5.58 (d, 1 H, $J = 12.4$ Hz), 7.47–7.65 (m, 3 H); $^{13}$C NMR ($CDCl_3$, 300 MHz) $\delta$ 52.68, 52.85, 78.77, 85.08, 115.75, 123.61, 125.28, 127.39, 131.98, 134.80, 138.06, 142.59, 147.16, 161.00, 162.81, 186.96. Anal. Calcd for $C_{16}H_{12}O_7$: C, 60.76; H, 3.82. Found: C, 60.81; H, 3.84.

A solution containing 350 mg of **28** and 400 mg of *N*-phenylmaleimide in 20 mL of methylene chloride was treated with a catalytic amount of rhodium(II) acetate at 25 °C. The mixture was stirred for 12 h and filtered through Celite, and the solvent was removed under reduced pressure. The resulting residue was subjected to silica gel chromatography using a hexane–ethyl acetate mixture as the eluent, and the major fraction contained 470 mg (79%) of the expected dipolar cycloadduct **33**: mp 174–175 °C; IR (KBr) 3080, 2950, 2890, 1725, 1605, 1510, 1400, 1205, 1015, 795, 715 cm$^{-1}$; $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 4.04 (d, 1 H, $J = 9.5$ Hz), 4.27 (t, 1 H, $J = 9.5$ Hz), 5.09 (d, 1 H, $J = 9.3$ Hz), 5.34 (d, 1 H, $J = 12.6$ Hz), 5.70 (d, 1 H, $J = 12.6$ Hz), 6.63 (m, 2 H), 7.26–7.94 (m, 6 H); $^{13}$C NMR ($CDCl_3$, 300 MHz) $\delta$ 46.3, 52.4, 77.1, 80.7, 124.1, 125.6, 125.7, 128.0, 128.3, 128.4, 129.1, 130.8, 132.0, 132.7, 143.3, 171.6, 172.3, 190.5. Anal. Calcd for $C_{20}H_{13}NO_5$: C, 69.16; H, 3.77; N, 4.03. Found: C, 69.09; H, 3.80; N, 4.01.

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# Free Energies of Transfer of Carbon Acids and Their Conjugate Carbanions from Water to $Me_2SO$–Water Mixtures

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**Abstract:** Free energies (or solvent activity coefficients) of transfer of nitromethane, phenylnitromethane, acetylacetone, 1,3-indandione, 9-carbomethoxyfluorene, and 9-cyanofluorene from water to various $Me_2SO$–water mixtures were determined from partitioning experiments between *n*-heptane and the solvent of interest. In combination with the p$K_a$ values of the various carbon acids in the different solvents and the solvent activity coefficients of the hydronium ion taken from the literature, free energies of transfer of the respective carbanions were also calculated. These latter values are of particular relevance with respect to recent suggestions that solvent effects on the intrinsic barriers of proton-transfer reactions may be understood in terms of nonsynchronous solvation/desolvation effects of the ions involved in these reactions (principle of nonperfect synchronization). The availability of free energies of transfer of the carbon acids and their conjugate bases also allows a better understanding of the solvent effects on the p$K_a$ values of the carbon acids.

The reactivity of carbanions acting as bases or nucleophiles is generally substantially affected by the solvent although the degree of their dependence varies greatly with the nature of the carbanion. One may distinguish three major categories of carbanions with respect to solvent effects on their reactivity. In the first are the carbanions whose basicity and nucleophilic reactivity increase dramatically upon transfer from water to $Me_2SO$. These are ions in which the negative charge is highly localized on an oxygen atom, as is the case with enolate and nitronate ions. The second category consists of carbanions whose reactivity is also significantly solvent dependent but in the direction of *decreased* basicity in $Me_2SO$ compared with water. Typical examples would be highly delocalized carbanions derived from aromatic hydrocarbons. The third category comprises carbanions with p$K_a$ values that are about the same in water and $Me_2SO$, such as the malononitrile anion. Table I summarizes p$K_a$ values for some representative examples.

In a first approximation the p$K_a$ differences shown in Table I can be attributed to differences in the solvation of the respective carbanions in the two solvents. Thus, the sharp increase in p$K_a$ upon transfer from water to $Me_2SO$ for the nitroalkanes, diketones, and diesters may primarily be seen to be the consequence of the loss of hydrogen bonding solvation of the nitronate and enolate ions. This contrasts with the carbanions derived from the aromatic hydrocarbons, which seem to be better solvated in the dipolar aprotic solvent than in water, and hence their p$K_a$ decreases.

For a more accurate assessment of the effect of solvation on carbanion reactivity, a more quantitative evaluation of solvation energies is needed than that provided by mere comparisons of the solvent effects on p$K_a$ values. This is because the p$K_a$ changes are not only the result of the solvent effect on the stability of the carbanion but on the stability of the carbon acid and the hydronium ion as well.

**Table I.** p$K_a$ Values for Some Carbon Acids in Water and $Me_2SO$

| carbon acid | p$K_a$ $H_2O$ | p$K_a$ $Me_2SO$ | carbon acid | p$K_a$ $H_2O$ | p$K_a$ $Me_2SO$ |
|---|---|---|---|---|---|
| $CH_3NO_2$ | 10.2[a] | 17.2[b] | $CH_2(CN)_2$ | 11.1[g] | 11.0[h] |
| $PhCH_2NO_2$ | 6.88[c] | 12.03[d] | 4-$NO_2C_6H_4CH_2CN$ | 13.4[i] | 12.3[j] |
| $CH_2(COCH_3)_2$ | 9.0[a] | 13.4[b] | 9-COOMe-fluorene | 15.8[k,l] | 10.35[m] |
| $CH_2(COOEt)_2$ | 13.3[a] | 16.4[b] | 9-CN-fluorene | 10.71[n,p] | 8.3[m] |
| $CH_3CH(NO_2)_2$ | 5.2[e] | 6.6[f] | | | |

[a] Pearson, R. G.; Dillon, R. L. *J. Am. Chem. Soc.* **1953**, *75*, 2439. [b] Olmstead, W. N.; Bordwell, F. G. *J. Org. Chem.* **1980**, *45*, 3299. [c] Reference 16a. [d] Keeffe, J. R.; Morey, J.; Palmer, C. A.; Lee, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 1295. [e] Bell, R. P.; Tranter, R. L. *Proc. R. Soc. London, Ser. A* **1974**, *337*, 578. [f] Cox, B. G.; Gibson, A. *Faraday Symp. Chem. Soc.* **1975**, *10*, 107. [g] Bowden, K.; Stewart, R. *Tetrahedron* **1965**, *21*, 261. [h] Ritchie, C. D.; Uschold, R. E. *J. Am. Chem. Soc.* **1967**, *89*, 2752. [i] Stearns, R. S.; Wheland, G. W. *J. Am. Chem. Soc.* **1947**, *69*, 2025. [j] Bordwell, F. G., cited by: Walters, E. *J. Phys. Chem.* **1977**, *81*, 1995. [k] Ritchie, C. D. *J. Am. Chem. Soc.* **1969**, *91*, 6749. [l] In MeOH. [m] Bordwell, F. G.; Branca, J. C.; Hughes, D. L.; Olmstead, W. N. *J. Org. Chem.* **1980**, *45*, 3305. [n] Reference 4a. [p] In 10% $Me_2SO$–90% water.

Adopting the formalism used by Parker[1] one can express the change in p$K_a$ upon transfer from water(W) to $Me_2SO$(D) as eq 1. ${}^{W}\gamma^{D}{}_{C^-}$, ${}^{W}\gamma^{D}{}_{H^+}$, and ${}^{W}\gamma^{D}{}_{CH}$ are the solvent activity coefficients

$$ {}^{W}\Delta^{D}pK_a = \log {}^{W}\gamma^{D}{}_{C^-} + \log {}^{W}\gamma^{D}{}_{H^+} - \log {}^{W}\gamma^{D}{}_{CH} \qquad (1) $$

for the transfer of the carbanion, the hydronium ion, and the carbon acid, respectively, from water to $Me_2SO$. Alternatively, one may express eq 1 in terms of free energies as eq 2, with the

$$ {}^{W}\delta^{D}\Delta G^\circ = {}^{W}\delta^{D}G_{tr}(C^-) + {}^{W}\delta^{D}\Delta G_{tr}(H^+) - {}^{W}\delta^{D}\Delta G_{tr}(CH) \qquad (2) $$

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(1) Parker, A. J. *Chem. Rev.* **1969**, *69*, 1.

**Table II.** Partition Coefficients between *n*-Heptane and Water[a] and between *n*-Heptane and $Me_2SO$–Water Mixtures[b] for Various Carbon Acids at 20 °C

| CH acid | $H_2O$[c] | $Me_2SO$ concn 10%[c] | 50%[c] | 70%[d] | 90%[e] | 95%[f] |
|---|---|---|---|---|---|---|
| nitromethane | $1.01 \times 10^{-1}$ | | $8.06 \times 10^{-2}$ | $3.32 \times 10^{-2}$ | $1.35 \times 10^{-2}$ | |
| phenylnitromethane | $1.49 \times 10^{1}$ | | 1.17 | $1.49 \times 10^{-1}$ | $2.04 \times 10^{-2}$ | |
| acetylacetone | $3.25 \times 10^{-2}$ | | $5.26 \times 10^{-2}$ | | $1.95 \times 10^{-2}$ | $1.41 \times 10^{-2}$ |
| acetylacetone enol | $9.16 \times 10^{-1}$ | | 1.23 | | $3.03 \times 10^{-1}$ | $2.19 \times 10^{-1}$ |
| 1,3-indandione | $5.57 \times 10^{-1}$ | $4.74 \times 10^{-1}$ | $1.95 \times 10^{-1}$ | $6.50 \times 10^{-2}$ | $1.20 \times 10^{-2}$ | |
| 9-carbomethoxyfluorene | | $1.81 \times 10^{3}$ | $2.28 \times 10^{1}$ | | $1.31 \times 10^{-1}$ | |
| 9-cyanofluorene | | $2.44 \times 10^{2}$ | 5.62 | | $3.20 \times 10^{-2}$ | |

[a] ${}^{W}P^{H}$ (eq 7). [b] ${}^{D}P^{H}$ (eq 8). [c] $\mu = 0.5$ M (KCl). [d] $\mu = 0.25$ M (KCl). [e] 0.06 M (KCl). [f] 0.005 M (KCl).

**Table III.** p$K_a$ Values and Solvent Activity Coefficients for the Transfer of Carbon Acids and their Carbanions from Water to $Me_2SO$–Water Mixtures (${}^{W}\gamma^{D}$), from 10% $Me_2SO$ to other Mixtures (${}^{10}\gamma^{D}$), and from 50% $Me_2SO$ to Other Mixtures (${}^{50}\gamma^{D}$), at 20 °C

| CH acid | % $Me_2SO$[a] | p$K_a$[b] | log ${}^{W}\gamma^{D}_{CH}$ | log ${}^{W}\gamma^{D}_{C^-}$ | log ${}^{10}\gamma^{D}_{CH}$ | log ${}^{10}\gamma^{D}_{C^-}$ | log ${}^{50}\gamma^{D}_{CH}$ | log ${}^{50}\gamma^{D}_{C^-}$ |
|---|---|---|---|---|---|---|---|---|
| nitromethane | 0 | 10.28 | | | | | | |
| | 50 | 11.32 | −0.10 ± 0.03 | 2.87 ± 0.04 | | | | |
| | 70 | 12.44 | −0.48 ± 0.03 | 4.51 ± 0.04 | | | | |
| | 90 | 14.80 | −0.87 ± 0.03 | 6.70 ± 0.04 | | | −0.77 ± 0.03 | 3.83 ± 0.04 |
| phenylnitromethane | 0 | 6.77 | | | | | | |
| | 50 | 7.93 | −1.11 ± 0.02 | 1.99 ± 0.03 | | | | |
| | 70 | 8.53 | −2.00 ± 0.02 | 2.59 ± 0.03 | | | | |
| | 90 | 10.68 | −2.86 ± 0.03 | 4.09 ± 0.04 | | | −1.75 ± 0.03 | 2.10 ± 0.04 |
| acetylacetone | 0 | 8.90[c,d] | | | | | | |
| | 50 | 9.12[c] | 0.21 ± 0.03 | 2.36 ± 0.04[e] | | | | |
| | 90 | 11.10[c] | −0.22 ± 0.03 | 5.03 ± 0.04[e] | | | −0.43 ± 0.03 | 2.67 ± 0.04 |
| 1,3-indandione | 10 | 7.00 | −0.07 ± 0.02 | | | | | |
| | 50 | 6.35 | −0.46 ± 0.02 | | −0.39 ± 0.02 | 0.41 ± 0.03 | | |
| | 70 | 6.56 | −0.93 ± 0.02 | | −0.87 ± 0.02 | 1.04 ± 0.03 | | |
| | 90 | 7.82 | −1.67 ± 0.04 | | −1.60 ± 0.04 | 1.79 ± 0.05 | −1.21 ± 0.04 | 1.38 ± 0.05 |
| 9-carbomethoxyfluorene | 50 | 10.97 | | | −1.90 ± 0.04 | | | |
| | 90 | 10.03 | | | −4.14 ± 0.04 | | −2.24 ± 0.04 | −2.12 ± 0.05 |
| 9-cyanofluorene | 10 | 10.71 | | | | | | |
| | 50 | 9.53 | | | −1.64 ± 0.04 | −1.37 ± 0.05 | | |
| | 90 | 8.01 | | | −3.88 ± 0.04 | −4.02 ± 0.05 | −2.24 ± 0.04 | −2.65 ± 0.05 |

[a] $\mu = 0.5$ M (KCl) in water, 10% and 50% $Me_2SO$; $\mu = 0.25$ M (KCl) in 70% $Me_2SO$; $\mu = 0.06$ M (KCl) in 90% $Me_2SO$. [b] p$K_a$ values from ref 2–5. [c] p$K_a$ refers to the keto form. [d] This p$K_a$ was redetermined and is 0.21 unit lower than reported in ref 2. [e] These values are based on the redetermined p$K_a$ (footnote *d*) and are 0.21 unit higher than reported in ref 3, 4b, and 5.

terms on the right side of the equation being the respective transfer energies defined by eq 3–5.

$$ {}^{W}\delta^{D}\Delta G_{tr}(C^-) = 2.303RT \log {}^{W}\gamma^{D}_{C^-} \qquad (3) $$

$$ {}^{W}\delta^{D}\Delta G_{tr}(H^+) = 2.303RT \log {}^{W}\gamma^{D}_{H^+} \qquad (4) $$

$$ {}^{W}\delta^{D}\Delta G_{tr}(CH) = 2.303RT \log {}^{W}\gamma^{D}_{CH} \qquad (5) $$

Our primary motivation in determining solvent activity coefficients or free energies of transfer of carbanions has its origins in our recent studies of solvent effects on proton transfers involving carbon acids.[2-5] These studies have suggested that late development of the solvation of the incipient carbanion has the effect of increasing the intrinsic barrier of proton transfer. This phenomenon manifests itself, e.g., by a decrease in the intrinsic barrier upon transfer to a solvent that is less effective in solvating the carbanion and by an increase in the intrinsic barrier upon transfer to a better solvent. In order to quantify the relation between the solvent effect on these intrinsic barriers and the changes in solvation energy of the carbanion, the solvent-transfer energies [${}^{W}\delta^{D}\Delta G_{tr}(C^-)$] or solvent activity coefficients of transfer (${}^{W}\gamma^{D}_{C^-}$) need to be known. This paper describes our approach and results in determining such coefficients for six carbanions in various $Me_2SO$–water mixtures.

## Results

If eq 1 is rearranged to solve for log ${}^{W}\gamma^{D}_{C^-}$ we obtain eq 6. ${}^{W}\Delta^{D}\mathrm{p}K_a = \mathrm{p}K_a^{D} - \mathrm{p}K_a^{W}$ is experimentally accessible, while log ${}^{W}\gamma^{D}_{H^+}$ has been determined by Wells.[6] Hence, in order to obtain

$$ \log {}^{W}\gamma^{D}_{C^-} = {}^{W}\Delta^{D}\mathrm{p}K_a + \log {}^{W}\gamma^{D}_{CH} - \log {}^{H}\gamma^{D}_{H^+} \qquad (6) $$

log ${}^{W}\gamma^{D}_{C^-}$ for the carbanion we need only to determine log ${}^{W}\gamma^{D}_{CH}$ for the carbon acid. This was achieved by carrying out distribution experiments between *n*-heptane and the various $Me_2SO$–water mixtures of interest, essentially following the procedures of Watarai and Suzuki.[7]

The partition coefficient between *n*-heptane (H) and water (W) is defined as the ratio of the equilibrium concentrations of the carbon acid, [CH], in the two solvents (eq 7). In a similar way,

$$ {}^{W}P^{H} = [CH]_H/[CH]_W \qquad (7) $$

the partition coefficient between *n*-heptane (H) and a $Me_2SO$–water mixture (D) is defined by eq 8.

$$ {}^{D}P^{H} = [CH]_H/[CH]_D \qquad (8) $$

The partition coefficient between a $Me_2SO$–water mixture and water, or between a $Me_2SO$-rich and a $Me_2SO$-poor $Me_2SO$–water mixture, is then given by eq 9, while the solvent activity coefficient

$$ {}^{W}P^{D} = {}^{W}P^{H}/{}^{D}P^{H} \qquad (9) $$

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(2) Bernasconi, C. F.; Bunnell, R. D. *Isr. J. Chem.* **1985**, *26*, 420.

(3) Bernasconi, C. F.; Paschalis, P. *J. Am. Chem. Soc.* **1986**, *108*, 2969.

(4) (a) Bernasconi, C. F.; Terrier, F. *Can. J. Chem.* **1986**, *64*, 1273. (b) Bernasconi, C. F.; Terrier, F. *J. Am. Chem. Soc.* **1987**, *109*, 7115.

(5) Bernasconi, C. F.; Bunnell, R. D.; Kliner, D. A.; Mullin, A.; Paschalis, P.; Terrier, F. In *Physical Organic Chemistry 1986*; Kobayashi, M., Ed.; Elsevier: Amsterdam, 1987; p 583.

(6) Wells, C. F. In *Thermodynamic Behavior of Electrolytes in Mixed Solvents*; Furter, W. F., Ed.; Advances in Chemistry 177; American Chemical Society: Washington, DC, 1979; p 53.

(7) (a) Watarai, H.; Suzuki, N. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1848. (b) Watarai, H. *Ibid.* **1980**, *53*, 3019.

for the transfer from W to D is the inverse of $^{W}P^{D}$ (eq 10).

$$^{W}\gamma^{D}_{CH} = (^{W}P^{D})^{-1} = {}^{D}P^{H}/{}^{W}P^{H} \qquad (10)$$

Table II summarizes $^{W}P^{H}$ and $^{D}P^{H}$ values for six carbon acids in several solvents determined in the present study. All measurements, which are described in detail in the Experimental Section, were carried out under the same conditions as our kinetic experiments[2-5] and p$K_a$ determinations,[2-5] i.e., at 20 °C and an ionic strength of 0.5 M (KCl) in water, 10% and 50% $Me_2SO$, 0.25 M in 70%, 0.06 M in 90%, and 0.005 M in 95% $Me_2SO$; the percent $Me_2SO$ refers to volume percent. The error limits for the partition coefficients were typically 5–10%.

In Table III we have summarized log $^{W}\gamma^{D}_{CH}$ values for the carbon acids obtained from eq 10 and log $^{W}\gamma^{D}_{C^-}$ values for the carbanions calculated via eq 6. These latter values were obtained via eq 6, using previously determined p$K_a$ values that are also included in the table, and the following log $^{W}\gamma^{D}_{H^+}$ values:[6] 10% $Me_2SO$, –0.48; 50% $Me_2SO$, –1.93; 70% $Me_2SO$, –2.83; 90% $Me_2SO$, –3.05. The table also lists log $^{10}\gamma^{D}_{CH}$, log $^{10}\gamma^{D}_{C^-}$, log $^{50}\gamma^{D}_{CH}$, log $^{50}\gamma^{D}_{C^-}$ values for the transfer from 10% or 50% $Me_2SO$, respectively, to solvents of higher $Me_2SO$ content. The estimated error limit for the various quantities listed in Table III are included in the table.

## Discussion

**Solvent Activity Coefficients.** The focus of our discussion is on the results summarized in Table III. We begin by reminding ourselves that a positive log $^{W}\gamma^{D}_{CH}$, log $^{W}\gamma^{D}_{C^-}$, etc., means the molecule or ion is less solvated and thus is less stable in the solvent of higher $Me_2SO$ content, while a negative value means better solvation in the $Me_2SO$-rich solvent.

For the carbon acids addition of $Me_2SO$ is seen to enhance solvation in all but one case. The exception is acetylacetone, which is slightly better solvated in water than in 50% $Me_2SO$ (log $^{W}\gamma^{D}_{CH}$ = 0.21). Apparently, the two carbonyl groups act as strong hydrogen bond acceptors. Even in 90% and 95% $Me_2SO$ the stability of acetylacetone is not strongly different from that in water. Incidentally, our results for acetylacetone are in good agreement with those of Watarai,[7b] who reports log $^{W}\gamma^{D}_{CH}$ = 0.14 for 50% $Me_2SO$ and log $^{W}\gamma^{D}_{CH}$ = –0.096 for 81.5% $Me_2SO$ at 25 °C and zero ionic strength; the slight difference between Watarai's and our result in 50% $Me_2SO$ can probably be accounted for by the different temperatures and ionic strengths.

Nitromethane also appears to benefit from strong hydrogen bonding solvation: log $^{W}\gamma^{D}_{CH}$ = –0.1 for the transfer from water to 50% $Me_2SO$ is very small, and even in 90% $Me_2SO$ nitromethane is only 7.4-fold more stable than in water.

As the molecules become larger and more hydrocarbon-like, solvation by $Me_2SO$ becomes substantially superior over that by water. In fact 9-carbomethoxy- and 9-cyanofluorene become so poorly water soluble that their p$K_a$ values could not be measured unless at least 10% $Me_2SO$ was added to the solvent.[4] The substantially increased solvation by $Me_2SO$ is reflected in the increasingly negative log $^{W}\gamma^{D}_{CH}$ or log $^{10}\gamma^{D}_{CH}$ values, e.g., –2.86, –3.88, and –4.14 in 90% $Me_2SO$ for phenylnitromethane (log $^{W}\gamma^{D}_{CH}$), 9-cyanofluorene (log $^{10}\gamma^{D}_{CH}$), and 9-carbomethoxyfluorene (log $^{10}\gamma^{D}_{CH}$), respectively.

For the carbanions we note the following patterns. Carbanions that have their negative charge largely localized on oxygen atoms are much better solvated by water than by $Me_2SO$, as reflected in large positive log $^{W}\gamma^{D}_{C^-}$ values. The anion of nitromethane shows the most extreme behavior in this respect, followed by the acetylacetone and phenylnitromethane anions. In fact log $^{W}\gamma^{D}_{C^-}$ for the nitromethane anion is comparable to log $^{W}\gamma^{D}_{RCOO^-}$ for acetate ion:[6] 3.08 for 50% $Me_2SO$, ≈4.40 for 70% $Me_2SO$, and ≈6.50 for 90% $Me_2SO$. This finding is, of course, in agreement with the generally accepted notion that $CH_2{=}NO_2^-$ is the dominant canonical form.

The addition of a benzene ring allows solvation by $Me_2SO$ to become more competitive with that by hydrogen bonding, as seen in the much reduced log $^{W}\gamma^{D}_{C^-}$ (log $^{10}\gamma^{D}_{C^-}$) values for phenylnitromethane anion compared with nitromethane anion and 1,3-indandione anion compared with acetylacetonate anion.

For the two fluorenyl anions whose charge is presumably highly dispersed, hydrogen bonding solvation by water is no longer effective, while solvation by the polarizable $Me_2SO$ becomes the dominant factor. The greater stability of these ions in $Me_2SO$ compared with water is reflected in their *negative* log $^{10}\gamma^{D}_{C^-}$ and log $^{50}\gamma^{D}_{C^-}$ values. It is interesting to note that the solvent activity coefficients of these anions are nearly the same as the solvent activity coefficients for the respective carbon acids, suggesting that the charge has become a minor factor in determining the solvation characteristics of these ions.

**Solvent Effects on p$K_a$ Values.** On the basis of the above patterns we can understand the solvent effects on the p$K_a$ values of the various carbon acids as follows:

(1) The p$K_a$ values of nitromethane and phenylnitromethane increase by similar amounts as the $Me_2SO$ content of the solvent increases, but the reasons are not the same. For nitromethane the major cause for this solvent effect is the strong destablization of the carbanion by $Me_2SO$, i.e., the large positive log $^{W}\gamma^{D}_{C^-}$ value (eq 1). There is a slight contribution by the modest stabilization of nitromethane by $Me_2SO$ (negative log $^{W}\gamma^{D}_{CH}$), but this is a very minor factor. In the case of phenylnitromethane the contribution by the positive log $^{W}\gamma^{D}_{C^-}$ is not nearly as great as for nitromethane, but this lack is made up by the much more negative log $^{W}\gamma^{D}_{CH}$ values.

(2) With acetylacetone the increase in p$K_a$ at higher $Me_2SO$ concentrations is virtually exclusively traceable to the destabilization of the enolate ion (positive log $^{W}\gamma^{D}_{C^-}$). The fact that the p$K_a$ only becomes larger than in water when the $Me_2SO$ content is more than 50% is due to the compensating effect of log $^{W}\gamma^{D}_{H^+}$, which is similar in absolute magnitude to log $^{W}\gamma^{D}_{C^-}$ but of different sign for the transfer from water to 50% $Me_2SO$. Incidentally, the compensating effect of log $^{W}\gamma^{D}_{H^+}$ affects $^{W}\Delta^{D}$p$K_a$ for all carbon acids equally. This means, e.g., that without this compensation the solvent effect on the p$K_a$ values for the nitroalkanes would be even more dramatic.

(3) For 1,3-indandione the effect of log $^{W}\gamma^{D}_{H^+}$ actually *over*compensates for the other terms in eq 1 up to 70%, which results in p$K_a$ values for the higher $Me_2SO$–water mixtures that are all lower than the p$K_a$ in 10% $Me_2SO$, except for 90% $Me_2SO$. In contrast to acetylacetone, the positive contributions to $^{W}\Delta^{D}$p$K_a$ are about equally shared by a positive log $^{W}\gamma^{D}_{C^-}$ and a negative log $^{W}\gamma^{D}_{CH}$ value.

(4) For the fluorenes the comparable values for log $^{W}\gamma^{D}_{CH}$ and log $^{W}\gamma^{D}_{C^-}$ lead to a virtual cancellation of these terms in eq 1, and hence the solvent effect on the p$K_a$ values is essentially completely determined by the increased solvation of the hydronium (negative log $^{W}\gamma^{D}_{H^+}$ values).

**Solvent Effects on Intrinsic Rate Constants of Proton Transfer.** As mentioned in the introduction, a major motivation for the determination of solvent activity coefficients for carbanions was to quantify the relation between solvent effects on the intrinsic barrier[8] or the intrinsic rate constant[8] of proton transfers and the solvation of the carbanion. It has been suggested that the solvent effects on the intrinsic rate constant of proton transfers may be largely understood by assuming that the solvation of developing ions lags behind the proton transfer at the transition state and/or that the desolvation of reactant ions is ahead of proton transfer at the transition state.[3-5,10,11]

For the deprotonation of a carbon acid by an oxyanion base ($B^-$) one may express this idea in terms of eq 11,[4b,11] while the

$$\delta \log {}^{W}k_o{}^{D}(CH/B^-) \approx \delta_{B^-} + \delta_{C^-} + \delta_{SR} \qquad (11)$$

corresponding expression for the deprotonation by an amine base

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[8] For a reaction with forward rate constant $k_1$ and reverse rate constant $k_{-1}$ the intrinsic rate constant is defined as $k_o = k_1 = k_{-1}$ when $K_1 = k_1/k_{-1} = 1$ and the intrinsic barrier as $\Delta G_0^{\ddagger} = \Delta G_1^{\ddagger} = \Delta G_{-1}^{\ddagger}$ when $\Delta G^{\circ} = 0$. In proton transfers statistical factors[9] are usually included so that $k_o = k_1/q = k_{-1}/p$ when $K_1 p/q = 1$.

[9] Bell, R. P. *The Proton in Chemistry*, Cornell University: Ithaca, NY, 1973; Chapter 10.

[10] Bernasconi, C. F. *Tetrahedron* **1985**, *41*, 3219.

[11] Bernasconi, C. F. *Acc. Chem. Res.* **1987**, *20*, 301.

(N) is given by eq 12. $\delta \log {}^{W}k_o{}^{D}(CH/B^-)$ or $\delta \log {}^{W}k_o{}^{D}(CH/N)$

$$\delta \log {}^{W}k_o{}^{D}(CH/N) \approx \delta_{NH^+} + \delta_{C^-} + \delta_{SR} \qquad (12)$$

is the solvent effect on the intrinsic rate constant upon transfer from water to a $Me_2SO$–water mixture, or from a $Me_2SO$-poor to a $Me_2SO$-rich mixture; $\delta_{C^-}$ is the contribution from late solvation of the carbanion; $\delta_{B^-}$ the contribution from early desolvation of the oxyanion (eq 11 only), $\delta_{NH^+}$ that from late solvation of the developing ammonium ion (eq 12 only); $\delta_{SR}$ is a term that cannot be accounted for by nonsynchronous solvation/desolvation effects and may represent a dynamic solvent effect.[4b,11-14] $\delta_{C^-}$, $\delta_{B^-}$, and $\delta_{NH^+}$, may be approximated by eqs 13–15,[11] respectively. log

$$\delta_{C^-} \approx (\alpha_{sol}{}^{C^-} - \beta)(-\log {}^{W}\gamma^{D}{}_{C^-}) \qquad (13)$$

$$\delta_{B^-} \approx (\alpha_{sol}{}^{B^-} - \beta) \log {}^{W}\gamma^{D}{}_{B^-} \qquad (14)$$

$$\delta_{NH^+} \approx (\alpha_{sol}{}^{NH^+} - \beta)(-\log {}^{W}\gamma^{D}{}_{NH^+}) \qquad (15)$$

${}^{W}\gamma^{D}{}_{B^-}$ and $\log {}^{W}\gamma^{D}{}_{NH^+}$ are defined in the same manner as $\log {}^{W}\gamma^{D}{}_{C^-}$; $\beta$ is the Bronsted coefficient (variation of rate with base), while $\alpha_{sol}{}^{C^-}$ and $\alpha_{sol}{}^{NH^+}$ measure the progress in the solvation of $C^-$ and $NH^+$, respectively, at the transition state ($\alpha_{sol}{}^{C^-} < \beta$, $\alpha_{sol}{}^{NH^+} < \beta$ for late solvation), and $\alpha_{des}{}^{B^-}$ measures the progress in the desolvation of $B^-$ ($\alpha_{des}{}^{B^-} > \beta$ for early desolvation).

One potential problem with eq 11 and 12 is that they neglect possible contributions by nonsynchronous solvation/desolvation effects of *un*charged reactants (CH, N) or products (BH). This neglect has been justified on the grounds that the solvation energies of these uncharged species are much smaller than for the ions and, more importantly, that the solvent activity coefficients for this transfer from one solvent to another are generally quite small.[6,10]

As the results in Table II show, for some of the carbon acids $\log {}^{W}\gamma^{D}{}_{CH}$ is far from negligible though. This is particularly true for the fluorenes, where the $\log {}^{W}\gamma^{D}{}_{CH}$ values are of comparable magnitude to the $\log {}^{W}\gamma^{D}{}_{C^-}$ values, and for phenylnitromethane, where $\log {}^{W}\gamma^{D}{}_{CH}$ is also quite large but of opposite sign from $\log {}^{W}\gamma^{D}{}_{C^-}$. The question must be posed whether this factor could significantly affect $\delta \log {}^{W}k_o{}^{D}(CH/B^-)$ or $\delta \log {}^{W}k_o{}^{D}(CH/N)$.

In contrast to the situation with ions,[9,15-17] we are unaware of relevant data that relate to the timing of solvation/desolvation of uncharged molecules during a reaction. In the absence of such data we shall assume that there is no fundamental difference between the timing of solvation/desolvation of charged and uncharged species. This assumption implies that the desolvation of the carbon acid should be ahead of the proton transfer and that eq 11 and 12 should be expanded by a $\delta_{CH}$ term as given by eq 16 with $\alpha_{des}{}^{CH} > \beta$.

$$\delta_{CH} \approx (\alpha_{des}{}^{CH} - \beta) \log {}^{W}\gamma^{D}{}_{CH} \qquad (16)$$

Since $\log {}^{W}\gamma^{D}{}_{CH}$ is generally negative (Table II), $\delta_{CH}$ should then also be negative. In the reactions of the fluorenes the $\delta_{CH}$ term would thus affect $k_o$ in the same direction as the $\delta_{C^-}$ term (lowering of $k_o$ upon addition of $Me_2SO$), while in the phenylnitromethane reaction $\delta_{CH}$ opposes the $\delta_{C^-}$ term. It is more difficult to estimate the absolute magnitude of $\delta_{CH}$ though, because it is not clear how large $|\alpha_{des}{}^{CH} - \beta|$ might be. It is unlikely that $|\alpha_{des}{}^{CH} - \beta|$ would be as large as $|\alpha_{sol}{}^{C^-} - \beta|$, because the lag in the solvation of a carbanion is exacerbated by the lag in the development of resonance.[4b,10,11] Hence, even in cases where $|\log {}^{W}\gamma^{D}{}_{CH}|$ is of comparable magnitude to $|\log {}^{W}\gamma^{D}{}_{C^-}|$, $|\delta_{CH}|$ should be significantly smaller than $|\delta_{C^-}|$. Work addressing these issues is in progress in our laboratory.

## Experimental Section

**Materials.** Acetylacetone (Aldrich) was distilled under $N_2$ prior to use. Nitromethane (Aldrich) was distilled over $CaSO_4$ before use. 1,3-Indandione (Aldrich) was recrystallized from ethanol, mp 131–132 °C (lit.[18] mp 130 °C). Phenylnitromethane, 9-cyanofluorene, and 9-carbomethoxyfluorene were available from previous studies.[4b,19]

**Partition Experiments.** The basic procedure consisted of equilibrating the carbon acid between an *n*-heptane phase and an aqueous phase or $Me_2SO$–water mixture by vigorous agitation in a thermostated shaker bath for 30–60 min. When the partition coefficient between the two phases was not far from unity, equal volumes (usually 5 or 10 mL) of *n*-heptane and the other solvent were used. When the solubility in one phase was much higher than in the other, larger volumes of the deficient phase were used, with volume ratios up to 20:1. In order to repress any ionization of the carbon acid, small amounts of HCl ($\leq 10^{-3}$ M) were usually added to the aqueous or $Me_2SO$–water phase.

Analysis of the equilibrated solutions was carried out spectrophotometrically with a Perkin-Elmer 559A spectrometer. When the concentration of the carbon acid in the *n*-heptane phase was lower than in the other phase, the analysis was performed on the *n*-heptane solution; when the converse was true, the water or $Me_2SO$–water solution was the one to be analyzed.

For the analysis of the water or $Me_2SO$–water solution KOH was added to make the solution $10^{-3}$–$10^{-1}$ M in KOH, depending on the $pK_a$ of the carbon acid. This had the effect of converting the carbon acid into its carbanion with a more convenient $\lambda_{max}$ (outside the range of $Me_2SO$ absorption) and higher extinction coefficient. For the determination of the carbon acid concentration in the *n*-heptane phase the carbon acid was usually first extracted from the *n*-heptane solution with $10^{-3}$ M KOH and then analyzed in a similar way as the $Me_2SO$–water solutions. In the case of 9-cyanofluorene and 9-carbomethoxyfluorene conversion to the carbanion was not necessary, and the concentrations of the carbon acid were determined directly in the *n*-heptane phase. HPLC and $^1H$ NMR analyses indicated some contamination of the 9-carbomethoxyfluorene solutions by an unknown compound. Hence, the determination of ${}^{W}P^{H}$ and ${}^{D}P^{H}$ was carried out by HPLC with a Hewlett-Packard Model 1084B instrument equipped with an Adsorbosphere C-18 analytical column and using acetonitrile as the mobile phase. Peak areas were analyzed at 256 nm using a Hewlett-Packard Model 79850B LC terminal.

With acetylacetone the analysis had to take into account that the enol is present in significant amounts, particularly in the $Me_2SO$–water mixtures of high $Me_2SO$ content. Our procedures were similar to those described by Watarai and Suzuki.[7] For example, for the partition between *n*-heptane and water, the partition coefficient of the keto form is given by eq 17, that of the enol form by eq 18. ${}^{W}P^{H}$ is the measured

$${}^{W}P^{H}{}_{keto} = [(1 - f^{H})/(1 - f^{W})]{}^{W}P^{H} \qquad (17)$$

$${}^{W}P^{H}{}_{enol} = (f^{H}/f^{W}){}^{W}P^{H} \qquad (18)$$

partition coefficient of the keto–enol mixture, while $f^{H}$ and $f^{W}$ represent the fraction of acetylacetone present as enol in the *n*-heptane and the water phase, respectively. $f^{W}$ is given by eq 19, with $K_a{}^{keto}$ and $K_a{}^{enol}$

$$f^{W} = K_a{}^{keto}/(K_a{}^{keto} + K_a{}^{enol}) \qquad (19)$$

being the respective acid dissociation constants,[2] while $f^{H} = 0.97$.[7a] Similar equations pertain to the partition between *n*-heptane and the $Me_2SO$–water mixtures.

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