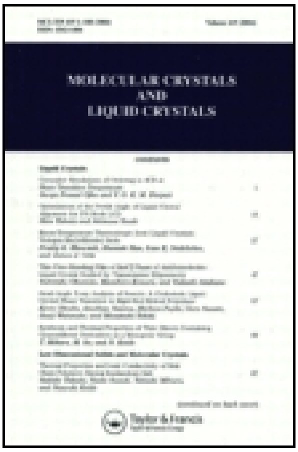


Molecular Crystals and Liquid Crystals Incorporating Nonlinear Optics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl17

Using Hydrogen Bonds to Design Acentric Organic Materials for Nonlinear Optical Users

Margaret C. Etter [a] , Gayle M. Frankenbach [a] & Daniel A. Adsmond [a]
[a] Department of Chemistry, University of Minnesota, Mineapolis, MN, 55455

Version of record first published: 22 Sep 2006.

To cite this article: Margaret C. Etter , Gayle M. Frankenbach & Daniel A. Adsmond (1990): Using Hydrogen Bonds to Design Acentric Organic Materials for Nonlinear Optical Users, Molecular Crystals and Liquid Crystals Incorporating Nonlinear Optics, 187:1, 25-39

To link to this article: http://dx.doi.org/10.1080/00268949008036024

Mol. Cryst. Liq. Cryst., 1990, vol. 187, pp. 25–39
Reprints available directly from the publisher
Photocopying permitted by license only

Printed in the United States of America

"Using Hydrogen Bonds to Design Acentric Organic Materials for Nonlinear Optical Users"

Margaret C. Etter*+, Gayle M. Frankenbach, Daniel A. Adsmond
Department of Chemistry, University of Minnesota
Mineapolis, MN 55455

Second order non-linear optical (NLO) effects, such as second harmonic generation, occur only in materials that are acentric. Finding ways to assure that a bulk material is acentric has been a serious hurdle in the design of new organic materials for non-linear optical uses.[1] A trivial, albeit useful, solution to the symmetry problem is to use chiral molecules which necessarily crystallize in acentric structures.[2] The general solution to the problem involves understanding how to promote self-assembly of molecules, regardless of their molecular symmetry, into acentric arrays. We have found a partial answer to the asymmetric self-assembly question using intermolecular hydrogen bonds.

Curtin and Paul[3] and Zyss[4] have previously noted that many crystal structures of hydrogen-bonding molecules are acentric and that many good organic NLO materials are also composed of hydrogen-bonding molecules. Thus, alcohols and anilines, they claimed, are likely to crystallize in acentric space groups because of their tendencies to form hydrogen bonds. We sought to determine whether there actually was a special role for hydrogen bonds in the design of organic NLO materials, whether that role was related to symmetry constraints, and whether understanding those relations would be helpful in designing new useful NLO materials.

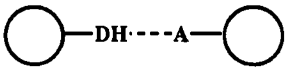
---

* Alfred P. Sloan Fellow, 1989-1991

+Author to whom correspondence should be addressed

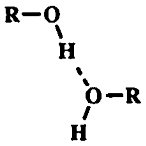
Symmetry Implications of Intermolecular Hydrogen Bonds

When two organic molecules are associated by a single hydrogen bond, the pair of molecules will be acentric.[5] In other words, a single hydrogen bond between neutral molecules is inherently acentric, as illustrated.

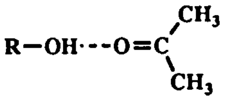


General Case of a Single Acentric Intermolecular Hydrogen Bond

i



A Single Acentric Alcohol ···· Alcohol Hydrogen Bond

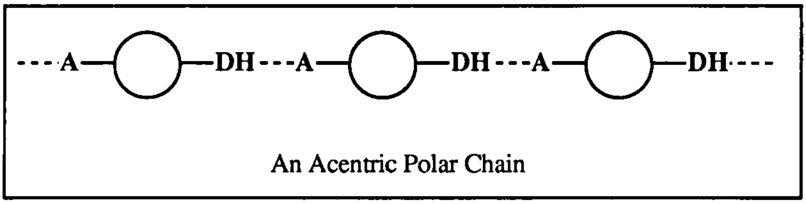


$$\mathrm{R{-}OH\cdots O{=}C(CH_3)_2}$$

An Acentric Dimer formed by a Single Intermolecular Hydrogen Bond

Note that mirror symmetry is not ruled out in the cases cited above, as long as the mirror plane contains the hydrogen bond and does not bisect it. Likewise, for proper rotation axes. Inversion symmetry is the only element this is forbidden for a pair of molecules associated by a single hydrogen bond. These symmetry restrictions are independent of the point group symmetry of the molecules. They hold even for molecules that have C_s point group symmetry prior to associating by hydrogen bonding. Thus, it is not necessary that the molecules themselves be chiral or polar before hydrogen bonding in order to form acentric hydrogen-bonded dimers.

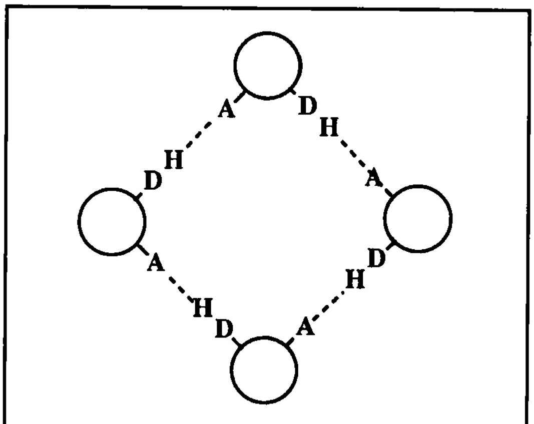
The challenge for materials' chemists is to generalize relationships between hydrogen bonding and symmetry in dimers to 1-, 2-, and 3-D arrays and ultimately to crystal structures. A logical progression follows directly from the principles outlined above. If a single acceptor (A) and a single donor (DH) are present on opposite ends of a molecule, then an acentric polar chain will result when intermolecular hydrogen bonds form.



An Acentric Polar Chain

ii

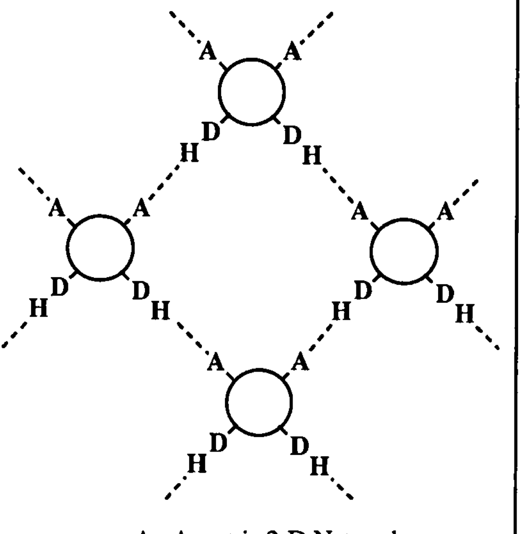
Depending on the angle between the donor and acceptor groups, the resulting chain will be linear, cyclic, or helical. The cyclic structures could be centric but each cycle will still be directional because of the hydrogen-bond asymmetry[6] Helices will be acentric and polar.



A Centric, Directional Hydrogen-Bonded Ring

iii

Acentric 2-dimensional networks can be designed using, at a minimum, two donors and two acceptors. Whether this array is planar or whether it fills space effectively will be

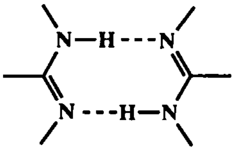


An Acentric 2-D Network

iv

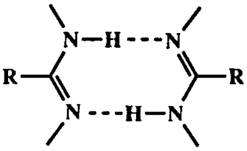
determined by the topography and conformational properties of the molecules. In **iv** one possible acentric hydrogen-bond pattern is shown.

If the third dimension is generated by forming hydrogen bonds between two acentric sheets, then the relative orientation of neighboring sheets must be controlled. This control can be effected in principle by constrained bidentate or multidentate hydrogen bonds, as found in nucleotide base pairs.

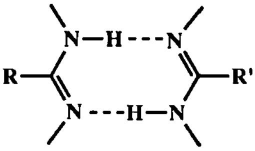


A Bidentate Base Pair

This pair will not make a mistake and put two acceptor groups together, so one molecule specifically orients the second in a preferred direction. The pair that is formed will be centric if both molecules are identical, but otherwise it will be acentric.



Centric



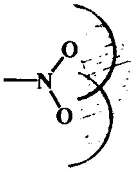
Acentric

Multidentate hydrogen bonding could thus be used to orient two or more one-dimensional chains or planes in the same direction.

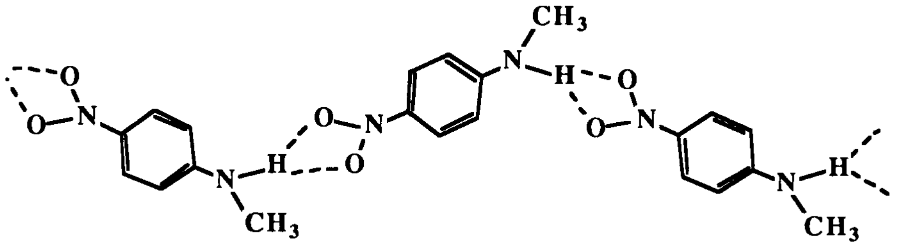
Nitroanilines - Why are they special?

Nitroanilines are polarizable molecules with large hyperpolarizabilities (β) due to internal charge transfer between the electron-withdrawing nitro group and the electron donating amino group[1]. These properties make nitroanilines good choices for nonlinear optical properties based solely on their intramolecular properties. But what about associated nitroaniline molecules? More importantly, do nitroanilines associate?

A study of all known small molecule crystal structures of nitroanilines was carried out, and their packing patterns were analyzed for the presence of recurring and recognizable hydrogen-bond motifs.[7] Despite considerable scatter in the lengths of the contacts between amino protons and nitro oxygens, several patterns were so common that we now use them as design tools for preparing new nitroaniline patterns. In all 30 structures examined the amino protons were always positioned near at least one nitro oxygen. Most often, the contact occurred on the *syn* side of the nitro groups, as found for carboxylate hydrogen bonds.[8] The nitro group traps amino protons in a 3-center interaction which has quite variable geometry, shown as the cross-hatched region below, implying that the potential well is very shallow and the final position of the amino proton in that well will be determined by other packing forces. Our results show that these other forces are not sufficient to dislodge amino protons from the vicinity of a nitro group even when the $NO_2 \cdots HN$ distances are several tenths of an Å longer than the expected van der Waals sums (shown as solid lines in the sketch below; the shaded area is where the closest acidic proton is found).



Thus, having established that nitro groups and amino groups do associate with one another through hydrogen bonding, we now address the symmetry consequences of such interactions. If molecules contain one nitro group and one amino proton, they should associate with one another and form an acentric dimer. If all the nitro groups and amino protons in the system are used, then an acentric chain will form analogous to scheme **ii** above. This polar chain motif is by far the most common pattern in nitroaniline crystal structures, even when the resulting crystal structure is centric.

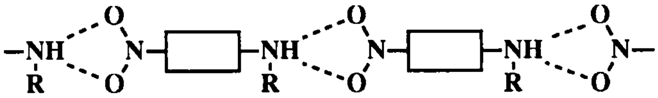


Thus, it may not be a coincidence that nitroanilines have been a useful class of compounds for second harmonic generation. They naturally associate into polar arrays, which are manifested in their crystal structures. The important question is whether or not these polar arrays are likely to bias the resulting crystal structures to be acentric. Although we do not have large enough data sets to make a statistically convincing case, from a set of 41 primary and secondary nitroanilines and analogs, 35 - 40% of their crystal structures were acentric, while only 11% of the 45 tertiary nitroanilines were acentric (compared to about 25% for all known organic crystals, including enantiomers).[9]

The other important role that hydrogen bonds play in nitroaniline crystal structures is related to charge redistributions, and hence changes in β, that occur during hydrogen bond formation. Our work has not focussed on this aspect of the hydrogen-bond problem, but Dannenberg has recently published a detailed study of hydrogen-bonded nitroanilines showing preferred geometries of hydrogen-bonded dimers.[10.] He has also found that nitro groups and aniline protons tend to associate and that charge redistributions during association increase the ground state polarization of the individual molecules. An important consequence of the increased polarization is that chain formation is promoted. In other words, formation of acentric polar chains of nitroaniline molecules is favored by more than just the sum of the energies of the often weak hydrogen bonds between nitro groups and aniline groups.

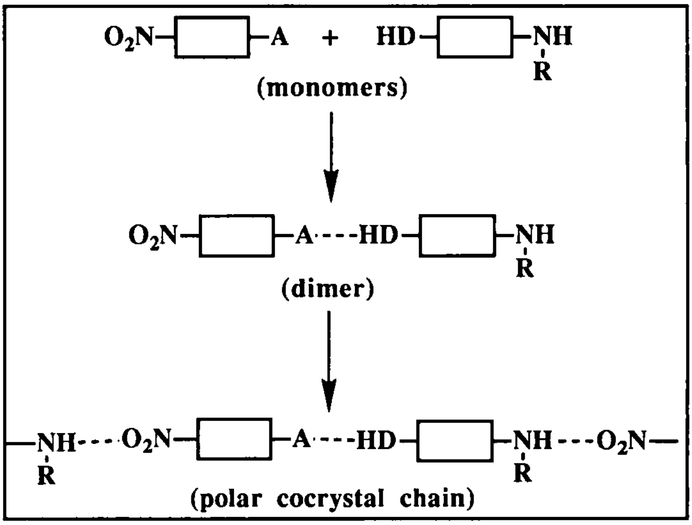
Using Nitroaniline Hydrogen-Bond Preferences to Design Cocrystals of New Acentric Materials

The generic nitroaniline hydrogen-bond pattern is a polar chain with a three-center hydrogen bond. Related acentric chains can be designed by modifying the molecular portions of the chain



Generic Nitroaniline Motif

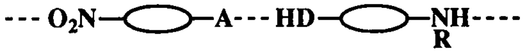
while retaining the hydrogen-bond motif. A particularly useful kind of modification involves a two-step process where a pair of molecules associate with one another into dimers by a strong hydrogen bond, leaving their respective nitro groups and aniline groups free to direct subsequent self-association of the dimers.



We have formed many donor/acceptor pairs which preferentially hydrogen bond to one another in the presence of nitro or aniline groups. These pairs are shown in Table I.

Table I

Nitroaniline Cocrystal Pairs



$$\text{---}\,O_2N\text{—}\bigcirc\text{—}A\text{---}HD\text{—}\bigcirc\text{—}\underset{R}{NH}\text{----}$$

 O_2N—A	 HD—NRH	Space Group	Reference
4-nitropyridine N-oxide	3-aminophenol	Cc	1
4-nitropyridine N-oxide	4-aminobenzoic acid	$P2_12_12_1$	2
3,5-dinitrobenzoic acid	4-aminobenzoic acid	Fdd2	3
4-chloro-3,5-dinitrobenzoic acid	4-aminobenzoic acid	-	4
3,5-dinitrosalicylic acid	4-aminobenzoic acid	-	4
4-methyl-3,5-dinitrobenzoic acid	4-aminobenzoic acid	-	4
3,5-dinitrobenzoic acid	4-aminobenzamide	$P2_1/c$	4
"	"	$P2_1/n$ (DMSO solvate)	4
3,5-dinitrobenzamide	4-aminobenzoic acid	-	4
3,5-dinitrobenzamide	4-aminobenzamide	-	4

---

1. J.R. Lechat, R. H. de A. Santos, and W.A. Bueno, *Acta Cryst.*, **B37**, 1468 (1981).
2. J.R. Lechat, private communication.
3. M.C. Etter and G.M. Frankenbach, *Chem. Mat.*, **1**, 10 (1989).
4. M.C. Etter and G.M. Frankenbach, unpublished data.

Cocrystal Preparation Methods

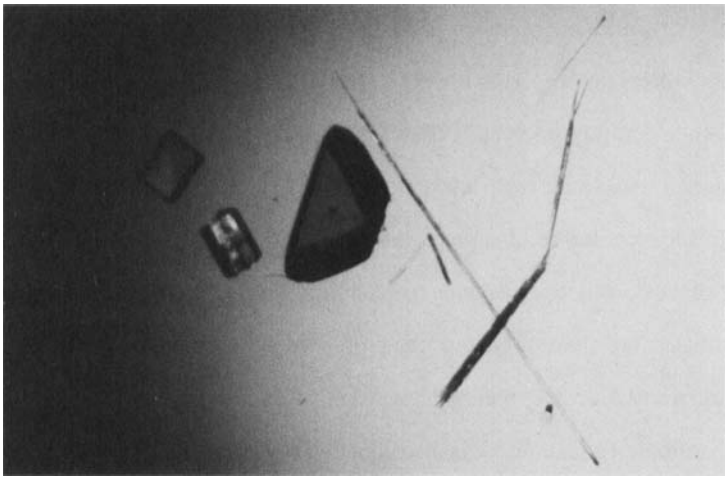
Cocrystals can be prepared in the usual manner by evaporation of a 1:1 solution of the two molecules, but most of them can also be prepared simply by grinding the two compounds together in a mortar and pestle or an amalgamator. Sometimes the solids need to be heated after grinding in order to get high yields (> 75% conversion) but in all cases the heating is at least 50° below the melting point of either solid, and no apparent melting or fusing of the particles is seen. For those compounds whose crystal structures have been done as indicated in Table I, we found that the X-ray diffraction powder patterns of the product formed by solid-state grinding matches that of powders of the single crystals (or of powder patterns generated from the single crystal data).

Other kinds of hydrogen-bonded cocrystals can also be prepared in this way. Two important factors in determining whether cocrystals will form by this method are: at least one of the components should have some volatility at the temperature of the grinding experiments, and the product dimers should have a stronger intermolecular hydrogen bond than any of the hydrogen bonds in the structures of the two starting materials.

The use of solid state preparative methods as a general materials design tool opens up new possibilities for preparing novel materials not isolable from solution such as nonstoichiometric solids, cocrystals of compounds not soluble in a common solvent, polymers doped with small molecules, or possibly new polymorphs not isolable from solution. In addition, the solid-state properties of both components are changed during the mixing process, as both molecules recrystallize within the solid so all their near-neighbor contacts are altered. Macroscopic properties such as solubility, color, melting point, and chemical reactivity will be changed in addition to electrooptic properties such as second harmonic generation. It is also conceivable that one particular molecule, for example p-nitroaniline, could be converted into many different solid state forms with appropriate cocrystallization partners, thus increasing the range of chemical and physical properties accessible to p-nitroaniline.

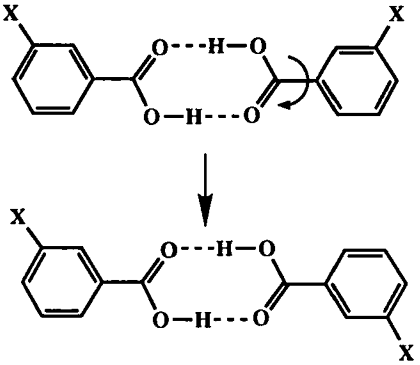
Cocrystallization and the Formation of Large High Quality Crystals

In the course of preparing cocrystals of nitroaniline dimers and of related compounds from solution we observed that large high-quality cocrystals often formed even when one or both of the component molecules formed poor crystals by themselves. This observation was first made for cocrystals of triphenylphosphine oxide with small proton-donating molecules like acids, amides, phenols, and anilines.[11] In those cases triphenylphosphine oxide imparted its own favorable crystal growth properties on the other component. While preparing cocrystals of nitroaniline dimers we have found several additional examples of improved crystal growth and quality (as determined by low power microscopic investigation of crystal clarity, edge development, fracture planes, and defect structures). Shown below is an example of the improved size and quality of a cocrystal of 3,5-dinitrobenzoic acid and 4-aminobenzoic acid juxtapositioned with crystals of the starting materials. Note that the polar nature of the cocrystal is also evident in its well-developed noncentric morphology. Presently we are testing other types of cocrystals to determine whether this is a general phenomenon.

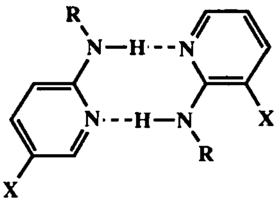


Biomimetic Design of Acentric Materials

Using polar chains and polar arrays to bias the formation of acentric bulk materials is a promising and potentially useful approach, but is somewhat unsatisfying because the nature of the bias is not well understood and is thus not easy to control. In searching for a more definitive and logical mechanism for preparing acentric bulk materials, we have borrowed one of nature's tricks. The nucleotide base pairs of DNA specifically orient the two DNA helices in a predictable orientation. The predictability arises because the base pairs are complementary in only those arrangements that pair donors with acceptors. Unlike carboxylic acids which are free to rotate after dimer formation, the base pairs are constrained by their heterocyclic backbones to retain their mutual orientations, as shown.

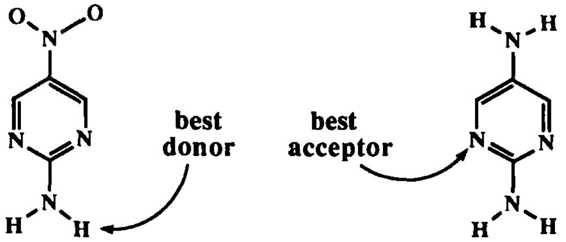


Acid Dimers have Non-constrained Orientations

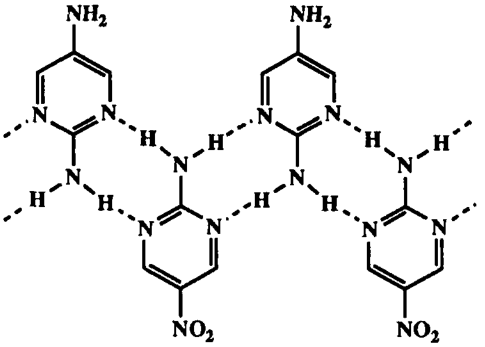


Base Pairs have Constrained Orientations

By preparing mixed dimer pairs, analogous to DNA base pairs, it is possible in principle to control the orientation of neighboring molecules, and of neighboring arrays. A biomimetic nitroaniline could conceivably be prepared by cocrystallizing derivatives of 2-aminopyrimidine.



If the best donors and acceptors couple, and the common aminopyrimidine bidentate hydrogen bonds form, then the following acentric structure is possible:



We have been unsuccessful in preparing this 1:1 cocrystal from solution but we have prepared a 1:1 cocrystal of the two components by solid state grinding and heating. Neither the crystal structure nor the hydrogen-bond pattern is known at this point, but the X-ray powder pattern of the cocrystal product is distinctly different than those of the starting materials. Further work is in progress to take advantage of 2-aminopyrimidine and related heterocyclic bases for preparing materials with controlled symmetry properties.

Conclusion

The use of intermolecular hydrogen bonds as an essential noncentric interaction to control self-assembly of organic molecules into noncentric arrays has been demonstrated. These arrays may be homomeric or heteromeric. In the latter case acentric cocrystals can be prepared by solution or solid-state cocrystallization methods. Cocrystals prepared from solution are frequently larger and of better quality than crystals of the component molecules themselves. Although nonlinear optical materials have further materials requirements besides acentricity (such as high polarizability, and phase matching), the ability to control acentricity has been one of the limiting steps in progress towards development of organic nonlinear optical materials. The approaches presented here have proven useful as solid-state design tools for controlling acentricity in organic materials.

References

[1] D. J. Williams, *Angew. Chem. Int. Ed. Engl.*, **23**, 690-703 (1984).

[2] J. F. Nicoud, R. J. Twieg, in: "Nonlinear Optical Properties of Organic Molecules and Crystals", ed. by D. Chemla and J. Zyss, Academic: Orlando, FL, pp 227-296, 1986.

[3] D. Y. Curtin and I. C. Paul, *Chem. Rev.* **81**, 525-541 (1981).

[4] a) J. Zyss, J. F. Nicoud, and M. Coquillay, *J. Chem. Phys.* **81**, 4160-4167 (1984). b) J. Zyss and G. Berthier, *J. Chem. Phys*, **77**, 3635-3653 (1982).

[5] Centric hydrogen bonds are known in special cases usually involving half acid salts (J. C. Speakman and K. W. Muir, *Croatica Chemica Acta*, **55**, 233-248 (1982).), and inorganic salts of strong acids (P. J. Desmeules and L. C. Allen, *J. Chem. Phys.*, **72**, 4731-4748 (1980).).

[6] M. D. Singh, J. Siegel, E. B. Silvio, and K. Mislow, *J. Am. Chem. Soc.*, **109**, 3397-3402 (1987).

[7] T. W. Panunto, Z. Urbanczyk-Lipkowska, R. Johnson, and M. C. Etter, *J. Am. Chem. Soc.*, **109**, 7786-7797 (1987).

[8] D. R. Gandour, *Bioorganic Chemistry*, **10**, 169-176 (1981).

[9] In a related study we found that among all carboxylic acid crystal structures, 75% of 12 that form polar hydrogen-bonded chains have acentric crystal structures while 4% of 106 that form cyclic dimers are acentric.

[10] L. K. Vinson, and J. K. Dannenberg, *J. Am. Chem. Soc.*, **111**, 2777-2781 (1989).

[11] M. C. Etter and P. W. Baures, *J. Am Chem. Soc.*, **110**, 639-640 (1988).