Polarizabilities Inside Molecular Containers**

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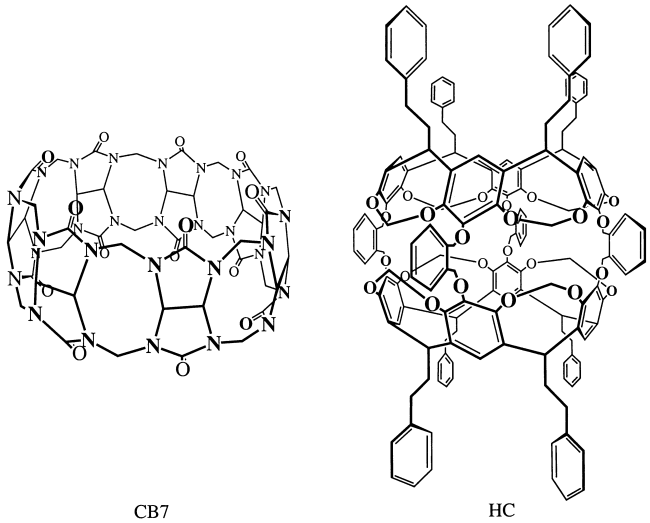
In memory of D. J. Cram

Molecular containers or related supramolecular hosts which are sufficiently large to enclose smaller guest molecules are well known to provide a partial or complete protection of the guest from the outside environment. A striking example is the storage of cyclobutadiene in a hemicarcerand (HC), which prevents bimolecular reactions of otherwise transient species.[1] Cram et al. have further suggested that the inside of a HC can be considered as a new phase of matter.[1, 2] This suggestion implies effects beyond mere spatial confinement and chemical isolation, for example, a marked change in the physical bulk properties, such as the polarity or polarizability, of the host cavity. An indication of such a change was obtained by Pina et al., who observed an unusual shift in the phosphorescence maximum of biacetyl when included in a hemicarcerand.[3] We have now examined 2,3-diazabicyclo-[2.2.2]oct-2-ene (DBO) in its complex with cucurbit[7]uril (CB7) and found an unprecedented effect on the UV absorption and fluorescence properties. We can rationalize these unusual observations, ours for CB7 and those of Pina et al. for HC, and provide evidence that the peculiar spectroscopic behavior of the guest molecules results from an extreme polarizability inside these molecular containers that lies close to the gas phase for CB7 and beyond diiodomethane for HC. This evidence supports the view of a new supramolecular phase of matter.



Addition of DBO to an aqueous solution of the molecular container compound CB7—the synthesis of which has been recently reported[4]—results in the immediate formation of a 1:1 inclusion complex, as evidenced by an additional set of NMR signals. The protons of the guest, which show resonances at $\delta = 1.18$ (*syn*-H), 1.63 (*anti*-H), and 5.08 (bridgehead-H) in D_2O, undergo characteristic[5] up-field shifts by 0.77, 0.79, and 0.40 ppm, respectively, upon complexation. UV spectrophotometric and steady-state fluorescence titrations provide a very large binding constant of $(4 \pm 1) \times 10^5\,\text{M}^{-1}$ for this complex, which indicates that there is essentially a perfect fit of the nearly spherical guest in the rigid hollow cavity of the pumpkin-shaped host. The goodness of fit is corroborated by molecular dynamics calculations, which suggest that not even a water molecule can be co-included together with DBO. The cavity of CB7 is thus completely filled by DBO without leaving a larger "empty" space.

Bulk properties such as polarity and polarizability are commonly studied by means of solvatochromic shifts on electronic spectra, such as, effects on absorption, fluorescence, or phosphorescence.[6, 7] The structural variations among the solvents means that a large data set is usually required to expose the underlying relationships of an experimental parameter with the solvent polarity, polarizability, or both. We have used this sensitive and well-accepted method to further characterize the chemical environment of the CB7 cavity sensed by the immersed DBO chromophore. Our solvatochromic studies[8] in the gas phase and in ten solvents reveal that the absorption and fluorescence maximum, the extinction coefficient ε, and the oscillator strength f (the integrated absorption intensity) all depend on the bulk polarizability P of the solvent (Table 1 and Figure 1a). The bulk polarizability is related to the refractive index n of the solvent by the relationship $P = (n^2 - 1)/(n^2+2)$, such that a relationship with n applies as well. A relationship with the solvent polarity is not observed. The dependence of the oscillator strength on the solvent is most pronounced, since it varies systematically over one order of magnitude. For example, perfluorohexane and water are prototypal nonpolar and polar solvents (dielectric constants of 1.57 and 80.2, respectively, at 293 K) but the experimental oscillator strength is nearly the same, as expected from their similar polarizability. Perfluorohexane and carbon disulfide, however, are both nonpolar, but are known for their very low and high polarizability, respectively. Accordingly, these two solvents claim extreme positions in the solvent series, that is, they produce the weakest and strongest oscillator strengths for this absorption. With respect to hydrocarbon solvents, the difference between *n*-hexane and benzene is also in line with the large polarizability of aromatic solvents. It should be noted that a similar correlation with the polarizability is also recognizable for the other solvatochromic parameters: the absorption and fluorescence maximum, and the extinction

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Table 1. Photophysical properties of DBO in different environments.

Environment	P[a]	Absorption			Fluorescence
		λ_{max} [nm]	ε_{max} [$M^{-1}cm^{-1}$]	$f/10^{-4}$[b]	λ_{max} [nm]
gas phase	0.000	374.3	56[c]	3.10[c]	444
CB7[d]	(0.12)[e]	374.0	40	4.87	440
perfluorohexane	0.159	376.3	105	6.79	442
water	0.206	364.4	53	7.30	431
acetonitrile	0.212	378.0	117	8.96	430
n-hexane	0.229	377.9	177	9.38	438
isopropanol	0.231	374.7	101	9.89	431
dichloromethane	0.255	377.4	126	10.33	432
chloroform	0.267	376.6	129	11.11	432
carbon tetrachloride	0.274	376.6	280	18.81	427
benzene	0.295	378.8	274	15.82	430
carbon disulfide	0.355	382.5	493	32.88	420

[a] At 293 K, $P=(n^2-1)/(n^2+2)$. [b] Oscillator strength of the n,π* transition, $f=4.32\times10^{-9}\int_{300\,nm}^{410\,nm}\varepsilon(\tilde{\nu})\,d\tilde{\nu}$. [c] Recorded at 335 K; the gas-phase concentration was calculated from the ideal gas law using the known pressure–temperature dependence (B. S. Solomon, T. F. Thomas, C. Steel, *J. Am. Chem. Soc.* **1968**, *90*, 2249–2258). [d] The data were recorded under conditions of quantitative (>99.9%) complexation (0.5 mM DBO and 4.0 mM CB7). We found that CB7, unlike CB6, is sufficiently water-soluble even in the absence of electrolytes. [e] Interpolated value, see text.

coefficient (Table 1). However, hydrogen-bonding solvents are known to cause an additional hypsochromic shift and band broadening of n,π* transitions,[6, 7] which results in the values for water and isopropanol being apparently too low. Effects arising from band broadening and spectral shift are corrected for when calculating the oscillator strength.

The above solvatochromic effects render DBO an excellent molecular probe for the polarizability of the chemical environment. Strikingly, the oscillator strength of DBO is much lower in the supramolecular complex, that is, inside the CB7 cavity, than in any solvent; for example, the oscillator strength in water is 50% larger than that in CB7. This observation provides spectroscopic evidence that the environment sensed by DBO inside CB7 is characterized by a polarizability even lower than for perfluorohexane. Such an effect of a host on the absorption properties of a guest has not previously been reported. The photophysical properties of DBO inside CB7 are in fact closer to those in the gas phase than to those in solution.

We find a good linear correlation between the inverse of the oscillator strength for DBO and the polarizability ($1/f=3020-8320P$, $r=0.979$, $n=11$, Figure 1a).[9, 10] By employing this equation, we can interpolate a very low polarizability for the CB7 cavity (0.12). A low polarizability of the CB7 cavity is not unexpected. High polarizability of molecules corresponds to high electron density and the ease of moving electrons within the same molecule. These features are facilitated by the presence of heavy atoms, nonpolar σ and in particular π bonds, and easily ionizable lone pairs of electrons. Therefore, iodo and phenyl groups and to some degree also C–H bonds, but much less O–H or C–F bonds, promote a high polarizability of solvents. The CB7 cavity contains only strongly polar bonds, no easily ionizable electron pairs, and no C–H bonds pointing inside.[5] This arrangement is in line with the exceptionally low polarizability detected by the probe.

The opposite is true for hemicarcerands (HCs), and also fullerenes, which possess electron-rich π systems with high electron density inside the cavity. A high polarizability is expected for these types of supramolecular hosts. Motivated by the findings for the CB7 cavity, we have also examined the absorption and phosphorescence characteristics of biacetyl in the gas phase and in 11 solvents[8] and compared it to the known photophysical data for its HC complex.[3] A correlation between the oscillator strength of absorption, as well as the absorption and phosphorescence maximum and the bulk polarizability, also results for biacetyl (Table 2 and Figure 1b). The very weakly polarizable perfluorohexane and the highly polarizable diiodomethane (which could not be assessed for DBO because of its strong UV absorption) result in the lowest and highest solution values for biacetyl.

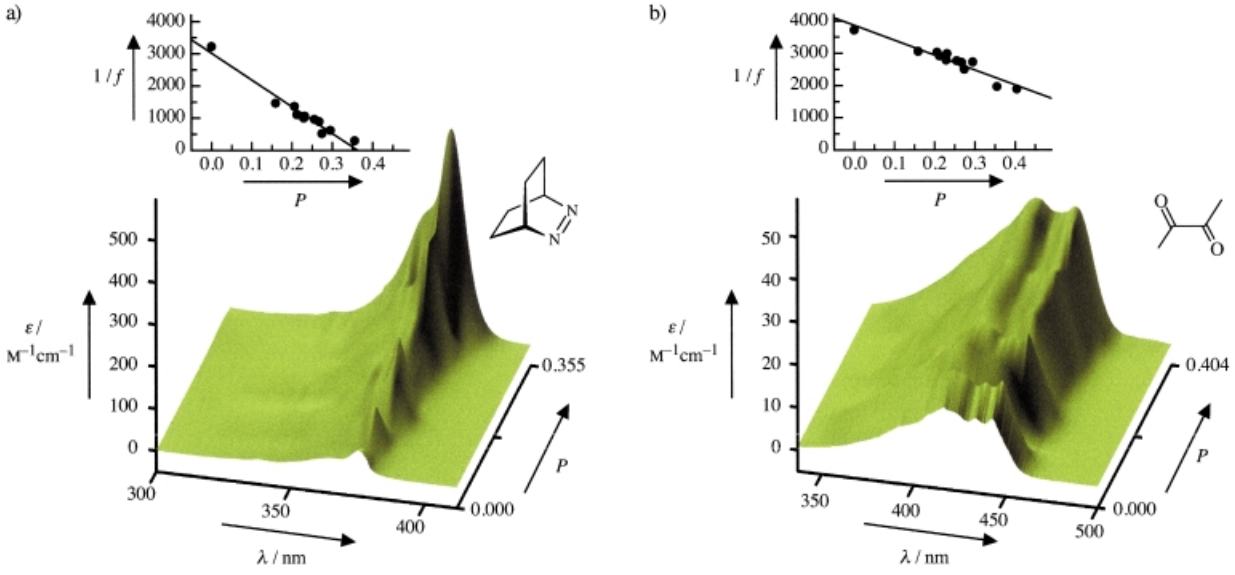

Figure 1. Contour plots of the combined absorption spectra of DBO (a) and biacetyl (b) as a function of the solvent polarizability *P*. Shown on the top are the resulting correlations of the inverse oscillator strength $1/f$, that is, the integrated absorption intensity versus bulk polarizability.

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Table 2. Photophysical properties of biacetyl in different environments.

Environment	P[a]	Absorption			Phosphorescence
		λ_{max} [nm]	ε_{max} [$M^{-1}cm^{-1}$]	$f/10^{-4}$[b]	λ_{max} [nm]
gas phase	0.000	416.6	16.6[c]	2.69[c]	512
perfluorohexane	0.159	418.5	20.1	3.27	514[d]
water	0.206	406.4	17.6[e]	3.30[e]	512
acetonitrile	0.212	415.9	19.8	3.43	515
n-hexane	0.229	421.2	21.9	3.59	519
isopropanol	0.231	419.9	19.2	3.35	518
dichloromethane	0.255	419.8	22.2	3.62	518
chloroform	0.267	420.8	22.2	3.68	519
carbon tetrachloride	0.274	422.6	24.7	4.00	520
benzene	0.295	422.1	22.5	3.67	521
carbon disulfide	0.355	425.7	29.4	5.09	523
diiodomethane	0.404	426.9	30.5	5.30	523
HC	(0.45)[f]	429[g]	–[h]	–[h]	533[g]

[a] At 293 K, $P=(n^2-1)/(n^2+2)$. [b] Oscillator strength of the transition in the visible region, $f=4.32\times10^{-9}\int_{340\,nm}^{500\,nm}\varepsilon(\tilde{\nu})\,d\tilde{\nu}$. [c] The gas-phase concentration was calculated from the ideal gas law using the known pressure–temperature dependence (W. C. Neely, T. D. Hall, *J. Chem. Eng. Data* **1972**, *17*, 294–295). [d] Phosphorescence sensitized by benzophenone. [e] Corrected for the amount of inactive biacetyl hydrate (68%) (H.-J. Buschmann, H.-H. Füldner, W. Knoche, *Ber. Bunsenges. Phys. Chem.* **1980**, *84*, 41–44). [f] Extrapolated value, see text. [g] From ref. [3], in dichloromethane. [h] The accurate intensity of the biacetyl absorption in HC is difficult to determine because of overlap with the host absorption bands and possible impurities (Z. S. Romanova, Ph.D. thesis, Bowling Green State University, USA, **1999**).

A peculiar behavior of biacetyl when included in HC was observed in the previous study[3] and a relationship between the phosphorescence properties and the polarity of the environment was implied in terms of a correlation with the dielectric constant. However, Table 2 reveals that a relationship with polarity does not apply, but rather a relationship with polarizability exists. The gas-phase photophysical properties (Table 2) are also no longer surprising[3] if one employs the polarizability, and not the polarity, for correlation. Since the solvatochromic effects of biacetyl inside HC exceed those in the most polarizable solvents, the conclusion can be drawn that biacetyl inside the HC cavity senses a polarizability even higher than for diiodomethane. Again, linear correlations for the oscillator strength ($1/f=3870-4630\,P$, $r=0.955$, $n=12$, Figure 1b) and for the absorption maximum ($\lambda_{max}=410.3+41.35\,P$, $r=0.918$, $n=11$, excluding the water value) apply, from which a very high polarizability of 0.45 inside the HC cavity can be extrapolated.

In conclusion, the present study establishes DBO and biacetyl as solvatochromic probes for the polarizability of the environment.[10] Evidence was obtained that molecules included in the cavities of molecular containers may experience unusually high or low polarizabilities, depending on the host system. CB7 has a very low polarizability inside its cavity, while HC has a very high one. These results are in agreement with the chemical structures and geometric peculiarities of these hosts.[11] The hypothesis[1, 2] that these cavities may behave like a new phase of matter is therefore confirmed through unexpected, extreme polarizabilities. The question as to what degree such uncommon polarizabilities could be exploited in the context of supramolecular functionality to influence photochemical or thermal chemical reactivity may now be raised. It should be noted that polarizability is considered an important factor in determining the binding strength of host–guest complexes.[12] Moreover, it has been proposed that the polarizability of a host assists supramolecular biomimetic catalysis.[13] This means that the polarizability of a host may become an important supramolecular design criterion, which sheds new light on our findings. Pronounced changes in the so-called "microenvironment" inside supramolecular assemblies are frequently postulated.[14–16] While the polarity of such environments has already been studied in some cases through established probes,[17] their polarizability may be equally important and can now be assessed with the presently introduced solvatochromic probes.

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[8] The solvents and biacetyl used were the highest purity grade (Fluka or Aldrich). Some were purified immediately before use by filtration over aluminum oxide (diiodomethane) or recondensation in vacuum (carbon disulfide). 3 mL of a particular solution were obtained by weighing DBO (490 mg, 1.49 mM) in an aluminum boat or addition of liquid biacetyl (3.00 μL, 11.4 mM) by using a previously calibrated Hamilton GC syringe. Three repeated measurements, measurements at double the concentration, and the use of freshly recondensed biacetyl yielded the same results for ε und f values within an error of 3%. A 1-cm cuvette was used for measurements, except for DBO in the gas phase (10-cm cell). Emission spectra were recorded with a FLS 900 fluorimeter (Edinburgh Analytical Instruments), and UV spectra with a Perkin–Elmer Lambda 19 spectrophotometer (0.1-nm resolution). Samples were degassed by freeze-pump-thaw cycles for the luminescence and gas-phase measurements. Spectra were taken at 22 °C.

[9] An increase in the oscillator strength with solvent polarizability was also found for the forbidden electronic transition of singlet oxygen, see M. Hild, R. Schmidt, *J. Phys. Chem. A* **1999**, *103*, 6091–6096.

[10] We see the origin of this peculiar solvatochromic dependence of the oscillator strength of DBO and biacetyl in a combination of two factors: the forbidden nature of the n,π* electronic transition and the small concomitant decrease in dipole moment upon excitation. According to cases A–D of the theory by Liptay (W. Liptay, *Z. Naturforsch. A* **1966**, *21*, 1605–1618) one expects an increase in the oscillator strength with an increase in refractive index (polarizability) in particular for chromophores with a small dipole moment (case A). This does not apply for DBO (dipole moment 3.5 Debye) and biacetyl (about 1.0 Debye). Furthermore, according to Liptay, a dependence on the dielectric constant dominates for forbidden transitions (case B), which is not observed for DBO and biacetyl. A comprehensive theoretical explanation for the observed solvatochromism is therefore not available at present.

[11] The phenomenon of extreme polarizabilities is not general for all host molecules, but depends on their specific structure. For example, the solvatochromic shifts of DBO in cyclodextrins fall in between those of water and alcohols, which indicates there is a similar polarizability inside the cyclodextrin cavity as in a 2:1 methanol:water mixture. In our previous study (W. M. Nau, X. Zhang, *J. Am. Chem. Soc.* **1999**,

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The Highly Flexible Bis(hydroxylamine) Ligand $[ON(Me)]_2CH_2^{2-}$ and Its Different Behavior in the Chemistry of Aluminum and Gallium**

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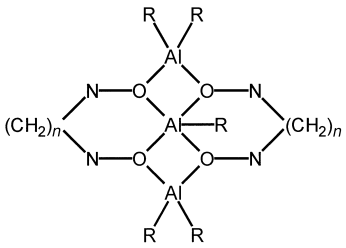
The coordinative flexibility of diolate substituents could be markedly improved if they contained additional donor atoms, preferably in close proximity to the primary donor sites. Such systems are accessible as anions of OH functional bis(hydroxylamines), that is as diolates that contain additional N-heteroatoms in geminal position relative to the metal to be bound. Such diolate ligands with improved flexibility should offer a diverse range of applications, because diolates and other difunctional ligands, in particular those of the salen type, are currently employed in a number of investigations in organoaluminum chemistry.[1] Interest in this area is directed towards the preparation of bimetallic complexes[2] and aluminum cations, which are exceedingly strong Lewis acids and capable of catalyzing reactions such as oxirane oligomerization,[3] where other Lewis acids fail to work. Fundamental investigations have recently produced a number of trinuclear aluminum diolate complexes of the type shown in Scheme 1.[4]

Herein we present the chemistry of the so far neglected tetrafunctional ligand system $[ON(Me)]_2CH_2^{2-}$ with organoaluminum and -gallium compounds. Until now this ligand has only been applied in the coordination chemistry of the nonmetal boron,[5] but not a single metal complex is known. $[HON(Me)]_2CH_2$ is available in high yields using a condensation reaction of *N*-methylhydroxylamine hydrochloride and formaldehyde mediated by potassium carbonate.[6]



Scheme 1. Typical structure of trinuclear diolate complexes of aluminum (and analogously gallium) as obtained from the reaction of AlR_3 with diols. R = alkyl, halogen, H.

The bis(hydroxylamine) $[HON(Me)]_2CH_2$ can be deprotonated with *n*-butyllithium in nonpolar solvents. The resulting suspensions of $[LiON(Me)]_2CH_2$ react with dimethylaluminum and dimethylgallium chloride to afford the heteronorbornane systems $[Me_2MON(Me)]_2CH_2$ (M = Al (**1**), Ga (**2**)); hereby four chemical bonds, including two dative ones, are formed in an one-step reaction. This reaction is completely selective for **2**, but if dimethylaluminum chloride is employed, both products **1** and **3** (see Scheme 2) are possible; subtle changes in conditions switch the selectivity completely to one or the other product. In several runs of this reaction we obtained **3** more often than **1**, but to date we have not been able to establish the conditions under which the selectivity is reliably predictable.

The heteronorbornane systems **1** and **2** parallel our recent findings using the isoelectronic ligand system $[^-CH_2N(Me)]_2CH_2$, which also leads to the heteronorbornane cages $[Me_2MCH_2N(Me)]_2CH_2$.[7] The only organoaluminum hydroxylamide compound published to date is the trimeric $[Me_2AlONMe_2]_3$ compound; its interesting intramolecular Al···N contacts lead to the coordination numbers 4, 5, and 6 in the same molecule.[8]

In an attempt to find a simpler synthetic route to the compounds $[Me_2MON(Me)]_2CH_2$ we treated the OH-functional bis(hydroxylamine) $[HON(Me)]_2CH_2$ with trimethylaluminum and -gallium. In the case of trimethylgallium, the product of this reaction was identical to **2**. This is in contrast to the reaction products of $GaMe_3$ with diols, which are usually analogous to the trinuclear aluminum compounds shown in Scheme 1.[2] It is clearly the presence of the nitrogen atoms in geminal position to the gallium atom, which induce this different reaction mode. The reaction with trimethylaluminum afforded colorless crystals of **3a**, which contains four- and five-coordinate aluminum atoms (Scheme 2) as indicated by the two resonance signals in the ^{27}Al NMR spectrum. Crystal structure analyses revealed the two different reaction modes with these earth metal organyl compounds. Both reactions are not sensitive to the stoichiometric ratio of the reagents. Compound **2** is formed even under a stoichiometry of $[HON(Me)]_2CH_2$:$GaMe_3$ of 2:3, while **3** results also from $[HON(Me)]_2CH_2$:$AlMe_3$ mixtures in the ratio 1:2.

The gallium heteronorbornane **2** is aggregated into endless chains in the crystal lattice (Figure 1) through the formation of four-membered Ga_2O_2 rings resulting from two Ga···O contacts (2.332(4) and 2.348(4) Å), which are substantially longer than the Ga–O bond in the norbornane skeleton (1.928(4) Å). The Ga–N distances are 2.256(5) and 2.257(5) Å

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