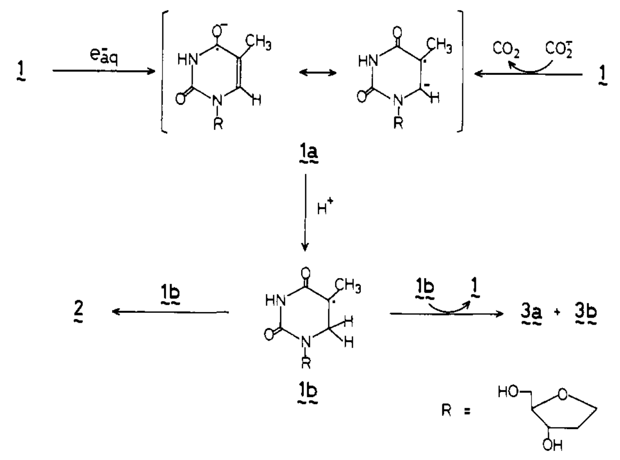
Scheme II



mine.[13] The formation of **3a,b** has been also observed in the radiolysis of **1** in the presence of alcohols.[7] Using HPLC data for a series of irradiated samples by reference to isolated **2** and authentic samples[7,14] of **3a,b**, the *G* values of these major products were evaluated as *G*(**2**) = 0.87 based on monomer unit (29% yield based on consumed **1**), *G*(**3a**) = 0.89 (30%), and *G*(**3b**) = 0.76 (26%) (Scheme I).

In a preparative work, a deaerated solution of **1** (10 mM) in 500 mL of triply distilled water containing sodium formate (0.2 M) (pH 7.0) was irradiated up to the quantitative conversion, condensed, and then chromatographed.[15] Evaporation of the fraction containing **2** and recrystallization from ethanol/petroleum ether gave a colorless crystal: mp 140–150 °C; IR (KBr) 3375, 1685 cm^{-1}. Anal. ($C_{20}H_{32}N_4O_{11}$, as monohydrate) C, H, N. The four hydroxyl groups of the sugar moieties (C3′, C(3′), C5′, and C(5′)) in **2** were trimethylsilylated[16] followed by measurement of mass spectrum: *m/e* 775 (M^+, $C_{32}H_{62}N_4O_{10}Si_4$ requires 775), 760 ($(M - CH_3)^+$).

The ^{13}C NMR (D_2O, 25 MHz) spectra[17] of **2** (Figure 1a,b) are consistent with the linkage of two monomer units, **1**, at their pyrimidine C5 positions. Thus, the ^{13}C chemical shifts assigned to the sugar moieties of **2** were substantially identical with those of **1** and other deoxyribonucleosides[18] and the hydrogenated products **3** as well.[19] In contrast, the pyrimidine C5 and C6 signals of **1** shifted to upfield by more than 65 ppm due to the dimerization to **2**, as was also the case for the hydrogenation to **3a,b**.[19] Moreover, the partially decoupled ^{13}C NMR spectrum (Figure 1b) shows that signals characteristic of the dimer pyrimidine C5,C(5) and C6,C(6) are singlet and triplet, respectively. It is also interesting to note the observation of ^{13}C NMR shielding differences, although small ($\Delta\delta_C$ 0.2 for all cases, see C2,C(2), C6,C(6), and C2,C(2′)).[17] Potentially, unhindered rotation around the linkage between asymmetric C5 and C(5) seems to account for such a magnetic nonequivalence.[20]

In accord with the structural evidence from ^{13}C NMR, the ^1H NMR (D_2O, 300 MHz) spectrum[21] of **2** showed the absence of protons at C5 and C(5) positions, while **3b** gave the corresponding C5 proton signal at δ_H 2.820 (1 H, m, *J* = 10.7, 6.0, 7.2 Hz).

The formation of **2** and **3a,b** may be rationalized by the reaction pathway outlined in Scheme II. In the initial step, reducing species of hydrated electron (e_{aq}^-, *G* = 2.7) and carbon dioxide radical anion ($CO_2^{-}\cdot$, *G* = 3.25) are created via radiolysis of water in the presence of excess formate.[22] The key step is one-electron reduction of **1** by both e_{aq}^- and $CO_2^{-}\cdot$ to the corresponding radical anion intermediate (**1a**), which subsequently undergoes protonation to produce hydrothymidin-5-yl radical (**1b**). Combination of two **1b** leads to **2**, while disproportionation to **3a** and **3b** is accompanied by regeneration of **1**. It is deduced from the *G* values of **2**, **3a**, and **3b** that the disproportionation is favored 3.8-fold over the combination on bimolecular encounter of **1b**.

Support for the $CO_2^{-}\cdot$-induced reduction of **1** was obtained by irradiation of an N_2O-saturated aqueous solution of **1** (1 mM) and sodium formate (0.1 M) at pH 7.0. Under these conditions only $CO_2^{-}\cdot$ (*G* = 5.95) could participate[22] in the decomposition of **1**, which occurred with efficiency (*G*(−**1**) = 2.65) comparable to the deaerated system. It is more remarkable that the observed product distribution, i.e., *G*(**2**) = 0.75 (28%), *G*(**3a**) = 0.70 (26%), and *G*(**3b**) = 0.68 (26%), is also almost identical with that of the deaerated system. Thus, comparison of both reaction systems indicates that $CO_2^{-}\cdot$ has the same reducing ability as e_{aq}^- toward **1**.

In summary we have found that **1** undergoes reduction of the pyrimidine base moiety by e_{aq}^- or $CO_2^{-}\cdot$ in aqueous solution to give the C5-linked dimer **2** along with **3a,b**.

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(14) (a) Kondo, Y.; Witkop, B. *J. Am. Chem. Soc.* **1968**, *90*, 764. (b) Konnert, J.; Karle, L.; Karle, J. *Acta Chrystallogr., Sect B* **1970**, *B26*, 770.

(15) The chromatography was carried out on a column of polystyrene resin (Mitsubishi Kasei HP20) by using methanol/water with linear methanol gradient from 0 to 10 vol %.

(16) Butts, W. C. *J. Chromatogr. Sci.* **1970**, *8*, 474.

(17) δ 18.2, 35.7, and 35.9 (C2′ and C(2′)), 44.3 and 44.5 (C6 and C(6)), 45.3, 62.1, 71.4, 84.5, 85.8, 153.8, and 154.0 (C2 and C(2)), 175.8. We thank B. Ohtani for the NMR measurements.

(18) (a) Jones, A. J.; Grant, D. M.; Winkley, M. W.; Robins, R. K. *J. Phys. Chem.* **1970**, *74*, 2684; (b) *J. Am. Chem. Soc.* **1970**, *92*, 4079.

(19) For example, 3b: ^{13}C NMR (D_2O, 25 MHz) δ 12.9 (Me), 35.4 (C5), 36.1 (C2′), 42.7 (C6), 62.4 (C5′), 71.6 (C3′), 86.0 (C4′), 155.0 (C2), 177.4 (C4).

(20) (a) van Gorkom, M.; Hall, G. E. *Quart. Rev.* **1968**, *22*, 14. (b) Kroschwitz, J. A.; Winokur, M.; Reich, H. J.; Roberts, J. D. *J. Am. Chem. Soc.* **1969**, *91*, 5927.

(21) The two dihydrothymine moieties: δ 1.406 and 1.431 (s, 5- and (5)-Me), 3.397 and 3.788 (d, *J* = −13.8 Hz, geminal 6- or (6)-H), 3.447 and 3.686 (d, *J* = −12.9 Hz, geminal (6)- or 6-H). Sugar moieties: δ 2.137–2.305 (4 H, 2′- and (2′)-H), 3.691–3.758 (4 H, 5′- and (5′)-H), 3.904 and 3.916 (2 H, 4′- and (4′)-H), 4.398 and 4.736 (2 H, 3′- and (3′)-H), 6.206 and 6.254 (2 H, 1′- and (1′)-H).

(22) The primary active species in the dilute aqueous solution system (pH 7.0) are derived from radiolysis of water as follows:

$$H_2O \rightsquigarrow \cdot OH\ (G = 2.7) + H\cdot\ (G = 0.55) + e_{aq}^-\ (G = 2.7)$$

The so-formed ·OH and H· are converted efficiently to the $CO^{-}\cdot$ in the presence of excess formate.

$$\cdot OH(H\cdot) + HCO_2^- \rightarrow H_2O(H_2) + CO_2^{-}\cdot$$

Since N_2O converts the e_{aq}^- to ·OH,

$$e_{aq}^- + N_2O \rightarrow \cdot OH + OH^- + N_2$$

the presence of both HCO_2^- and N_2O leads to generation of a single active species of $CO_2^{-}\cdot$.

Linear Solvation Energy Relationships. 26. Some Measures of Relative Self-Association of Alcohols and Water

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In two separate and completely unrelated investigations, we have generated information that allows estimates of bulk solvent properties that are related to the self-association energies of some aliphatic alcohols and water. We believe it to be of fundamental importance that these estimates are in quite good agreement with

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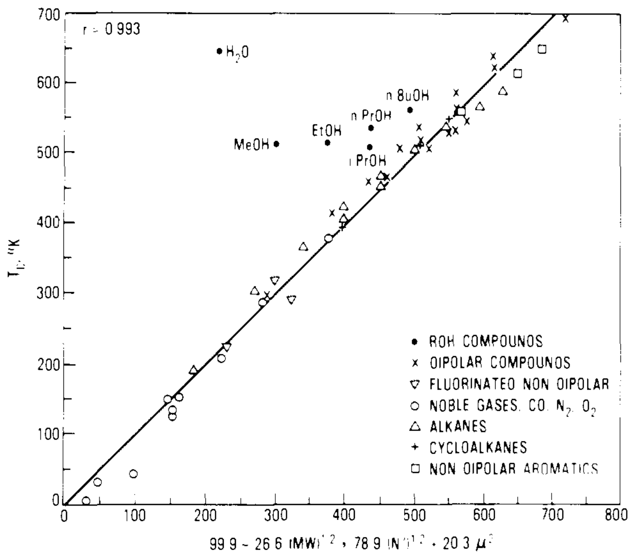

Figure 1. Observed critical temperatures plotted against values calculated through eq 5.

one another and with a recent analysis of factors that influence self-association of ROH compounds.

The first investigation was a continuation of recent work wherein we had shown[1] that free energies of solution of nondipolar solutes in nondipolar and dipolar solvents were well correlated through equations of the form of eq 1, where δ_H is the Hildebrand solubility

$$\Delta G_s^\circ = (\Delta G_s^\circ)_0 + h\delta_H \quad (1)$$

parameter. Values of δ_H for liquid compounds are obtained experimentally from vaporization enthalpies and eq 2, $-\Delta H_v^\circ$ being

$$\delta_H = [(-\Delta H_v^\circ - RT)/V]^{1/2} \quad (2)$$

the standard molal enthalpy of vaporization at 298 K and V being the molal volume.[2]

We have now found that values of the Hildebrand solubility parameter, back calculated for ROH compounds through eq 1 (we label these as δ_C for correlational) differ significantly from the δ_H values determined from molal heats of vaporization. We rationalize the differences as follows: Amphiprotic R–OH compounds are self-associated through hydrogen bonding, the ROH compounds acting simultaneously as hydrogen-bond donors (acids) and acceptors (bases). These hydrogen bonds are broken in both the vaporization process and the process of separating the ROH solvent molecules to form a cavity for the solute. The ROH compounds do not to any significant extent reassociate in the vapor phase. In the liquid phase, however, after the nondipolar solute has filled the cavity, a new pattern of hydrogen-bonded self-association is formed by the ROH molecules surrounding the solute. This contributes to the exogenic reorganization energy in the theory of regular solutions.[2]

On this basis, we considered that the differences between δ_H and δ_C should be measures of the self association energies of the ROH compounds. Accordingly we have defined by eq 3 a

$$\delta_{SA} = \delta_H - \delta_C \quad (3)$$

quantity, δ_{SA}, that is the self-association contribution to δ_H. We then used the correlation equations in the form of eq 1, which we had reported earlier,[1] for Ar, N_2, O_2, H_2, CO, CH_4, n-C_8H_{18}, and $(C_2H_5)_4Sn$, together with solubilities reported by Abraham[3] for these inert solutes in the alcohols and water, to arrive at individual estimates of δ_C. These were then averaged to arrive at the values

Table I. Properties Related to Self-Association Energies of Alcohols and Water

ROH compd	E_s[a]	δ_H[b]	δ_C	n[c]	δ_{SA}	CT_{exptl}, K	$CT_{calcd}^{eq\ 5}$, K	$(\Delta\Delta CT)_{SA}$, K	bp_{exptl}, K	$bp_{calcd}^{eq\ 6}$, K	$(\Delta\Delta bp)_{SA}$, K
1-butanol	−0.39	11.38	9.8 ± 0.2	7	1.6	562.9	490.2	72.7	390.0	320.9	70.0
2-propanol	−0.47	11.54	10.0 ± 0.2	7	1.5	508.1	435.3	72.8	355.6	281.9	73.6
1-propanol	−0.36	11.97	10.2 ± 0.2	7	1.8	536.7	436.4	100.2	370	282.7	87.2
ethanol	−0.07	12.73	10.6 ± 0.2	8	2.1	516.1	375.2	140.9	351.6	240.3	111.3
methanol	0.00	14.32	11.3 ± 0.2	7	3.0	513.1	302.6	210.4	337.8	190.0	147.7
water	+1.24	23.43	18.1 ± 0.4	4[d]	5.3	647.3	218.8	428.5	373.1	131.7	241.4

[a] Reference 8. [b] Calculated from ΔH_v° values at 298 K reported by Polak and Benson (Polak, J.; Benson, G. C. *J. Chem. Thermodyn.* **1971**, *3*, 235). [c] Number of individual solubilities used in estimating δ_C. [d] Because of the hydrophobic effect, the solubilities of CH_4, n-C_8H_{18}, and $(C_2H_5)_4Sn$ were not used in estimating the δ_C of water.

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that are assembled in Table I, together with the corresponding values of δ_H and δ_{SA}.

The second investigation involved an attempt to unravel and rationalize the interacting effects that contribute to critical temperatures, CT, and boiling points, bp, of nondipolar and dipolar compounds. We defined a polarizability term, N', by eq 4, where

$$N' = N + 3N_{Cl} + 3N_{Br} - N_F + 3N_{DB} + 8 \text{ (for cycloalkanes)} + 6.0\,(3.0 - \mu) \text{ (for aromatics)} \qquad (4)$$

N is the total number of atoms in the molecule, N_{Cl}, N_{Br}, N_F, and N_{DB} are the numbers of chlorine, bromine, and fluorine atoms and double bonds, and μ is the gas-phase electric dipole moment.[4] We then showed that the CT and bp of a large number of nondipolar and dipolar compounds were well correlated by eq 5 and 6.[5] A plot of CT_{exptl} vs. $CT_{calcd}{}^{eq\,5}$ is shown in Figure 1.

$$CT\ (K) = -99.9 + 26.6(M_r)^{1/2} + 78.9(N')^{1/2} + 20.3\mu^2 \qquad n = 48,\ r = 0.993,\ SD = 22.1\ K \qquad (5)$$

$$bp\ (K) = -86.6 + 17.7(M_r)^{1/2} + 56.1(N')^{1/2} + 13.5\mu^2 \qquad n = 48,^{5}\ r = 0.994,\ SD = 13.4\ K \qquad (6)$$

We then defined by eq 7 and 8 two quantities $(\Delta\Delta CT)_{SA}$ and $(\Delta\Delta bp)_{SA}$, which are the increments caused by self-association of the ROH compounds. The $(\Delta\Delta CT)_{SA}$ terms correspond to

$$(\Delta\Delta CT)_{SA} = CT_{exptl} - CT_{calcd}{}^{eq\,5} \qquad (7)$$

$$(\Delta\Delta bp)_{SA} = bp_{exptl} - bp_{calcd}{}^{eq\,6} \qquad (8)$$

the vertical displacements of the ROH data points from the regression line in Figure 1. Values of the $\Delta\Delta$ terms are also assembled in Table I.

If the $\Delta\Delta$ terms and the δ_{SA} terms all depend on the ROH self-association energies, they might be expected to bear simple relationships to one another. This is, indeed, the case, the three sets of properties showing very nice linear regressions (eq 9–11).

$$(\Delta\Delta CT)_{SA}\ (K) = -83.3 + 2.086(\Delta\Delta bp)_{SA} \qquad r = 0.998,\ SD = 8.6\ K \qquad (9)$$

$$(\Delta\Delta CT)_{SA}\ (K) = -68.5 = 93.9\delta_{SA} \qquad r = 0.998,\ SD = 6.3\ K \qquad (10)$$

$$(\Delta\Delta bp)_{SA}\ (K) = 7.8 + 44.7\delta_{SA} \qquad r = 0.995,\ SD = 6.1\ K \qquad (11)$$

It is of interest that eq 11 has a smaller intercept than the standard deviation of antecedent eq 6, suggesting a direct proportionality. That this is not the case with eq 9 and 10 may be because the bp are all at the same pressure, but the CT are at different critical pressures.

We were also interested in examining how the $\Delta\Delta$ and δ_{SA} values compared with other properties that depend on extents of self-association, but such information is quite sparse in the literature. The most informative study is by Abboud and coworkers,[6] who have reported the following dimerization constants, K_d, in cyclohexane solvent: t-BuOH, 22; i-PrOH, 39; n-PrOH, 47; EtOH, 48; MeOH, 56.[7]

Abboud and co-workers[6] also observed that their association constants seemed to depend primarily on the steric influence of R and hence were well correlated with Taft's steric parameter, E_s.[8] Accordingly we have also carried out correlations of the $\Delta\Delta$ terms with the E_s values of R in ROH, and we have found the linear fits to be quite good (eq 12 and 13).

$$(\Delta\Delta CT)_{SA}\ (K) = 172.6 + 211.0E_s \qquad r = 0.989,\ SD = 18.6\ K \qquad (12)$$

$$(\Delta\Delta BP)_{SA}\ (K) = 123.0 + 102.0E_s \qquad r = 0.981,\ SD = 11.6\ K \qquad (13)$$

On the above basis we conclude that the δ_{SA} terms are convenient measures of extents of self-association of amphiprotic solvents. We also suggest that for solution studies (or polymer swelling studies) δ_C is a more appropriate measure of the cavity term than δ_H.

Registry No. 1-Butanol, 71-36-3; 2-propanol, 67-63-0; 1-propanol, 71-23-8; ethanol, 64-17-5; methanol, 67-56-1; water, 7732-18-5.

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[4] For a number of compounds of different polarizability classes, $N' - N$ was found to be linear with $(n^2 - 1)/(2n^2 + 1)$ with a correlation coefficient of 0.989.

[5] Dimethylformamide and dimethylacetamide are two important solvents that do not fit eq 6. We will discuss possible reasons in the full paper.

[6] Frange, B.; Abboud, J.-L. M.; Benamou, C.; Bellon, L. *J. Org. Chem.* **1982**, *47*, 4553.

[7] They also concluded that tetramerization (K_{dd} for dimerization of dimers) is over an order of magnitude more important than dimerization. For the couple MeOH/t-BuOH in CCl_4, they found the ratios of K_d and K_{dd} values to be 1.83 and 3.49, respectively.

[8] Taft, R. W. In "Steric Effects in Organic Chemistry", Newman, M. S., Ed.; Wiley: New York, 1956; Chapter 13.

Models for Nitrite Reductases. Redox Chemistry of Iron Nitrosyl Porphyrins, Chlorins, and Isobacteriochlorins and π Cation Radicals of Cobalt Nitrosyl Isobacteriochlorins

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Nitrite reductases catalyze the multielectron reductions of nitrite to ammonia or to nitric oxide.[1,2] The identification of iron isobacteriochlorins (sirohemes) and chlorins (hemes d) as the prosthetic groups of these enzymes[1,2] and the detection of $Fe^{II}NO$ complexes in the catalytic cycles of both types of nitrite reductases[3] prompted us to investigate the redox chemistry of $Fe^{II}NO$ complexes of porphyrins (P), chlorins (C), and isobacteriochlorins (iBC). We find that the potentials for the one-electron reductions of these complexes are independent of macrocycle and thus offer no obvious advantage for biological selection among the three macrocycles. However, the progressive saturation of the macrocycles makes their $Fe^{II}NO$ complexes easier to oxidize, which results in π cation radical rather than Fe(III) formation, and renders the NO substrates considerably more labile when bound to oxidized Fe porphyrins than to isobacteriochlorins.

We have extended these studies to $Co^{II}NO$ complexes and demonstrate unambiguously the formation of $Co^{II}NOiBC$ π radicals. These results may themselves be biologically relevant because some sulfite reductases utilize cobalt iBCs to catalyze electron transport[4] and because sulfite reductases also reduce nitrite.[1]

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