concentration of **2** with pseudo-first-order conditions for trapping.

Efficient trapping of the tautomer **2** with benzaldehyde indicates its nucleophilic character and suggests that the enolic functionality dominates the quinone methide functionality. Bioreduction of daunomycin or adriamycin intercalated in DNA might then lead to formation of a covalent bond between the 7-position of **3** or 7-deoxyadriamycinone and the 2- or 4-position of a pyrimidine base or the 2- or 6-position of a purine base on the basis of electron density calculations.[11,12] Trapping experiments with simple pyrimidine and purine bases analogous to trapping with benzaldehyde have been unsuccessful to date because the high concentrations of trapping agent necessary cannot be achieved.

In summary we reported here the first experimental evidence for the nucleophilic reactivity, other than protonation, for the tautomer **2**, proposed as a biologically active form of daunomycin.

Acknowledgment. This investigation was facilitated by the following support: PHS Grant CA-24665, DHHS; University of Colorado, CCRW; Developmental Therapeutics Program, NCI; 3M Co.; University of Colorado Clinical Mass Spectrometry Resource, PHS Grant RR-01152, DHHS. We also thank Robert Murphy and Keith Clay for assistance with the FAB mass spectrometry.

---

(11) Pullman, B.; Pullman, A. *Adv. Heterocycl. Chem.* **1971**, *13*, 77.

(12) Kwiatkowski, J. S.; Pullman, B. *Adv. Heterocycl. Chem.* **1975**, *18*, 199.

Photodecomposition of Alkanones in Urea Inclusion Compounds

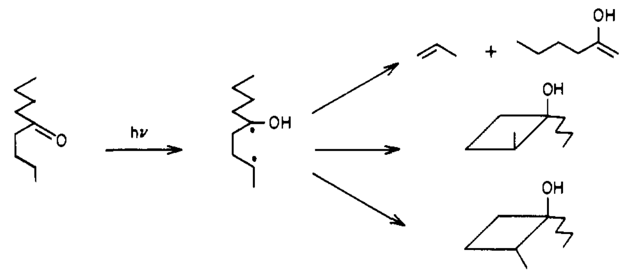
H. L. Casal,[1] P. de Mayo,*[2] J. F. Miranda,[2] and
J. C. Scaiano*[1]

Division of Chemistry
National Research Council of Canada[3a]
Ottawa, Canada K1A 0R6
Photochemistry Unit,[3b] *Department of Chemistry*
The University of Western Ontario
London, Canada N6A 5B7

Received February 10, 1983

During recent years, photochemical processes in ordered or constrained systems have been the object of considerable attention. Among such systems have been micelles,[4,5] vesicles,[6] microemulsions,[6,7] monolayers,[5,8] and liquid crystals.[9] Solid-phase studies have been reported on molecules adsorbed on surfaces[10] and in crystalline[11] and polymeric[12] systems. Only crystals and liquid monolayers, so far, offer a well-defined location and environment. In this context the recent reports by Lahav and coworkers of the photoaddition of guest ketones to deoxycholic acid are particularly interesting.[13] In this communication we report that urea inclusion compounds provide an environment wherein photoreactions may be carried out, with consequences different from those observed in homogeneous solution, and that the steric constraints imposed by the host upon the guest in the once-formed inclusion compound are not as severe as the ready steric inhibition of formation might suggest.

Scheme I



The crystal system, unit cell characteristics, and dimensions of urea inclusion compounds are well established.[14,15] Urea in the inclusion compounds crystallizes in an hexagonal lattice (as opposed to tetragonal for free urea) in which there are long channels of ~5 Å internal diameter.[14,15] This is sufficient to accommodate linear paraffin-like molecules in the planar zig-zag conformation. Longitudinal rotation of hydrocarbon segments is relatively free while other motions (e.g., gauche–trans isomerization) are more severely restricted. The steric restraints are such that one methyl substituent in a long chain is enough to make complex formation difficult.[14]

Most of our experiments have been carried out with 5-nonanone. This, in solution undergoes photodecomposition predominantly via the Norrish Type II reaction, leading to 2-hexanone, propylene, and two isomeric cyclobutanols, Scheme I. The inclusion compound is prepared by crystallization from concentrated urea solutions in methanol, following the addition of neat 5-nonanone. The samples were characterized by Raman spectroscopy;[17] this

---

(1) National Research Council.

(2) University of Western Ontario.

(3) (a) Issued as NRCC-21346. (b) Publication No. 297 from the Photochemistry Unit, University of Western Ontario.

(4) Thomas, J. K *Chem. Rev.* **1980**, *83*, 203–299. Lee, K. H.; Mayo, P. de *J. Chem. Soc., Chem. Commun.* **1979**, 493–495. Berenjian N.; Mayo, P. de; Sturgeon, M. E.; Sydnes, L. K.; Weedon, A. C. *Can. J. Chem.* **1982**, *60*, 425–436. Nakamura, Y.; Kato, T.; Morita, Y. *Tetrahedron Lett.* **1981**, 1025–1028. Nakamura, Y.; Imakura, Y.; Morita, Y. *Chem. Lett.* **1978**, 965–968. Turro, N. J.; Grätzel, M.; Braun, A. M. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 675. Turro, N. J. *Tetrahedron* **1982**, *18*, 809–817. Scaiano, J. C.; Abuin, E. B.; Stewart, L. C. *J. Am. Chem. Soc.* **1982**, *104*, 5673–5679.

(5) Whitten, D. G. *Angew. Chem., Int. Ed. Engl.* **1978**, *82*, 937–949.

(6) Fendler, J. H. *Acc. Chem. Res.* **1980**, *13*, 7–13; *J. Phys. Chem.* **1980**, *84*, 1485–1491.

(7) E. G.: Sakellariou-Fargues, R.; Maurette, M.-T.; Oliveros, E.; Riviére, M.; Lattes, A. *J. Photochem.* **1982**, *18* 101–107. Rico, I.; Maurette, M. T.; Oliveros, E.; Riviére, M.; Lattes, A. *Tetrahedron* **1980**, *36*, 1779–1783. Gregoritch, S. J.; Thomas, J. K. *J. Phys. Chem.* **1980**, *84*, 1491–1495.

(8) E. G.: Whitten, D. G.; Russell, J. C.; Schmehl, R. H. *Tetrahedron* **1982**, *38*, 2455–2487.

(9) Anderson, V. C.; Craig, B. B.; Weiss, R. G. *J. Am. Chem. Soc.* **1982**, *104*, 2972–2977. Nebonne, J. M.; Weiss, R. G. *Ibid.* **1979**, *101*, 402–407. Nakano, T.; Hirata, H., *Bull. Chem. Soc. Jpn.* **1982**, *55*, 947–948. Tanaka, Y.; Tsuchiya, H.; Suzuki, M.; Tsuda, K.; Takano, J.; Kurihara, H. *Mol. Cryst. Liq. Cryst.* **1981**, *68*, 113–125. Levanon, H. *Chem. Phys. Lett.* **1982**, *90*, 465–471.

(10) Avnir, D.; Johnston, L. J.; Mayo, P. de; Wong, S. K. *J. Chem. Soc., Chem. Commun.* **1981**, 958–959. Bauer, R. K.; Borenstein, R.; Mayo, P. de, Okada, K.; Rafalska, R.; Ware, W. R.; Wu, K. C. *J. Am. Chem. Soc.* **1982**, *104*, 4635–4644 and references cited therein. Bauer, R. K.; Mayo, P. de, Ware, W. R.; Wu, K. C. *J. Phys. Chem.* **1982**, *86*, 3781–3789. Johnston, L. J.; Mayo, P. de; Wong, S. K. *J. Chem. Soc., Chem. Commun.* **1982**, 1106–1107. Kessler, R. W.; Wilkinson, F. *J. Chem. Soc., Faraday Trans. 1* **1981**, *77*, 309–320.

(11) Schmidt, G. M. J. In "Solid State Photochemistry"; Monographs in Modern Chemistry; Ginsburg, D., Ed.; Verlag Chemie: Weinhein, 1976; Vol. 8. Ramasubbu, N.; Row, T. M. G.; Venkaresan, K.; Ramamurthy, V. *J. Chem. Soc., Chem. Commun.* **1982**, *178*–179. Jiang, Z. Q.; Scheffer, J. R.; Secco, A. S.; Trotter, J. *Tetrahedron Lett.* **1981**, 891–894. Scheffer, J. R. *Acc. Chem. Res.* **1980**, *13*, 283–290. Jones, W.; Subramanian, R.; Theocharis, C. R.; Thomas, J. M.; Thomas, N. W. *J. Phys. Chem.* **1981**, *85*, 2594–2597. Nakanish, H. I.; Jones, W.; Thomas, J. M.; Hursthouse, M. B.; Motevalli, M. *J. Chem. Soc., Chem. Commun.* **1980**, 611–612.

(12) Damen, J.; Neckers, D. C.; *J. Am. Chem. Soc.* **1980**, *102*, 3265–3267.

(13) Chang, H. C.; Popovitz-Biro, R.; Lahav, M.; Leiserowitz, L. *J. Am. Chem. Soc.* **1982**, *104*, 614–616. Popovitz-Biro, R.; Tang, C. P.; Chang, H. C.; Shochet, N. R.; M.; Leiserowitz, L. *Nouv. J. Chim.* **1982**, *6*, 75–78; *Ibid.* **1981**, *5*, 475–478. Lahav, M.; Leiserowitz, R.; Popovitz-Biro, R.; Tang, C. P. *J. Am. Chem. Soc.* **1978**, *100*, 2542–2544. Popovitz-Biro, R.; Chang, H. C.; Tang, C. P.; Shochet, N. R.; Lahav, M.; Leiserowitz, L. *Pure Appl. Chem.* **1980**, *52*, 2693–2704.

(14) Schlenk, H. *Prog. Chem. Fats Other Lipids* **1954**, *2*, 243–267. Fetterly, L. C. In "Non-Stoichiometric Compounds"; Mandelcorn, L., Ed.; Academic Press: New York, 1964; pp 491–567.

(15) Smith, A. E. *Acta Crystallog.* **1952**, *5*, 224–235.

(16) Gilson, D. F. R.; McDowell, C. A. *Mol. Phys.* **1961**, *4*, 125–134. Umemoto, K.; Danyluk, S. S. *J. Phys. Chem.* **1967**, *71*, 3757–3764.

(17) Raman spectra were recorded at a resolution of ca. 2 cm^{-1} with a Jarrell-Ash Model 15-100 double monochromator equipped with photon-counting detection. Excitation was provided by the 5145-Å line from a Spectra-Physics 164 Argon ion laser delivering 150 mW at the sample. See: Fawcett, V.; Long, D. A. *J. Raman Spectrosc.* **1975**, *3*, 263–275.

0002-7863/83/1505-5155$01.50/0

can differentiate unequivocally between urea in tetragonal or hexagonal lattices, which correspond to free urea and the clathrate, respectively. According to this analysis, typical samples contained over 90% of the urea in the hexagonal form. Scanning electron micrographs revealed the presence of both types of crystals—predominantly those that were hexagonal—and was in qualitative agreement with the Raman data (which has been established to correlate with X-ray structures)[17] as was the elemental analysis.[18] The latter yielded an urea–ketone molar ratio of 8.6, to be compared with 7.6 that can be estimated on the basis of molecular dimensions. Irradiation of the 5-nonanone clathrate at room temperature under nitrogen[19] followed by addition of methanol led to Type II products, though, to our surprise, essentially *only one cyclobutanol isomer*.[20] This was characterized as the one having the methyl and hydroxyl groups in the cis configuration.[21] Neither Type I products, such as valeraldehyde or *n*-octane, nor products containing urea moieties were detected. This is consistent with laser flash photolysis experiments which show that urea is a very inefficient quencher of carbonyl triplets.[23]

Prolonged irradiation of the samples led to further photodecomposition of the 2-hexanone produced, affording acetone and, similarly, essentially only one cyclobutanol.[24] This, judging from its gas-chromatographic behavior, is also believed to be the cis isomer.

The cyclization to fragmentation ratio for 5-nonanone in urea was 0.67, compared with 0.32 in methanol, taking into account total cyclobutanol. The two ratios are 0.65 and 0.19, respectively, if only the cis isomer is taken into consideration. Product quantum yields for solid samples such as these are difficult to measure, although judging from the irradiation times required (by comparison with liquid samples), they must be only slightly lower.

The absence of Type I products is surprising in view of the fact that some Type I reaction usually takes place in solution[25] and that this is the only decay path available to the excited ketone that does not require the formation of a ring structure or transition state. Some Type I process may of course occur, provided the only reaction path of the germinate radical pair is its recombination to yield the parent ketone.

The Type II reaction involves a six-center transition state;[26] the steric demands of this transitional conformation, as well as those of the cyclobutanol produced, are such that the preparation of an inclusion product meeting such demands would be very difficult.[14] However, the geometry that can be attained by an included molecule may not necessarily be that permitting inclusion to occur. Examination of space filling models shows that the formation of the *cis*-cyclobutanol has less stringent rotational requirements, thus favoring the formation of this isomer. In fact, the cyclobutanol obtained, having both alkyl groups in pseudoequatorial positions, is expected to be more compact. Hydrogen bonding to the crystal lattice may help keep the biradical conformation quasi-frozen long enough for cyclization to occur (included molecules are known to have preferred orientations[15] in the urea channels). Related observations have been made in the irradiation of benzoin alkyl ethers adsorbed on silica gel,[27] where the formation of only one cyclobutanol was noted.

An obvious concern is whether the six-center abstraction required for the Type II reaction occurs at the expense of the integrity of the crystal lattice. This seems not to be the case for the 2-hexanone produced in the primary photodecomposition, since further photocyclizaton follows the same pattern, i.e., stereospecificity. Preliminary experiments with 2-undecanone show the same type of behavior, although in this case ~7% *trans*-cyclobutanol is also formed. These observations suggest, but do not completely confirm, that the cyclobutanols also remain included molecules.

Acknowledgment. We thank Dr. A. P. Roth for recording the electron micrographs.

---

(18) The sample used in most studies gave C, 32.14%; N, 36.67%; H, 8.09%.

(19) Typically the 313-nm line for a mercury lamp was isolated with an interference filter. A few experiments using Rayonet RPR-3000 lamps did not show any difference with the 313-nm experiments.

(20) Only 3% of the trans isomer could be detected, even in an experiment exceeding 95% conversion.

(21) The two isomers were obtained in better than 90% purity by preparative gas chromatography of the reaction products in *tert*-butyl alcohol and characterized by ^{13}C and ^{1}H NMR spectroscopy. One isomer had ^{13}C chemical shifts (in ppm from Me_4Si) of 76.3 (C-1), 39.1 (C-2), 14.7 (Me at C-2), and 40.9 (CH_2 at C-1), consistent with the methyl being cis to the OH group. The other isomer showed the corresponding signals at 77.0, 43.8, 14.1, and 33.5, respectively, which is consistent with the methyl group being trans to the OH.[22] The ^{1}H chemical shift of the Me at C-2 were affected by successive additions of the shift reagent Pra-Resolve-II-d_{30} to a different extent for each isomer. The cis isomer was more affected, consistent with the above assignment. The isomer obtained in the urea complexes has the same mass spectra (GC–MS) as the authentic cis isomer.

(22) Christe, M.; Reich, H. J.; Roberts, J. D. *J. Am. Chem. Soc.* **1971**, *93*, 3463–3468.

(23) These experiments were carried out by using benzophenone in wet acetonitrile and led to $k_q \ll 4 \times 10^4\ M^{-1}\ s^{-1}$.

(24) This fragmentation may introduce some error in the cyclization–fragmentation ratios from 5-nonanone as a result of product photolysis. The cyclization product from 2-hexanone contains 5% of the trans isomer.

(25) Encina, M. V.; Lissi, E. A. *J. Photochem.* **1978**, *8*, 131–143.

(26) Wagner, P. J. *Acc. Chem. Res.* **1971**, *4*, 168–177. Lewis, F. D.; Johnson, R. W. *J. Am. Chem. Soc.* **1972**, *94*, 8914–8916. Lewis, F. D.; Johnson, E. W.; Ruden, R. A. *Ibid.* **1972**, *94*, 4292–4297. Wagner, P. J.; Kelso, P. A.; Kemppainen, A. E.; Zepp, R. G. *Ibid.* **1972**, *94*, 7500–7506.

(27) Benzoin methyl ether adsorbed on dry silica gel at −78 °C gives 40% Type I rearrangement product, 6% Type II cleavage (to deoxybenzoin), and 6% of a single oxetanol. The isopropyl ether under the same condition gives 50% Type I rearrangement product, 13% Type II cleavage, and 20% of a single oxetanol. The nature of the products is attributed to conformational control and restricted movement induced by the silica gel (Mayo, P. de; Nakamura, J.; Tsang, P. W. K.; Wong, S. K. *J. Am. Chem. Soc.* **1982**, *104*, 6824–6825. Nakamura, A., unpublished observations).

Determination of the Heat of Reaction for the Formation of Diphenylcarbene from Diphenyldiazomethane Using Photoacoustic Calorimetry

John D. Simon and Kevin S. Peters*

Department of Chemistry, Harvard University
Cambridge, Massachusetts 02138

Received March 28, 1983

In recent years, there has been a growing interest in elucidating the energetics of carbene reactions. In part, this growth has been stimulated by the use of these intermediates as a testing ground for molecular orbital theory.[1] To date, the central thrust of carbene research has been directed toward establishing both the spin multiplicity and the energy separation between the ground and excited states.[2] With the exception of methylene,[3] there has been no experimental determination of either the heats of formation of these reactive intermediates or the energetics for their reactions. In this communication, a direct measurement of the heat of reaction is reported for both the formation of diphenylcarbene from diphenyldiazomethane in degassed benzene and the formation of diphenylmethyl ethyl ether resulting from singlet carbene insertion into the O–H bond in ethanol.

Photoacoustic calorimetry is a method we have recently developed for determining the heat of reaction from ground-state

---

(1) (a) Bender, C. F.; Schaefer, H. F., III *J. Am. Chem. Soc.* **1970**, *92*, 4984. (b) Lathan, W. A.; Hehre, W. J.; Curtiss, L. A.; Pople, J. A. *Ibid.* **1971**, *93*, 6377. (c) Hay, P. J.; Hunt, J.; Goddard, W. A., III *Chem. Phys. Lett.* **1972**, *13*, 30. (d) Dewar, M. J. S.; Haddon, R. C.; Weiner, P. K. *J. Am. Chem. Soc.* **1974**, *96*, 253. (e) Shih, S. K.; Peyerimhoff, S. D.; Buenker, R. J.; Perič, M. *Chem. Phys. Lett.* **1978**, *55*, 206. (f) Harding, L. B.; Goddard, W. A., III *Ibid.* **1978**, *55*, 217.

(2) (a) Zittel, P. F.; Ellison, G. B.; ONeal, S. V.; Herbst, E.; Lineberger, W. C.; Reinhardt, W. P. *J. Am. Chem. Soc.* **1976**, *98*, 3731. (b) Feldmann, D.; Meier, K.; Zacharias, H.; Welge, K. H. *Chem. Phys. Lett.* **1978**, *59*, 171. (c) Lengel, R. K.; Zare, R. N. *J. Am. Chem. Soc.* **1978**, *100*, 7495. (d) Eisenthal, K. B.; Turro, N. J.; Aikawa, M.; Butcher, J. A., Jr.; DuPuy, C.; Hefferon, G.; Hetherington, W.; Korenowski, G. M.; McAuliffe, M. J. *Ibid.* **1980**, *102*, 6563.

(3) Laufer, A. H.; Okabe, H. *J. Am. Chem. Soc.* **1971**, *93*, 4137. In this paper they report the upper limit of $\Delta H_f(CH_2N_2) \leq 60$ kcal/mol and ΔH_f^0-(triplet CH_2:) = 93 kcal/mol.

0002-7863/83/1505-5156$01.50/0