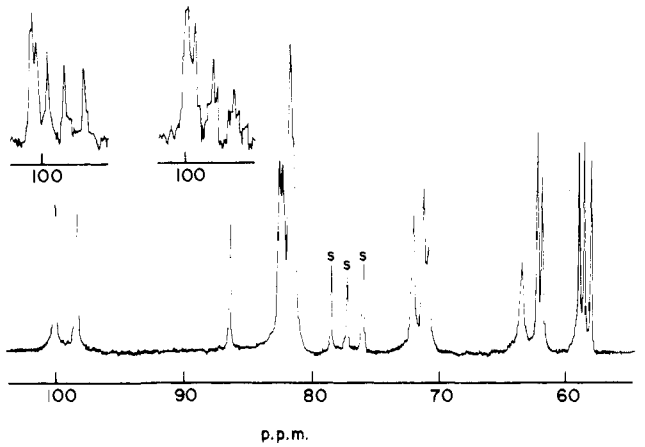

Figure 2. ^{13}C NMR spectrum of symmetrical tritrityl-per-*O*-methyl-α-cyclodextrin (**4**): solution in $CDCl_3$, chemical shifts from Me_4Si. The downfield trityl signals are not shown. Insets show the C-1 signals from the spectra of two isolated *un*symmetrical derivatives.

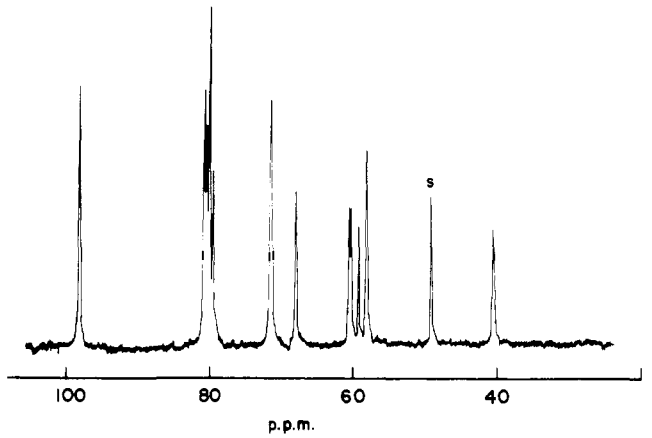

Figure 3. ^{13}C NMR spectrum of symmetrical triamino-per-*O*-methyl-α-cyclodextrin (**1**): solution in D_2O with internal methanol standard, chemical shifts from methanol referred to external Me_4Si.

Characterization. The characterization of compound **1** and of compounds **3**–**7** relied on their threefold rotational axis of symmetry, which is exhibited in their ^1H and ^{13}C NMR spectra.[10] Of the *four* possible primary trisubstituted isomers, only the desired isomer retains any rotational symmetry. For instance, the ^{13}C NMR spectrum of **3** (Figure 2) shows only *one* kind of trityl group and *two* kinds of α-glucose unit. Although the expected two pairs of signals for the 12 C-2 and C-3 atoms are not resolved (81.3 and 81.5 ppm), all other predicted signals are seen: C-1 at 100.2 and 98.5; C-4 at 82.4 and 82.2; C-5 at 71.8 and 70.9; and C-6 at 70.6 and 63.2 ppm. Remarkably, the threefold symmetry is exhibited even by the 15 *O*-methyl groups, 12 of which are on the secondary side of the cyclodextrin torus, away from the substitution site: C-2 OCH_3 at 61.9 and 61.5; C-3 OCH_3 at 58.2 and 57.6; and C-6 OCH_3 at 58.6 ppm. As expected, only one type of trityl group is observed, with the single quaternary carbon signal at 86.3 ppm (the four other singlets, for the ortho, meta, para, and ipso carbons, are downfield and are not shown in Figure 2). (In contrast, two of the *un*symmetrically substituted tri-*O*-trityl derivatives isolated from the tritylation reaction showed *three* different trityl groups plus a multiplicity (theoretically six) of α-glucose units. The number of spectroscopically distinct α-glucose units was most clearly seen in the C-1 signals of the ^{13}C NMR spectra (see insets in Figure 2).) The NMR spectra[10] for **1** and **3**–**7** all exhibit the expected symmetry, while those for unsymmetrical derivatives do not. In the ^{13}C NMR spectrum of **1** (Figure 3), the two C-1 signals are not resolved, but other signals (for C-3 through C-6) show the expected symmetry doubling. These results confirm that **1** is the desired isomer in high purity.[8]

The procedure outlined here provides access to a wide variety of cyclodextrin derivatives, and the rational synthesis of sophisticated model systems employing regiospecifically disposed functionality at the primary end of the cyclodextrin cavity and additional functionality at the secondary end, is now possible.

Acknowledgments. We are indebted to Teijin Ltd. (Tokyo) for gifts of cyclodextrins and to the National Science Foundation for support.

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(7) The compounds of R_f 0.28, 0.26, 0.23, and 0.20 were separated and identified by ^1H and ^{13}C NMR spectroscopy as primary substituted tritritylated α-cyclodextrins. Thus each of the *four* possible primary substituted products was formed. The material at R_f 0.37 proved to be a mixture of primary (C-6) substituted tetratritylcyclodextrins, while that at R_f 0.14 was identified as a mixture of the ditritylcyclodextrins. The reaction conditions could be adjusted to favor di-, tri-, or tetrasubstitution. Isolation and characterization of symmetrical di- and tetrasubstituted products is possible, in addition to various unsymmetrical isomeric products, the identity of which is more difficult to establish precisely (Boger, J.; Knowles, J. R., unpublished results).
(8) Chemical shifts are reported with reference to tetramethylsilane. Satisfactory elemental analyses were obtained for all compounds; infrared spectra and optical rotations were performed where appropriate. Each compound was examined critically on several TLC systems and found to be free from impurities (<1%).
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(10) Assignments for most of the signals in the ^{13}C NMR spectra for all compounds reported were based upon correlations from this work, including unpublished results on di- and tetrasubstituted compounds, studies of the primary hexasubstituted cyclodextrins,[1] and other data on cyclodextrins and other carbohydrates. E.g.: Colson, P.; Jennings, H. J.; Smith, I. C. P. *J. Am. Chem. Soc.* **1974**, *96*, 8081. Takeo, K.; Hirose, K.; Kuge, T. *Chem. Lett.* **1973**, 1233. Breitmaier, E.; Voelter, W. "^{13}C NMR Spectroscopy"; Verlag-Chemie: Weinheim/Berstr., Germany, 1975, pp 223–242. However, the identity of the symmetrical derivative **1** and of its precursors does not rest on the individual assignments of signals, but on the simple spectra obtained by virtue of the symmetry of the compounds.
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Symmetrical Triamino-per-*O*-methyl-α-cyclodextrin: A Host for Phosphate Esters Exploiting Both Hydrophobic and Electrostatic Interactions in Aqueous Solution

Sir:

With the aim of designing a host molecule that would catalyze a simple chemical reaction by specific stabilization of its transition state,[1] we have opted first to investigate the synthesis

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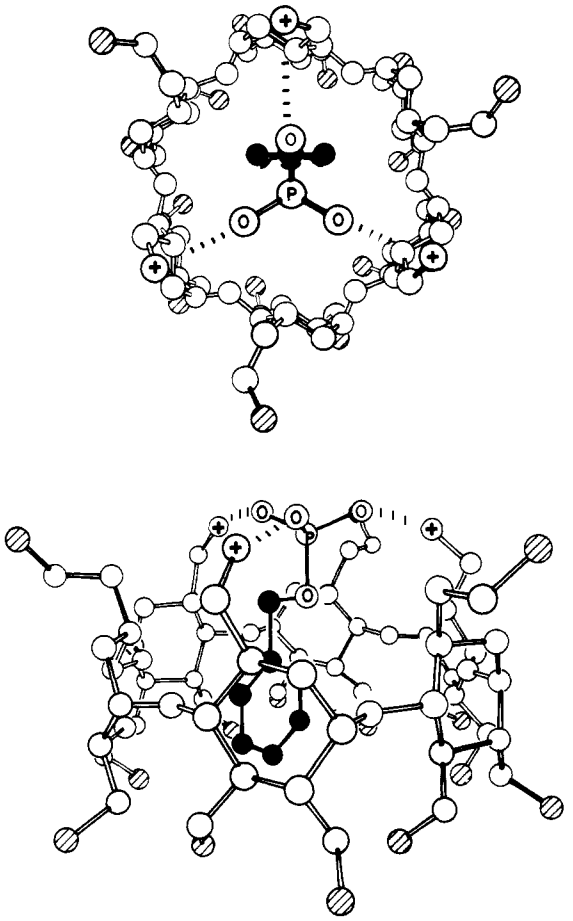

Figure 1. Drawings of symmetrical triammonio-per-*O*-methyl-α-cyclodextrin (**1**) complexed with benzyl phosphate. Each of the three ammonium ions is shown by the symbol ⊕. The 15 methyl groups are shaded. All hydrogen atoms are omitted. The size of the atoms is arbitrary.

of a multifunctional host for the complexation of a multifunctional guest species. Our chosen guest is a phosphate monoester such as the benzyl phosphate dianion, a complementary host for which requires four binding loci: a hydrophobic pocket for the encapsulation of the benzyl group, and three cationic (or hydrogen-bond donor-acceptor) groups to complement the three partially anionic peripheral oxygen atoms of the phosphoryl group. These loci must, of course, be rather precisely positioned with respect to one another, and an inspection of molecular models suggested that the symmetrical triammonium-per-*O*-methyl-α-cyclodextrin **1** (6,6″,6‴-triammonio-6,6″,6‴-trideoxy-6′,6″″,6‴″,2,2′,2″,2‴,2″″,2‴″,-3,3′,3″,3‴,3″″,3‴″-pentadeca-*O*-methyl-α-CD) would be a promising candidate, the synthesis and characterization of which has been described.[2] We report here binding experiments that demonstrate specific complexation involving simultaneous hydrophobic and electrostatic (or hydrogen-bonding) interactions in aqueous solution.

Binding of Protons; pK_a' Values. Potentiometric titration of **1**, followed by computer analysis of the titration curve, gave apparent pK_a values of 7.42, 8.02, and 8.79.[3] The single pK_a' for the mono-6-ammonio-per-*O*-methyl-α-cyclodextrin **2**[2] is 8.06.[3] The pK_a' values are surprisingly low for primary ammonium groups, at least 0.5 units lower than expected from the known values for 6-amino-6-deoxy-α-methylglucose and related compounds.[4] This could reflect the relatively nonpolar environment of the ammonium groups, which are surrounded by methyl ethers. For the triammonium compound **1**, the three pK_a' values differ by slightly more than the statistical minimum,[3,5] indicating that the environment of each amine is slightly affected by the presence of the other two, although the effect is not large. These titrations show that, at pH 7, the host compounds are present primarily as the fully protonated species.

Table I. Dissociation Constants of Complexes of Charged Per-*O*-methyl-α-cyclodextrins with Benzyl Alcohol, Benzyl Phosphate, and 2,4-Dinitrophenol[a]

guest	monoammonium **2**	triammonium **1**
benzyl alcohol	11 ± 1.3	24.3 ± 3.5
benzyl phosphate[b]	30 ± 7[c]	0.031 ± 0.005[d]
2,4-dinitrophenol	0.316 ± 0.017[e]	0.991 ± 0.033[e]

[a] Dissociation constants (millimolar) determined from the inhibition of 2,4-dinitrophenol binding, at 30.0 °C; I = 0.10. Errors indicated are standard deviations from the means of several determinations at different concentrations of guest, each measured at several different wavelengths. pH was 7.00 ± 0.05 with triethanolamine-HCl buffer. At this pH, the cyclodextrins are nearly fully protonated, the benzyl phosphate is predominantly the dianion, and the 2,4-dinitrophenol is the monoanion. [b] Added as the bis(cyclohexylammonium) salt.[9] [c] Ionic strength varied from 0.1 to 0.2. No effect was seen on the binding of 2,4-dinitrophenol by varying the ionic strength in this range with KCl. [d] Extrapolated to zero benzyl phosphate concentration. [e] Determined directly by a nonlinear fit to the unsimplified equilibrium expression.[7]

Table II. pH Dependence of the Binding of Benzyl Phosphate to Triammonio-per-*O*-methyl-α-cyclodextrin **1**[a]

pH	guest: benzyl alcohol	guest: benzyl phosphate
5.50[b]	33 ± 5	2.1 ± 0.2
7.00[c]	24 ± 4	0.031 ± 0.005
9.50[d]	25 ± 4	>100

[a] See footnote *a* of Table I. [b] In *N,N,N′,N′*-tetramethylethylenediamine-HCl. [c] In triethanolamine-HCl. [d] In ethanolamine-HCl.

Binding of Benzyl Phosphate. The symmetrical triammonium compound **1** was designed as a host for benzyl phosphate. Inspection of Corey-Pauling-Koltun models suggested that, with the phenyl ring placed in the cyclodextrin cavity, the three charged phosphate oxygen atoms can occupy the plane of the three ammonium groups. Adjustment of the position of the phenyl ring within the cyclodextrin cavity raises or lowers this plane of charged oxygen atoms with respect to the plane of ammonium groups. In these arrangements the O to N distance varies between 2 and 3 Å. One such arrangement is shown in Figure 1.

The complexation of benzyl phosphate[6] by **1** or **2** was measured indirectly by competitive inhibition of the binding of 2,4-dinitrophenol, which forms a 1:1 complex with these cyclodextrins.[7] The dissociation constants (K_{diss}) thus obtained are shown in Table I. While the K_{diss} for the binding of benzyl alcohol to **1** is slightly *larger* than that for its binding to **2**, the K_{diss} for the binding of benzyl phosphate (70% of which is present as the dianion and 30% as the monoanion at pH 7) to **1** is almost *three orders of magnitude smaller*.[8] The charged host **1** is clearly selective in its binding preference for benzyl phosphate.

The dissociation constants for the complex of benzyl alcohol with **1** are independent of pH in the region studied, while those for benzyl phosphate are strongly pH dependent (Table II). At pH 5.5, where the dominant phosphate species is the monoanion, K_{diss} is 70 times larger than at pH 7. At pH 9.5, where the benzyl phosphate is exclusively the dianion, and **1** is predominantly neutral, K_{diss}[9] is more than 3000 times larger than at pH 7. The pH dependence observed is in accord with the binding of the benzyl phosphate in the cyclodextrin cavity, with

the phosphate oxygens interacting (at pH 7) strongly with the three symmetrically disposed ammonium ions. A determination of the binding of benzyl phosphate to **1** in the presence of inorganic phosphate gave a K_{diss} value identical with that obtained in its absence, indicating that, within the errors of such an indirect determination, inorganic phosphate itself does not bind ($K_{diss} > 200$ mM) to **1**.[10]

In this model system, highly specific recognition of complex molecules depends on independent recognition sites, one hydrophobic and the other electrostatic, providing a model for multiple recognition sites common in biological systems.[11] We anticipate that variations in the structure of the hydrophobic moiety of the guest molecule will cause predictable variations in the equilibrium position of the guest within the cyclodextrin cavity, leading to a change in the observed K_{diss}. Direct study of the precise geometry of the interactions in the observed complexes (e.g., by ^1H, ^{13}C, and ^{31}P NMR spectroscopy or X-ray crystallography) should clarify the energetic relationships between these hydrophobic and electrostatic recognition sites and the effects of such binding on the geometry and reactivity of the bound guest molecule.

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(3) Potentiometric titrations were done at 30 ± 0.02 °C, *I* 0.10 (KCl). The method of Sayce (Sayce, I. G. *Talanta* **1968**, *15*, 1397) was used to derive the individual pK_a values. This method minimizes the deviation of the actual base titer from that calculated on the basis of the pK_a values. For the triammonio-α-cyclodextrin **1**, the mean deviation was 0.14%; for the monoammonio-α-cyclodextrin, **2**, the mean deviation was 0.9%. For **1**, the successive pK_a values differ by 4.0-fold and 5.9-fold (compared with the statistical minimum of 3-fold).

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(8) The K_{diss} values determined for benzyl phosphate and **1** at pH 7 were dependent on the concentration of benzyl phosphate added. This phenomenon has been noted before in a similar competitive inhibition study of the binding of thiocyanate anion to α-cyclodextrin: Rohrbach, R. P.; Rodriguez, L. J.; Eyring, E. M.; Wojcik, J. F. *J. Phys. Chem.* **1977**, *81*, 944. Those authors attributed the variation to a breakdown in the assumption that the binding of the thiocyanate completely expelled the reporting chromophore. This appears to be the case for benzyl phosphate and **1** reported here. At each of several wavelengths, plots of the calculated K_{dlss} vs. the concentration of benzyl phosphate (seven concentrations, spanning an order of magnitude) were extrapolated to zero concentration, and the values obtained at the several wavelengths were averaged to give the K_{dlss} shown in Table I. In no other case was any systematic variation of K_{diss} with concentration observed. Using models of the complex, there is ample room for some interaction of 2,4-dinitrophenol with the secondary end of the cyclodextrin, although the chromophore cannot penetrate significantly into the cavity without expelling the benzyl phosphate. The binding of 4-*tert*-butylbenzyl phosphate to **1** at pH 7 (K_{diss} = 16 μM) shows no such variation with concentration. In models, the *tert*-butyl group should prevent the formation of the proposed ternary complex. (The ternary complex may be present to some extent with benzyl alcohol or with the weaker benzyl phosphate complexes, but it would be undetectable using the indirect method since small variations in the observed absorbance do not greatly affect the calculated K_{dlss} for such weak complexes.)

(9) Benzyl phosphate was added as its bis(cyclohexylammonium) salt. Cyclohexylamine does not bind to the cyclodextrin derivatives at pH 5.5 or 7. However, at pH 9.5 the K_{diss} for cyclohexylammonium and **1** is ~50 mM. At pH 9.5, additions of the benzyl phosphate salt to the solution of **1** and 2,4-dinitrophenol caused some spectral change, which could be ascribed to the binding of cyclohexylamine (or cyclohexylammonium ion). Residual absorbance changes placed a lower limit of 100 mM on the binding of benzyl phosphate at this pH.

(10) The addition of inorganic phosphate caused no spectral changes in the indirect determination, indicating only that, if inorganic phosphate binds, it does so in a way that does not expel the reporting chromophore. This would not appear to exclude interaction with the ammonium groups. However, the failure of added inorganic phosphate to alter the K_{diss} for benzyl phosphate does establish that the inorganic phosphate does not interact strongly with the ammonium groups, since such an interaction would be expected to alter benzyl phosphate binding.

(11) There have been two recent reports of the associative properties of charged cyclodextrin derivatives: (a) Tabushi, I.; Shimizu, N.; Sugimoto, T.; Shiozuka, M.; Yamamura, K. *J. Am. Chem. Soc.* **1977**, *99*, 7100. (b) Matsui, Y.; Okimoto, A. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 3030. The reported effects of the electrostatic interaction on dissociation constants was small. In the former, a monoanion guest interacting with a dicationic (metal complex) cyclodextrin host gave a K_{dlss} 23 times smaller than with a neutral host. In the latter, a monocation host and monoanionic guest showed a K_{diss} lowering of only 4.

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7.3% Efficient Thin-Film, Polycrystalline n-GaAs Semiconductor Liquid Junction Solar Cell

Sir:

In a series of recent papers, we reported that the n-GaAs|0.8 M K_2Se–0.1 M K_2Se_2–1 M KOH|C cell shows good stability and higher efficiency than other photoelectrochemical cells.[1] Further, the solar to electrical conversion efficiency of this cell can be increased to 12% by chemisorbing a layer of ruthenium ions[2] which also substantially reduces the surface recombination velocity, not only at n-GaAs–electrolyte interfaces, but also at the n-GaAs–oxide (air) interface.[3] Most importantly, if the ruthenium ions are allowed to diffuse into boundaries of n-GaAs grains, recombination in these is substantially reduced.[4] After such diffusion, the efficiency of a semiconductor–liquid junction solar cell made with a thin-film, polycrystalline chemically vapor deposited layer of n-GaAs on carbon increases by a factor of 4.[4] We proposed that this improvement derived from the fact that a strongly chemisorbed ion reacting with a surface will split a surface state to levels from which it is no longer accessible by tunneling to majority carriers. This region is, in n-type semiconductors, below the edge of the conduction band and, in p-type semiconductors, above the edge of the valence band. By our model, the chemisorption of ruthenium ions causes in n-GaAs the splitting of initially present surface states located below the edge of the conduction band both to states above this edge and to states too deep in the band gap to be accessible by tunneling.[2,5]

Ideally, by elimination of grain boundary effects, it would be possible to approach single-crystal efficiency provided that the mobility remains high and an optimal, uniform doping level is maintained throughout the grains. We now report that such a situation is approached in thin-film, chemically vapor deposited n-GaAs, following exposure to a Ru(III) solution.

The anode used was n-GaAs/n^+-GaAs/W/graphite.[6,7] A 24-μm thick layer of n-GaAs was deposited on a 2–3-μm tungsten-on-POCO graphite substrate by the reaction by hydrogen chloride, gallium, and arsine at 775 °C. The grains were of 1–20-μm diameter, with an average linear dimension of 9 μm. Figure 1 shows a scanning electron micrograph of the grains. The samples, of ~0.5 × 0.3 cm size, were mounted as

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