Entropies in Solution from Entropies in the Gas Phase

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Ab initio calculations at the B3LYP/6-31G(d) level and scaled particle theory, combined with entropies of activation derived from experimental Arrhenius *A* factors, were applied to examine the origin of the loss of gaseous-phase entropy of a substance upon solution. Eight reactions in water were analyzed: H atom reacting with methanol, ethanol, 2-propanol, methanediol and ethylene glycol; and methanethiol reacting with the radicals, methyl, hydroxymethyl, and 2-hydroxy-2-propyl. The results suggest that the observed entropy loss is entirely due to changes in the solvent. The dominant factor is a loss of entropy due to cavity formation. This is partially offset by a corresponding increase in the disorder of the H-bonding network in the case of the larger species.

Introduction

The a priori prediction of the free energy of a species in solution, $G_{(aq)}$, remains a largely unsolved problem, although, at least for small molecules, it is straightforward to calculate this quantity, $G_{(g)}$, in the gaseous phase. Significant advances in the development of self-consistent reaction field (SCRF) methods for the treatment of the mutual response between solute and solvent upon mixing permit nearly quantitative descriptions of $G_{(aq)}$ in favorable cases. For each species in the gaseous phase, the free energy of solvation, $\Delta G_{(solv)}$, is calculated by an SCRF method. Thus,

$$G_{(aq)} = G_{(g)} + \Delta G_{(solv)} \qquad (1)$$

where $G_{(g)}$ has been corrected to 1 mol L^{-1}. This simple approach is justified for continuum solvation models, like COSMO,[1] because they are parametrized against experimental free energies for a test suite of molecules.[2] However, it has been argued this procedure may greatly overestimate entropic effects.[3,4] Numerous tabulations indicate that the entropy of a substance in solution is substantially less than its entropy in the gaseous phase.[5−9] For instance, the entropy of an aqueous solution of each of the inert gases is a fairly constant fraction, about 50%, of its gaseous-phase entropy. The same observation has been made for many classes of compounds, the actual fraction of entropy lost depending on the compound type. Opinions vary as to the origin of the loss. The widely held view is that the partition functions of the gaseous-phase (ideal gas) molecule are the same as those in solution and the entire observed change in entropy upon solution originates from changes in the solvent, primarily due to the formation of a cavity.[10−19] However, it has been argued that the solute itself suffers a significant decrease in entropy, for instance, as a result of restriction of its molecular rotation and translation in the solvent cage.[9,20−22] In application of continuum solvation models to describe rates of reaction in which the molecularity changes, it was necessary to adjust the gaseous-phase entropy.[3,4] This arises from the fact that, in the gaseous phase, at least for small molecules, the major contributors to the entropy are the translational and rotational degrees of freedom. In a bimolecular reaction, A + B → AB, six translational and rotational degrees of freedom are converted to internal vibrations that have a smaller contribution to the entropy. Consequently, bimolecular reactions in the gaseous phase have a large negative entropy of activation or association. Internal vibrations and the entropy associated with them should be less affected by the dense medium than rotational and translational degrees of freedom that may be significantly reduced in solution as a result of specific solute−solvent interactions. In effect, the solvent cage converts these degrees of freedom also into "vibrations", which contribute less to the entropy. In the case of a bimolecular reaction in solution, the entropy of activation or association is observed to be less negative than in the gaseous phase. It is tempting to say this is because the six rotations/translations that are lost had a smaller contribution to the entropy. The corollary is that bimolecular reactions in solution are subject to a smaller entropic barrier ($-T\Delta S$) and, provided the enthalpic barrier is not correspondingly increased, will be faster than in the gaseous phase.[23]

The objective of the present work is to examine in detail the origin of differences in the entropies of activation, $\Delta S^{\ddagger}$, of bimolecular reactions in the gaseous phase and in aqueous solution, where the solution entropy changes are obtained from experimental Arrhenius *A* factors. The *A* factors can serve as an experimental probe to break down the components of solution-phase entropies, something which has not been possible by examination of individual solute entropies alone.

The gaseous-phase entropy, $S_{(g)}$, of a substance is expressed in terms of its vibrational, electronic, and translational/rotational components, as[24]

$$S_{(g)} = S_{(g)}^{\mathrm{vib}} + S_{(g)}^{\mathrm{elec}} + S_{(g)}^{\mathrm{trans}} + S_{(g)}^{\mathrm{rot}} \qquad (2)$$

We assume that a parallel equation, with additional terms, can be written for the entropy in aqueous solution:

$$S_{(aq)} = S_{(aq)}^{\mathrm{vib}} + S_{(aq)}^{\mathrm{elec}} + S_{(aq)}^{\mathrm{trans,rot}} + \Delta S_{(cav)}^{\mathrm{water}} + \Delta S_{(pol)}^{\mathrm{water}} \qquad (3)$$

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The first three terms on the right-hand side of eq 3 correspond to the vibrational, electronic, and translational + rotational entropy components of the dissolved species. They may differ from the equivalent terms of eq 2. The last two terms of eq 3 correspond to changes of the entropy of the solvent (water in the present case) due to the fact that the substance is dissolved in it. The entropy change due to cavity formation, $\Delta S_{(cav)}{}^{water}$, will be negative and will depend on the size and shape of the cavity. $\Delta S_{(cav)}{}^{water}$ will be the same whether or not the cavity is occupied. The last term, $\Delta S_{(pol)}{}^{water}$, reflects the fact that occupancy of the cavity will cause a reorganization (or polarization) of the solvent as a result of specific interactions with the solute. Thus, $\Delta S_{(pol)}{}^{water}$ may be positive or negative depending upon whether the macroscopic order of the water molecules is decreased or increased, respectively. The electronic contribution to the entropy is zero for a singlet state and R ln2 for a doublet state, that is, a radical. We further approximate that the vibrational and electronic parts of the entropy are the same for all conformers and the same in the gaseous phase and in solution.

The present study is concerned with the entropy of activation, $\Delta S^{\ddagger}$, of a process, A + B → TS, that is, one in which the molecularity changes. It is straightforward to calculate $\Delta S^{\ddagger}$ in the gaseous phase:

$$\Delta S^{\ddagger}{}_{(g)} = \Delta S^{\ddagger}{}_{(g)}{}^{vib} + \Delta S^{\ddagger}{}_{(g)}{}^{elec} + \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot} + R\ \ln(n_{TS}/n_A n_B) \quad (4)$$

where R is the gas constant. The last term gives the approximate change in the entropy of mixing if the individual components, A, B, and TS, have n_A, n_B, and n_{TS} significantly populated conformations.[25] All of the terms of eq 4 can be calculated accurately from quantum and statistical mechanics for moderately sized molecules. Thus, $\Delta S^{\ddagger}{}_{(g)}$ is available from theory if it is not available from experiment. For many bimolecular reactions in solution, $\Delta S^{\ddagger}{}_{(aq)}$ is also available from experiment, either by application of Eyring transition state theory or from comparison of Arrhenius theory and Eyring transition state theory. In the latter case, one has the following relationship between the entropy of activation in solution, $\Delta S^{\ddagger}$, and the A factor of Arrhenius theory:[26]

$$\Delta S^{\ddagger} = R\ \ln(Ah/k_B T) - R \quad (5)$$

where T is the temperature in Kelvin and h and k_B are Planck's and Boltzmann's constants, respectively. The entropy of activation thus obtained may be expanded in terms of the components identified in eqs 3 and 4:

$$\Delta S^{\ddagger}{}_{(aq)} = \Delta S^{\ddagger}{}_{(aq)}{}^{vib} + \Delta S^{\ddagger}{}_{(aq)}{}^{elec} + \Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} + \Delta S^{\ddagger}{}_{(cav)}{}^{water} + \Delta S^{\ddagger}{}_{(pol)}{}^{water} + R\ \ln(n_{TS}/n_A n_B) \quad (6)$$

Subtraction of eq 4 from eq 6 yields

$$\Delta S^{\ddagger}{}_{(aq)} - \Delta S^{\ddagger}{}_{(g)} \approx \Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} - \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot} + \Delta S^{\ddagger}{}_{(cav)}{}^{water} + \Delta S^{\ddagger}{}_{(pol)}{}^{water} \quad (7)$$

The left-hand side of eq (7) is known, and we have assumed that the entropies of vibration and mixing, as well as the electronic entropy, are the same in the gaseous phase as they are in solution. In principle, $\Delta S^{\ddagger}{}_{(cav)}{}^{water}$ is available from scaled particle theory,[27] as explained below. The polarization term, $\Delta S^{\ddagger}{}_{(pol)}{}^{water}$, is unknown. In order to focus on a possible difference in the entropy of translation/rotation in the two phases, we have chosen systems for which it is reasonable that $\Delta S^{\ddagger}{}_{(pol)}{}^{water}$ is close to zero, namely,

$$H^{\bullet} + CH_3OH \rightarrow H_2 + {}^{\bullet}CH_2OH \quad (8)$$

$$H^{\bullet} + CH_3CH_2OH \rightarrow H_2 + CH_3C^{\bullet}HOH \quad (9)$$

$$H^{\bullet} + (CH_3)_2CHOH \rightarrow H_2 + (CH_3)_2C^{\bullet}OH \quad (10)$$

$$H^{\bullet} + CH_2(OH)_2 \rightarrow H_2 + {}^{\bullet}CH(OH)_2 \quad (11)$$

$$H^{\bullet} + (CH_2OH)_2 \rightarrow H_2 + {}^{\bullet}CH(OH)CH_2OH \quad (12)$$

$$CH_3SH + {}^{\bullet}CH_3 \rightarrow CH_3S^{\bullet} + CH_4 \quad (13)$$

$$CH_3SH + {}^{\bullet}CH_2OH \rightarrow CH_3S^{\bullet} + CH_3OH \quad (14)$$

$$CH_3SH + (CH_3)_2C^{\bullet}OH \rightarrow CH_3S^{\bullet} + (CH_3)_2CHOH \quad (15)$$

Arrhenius A-factors for reaction in aqueous solution are available from experiment for reactions 8,[28] 9,[29] 10,[29] 11[30], and 12.[30] In addition, A factors for reactions 9 and 10 with ethanol-d_5 and 2-propanol-d_7 are available from experiment. Calculated values based on experimental data for model solutes are available for reactions 13−15 in aqueous solution.[31]

Each of these systems has the characteristic that one of the reagents is hydrophobic, namely the H atom or CH_3SH. Second, the polar group in the TS remains unchanged from that in the other reactant. Because of this, we anticipate that the change in the polarization of the solvent during the reaction should be small ($\Delta S^{\ddagger}{}_{(pol)}{}^{water} \approx 0$). Assuming this to be the case, the change in the translational and rotational components of the entropy upon change of state (gaseous vs aqueous phase) may be examined by a rearrangement of eq 7.

$$\Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} - \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot} \approx \Delta S^{\ddagger}{}_{(aq)} - \Delta S^{\ddagger}{}_{(g)} - \Delta S^{\ddagger}{}_{(cav)}{}^{water} \quad (16)$$

For each of the above systems, transition structures for H-atom abstraction were located and gaseous-phase entropies of activation, $\Delta S^{\ddagger}{}_{(g)}$, adjusted for a standard state of 1 M, were calculated. The magnitude and sign of the right-hand side of eq 16 provides a measure for the extent to which the translational and rotational components of the entropy of activation have changed upon change of phase from gaseous to solution.

Entropy of Cavity Formation, $\Delta S_{(cav)}{}^{water}$. The free energy of formation of a spherical cavity in water is derivable from scaled particle theory (SPT)[32] and has a direct dependence on the size of the sphere. Arbitrary-shaped cavities may be expanded as a sum of overlapping spheres. In the solvation model, COSMO,[1] the contribution of each sphere to the total free energy of cavity formation, $\Delta G_{(cav)}{}^{water}$, is its SPT value weighted by the fraction of its exposed surface area.[2] At 1 atm, near 298K, in water, the enthalpic part of the free energy of cavitation, $\Delta H_{(cav)}{}^{water}$, is small.[32] Thus, $\Delta S_{(cav)}{}^{water}$, given by

$$\Delta S_{(cav)}{}^{water} = (1/T)(\Delta H_{(cav)}{}^{water} - \Delta G_{(cav)}{}^{water}) \quad (17)$$

is largely determined by $\Delta G_{(cav)}{}^{water}$. $\Delta H_{(cav)}{}^{water}$ is a function of the molecular "radius" and may be evaluated from eq 41 of Pierotti's paper.[32]

In the present work, we define the cavity for each species in terms of its isodensity surface and fit the surface thus defined

TABLE 1: Gaseous-Phase Entropy Components and Entropy of Cavity Formation in Water (J mol^{-1} K^{-1}) for All Species at 298K and 1 M Standard State

							$\Delta S_{(cav)}^{water}$			
species	S^{vib}	S^{trans}	S^{rot}	S^{elec}	$S^{total\ a}$	n^{b}	0.0004[c]	0.001[c]	0.002[c]	0.003[c]
$H^{\bullet}$	0.0	82.2	0.0	5.8	88.0	1	−59.1	−47.8	−39.7	−34.8
$^{\bullet}CH_3$	3.6	115.9	43.3	5.8	168.9	1		−78.5	−69.4	−64.5
$^{\bullet}CH_2OH$	5.5	125.0	76.7	5.8	218.7	2		−102.5	−94.0	−88.8
CH_3OH	6.1	125.4	79.5	0.0	211.0	1	−124.4	−111.9	−102.8	−97.5
CD_3OH	8.0	126.5	83.7	0.0	218.3	1	−124.4	−111.9	−102.8	−97.5
$CH_3CH_2OH^{d}$	19.0	129.9	93.6	0.0	251.7	3	−163.4	−151.0	−141.2	−134.6
$CD_3CD_2OH^{d}$	26.8	131.2	96.7	0.0	263.8	3	−163.4	−151.0	−141.2	−134.6
$(CH_3)_2C^{\bullet}OH$	42.1	133.0	101.9	5.8	288.5	2		−181.5	−172.7	−166.0
$(CH_3)_2CHOH^{d}$	35.9	133.2	102.2	0.0	280.5	3	−201.6	−186.9	−177.5	−171.3
$(CD_3)_2C^{\bullet}OH$	53.6	134.2	104.6	5.8	304.0	2		−181.5	−172.7	−166.0
$(CD_3)_2CDOH^{d}$	48.3	134.6	105.0	0.0	297.0	3	−201.6	−186.9	−177.5	−171.3
$CH_2(OH)_2$	12.2	130.4	85.7	0.0	239.8	4		−128.3	−118.9	−113.9
$(CH_2OH)_2$	39.3	133.6	100.8	0.0	297.7	18		−167.3	−155.8	−151.2
CH_3SH	10.4	130.4	86.0	0.0	226.8	1		−135.8	−124.2	−118.3
$H\cdots H\cdots CH_2OH]^{\bullet}$	13.1	125.8	84.1	5.8	234.5	2	−147.4	−137.6	−125.4	−116.3
$H\cdots H\cdots CH(CH_3)OH]^{\bullet}$	29.5	130.2	95.6	5.8	272.9	4	−186.1	−169.0	−159.5	−153.2
$H\cdots D\cdots CD(CD_3)OH]^{\bullet}$	37.6	131.4	98.3	5.8	284.6	4	−186.1	−169.0	−159.5	−153.2
$H\cdots H\cdots C(CH_3)_2OH]^{\bullet}$	48.2	133.4	103.0	5.8	296.2	2	−223.6	−204.6	−197.4	−190.0
$H\cdots D\cdots C(CD_3)_2OH]^{\bullet}$	61.1	134.8	105.7	5.8	313.1	2	−223.6	−204.6	−197.4	−190.0
$H\cdots H\cdots CH(OH)_2]^{\bullet}$	24.5	130.7	94.2	5.8	275.9	12		−148.6	−138.6	−132.8
$H\cdots H\cdots CH(OH)CH_2OH]^{\bullet}$	41.8	133.8	102.2	5.8	316.8	54		−184.0	−173.1	−167.9
$CH_3S\cdots H\cdots CH_3]^{\bullet}$	67.4	139.0	105.1	5.8	317.2	1		−194.2	−181.0	−173.9
$CH_3S\cdots H\cdots CH_2OH]^{\bullet d}$	86.8	140.9	111.0	5.8	357.0	4		−207.3	−199.6	−192.7
$CH_3S\cdots H\cdots C(CH_3)_2OH]^{\bullet d}$	134.0	143.7	118.8	5.8	412.6	4		−290.5	−277.8	−268.0

[a] Includes entropy of mixing from n principal conformations (including enantiomers, where appropriate). [b] The number of principal conformations, including enantiomers. [c] The value of isodensity which defines the cavity in electrons bohr^{-3}. [d] The most stable conformation: the individual components of the entropy are very similar for different conformations.

TABLE 2: Entropies of Activation, $\Delta S^{\ddagger}$ (J mol^{-1} K^{-1}) in the Gaseous Phase and in Aqueous Solution (from Arrhenius *A* Factors)

			$\Delta S^{\ddagger}{}_{(cav)}^{water}$			
reaction (reactants → transition structure)	$\Delta S^{\ddagger}_{(g)}$	$\Delta S^{\ddagger}_{(aq)}$	0.0004[a]	0.001[a]	0.002[a]	0.003[a]
$H^{\bullet} + CH_3OH \rightarrow H\cdots H\cdots CH_2OH]^{\bullet}$	−64.5	−30.4 ± 3.3	36.2	22.1	17.1	16.1
$H^{\bullet} + CH_3CH_2OH \rightarrow H\cdots H\cdots CH(CH_3)OH]^{\bullet}$	−66.9	−32.5 ± 1.7	36.4	29.8	21.5	16.3
$H^{\bullet} + (CH_3)_2CHOH \rightarrow H\cdots H\cdots C(CH_3)_2OH]^{\bullet}$	−72.4	−26.2 ± 1.0	37.2	30.2	19.8	16.1
$H^{\bullet} + CD_3CD_2OH \rightarrow H\cdots D\cdots CD(CD_3)OH]^{\bullet}$	−67.2	−22.9 ± 4.0	36.4	29.8	21.5	16.3
$H^{\bullet} + (CD_3)_2CDOH \rightarrow H\cdots D\cdots C(CD_3)_2OH]^{\bullet}$	−71.9	−23.5 ± 1.2	37.2	30.2	19.8	16.1
$H^{\bullet} + CH_2(OH)_2 \rightarrow H\cdots H\cdots CH(OH)_2]^{\bullet}$	−51.9	−12.8 ± 3.8		27.5	20.0	15.9
$H^{\bullet} + (CH_2OH)_2 \rightarrow H\cdots H\cdots CH(OH)CH_2OH]^{\bullet}$	−68.9	−43.6 ± 3.4		31.1	22.4	18.1
$CH_3SH + {}^{\bullet}CH_3 \rightarrow CH_3S\cdots H\cdots CH_3]^{\bullet}$	−92.5[b]	−58.1[b]		20.1	12.6	9.0
$CH_3SH + {}^{\bullet}CH_2OH \rightarrow CH_3S\cdots H\cdots CH_2OH]^{\bullet}$	−100.2[b]	−78.8[b]		31.0	18.7	14.4
$CH_3SH + (CH_3)_2C^{\bullet}OH \rightarrow CH_3S\cdots H\cdots C(CH_3)_2OH]^{\bullet}$	−106.9[b]	−67.1[b]		26.7	19.1	16.3

[a] Value of isodensity which defines the cavity in electrons bohr^{-3}. [b] From Table 5 of ref 31.

as a sum of overlapping atom-centered spheres with appropriately adjusted radii. The fitting procedure is required because the implementation of COSMO[1] available to us uses a sum of overlapping spheres to define the SPT cavity. The COSMO solvation model[1] is then employed to obtain $\Delta S_{(cav)}^{water}$ via eq 17, where the reported molecular surface area and volume are used to derive effective "radii" and geometric mean used to derive $\Delta H_{(cav)}^{water}$. The choice of isodensity value, which directly determines the size and shape of the cavity, and hence $\Delta S_{(cav)}^{water}$, is the only adjustable parameter. We have examined values in the range from 0.0004 to 0.003 electrons bohr^{-3}. These span the values typically assumed in continuum models of solvation which are based on an isodensity surface but do not include a calculation of the free energy of cavity formation. The lower value, 0.0004 electrons bohr^{-3}, yields a cavity whose surface corresponds approximately to the van der Waals surface and is the default for the SCIPCM[33] procedure implemented in Gaussian 98. A value of 0.001 electrons bohr^{-3} is recommended in combination with the SS(V)PE model[34] as implemented in a version of HONDO.[35] Computer simulations of cavity formation in water using molecular dynamics were in agreement with SPT for cavities of the size considered here, although deviations increased with increasing cavity size.[19]

Results and Discussion

The calculated entropies and their separate components (as in eq 2) for all species of interest here are listed in Table 1. The entropy change associated with cavity formation in water for cavities defined by up to four different values of the isodensity surface are also listed in Table 1. The entropies of activation in the gaseous phase and in aqueous solution for all of the reactions are listed in Table 2. Comparison of $\Delta S^{\ddagger}_{(g)}$ and $\Delta S^{\ddagger}_{(aq)}$ in Table 2 shows that both are negative as expected and that the magnitude is significantly reduced in aqueous solution. The reduction in magnitude ranges from 21% in the case of $CH_3SH + {}^{\bullet}CH_2OH$, to 75% in the case of $H^{\bullet} + CH_2(OH)_2$.

From Table 1, it is immediately apparent that the translational and rotational components of the gaseous-phase entropy make up the overwhelming portion of the total entropy, except in the case of the transition structures which have a number of low-frequency vibrations. Even in those cases (for example, [$CH_3S\cdot$

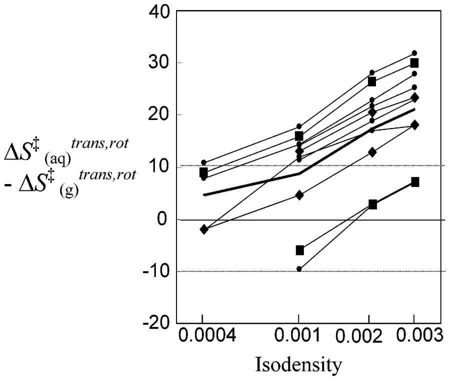

Figure 1. The difference in the translational and rotational components of the entropy of activation upon solution (eq 16) as a function of isodensity value (cavity size) from data in Table 2: Each light line with points corresponds to one of the reactions studied. The heavy line connects the average values at each isodensity.

$\cdot\cdot$H$\cdots$C(CH_3)$_2$OH]$^\bullet$), the combined rotational and translational components are more than 65% of the total. Thus, the loss of the entropy derived from six of these degrees of freedom in a bimolecular reaction accounts for virtually all of the large negative entropy of activation for such reactions in the gaseous phase (Table 2). If, for the participating species, the entropy from these components is substantially reduced in solution, this alone may account for the observed reduction in magnitude (Table 2). However, inspection of the last columns of Table 1 reveals that the entropy of formation of a cavity in solution ($\Delta S_{(cav)}{}^{water}$) for a species is negative and comparable in magnitude to the total gaseous-phase entropy. Furthermore, $\Delta S_{(cav)}{}^{water}$ is strongly dependent on the value of the isodensity surface which encloses the cavity, that is, on the size of the cavity. In a bimolecular reaction, two cavities combine to make a smaller cavity (that contains the TS). As a consequence, $\Delta S^{\ddagger}{}_{(cav)}{}^{water}$ is positive and comparable in magnitude to the difference between the entropies of activation, $\Delta S^{\ddagger}{}_{(g)}$ and $\Delta S^{\ddagger}{}_{(aq)}$.

The value of the right-hand side of eq 16, which measures the change in the translational and rotational entropies, $\Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} - \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot}$, when a substance is dissolved in water, is plotted for each of the reactions as a function of the isodensity value in Figure 1.

It is noteworthy that in each case, the value of $\Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} - \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot}$ increases monotonically with increasing isodensity value (i.e., decreasing volume of the cavity). The average values (in J mol^{-1} K^{-1}), shown as the bold line in the figure, are 4.7, 8.8, 17.4, and 21.2 for cavities defined by isodensity values 0.0004, 0.001, 0.002, and 0.003 electrons bohr^{-3}, respectively. It should be noted that the result of eq 16 is expected to be less than or equal to zero within the uncertainties introduced by various approximations. A positive sign is not physically acceptable because it would imply that the translational and rotational contributions to the entropy of activation actually increase upon solvation. The results in Figure 1 and Table 2 suggest that for cavities defined by isodensity values in the range of 0.0004−0.001 electrons bohr^{-3}, $\Delta S^{\ddagger}{}_{(aq)}{}^{trans,rot} - \Delta S^{\ddagger}{}_{(g)}{}^{trans,rot}$ is effectively zero. It appears then that, in the case where solvent polarization effects should cancel, the total entropy of activation in aqueous solution may be calculated from the gaseous-phase quantity by addition of the entropy change due to cavity formation alone, for cavities defined by isodensity surfaces in the range of 0.0004−0.001 electrons bohr^{-3}.

Acceleration Due to Solution. Although the primary emphasis of this work is probing the origin of reduction of the entropy of a substance due to solution, it is informative to examine the effect of solvation on the relative rates of reaction in the gaseous phase (k^g) compared to the aqueous phase (k^w) as predicted by the COSMO continuum model. Of the reactions considered here, $H^\bullet + CH_3OH$ (eq 8) has been investigated in both phases and shown to be accelerated by a factor of $k^w/k^g = 2$ at 298 K.[36] The relative rate constants, k^w/k^g, derived from transition state theory, may be expressed as

$$k^w/k^g = \kappa \exp(-(\Delta G^{\ddagger}{}_{(aq)} - \Delta G^{\ddagger}{}_{(g)})/RT) \tag{18a}$$

$$= \kappa \exp(-(\Delta H^{\ddagger}{}_{(aq)} - \Delta H^{\ddagger}{}_{(g)})/RT + (\Delta S^{\ddagger}{}_{(aq)} - \Delta S^{\ddagger}{}_{(g)})/R) \tag{18b}$$

$$\approx \kappa \exp(-\Delta\Delta H^{\ddagger}{}_{(solv)}/RT + (\Delta S^{\ddagger}{}_{(aq)} - \Delta S^{\ddagger}{}_{(g)})/R) \tag{18c}$$

$$\approx \kappa \exp(-\Delta\Delta G^{\ddagger}{}_{(solv)}/RT) \tag{18d}$$

where κ is the ratio of corrections for quantum mechanical tunneling. Experience suggests that tunneling is somewhat quenched in solution.[36] For the reaction considered here, $\kappa \approx 0.75$.[37] The approximations in eqs 18c and d ensue from two different treatments of the effect of solvent. The approximation in eq 18d follows from eq 1 where $\Delta G_{(solv)}$ is as reported by COSMO for a cavity based on an isodensity surface as described above. In eq 18c, entropies of activation are taken from Table 2 whereas $\Delta\Delta H^{\ddagger}{}_{(solv)}$ is assembled from the electrostatic and nonelectrostatic components of $\Delta G_{(solv)}$ that are temperature-independent. The acceleration due to the entropy change alone (i.e., assuming $\Delta H^{\ddagger}{}_{(aq)} - \Delta H^{\ddagger}{}_{(g)} = 0$ in eq 18b) is $k^w/k^g = 45$. The arguments presented above suggest that the entropy change is largely due to cavity formation. That the actual acceleration is very much lower is a manifestation of the well-known "enthalpy−entropy compensation" that accompanies solution.[10,12,18] The compensating increase in the enthalpy of activation due to the solvent must be $\Delta\Delta H^{\ddagger}{}_{(solv)} = +7.8$ kJ mol^{-1} for $H^\bullet + CH_3OH$ (eq 8) in order to reproduce the experimentally observed acceleration. The origins of the enthalpy−entropy compensation have been widely discussed.[10] It is likely due to reorganization of the H-bonding network with an important contribution from dispersive interactions which grow with the size of the cavity (i.e., the solute). Continuum models of solvation must introduce this effect through suitable parametrization, possibly after incorporation of one or more water molecules with the solute in a "supermolecule" approach. From eq 18d, using the COSMO-derived $\Delta\Delta G^{\ddagger}{}_{(solv)}$ for the 0.001-isodensity-defined cavity, one finds $k^w/k^g = 15$. The value is strongly dependent on the choice of cavity: $k^w/k^g = 92$ and $k^w/k^g = 6.4$ for 0.0004 and 0.002 isodensity cavities, respectively. From the COSMO results, the change in the enthalpy of activation due to solvation is almost zero, $\Delta\Delta H^{\ddagger}{}_{(solv)} = -0.6$ kJ mol^{-1}. The dispersive component is positive, as expected, but not large enough compared to the negative electrostatic and cavity components to raise $\Delta\Delta H^{\ddagger}{}_{(solv)}$ to +7.8 kJ mol^{-1}.

Entropies of Solution of Individual Substances. The entropies of an aqueous solution of many individual substances, $S_{(aq)}$, are available from experiment,[6,38,39] including a number of the species involved in this paper, namely, CH_3OH,[5] CH_3CH_2OH,[5] and $(CH_3)_2CHOH$.[6] Taken together with the gaseous-phase entropy from theory or experiment, one may write eq 19 as a means of estimating $\Delta S_{(pol)}{}^{water}$:

$$\Delta S_{(pol)}{}^{water} \approx S_{(aq)} - S_{(g)} - \Delta S_{(cav)}{}^{water} \tag{19}$$

The approximate equality obtains from the results of the previous

TABLE 3: Entropy Components of Selected Substances ($J\ mol^{-1}\ K^{-1}$) at 298 K and 1 M Concentration

substance	$S_{(g)}$[a]	$S_{(aq)}$[a]	$\Delta S_{(cav)}{}^{water}$ 0.001[b]	$\Delta S_{(pol)}{}^{water}$ 0.001[b]	radii 0.001[b]	radii exptl[c]
H	88.0	44.0[d]	−47.8	3.8	1.58	
H_2	104.1	57.7	−49.8	3.4	1.56	
He	99.6	54.4	−37.7	−7.5	1.35	1.32
Ne	119.7	66.1	−44.1	−9.5	1.50	1.40
Ar	128.2	59.4	−69.5	0.7	2.00	1.71
Kr	137.5	61.5	−78.2	2.2	2.15	1.84
O_2	178.5	110.9	−72.5	4.9	1.95	
CO	171.1	104.6	−77.2	10.7	2.04	
CH_4	159.7	83.7	−91.1	15.1	2.14	
H_2S	179.2	121.0	−91.0	32.8	2.21	
Cl_2	196.5	121.0	−110.3	34.8	2.48	
SO_2	221.6	161.9	−107.8	48.1	2.39	
CH_3Cl	208.0	144.8	−118.6	55.4	2.44	
CH_3NH_2	216.8	123.4	−120.3	26.9	2.43	
CH_3OH	213.2	133.1	−111.9	31.8	2.33	1.86
CH_3CH_2OH	256.1	148.5	−151.0	43.4	2.66	2.18
$(CH_3)_2CHOH$	280.5[e]	148.9[f]	−186.9	55.3	2.94	
H_2O, $T = 298$	162.2	100.3[g]	−66.7	4.8	1.84	1.38
H_2O, $T = 273$ (l)		96.6[g]				
H_2O, $T = 273$ (s)		74.4[g]				

[a] From ref 5 unless otherwise noted. [b] Value of the isodensity which defines the cavity in electrons $bohr^{-3}$. [c] From ref 32. [d] From $S_{(aq)}$ (H_2) by subtracting $S_{(g)}$ (H_2) and $\Delta S_{(cav)}{}^{water}$ (H_2) and adding $S_{(g)}$ (H) and $\Delta S_{(cav)}{}^{water}$ (H). [e] From Table 1. [f] Reference 35. [g] Adjusted to 1 M from 55.6 M.

section, in which it was seen that the difference in entropies of activation between the gaseous phase and aqueous solution was due almost entirely to the changes in the entropy of cavity formation under conditions where solvent polarization could be expected to cancel. Equation 19 then permits one to obtain a magnitude for the missing component, $\Delta S_{(pol)}{}^{water}$, if one chooses a cavity defined by an isodensity surface of approximately 0.001 electrons $bohr^{-3}$.

The gaseous-phase and aqueous-phase entropies of a number of species are collected in Table 3,[40] together with $\Delta S_{(cav)}{}^{water}$ for a cavity defined by an isodensity value of 0.001 electrons $bohr^{-3}$, the corresponding $\Delta S_{(pol)}{}^{water}$ calculated by eq 19, and hard-sphere-equivalent radii. It is noted that "radii" derived from the isodensity surfaces as described above are larger than experimental values based on aqueous solubility measurements.[32] It was seen above that isodensities in the range of 0.0004−0.001 electrons $bohr^{-3}$ yield $\Delta S^{\ddagger}{}_{(cav)}{}^{water}$ values that largely account for the change of entropy of activation upon solution. The "size" observation suggests that the larger value, 0.001 electrons $bohr^{-3}$, is to be preferred.

A negative value of $\Delta S_{(pol)}{}^{water}$ implies that the presence of the solute increases the average order of the solvent, whereas a positive value indicates a decrease in the overall order. Values of $|\Delta S_{(pol)}{}^{water}|$ that are less than 10 $J\ mol^{-1}\ K^{-1}$ in absolute magnitude probably should be regarded as zero. The results in Table 3 suggest that the smaller species, including the inert gases and water itself, do not significantly affect the overall order of water. However, the larger species, including Cl_2, H_2S, and the three alcohols, appear to *increase* the degree of disorder in each case. This result is not entirely unanticipated. The structure of liquid water is a fairly ordered network of tetrahedrally arranged H-bonded structures, differing only in degree from that of ice.[10] This is evident in the rather small entropy of fusion, 22.2 $J\ mol^{-1}\ K^{-1}$ (Table 3), and the even smaller change upon warming to 298 K, 3.7 $J\ mol^{-1}\ K^{-1}$ (Table 3). Theoretical modeling suggests that neither alcohols[41] nor nonpolar solutes[42] induce significant "iceberg-like" structure in the hydration shells of their cavities.

Methods

The ab initio calculations presented here were performed using the Gaussian 98 molecular orbital package.[43] All calculations including geometry optimizations and frequency calculations, unless stated otherwise, were carried out using the B3LYP hybrid HF-DFT procedure implemented in the Gaussian molecular orbital packages with the 6-31G(d) basis set. The frequencies were scaled by a factor of 0.98 in the calculation of the entropy, S, at 298 K.[44]

For the purpose of scaled particle theory (SPT) evaluations of the free energy of cavity formation in water, $\Delta G_{(cav)}{}^{water}$, isodensity surfaces were derived from B3LYP/6-31G(d) wave functions and visually fitted by overlapping atom-centered spheres whose radii were then used as input to the COSMO[1] procedure as implemented in Gaussian 98.[43] The geometric mean of the radii of hard spheres corresponding to the surface area and volume reported for the cavities by COSMO were used in conjunction with a hard-sphere radius of water of 1.39 to evaluate the SPT enthalpy of cavity formation, $\Delta H_{(cav)}{}^{water}$, by eq 41 of Pierotti's review.[32]

Conclusions

The entropies of activation of a number of bimolecular reactions in the gaseous phase were compared with entropies of activation in aqueous solution in order to understand the origin of the dramatic reduction in magnitude. It was assumed that the entropy of a solution could be decomposed into separate contributions attributable to the solute and to the solvent, with the solute entropy written as a sum of components analogous to those of the substance in isolation and the solvent components arising from creation of a cavity for the solute and from polarization in response to the presence of the solute in the cavity. The entropy of cavity formation was derived from scaled particle theory. In the case of the eight test reactions which were chosen to have a small polarization entropy, it was found that the entire gaseous-phase-to- solution reduction of the entropy of activation could be accounted for by the change in the entropy of cavitation for a cavity defined by an isodensity contour of about 0.001 electrons $bohr^{-3}$. In other words, no changes in the translational or rotational components of the entropy upon solution need be invoked. The corollary is that the difference between the gaseous-phase and aqueous-phase entropies of the substances involved in the present study is entirely attributable to changes in the solvent, namely, cavity formation and possibly polarization. The polarization part of the entropy change for these substances, $\Delta S_{(pol)}{}^{water}$, was determined from the experimental values of their gaseous-phase and aqueous-phase entropies and the entropy of cavity formation. $\Delta S_{(pol)}{}^{water}$ was found to be close to zero for the smaller species (H, H_2, He, Ne, Ar, Kr, CO, O_2, and H_2O) and positive for the larger species (Cl_2, H_2S, CH_3Cl, CH_3NH_2, CH_4, CH_3OH, CH_3CH_2OH, $(CH_3)_2$-CHOH), indicating an increase in the disorder of water upon dissolution of these substances.

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