

seen that the HOMO-LUMO interaction increases as the hydrogen electronegativity is increased. Since the LUMO is a  $\sigma^*$  MO with a significant contribution from the nitrogen 2s AO, the more the LUMO is mixed into the HOMO, indeed, the greater is the s character in the resulting lone pair MO. In most cases the frontier orbital approach presented in this Account is not at variance with a hybridization description of the effects discussed here. In fact, consideration of HOMO-

LUMO interactions can be seen as offering justification, in the context of MO theory, for the description of these effects that emerge from the less rigorous concept of hybridization in resonance theory.<sup>40</sup>

(40) Note Added in Proof. In connection with the discussion of molecules containing  $\pi$  bonds,<sup>34</sup> it is interesting to note that the x-ray structure of a compound possessing a Sn-Sn double bond shows the tin atoms to be pyramidal: P. J. Davidson, D. H. Harris, and M. F. Lappert, *J. Chem. Soc., Dalton Trans.*, 2268 (1976).

## Photochemical Probes of Hydrocarbon Chain Conformation in Solution

Mitchell A. Winnik

Lash Miller Chemical Laboratories and Erindale College, Department of Chemistry, University of Toronto, Toronto, Canada M5S 1A1

Received September 30, 1976

Concern about the shape of hydrocarbon chains began in the 1920's with the surface-tension studies of fatty acid monolayers by Langmuir.<sup>1</sup> For various reasons, which have been reviewed recently by Meyer and Stec,<sup>2</sup> he concluded that the normal alkanes would fold up into tight, ball-like configurations in the gas phase. This kind of argument assumes that the attractive enthalpy of pairwise contacts between remote  $\text{CH}_2$  groups is sufficient to overcome the maximum entropy associated with the random coil. The early arguments preceded our understanding that alkanes have access to only three rotational states about each carbon-carbon bond, with trans rotamers essentially half a kilocalorie more stable than gauche.<sup>3</sup>

The point of view persists, however, that hydrocarbon chains form compact configurations in the gas phase which maximize intramolecular contacts.<sup>4</sup> Various experiments have been given conflicting interpretations; however, electron diffraction studies by Bartell<sup>5</sup> firmly establish that butane, pentane, hexane, and heptane achieve conformations randomly distributed among rotamers favoring trans over gauche by  $E_g = 600$  cal/mol. For tetracosane in the gas phase, current evidence supports a random conformation.<sup>2</sup> The evidence is thermodynamic, and the choice in interpretation, as Meyer and Stec point out, is a rather delicate one.<sup>2</sup>

For hydrocarbon chains in solution, various points of view have been put forward. The weight of the evidence supports the contention that in dilute solution hydrocarbon chains are reasonably described as randomly oriented.<sup>6,7</sup> The number of compelling experiments are few. The conclusions rest on comparisons of these experimental results with semiempirical conformational calculations. There is also a growing body of evidence

suggesting that alkane-chain-containing molecules aggregate at modest concentrations, even in nonpolar solvents.<sup>8,9</sup> Contemporary interest in biological membranes and other phospholipid systems, in micelles, in microemulsions, in monolayers, and in other semi-structured systems is sufficiently intense that we can no longer be satisfied with a general picture of hydrocarbon chains in solution. Experiments are necessary which detail the shapes of these flexible molecules in dilute solution and in aggregates. These experiments in turn must be used to test the limits of current semiempirical models.

What are needed are sets of experiments which probe hydrocarbon chain shape from many points of view. Solvent effects on chain conformation must be investigated. In spite of suggestions that these effects are "small", they will be of considerable importance for our understanding if they can be described with sufficient precision. To choose an extreme example, few would doubt that a hydrocarbon chain in a phospholipid vesicle has a different average configuration than the

(1) I. Langmuir, "Third Colloid Symposium Monograph", The Chemical Catalog Co., New York, N.Y., 1925, pp 53-54.

(2) E. F. Meyer and K. S. Stec, *J. Am. Chem. Soc.*, **93**, 5451 (1971).

(3) (a) H. Morawetz, "Macromolecules in Solution", 1st ed, Interscience, New York, N.Y., 1965; (b) ref 3a, p 124; (c) ref 3a, Chapter II.

(4) J. C. McCoubrey, J. N. McCrae, and A. R. Ubbelohde, *J. Chem. Soc.*, 1961 (1951).

(5) L. S. Bartell and D. A. Kohl, *J. Chem. Phys.*, **39**, 3097 (1963).

(6) (a) G. D. Patterson and P. J. Flory, *J. Chem. Soc., Faraday Trans. 2*, **68**, 1098 (1972); (b) W. J. Leonard, Jr., R. L. Jernigan, and P. J. Flory, *J. Chem. Phys.*, **43**, 2256 (1965).

(7) M. A. Winnik, A. Lemire, D. S. Saunders, and C. K. Lee, *J. Am. Chem. Soc.*, **98**, 2000 (1976).

(8) G. W. Brady, *Acc. Chem. Res.*, **7**, 174 (1974); (b) G. W. Brady and D. B. Fein, *J. Appl. Crystallogr.*, **8**, 261 (1975); (c) G. W. Brady, C. Cohen-Addad, and E. F. X. Lyden, *J. Chem. Phys.*, **51**, 4320 (1969).

(9) (a) P. Tancrède, P. Bothorel, P. de St. Romain, and D. Patterson, *J. Chem. Soc., Faraday Trans. 2*, **73**, 15 (1977); P. Tancrède, P. Bothorel, and D. Patterson, *ibid.*, **73**, 29 (1977); (b) V. T. Lam, P. Picker, D. Patterson, and P. Tancrède, *J. Chem. Soc., Faraday Trans. 2*, **70**, 1465 (1974); M. D. Croucher and D. Patterson, *ibid.*, **70**, 1479 (1974); (c) P. Bothorel and G. Fourche, *ibid.*, **69**, 441 (1973); (d) P. Bothorel, C. Such, and C. Clément, *ibid.*, **69**, 1453 (1972); (e) C. Clément and P. Bothorel, *J. Chim. Phys.-Phys.-Chim. Biol.*, **61**, 878 (1964).

Mitchell A. Winnik was born in Milwaukee, Wis., in 1943. He did his undergraduate work first at the University of Wisconsin and later at Yale University. He took his graduate training at Columbia University in New York City, with Ronald Breslow. After a year's postdoctoral research at California Institute of Technology with George Hammond and a summer spent teaching chemistry in what is now Bangladesh, Dr. Winnik joined the faculty at the University of Toronto, where he is Associate Professor of Chemistry.

same length alkane in carbon tetrachloride solution.<sup>10,11</sup>

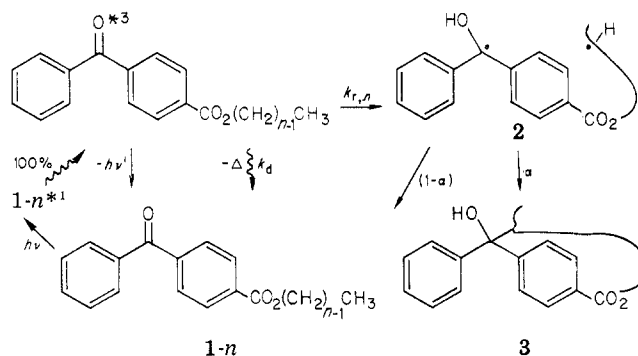
This Account describes our initial approaches to design new chemical probes of hydrocarbon chain conformation in dilute solution. Since we are looking for effects that may be small in magnitude, yet crucial in choosing between models on which calculations may be based, the problem is obviously complex. High precision is necessary. The chemistry and the physics of the probes themselves must be thoroughly understood. In addition, detailed comparison is necessary between various conformational models for their applicability to these new kinds of experiments.

### Conformational Analysis of Hydrocarbon Chains

There are many kinds of experiments with hydrocarbon chains which lend themselves to a conformational interpretation. Some are thermodynamic<sup>9a,b</sup> (entropy of melting<sup>10,11</sup>); others involve vectorial (dipole moments<sup>6b</sup>) or tensorial (optical anisotropy<sup>9</sup>) properties of the chains. Those easiest to visualize involve aspects of the mean separation of the chain ends.<sup>12</sup> Among these is the cyclization probability of the chain.<sup>13,14</sup> Cyclized chains represent only a small fraction of the total number of chain conformations. Probed accurately, they might be more sensitive than other chain properties to medium effects and excluded volume interactions.

While many such experiments were published by Ziegler and by Carothers 40 years ago,<sup>15</sup> little of an appropriate quantitative nature was reported. One sad facet of this new field of hydrocarbon chain conformation is that the theoretical calculations must draw upon experimental data not always in the proper form for direct comparison of theory and experiment. There is a wealth of new data on chain-length-dependent phenomena coming from the laboratories of NMR and ESR spectroscopists,<sup>16a</sup> photophysicists,<sup>16b</sup> polymer chemists,<sup>16c</sup> kineticists,<sup>16d</sup> and synthetic organic chemists.<sup>16e-g</sup> These scientists are often unaware of each others' work and of the rather stringent demands of the theoretical models now available. Part of the challenge of developing a conformational analysis of hydrocarbon chain conformation will be in trying to coordinate the presentation of this data in the proper form for theo-

Scheme I

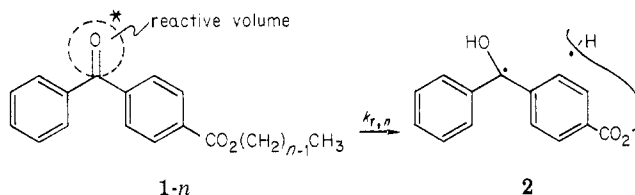


retical analysis. One can then focus on the contribution of chain shape to the phenomena of more immediate interest to these scientists.

### The Photochemical Probe

The most sensitive probes for studies in dilute solution are luminescent molecules. Emitted light is easy to measure, and the lifetime of the excited chromophore serves as a clock to establish the time scale of the intended observations. Hydrocarbon chains reach conformational equilibrium on the time scale of tens of nanoseconds. Benzophenone derivatives phosphoresce in fluid solution from their lowest triplet state with lifetimes  $\tau$  on the order of 10 to 100  $\mu$ s. Chemical reactions which quench the excited state shorten the triplet lifetime. These derivatives make ideal probes for the configuration of hydrocarbon chains at equilibrium.

Our probe of hydrocarbon chain conformation is the molecule 1-n, whose photochemistry was first studied



by Breslow.<sup>17</sup> In its excited triplet state it undergoes intramolecular hydrogen abstraction with a rate constant  $k_{r,n}$ . This rate constant is proportional to the probability that a  $\text{CH}_2$  group from the chain will occupy the reactive volume around the ketone carbonyl during the triplet lifetime. Each  $\text{CH}_2$  group can contribute to this reactivity, so we must note that  $k_{r,n}$  is a sum of reactivities over all the  $\text{CH}_2$  groups that can reach the reactive volume.

$$k_{r,n} = \sum_{i=1}^{n-1} k_{r,i} \propto P_n = \sum_{i=1}^{n-1} P_i \quad (1)$$

The rate constant  $k_{r,i}$  is that for reaction of the  $i$ th  $\text{CH}_2$  group. Since each of the  $\text{CH}_2$  groups is equally reactive toward hydrogen-abstracting agents,<sup>18</sup> each  $k_{r,i}$  is proportional to  $P_i$ , the probability of finding the  $i$ th  $\text{CH}_2$  group in the reactive volume.  $P_n$ , the total cyclization probability, is equal to the sum of the  $P_i$  values.

The rate constants  $k_{r,n}$  are obtained from flash photolysis experiments. The benzophenone derivatives

(17) R. Breslow and M. A. Winnik, *J. Am. Chem. Soc.*, **91**, 3083 (1969).

(18) N. C. Deno, R. Fishbein, and C. Pierson, *J. Am. Chem. Soc.*, **92**, 1451 (1970); P. Smit and H. J. den Hertog, *Recl. Trav. Chim. Pays Bas.*, **83**, 891 (1964).

(10) D. Marsh, *J. Membr. Biol.*, **18**, 145 (1974).

(11) (a) P. Bothorel and J. Belle, *C. R. Hebd. Seances Acad. Sci., Ser. C*, **282**, 437 (1976); (b) P. Bothorel, C. Lussan, and J. Belle, *ibid.*, **274**, 1541 (1972); (c) J. Belle and P. Bothorel, *ibid.*, **275**, 335 (1972); (d) *Biochem. Biophys. Res. Commun.*, **58**, 433 (1974); (e) J. Belle, P. Bothorel, and B. Lemaire, *FEBS Lett.*, **39**, 115 (1974).

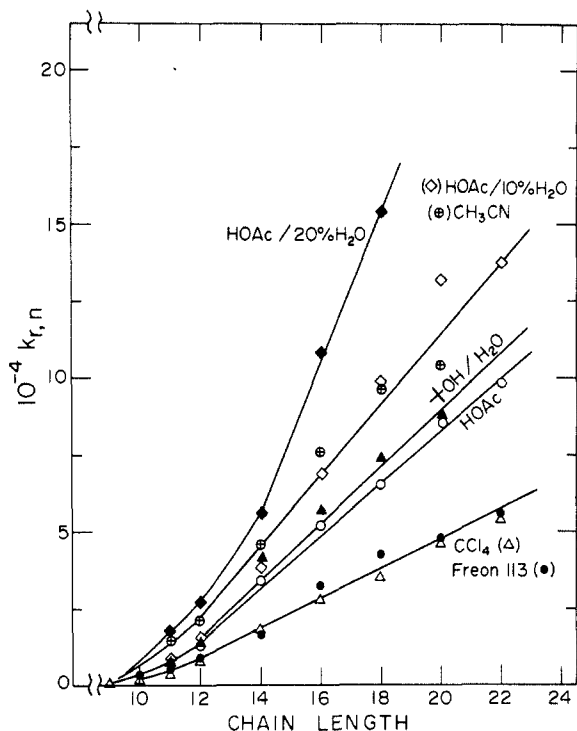
(12) (a) D. Y. Yoon and P. J. Flory, *J. Chem. Phys.*, **61**, 5366 (1974); (b) M. Fixman and R. Alben, *ibid.*, **58**, 1553 (1973).

(13) H. Jacobsen and W. H. Stockmayer, *J. Chem. Phys.*, **18**, 1600 (1950).

(14) (a) J. F. Brown and G. M. J. Slusarczuk, *J. Am. Chem. Soc.*, **87**, 931 (1965); (b) P. J. Flory and J. A. Semlyen, *ibid.*, **88**, 3209 (1966); (c) J. A. Semlyen and P. V. Wright, *Polymer*, **10**, 543 (1969); J. A. Semlyen, *Adv. Polymer Sci.*, **21**, 42 (1976).

(15) For a review, see G. M. Bennet, *Trans. Faraday Soc.*, **37**, 794 (1941).

(16) (a) K. Shimada and M. Szwarc, *J. Am. Chem. Soc.*, **97**, 3313, 3321 (1975); (b) K. Zachariasse in "The Exciplex", G. Gordon and W. R. Ware, Ed., Academic Press, New York, N.Y., 1975, p 275; K. Zachariasse and W. Kühnle, *Z. Phys. Chem. (Frankfurt am Main)*, **101**, 267 (1976); (c) J. Put and F. C. DeSchryver, *J. Am. Chem. Soc.*, **95**, 137 (1973); L. H. Leenders and F. C. DeSchryver, *J. Org. Chem.*, **38**, 957 (1973); N. Boens, M. DeBrackeleire, J. Huybrechts, and F. C. DeSchryver, *Z. Phys. Chem. (Frankfurt am Main)*, **101**, 417 (1976); (d) G. Illuminati, L. Mandolini, and B. Masci, *J. Am. Chem. Soc.*, **96**, 1422 (1974); **97**, 4960 (1975); (e) Y. Sato, H. Nakai, T. Mizoguchi, Y. Hatanaka, and Y. Kanaoka, *ibid.*, **98**, 2349 (1976); (f) C. R. Eck, D. J. Hunter, and T. Money, *J. Chem. Soc., Chem. Commun.*, **865** (1974); (g) M. A. Winnik and D. S. Saunders, *ibid.*, **156** (1976).



**Figure 1.** Values of the rate constant  $k_{r,n}$  in 1 for intramolecular emission quenching in various solvents:  $\text{CCl}_4$  ( $\Delta$ ), Freon 113 ( $\bullet$ ), acetic acid ( $\circ$ ), 10% water-acetic acid, v/v ( $\diamond$ ), 20% water-acetic acid, v/v ( $\blacklozenge$ ), *tert*-butyl alcohol-water azeotrope ( $\blacktriangle$ ), acetonitrile ( $\oplus$ ).

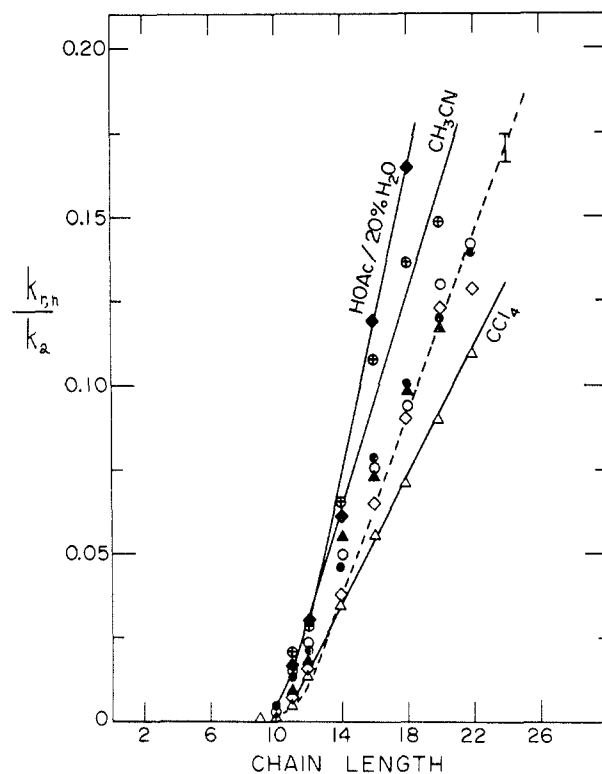
1, when irradiated, emit light in fluid solution. These solutions must be carefully purified and rigorously degassed. The reciprocal lifetime  $\tau_n^{-1}$  of this emission is equal to the sum of first-order and pseudo-first-order processes which lead to the decay of the phosphorescent state.<sup>19</sup> These steps (and the photoproducts<sup>17</sup>) are shown in Scheme I.

Three processes lead to depopulation of the triplet state of 1-*n*: (i)  $k_p$  describes the emission probability. It has a value of  $180 \pm 20 \text{ s}^{-1}$  for all chain lengths and all solvents so far investigated.<sup>19c</sup> (ii)  $k_d$  describes the sum of all chain-length-independent processes which deactivate  $1^*3$  radiationlessly. These include solvent quenching, solvent impurity quenching, and internal conversion. Its value is primarily a measure of solvent purity. (iii)  $k_{r,n}$  describes the chain-length-dependent radiationless decay processes, which are best understood as intramolecular hydrogen abstraction reactions. This scheme allows all the irreproducible aspects of our experiments associated with the delicate problem of solvent purity to show up only in the  $k_d$  term. Flash irradiation of solutions of 1-*n* gives exponential decays of emission from which  $\tau_n$  values are obtained. These lifetimes are independent of chain length for  $n < 9$ ; therefore,  $k_{r,n} = 0$  for these chain lengths. For longer chain lengths, intramolecular quenching causes a decrease in  $\tau_n$ , and  $k_{r,n}$  can be calculated from eq 2. The

$$\frac{1}{\tau_n} - \frac{1}{\tau_1} = k_{r,n} \quad (\tau_1 \equiv \tau_{n=1}) \quad (2)$$

precision in  $k_{r,n}$  is  $\pm 5\%$ .

(19) (a) M. A. Winnik, C. K. Lee, S. Basu, and D. S. Saunders, *J. Am. Chem. Soc.*, **96**, 6182 (1974); (b) M. A. Winnik, S. Basu, C. K. Lee, and D. S. Saunders, *ibid.*, **98**, 2928 (1976); (c) M. A. Winnik and A. Lemire, *Chem. Phys. Lett.*, **46**, 283 (1977).

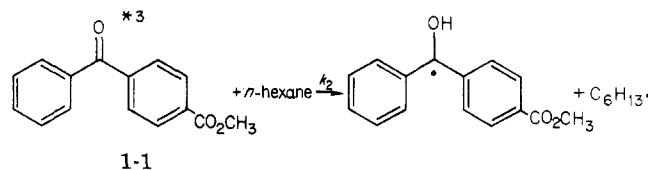


**Figure 2.** Values of the effective concentration  $k_{r,n}/k_a$  for the same solvents as in Figure 1. The dashed line represents the results of theoretical calculations, reweighted to 25 °C, assuming that the reactive radius in 1 is 1.9 Å (see text). The error bar on the plot represents one standard deviation when the cyclization probability is reweighted to 25 °C with  $E_g = 0.5 \text{ kcal/mol}$ . For temperature effects on cyclization probability, see Figure 5.

Values of  $k_{r,n}$  can be obtained in any solvent in which benzophenone emission can be observed at room temperature and for which  $\tau_1 \geq 10 \mu\text{s}$ . We have obtained these values in carbon tetrachloride, acetic acid, Freon 113 (1,1,2-trichlorotrifluoroethane), acetonitrile, and various mixtures of *tert*-butyl alcohol and acetic acid with water. Other solvents not yet examined are neopentane, benzene, fluorocarbons,  $\text{SO}_2$ , and acetone. Experimental results are summarized in Figure 1.

It is clear from the data in Figure 1 that  $k_{r,n}$  increases monotonically with chain length. No quenching occurs for chains with fewer than nine carbons, and this provides experimental proof that quenching benzophenone emission by alkanes requires contact between the alkane and the ketone carbonyl group. It also appears that polar solvents markedly increase  $k_{r,n}$ .

The increase of  $k_{r,n}$  with increase in solvent polarity could have two sources: solvent polarity could affect the reactivity of the excited chromophore or it could perturb  $P_n$ , the cyclization probability of the chain. Neither effect has a solid precedent in the chemical literature. In order to separate these effects we chose to model solvent effects on triplet reactivity by examining the bimolecular reaction between *n*-hexane and the triplet state of 1-1. We made the explicit as-



sumption that all solvent effects on the photoreactivity

of the 4-carboxybenzophenone chromophore will appear in this reaction.

Values of  $k_2$  turn out to be sensitive to solvent polarity in much the same way as  $k_{r,n}$ . Thus the differences in  $k_{r,n}$  values (Figure 1) largely disappear in the corresponding ( $k_{r,n}/k_2$ ) values (Figure 2).

Significant differences remain, however, and these are of fundamental importance. The ratio ( $k_{r,n}/k_2$ ) has units of molarity. It may be thought of as the effective concentration ( $C_{\text{eff}}$ ) of chain elements in the reactive volume.<sup>20</sup> Its solvent dependence should reflect solvent effects only on chain shape.  $C_{\text{eff}}$  is proportional to  $P_n$ ; it is clear that the cyclization probability of the chain is enhanced in acetonitrile and 20% aqueous acetic acid over its values in the other five solvents. Furthermore, carbon tetrachloride suppresses the chain cyclization probability.<sup>7</sup>

### Polymer Theory and Short Chains

Before commenting on the specific nature of the solvent-chain interactions, we must consider theoretical models which allow us to interpret ( $k_{r,n}/k_2$ ) values in terms of the detailed conformation of the chain.

Methods for calculating the time-averaged dimensions of polymer molecules have become quite sophisticated. The most successful model from a quantitative point of view has been the rotational isomeric state model.<sup>21a</sup> This model takes detailed account of bond lengths and bond angles in the repeat unit and short-range interactions usually not over more than two bonds. Because this model neglects excluded volume effects, its success is limited to those unique solvent conditions called " $\theta$  solvents". These poor solvents compress the polymer just sufficiently to overcome the expansion due to remote steric effects which keep two elements of the molecule from occupying the same space.

One of Flory's major contributions to polymer science has been an experimental definition of  $\theta$  solvents. Under these conditions, experiment and theory can be compared, and the agreement has been quite good. Flory has argued that  $\theta$  conditions are achieved in the bulk amorphous state of a polymer,<sup>21b</sup> a point of view supported by neutron-scattering studies of molten polyethylene.<sup>22</sup> Consequently, his calculations can provide mean dimensions for high polymers in a wide variety of realistic environments.

For short chains one cannot experimentally determine  $\theta$  conditions independent of the conformation-dependent measurement. Nonetheless, when experiments with short chains have been compared with rotational isomeric state calculations, general features have indeed been described. Differences exist, especially in case of cyclization phenomena.<sup>23</sup> It is difficult to know whether these differences are due to problems with the experimental results, limitations of the model, or failure of the experimental conditions to satisfy certain assumptions in the model. These problems, of

course, exist for every theoretical model.

It is important to distinguish the mean dimensions of a polymer, by which one refers to its time-averaged shape, from classes of configurations which contribute to a particular experimental phenomenon. In the study of cyclization phenomena, one focuses primarily on chains which have their termini in proximity. These chains may represent only a small fraction of the total number of accessible configurations and thus contribute relatively little to the mean dimensions of the chain. They may also be much more sensitive to excluded volume effects than other configurations which are more extended. Similarly, a bulky substituent attached to the end of the chain might affect the mean dimensions of the chain very differently from its effect on various subclasses of configurations which contribute to those dimensions.

**The Excluded Volume Effect.** There are many definitions of excluded volume, a situation which has led to controversy and confusion over the use of the term. One can envision four factors which affect the shape of a polymer beyond that dictated by its accessible rotational states. These are: (i) the steric bulk of the chain and other bulky substituents; (ii) other repulsive interactions (coulombic, dipolar); (iii) attractive potentials between chain elements; and (iv) solvent effects. In the  $\theta$  state, the solvent is chosen to compress the polymer sufficiently to overcome exactly the effects of i, ii, and iii. This yields the "unperturbed dimensions", and  $\theta$  conditions become the reference state.<sup>21</sup> For polymer chemists who think in terms of the rotational isomeric state model, the excluded volume effect is the complex combination of effects i-iv.

Polymer physicists prefer to separate solvent effects from those intrinsic to the chain. They work with various models which share in common an account of the steric volume of the chain.<sup>24</sup> As physicists, they tend to be more concerned with fundamental implications of their models than with application of their models to the detailed properties of polymers in solution. Specifying a reference state is less important; the choice of a reference state would depend on the form of the potential of mean force between chain elements introduced into the model. If no interactions beyond steric repulsion are considered, the athermal solution becomes the reference state. This is stated explicitly by Bellemans.<sup>24c</sup> In his lattice model, each site not occupied by part of the polymer is taken to be filled by a solvent molecule. For nonpolar polymers, where long-range forces are not present, the athermal solvent exactly cancels the effects of attractive and repulsive terms which are not steric in origin. Here excluded volume is simply a steric effect.

The importance of steric effects in determining the shape of chains of under 50 atoms is not well understood. The mean-squared end-to-end length ( $\langle r^2 \rangle$ ) of hydrocarbon chains has been calculated for several models. Smith evaluated  $\langle r^2 \rangle$  for chains up to 18 carbons on a diamond lattice.<sup>25a</sup> Other authors have

(20) H. Morawetz, *Pure Appl. Chem.*, **38**, 267 (1974).

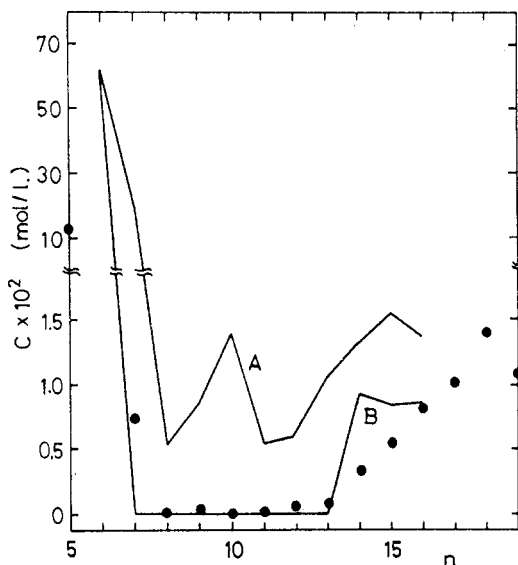
(21) (a) P. J. Flory, "Statistical Mechanics of Chain Molecules", Interscience, New York, N.Y., 1969; (b) P. J. Flory, "Principles of Polymer Chemistry", Cornell University Press, Ithaca, N.Y., 1953, p 426.

(22) G. Lieser, E. W. Fischer, and K. Ibel, *Polymer Lett.*, **33**, 39 (1975).

(23) (a) P. J. Flory, U. W. Sutter, and M. Mutter, *J. Am. Chem. Soc.*, **98**, 5733 (1976); (b) U. W. Sutter, M. Mutter, and P. J. Flory, *ibid.*, **98**, 5740 (1976); (c) M. Mutter, U. W. Sutter, and P. J. Flory, *ibid.*, **98**, 5745 (1976);

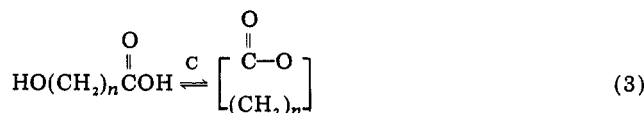
(24) (a) J. G. Curro, *J. Chem. Phys.*, **61**, 1203 (1974); (b) F. T. Wall and F. Mandel, *ibid.*, **63**, 4592 (1975); (c) E. DeVos and A. Bellemans, *Macromolecules*, **8**, 651 (1975); **7**, 812 (1974); (d) S. F. Edwards, *J. Phys. A*, **8**, 1670 (1975).

(25) (a) R. P. Smith, *J. Chem. Phys.*, **40**, 2963 (1964); **42**, 1162 (1965); **47**, 5364 (1967); (b) K. Suzuki and Y. Nakata, *Bull. Chem. Soc. Jpn.*, **43**, 1006 (1970); (c) M. Lal and D. Spencer, *Mol. Phys.*, **22**, 649 (1971).

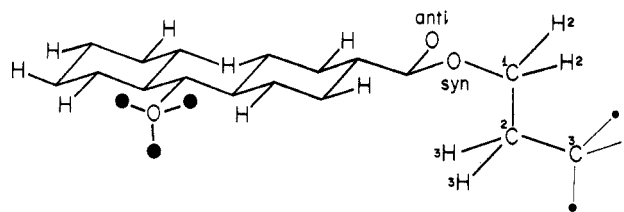


**Figure 3.** Plot of  $C$ , the equilibrium constant (●) for lactone formation in  $\text{HO}(\text{CH}_2)_n\text{CO}_2\text{H}$ , vs.  $n$ , the number of  $\text{CH}_2$  groups. The curves derive from off-lattice exact enumeration calculations by Sisido.<sup>28</sup> Curve A shows the effect of first neighbor exclusions, and curve B, the effect of second neighbor exclusions on the cyclization probability. Second neighbor exclusions imply that steric effects of the hydrogens on  $\text{CH}_2$  groups are taken into account in the calculation.

employed off-lattice models with excluded volume considered,<sup>25</sup> the most sophisticated being that of Lol and Spencer.<sup>25c</sup> The values of  $\langle r^2 \rangle$  are difficult to compare because the authors have chosen different values of  $E_g$ , the gauche-trans potential difference, and different forms for the nonbonded interaction potential. The similarity between their values and those of Flory,<sup>26</sup> which neglect remote steric interactions, suggests that these steric effects have only a minor effect on properties related to fairly extended chains of these lengths. For properties more sensitive to chain ends in closer proximity, the situation is far from clear. Freire and Horta have considered it necessary to account for remote interactions in estimating mean reciprocal distances  $\langle R_{ij}^{-1} \rangle$  between carbons in  $n$ -alkanes up to  $\text{C}_{50}$ . From these values, they were able to calculate the translational diffusion coefficients measured for these alkanes in nonpolar solvents.<sup>27</sup>



For cyclization reactions, Sisido's calculations<sup>28</sup> underscore the importance of taking account of excluded volume. To simulate the equilibrium constant  $C$  for the lactonization reaction<sup>29</sup> (3), Sisido calculated the partition function for cyclized chains,  $Z_0$ , and that for all chains,  $Z_T$ . From their ratio he calculated  $C$  as a function of chain length. His data in Figure 3 make it



**Figure 4.** Diamond lattice model of benzophenone-4-carboxylate, showing the first three carbons of an  $n$ -alkyl ester. The benzophenone rings and ester group are coplanar. The two rotamers of the ester group are designated syn and anti and the ester group is in the trans configuration. Equal numbers of chains are grown from each rotamer. The first three carbons in the chain are labeled  $C_1, C_2, C_3$ . The circles (●) indicate possible loci for  $C_4$ . The sites designated (●) represent "hit" sites. If any of these sites are occupied by an H from a  $\text{CH}_2$  group, that chain is counted as a reactive (hitting) conformation.

clear that even general features of the experimental results are not obtained unless account is taken of the thickness of the chain.<sup>30</sup>

**Regular Solutions.** The athermal solution is an unrealistic reference state for comparing conformational calculations with experiments, since the heat of mixing of two components is rarely zero. More versatile is the concept of a regular solution, developed by Hildebrand<sup>31</sup> to overcome this restriction. In a regular solution, the heat of mixing,  $\Delta H_m$ , is sufficiently small relative to  $RT$  that the mixing process allows the entropy of the system to reach a maximum. The thermodynamics of regular solutions have been elaborated in some detail.

Polymers, dilute in a regular solution, achieve maximum conformational entropy. Properties obtained experimentally in these solutions may be compared with those deduced from conformational models which account for remote steric interactions but which ignore the pair potentials associated with solvent-solute and nonsteric intramolecular solute-solute interactions. Among the solvents we have studied, carbon tetrachloride has a very small heat of mixing with the  $n$ -alkanes.<sup>32</sup> Hydrocarbon chains in  $\text{CCl}_4$  should satisfy the assumptions of a regular solution. We take the regular solution as the reference state for our lattice-based model.

### Calculations Applied to the Photocyclization of 1

In our own experiments, steric effects of the benzophenone chromophore, as well as excluded volume effects, are undoubtedly important. Lattice-based models allow one to take these effects into account. A diamond lattice closely resembles the tetrahedral geometry of the hydrocarbon chains, and adequate mathematical techniques exist for exploring random walks on a lattice. In collaboration with my colleague, Professor Whittington, we worked to develop a mathematical model general enough to describe cyclization in any specific molecule.<sup>33</sup>

(30) The reader is referred to similar and very important analogous studies of cyclization of poly( $N$ -methylglycine) by Sisido and his co-workers: (a) M. Sisido, T. Mitamura, Y. Imanishi, and T. Higashimura, *Macromolecules*, **9**, 316 (1976); (b) M. Sisido, Y. Imanishi, and T. Higashimura, *ibid.*, **9**, 320 (1976); (c) M. Sisido, Y. Imanishi, and T. Higashimura, *ibid.*, **9**, 389 (1976).

(31) J. H. Hildebrand, J. M. Prausnitz, and R. L. Scott, "Regular and Related Solutions", Van Nostrand Reinhold Co., New York, N.Y., 1970.

(32) (a) J. R. Goates, R. J. Sullivan, and J. B. Ott, *J. Phys. Chem.*, **63**, 589 (1963); (b) V. Mathot and A. Desmyter, *J. Chem. Phys.*, **21**, 782 (1953).

(26) (a) R. L. Jernigan and P. J. Flory, *J. Chem. Phys.*, **50**, 4178 (1969); (b) *ibid.*, **50**, 4185 (1969).

(27) J. J. Freire and A. Horta, *J. Chem. Phys.*, **65**, 4049 (1976); see also *ibid.*, **65**, 2860, 2867 (1976).

(28) M. Sisido, *Macromolecules*, **4**, 737 (1971).

(29) (a) M. Stoll and A. Rouve, *Helv. Chim. Acta*, **17**, 1283, 1289 (1934); (b) **18**, 1807 (1935); (c) H. Morawetz and N. Goodman, *Macromolecules*, **3**, 699 (1970).

In this model, the bulky chromophore (the "head group") is modeled in the lattice by specifying as occupied those sites which best resemble the bulk of head group. For 1-*n*, a remarkably good fit can be obtained by simulating benzophenone-4-carboxylate as 4-carboxycyclohexyl cyclohexyl ketone, omitting the axial hydrogens. This model is shown in Figure 4. Chains are grown stepwise to a length of 30 carbons. C<sub>1</sub> is added so that the ester is constrained to be trans and coplanar with the rings of the benzophenone. C<sub>2</sub> is added at random to one of the three lattice sites adjacent to C<sub>1</sub>. After C<sub>2</sub> is chosen, the remaining valences on C<sub>1</sub> are assigned to hydrogens. C<sub>3</sub> is added at random to one of the three lattice sites adjacent to C<sub>2</sub>. Hydrogens are then added to the remaining valences on C<sub>2</sub>. The process is continued until the chain is trapped and "dies" or until it reaches 30 steps.

By growing many chains, we can use Monte Carlo techniques to estimate the number of conformations of all chains up to 30 carbons.<sup>33</sup> We can estimate partition functions, end-to-end distances, moments of the chain distribution, temperature effects, and cyclization probability. Cyclization probability is obtained in a very easy manner. We designate the three lattice sites adjacent to the ketone oxygen as reactive (see Figure 4). If a hydrogen from a CH<sub>2</sub> group should occupy a reactive site, we call that a "hit". We then use the computer to count the sample of hitting chains separately from the sample of all chains.

The cyclization probability,  $P_n$ , is the ratio of the estimated partition functions for hitting chains ( $Z_0$  and all chains ( $Z_T$ ), respectively (see eq 4).  $P_n$  is obtained

$$P_n = \frac{Z_{\text{hitting conformations}}}{Z_{\text{all conformations}}} = \frac{Z_0}{Z_T} \quad (4)$$

by summing  $P_i$ , the ratio  $Z_0/Z_T$  for chains of length  $n$  which suffer a hit at the  $i$ th CH<sub>2</sub> group. From the individual  $P_i$  values, we can also estimate the relative amount of hydrogen abstraction at each of the CH<sub>2</sub> groups in an  $n$  carbon chain.<sup>33</sup>

Lattice-based models have a number of potentially serious weaknesses. Short-range effects are accommodated in a far less sophisticated manner than in the rotational isomeric state model. There are problems with modeling the head group in the lattice, which fortunately seem not to affect us here. Only even-membered rings can be formed on a diamond lattice, which appears to be merely an annoyance in the calculation of the chain-length dependence of the cyclization probability. It does, however, limit the utility of the model for examining the relative cyclization probability of each carbon in a chain. Two serious artifacts, that C-H bond lengths are exaggerated and that we resort to hard sphere nonbonded interactions, fortunately, have offsetting effects. One lives with the weaknesses of a fairly simple model in order to take account of proximate and remote steric (excluded volume) effects which we believe predominate in the experiments we wish to simulate.

In our calculations, typical samples involved 60 000 to 400 000 chains. Several important sampling tech-

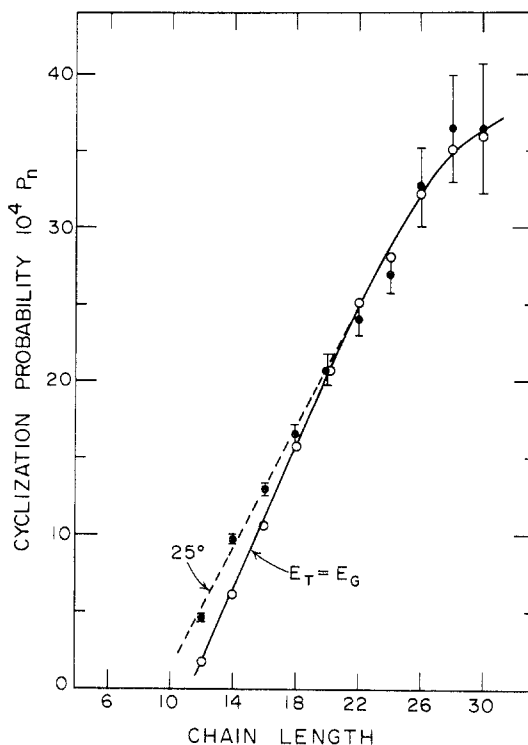


Figure 5. Temperature effects in the cyclization probability of 1 as a function of chain length. The solid line and the points (O) are values calculated for  $E_t = E_g$ . Here, error bars representing one standard deviation are smaller than the points. When each gauche rotamer is reweighted to 25 °C using  $E_g = E_t + 0.5$  kcal/mol, the dashed line is obtained. These error bars indicate one standard deviation.

niques were used.<sup>33</sup> Since the calculations require significant amounts of computer time, we must not throw any information away. The coordinates of each step in the random walk and its corresponding counting weight were stored on tape. Temperature effects were introduced by reweighting gauche conformations in the sample by  $\exp(-\Delta E/RT)$ , where  $\Delta E = 500$  cal/mol. Reweighting increases the error bars in the estimates; current methods allow us to examine chains only for temperatures above -20 °C.

Figure 5 shows that cyclization probability in 1 is remarkably insensitive to temperature. The major discernible effect in changing the temperature from infinity ( $E_t = E_g$ ) to 25 °C is to increase the error bars representing one standard deviation. This surprising result is a consequence of the fraction of gauche bonds in the sample of cyclized chains. This fraction is virtually identical to the fraction of gauche bonds estimated for all chains. Both numerator and denominator in eq 4 are equally affected by a change in temperature.

**Quantitative Comparisons.** The most important question to ask is whether the experimental data can be described by a model which presumes randomly oriented chains in an indifferent solvent. It appears from the shape of the curve in Figure 5 that the theoretical cyclization probabilities are at least proportional to the  $(k_{r,n}/k_2)$  ratios in Figure 2. A more quantitative comparison is possible. The ratio  $k_{r,n}/k_2$  has units of molarity. It represents the effective concentration,  $C_{\text{eff}}$ , of chain elements in the reactive volume.<sup>19</sup>  $P_n$  may be related to  $C_{\text{eff}}$  as in eq 5, where  $P_n$  is the probability of finding a CH<sub>2</sub> group with an H in the reactive volume,  $P_n/N_A$  is the number of moles of CH<sub>2</sub> groups in that

(33) (a) M. A. Winnik, R. E. Trueman, G. Jackowski, D. S. Saunders, and S. G. Whittington, *J. Am. Chem. Soc.*, **96**, 4843 (1974); (b) M. A. Winnik, D. S. Saunders, G. Jackowski, and R. E. Trueman, *ibid.*, **96**, 7510 (1974).

$$C_{\text{eff}} = \frac{P_n}{N_A V} \quad (5)$$

volume  $V$ , and  $N_A$  is Avogadro's number.

A serious difficulty arises in deciding what volume about the carbonyl group is reactive to hydrogen abstraction. On one hand one might presume that volume is defined by the shape of the  $n$  orbitals from which an electron is promoted in the  $n\pi^*$  excited state. There is some evidence to that effect in charge-transfer quenching of aliphatic ketone singlet states.<sup>34</sup> Under those circumstances only the "in-plane" hit sites should be included in the model for calculation of  $Z_0$ . We have carried out this calculation and find  $P_n$  reduced by somewhat less than one-third over the values in Figure 5. The problem is akin to the one raised several years ago by the question of "orbital steering".<sup>35</sup> It is no easy matter to define the orientation of reacting groups. Sisido took his reactive volume to be a sphere with its radius treated as an adjustable parameter.<sup>28</sup> This is not a weakness inherent in his calculation. Rather it represents the state of the art in understanding those details of organic chemical reaction mechanisms.

If, for simplicity, we take the reactive volume in 1 as spherical, with radius  $r$  in ångströms, and appropriate values are substituted into eq 5, then  $C_{\text{eff}} = 397P_n/r^3$ . This equation allows a quantitative comparison between the experimental data and the theoretical calculations, where  $r$  is the only adjustable parameter. Chemical intuition sets rather severe limits on  $r$ , and the equation describing  $C_{\text{eff}}$  is very sensitive to small changes in  $r$ . The dashed line in Figure 2 describes the effective concentration calculated from values of  $P_n$  with the reactive radius chosen to be 1.9 Å. For  $r = 2.1$  Å, the theoretical line passes through the experimental points for  $\text{CCl}_4$  as a solvent. This agreement for chemically reasonable values of  $r$  gives us confidence that the most

(34) N. J. Turro, J. C. Dalton, G. Garrington, M. Niemczyk, and D. M. Pond, *J. Am. Chem. Soc.*, **92**, 6978 (1970).

(35) (a) A. Dafforn and D. A. Koshland, *Biochem. Biophys. Res. Commun.*, **52**, 779 (1973), and references therein; (b) H. B. Burgi, and J. D. Dunitz, J. M. Lehn, and G. Wipff, *Tetrahedron*, **30**, 1563 (1974).

important physical features of molecule 1 have been incorporated into the theoretical model.

We can now begin to interpret the data in Figure 2 in terms of solvent effects on chain shape. Carbon tetrachloride is clearly the best solvent for hydrocarbon chains. In terms of our reference state, hydrocarbon chains in  $\text{CCl}_4$  best fit the assumptions of our model. Acetic acid, Freon 113, and the mixed solvents containing small amounts of water are equally poorer solvents than carbon tetrachloride, but not so bad as acetonitrile and 20% aqueous acetic acid, which seriously perturb chain shape and increase the cyclization probability.

The "goodness" of acetic acid as a solvent for hydrocarbon chains requires comment. Acetic acid exists in solution as a dimer. The dimer has a dielectric constant of 6, only slightly more polar than benzene. Addition of small amounts of water may disrupt some of the dimers, but our experimental results suggest that the chain remains solvated by the nonpolar dimer. Only when the mole fraction of water approaches 0.5 is the chain forced to interact with water and the polar acetic acid monomer.

The details of the conformational changes in 1 that occur in different solvents are not yet apparent. Polar and protic solvents increase the cyclization probability of the chain. Specific solvation effects are probably responsible. Repulsive solvent-chain interactions, which might locally disrupt favored solvent-solvent interactions, would serve to increase the fraction of chains in the environment of the chromophore.

*I wish to express my appreciation to the graduate students and postdoctoral fellows who carried out all the calculations and virtually all the experiments described here. Their labors and their ideas, along with the generous financial support of the Research Corporation and the National Research Council of Canada, brought this research to fruition. Professor S. G. Whittington has made many valuable contributions to this research. It is a pleasure to acknowledge his help on all aspects of our theoretical calculations. I also wish to thank Professor Herbert Morawetz for his critical comments on many aspects of this work.*

## Ylide Formation and Rearrangement in the Reaction of Carbene with Divalent Sulfur Compounds

Wataru Ando

*Department of Chemistry, The University of Tsukuba, Niiharigun, Ibaraki 300-31, Japan*

*Received September 16, 1976*

Sulfur ylides are being used increasingly in synthetic chemistry,<sup>1</sup> and some evidence is available suggesting their involvement in biochemical processes. One of the features of ylides which adds interest to their study is

Wataru Ando was born in Shizuoka, Japan, in 1934. He worked for his Ph.D. degree under S. Oae (Osaka City University) and did postdoctoral work at UCLA with C. S. Foote and at Princeton University with M. Jones, Jr. From 1967 to 1974 he was associate professor at Gunma University, and from 1975 professor at the University of Tsukuba. His research has involved the study of the mechanism of reactive intermediates, such as carbene, nitrene, sulfur ylide, singlet oxygen, and silicon-carbon double bond, in hetero compounds, and photochemistry.

their unique molecular structure, involving as it does the question of multiple bonding between a carbanion and the onium atom.

Two fundamentally distinct approaches to the generation of these ylides exist. The most widely employed method for the preparation of sulfur ylides is the so-called "salt method", whereby a sulfide effects a nucleophilic substitution on an alkyl halide to form a

(1) B. M. Trost and L. S. Melvin, Jr., "Sulfur Ylides", Academic Press, New York, N.Y., 1975.