Solubility properties (SP) of a protonic solute in a series of nonprotonic solvents have been correlated in the form of eq 1 using

SP = SP_0 + dipolar term + hydrogen bonding term + cavity term (1)

the *solvent* π^*, β, and δ_H values, respectively. δ_H, the Hildebrand solubility parameter,[8] is the *solvent* parameter that gives the magnitude of the cavity term.[9] Equation 1 can also be used to correlate solubility properties, e.g., log P values, for a series of nonprotonic solutes in protonic solvents using the *solute* π^*, β, and $\bar{V}/100$ values.[10] $\bar{V}$, the mean molar liquid volume is the *solute* property that determines the magnitude of the cavity term. For nonprotonic solutes in protonic solvents, we suggest that eq 2

$$SP = SP_0 + A\delta_{H,1}\bar{V}_2/100 + B\pi^*_1\pi^*_2 + C\alpha_1\beta_2 \quad (2)$$

applies, where subscript 1 refers to the solvent and subscript 2 to the solute, and A, B, and C, are constants for the endoergic cavity term, the exoergic dipolar term, and the exoergic hydrogen-bonding term, respectively.

Equation 2 gives, for nonprotonic solutes, the following predictions: since π^* of H_2O (1.09) is higher than π^* of octanol (ca. 0.4), higher solute π^* should favor solution in water; since α of H_2O (1.17) is higher than α of octanol (ca. 0.6), higher solute β should favor solution in water; since δ_H of water (23.4)[11] is higher than δ_H of octanol (10.2), higher solute $\bar{V}$ should favor solution in octanol. Values of log P for 47 widely varying nonprotonic solutes (cf. Table I) confirm these predictions by adherence to correlation eq 3. The data correlated, to our knowledge, include

$$\log P = 0.24(\pm 0.18) + 2.66(\pm 0.12)\bar{V}/100 - 0.96(\pm 0.11)\pi^* - 3.38(\pm 0.12)\beta \quad (3)$$

$$n = 47,\ r = 0.991,\ \text{sd} = 0.18$$

all nonprotonic aliphatic solutes[12] for which the Hansch-Leo parameters and the solvatochromic parameters are known (excluding dioxan and other compounds having multiple oxygen atom base centers[13]).

It is significant that the intercept in eq 3 is close to the theoretical value of 0.00[14] and that the standard deviation is well within the range of experimental error. Equation 3 shows that the major effects are the opposing influences of solute molecular volume and HBA basicity, with solute dipolarity exerting second-order influences. Unless correctly unraveled, the log P vlues can appear complex. For example, 2-butanone, hexamethylphosphoramide, methyl acetate, and trimethylamine (Table I, 37-40) have quite similar log P_H values, although $\bar{V}/100$, π^*, and β values range from 0.80 to 1.75, from 0.14 to 0.87, and from 0.42 to 1.05, respectively. In demonstrating how the specific molecular properties influence partition, eq 3 provides guidance in the design of pharmacologically active molecules.

It is also of interest to compare eq 3 with our preliminary correlation equation[12b] for cyclohexane/water partitioning of nonprotonic aliphatic solutes:

$$\log P(C_6H_{12}/H_2O) = -0.05 + 3.69\bar{V}/100 - 1.15\pi^* - 5.64\beta \quad (4)$$

$$n = 17,\ r = 0.998,\ \text{sd} = 0.07$$

The relevant solvent parameters for cyclohexane are $\pi^* = \alpha = 0$ and $\delta_H = 8.2$. In accord with eq 2 and the greater differences between the solvent parameters for cyclohexane/water compared with ocatanol/water, the coefficients of $\bar{V}/100$, π^*, and β are larger in eq 4 than eq 3.

Equations 3 and 4 are particularly significant from the standpoint of the leading hydrogen bond term, since they, for the first time, confirm the general applicability of the β scale of HBA strengths *in aqueous and hydroxylic environments*. We have earlier shown that the β scale has marked differences from the familiar and frequently invoked pK_a scale or the gas-phase basicity scale.[3,15,16] Thus, our methodologies for measuring[3] and for correlating and predicting β values based on molecular structural parameters[12b,17] are directly applicable to most biologically important bases in biological media.

Acknowledgment. We are pleased to acknowledge the assistance of Prof. C. Hansch in providing comments and log P values.

Registry No. 1-Octanol, 111-87-5.

(8) Hildebrand, J. H.; Scott, R. L. "The Solubility of Nonelectrolytes", 3rd ed.; Dover Publications: New York, 1964; "Regular Solutions"; Prentice Hall: Englewood Cliffs, NJ, 1962.

(9) Kamlet, M. J.; Carr, P. W.; Taft, R. W.; Abraham, M. H. *J. Am Chem. Soc.* **1981**, *103*, 6062.

(10) $\bar{V}/100$ is used so that the magnitude of the scale for the cavity term is similar to those for the terms in π^* and β. Values of $\bar{V}$ are estimated from molecular weights and liquid densities of 20 °C, as obtained from: Weast, R. C., Ed. "Handbook of Chemistry and Physics", 51st ed.; Chemical Rubber Publishing Co.: Cleveland, OH, 1971.

(11) Kamlet, M. J.; Doherty, R. M.; Taft, R. W.; Abraham, M. H. *J. Am. Chem. Soc.* **1983**, *105*, 7641.

(12) (a) In the full paper, aromatic bases will be considered, as well as partition functions for other solvent/water systems. (b) Work in progress.

(13) If one uses $\beta = 0.74$ for dioxan (0.37 for each site), log P calculated (-0.52) by eq 3 is only slightly more negative than the experimental value (-0.27). Both $(RO)_3PO$ and RNO_2 compounds appear by negative derivations of ca. 0.5 to behave as more complicated multiple-site bases. The calculated values of all cyclic compounds of Table I are too negative by 0.4 ± 0.1, suggesting that $\bar{V}$ for these is too small by ca. 13 cm^3/mol.

(14) A compound with zero values of $\bar{V}/100$, π^*, and β should distribute equally between water and octanol. Helium, with a log P_H value of 0.28 comes near to meeting this provision.

(15) Gurka, D.; Taft, R. W. *J. Am. Chem. Soc.* **1969**, *91*, 4797. Taft, R. W.; Gurka, D.; Joris, L.; Schleyer, P. v. R.; Rakshys, J. W. *Ibid.* **1969**, *91*, 4801.

(16) In ref 3 we have shown that the relationship between aqueous pK_A and β is given to good approximation by the equation: ΔpK_a(relative to NH_4^+) = $-19.4 + 12.8\beta + 11.5\zeta$, where ζ is a coordinate covalency parameter having the values -0.20 for P=O bases, 0.00 for S=O and C=O bases, 0.20 for single-bonded oxygen bases, 0.60 for pyridine bases, and 1.00 for single-bonded sp^3-hybridized nitrogen bases.

(17) Taft, R. W.; Gramstad, T.; Kamlet, M. J. *J. Org. Chem.* **1982**, *47*, 4557.

Photodimerization of Lewis Acid Complexes of Cinnamate Esters in Solution and the Solid State

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Photochemical cyclodimerization of cinnamic acid derivatives is highly inefficient in dilute solution due to very rapid cis-trans photoisomerization.[1] Efficient photodimerization of *trans*-cinnamic acid derivatives is observed in the solid state[2] (subject to topological control) and in solution, when high local concentrations are achieved either by omission of solvent[1] or by linking two or more cinnamate residues together as a diester so that intramolecular photodimerization can occur.[3] We recently reported that

(1) Egerton, P. L.; Hyde, E. M.; Trigg, J.; Payne, A.; Beynon, P.; Mijovic, M. V.; Reiser, A. *J. Am. Chem. Soc.* **1981**, *103*, 3859-3863.

(2) (a) Cohen, M. D.; Schmidt, G. M. J.; Sonntag, F. I. *J. Chem. Soc.* **1964**, 2000-2013. (b) Schmidt, G. M. J. *Ibid.* **1964**, 2014-2021. (c) Bregman, J.; Osaki, K.; Schmidt, G. M. J.; Sonntag, F. I. *Ibid.* **1964**, 2021-2030. (d) Schmidt, G. M. J. *Pure Appl. Chem.* **1971**, *27*, 647-678. (e) Cohen, M. D. *Angew Chem., Int. Ed. Engl.* **1975**, *14*, 386-393. (f) Bolt, J.; Quina, F. H.; Whitten, D. G. *Tetrahedron Lett.* **1976**, 2595-2598.

(3) (a) Rennert, J.; Soloway, S.; Waltcher, I.; Leong, B. *J. Am. Chem. Soc.* **1972**, *94*, 7242-7244. (b) Green, B. S.; Rabinsohn, Y.; Rejtö, M. *J. Chem. Soc., Chem. Commun.* **1975**, 313-314. (c) Williams, J. L. R.; Farid, S. J.; Doty, J. C.; Daly, R. C.; Specht, D. P.; Searle, R.; Borden, D. G.; Chang, H. J.; Martic, P. A. *Pure Appl. Chem.* **1977**, *49*, 523-538.

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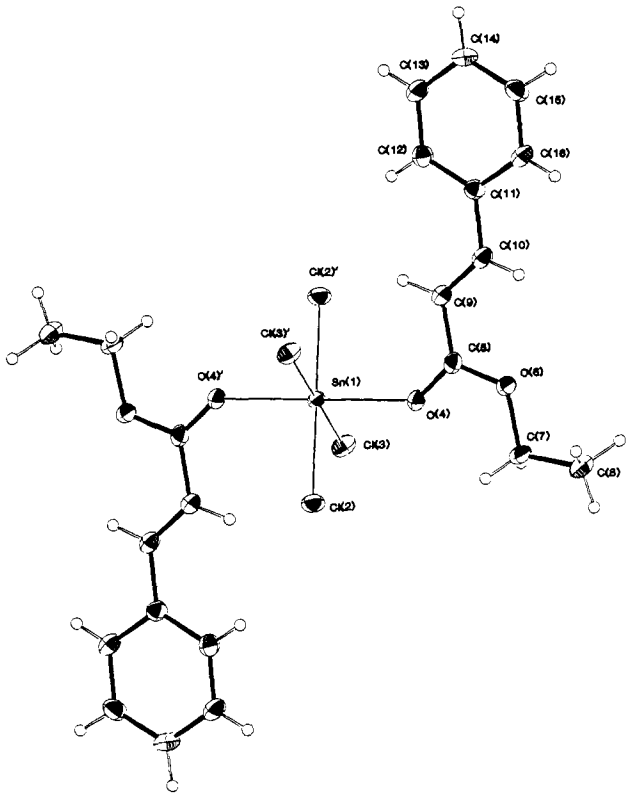
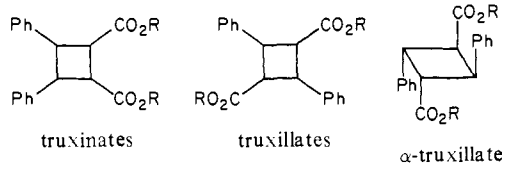


Figure 1. ORTEP drawing of the (ethyl cinnamate)$_2$:$SnCl_4$ complex.

the solution-phase photodimerization of coumarin can be catalyzed by the Lewis acid BF_3, resulting in a substantial increase in quantum yield and a change in dimer regiochemistry from syn head to head (uncatalyzed) to syn head to tail (catalyzed).[4] We had previously observed that irradiation of dilute solutions of cinnamate esters in the presence of Lewis acids leads to photostationary states highly enriched in the cis isomer.[5] We report here the effects of the Lewis acids BF_3 and $SnCl_4$ upon the solution and solid-state photodimerization of cinnamate esters. While efficient photodimerization is observed for both cases, only in the solid state is the reaction highly stereo- and regioselective.

Preparative irradiation ($\lambda > 300$ nm) of a methylene chloride solution of *trans*-methyl cinnamate (0.2 M) and BF_3·OEt_2 (0.1 M) for 36 h results in 86% conversion to a mixture of seven truxinate and truxillate dimers, which accounts for 95% of the



methyl cinnamate consumption.[6] Irradiation using $SnCl_4$ in place of BF_3·OEt_2 results in 20% conversion to a substantially different mixture of isomers, which accounts for 74% of the methyl cinnamate consumption. Heat-to-head dimers (truxinates) account for >90% of the dimers obtained from irradiation of neat ethyl cinnamate[1] but only 76% and 55% of the dimers obtained from the $SnCl_4$- and BF_3·OEt_2-catalyzed reactions. Thus head-to-tail (truxillate) dimers are favored in the catalyzed vs. uncatalyzed reaction, as is the case for coumarin photodimerization.[4]

Quantum yields for BF_3-catalyzed photodimerization increase with increasing methyl cinnamate concentration (constant BF_3), decrease with increasing BF_3 concentration (constant methyl

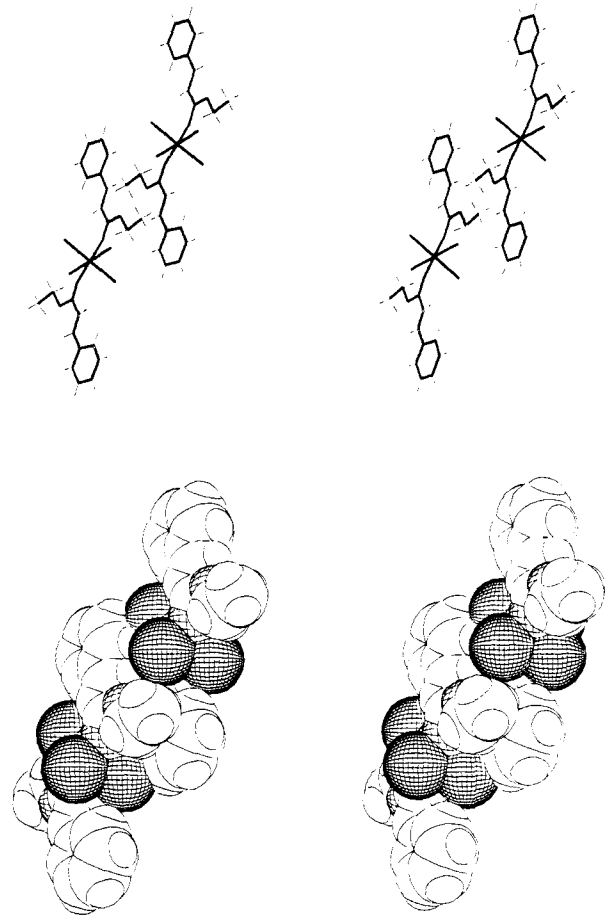


Figure 2. Space-filling and stick model drawing of a pair of molecular complexes. Oxygen atoms are loosely crosshatched and chlorine atoms are tightly crosshatched.

cinnamate), and are vanishingly small ($<10^{-3}$) in the absence of BF_3.[7] The quantum yield for a methylene chloride solution of 0.2 M methyl cinnamate and 0.03 M BF_3 (313-nm monochromatic irradiation, *trans*-stilbene actinometry) is 0.011. These results are consistent with the mechanism proposed for BF_3-catalyzed photodimerization of coumarin, namely, absorption of light by the ground-state complex ($K = 430$) followed by reaction of the excited-state complex with ground-state methyl cinnamate.[4,6]

Ethyl cinnamate forms a crystalline 1:1 complex with BF_3 and a 2:1 complex with $SnCl_4$.[8] The molecular structure[9] of the 2:1 $SnCl_4$ complex at −163 °C is shown in Figure 1 and displays the expected octahedral geometry with Sn at the center of inversion. Irradiation of the 1:1 BF_3 complex in microcrystalline form for 5 h results in 12% conversion to a mixture of dimers in which the α-truxillate is the major isomer (ca. 60%). Liquification of the crystalline material and trans → cis photoisomerization are observed even at low conversions. Irradiation of the 2:1 $SnCl_4$ complex for 5 h results in 34% conversion and prolonged irradiation 85% conversion to a single dimer (>95%), the α-truxillate.[10]

(4) Lewis, F. D.; Howard, D. K.; Oxman, J. D. *J. Am. Chem. Soc.* **1983**, *105*, 3344–3345.
(5) Lewis, F. D.; Oxman, J. D. *J. Am. Chem. Soc.* **1981**, *103*, 7345.
(6) Details concerning the separation and characterization of the photodimers and the mechanism of the solution-phase reaction will be presented in a full paper.
(7) The quantum yield for photodimerization of neat ethyl cinnamate is 0.08.
(8) Ichiba, S.; Mishima, M.; Negita, H. *Bull. Chem. Soc. Jpn.*, **1969**, *42*, 1486–1489.
(9) Crystallographic data at −163 °C: space group $P\bar{1}$, $a = 9.853$ (3) Å, $b = 8.557$ (2) Å, $c = 8.016$ (2) Å, $\alpha = 106.85$ (2)°, $\beta = 103.01$(2)°, $\gamma = 99.05$ (2)°, $D_{calcd} = 1.663$ gm/cm^3 for $Z = 1$. Data collection and reduction techniques are as described previously (Huffman, J. C.; Lewis, L. N.; Caulton, K. G. *Inorg. Chem.* **1980**, *19*, 2755–2762). Data were corrected for absorption (min/max = 0.807/0.846). Full-matrix refinement for the 1557 observed (out of 1608 unique) data yielded $R = 0.023$ and $R_w = 0.027$ for the diffractometer collected data.
(10) α-Truxillate dimers are also formed upon irradiation of noncomplexed crystalline methyl cinnamate (cooled to 0 °C) and octadecyl cinnamate.[1f] The crystal structures of these esters are unknown but clearly must differ from the hydrogen-bonded dimer structure of the cinnamic acids.[1b]

The exclusive formation of the syn head-to-tail dimer upon irradiation of the crystalline 2:1 $SnCl_4$ complex is in accord with the postulate of topochemical control of solid-state photodimerization.[2] The computer-drawn space-filling model of two neighboring 2:1 complexes (Figure 2) shows the head-to-tail stacking of a symmetry-related pair of ester molecules. The distance between the reactive double bonds in the infinite stacks of esters is 4.023 (8) Å for one symmetry-related pair and 4.125 (8) Å for the second symmetry-related pair, well within the range of values observed for photodimerizable cinnamic acids.[2] Efficient solid-state photodimerization to yield α-truxillate dimers is also observed for the 2:1 $SnCl_4$ complexes of the trans isomers of methyl and *n*-propyl cinnamate and methyl α-methylcinnamate, but not for the isopropyl cinnamate. While the crystal structure of these complexes is not known, space-filling models of these esters indicate that close-packed head-to-tail stacking can be achieved with the photoactive esters, but not with the isopropyl ester.

In summary, we find that Lewis acids can serve as catalysts for the photodimerization of cinnamate esters in solution and the solid state. The two reactions differ in stereoselectivity and mechanism: the solid-state reaction involving two complexed ester molecules and the solution reaction involving an excited state complexed ester and ground-state noncomplexed ester molecule. The only other reported examples of solid-state photodimerization reactions of Lewis acid complexes are those of the 2:1 complexes of dibenzylideneacetone with UO_2^{+} or $SnCl_4$, which proceeds in poor yield to the syn head-to-tail dimer,[11] and of the 1:1 complex of coumarin with $HgCl_2$, which proceeds in unspecified yield to the syn head-to-head dimer.[2c] In these cases the Lewis acid occupies the apices of the unit cell, whereas, in the 2:1 complex of ethyl cinnamate with $SnCl_4$ (Figure 2), $SnCl_4$ occurs in infinite edge-to-edge stacks, which may serve to keep the crystal lattice intact even at high conversions to dimer. Thus our results present perhaps the best example of control of photodimerization by "crystal engineering"[2d] reported to date.

Acknowledgment. We thank the National Science Foundation (CHE8026020) for support of this work and the Marshall H. Wrubel Computing Center at Indiana University for a gift of computer time.

Registry No. *trans*-Methyl cinnamate, 1754-62-7; *trans*-ethyl cinnamate, 4192-77-2; *trans*-ethyl cinnamate·BF_3 complex, 88228-94-8; *trans*-ethyl cinnamate·$^1/_2SnCl_4$ complex, 88270-63-7; BF_3·OEt_2, 109-63-7; $SnCl_4$, 7646-78-8.

Supplementary Material Available: Listing of fractional coordinates, anisotropic thermal parameters, and bonded distances and angles (3 pages). Ordering information is given on any current masthead page.

(11) (a) Stöbbe, H.; Farber, E. *Chem. Ber.* **1925**, *58*, 1548–1553. (b) Alcock, N. W.; de Meester, P.; Kemp, T. J. *J. Chem. Soc., Perkin Trans. 2* **1979**, 921–926.

Book Reviews

Physical Chemistry. By R. Stephen Berry and Stuart A. Rice (University of Chicago) and John Ross (Massachusetts Institute of Technology). John Wiley and Sons, Inc., New York. 1980. xvi + 1260 + 40 pp. $38.95. (Also available in three parts individually priced.)

To anyone who "grew up" in terms of physical chemistry in the late 1940's, publication of a new comprehensive physical chemistry inevitably invites some comparison with the earliest example of the genre, Glasstone's "Textbook of Physical Chemistry". At that time, that book illuminated the way in which physical chemistry impacted upon the broader subject of chemistry and, it seemed to us as students, it represented a significant change from the previous, essentially monographic, texts in that it served as a report on the status of pre-1940 physical chemistry.

The publication of "Physical Chemistry" by Berry, Rice, and Ross has now set another mark in this tradition, albeit 40 years later. The comparison is worthwhile in that it enables one to appreciate just how far, and in what directions, the physical aspects of chemistry have gone during the past 40 years and, in these terms alone, BRR is a valuable addition to the otherwise rather large collection of physical chemistry books.

Even taking into account its somewhat forbidding size, BRR is deceptive in the same way that the "Structure of Matter" by Rice and Teller was deceptive. By this I mean that the writing is terse and the concepts are often somewhat implicit, rather than explicit in their elaboration. In this sense, the book is more a precis of the current state of physical chemistry complete with adequate suggestions for further reading than it is a text. This style is excellent for the serious student but, as a result, the book is hardly likely to displace the more explicit and pedagogically orthodox texts so frequently used for introductory courses. The book consists of 31 chapters subdivided into three main divisions, Structure, Equilibrium, and Dynamics, and within each division, there is an excellent coverage of all of the usual—and some of the unusual (nonequilibrium processes, dense phases, etc.)—subjects.

It may sound gratuitous to note that the book is remarkably error free, apart from a few typographical slips, but this suggests that the authors themselves have been responsible for the proof reading—an onerous task which is not always taken seriously these days. What appears to be a further involvement of the authors is the fact that the index is actually useful and relatively complete.

Many books written by groups of authors have considerable uneveness of presentation, with the individual areas and their separate authors often being easily identifiable. BRR does not suffer from this defect. The level of writing is remarkably uniform with individual topics expounded to a satisfying level of detail without obscurity. Balance has also been maintained in the structural and the dynamic components, and even the thermodynamic contribution has an agreeable freshness to it. This reviewer, in particular, did not find those chapters overly long. The physical size of the volume is, to some, intimidating and there is no doubt that a useful purpose was served by splitting the volume into three separate parts for convenience.

Finally, it should be noted that this book, in a sense, marks the end of an era. One might expect during the next 20 or 30 years a huge development of physical chemistry based upon detailed computation utilizing the new generations of computers which are now becoming available. BRR has appeared sufficiently late to take into account some of the early work in this field and at a stage late enough for the authors to have contributed their understanding of the impact that these detailed studies will have. Their contribution is unlikely to be duplicated either in range or degree of sophistication in the foreseeable future. It is a significant achievement that will serve both as a text in physical chemistry and as a summary of the status of the subject at the end of an era.

Thomas M. Dunn, *University of Michigan*

Presynaptic Receptors: Mechanism and Functions. Edited by J. deBelleroche (Charing Cross Hospital Medical School). John Wiley & Sons, New York. 1982. 223 pp. $64.95.

This book is based on a Neurochemical Group Meeting of the Biochemistry Society and it deals with the rapidly developing field of presynaptic receptor research. Presynaptic receptors, which are distinct from the classical postsynaptic receptors, have attracted considerable attention in the past 10 years as targets for drug design. This book examines the role of presynaptic receptors in the main transmitter systems of the body (e.g., adrenergic, dopaminergic, cholinergic, and serotoninergic) and their characteristics and functions as demonstrated by electrophysiological, biochemical, behavioral, immunological, and pharmacological methodologies. Efforts are made to clearly distinguish from a structural and functional veiwpoint between pre- and postsynaptic receptors. The book also reviews the action of presynaptic agonists and antagonists in terms of effects on ion currents, release of transmitter and changes in metabolic activity. From a physiological viewpoint, the localization of presynaptic receptors and their involvement in mediating motor activities are discussed. Overall this volume will serve as a useful reference text in the rapidly developing field of presynaptic receptor research. For medicinal chemists involved in the design of drugs specific for presynaptic receptors, it is mandatory reading.

Ronald T. Borchardt, *The University of Kansas*