

CYCLODEXTRIN COMPLEXATION AS A PROBE OF MOLECULAR PHOTOPHYSICS

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Abstract - Three examples are described in which complexation of organic guests by a cyclodextrin (CD) alters the photophysical paths for excited state decay of the host-guest complex. The fluorescence properties of the complexes between β - and γ -CD and the bichromophoric molecule 1,1'-bis-(α -naphthylmethyl)dithiane are presented to illustrate how complexation alters the dynamics of conformational interconversion. The complexation of β -naphthol by β -CD is shown by time-correlated emission spectroscopy to prevent the adiabatic deprotonation of the excited alcohol normally observed in aqueous solution. Lastly, solid complexes of CD's and aromatic donor-acceptor molecules such as *p*-nitroaniline (PNA) are shown to be active for generation of second harmonic radiation (SHG) when irradiated by 1.06 μ light from a Nd-YAG laser. Since PNA itself crystallizes in a centrosymmetric space group incapable of producing SHG, the complexation method effectively induces SHG activity in this polarizable, but nonpolar material.

INTRODUCTION

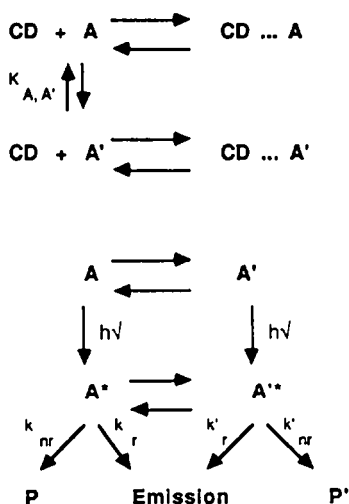
Complexation of a substrate by a host can markedly influence the chemistry of the guest. The effects of complexation are important in biological and catalytic processes, among others, in ground state chemistry. Our work concentrates on delineating the effects manifested in excited state processes by complexation. In this paper we describe three effects ascribable to complexation of organic chromophores by cyclodextrins [CD's]. (1.) Complexation which influences the relative population of ground state conformers available for excitation. (2.) Complexation which directly effects excited state radiationless decay processes. (3.) The effect of complexation on solid state optical nonlinearity of polar materials.

COMPLEXATION AND MULTIPLE CHROMOPHORE INTERACTIONS

The general situation is illustrated in Scheme I, in which a cyclodextrin, (CD) is considered in equilibrium with a potential guest, A, and its conformational

isomer **A'**. The conformers **A** and **A'** are assumed to be in rapid equilibrium. Two complexation equilibria are possible, that between **CD** and **A**, and that with **A'**. Each will have a characteristic binding constant. If the conformers **A** and **A'** exhibit photochemical (or photophysical) properties that are different, then complexation by **CD** could in principle be expected to favor one process over another (compared to the relative proclivities of the uncomplexed substrate). Two possible explanations for altered reactivity can be envisioned. In one, complexation could modify the equilibrium constant ($K_{A,A'}$) between the conformers, so that excitation of one conformer was preferred. Alternatively, complexation could influence in a more fundamental way the radiative (k_r) or nonradiative (k_{nr}) rate constants for decay of the excited state **A*** (or for **A****). We present a clear cut example in which it can be shown that the effect of complexation is to preselect one conformational isomer over others.

Scheme I



The photochemistry of the multiple chromophoric molecule 1,1'-bis-(α -naphthylmethyl)dithiane, **1**, and related molecules has been described by Arad-Yellin.¹ This compound is typical of many 1,3-dinaphthylpropane derivatives² which exhibit dual emission behavior. Excitation of solutions of such compounds gives fluorescence at short wavelength, near 320 nm, from the naphthyl-localized aromatic chromophore, but often also produces a broad, structureless emission at longer wavelengths (near 400 nm). Considerable evidence indicates that this emission originates from an excimer state populated by geometrical reorganization of the predominant ground state conformer, the extended conformer, through bond rotation to give a face-to-face conformer in which the two aromatic chromophores can interact. Such emission was observed for **1**, Figure 1.¹ Additionally, compound **1** and its derivatives produce new materials as a result of photoexcitation. The photoproducts of **1** result from C-S bond

cleavage. Mechanistic studies support the pathway proposed in Scheme II for this process. Interaction of a naphthyl-localized singlet state with the electron-rich sulfur center occurs with (partial) charge transfer. This weakens the C-S bond of the dithiane ring and allows cleavage. Electron demotion gives a diradical which is the common intermediate to the olefinic and ketonic products shown in the scheme. Evidence for the naphthyl-sulfur interaction comes from fluorescence studies. Table I lists photophysical data obtained for **1** and for the prototype 1,3-bis-(α -naphthyl)propane, and the mono-naphthyl model compound 1-(α -naphthylmethyl)dithiane, as well as the "parent" chromophore 1-methylnaphthalene. The data support the concept that the photochemistry and photophysics of **1** are profoundly influenced by the conformational relationships that can be attained between the various chromophores in the system.

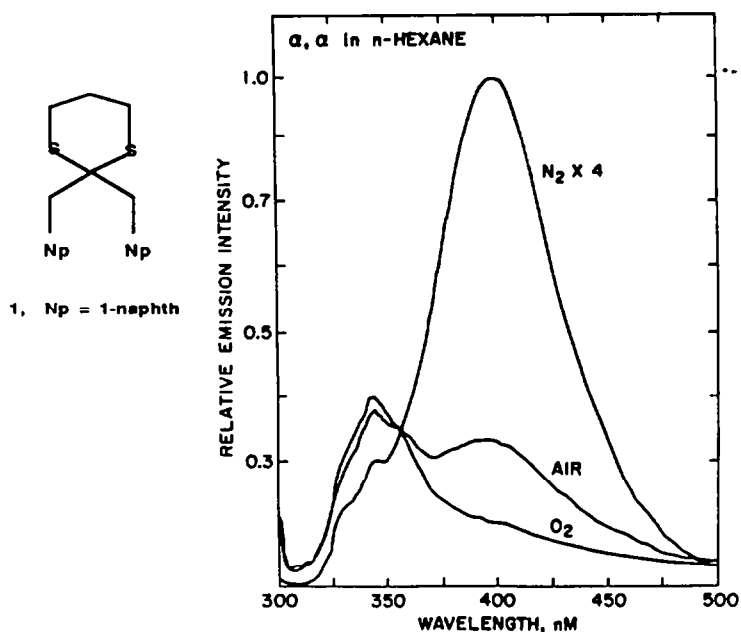


Fig. 1. Fluorescence spectra of **1** in *n*-hexane, degassed (top) or in the presence of air (middle) or oxygen (bottom). $[1] = 3 \times 10^{-5}$ M, excitation 280 nm.

We have found that complexation of **1** with β - and γ -CD significantly changes the photophysics and photochemistry observed.³ Pure, crystalline inclusion complexes of **1** and CD's can be isolated by mixing aqueous solutions of the CD with ethereal solutions of **1** and allowing the organic solvent to slowly evaporate. X-ray powder spectra, elemental analysis, NMR (¹H and ¹³C) and IR spectroscopy all indicate that new materials, not mixtures, are formed. Analysis shows the stoichiometry to be approximately 1:1.

Scheme II

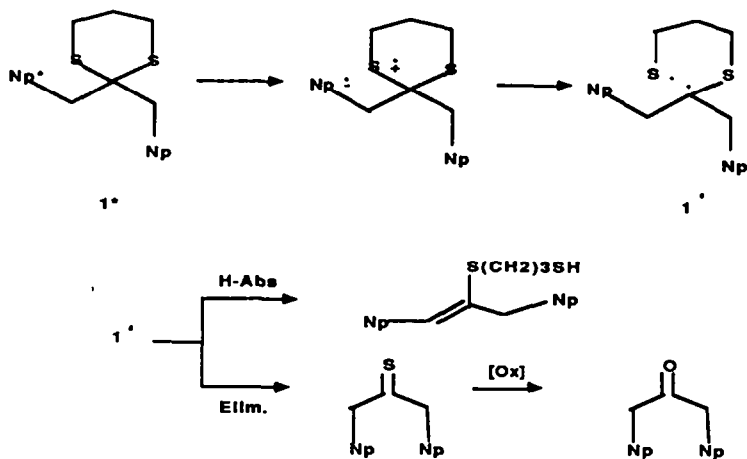


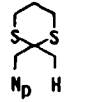
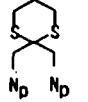


Table I. Photophysical Data for Compounds 1, 2 and Reference Materials.

				
ϕ_{Np}^f	0.21	(0.022)*	0.023	0.022
τ_{Np}^f	76.6 ns	8 ns	5.1 ns	3.75 ns
ϕ_{ex}^f	--	(~0.02)*	--	0.039
τ_{ex}^f	--	32 ns	--	69.8 ns
$k_{M \rightarrow Ex}$	--	$1.2 \times 10^8 \text{ sec}^{-1}$	--	$3 \times 10^8 \text{ sec}^{-1}$
ϕ_p (77K)	0.023	--	0.20	0.27
τ_p	2.1 sec	--	0.6 sec	0.5 sec
* ESTIMATED FROM $\tau_f = \tau_f^0 \phi_f$ AND I_{EX}/I_M DATA				

1-- γ -CD Complex

The fluorescence spectrum observed for the 1-- γ -CD complex is shown in Figure 2. Comparison of this spectrum to that shown in Figure 1 for 1 in hexane solution immediately shows that no short wavelength, naphthyl-localized emission is observed for 1-- γ -CD. Only long wavelength emission, characteristic of the excimer emission is noted. Further, the behavior of the emission of 1-- γ -CD in the presence of various levels of oxygen is dramatically different than that of 1 itself. The emission of

the parent compound **1** is quenched by the addition of air or oxygen (Figure 1). That of **1- γ -CD** is nearly unaffected by air or oxygen. This behavior strongly suggests that the compound **1** is included within the CD in a manner that places both naphthalene rings within the torus in a face to face orientation:

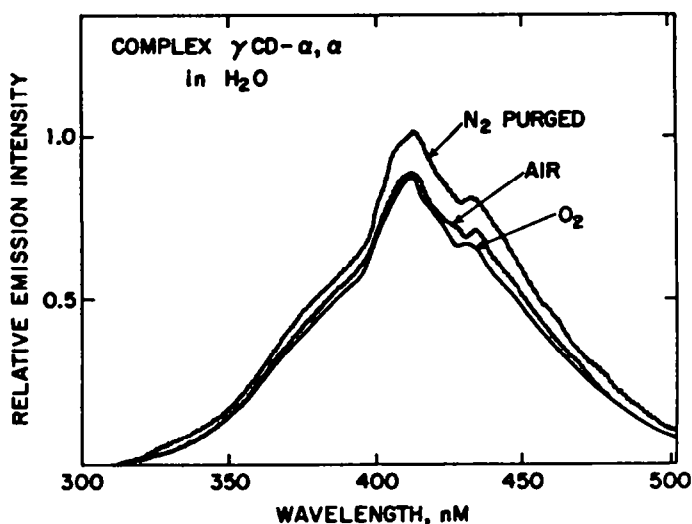
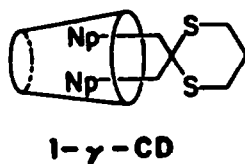


Figure 2. Fluorescence spectrum of **1- γ -CD** ($\sim 10^{-5}$ M), under nitrogen (top), air (middle) or oxygen.

Several other pieces of evidence support this picture.³ First, the emission lifetime of the **1- γ -CD** emission is 50-70 ns, near that of the excimer lifetime of **1** itself (Table I). Second, the emission of complex **1- γ -CD** is prompt. That is, unlike uncomplexed **1** whose excimer emission at long wavelength appears, in a time-correlated experiment, only after the initial extended conformer has time to rotate into the folded conformation that favors excimer formation, the emission of **1- γ -CD** appears immediately (during) the excitation. There is no kinetic delay associated with excimer formation. Third, the complex exhibits an induced circular dichroism spectrum. A split exciton band is observed near 227 nm. Such a feature is only to be expected from the symmetrical face to face orientation of naphthyl groups.⁴ Finally, the complex **1- γ -CD** is photochemically stable. This is consistent, within the mechanistic picture of Scheme II, with the inability of **1- γ -CD** to attain the correct conformation that favors naphthyl-sulfur charge transfer. Within its lifetime, **1- γ -CD** is held in the face-to-face geometry. No rotation is allowed without exiting the CD torus. That process is disfavored by the hydrophobicity of **1** itself.

All the observations cited above compel the view that the 1- γ -CD complex is tightly held, within the CD ring, in the u-conformation in which naphthalene rings are in proximity. The diameter of the γ -CD interior, roughly 9 Å, is large enough to accommodate two naphthalene rings, whose thickness is about 3 Å, if they are held about 3 Å apart. This is almost the ideal distance of separation for an excimer pair. Turro has shown a similar ability of γ -CD to accommodate a simple 1,3-dinaphthylpropane,⁵ and two pyrene molecules have been included in cyclodextrins by several groups.⁶ A smaller cyclodextrin cavity would not be anticipated to form such a complex with 1. We have confirmed this to be the case for 1 and β -CD.

1- β -CD Complex

This complex exhibits emission only at short wavelength. No longer wavelength emission characteristic of an excimer is observed. Figure 3 compares the emission for 1, 1- β -CD, 1- γ -CD and the model compound 2. The time-correlated emission lifetime of 1- β -CD is two component. Degassed solutions of 1- β -CD show a long (53 ns) and a short (4.4 ns) lifetime in about equal proportions. In the presence of air the longer lifetime is diminished only slightly (to 46 ns) while the shorter lifetime is reduced to 2.6 ns. In comparison, the lifetime of the β -CD complex of 1-methylnaphthalene is 39 ns (degassed) and 31 ns in the presence of air. Model compound 2 has a lifetime of 20 ns (in air) when complexed to β -CD. The complex of 1 with beta CD is photochemically active. We conclude from these observations that there are two distinct naphthalene chromophores in 1- β -CD: one is inside the CD cavity and one is outside:

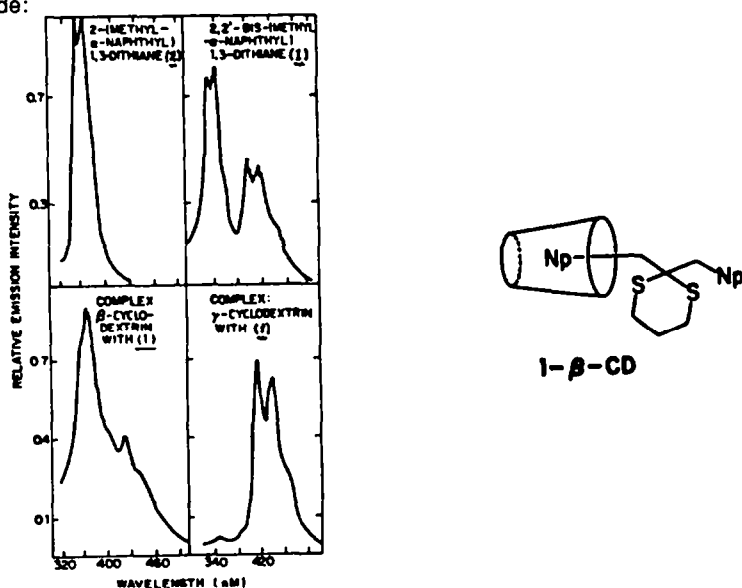


Figure 3. Emission spectra of the β - and γ -CD complexes of 1 compared to the emission of 1 and 2 in hexane. The apparent vibrational structure in 1- γ -CD is due to the presence of crystallites.

The "outside" chromophore is accessible to quenching by oxygen, so it must be the one with the shorter lifetime. The "inside" chromophore is protected from quenching by the kinetic barrier of the CD torus, and so its long lifetime is essentially unaffected by the addition of air. That the shorter lifetime is associated with the "outside" chromophore is also consistent with it being free to come into proximity to the sulfur atom, which presumably shortens its lifetime through CT interactions and contributes to the photoactivity of the complex 1- β -CD.

The remarkable effect of the complexation of beta CD with 1 is that it differentiates the formally degenerate naphthyl chromophores of 1. They now act independently of one another and presumably do not communicate electronically. We are currently seeking information on these points.

We conclude from the work just reported that complexation of CD's with multiple chromophoric species such as 1 can markedly influence the molecular conformation that is "chosen" for study. By carefully matching the CD cavity diameter to the space-filling volume of a conformer, one effects near perfect selection of a high energy, folded, u-shaped conformer, in the case of 1- γ -CD, over the more stable sickle-shaped conformer normally present in solutions of 1. Similarly, the use of β -CD selects the extended conformers for inclusion, but enables one to differentiate the included from the excluded chromophore by physical techniques. We expect that these new tools will expand the ability of the photochemist to dissect complex photochemical pathways.

COMPLEXATION AND ADIABATIC PHOTOCHEMISTRY OF β -NAPHTHOL

In the example to be discussed next we report that complexation of the aromatic alcohol β -naphthol by β -cyclodextrin alters the radiationless decay pathways available to the excited naphthol.

The dual emission of β -naphthol is a prototype for species which undergo adiabatic prototropy on excitation in aqueous solutions of appropriate pH. Weller^{7, 8} observed that β -naphthol is a stronger acid in its excited singlet state than it is in its ground state, and that the loss of proton from singlet excited naphthol produced the excited state of the naphtholate. These observations form the basis for extensive use of materials such as the naphthols to study the process of loss of electronic energy during

proton transfer. Such studies can provide valuable information about the radiationless processes that occur in hydrogen bonded complexes.

Excited β -naphthol has been extensively studied by steady state and time-correlated emission techniques. Effects of solvent,⁹ pH,^{10, 11} temperature¹² and other environmental additives, such as micellar hosts¹³ or crown ether complexes¹⁴ of added bases, have been examined by others. In fact it has become common to use naphthol emission as a "pH probe" in order to determine the microenvironment encountered by the probe in a sample of unknown basicity.

We wished to examine the influence of cyclodextrin complexation on the process of proton loss in excited naphthol. Earlier work by Yorozu and coworkers¹⁵ reported the steady state emission of complexes of cyclodextrins and β -naphthol. Our work extends and complements the Yorozu work, and provides a more detailed view of the complexation process and its influence on the photochemistry of β -naphthol in the inclusion environment by directly addressing the dynamics of the process.

Yorozu¹⁵ reported that the β -naphthol/ β -CD complex is characterized by a dissociation constant at pH 6.2 of 0.0016 M. A large, positive, induced circular dichroism band was observed between 210 and 250 nm in the complex, and negative bands were seen at longer wavelengths (near 270 and 330 nm). Emission quantum yields for the protonated complex were found to be 1.4 times greater than the emission yield for the uncomplexed naphthol,¹⁵ while the unprotonated species was judged to have unchanged emission yield as a consequence of complexation. The emission lifetime of β -naphthol/ β -CD was stated to be 6.5 ns compared to 4.6 ns for the uncomplexed, protonated alcohol, in aerated solutions at pH 6.2.

A more rigorous treatment of the two-state decay of β -naphthol, such as that provided in the present work, is required to adequately analyze the complexation process, but the preliminary analysis by Yorozu and coworkers is basically correct. They concluded that the rate of deprotonation of β -naphthol is significantly slowed within the CD cavity, and that the hydroxyl group is located within the cavity where it is unable to interact with the aqueous environment.¹⁵

We determined the dissociation constant for the equilibrium of β -CD and β -naphthol by the fluorescence enhancement method.¹⁶ The dissociation constant at 23°C and pH 7.1 was found to be 0.009 M, a value only somewhat smaller than that found by Yorozu at a more acid pH. The deprotonated form does not bind to β -CD. Figure 4 illustrates the changes observed in the fluorescence spectra of β -naphthol at

pH 7.1 as β -CD is added, and the reciprocal plot of change in fluorescence intensity (ΔF) versus increasing $[\text{CD}]$ is shown in Figure 5.

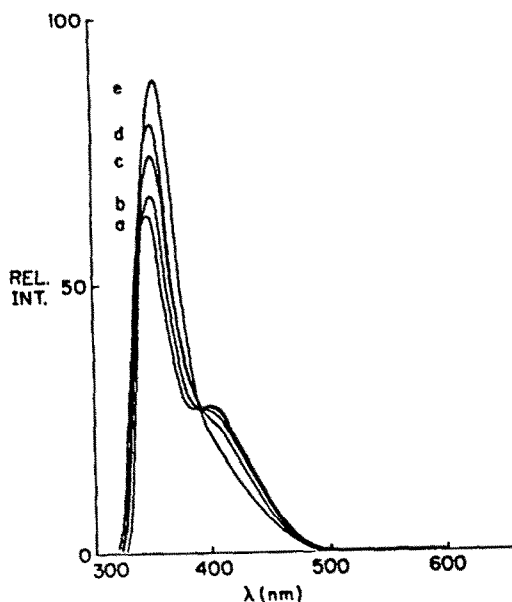


Figure 4. Emission spectrum of β -naphthol in the presence of added β -CD. In water, $[\beta\text{-NpOH}] = 5 \times 10^{-5} \text{ M}$; curve a, $[\text{CD}] = 0$; b, 0.0004 M; c, 0.001 M; d, 0.002 M; e, 0.004 M.

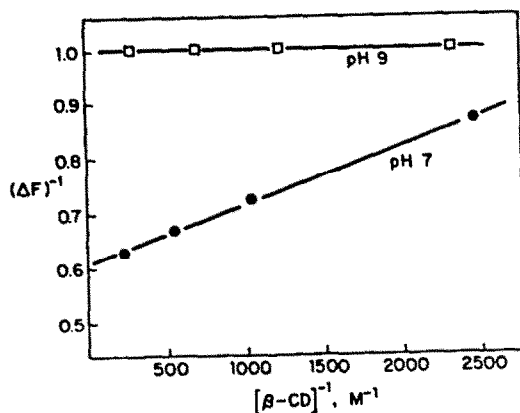


Figure 5. Double reciprocal plot of fluorescence intensity enhancement observed for β -NpOH on addition of β -CD. See Fig. 4 for concentrations.

We infer from Figures 4 and 5 that the anionic naphtholate does not bind. This contrasts with the view of Yorozu and will be discussed later.

We have examined the emission decay of the system β -naphthol/ β -CD using single photon counting techniques.¹⁷ Full solution of the time dependent kinetics of the evolution of the various excited states of the β -naphthol/ β -naphtholate pair has been treated by other authors. Under conditions in which initial light absorption is restricted to one component, a simple biexponential decay is anticipated for the emission associated with the protonated naphthol (if the excited state protonation/deprotonation is reversible). A rise and fall (sum and difference of exponentials) is expected for the emission of the naphtholate anion. For a more detailed discussion of the naphthol system, see Laws and Brand¹¹ and Lakowicz.¹⁸ The more general case of multiexponential decay kinetics is described by Zachariasse¹⁹ for intramolecular examples.

Figure 6a shows representative decay data for β -naphthol at pH 7.2, at a concentration of $5 \times 10^{-5} \text{ M}$, for excitation at 280 nm and observation of emission at 340

nm. Under these conditions, no naphtholate is present in the ground state before excitation, and at the pH examined, the deprotonation is irreversible. Therefore a single exponential decay is noted (Table II). Figure 6a also shows similar data for the same sample, with the emission observed at 420 nm, a region in which the naphtholate anion emits. A biexponential, rise and fall behavior is observed (Table II). The data are entirely consistent with observations of others.¹¹ Under these conditions a rate constant for the deprotonation of excited β -naphthol can be calculated¹¹ to be $7 \times 10^7 \text{ s}^{-1}$.

Table II. Emission Decay Parameters for β -NpOH and β -NpOH-- β -CD Complex^{a,b,c}

λ_{em}	I_1	A_1	I_2	A_2	I_3	A_3	χ^2	D-W
β-NpOH								
320 nm	4.83	0.0964	--	--	--	--	1.51	1.29
420 nm	4.81	-0.129	9.11	0.162	--	--	1.15	1.79
β-NpOH--β-CD								
320 nm	4.36	0.0285	--	--	7.17	0.0561	1.27	2.20
420 nm	4.26	-0.072	10.11	0.094	6.21	0.0108	1.09	2.19

(a) Excitation 280 nm; $[\beta\text{-NpOH}] = 5 \times 10^{-5} \text{ M}$ in water (degassed by purging with nitrogen).

(b) $[\beta\text{-CD}] = 0.02 \text{ M}$.

(c) Lifetimes (τ) in ns, obtained from single photon counting data. D-W is the Durbin-Watson criterion. In addition, all fits exhibited random residual and autocorrelation plots.

In the presence of added β -CD (0.02 M), the observed emission decays are different (Figure 6b and Table II). In the naphthol region (320 nm; Fig. 6b), a single exponential fit is no longer appropriate. The data are best fit by a two-component decay, one of which is identical to that observed in the absence of the cyclodextrin (4.3 ns), and a new decay, 7.2 ns, with greater amplitude. For the emission region at longer wavelength (420 nm, Fig. 6b), a three-exponential decay is found to best fit the data. One pair of decay constants is identical to those found in the absence of the cyclodextrin, and the other, at low amplitude is the near that calculated for the short wavelength emission decay, 6.2 ns. We conclude that under the conditions of the experiment, we are sampling a small amount of emission from uncomplexed naphthol, and a major component, with single exponential decay, emitting at short wavelength, but not substantially at long wavelength. These data imply that the β -naphthol/ β -CD complex does not deprotonate nearly as efficiently as the free naphthol. This is as concluded by Yorozu,¹⁵ but we favor a different interpretation than that group of the significance of the result, and do not agree with the method they use to arrive at their conclusion.

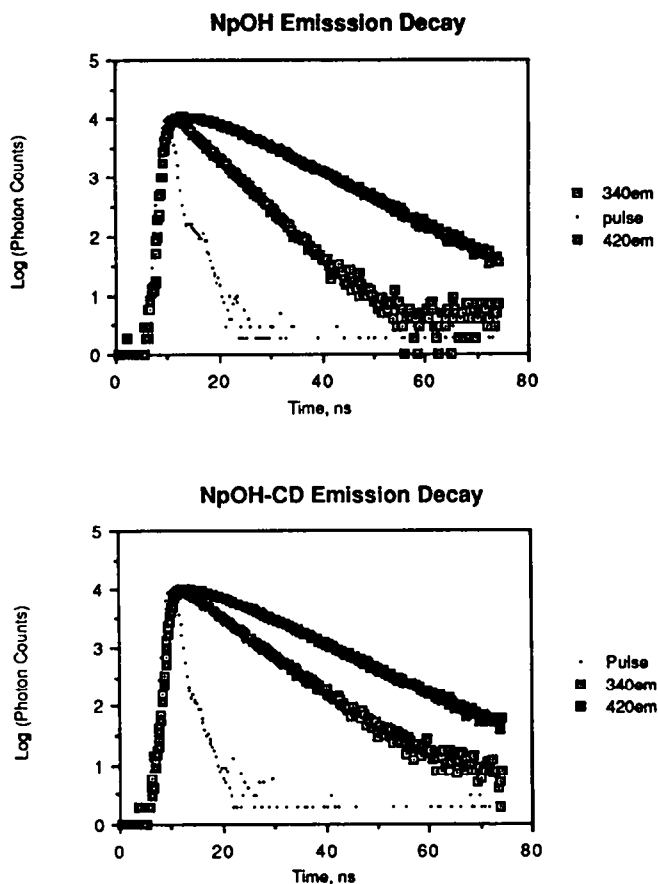


Figure 6 : (a) emission decay of β -NpOH (5×10^{-5} M) in H_2O , excitation 300 nm, observed at 340 nm and 420 nm (top panel); (b) emission decay of β -NpOH as in (a), but in the presence of β -CD (0.2 M).

In the pH region below pH ~ 5 , the lifetime of β -naphthol in water is monoexponential and given by (eq 1). It is the inverse of the sum of the rate constants for emission,

$$\tau = (k_f + k_{nr} + k_H)^{-1} \quad (1)$$

radiationless deactivation and deprotonation. In order to determine k_H it is necessary to know not only the lifetime of β -naphthol at the pH in question, but also the value of the sum $(k_f + k_{nr})$, which is independent of pH. Yorozu and coworkers, in their derivation of the rate constant for the deprotonation of excited naphthol within the cavity of the CD, use the steady state emission quantum yields for bound and free naphthol and the observed lifetime of bound NpOH-CD (they observe 6.5 ns, which is a weighted average of the components we extract) to calculate k_{nr} .¹⁵ Our data

suggest that there is no significant binding between naphtholate anion and β -CD, so there is no meaning to a quantum yield for emission from this species. It is therefore inappropriate to use this value in a calculation.

We observe a lifetime of 7.17 ns for the bound β -NpOH/ β -CD complex (Table II; we consider the value obtained by observation of the 320 nm region emission more precise than that at 420 nm). This value is identical to the value of the sum ($k_f + k_{nr}$) for β -naphthol determined by Laws and Brand.¹¹ It is somewhat larger than the value of the lifetime of β -naphthol in nonaqueous protic solvents such as methanol (5.9 ns^{9b}), but smaller than the value in ethanol (8.9 ns) or in aprotic solvents, e.g. cyclohexane (13.3 ns).²⁰ Deprotonation does not occur in methanol or ethanol from excited β -naphthol.^{9b}

We suggest that the value of the lifetime we observe for the complex is consistent with a complete suppression of "deprotonation" and that it reflects the inherent radiative and nonradiative decay of the molecule in the cavity. We conclude that the interior of the cavity of the cyclodextrin is very much like an alcohol medium, as experienced by β -naphthol. Studies using other probes have concluded that the polarity of the β -CD cavity is similar to that of ethanol.^{21, 22} We now suggest that the proton acceptor ability of the cavity is also similar to that of ethanol. That is, the basicity of the hydroxyl groups on the sugar subunits in the cyclodextrin is too low to accept proton from excited naphthol within the cavity. A corollary of this conclusion is that the naphthol hydroxyl group is therefore associated with the CD structure and does not interact with the water solvent.

INCLUSION INDUCED SECOND HARMONIC GENERATION

The final example of the influence of complexation on the photophysical processes of organic inclusion species is the startling observation of induced polarization of an organic solid by incorporation into the solid state structure of β -cyclodextrin.

General principles: molecular vs. bulk polarization

Nonlinear optics is the study of the interaction of electromagnetic fields with materials to produce new fields which are different from the input field in phase,

frequency or modulation. The most familiar example to many chemists is second harmonic generation, in which the frequency of the output field is twice that of the incident field. Materials such as potassium dihydrogen phosphate (KDP) or potassium titanyl phosphate (KTP) are used routinely in laser systems to produce frequency doubled light from, for example, the neodymium-YAG laser (incident light 1.06 μ ; output at 532 nm).

Recent activity in many laboratories has been directed toward understanding and enhancing second and third order nonlinear effects in inorganic, organic and polymeric materials. Several recent reviews attest to the high interest in this area.²³⁻²⁷

Effective second harmonic generation is attained in materials which have both high molecular polarizability and high bulk polarizability. Molecular polarization is described by the field dependent molecular dipole moment, μ (eq 2), expanded as a function of the applied field strength, E , which may be electric or optical (that is, electromagnetic) in nature. The field strength E is a vector, and μ_0 is the intrinsic dipole moment of

$$\mu = \mu_0 + \alpha.E + \beta.E.E + \gamma.E.E.E + \dots \quad (2)$$

the material. Many organic materials are highly polarizable and are thus inherently good candidates for second harmonic generation. However, because the field strength is a vector, the equation for induced molecular polarization is not scalar, and the constants in (2) are tensors. Second harmonic generation is in fact measured on bulk samples which consist of ensembles of individual molecules. It is therefore necessary to consider the bulk polarization of the material, which again can be expanded with the applied field, as in eq. 3:

$$P = P_0 + \chi^{(1)}.E + \chi^{(2)}.E.E + \chi^{(3)}.E.E.E + \dots \quad (3)$$

It can be shown²⁷ that the odd-order terms in (3) are orientationally independent, but that the even terms depend critically on the symmetry projections of the individual molecular components of the polarizability on the field orientation. One effect is that bulk materials for second harmonic generation must be noncentrosymmetric. That is they must be members of an acentric space group. An ancillary effect is that, while there is not a one-to-one mapping between the molecular second order term (β) and the bulk coefficient [$\chi^{(2)}$], the most advantageous relationship between β and $\chi^{(2)}$ can be shown²⁷ to exist for polar molecules which

crystallize in point groups 1, 2, m or mm2. This is both an advantage and a disadvantage for organic chemists interested in optimum materials for second harmonic generation. The advantage is that it allows one to search crystal structure literature seeking molecules which are members of only several of many possible symmetry groups. This tack has been taken by Tweig²⁸ in a systematic search for suitable materials. The disadvantage of this approach is that it prevents the physical organic chemist from choosing the *BEST* molecule (highest molecular polarizability), because it may or may not crystallize in an appropriate space group. The technique we have developed is one of dipolar alignment, in which a general, polarizable guest, is inserted into a cyclodextrin host in a manner that ensures bulk acentric orientation.²⁹⁻³¹ A similar approach has been reported by a Japanese group³² independent of our own work.

We describe the principle for the specific example of the inclusion of *p*-nitroaniline derivatives in β -cyclodextrin. Nitroanilines were chosen for study because of their high inherent polarizability²⁵ and analogy to known effective SHG active materials (2-methyl-4-nitroaniline, **MNA**³³), and the fact that *p*-nitroaniline itself is centrosymmetric and therefore inactive for SHG itself.

Nitroaniline-cyclodextrin inclusion complexes

Addition of progressively increasing amounts of β -CD to *p*-nitroaniline (PNA, 3×10^{-5} M) in water results in enhanced and red-shifted absorption (Figure 7).

Benesi-Hildebrand analysis shows that the complex formed is 1:1

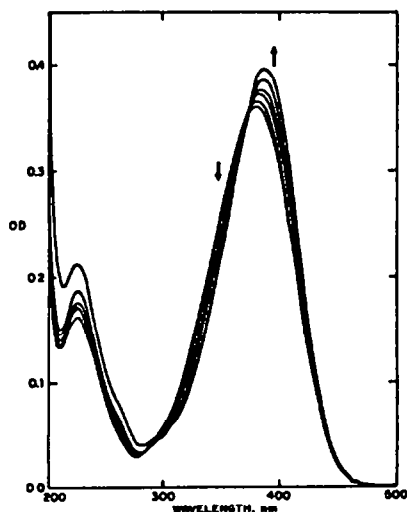


Figure 7. UV spectra of PNA with added β -CD.

and the formation constant is 160 M^{-1} . The long wavelength absorption band exhibits a positive Cotton effect when probed by circular dichroism spectroscopy. Since the 385 nm transition is associated with an internal charge transfer transition in **PNA**, which has its transition moment along the **PNA** long axis of symmetry, the observation of a positive Cotton effect indicates that this long axis of symmetry is oriented within the cavity parallel to the **CD** ring axis.

The 1:1 inclusion stoichiometry is confirmed by NMR studies which also provide further information about the orientation of the **PNA** within the β -**CD** cavity. The 400 MHz NMR spectrum, in the region of absorption associated with the cyclodextrin, of the **PNA-CD** complex is shown in Figure 8.

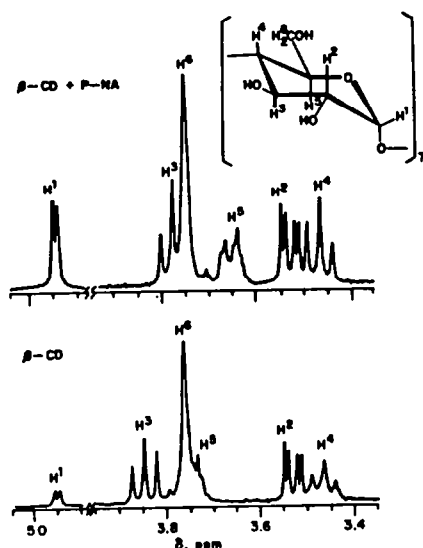
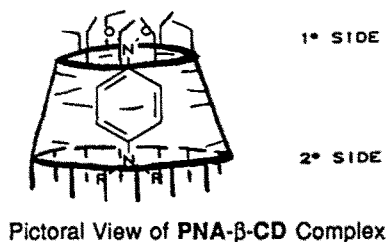


Figure 8. NMR spectrum of **PNA-β-CD** in H_2O (top). The sample was prepared from pure, crystalline complex. At the concentration used, ($\sim 10^{-2} \text{ M}$), the major species present (>95%) is the complex. A spectrum of β -**CD** is shown (bottom) for comparison.

Proton assignments for the observed resonances are indicated in the figure, and a spectrum of free β -**CD** are also shown for comparison. Under the conditions of the experiment, the **PNA** is essentially entirely associated. Two features of the spectra are relevant. First, the protons interior to the **CD** torus (H_3 and H_5) shift upfield on inclusion of **PNA**, while those on the exterior of the **CD** (H_1 , H_2 , H_4 and H_6) are relatively unaffected. This observation is only consistent with complexation within the **CD** cavity. It excludes the possibility of simple association with the exterior of the **CD** ring. Second, the low field region of the spectrum (not shown in Fig. 8), associated with **PNA** protons, exhibits the following changes on complexation. The protons ortho to the nitro group shift upfield by 0.06 ppm upon complexation with β -**CD**, while the protons ortho to the amino group are unshifted. We interpret these observations to indicate that **PNA** enters the β -**CD** cavity preferentially from the secondary hydroxyl

side of the CD and inserts the nitro group first. This deduction produces the picture shown below for the PNA- β -CD complex. It is consistent with the observed orientation of a similar complex between *p*-nitrophenolate and β -CD.³⁴



Solid state properties of PNA- β -CD

Microcrystalline PNA-CD complex can be prepared and isolated in two ways. Near-saturated aqueous solutions of β -CD can be treated with an equal molar amount of solid PNA, stirred overnight and filtered to afford product. Alternatively, an aqueous solution of CD can be overlaid with an ethereal solution containing an equal molar portion of PNA and allowed to stand overnight. Filtration affords analytically pure 1:1 complex which includes variable amount of water of solvation.

X-ray powder diffraction analysis of the complex indicated it was an authentic complex, not a 1:1 admixture of the starting materials. Solid state infrared studies support the complex structural assignment. For example, the nitro bending mode observed in uncomplexed PNA at 1282 cm^{-1} is seen in the complex at slightly higher frequency (1300 cm^{-1}), but with a similar band shape and width (Figure 9).

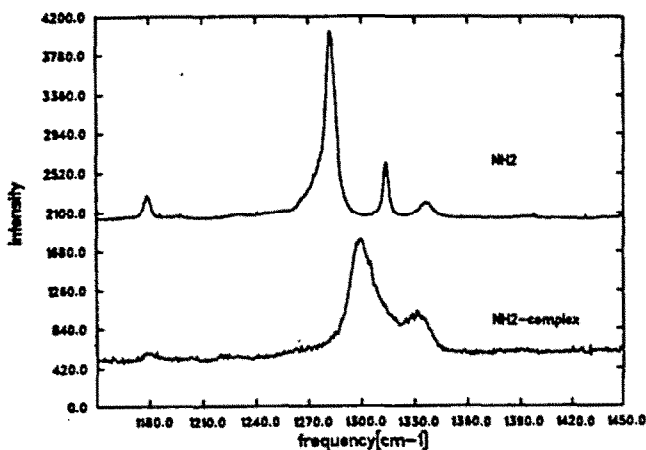


Figure 9. Infrared spectra of PNA (top) and PNA- β -CD (bottom), in the spectral region $1150\text{--}1450\text{ cm}^{-1}$. Samples were prepared in KBr from crystalline materials.

The ability of powdered complex to generate second harmonic radiation was demonstrated in the apparatus shown schematically in Figure 10. The technique is based on the the method of Kurtz and Perry [35]. A Nd-YAG laser

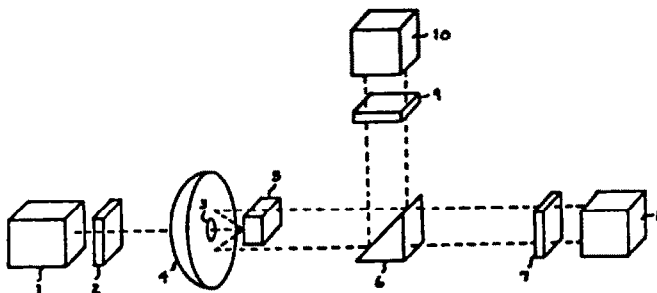


Figure 10. Schematic representaion of apparatus used to measure second harmonic generation. Components are described in the text.

(element 1 in Fig 10) was directed through an optical neutral density filter (2) to adjust the light intensity. The beam then passes through a hole (3) in a parabolic mirror (4) and illuminates a sample (5). Light emerging from the sample is collected by the mirror and passed through beam splitter 6. One portion of the signal is passed through the optical narrow band-pass filter 7 (FWHM 10 nm) which passes light at the second harmonic frequency only (532 nm). The second portion passes through filter 9 which is a broad band filter (FWHM 70 nm). Each portion of the split beam is detected with photomultipliers (8 and 10). The detected signals are compared electronically. Thus in each experiment, two channel detection is employed to discriminate against spurious signals (fluorescence or scattered light) which can be generated. Polycrystalline urea having an average particle size of 90-125 μm was used as a reference material [25, 36].

In a series of experiments, microcrystalline PNA-- β -CD complex was shown to produce SHG with efficiencies of 2-4 times that of urea. By examining the SHG efficiency as a function of particle size, the material was judged to be phase-matchable.³⁵

Other nitroaniline derivatives, and several other polarizable small organics, have also been included within β -CD and their crystalline powders shown to generate SHG. Table III lists observed SHG efficiencies relative to urea.

Table III. Relative SHG Signals for Various Cyclodextrin Complexes

<u>Aromatic Guest</u>	<u>Relative SHG Signal</u>
<i>p</i> -Nitroaniline (PNA)	2-4
<i>p</i> -(N,N)-dimethylaminocinnamaldehyde	0.37
N-Methyl- <i>p</i> -nitroaniline	0.25
2-Amino-5-nitropyridine	0.07
<i>p</i> -(Dimethylamino)benzonitrile	0.015

Though none of the materials listed in Table III was better than the **PNA-CD** complex, the results illustrate the generality of the technique. This is particularly important to note, since none of the organic guests themselves are capable of generating SHG. Thus the host-guest inclusion methodology is capable of inducing optical nonlinearity in situations in which molecular characteristics would suggest that the material would be useful, but the natural solid state structure prohibits their effective use.

Solid state structure of **PNA- β -CD**

Crystals of the complex can be grown by slow diffusion of ethereal **PNA** into **CD** solutions or by slow evaporation. However, water of hydration is retained in varying amounts by the crystals depending on method of crystal growth. Data was collected, but solution and refinement of the structure could not be effected because of disorder in either the **CD** or the **PNA**.

For the many cyclodextrin inclusion structures that have been solved,³⁷ two main structural types are normally observed, channels and cages. Among the channel types, head to head or head to tail arrangement of **CD** units within the channels can occur. For the cage structures, herringbone and brick-work arrangements are noted. Figure 11 illustrates these common arrangements. Only the head to tail channel structure or the cage structure is capable of exhibiting SHG. Crystals of those types would be polar.

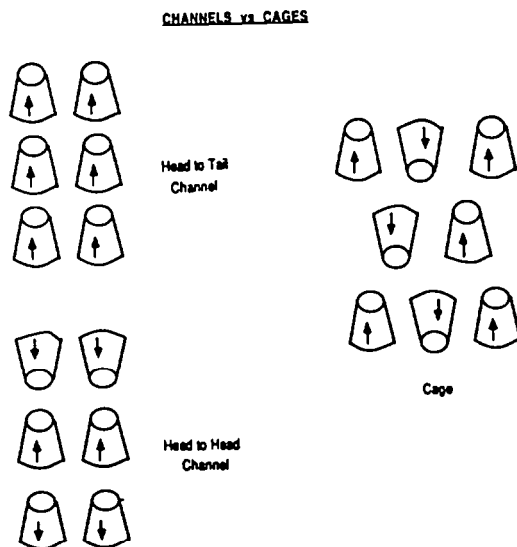


Figure 11: CD crystal habits, after Sanger³⁷.

We have been unable to grow adequate single crystals of PNA- β -CD for x-ray structural analysis. We therefore are unable at this time to assign a solid state structure unambiguously. The SHG results do indicate unequivocally that the structure is acentric. We currently favor the idea that a cage structure (head to tail) is the actual solid state arrangement in PNA- β -CD. We are actively expanding the range of inclusion matrices that can be used to effect dipolar alignment of polarizable organic and organometallic species.

CONCLUSIONS

The work reported here has shown that inclusion complexation of organic chromophores by cyclodextrins can profoundly influence the response of the material to light. Molecular photophysics can be altered in the complex by simple conformational selection processes, or by changing the environment experienced by the excited species. The interaction with light does not need to be resonant: inclusion complexation can be used to alter the solid state properties of a bulk material and make it active for second harmonic generation. Further advances can be anticipated if not fully predicted.

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REFERENCES

- [1] Arad-Yellin, R., and Eaton, D. F., *J. Amer. Chem. Soc.*, **1982**, *104*, 6147
- [2] a. Chandross, E. A. and Dempster, C. J., *J. Amer. Chem. Soc.*, **1970**, *92*, 703, 704, 3586.
b. Beecroft, R. A., Davidson, R. S., and Goodwin, D., *Tetrahedron*, **1984**, *40*, 4497.
- [3] Arad-Yellin, R., and Eaton, D. F., *J. Phys. Chem.*, **1983**, *87*, 5051.
- [4] Harada, N., and Nakanishi, K., "Circular Dichroic Spectroscopy- Exciton Coupling in Organic Stereochemistry," University Science Books, Mill Valley, CA, 1983.
- [5] Turro, N. J., Okubo, T., and Weed, G. C., *Photochem. Photobio.*, **1982**, *35*, 325.
- [6] a. Kobayashi, N., Saito, R., Hino, Y., Ueno, A., and Osa, T., *J. Chem. Soc., Chem. Commun.*, **1982**, 706.
b. Kano, K., Matsumoto, H., Hashimoto, S., Sisido, M., and Imanishi, Y., *J. Amer. Chem. Soc.*, **1985**, *107*, 6117.
c. Ueno, A., Moriwaki, F., Osa, T., Hamada, F., and Murai, K., *Tetrahedron Letts.*, **1985**, *26*, 3339.
d. Patomy, G., Shapira, A., Diamond, P., and Warner, I. M., *J. Phys. Chem.*, **1986**, *90*, 1963.
- [7] Weller, A., *Z. phys. Chem.*, **1958**, *17*, 224.

- [8] Weller, A., in "Prog. in Reaction Kinetics," Porter, G., ed., Vol. I, Pergamon Press, New York (1961), p 187.
- [9] a. Huppert, D., and Klodny, E., *Chem. Phys. Lett.*, **1981**, *63*, 401.
b. Lee, J., Griffin, R. D., and Robinson, G. W., *J. Chem. Phys.*, **1985**, *82*, 4920.
- [10] Harris, C. M., and Selinger, B. K., *J. Phys. Chem.*, **1980**, *84*, 891.
- [11] Laws, W. R., and Brand, L., *J. Phys. Chem.*, **1979**, *83*, 795.
- [12] Kishi, T., Tanaka, J., and Kouyama, T., *Chem. Phys. Letts.*, **1976**, *41*, 497.
- [13] Amire, S. A., and Burrows, H. D., *J. Chem. Soc., Faraday Transactions, I*, **1982**, *78*, 2033.
- [14] Lemmetyinen, H., Demayashkevich, A. B., and Kuzmin, M. G., *Chem. Phys. Letts.*, **1980**, *73*, 98.
- [15] Yorozu, T., Hoshino, M., Imamura, M., and Shizuka, H., *J. Phys. Chem.*, **1982**, *86*, 4422.
- [16] Kondo, H., Nakatani, H., and Hiromi, K., *J. Biochem.*, **1976**, *79*, 393.
- [17] See McCullough, J. J., MacInnis, K., and Eaton, D. F., *Chem. Phys. Letts.*, **1986**, *125*, 155 for a description of our apparatus and methods.
- [18] Lakowicz, J. R., "Principles of Fluorescence Spectroscopy," Plenum Press, New York, 1983, pps. 394-399.
- [19] Zachariasse, K. A., Busse, R., Duveneck, G., and Kuhnle, W., *J. Photochem.*, **1985**, *28*, 237.
- [20] Berlan, I., "Handbook of Fluorescence Spectra of Aromatic Molecules," Academic Press, New York, 1971.
- [21] Cox, G. S., Hauptmann, P. J., and Turro, N. J., *Photochem. and Photobiol.*, **1984**, *39*, 597.
- [22] Heredia, A., Requena, G., and Sanchez, F. G., *J. Chem. Soc., Chem. Commun.*, **1985**, 1814.
- [23] Gedanken, A., Robb, M. B., and Keubler, N. A., *J. Phys. Chem.*, **1982**, *86*, 4096.
- [24] "Nonlinear Optical Properties of Organic and Polymeric Materials," Williams, D. J., ed., *ACS Symposium Ser. No. 233*, Washington, D. C., 1983.
- [25] Williams, D. J., *Angew. Chem. Int. Ed. Eng.*, **1984**, *23*, 690.
- [26] Basu, S., *Ind. Eng. Chem. Prod. Res. Dev.*, **1984**, *23*, 183.
- [27] Glass, A. M., *Science*, **1984**, *226*, 657.
- [27] Oudar, J. L., and Zyss, Z., *Phys. Rev.*, **1982**, *A26*, 2016, 2028.
- [28] a.) Jain, K., Crowley, J. J., Hewig, G. H., Cheng, Y. Y., and Twieg, R., *Opt. Laser Tech.*, **1981**, *13*, 297.
b.) Twieg, R., Azema, A., Jain, K., and Cheng, Y. Y., *Chem. Phys. Letts.*, **1982**, *92*, 208.
- [29] Wang, Y., and Eaton, D. F., U. S. Ser. No. 732, 652 (May 10, 1985).
- [30] Wang, Y., and Eaton, D. F., *Proc. Conf. Lasers and Electroopt. (CLEO '85)*, Paper THM44, p 212, Baltimore, Md., May 20-24, 1985.
- [31] Wang, Y., and Eaton, D. F., *Chem. Phys. Letts.*, **1985**, *120*, 441.
- [32] Tomaru, S., Zembutsu, S., Kawachi, M., and Kobayashi, M., *J. Chem. Soc., Chem. Commun.*, **1984**, 1207.
- [33] Levine, B. F., Bethea, C. G., Thurmond, C. D., Lynch, R. T., and Bernstein, J. L., *J. Appl. Phys.*, **1979**, *50*, 2523.
- [34] Bergeron, R., and Rowan, R., III, *Bioorg. Chem.*, **1976**, *5*, 425.
- [35] Kurtz, S. K., and Perry, T. T., *J. Appl. Phys.*, **1968**, *89*, 8798.
- [36] Halbout, J. M., Blit, S., and Tang, C. L., *IEEE J. Quantum Electron.*, **1981**, *QE-17*, 513.
- [37] Saenger, W., "Structural Aspects of Cyclodextrins and their Inclusion Complexes," in *Inclusion Compounds*, Vol. 2, J. L. Atwood, J. E. Davies and D. D. MacNicol, eds., Academic Press, New York, 1984, Chapter 8.