affording a brown concentrate which was found by nmr analysis to consist of 43–44% **2a**, 46–47% **3a**, 5–6% **4a**, and 4–5% **5a**.

An identical photolysis in the all-Pyrex vessel provided a colorless solution which contained 70% **2a** and 30% **3a** as determined by nmr analysis. Vpc analysis of the product revealed 1–2% **4a**, indicating that the reaction afforded a 1–2% total yield of oxygen migration.

Optimum conditions for the reaction at 3000 Å in Pyrex appeared to be 3.33–3.50 hr of irradiation per 50 mg of **2a** in 50 ml of methanol. At this point, an apparent equilibrium mixture of **2a** (56%) and **3a** (44%) was generated. Under these conditions, a total of 2–3% **4a** plus **5a** was evident by vpc analysis.

Photolysis of 2a at 2537 and 3000 Å in an Oxygen Atmosphere. A solution of 40 mg of **2a** in 50 ml of methanol (in Pyrex) was purged for 10 min with oxygen and then irradiated at 3000 Å for 2 hr under an oxygen atmosphere. Nmr analysis of the reaction mixture indicated that 70% **2a** and 30% **3a** were present.

A similar reaction of **2a** using 2537-Å irradiation and the quartz reaction vessel resulted in the formation of isomers **3a**, **4a**, and **5a** in proportions essentially the same as when the reaction was carried out under nitrogen atmosphere.

Photolysis of 4a at 2537 Å. A vpc pure sample of **4a** (34 mg) was dissolved in 50 ml of methanol and the solution was photolyzed at 2537 Å for 1.7 hr in the quartz vessel. The resulting brown solution was concentrated under reduced pressure, affording a dark brown concentrate containing a significant quantity of $CDCl_3$-insoluble material. An nmr analysis of the concentrate showed 57% **4a** and 43% **5a**. There was no evidence in the spectrum of either **2a** or **3a**.

Photolysis of 4a at 3000 Å. The reaction mixture from the photolysis of **4a** at 2537 Å was dissolved in methanol (50 ml) and irradiated at 3000 Å in quartz for 1.25 hr. Nmr analysis of the concentrated reaction product revealed 41% **4a** and 59% **5a**. Neither nmr nor vpc analyses showed the presence of **2a** or **3a**.

Photolysis of 4b at 2537 Å. Approximately 15 μl of vpc-pure **4b** was dissolved in 5 ml of *n*-pentane, and the solution was photolyzed at 2537 Å in the quartz vessel for 1 hr. The pentane was then removed under a slow nitrogen flow. Analysis of the concentrate by nmr showed 79% **4b** and 21% **5b**.

Further photolysis of the above mixture in methanol (5 ml) for 2.5 hr provided a reaction product relatively enriched in **5b** but containing a substantial amount of $CDCl_3$-insoluble material.

Thermal Isomerization of 3a. A solution of 54 mg of **3a** in 25 ml of dry, distilled benzene was immersed in an oil bath preheated to 84°. The solution was then stirred at reflux under nitrogen for 3 hr. An nmr spectrum of the concentrate obtained by removal of the benzene under reduced pressure showed signals due only to **3a**. The sample from the benzene reflux was then dissolved in 12 ml of dry, distilled toluene, immersed in a preheated oil bath (118–121°), and refluxed under a nitrogen atmosphere for 0.75 hr. Nmr analysis of the product showed it to consist of 81% **3a** and 19% **2a**. Refluxing of the product in toluene was then repeated three times which provided the following data: 1.75 hr of total reflux, 52% **3a** and 48% **2a**; 2.75 hr, 38% **3a** and 62% **2a**; 3.50 hr, 22% **3a** and 78% **2a**.

Thermal Isomerization of 3b. A solution of 35 μl of pure **3b** in 4 ml of benzene was stirred at reflux for a total of 5 hr. No cis to trans isomerization could be detected by nmr analysis of the product.

The compound was subsequently refluxed in 4 ml of toluene for 2.5 hr. Analysis of the product revealed 35% **3b** and 65% **2b**. A further 2.5 hr of thermal treatment of the reaction product in toluene resulted in a complete cis to trans conversion.

Relative Thermal Stability of 3a and 5a. A photolysis mixture containing by nmr integration the relative proportions of 28% **2a**, 39% **3a**, 22% **4a**, and 10% **5a** was dissolved in toluene, immersed in a preheated (115°) oil bath, and refluxed for 1.5 hr. Nmr analysis of the concentrate showed the following relative proportions: 35% **2a**, 35% **3a**, and 30% **4a**. No *cis*-**5a** was detected by nmr.

Acknowledgment. The authors wish to thank Drs. C. L. Stevens and P. M. Pillai for helpful discussions and nmr spectra of elaiomycin. Funds for the Hitachi RMU-6 mass spectrometer were provided, in part, by Grant No. GP8643 from the National Science Foundation.

Organic Photochemistry. XVII. The Solution-Phase Photodimerization of Dimethylthymine[1,2]

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Abstract: Dimethylthymine photodimerizes in solution to give four cis-fused cyclobutane-type dimers. Dimerization of a 0.1 *M* aqueous solution is efficient and apparently singlet derived (intersystem crossing in this solvent seems to be negligible). Thermal osmometry data give evidence for appreciable ground-state aggregation, and dimerization from these aggregates through excimer intermediates is proposed. Dimerization in nonaqueous solvents is less efficient and arises from both the singlet and triplet states (reaction from the singlet state may involve efficient dimerization of trace amounts of aggregates). The product distribution, percentage of triplet involvement, and efficiency of DMT intersystem crossing (ϕ_{ic}) all vary with solvent polarity, and an explanation of the latter two phenomena, involving level inversion, is presented. A wavelength dependence of ϕ_{ic} may also be due to the population of upper excited states. The extensive base stacking of DMT in water makes this system a reasonable model for the thymine units in DNA.

The photodimerization of thymine has been a subject of intense interest to the area of photobiology for a number of years, primarily because this reaction is known to be involved in the photoinactivation of deoxyribonucleic acid (DNA) *in vivo* and *in vitro*.[4] Our attention was drawn to this area several years ago, since the considerable effort which had been

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(1) Part XVI: O. Rodriquez and H. Morrison, *Chem. Commun.*, 679 (1971).

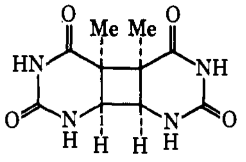
(2) Abstracted from the doctoral dissertation of Robert Kleopfer, Purdue University, January, 1971. Presented, in part, at the 155th National Meeting of the American Chemical Society, April 1–5, 1968, San Francisco, Calif. For preliminary communications, see (a) H. Morrison, A. Feeley, and R. Kleopfer, *Chem. Commun.*, 358 (1968); (b) H. Morrison and R. Kleopfer, *J. Amer. Chem. Soc.*, **90**, 5037 (1968).

(3) Address inquiries to this author.

(4) For a recent review, see: J. G. Burr, *Advan. Photochem.*, 6, 193 (1968).

directed toward elucidating the mechanism of this dimerization[5] had neglected the photochemical properties of thymine (and its derivatives) in solution at high concentrations. We felt that such a reaction environment might prove to be a reasonable model for the situation in DNA, in which base stacking[6] brings pyrimidine units into close proximity. Detailed studies had been made on a model system involving photodimerization of thymine and its analogs in an ice matrix, conditions chosen as a result of suggestions by Szent-Gyorgyi of "structured water" in biological systems.[7] Photolyses in ice were, in fact, strikingly fruitful in providing efficient photodimerization of thymine,[8] but it soon became apparent that this success was due to aggregation of thymine into microcrystals of the hydrate,[9–11] whereby photolysis could, in effect, be viewed as proceeding from the solid state.

Attempts to obtain efficient photodimerization of thymine in solution had been, by and large, unsuccessful,[8a,12] since the dilute solutions which had been studied gave rise only inefficiently to such dimerization.[13–15] We were struck by two apparent similarities between the photochemical properties of thymine (in ice, dinucleotides, and DNA) and the photodimerization of concentrated solutions (0.3 M) of coumarin in polar media.[16–18] First, it had been observed that the structure of the thymine "ice dimer,"[15b,19] the dominant dimer in TpT,[15] and the major thymine dimer in DNA[15b,20] all had the syn head-to-head (syn h–h) cyclobutane structure I, a stereochemistry identical with that observed for the dimer II formed by irradiation of coumarin in polar media (four isomers are possible; see Scheme I). Second, we had proposed[16,18] that a singlet excimer preceded formation of the syn h–h coumarin dimer, and excimer emission from di- and polynucleotides, as well as from DNA itself, had been reported.[21] It thus seemed (a) that efficient photodimerization of thymine (or a derivative thereof, see below) in concentrated solutions might be feasible, (b) that such dimerization might exhibit some of the sensitivity to solvent, substrate concentration, and temperature which led to our proposal of an excimer precursor for coumarin dimerization, and (c) were such observations forthcoming, extrapolation to the mechanism of thymine dimerization in polynucleotides and DNA might be possible.



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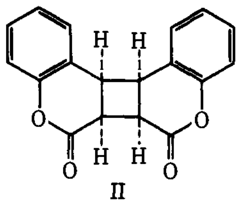

II

We chose to initiate these studies with the N,N-dimethylated derivative of thymine (DMT), rather than with thymine itself, because of the lower melting points of its (three) known dimers and its greater solubility in both aqueous and organic solvents. It was known that irradiation of DMT at 254 nm, in frozen aqueous media, gives rise to two dimers[10a,22] in approximately equal amounts; the higher melting of these (mp 256°) had been identified as the syn h–h dimer IV[23] with the second isomer (mp 229°) tentatively assigned as the syn h–t structure III.[15b] A third dimer (mp 254°) had been prepared by methylation of a 1-methylthymine dimer and suggested to be the anti h–h structure VI.[23,24] The fourth of the four possible dimers, V, was as yet unreported.

Results

A. Preparative Photolysis of Dimethylthymine in Aqueous Solution. Identification of Four DMT Dimers. Photolysis of DMT (0.10 M) in aqueous solutions with Pyrex filtered light from a medium-pressure mercury lamp ($\lambda > 280$ nm) leads to the formation of all four DMT dimers (glpc), one of which precipitates out in essentially pure form as a white solid, mp 261–262°. Column chromatography on acid-washed alumina provided pure samples of two additional dimers, mp 229 and 256°; a fourth dimer was observed by glpc as a minor component of the reaction mixture.

The two dimers obtained by chromatography were shown to be the same as those formed by irradiation of DMT in ice, the higher melting of these now having been shown by several groups[23,25–27] to be the syn h–h dimer IV. The lower melting product has been unambiguously assigned the syn h–t stereochemistry III on the basis of X-ray diffraction[28] and other data.[2a,25,26] The minor component was shown to be identical with Weinblum's dimer "B" (mp 255°)[26] by comparative

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(5) For recent discussions, see (a) A. A. Lamola, *Photochem. Photobiol.*, 7, 619 (1968); (b) J. Eisinger and R. G. Shulman, *Science*, **161**, 1311 (1968); (c) J. Eisinger and A. A. Lamola, *Mol. Photochem.*, **1**, 209 (1969).

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(7) A. Szent-Gyorgyi, "Bioenergetics," Academic Press, New York, N. Y., 1957; A. Szent-Gyorgyi, *Science*, **124**, 873 (1956).

(8) (a) R. Beukers, J. Ijlstra, and W. Berends, *Recl. Trav. Chim. Pays-Bas*, 77, 729 (1958); (b) R. Beukers and W. Berends, *Biochim. Biophys. Acta*, **41**, 550 (1960).

(9) A. Szent-Gyorgyi, "Introduction to a Submolecular Biology," Academic Press, New York, N. Y., 1960.

(10) (a) S. Y. Wang, *Nature (London)*, **190**, 690 (1961); (b) S. Y. Wang, *Photochem. Photobiol.*, 3, 395 (1964); (c) S. Y. Wang, *Fed. Proc., Fed. Amer. Soc. Exp. Biol.*, 24, S-71 (1965).

(11) R. Gerdil, *Acta Crystallogr.*, 14, 333 (1961).

(12) A. Rorsch, R. Beukers, J. Ijlstra, and W. Berends, *Recl. Trav. Chim. Pays-Bas*, 77, 423 (1958).

(13) A. A. Lamola and J. P. Mittal, *Science*, **154**, 1560 (1966).

(14) See also R. Alcantara and S. Y. Wang, *Photochem. Photobiol.*, 4, 473 (1965).

(15) Not surprisingly, relatively efficient ($\phi = 0.02$) internal "dimerization" had been reported for thymidylyl-(3′-5′)-thymidine (TpT): (a) H. E. Johns, M. L. Pearson, J. C. Le Blanc, and C. W. Helleiner, *J. Mol. Biol.* 9, 503 (1964); (b) D. Weinblum and H. E. Johns, *Biochim. Biophys. Acta*, **114**, 450 (1966).

(16) H. Morrison, H. Curtis, and T. McDowell, *J. Amer. Chem. Soc.*, **88**, 5415 (1966).

(17) C. H. Krauch, S. Farid, and G. O. Schenck, *Chem. Ber.*, **99**, 625 (1966).

(18) For a recent discussion, see: R. Hoffman, P. Wells, and H. Morrison, *J. Org. Chem.*, 36, 102 (1971).

(19) G. M. Blackburn and R. J. H. Davies, *Chem. Commun.*, 215 (1965).

(20) G. M. Blackburn and R. J. H. Davies, *Biochem. Biophys. Res. Commun.*, 22, 704 (1966).

(21) J. Eisinger, M. Gueron, R. G. Shulman, and T. Yamane, *Proc. Nat. Acad. Sci. U. S.*, **55**, 1015 (1966).

(22) D. L. Wulff and G. Fraenkel, *Biochim. Biophys. Acta*, **51**, 332 (1961).

(23) G. M. Blackburn and R. J. H. Davies, *J. Chem. Soc. C*, 1342 (1966).

(24) R. F. Stewart, *Biochim. Biophys. Acta*, **75**, 129 (1963); R. F. Stewart as reported in ref 15b.

(25) D. P. Hollis and S. Y. Wang, *J. Org. Chem.*, **32**, 1620 (1967).

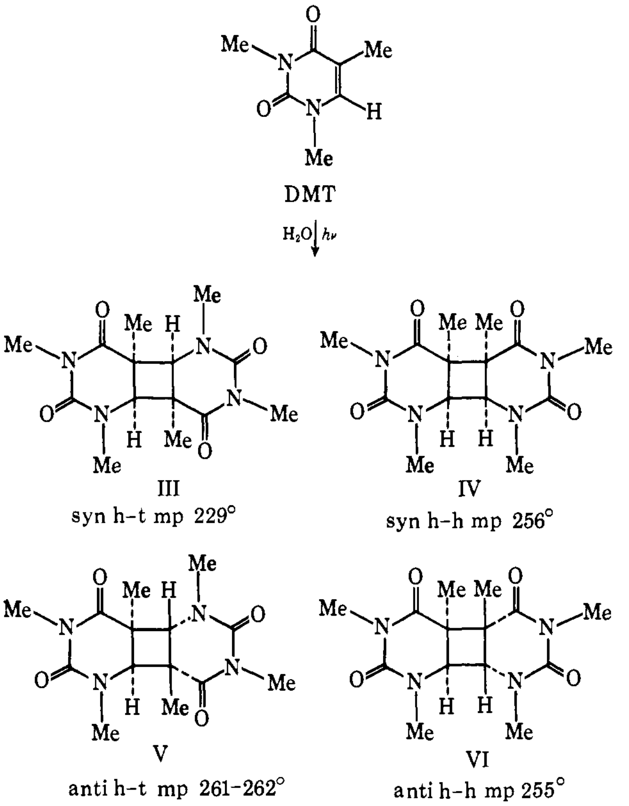
(26) D. Weinblum, F. P. Ottensmeyer, and G. F. Wright, *Biochim. Biophys. Acta*, **155**, 24 (1968).

(27) N. Camerman and A. Camerman, *J. Amer. Chem. Soc.*, **92**, 2523 (1970).

(28) N. Camerman, D. Weinblum, and S. C. Nyburg, *ibid.*, **91**, 982 (1969).

glpc[29] and is therefore assigned[2a,26] the anti h-h structure VI. This leaves the anti h-t stereochemistry V as the logical choice for the new (mp 261-262°) dimer,[30] an assignment verified by the appearance of a singlet ^{13}C-H satellite peak (J = 158 ± 2 Hz) for the cyclobutane hydrogens.[25,31,32] The dimer structures are shown in Scheme I.

Scheme I


DMT

III
syn h-t mp 229°

IV
syn h-h mp 256°

V
anti h-t mp 261-262°

VI
anti h-h mp 255°

B. Quantum Efficiencies for Dimer Formation (ϕ_{DF}). The quantum efficiency for dimer formation in water was determined using a Bausch and Lomb monochromator set at 297 ± 11 nm, with the light intensity measured by uranyl oxalate actinometry. A value of 0.014 was measured.[33] Values for other solvents were then determined relative to water by turntable experiments (actually ϕ_{DF} was measured in methanol, relative to water, and then other organic solvents were measured relative to methanol); corrections were made where necessary for the difference in light absorption by DMT from solvent to solvent. The data are presented in Table I. For all the solvents shown, dimers were the only observable products (at 0.1 M DMT)[35] and it was demonstrated for water and benzene that all the loss of DMT could be accounted for by dimer formation. Dimerization in water is clearly much faster than in the organic solvents.

Table I. ϕ_{DF} Values for Various Solvents[a,b]

Solvent	ϕ_{DF}	Solvent	ϕ_{DF}
Dioxane	0.0018	Toluene	0.0025
Benzene	0.0026	Glyme	0.0024
Ethyl acetate	0.0025	Water[c]	0.0141
Methanol	0.0020	D_2O	0.015
DMF	0.0023	Water-15% EtOH	0.006
Acetonitrile	0.0015		
CH_3CN-1 M $NaClO_4$	0.0013		

[a] All solutions were 0.10 M in DMT. [b] $\lambda \geq 280$ nm. [c] $\lambda = 297 \pm 11$ nm.

C. Dimer Distribution upon Direct Irradiation of DMT. The effect of solvent on the product distribution among the four dimers was determined by a series of turntable experiments, with conversions limited in most cases to ≤15%. The data are shown in Table II.

Table II. Solvent Effect on Dimer Distribution[a]

Solvent (ϵ)	Syn h-t	Syn h-h	Anti h-t	Anti h-h
Dioxane (2)	61	11	26	1
Toluene (2)	62	16	21	2
Benzene (2)	57	20	20	3
Ethyl acetate (6)	52	32	14	3
Glyme (8)	55	27	17	2
tert-Butyl alcohol (11)	61	17	21	2
1-Butanol (17)	51	31	16	2
Methanol (33)	42	37	18	3
Acetonitrile (38)	37	49	11	4
Dimethylformamide (38)	31	56	9	5
Glyme-1 M $NaClO_4$	29	54	12	5
CH_3CN-1 M $NaClO_4$	28	49	12	12
Water-15% ethanol	39	38	18	5
Deuterium oxide (78)	37	39	19	6
Water (79)	38	39	18	6
Water-1 M $NaClO_4$	35	42	17	6

[a] All solutions were 0.1 M in DMT; distributions are in percentages and are averages rounded off to the nearest whole number.

Data for several solutions containing sodium perchlorate are included in Table II (and in Table I) because of our observation that the addition of this salt provides an additional probe into a photoreaction's sensitivity to solvent polarity.[36]

D. Quenching of the Photodimerization by *cis*-Piperylene. Partial quenching of the photodimerization by the triplet quencher, *cis*-piperylene, is observed.[37] Maximum quenching is reached at 0.05 M diene or less, with concentrations as high as 0.2 M diene having been tested. The limiting value for quenching does vary with the solvent, however, as evidenced by the data in Table III,[38] *i.e.*, there is only a small triplet component for dimerization in polar solvents but a substantial fraction in nonpolar solvents.

By combining the data in Tables I and III, one can calculate the quantum efficiencies for dimerization from the singlet state ($\phi_{DF}{}^1$) as a function of solvent (Table IV). Values of $\phi_{DF}{}^1$ for *all* organic solvents are essen-

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(29) We are grateful to Dr. Weinblum for providing us with a sample of this dimer.

(30) This assumes only cis ring fusion for the thymine dimers; this dimer was, in fact, shown not to be isomerized by base. We also verified that this product could be cleaved to DMT monomers upon irradiation with 254-nm light.

(31) We are grateful to Dr. H. Ziffer of the National Institutes of Health for the ^{13}C-H measurement.

(32) R. Anet, *Tetrahedron Lett.*, 3713 (1965).

(33) This value corrects our initial report[2a,b] of ϕ_{DF} = 0.05 and is in good agreement with data of Lisewski and Wierzchowski.[34]

(34) R. Lisewski and K. L. Wierzchowski, *Chem. Commun.*, 348 (1969).

(35) Several other products, presently under study, are formed in dilute solution in addition to the dimers.

(36) H. Morrison and R. Hoffman, *Chem. Commun.*, 1453 (1968).

(37) All of the DMT loss in benzene in the presence of piperylene is accountable as dimer.

(38) The data in Table III are from experiments using 0.1 M piperylene throughout; the assumption that this is sufficient to quench all of the triplet component is verified by the correspondence of the two sets of "triplet distribution" data (*cf.* Tables VI and VII).

Table III. Solvent Effect on the Fraction of Dimerization Which Is Quenchable[a]

Solvent	No. of runs[b]	% quenching[c]
Toluene	4	31 ± 4
Benzene	8	46 ± 8
Ethyl acetate	5	38 ± 8
Glyme	3	32 ± 13
Methanol	5	4 ± 5
Acetonitrile	10	11 ± 3

[a] All solutions were 0.10 *M* in DMT and 0.1 *M* in *cis*-piperylene. [b] This indicates the number of pairs of solution (with and without piperylene) which were irradiated to determine the per cent quenching. [c] Standard deviations are given.

Table IV. Quantum Efficiencies for Singlet Dimerization as a Function of Solvent[a]

Solvent	$\phi_{DF}{}^1$	Solvent	$\phi_{DF}{}^1$
Toluene	0.0017	Glyme	0.0016
Benzene	0.0014	Methanol	0.0019
Ethyl acetate	0.0016	Acetonitrile	0.0013
		(Water	0.014)[b]

[a] All solutions were 0.10 *M* in DMT. [b] Assuming all DMT dimerization in water is from the singlet state (see Discussion).

tially constant and about an order of magnitude smaller than water.

Because it had been reported[39] that fluorescence from dilute rigid solutions at 77°K of thymidylic acid could be decreased through addition of acetone by a factor of seven (presumably by singlet–singlet energy transfer), an attempt was made to quench DMT singlet dimerization by 0.10 *M* acetone (solutions were also 0.10 *M* in *cis*-piperylene to eliminate triplet dimerization). In fact, the difference in conversion to dimers with (5.85%) and without (6.6%) acetone can be explained by internal filtering by acetone, and no obvious quenching could be noted (presumably as a consequence of the short DMT singlet lifetime at room temperature; see Discussion).

E. Product Distribution from the Singlet Excited State as a Function of Solvent. Since the triplet contribution to dimerization is a function of the solvent (*cf.* Table III), the dimer distributions shown in Table II required revision in order to reflect effects on just one of the two excited states. We thus measured product distributions formed in the presence of 0.10 *M* *cis*-piperylene[38] with the results shown in Table V. A pronounced polarity effect is evident with polar solvents seemingly favoring formation of h–h dimers.

Table V. Solvent Effect on Dimer Distribution from the Excited Singlet State[a]

Solvent (ε)	Syn h-t	Syn h-h	Anti h-t	Anti h-h
Dioxane (2)	62	10	27	1
Toluene (2)	66	11	24	0
Benzene (2)	64	11	25	0
Ethyl acetate (6)	59	22	19	1
Glyme (8)	60	20	20	0
Methanol (33)	43	36	18	3
Acetonitrile (38)	39	46	12	3
Dimethylformamide (38)	37	49	11	4
Water (79)[b]	38	39	18	6
Glyme-1 *M* $NaClO_4$	32	51	11	6
Water-15% ethanol[c]	40	39	17	5

[a] All solutions 0.10 *M* in DMT and in *cis*-piperylene; distributions are in per cents and are rounded off to the nearest whole number. [b] Assuming all DMT dimerization in water is from the singlet state (see Discussion). [c] 2,4-Hexadienol used as quencher.

F. Product Distribution from the Triplet State as a Function of Solvent. The triplet-derived product distribution was obtained by two independent methods. First, the distribution of the dimers *eliminated* by the presence of 0.1 *M* cis-piperylene was calculated for each of the solvents, *i.e.* the distributions of "quenched dimers" were determined. The results are presented in Table VI.

Table VI. "Quenched Dimer" Distribution as a Function of Solvent[a]

Solvent (ε)	Syn h-t	Syn h-h	Anti h-t	Anti h-h
Toluene (2)	55	24	15	7
Benzene (2)	49	31	13	6
Ethyl acetate (6)	42	46	7	5
Glyme (8)	41	44	9	7
Acetonitrile (38)	16	74	4	7
Dimethylformamide (38)	26	64	6	5

[a] All solutions were 0.10 *M* in DMT with the distributions (per cent) calculated from the differences in individual dimer yields obtained with and without 0.10 *M* *cis*-piperylene present.

The distributions of dimers produced by the DMT triplet state were also obtained by triplet photosensitization using benzophenone. Solutions were 0.10 *M* in DMT and 0.03 *M* in sensitizer; the mercury arc was filtered through uranium yellow glass (λ > 330 nm) so that only the benzophenone absorbed the incident light. The data are presented in Table VII. The agreement between the values shown in Table IV and those in Table VII provides further support for the validity of the assumptions used in compiling Tables IV and V. There is, as with the singlet dimerization, a noticeable increase in h–h and decrease in h–t dimerization as solvent polarity increases.

Table VII. Photosensitized Dimer Distribution as a Function of Solvent[a]

Solvent (ε)	Syn h-t	Syn h-h	Anti h-t	Anti h-h
Toluene (2)	59	25	12	4
Benzene (2)	52	30	13	6
Ethyl acetate (6)	41	46	7	5
Methanol (33)	22	72	2	5
Acetonitrile (38)	16	74	2	8
CH_3CN-1 *M* $NaClO_4$	13	69	2	16

[a] All solutions were 0.10 *M* in DMT and 0.03 *M* in benzophenone; distributions are given in per cents.

G. Stern–Volmer Analysis of the Photodimerization. Since 0.10 *M* piperylene suffices for total quenching of DMT triplet dimerization, conversions obtained with this concentration of quencher should represent the extent of singlet dimerization for any given turntable run. Furthermore, this amount of singlet dimerization should be independent of decreases in the piperylene concentration.[40] We, therefore, did the

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(39) A. A. Lamola, M. Gueron, T. Yamane, J. Eisinger, and R. G. Shulman, *J. Chem. Phys.*, 47, 2210 (1967).

(40) This assumes absence of singlet quenching by piperylene, a reasonable assumption in the light of the short DMT singlet lifetime (*cf.* Discussion).

following: the conversions of (0.1 *M*) DMT to dimers in ethyl acetate containing varying concentrations of piperylene were measured during a single turntable experiment (450-W lamp, Corex filter, Pyrex tubes, 25°), the amount of singlet-derived dimer was subtracted for each tube, and the amount of triplet dimerization was then plotted *vs.* piperylene concentration in the usual Stern–Volmer manner (*i.e.* $\phi_{DF_0}{}^3/\phi_{DF}{}^3$ *vs.* [Q], where $\phi_{DF_0}{}^3$ represents triplet conversion at zero piperylene concentration). The plot is shown in Figure 1. The straight line obtained by a least-squares treatment of the data has a slope of 1397 ± 135 M^{-1}. If one treats the data for the syn h-t and h-h dimers individually (they represent 87% of the triplet dimers in ethyl acetate), slopes of 1250 ± 128 and 1396 ± 100, respectively, are calculated.

H. Quantum Efficiencies for Sensitized Photodimerization (ϕ_{sens}). The quantum efficiencies for sensitized dimerization using benzophenone as sensitizer and ethyl acetate solutions 0.10 *M* in DMT were measured once using a monochromator (λ = 366 ± 11 nm) and once using a Rayonet reactor (3500-Å lamps). Uranyl oxalate actinometry was used for the first system and benzophenone-sensitized isomerization of piperylene for the second; measured values were ϕ_{sens} = 0.023 and 0.026, respectively. Since benzophenone has a triplet energy of 69 kcal/mol[41] while that for DMT is estimated at 74 kcal/mol,[42] one would expect that a change to acetophenone as sensitizer (E_t = 74 kcal/mol[41]) or an increase in acceptor (DMT) concentration would result in raising ϕ_{sens}.[43] Both such effects are observed with ϕ_{sens} = 0.061 for 0.1 *M* DMT with acetophenone[44] and ϕ_{sens} = 0.017 and 0.031 for 0.05 and 0.20 *M* DMT with benzophenone. No significant variation of ϕ_{sens} was observed when toluene, methanol, or acetonitrile was used as solvent.

I. Quantum Efficiencies for DMT Intersystem Crossing (ϕ_{ic}). In order to make a meaningful evaluation of those factors influencing DMT dimerization from the triplet state, the quantum efficiency for intersystem crossing was measured on the monochromator at 297 ± 11 nm using 0.10 *M* DMT in ethyl acetate and observing the sensitized isomerization of 0.10 *M* *cis*-piperylene[45] (uranyl oxalate actinometry was employed). The value of 0.016 so obtained compared well with a value of 0.017 measured using the Rayonet reactor, 3000-Å lamps, and Pyrex photolysis tubes, and values for other solvents were then measured relative to ethyl acetate using the Rayonet and a turntable; the data are shown in Table VIII. Since ϕ_{ic} has been shown to be wavelength dependent for both uracil[46] and orotic acid,[47] measurements were also made at 2537 Å using a low-pressure mercury lamp and Vycor tubes. These data are included in Table VIII. The data in Table VIII demonstrate that intersystem crossing is less efficient in polar solvents and, as with other pyrimidines,[46] increases with an increase in the frequency of exciting light.

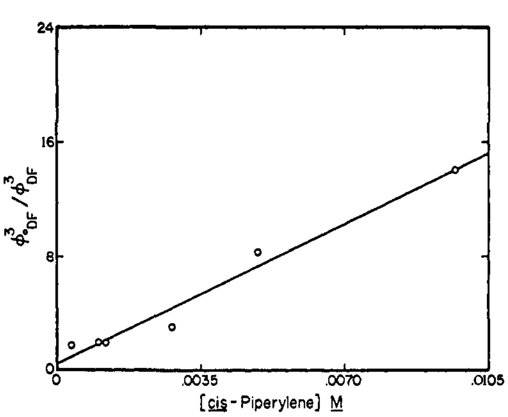

Figure 1. Quenching of 0.1 *M* DMT photodimerization in ethyl acetate by *cis*-piperylene.

Table VIII. Effect of Solvent and Wavelength on ϕ_{ic}[a]

Solvent	ϕ_{ic} (2537 Å)	ϕ_{ic} (λ > 280 nm)
Toluene		0.025
Ethyl acetate	0.032	0.017
Glyme		0.019
Methanol	0.017	0.005
Acetonitrile	0.017	0.006

[a] All solutions were 0.10 *M* in DMT and 0.10 *M* in *cis*-piperylene.

In one experiment, ϕ_{ic} was determined at 2537 Å with three different concentrations of DMT in acetonitrile (a value of ϕ_{ic} = 0.017 for 0.1 *M* DMT was used as a reference). Measured ϕ_{ic}'s (DMT) are: 0.018, 0.016 (0.30 *M*); 0.018 (0.05 *M*); and 0.022, 0.022, 0.021 (0.01 *M*). There would seem to be a real increase in ϕ_{ic} at the 0.01 *M* concentration.

J. Effect of Temperature on the Photodimerization. Since the decrease in formation of coumarin's syn h-h dimer II upon an increase in temperature[17] was used to support a proposal of excimer intermediacy,[16] a similar study was carried out on the DMT system. The experiment was considerably simplified by a report,[34] during the course of this work, on the temperature dependence of total dimerization in water. Data were thus obtained for methanol, acetonitrile, and ethyl acetate at 45° using as a standard the reported[34] value of 0.012 for water at this temperature. Piperylene (0.1 *M*) was added to these organic solvents to assure that only singlet-state dimerization would be measured. Total quantum efficiencies ($\phi_{DF}{}^1$) and product distributions are presented in Table IX. It is clear that the efficiency of singlet dimerization decreases at higher temperatures for all solvents measured, with the dimer distribution pattern apparently unaffected (*i.e.* no temperature effect on distribution is observed).

K. Effect of DMT Concentration upon Its Photodimerization. All of the above data were gathered at a constant 0.10 *M* concentration of DMT. We also examined the effect of a change in DMT concentration on several of the parameters thus far discussed. The singlet dimer distributions as a function of concentration in four solvents are presented in Table X. Al-

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[41] W. G. Herkstroeter, A. A. Lamola, and G. S. Hammond, *J. Amer. Chem. Soc.*, 86, 4537 (1964).

[42] A. A. Lamola, private communication.

[43] G. Porter and F. Wilkinson, *Proc. Roy. Soc., Ser. A*, 264, 1 (1961).

[44] This contrasts with the surprising report of a sevenfold greater efficiency for benzophenone relative to acetophenone in sensitizing thymine dimerization; *cf.* C. L. Greenstock and H. E. Johns, *Biochem. Biophys. Res. Commun.*, 30, 21 (1968).

[45] A. A. Lamola and G. S. Hammond, *J. Chem. Phys.*, 43, 2129 (1965).

[46] I. H. Brown and H. E. Johns, *Photochem. Photobiol.*, 8, 273 (1968).

[47] D. W. Whillans and H. E. Johns, *ibid.*, 9, 323 (1969).

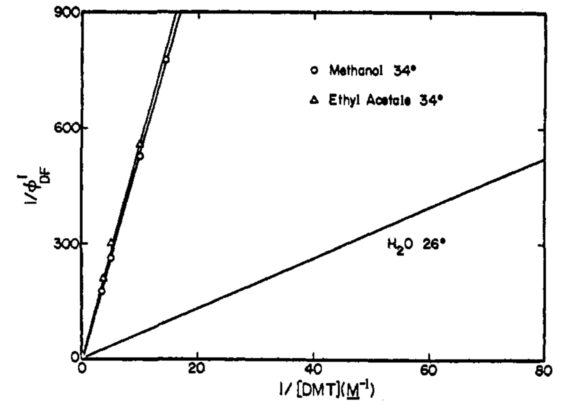

Figure 2. Singlet photodimerization of DMT as a function of concentration. Plot for water is from ref 34.

though the changes are not large, a decrease in the percentage of syn h-h dimer and associated increases in the h-t dimer percentages are evident at 0.01 *M* concentrations.

Table IX. Temperature Effects on the Photodimerization[a]

Solvent	Temp, °C	Syn h-t	Syn h-h	Anti h-t	Anti h-h	$\phi_{DF}{}^{1\,b}$
Water	25	38	39	18	6	0.014
Water	45	38	38	18	6	0.012[c]
Methanol	25	43	36	18	3	0.0019
Methanol	45	44	33	19	4	0.0014
Acetonitrile	25	39	46	12	3	0.0013
Acetonitrile	45	38	45	13	4	0.0008
EtOAc	25	59	22	19	1	0.0016
EtOAc	45	57	22	20	2	0.0010

[a] All solutions were 0.10 *M* in DMT; the organic solvents contained 0.10 *M* *cis*-piperylene. [b] Values were measured assuming a value of 0.012 for water at 45°. [c] Reference 34.

Table X. Effect of DMT Concentration on the Product Distribution from the Excited Singlet State[a]

Solvent	[DMT], *M*	Syn h-t	Syn h-h	Anti h-t	Anti h-h
Methanol	0.30	42	37	18	4
Methanol	0.20	42	37	17	4
Methanol	0.10	43	36	18	3
Methanol	0.07	43	36	18	3
Methanol	0.05	44	35	18	3
Methanol	0.01	51	25	20	5
Water	0.21	37	39	17	7
Water	0.13	37	39	18	6
Water	0.10	38	39	18	6
Water	0.07	37	38	18	7
Water	0.05	40	37	16	7
Water	0.01	50	26	18	6
CH_3CN	0.10	39	46	12	3
CH_3CN	0.01	44	39	14	3
Benzene	0.10	64	11	25	0
Benzene	0.01	65	8	27	0

[a] The organic solvents were each 0.10 *M* in *cis*-piperylene.

A similar study was made for photosensitized dimer formation in ethyl acetate with the results shown in Table XI.

The effect of DMT concentration on $\phi_{DF}{}^1$ was determined at 34° in methanol and ethyl acetate using the Rayonet reactor (3000-Å lamps) and Pyrex tubes. Light intensities for the methanol study were obtained using ϕ_{DF}'s for dimerization in aqueous solutions;[34] methanol runs were then used to provide actinometry for the ethyl acetate experiment (concentrations in the sample and actinometer tubes were adjusted to give identical absorbancies). The data are plotted in Figure 2 as $1/\phi_{DF}{}^1$ *vs.* 1/[DMT] with the plot for water[34] superimposed for purposes of comparison. The least-squares straight lines have slopes of 53.5 ± 0.9 (methanol) and 53.9 ± 4.4 (ethyl acetate); the calculated intercepts and their standard deviations are −0.18 ± 7.9 and 18.7 ± 30.1 (the large deviations reflect the steepness of the slope).

Table XI. Effect of DMT Concentration on the Product Distribution from Photosensitization[a]

[DMT], *M*	Syn h-t	Syn h-h	Anti h-t	Anti h-h
0.20	42	46	6	5
0.10	42	47	7	5
0.05	43	45	7	5
0.01	41	52	3	4

[a] All solutions were in ethyl acetate with 0.02 *M* benzophenone.

L. **Thermal Osmometry.** In order to determine whether DMT is associated in solution, apparent molecular weights for several concentrations in water and methanol were recorded (the calculated molecular weight of DMT is 154.17). The data are shown in Table XII. There is an obvious increase in apparent molecular weight at higher concentrations of DMT in water, an effect not observed with methanol. Interestingly, 1,3-dimethyl-6-azathymine (mol wt 155.16) gave a measured value of 154 at 0.20 *M* in water.

Table XII. Thermal Osmometry Data

Solvent	Concn, *M*	Mol wt
Water	0.05	155
Water	0.08	166
Water	0.10	170
Water	0.20	190
Water	0.35	192
Methanol	0.025	153, 151
Methanol	0.10	154
Methanol	0.20	155

Discussion

The data presented herein show DMT photodimerization occurs in solution with reasonable efficiency, but the reaction is a complex function of solvent, temperature, wavelength of excitation, and DMT concentration.

Dimerization in Water. The best place to begin a discussion of these data is for DMT in water where the quantum efficiency (ϕ_{DF}) is comparable to that found for TpT[15a] and DNA,[48] and uniquely higher than the values for organic solvents. Any mechanism proposed must take into account the exceedingly short lifetime ($\leqslant 10^{-12}$ sec) measured[49–51] for thymine and DMT in

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[48] D. Wulff, *Biophys. J.*, 355 (1963).

[49] (a) J. Eisinger and R. G. Shulman, *Proc. Nat. Acad. Sci., U. S.*, **58**, 895 (1967); (b) W. Hauswirth and M. Daniels, *Photochem. Photobiol.*, 13, 157 (1971).

[50] A. A. Lamola and J. Eisinger, "Molecular Luminescence," E. C. Lim, Ed., W. A. Benjamin, New York, N. Y., 1969, p 801.

[51] A. A. Lamola, private communication.

solution at room temperature. It has been shown[34] that even a diffusion-controlled reaction between a DMT excited singlet species and a ground-state molecule would be insufficiently competitive with singlet decay to account for the observed ϕ_{DF} in water (if one assumes $k_d = 10^{12}$ sec^{-1}, the maximum ϕ_{DF} would be 8×10^{-4}; 1.4×10^{-2} is observed). The obvious alternative is preassociation of the DMT molecules in the ground state,[34] *i.e.*, vertical base stacking,[6] and the osmometry data presented herein (Table XII) provide ample confirmation for such ground-state aggregation. The K_a calculated[52] from these data (assuming a model in which aggregation occurs beyond the dimer state[52,53]) is 1.1 ± 0.2; K_a's of 0.9 and 1.2 have been reported for aqueous solutions of deoxythymidine.[52,54]

Having demonstrated the existence of such van der Waal's complexes, it is logical to assume that excitation of these species might lead directly to an excited state complex (*i.e.*, an excimer) which could proceed on to dimer or decay back to two DMT ground-state molecules; in fact, during the course of this research, a number of elegant experiments have provided support for the singlet excimer as an intermediate in the photodimerization of thymine in ice, TpT, and DNA.[5c,55-57] It has been reported[34] that neither oxygen nor halides quench DMT dimerization in aqueous solutions, although both reagents have been shown to quench the triplet state of other uracil derivatives.[34,58] We have also observed a lack of oxygen quenching in water,[59] as well as an invariance in product distribution upon adding the water-soluble, triplet quencher 2,4-hexadienol.[13,60] It would, therefore, appear that dimerization in water occurs either *via* a singlet species or a triplet aggregate capable of dimerizing too rapidly for energy transfer to an external quencher to be competitive. We favor the first alternative because of the analogies cited above, and the excellent correlation between "sensitized" and "quenched" dimer distributions in organic solvents, which suggests that all *triplets* formed by direct irradiation are quenchable (there is reason to believe that aggregation occurs in the organic media also; see below[61]). One can say further that since DMT triplets do dimerize in organic solvents (see below), unique dimerization from the singlet state in water implies very inefficient intersystem crossing for DMT in aqueous media, or (less likely) a triplet reactivity which is somehow negated in this solvent.

A mechanism[34] incorporating these conclusions is shown in eq 1–6. In this scheme, D_2 represents the

$$D_0 + D_0 \underset{}{\overset{K_a}{\rightleftarrows}} D_2 \tag{1}$$

$$D_0 \xrightarrow{h\nu} {}^1D \tag{2}$$

$$D_2 \xrightarrow{h\nu} {}^1D_2^* \tag{3}$$

$$^1D \xrightarrow{k_d} D_0 \tag{4}$$

$$^1D_2^* \xrightarrow{k_5} \text{dimer} \tag{5}$$

$$^1D_2^* \xrightarrow{k_6} 2D_0 \tag{6}$$

ground-state complex[62] and $^1D_2^*$ represents a singlet excimer; for reasons discussed above, intersystem crossing has been omitted. The fact that an increase in temperature decreases equally the rate of formation of all four dimers could be compatible with either (a) a single D_2 and $^1D_2^*$ precursor to the four products or (b) four ground-state complexes, each leading to a different dimer. We find it easier to accept similar temperature dependencies for dissociation of four π complexes, than the probability that one precursor would collapse to form dimers of such different geometries. Thus, eq 1, 3, 5, and 6 should probably be written individually for each complexed species.

A kinetic treatment of eq 1–6 leads to 7, where F_{ex} is

$$\frac{1}{\phi_{DF}} = \frac{1}{F_{ex}} + \frac{1}{F_{ex}}\left(\frac{1}{2K_a[D_0]}\right) \tag{7}$$

the fraction of excimer (*and therefore of excited aggregate*) which dimerizes. The data for water, when fitted to this expression, give a K_a of 0.6 M^{-1} and F_{ex} of 0.125.[34] The latter value has been compared[34] with the ϕ_{DF} of 0.165 for photodimerization of DMT in a KBr matrix.[63] The inverse temperature dependence observed for ϕ_{DF} in water[34] supports the existence of an equilibrium between monomers and aggregates, with the effect entering either in eq 1[64] or in a probable equilibrium between the excimer and $^1D + D_0$ (there is also the possibility for a temperature effect on eq 6).

Finally, it may be of considerable import that 1,3-dimethyl-6-azathymine (DMAT) does *not* show evidence for ground-state complexing in water, since it is known to be comparatively inert photochemically.[65,66] Current theory has not been able to explain this lack of reactivity[67,68] and it is tempting to view the existence of both phenomena as more than coincidental, especially in the light of the above mechanism. However, one must of course prove that DMAT can lead to stable dimers, and studies in this direction are in progress.[69]

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(52) T. N. Solie and J. A. Schellman, *J. Mol. Biol.*, **33**, 61 (1968).

(53) For the model in which there is complexation just to a dimer, $K_a = 1.7 \pm 0.4$.

(54) A similar conclusion has recently been reached for thymine photodimerization in concentrated aqueous solution; *cf.* G. J. Fisher and H. E. Johns, *Photochem. Photobiol.*, **11**, 429 (1970).

(55) J. Eisinger and A. A. Lamola, *Biochem. Biophys. Res. Commun.*, **28**, 558 (1967).

(56) J. Eisinger, *Photochem. Photobiol.*, **7**, 597 (1968).

(57) A. A. Lamola and J. Eisinger, *Proc. Nat. Acad. Sci. U. S.*, **59**, 4 (1968).

(58) C. L. Greenstock, I. H. Brown, J. W. Hunt, and H. E. Johns, *Biochem. Biophys. Res. Commun.*, **27**, 431 (1967).

(59) Oxygen enhances photodimerization of DMT in organic solvents by formation of trace amounts of a sensitizer. The nature of this oxidation product is under study.

(60) A. A. Lamola, *Photochem. Photobiol.*, **8**, 601 (1968).

(61) The argument assumes that triplet energy transfer to ground-state aggregates would occur and that monomeric and aggregated triplets would have measurably different product distributions. Fisher and Johns[54] also favor a singlet species (for thymine) because dimer formation is independent of photon energy whereas ϕ_{ic} for thymine is known to increase at higher photon energies.

(62) Association limited to the dimer stage has been assumed for simplicity.

(63) R. Lisewski and K. L. Wierzchowski, *Photochem. Photobiol.*, **11**, 327 (1970).

(64) A similar phenomenon, observed for DNA, has been attributed to a temperature effect on base stacking; *cf.* R. O. Rahn and J. L. Hoszzu, *ibid.*, **7**, 637 (1968).

(65) A. Wacker, *et al.*, *ibid.*, **3**, 369 (1964).

(66) H. L. Gunther and W. H. Prusoff, *Biochim. Biophys. Acta*, **149**, 361 (1967).

(67) B. Pullman, *Photochem. Photobiol.*, **7**, 525 (1968).

(68) V. I. Danilov, Y. A. Kurglyak, V. A. Kuprievich, and V. V. Ogloblin, *Theoret. Chim. Acta*, **14**, 242 (1969).

(69) We did *not* find DMAT to be an effective quencher of DMT dimerization, beyond that caused by competitive light absorption; see ref 66.

Table XIII. Nearest Neighbor Fractions and $\phi_{DF}{}^1$ in Organic Solvents[a]

Solvent	X_s	F_2	$\phi_{DF}{}^1$	$\phi_{DF}{}^1$ (max)[b]
Water	0.0018	0.0036	0.0141	0.0008
Methanol	0.0041	0.0082	0.0019	0.0012
Ethyl acetate	0.0099	0.0197	0.0016	0.0015
Toluene	0.0106	0.0211	0.0017	

[a] All data are for 0.1 *M* DMT. [b] Calculated assuming diffusion-controlled dimerization of excited singlet monomers having $k_d = 10^{12}$ sec^{-1}.

Dimerization in Organic Solvents. DMT dimerization in nonaqueous solutions introduces a number of new features which require consideration. The most obvious of these is the diminished quantum efficiency for *singlet* dimerization ($\phi_{DF}{}^1$) (for example, H_2O, 0.014; glyme, 0.0016). This diminution does not seem to be the consequence of a change in intersystem crossing rate, since polar and nonpolar organic solvents have comparable $\phi_{DF}{}^1$'s even while ϕ_{ic}'s are measurably smaller in polar media. Since ground-state complexation appears to be intimately involved with DMT dimerization in water, and since our osmometry experiments provide no evidence for such aggregation in methanol, the source of inefficiency in organic solvents could be the lack of such aggregates.[34] In fact, the slopes of a $1/\phi_{DF}{}^1$ *vs.* 1/[DMT] plot for methanol and ethyl acetate are virtually identical, and the application of eq 7 provides K_a values of *ca.* 0.01 (assuming intercepts, and therefore F_{ex}'s equal to 1.0; the data do not allow for an accurate fix on this number; see Results). Were such a K_a to exist, it would be too small to be measured experimentally by osmometry. Note, however, that eq 7 is one possible treatment of the observed linear dependence; it is not a required consequence of it.

In fact, the magnitude of $\phi_{DF}{}^1$ in the organic solvents is sufficiently small so that a relatively efficient dimerization of monomeric excited DMT molecules with "nearest neighbor" ground-state species might also accommodate the data. The fraction of total solute molecules with one solute molecule as a nearest neighbor (F_n) (n being the total possible nearest neighbors) can be calculated from eq 8,[70] in which X_s represents the mole fraction of solute molecules. Calculated values for F, when $n = 2$,[71] are shown in Table XIII for 0.1 *M* DMT

$$F_n = 1 - (1 - X_s)^n \qquad (8)$$

in several solvents. Also included in Table XIII are the $\phi_{DF}{}^1$ (max) values calculated for several solvents assuming competition between diffusion-controlled dimerization and radiationless decay (see above). As has already been noted, ϕ_{DF} in water is too large to be accommodated by the competition mechanism (*cf.* $\phi_{DF}{}^1$ (max)) and the nearest neighbor fraction is likewise too small. However, the F_2 values in the organic solvents are considerably larger than $\phi_{DF}{}^1$ and modest efficiencies for dimerization of ^1D with D_0 as a nearest neighbor would suffice to explain the data.[71] Furthermore, the $\phi_{DF}{}^1$ (max) values demonstrate that for organic solvents even a diffusion-controlled bimolecular mechanism is not out of the question.

However, whichever of these three mechanisms is operative, there is yet to be explained (a) the similarity in product distributions for water and the polar organic solvents (Table V), (b) the fact that addition of ethanol to water changes the rate of dimerization but not the dimer distribution (Table I), and (c) the fact that methanol and acetonitrile show an inverse temperature dependence of $\phi_{DF}{}^1$ which, as with water, is without any obvious effect on product distribution. To our minds, these data are most compatible with efficient dimerization from trace amounts of aggregates, a concept of considerable potential import in the area of photodimerization and perhaps more generally photocycloaddition. The prime problem for the experimentalist is finding a reliable physical method for detecting small amounts of ground-state aggregation.[72]

What then is the situation for singlet dimerization in nonpolar organic solvents? The salt effect observed with sodium perchlorate in glyme (Table V) confirms the importance of solvent dielectric to the product distribution. It has been suggested that the effect of solvent on product distribution in (concerted) photodimerization may be related to the dipole moments of the dimers, *i.e.*, transition states leading to the dimers of highest dipole moments should become increasingly favored as the polarity of the solvent is increased.[73–75] This rationale can be used successfully to predict the favored formation of isophorone,[74] cyclohexenone,[73] and cyclopentenone[76] h-h dimers in polar solvents. However, the dipole moments of the syn h-h, syn h-t, and anti h-h DMT dimers are 6.04, 5.75, and 2.79 D,[26] respectively (the anti h-t dimer is centrosymmetric and should have no net dipole moment).[26] Dimethyluracil, a reasonable model for DMT, has a dipole moment of 3.61 D.[26] *One would thus predict that formation of both the syn h-h and the syn h-t dimers should be favored in polar solvents—an increase in syn h-h, but a decrease in syn h-t dimerization is, in fact, observed.*

An alternative approach has been used for the coumarin system, where the favored formation of syn h-h dimer has been attributed to a polarity effect on excimer collapse to dimer.[18] The inverse temperature effect for DMT dimerization in ethyl acetate suggests that excimer and/or ground-state complexing is indeed present in the nonpolar solvents, but the lack of a differential effect among the four dimers suggests the entire group is excimer derived and it is difficult to conceive how dimerization from a specific excimer geometry might be uniquely prone to such a solvent effect (note also that total dimerization rates are comparable in the polar and nonpolar organic solvents).

We are thus left with the postulate that trace aggregation occurs in nonpolar solvents as in polar media (the slopes for the $1/\phi_{DF}{}^1$ *vs.* 1/[DMT] plots for ethyl acetate and methanol are identical (see above)), but that

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[70] H. P. Waits and G. S. Hammond, *J. Amer. Chem. Soc.*, **86**, 1911 (1964).

[71] If $n > 2$, the F_n values increase and the arguments being made become even more feasible.

[72] It is worth noting that even for DMT in water, our (continuing) attempts to observe deviations from Beer's law have so far been without success.

[73] E. Lam, Ph.D. Thesis, California Institute of Technology, 1968; E. Lam, D. Valentine, and G. S. Hammond, *J. Amer. Chem. Soc.*, **89**, 3482 (1967).

[74] O. L. Chapman, P. J. Nelson, R. W. King, D. J. Trecker, and A. A. Griswald, *Rec. Chem. Progr.*, **28**, 167 (1967).

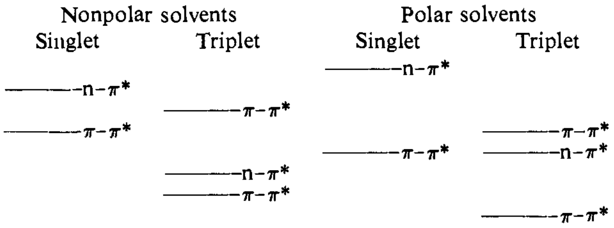
[75] B. H. Jennings, S. Pastra, and J. L. Wellington, *Photochem. Photobiol.*, **11**, 215 (1970).

[76] P. E. Eaton, *J. Amer. Chem. Soc.*, **84**, 2344 (1962); P. E. Eaton and W. S. Hurt, *ibid.*, **88**, 5038 (1966).

the distribution among the four possible geometries is altered by solvent polarity.[77]

Among the prominent solvent effects in the DMT system, there remains to be explained the increased fraction of triplet dimerization and associated increase in intersystem crossing characteristic of the nonpolar solvents (Table III and VIII). It is well known that excited-state level inversion can result from a change in solvent polarity[78] and this, together with the prediction[79] of enhanced intersystem crossing between states of different ($n-\pi^*$; $\pi-\pi^*$) character, has allowed for a rationalization of several observations involving a solvent effect on intersystem crossing.[80] Thus, an arrangement of levels for DMT as shown in the state diagrams in Chart I might lead to the observed solvent dependence of triplet contribution to dimerization and ϕ_{ic}. It seems likely that both of the lowest excited states of DMT are $\pi-\pi^*$ in character.[53,81,82] Unfortunately, little is known about the upper states of uracil and its derivatives. Evidence has recently been presented, from circular dichroism studies, for four singlet transitions between 185 and 275 nm,[83] and though all four were considered likely to be $\pi-\pi^*$, an $n-\pi^*$ assignment for the second excited singlet was considered a possibility. The complete absence of a triplet component in water may be an extreme example of the factors discussed above, or may be a consequence of the extensive base stacking, which could preclude intersystem crossing through accelerated complexation of the singlet excited state.[84]

Chart I. State Diagrams for DMT Which Would Be Consistent with the Observed Solvent Effects on Per Cent Triplet Dimerization and ϕ_{ic}



A related phenomenon may be the increase in ϕ_{ic} which we observed in polar and nonpolar solvents upon increasing the frequency of irradiation. Comparable observations have been reported for uracil[46] and orotic acid,[47] and were attributed either to a dependence of ϕ_{ic} on the vibrational level initially populated or on the existence of two tautomeric forms in solution. The latter is, of course, not possible for DMT and these observations may be, at least in part, due to excitation into an upper electronic state.[85]

This leads us to the next aspect of DMT dimerization in solution: photodimerization from the triplet state. Both the quenching and sensitization[86] experiments confirm that dimerization from this state can and does occur in concentrated solutions. As with the singlet state, all four dimers are formed, although h–t dimerization plays a much greater role in singlet dimerization from any given solvent. The fact that the two major dimers (syn h–h and syn h–t), when treated separately, have identical Stern–Volmer slopes (within experimental error) is suggestive of a common (lowest $^3\pi-\pi^*$) triplet precursor. Additional evidence for this supposition derives from the like distributions of dimers obtained with sensitizers with triplet energies ranging from 69 to 80 kcal/mol (benzophenone to acetone). As with singlet dimerization, there is an increase in h–h dimerization as solvent polarity increases although the rate of triplet (sensitized) dimerization does not seem to be solvent dependent. It is not possible to say whether the DMT singlets which undergo intersystem crossing are monomeric or aggregated (see the comments on water, above); however, the modest size for the rate constant associated with triplet reaction (k_r), as calculated below, would seem to suggest that triplets are initially formed as monomers.

The slope of the Stern–Volmer quenching plot (1397 M^{-1}, Figure 1) can be set equal to $k_q/(k_d + k_r[D_0])$, where k_q represents the rate constant for quenching, k_d represents radiationless decay from the triplet state, and k_r equals the rate constant for reaction of the DMT triplet with another DMT molecule.[87] Since the k_d/k_r ratio is of the order[87,88] of 10^{-4}, and k_q for piperylene in ethyl acetate can be assumed to have the diffusion-controlled value[89] of 1.5×10^{10} M^{-1} sec^{-1}, k_r may be calculated to be 1.1×10^8 M^{-1} sec^{-1} (values of *ca.* 6×10^8 M^{-1} sec^{-1} have been measured for thymine[87,88]).

In summary, one can now say that for DMT, *under the conditions of base stacking common to DMT in concentrated aqueous solution and to DNA*, (a) photodimerization is comparable in efficiency to that observed for DNA, and competitive with radiationless decay, (b) photodimerization is best rationalized by a singlet excimer, (c) intersystem crossing appears to be negligible, and (d) all four dimers are formed (thus requiring that the preference for syn h–h dimerization in DNA be a consequence of specific geometric factors and not intrinsic to the dimerization process).

Experimental Section

Instrumentation. Infrared spectra were obtained on the Beckman IR-8 or Perkin-Elmer 221 spectrophotometer, ultraviolet spectra were obtained on a Bausch and Lomb Model 505 or Cary Model 14 spectrophotometer, and nmr spectra were obtained on a Varian A-60 spectrometer with tetramethylsilane as internal stan-

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(77) It is conceivable, but not considered probable, that the enhanced ϕ_{ic} of DMT in nonpolar organic solvents is somehow related to this distribution (see the discussion which follows).

(78) For example, see P. Suppan, *Ber. Bunsenges. Phys. Chem.*, **72**, 321 (1968); P. Suppan, *J. Chem. Soc. A*, 3125 (1968); A. A. Lamola, *J. Chem. Phys.*, 47, 4810 (1967).

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(80) See, for example, L. A. Singer, *Tetrahedron Lett.*, 923 (1969).

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(85) For a comparable discussion, see ref 49b.

(86) See D. Elad, C. Kruger, and G. M. J. Schmidt, *Photochem. Photobiol.*, 6, 495 (1967), and ref 75 for other sensitization studies relevant to our data.

(87) The initial product of reaction between DMT triplet and DMT ground state is undoubtedly a 1,4 diradical; *cf.* P. J. Wagner and D. J. Bucheck, *J. Amer. Chem. Soc.*, 90, 6530 (1968); P. J. Wagner and D. J. Bucheck, *ibid.*, **92**, 181 (1970). Our value for the efficiency of closure for this diradical in ethyl acetate is 0.05, a value comparable to that found by Wagner and Bucheck for thymine and uracil in acetonitrile (*cf.* R. Kleopfer, Ph.D. Thesis, Purdue University, Jan 1971).

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dard. Melting points were determined on a Fisher–Johns hot stage and are corrected. Elemental analyses and thermal osmometry were by Dr. C. S. Yeh of the Purdue Chemistry Department. Mass spectra (Hitachi RMU-6A) were determined by the Purdue Chemistry Department Mass Spectroscopy Center.

Analyses. All gas–liquid partition chromatography (glpc) data were obtained using a Varian-Aerograph A-90P chromatograph and a disk integrator. Analyses for dimers were performed on a 5 ft × $^1/_4$ in. copper column packed with 5% Carbowax 20M on Chromosorb W (acid washed, DMCS treated, 60–80 mesh) and operated at 245°. Pyrene was used as an internal standard and retention times (helium flow 120 ml/min) were: pyrene, 3 min; V, 10 min; III, 13 min; VI, 14.5 min; and IV, 30 min. Analysis for DMT was done at a column temperature of 200° (flow 100 ml/min) with a DMT retention time of 5 min and anthracene (internal standard) at 10 min. Analyses for *cis*- and *trans*-piperylene were on a 20 ft × $^1/_4$ in. copper column packed with a 30% β,β'-oxydipropionitrile on Chromosorb W (acid washed, 60–80 mesh). Using a column temperature of 0° and helium flow of 100 ml/min, retention times were 28 min for the trans isomer, 34 min for the cis isomer, and 11 min for the internal standard, *n*-hexane. Analyses for DMT and dimers were performed after evaporation of the solvent on a rotary evaporator; in almost all cases, 97–100% material balance was obtained.

Photochemical Apparatus. Most comparative runs were done using a rotating turntable holding 25-mm o.d. Pyrex or Vycor glass tubes, each filled with 45 ml of solution. A Hanovia 450-W type L mercury arc lamp filtered through Corex or Uranium Yellow glass or through a potassium chromate–potassium hydroxide solution (for the 313-mm line)[90] was used. A Hanovia low-pressure resonance lamp was used for 2537-Å irradiations, and a Rayonet Photochemical Reactor and associated turntable (Southern New England Ultraviolet Co.) was used in some experiments. Some of the quantum yield data were obtained with a Bausch and Lomb high intensity grating monochromator (no. 33-86-25) coupled to a Hanovia, Hg–Xe compact arc lamp (no. 901B1). Light intensities were determined by uranyl oxalate actinometry with the quantum yields for decomposition of oxalic acid at 254, 297, and 366 mm taken as 0.63, 0.58, and 0.49, respectively.[91]

Chemicals. Dioxane (Matheson Coleman and Bell (MC&B) spectroquality) and glyme ((1,2-dimethoxyethane) Ansul Co., Ansul Ether 121) were freed of peroxides by refluxing 100 ml of of solvent/g of $SnCl_2 \cdot 2H_2O$ for 2 hr. The solvent was then dried over calcium hydride and distilled. A negative test with 2% KI and HCl was taken to indicate the solvent to be peroxide free. Acetonitrile (Mallinckrodt analytical reagent grade), benzene (Mallinckrodt spectral grade (M); Fisher (F); MC & B spectroquality; Baker reagent grade (B)), and toluene (Baker reagent grade) were dried over calcium hydride and distilled. *n*-Butyl alcohol (Baker reagent grade), *tert*-butyl alcohol (Baker reagent grade), carbon tetrachloride (Baker spectral grade), dimethylformamide (Du Pont technical grade), ethanol (stockroom bulk, absolute), ethyl acetate (MC & B anhydrous, 99.5%), and methanol (Baker anhydrous, spectrophotometric grade) were distilled following treatment with Fisher type 4A molecular sieve. Deuterium oxide (99.5%, Columbia Organic Chemicals) was used as received. Distilled water from the building supply was distilled from alkaline potassium permanganate and then redistilled. The solvent did not absorb in the uv.

cis-Piperylene ((1,3-pentadiene), Chemical Samples Co.), *n*-hexane (Phillips spectral grade), and 2,4-hexadien-1-ol (MC & B) were distilled immediately prior to use in a microdistillation apparatus.[92] The piperylene was glpc pure cis isomer. Pyrene (Aldrich Chemical Co.) was purified by vacuum sublimation (105° (0.2 mm)). Sodium perchlorate (G. Frederick Smith Co., anhydrous) was dried overnight in a drying pistol using P_2O_5 and an oil pump vacuum while heating with refluxing benzene.

1,3-Dimethylthymine. This compound was prepared in a manner similar to that used[93] for methylation of uracil. Yields were of the order of 85% after recrystallization from absolute ethanol (mp 154°; lit.[94] mp 153°); the DMT was further purified by vacuum sublimation (100° (0.5 mm)).

1,3-Dimethyl-6-azathymine. This compound was made by the same procedure in 68% yield, mp 102°.

Preparation of the DMT Dimers. Approximately 1.4 g of DMT was dissolved in 100 ml of water and irradiated with the 450-W mercury lamp equipped with a Corex filter. After 24 hr of irradiation, the precipitate which had formed was collected on a fine sintered-glass filter. The white crystals were washed once with cold methanol and then dried in an oven at 130° for about 2 hr to yield 100 mg of dimer V: mp 261–262°; pure by glpc; $\lambda_{\max}^{\mathrm{KBr}}$ 5.90, 6.00, 9.20, 9.57, 13.40 μ; nmr ($CDCl_3$) δ 1.43, 3.08, 3.28, 3.71 (all singlets with relative areas 3:3:3:1).

Anal. Calcd for $C_{19}H_{20}N_4O_4$: C, 54.54; H, 6.54; N, 18.17. Found: C, 54.82; H, 6.30; N, 17.93.

For isolation of dimers III and IV, about 250 mg of the residue formed by evaporation of the water was dissolved in 3 ml of dichloromethane and placed on a column of 18 g of Merck acid-washed alumina in benzene. The column was eluted successively with 100 ml of dry ether, 100 ml of 1% ethanol, 100 ml of 2% ethanol, and 100 ml of methanol. The solvent was removed from each fraction (20-ml fractions were collected) by evaporation with a stream of nitrogen and the residues were examined by glpc. Typically, we obtained 2 mg of pure DMT in fractions 4–6, 25 mg of pure V in fractions 8–11, 16 mg of a mixture of V and III in fraction 12, 77 mg of pure III in fractions 13–15, 14 mg of a mixture of III and VI in fractions 16–18, and 64 mg of pure IV in fractions 20–26. III showed the following characteristics: $\lambda_{\max}^{\mathrm{KBr}}$ 5.85, 5.95, 9.15, 9.38, 13.30, 13.60 μ; nmr ($CDCl_3$) δ 1.62, 3.09, 3.18, 3.31 (all singlets with relative areas of 3:3:3:1). IV showed the following characteristics: $\lambda_{\max}^{\mathrm{KBr}}$ 5.85, 5.99, 9.45, 9.58, 13.43 μ; nmr ($CDCl_3$) δ 1.51, 3.02, 3.14, 3.78 (all singlets with relative areas of 3:3:3:1) (nmr solutions *ca.* 10% by weight).

Quantum Efficiencies for Dimer Formation (ϕ_{DF}). The quantum efficiency for water was determined using 0.10 *M* DMT and the Bausch and Lomb monochromator set at 297 ± 11 mm (20°); all the light is absorbed by the 6 cm (62 ml) cell under these conditions; 112.9 hours of irradiation were necessary for 2.5% conversion to dimers at an average light intensity of 7.9×10^{15} photons/sec.

The efficiency of dimer formation in methanol was determined relative to the efficiency in water using the Rayonet reactor with the 3000-Å lamps and Pyrex tubes at 34°. It was determined that 0.07 *M* DMT in water and 0.10 *M* DMT in methanol have essentially identical uv absorption spectra (1-cm path length). Hence, the dimer formation in water at 0.07 *M* DMT was analyzed to determine the light intensity absorbed by 0.10 *M* DMT in methanol. (The quantum yield for dimer formation in water at 0.07 *M* DMT was taken to be 0.009.[34]) The light intensity was measured during the first and last 8 hr of irradiation. The methanol solution contained 0.10 *M* *cis*-piperylene to assure that only singlet dimerization was measured, and a $\phi_{DF}{}^1$ of 0.0019 was determined ($I_{\mathrm{initial}} = 3.4 \times 10^{17}$ photons/sec; $I_{\mathrm{final}} = 3.1 \times 10^{17}$ photons/sec; 55.5 hr; 8.9% conversion). Since photodimerization in methanol is 96% singlet derived, ϕ_{DF}(total) is 0.0020.

The efficiencies of dimer formation in other organic solvents at 0.10 *M* DMT were determined relative to the efficiency in methanol; Pyrex tubes, a Corex filter, and the 450-W Hanovia lamp were used. Corrections were made to take into account differences in DMT absorption in the various solvents, *i.e.*, water, D_2O, water–15% ethanol: 100%; methanol: 87%; acetonitrile, DMF: 70%; ethyl acetate, glyme, dioxane, toluene, benzene: 67%.

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