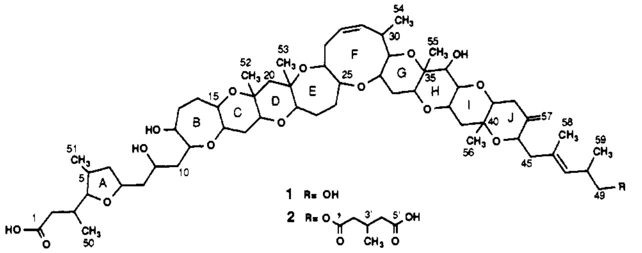
even by HPLC. Negative FABMS of the mixture suggested molecular weights of 1184 for GA-C and 1198 for GA-D. Hydrolysis of the mixture in a methanolic NaOH solution yielded GA-A (4.1 mg), GA-B (0.9 mg), and 3-methylglutaric acid, which was identified by ^{1}H NMR and FABMS data.[11] Thus, GA-C and GA-D apparently were 3-methylglutarate hemiesters of GA-A and GA-B, respectively. Structural studies were carried out mainly on GA-A and GA-C.

GA-A (**1**) was obtained as a white amorphous solid: $[\alpha]^{20}_D$ +33° (c 0.488, CH_3OH); UV (MeOH) λ_{max} < 210 nm; IR (KBr) 3500, 1735 cm^{-1}; HR-FABMS $[M + Na]^+$ m/z 1079.6330 (1079.6280 calcd for $[C_{59}H_{92}O_{16}Na]^+$). A carboxylic acid, suggested by the IR band at 1735 cm^{-1}, was proven to be present by measuring the IR, FABMS, and ^{13}C and ^{1}H NMR spectra of the methylated product,[12] although no corresponding signal was observed in the ^{13}C NMR spectrum of **1**.



Detailed analyses of ^{1}H–^{1}H COSY and 2D-HOHAHA spectra[13] allowed us to deduce partial structures H4–H18, H22–H34, and H36–H39, and H41–H49. The location of Me-50 was unassignable due to overlapping of the ^{1}H NMR signals and large second-order couplings between H2 and H3. One-dimensional HOHAHA experiments[14] solved the problem; magnetization was transferred from Me-50 to H4 through H3 upon irradiation at Me-50.

HMBC spectra[15] clarified the connectivities around the quaternary carbons by giving cross peaks due to $^{2,3}J_{CH}$ couplings between C52/H18, C52/H20, C53/H20, C53/H22, C55/H34, C55/H36, C56/H39, and C56/H41. Eventually, a remaining carboxyl carbon could be connected to C2; chemical shifts of H_2-2 (δ 2.04/2.35) are typical for an α-methylene of a carbonyl group.

The number and location of hydroxyl groups were clarified on the basis of deuterium shifts observed on ^{13}C NMR signals.[16] Detection of $^3J_{CH}$ couplings in the HMBC experiment revealed ether linkages of H11–C16 (B ring) and H25–C32 and C25–H32 (F ring). The presence of rings C, D, E, H, and J was confirmed by NOESY measurements,[17] which showed NOEs between angular protons or between an angular proton and a singlet methyl. The presence of rings G and I was clarified on the basis of proton coupling constants[18] and NOEs between H37 and H41 (1D NOE difference spectra at −25 °C). We could not obtain direct evidence of an ether linkage between C4 and C7 in ring A. The five-membered ring was deduced from the deuterium shift experiment. Moreover, the chemical shifts of C4 (δ 86.4) and H7 (δ 4.40) were deshielded significantly in comparison with those of an acyclic system, presumably due to the steric effect of the five-membered ring.

These results led us to **1** as the planar structure for GA-A. Assignments of ^{1}H and ^{13}C NMR signals of **1** are given in the supplementary material. The structure of GA-C (**2**) was readily determined by detailed comparison of the 1D and 2D NMR spectra with those of **1**.[19] GA-A is unique in possessing an isolated ring in its terminal chain in addition to a continuous chain of fused rings. The absence of ciguatoxins in this GII1 strain indicates the biosynthetic versatility of this organism. It is conceivable that these extremely potent antifungal metabolites released from the cells may act as repellents against other epiphytic microorganisms.

Acknowledgment. We are grateful to Prof. A. Inoue, Kagoshima University, for donation of the GII1 strain and Prof. P. J. Scheuer, University of Hawaii, and Prof. T. Kusumi, Tsukuba University, for discussions. This study was partly supported by a grant from the Ministry of Education, Science and Culture, Japan.

Supplementary Material Available: Tables of ^{13}C and ^{1}H NMR assignments and 1D ^{1}H NMR, 1D and 2D HOHAHA, ^{1}H–^{1}H COSY, ^{13}C–^{1}H COSY, HMBC, and NOESY spectra of gambieric acid A (**1**) and NOESY (−20 °C) and NOE difference spectra (−25 °C) of the mixture of gambieric acid C (**2**, major) and gambieric acid D (13 pages). Ordering information is given on any current masthead page.

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(11) 3-Methylglutaric acid: FABMS $(M - H)^-$ m/z 145; ^{1}H NMR (400 MHz, CD_3OD) δ 2.39 (1 H, multiplet), 2.36 (2 H, multiplet), 2.19 (2 H, q, J = 8 Hz), 1.02 (3 H, d, J = 6 Hz).

(12) **1** was treated with CH_2N_2 to give the methyl ester of **1**: IR (KBr) 1740 cm^{-1}; FABMS $(M + Na)^+$ m/z 1093. The ^{1}H and ^{13}C NMR spectra of the ester agreed well with those of **1**, except for signals due to C-1 and C-2: ^{13}C NMR (100 MHz, CD_3OD/C_5D_5N 1:1) δ 174.7 (C-1), 52.8 (CH_3O), 39.9 (C2); ^{1}H NMR (400 MHz, CD_3OD/C_5D_5N 1:1) δ 3.61 (3 H, s, CH_3O), 2.31 (1 H, d, J = 12 Hz, H-2), 1.97 (1 H, dd, J = 12, 4 Hz, H-2′).

(13) ^{1}H–^{1}H COSY, 2D HOHAHA (mixing time 85 ms), and phase-sensitive ^{13}C–^{1}H COSY spectra were recorded on a GSX-400 (JEOL, 400 MHz) spectrometer in C_5D_5N/CD_3OD (1:1).

(14) The 1D HOHAHA spectrum of **1** was measured at 400 MHz in C_5D_5N/CD_3OD (1:1), with increasing duration of spin locking from 20 to 80 ms while Me-50 was being excited selectively with the use of a long 180° pulse (50 ms).

(15) HMBC of **1** was recorded on an AM-500 (Bruker, 500 MHz) spectrometer in C_5D_5N/CD_3OD (1:1). The experiment was optimized for J_{CH} of 8.3 Hz.

(16) Deuterium shifts were measured on the mixture of **2** (major) and GA-D by comparison of ^{13}C NMR signals of hydroxyl-bearing carbons between spectra measured in C_5D_5N/CD_3OD (1:1) and in C_5D_5N/CD_3OH (1:1). Significant shifts (0.08–0.12 ppm) were observed for C9, C12, and C36, indicating the presence of three hydroxyl groups.

(17) The NOESY spectrum of **1** was measured at 500 MHz with a mixing time of 130 ms in C_5D_5N/CD_3OD (1:1) at 20 °C. Both positive and negative NOEs were observed. NOESY spectrum of the mixture of **2** (major) and GA-D was recorded at 400 MHz with a mixing time of 150 ms in C_5D_5N/CD_3OD (1:1) at −20 °C. All NOEs were negative under these conditions. The spectra are available as supplementary material.

(18) The coupling constants of protons on ring G are typical for those of a substituted tetrahydropyran: $^{2,3}J_{H,H}$, H32/H33a, 12 Hz; H32/H33b, 5 Hz; H33a/H33b, 11 Hz; H33a/H34, 12 Hz; H33b/H34, 5 Hz.

(19) The location of the 3-methylglutarate ester in GA-C was determined on the basis of ^{1}H NMR chemical shifts of H_2-49 (3.80/3.93), which were significantly deshielded in comparison with those of **1** (δ 3.34/3.37).

Synthesis and Characterization of $C_{60}O$, the First Fullerene Epoxide

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The isolation of C_{60} in preparatively useful quantities by Krätschmer et al.[1] has stimulated intensive efforts to generate and characterize functional derivatives. Many reactions of C_{60} furnish complex, inseparable mixtures of products,[2] and only a few dis-

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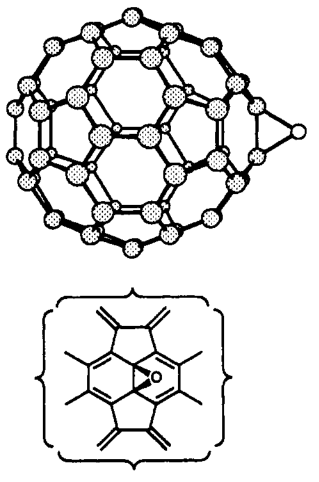
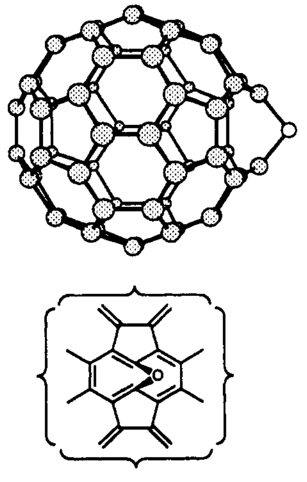
(1) Krätschmer, W.; Lamb, L. D.; Fostiropoulos, K.; Huffman, D. R. *Nature* **1990**, *347*, 354. Krätschmer, W.; Fostiropoulos, K.; Huffman, D. R. *Chem. Phys. Lett.* **1990**, *170*, 167.

crete, monofunctional congeners have been described to date.[3] In previous studies of simple oxygenated fullerenes, Diederich and co-workers isolated $C_{70}O$, a minor component of the fullerene mixture generated by resistive heating of graphite.[4] Wood et al.[5] detected $C_{60}O$ in a similar sample via mass spectrometry, and Kalsbeck and Thorp reported generating $C_{60}O_n$ (n = 1–4) via electrochemical oxidation of C_{60}.[6] We now report that photooxidation of C_{60} in benzene furnishes a single monooxide, $C_{60}O$, as the sole isolable product. Moreover, we have obtained the same species as a byproduct of the synthesis of C_{60}. Spectroscopic analysis strongly supports the epoxide structure **1**, and not the isomeric 1,6-oxido[10]annulene **2**.



1



2

The photooxygenation was effected by irradiating an oxygenated benzene solution of C_{60} (24 mM) with a medium-pressure Hanovia lamp in a quartz immersion well (18 h, room temperature). Flash chromatography on silica gel followed by semipreparative HPLC then furnished pure $C_{60}O$ in 7% yield.[7] The addition of benzil[8] (0.2 equiv) significantly enhanced both the yield (16%; ca. 27% based on recovered C_{60}) and the rate of oxidation (ca. 25% conversion within 2 h). The Purdue group noted earlier that photolysis of a crude fullerene mixture gave increased amounts of $C_{60}O$ and $C_{70}O$ accompanied by higher oxides $C_{60}O_n$ (n = 2–5) and $C_{70}O_2$, as judged by mass spectrometry.[5] Extensive oxidation and fragmentation of C_{60} are also induced by UV irradiation in hexane[9] or heating[10,11] in the presence of oxygen.

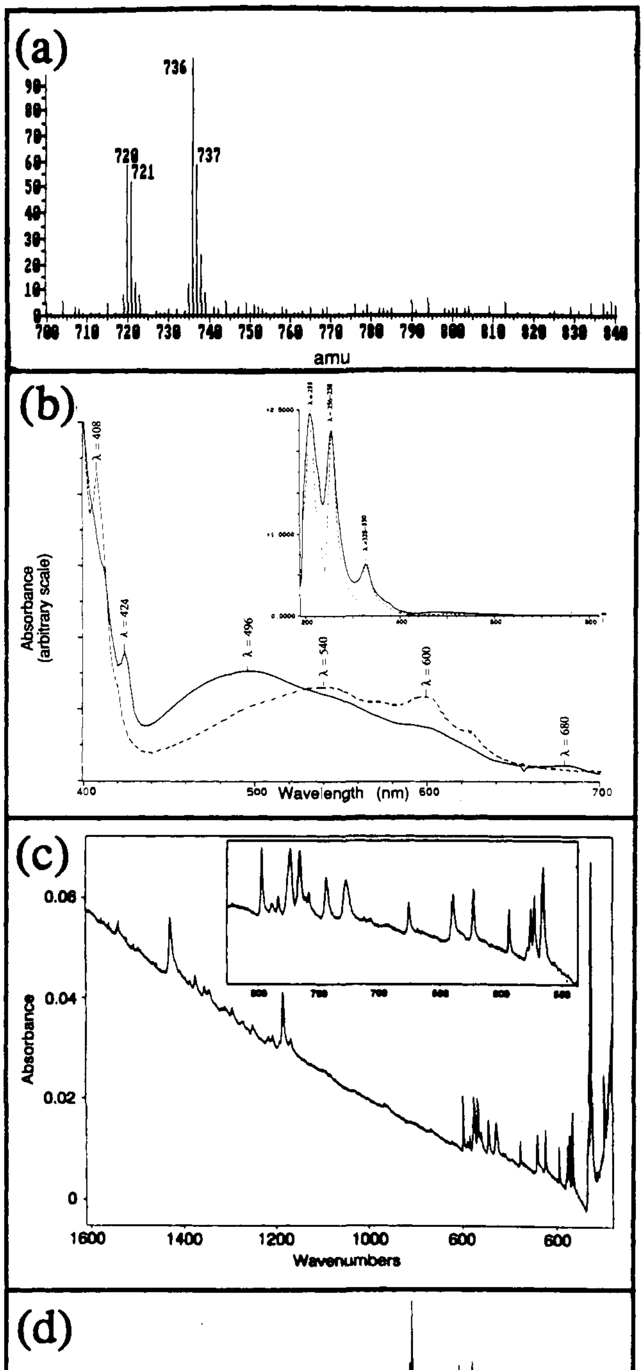


Figure 1. (a) Thermospray mass spectrum of $C_{60}O$. (b) UV–Vis spectra of C_{60} (- - -) and $C_{60}O$ (—) from 400 to 700 nm in toluene. Inset: Spectra of C_{60} (- - -) and $C_{60}O$ (—) from 190 to 820 nm in hexane. (c) FTIR spectrum of $C_{60}O$ film, deposited on a KBr plate from toluene solution. Inset: Expanded view of the 540–820-cm^{-1} region. (d) ^{13}C NMR spectrum of $C_{60}O$.

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(2) Haufler, R. E.; Conceicao, J.; Chibante, L. P. F.; Chai, Y.; Byrne, N. E.; Flanagan, S.; Haley, M. M.; O'Brien, S. C.; Pan, C.; Xiao, Z.; Billups, W. E.; Ciufolini, M. A.; Hauge, R. H.; Margrave, J. L.; Wilson, L. J.; Curl, R. F.; Smalley, R. E. *J. Phys. Chem.* **1990**, *94*, 8634. Bausch, J. W.; Surya Prakash, G. K.; Olah, G. A. *J. Am. Chem. Soc.* **1991**, *113*, 3205. Selig, H.; Lifshitz, C.; Peres, T.; Fischer, J. E.; McGhie, A. R.; Romanow, W. J.; McCauley, J. P., Jr.; Smith, A. B., III. *J. Am. Chem. Soc.* **1991**, *113*, 5475. Wudl, F.; Hirsch, A.; Khemani, K. C.; Suzuki, T.; Allemand, P.-M.; Koch, A.; Srdanov, G. *Angew. Chem., Int. Ed. Engl.*, in press. Hirsch, A.; Li, Q.; Wudl, F. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1309. Olah, G. A.; Bucsi, I.; Lambert, C.; Aniszfeld, R.; Trivedi, N. J.; Sensharma, D. K.; Surya Prakash, G. K. *J. Am. Chem. Soc.* **1991**, *113*, 9385 and 9387.

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(6) Kalsbeck, W. A.; Thorp, H. H. *J. Electroanal. Chem.* **1991**, *314*, 363.

(7) Significant quantities of brown precipitates are also formed, presumably via further oxidation of $C_{60}O$ and/or C_{60}. Cf. ref 8.

(8) Benzil and other carbonyl compounds have been employed in photooxidation of olefins: Shimizu, N.; Bartlett, P. D. *J. Am. Chem. Soc.* **1976**, *98*, 4193.

(9) Taylor, R.; Parsons, J. P.; Avent, A. G.; Rannard, S. P.; Dennis, T. J.; Hare, J. P.; Kroto, H. W.; Walton, D. R. M. *Nature* **1991**, *351*, 277.

Another phase of our collaborative venture simultaneously led to optimized chromatographic purifications of C_{60} and higher fullerenes.[12] In the course of these studies, an anomaly in the UV–vis spectrum of the C_{60} fraction led to the detection and isolation of the same oxide $C_{60}O$. The elemental composition was revealed by thermospray mass spectrometry.[13] The spectrum of a slightly impure sample appears in Figure 1a. The most intense peak, at 736 amu, corresponds to $C_{60}O$; the only other strong peak, at 720 amu, derives from C_{60}.[14]

The UV–vis absorption spectra for C_{60} and $C_{60}O$ in toluene are quite similar except for subtle differences in the 400–700-nm region (Figure 1b). $C_{60}O$ exhibits a new band at 424 nm but lacks the C_{60} band at 408 nm.[15] Relative to C_{60}, $C_{60}O$ displays stronger absorption at 496 nm and weaker absorptions at 540 and 600 nm.

To establish a vibrational fingerprint of the new material, FTIR spectra of triply chromatographed $C_{60}O$ were recorded with 0.5-cm^{-1} resolution (Figure 1c). The spectra contain no detectable absorptions above 1600 cm^{-1}, consistent with the absence of C—H or C═O bonds. Seventeen relatively strong bands and 25 weaker ones are observed between 450 and 1600 cm^{-1}. Four of the stronger bands (1427.8, 1184.6, 575.4, and 526.0 cm^{-1}) resemble the principal absorptions of C_{60} (1429.0, 1182.7, 575.9, and 526.9 cm^{-1} as recorded on the same instrument).[16]

The ^{13}C NMR spectrum of $C_{60}O$ (Figure 1d) was acquired at 125 MHz in benzene-d_6 with $Cr(acac)_3$ added as a relaxant. Sixteen lines are resolved, one at 90.18 ppm and the remainder between 140 and 146 ppm, referenced to the central peak of the benzene triplet (128 ppm).[17] The chemical shifts are consistent with the values reported for C_{60} (142.68[18a] or 143.2[18b] ppm), C_{70} (130–151 ppm),[12,18a,b] and C_{76} (129–150 ppm).[18c]

The ^{13}C NMR, FTIR, and UV–vis spectra of $C_{60}O$ contain a number of unique features, but also suggest that this new fullerene retains the essential electronic and structural character of C_{60}. The epoxide structure **1**, of C_{2v} symmetry, would derive from oxidation of one of the 30 equivalent C_{60} double bonds.[3,4] Oxidoannulene **2**, analogous to the structure proposed for $C_{70}O$,[4] could arise via isomerization of **1**. Pioneering studies of the parent oxidoannulene and related species by Vogel[19a] suggest that **2** should contain a delocalized annulene moiety[19b] and thus should also embody C_{2v} symmetry.

Both **1** and **2** contain 17 sets of inequivalent carbons: 13 groups of four carbons each and four comprising two carbons each. The relative intensities in the ^{13}C NMR spectrum of $C_{60}O$ follow the predicted pattern. The chemical shift of the two-carbon signal at 90.18 ppm is fully consistent with expectations for the epoxide carbons in **1**.[20] Although a priori the vinyl ether β carbons of **2** might also be expected to resonate near 90 ppm, **2** contains four such carbons rather than two. In contrast, the ^{13}C NMR spectrum of the parent 1,6-oxido[10]annulene comprises three lines between 124 and 131 ppm.[21] Thus, the room temperature NMR data cannot be reconciled with oxidoannulene **2**, but strongly support the isomeric epoxide structure **1**.

Finally, we have demonstrated that $C_{60}O$ is efficiently converted to C_{60} (ca. 91% yield) during chromatography on neutral alumina. The widespread use of alumina for purification of the fullerenes may explain why $C_{60}O$ has not been isolated previously.

Acknowledgment. This work was supported by the National Science Foundation, through Grant DMR 89-01219. Additional support was provided by the National Science Foundation, MRL Program, through Grant DMR-8819885. We also gratefully acknowledge the technical assistance of B. Liang, D. A. Lemp, R. W. Schramm, and L. H. Kaplan of Exxon Research and Engineering and P. Dormer, G. Furst, J. Dykins, and P. Sprengeler at the University of Pennsylvania. In addition, we thank Drs. R. Haddon, C. Foote, and P. Eaton for early communication of preliminary results.

Supplementary Material Available: Detailed procedures for the preparation of $C_{60}O$ and tables of IR and NMR data (2 pages). Ordering information is given on any current masthead page.

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[10] Heating C_{60} to 350 °C in air (10 °C/min) resulted in a 2% weight increase, consistent with the formation of $C_{60}O$. However, the product was insoluble in toluene and $C_{60}O$ was not detected by HPLC analysis. Unpublished results of Dr. Andrew R. McGhie, University of Pennsylvania. See also ref 5.

[11] Vassalo, A. M.; Pang, L. S. K.; Coke-Clarke, P. A.; Wilson, M. A. *J. Am. Chem. Soc.* **1991**, *113*, 7820.

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[13] Thermospray mass spectra were measured by Dr. Robert T. Rosen, Food Sciences Department, Rutgers University, New Brunswick, NJ, using a Vestec 201 LC-MS instrument operated in the negative ion discharge mode with benzene as eluant. The benzene solution was transferred directly into the heated (200 °C) capillary for analysis.

[14] A significant fraction of the C_{60} ion signal likely results from thermal decomposition of $C_{60}O$. Thermal desorption mass spectrometry ($T \geq 300$ °C) of similar $C_{60}O$ samples shows C_{60} (720 amu) signals markedly stronger than those of $C_{60}O$ (736 amu); ca. 2.5 and 100 times larger for TD-FAB-MS and TD-CI-MS, respectively.

[15] Bathochromatic shifts (2–10 nm) and changes in relative absorption in the optical spectra of fullerenes are observed in different aromatic solvents. Unpublished results of K. Creegan.

[16] Thermal decomposition of $C_{60}O$ in air at 175 °C as monitored by IR absorption furnished an as-yet-unidentified product (not C_{60}). Unpublished results of Dr. John Robbins.

[17] (a) ^{13}C chemical shift values (and relative intensities) for $C_{60}O$ in benzene-d_6: 145.47 (3.6), 145.41 (3.6), 145.34 (3.6), 145.20 (1.7), 144.54 (4.1), 144.54 (4.2), 144.16 (8.5),[17b] 143.78 (2.2), 143.27 (4.1), 143.25 (4.1), 142.70 (2.4), 142.56 (4.0), 142.41 (4.0), 141.18 (4.0), 141.00 (3.6), 90.18 ppm (2.0). (b) Resolves into two resonances in CS_2.

[18] (a) Taylor, R.; Hare, J. P.; Abdul-Sada, A. K.; Kroto, H. W. *J. Chem. Soc., Chem. Commun.* **1990**, 1423. (b) Ajie, H.; Alvarez, M. M.; Anz, S. J.; Beck, R. D.; Diederich, F.; Fostiropoulos, K.; Huffman, D. R.; Krätschmer, W.; Rubin, Y.; Schriver, K. E.; Sensharma, D.; Whetten, R. L. *J. Phys. Chem.* **1990**, *94*, 8630. (c) Ettl, R.; Chao, I.; Diederich, F.; Whetten, R. L. *Nature* **1991**, *353*, 149.

[19] (a) Vogel, E.; Bishup, M.; Pretzer, W.; Boll, W. A. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 642. Sondheimer, F.; Shani, A. *J. Am. Chem. Soc.* **1964**, *86*, 3168. For a review on bridged annulenes, see: Vogel, E. *Pure Appl. Chem.* **1982**, *54*, 1015. (b) Baley, N. A.; Mason, R. *J. Chem. Soc., Chem. Commun.* **1967**, 1039.

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[21] The spectrum, measured in $CDCl_3$ containing 0.02 M $Cr(acac)_3$ as relaxant, consists of resonances at 123.60 (4), 128.11 (4), and 131.37 (2) ppm.

Accommodation of Polar Guests in Unimolecular Polyamine–Polyhydroxy Cores: Solubilization of Sugars in Apolar Organic Media via Intramolecular Polar Microsolvation[1]

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Highly polar compounds as guests can be solubilized in apolar organic media upon selective complexation with *rigid* hosts having preorganized binding sites.[3] A three-dimensional encapsulation

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[1] Molecular Recognition. 19. Part 18: Kikuchi, Y.; Kobayashi, K.; Aoyama, Y. *J. Am. Chem. Soc.*, in press.

[2] Present address: Section of Bioorganic Chemistry, Department of BioEngineering, Nagaoka University of Technology, Kamitomioka, Nagaoka, Niigata 940-21, Japan.

[3] For examples of the extraction of amino acids, nucleotides, vitamins, and sugars, see: (a) Tabushi, I.; Imuta, J.; Seko, N.; Kobuke, Y. *J. Am. Chem. Soc.* **1978**, *100*, 6287–6288. (b) Rebek, J., Jr.; Askew, B.; Nemeth, D.; Parris, K. *Ibid.* **1987**, *109*, 2432–2434. (c) Aoyama, Y.; Tanaka, Y.; Toi, H.; Ogoshi, H. *Ibid.* **1988**, *110*, 634–635. (d) Aoyama, Y.; Tanaka, Y.; Sugahara, S. *Ibid.* **1989**, *111*, 5397–5404. (e) Aoyama, Y.; Asakawa, M.; Yamagishi, A.; Toi, H.; Ogoshi, H. *Ibid.* **1990**, *112*, 3145–3151.

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