

Unveiling the Mechanism of Hydrotropy: Water-Mediated Interactions and The Role of Apolarity

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Abstract: A recent proposal attributes the origin of hydrotropy to the water-mediated aggregation of hydrotrope molecules around the solute. For the first time, direct experimental evidence for this hypothesis is obtained using ¹H-NMR spectra of glycerol ether-based hydrotropic systems. The data is at odds with previous hypotheses, such as hydrotrope pre-clustering, because the extent of hydrotrope aggregation changes drastically in the presence solute. The solubility enhancement is shown to correlate positively with the apolarity (computationally quantified on a structural basis) of the corresponding hydrotrope. In addition, an apolarity match between solute and hydrotrope maximizes the number of hydrotropes that aggregate around the solute. Both results demonstrate water-mediated aggregation as the real mechanism of hydrotropy, showing that the driving force of hydrotropy is the apolarity of the hydrotrope, and paving the way for the rational design of new hydrotropic systems.

Hydrotropes, in their ability to increase the solubility of hydrophobic substances in water, can expand the applicability of the greenest and most abundant of all solvents. Broadening the repertoire of safer solvents is in line with the principles of green chemistry^[1] and is essential for a sustainable future^[2-4]. Besides, the addition of water suffices to force the precipitation of a solute dissolved in a hydrotropic solution, facilitating its purification.

The mechanism of hydrotropy is still not clearly understood, despite a century of research^[5] and a large debate in the literature^[6-13]. Traditional speculations regarding the mechanism of hydrotropy revolved around (i) bulk-phase self-aggregation (or pre-clustering) of hydrotropes analogous to micellar solubilization^[6,7], (ii) “water structure” disruption just like how chaotropic agents are supposed to weaken the hydrophobic effect^[8,9] and (iii) specific stoichiometric association between solute and hydrotrope^[10,11]. However, none of these hypotheses stood the test of statistical thermodynamics^[12,13] and have been replaced by a new view: hydrotrope accumulation around the solute, driven by a strong water-mediated (or hydrophobic) interaction between hydrotrope and solute. Because the apolar (or hydrophobic) moiety of a molecule interacts with water much weaker than a water-water hydrogen bond, it is driven out to associate with another hydrophobic moiety, resulting in strong agglomeration of hydrotrope around the solute.

Despite stemming from the principles of statistical thermodynamics and its consequent superiority, in terms of theoretical grounds, to the previous hypothesis, no direct experimental evidence has been reported for the water-mediated accumulation mechanism proposed. In this work it will be shown that (1) the hydrophobic interaction between a hydrotrope and a solute is the driving force for the accumulation and that (2) such interaction can be quantified via a measure for apolarity derived using COSMO-RS. Both results are crucial to understand the mechanism of hydrotropy and support the hypothesis of strong water-mediated solute-hydrotrope interactions.

Proton nuclear magnetic resonance (¹H-NMR) is herein employed to provide experimental evidence for hydrotrope-solute aggregation. The strategy is based on the well-known principle that the chemical shifts of the protons of a molecule dissolved in water may change due to the presence of another substance. More precisely, a chemical shift that diminishes in the presence of another substance infers a higher shielding of that proton or a less probable contact between it and water. Thus, the chemical shifts of the protons associated to apolar moieties (namely methyl groups) of an hydrotrope dissolved in water can be measured in the presence and absence of a solute. If the solute induces the aggregation of hydrotrope around itself through water-mediated apolar interactions, as is predicted by statistical thermodynamics, the chemical shift of the protons associated to the apolar moieties of the hydrotrope should decrease.

Galic acid and syringic acid were chosen as solutes and monoalkylglycerol ethers, listed in Table S1, as hydrotropes. Note that the apolarity of monoalkylglycerol ethers can be made to vary smoothly through the progressive increase in the length of their alkyl chain.

Likewise, gallic acid and syringic acid are structurally very similar but present different hydrophobicity. The solubility of both acids in monoalkylglycerol ether aqueous solutions have been reported elsewhere^[14].

For each hydrotrope-solute pair, NMR spectra were acquired thrice. In each case, the molar concentration of hydrotrope was maintained (0.4 M) but solute concentration was changed, from zero solute, which serves as reference for the chemical shifts of the hydrotrope, to concentrations below and above solute solubility in pure water. The NMR peaks considered, clearly marked in Figure S1 of supporting information, were those of the protons of the side alkyl chain of the monoalkylglycerol ether along with the sole proton of the second carbon of the glycerol head. The protons of the first and third carbon of the glycerol head were not analysed due to the difficulty of distinguishing their corresponding peaks in the NMR spectra.

The results obtained using gallic acid as a solute (Figure 1a as an illustrative example and Figure S2) show that the chemical shift of the protons diminishes as the concentration of solute increases. This means that the apolar moieties of the hydrotropes are statistically less prone to interact with water, providing evidence for the idea of association between these moieties and the apolar moieties of the solute. Moreover, the decrease in chemical shift seen in Figures 1a and S2 is proportional to the concentration of solute. This is reasonable since the more solute present in the system the more hydrotrope is needed to interact with it. Since syringic acid is much less soluble, its concentration was one order of magnitude inferior to that of gallic acid in the NMR experiments, leading to smaller changes in the chemical shifts of the hydrotrope. In some cases, the changes produced are comparable to the experimental uncertainty of the technique. Nevertheless, the conclusions taken from the NMR results of gallic acid hold true for syringic acid as well, as depicted in Figures 1b and S3.

The NMR results question the idea that pre-clustering of the hydrotrope is fundamental in hydrotropy. Hydrotropes unquestionably do possess a degree of aggregation (clustering) with themselves. However, the hydrotrope aggregation (whether it is present depends on the system) clearly changes with the addition of the solute, providing clear evidence that the solute is not merely entering a “micelle”-like bulk-phase pre-clustering of the hydrotrope. If this were the case, there should be no change in the chemical shifts of the hydrotrope protons, since alternating from a previously hydrotrope-hydrotrope contact to a hydrotrope-solute contact would not make the hydrotrope less prone to interact with water, hence would not lead to inferior chemical shifts.

Insight is given by Figures 1, S2 and S3 not only into its existence but also into the geometry of aggregation. In fact, the peak assigned to the protons of the second carbon of the hydrotrope always shifts less than the remaining peaks. This means that the second carbon is less prone to aggregation, which is explained by its higher degree of polarity, brought about by the presence of hydroxyl groups in its vicinity. Moreover, for all systems, the peak assigned to the protons in the last methyl group of the side alkyl chain is consistently the second less-shifting peak. That is, the second less-shifting peak for [2.0.0] is that of carbon 5, for [3.0.0] is that of carbon 6, for [4.0.0] is that of carbon 7 and for [5.0.0] is that of carbon 8 (see insets of Figure S2 for clarification). This can be interpreted in terms of interaction geometry; a parallel contact between hydrotrope and solute covers more apolar area, thus being more energetically favourable to water, than a hydrotrope tail-solute contact.

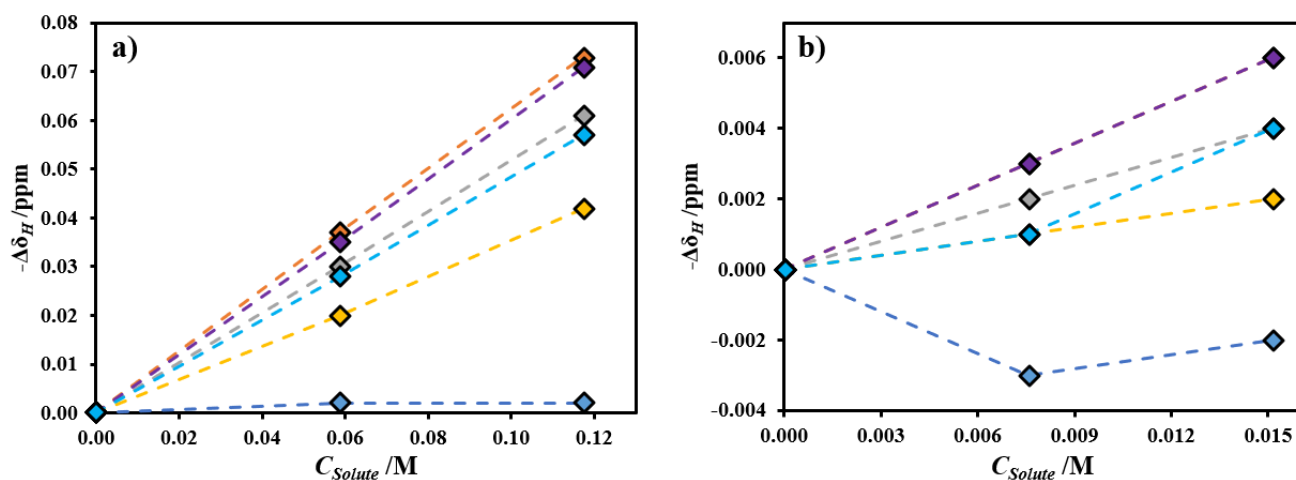


Figure 1. Change in chemical shift of the protons ($-\Delta\delta_H$) associated to water and several methyl groups of [4.0.0] dissolved in water (0.4 M) as a function of a) gallic acid or b) syringic acid concentration. Legend: Legend: \blacklozenge - water; \blacklozenge - 2nd carbon; \blacklozenge - 4th carbon; \blacklozenge - 5th carbon; \blacklozenge - 6th carbon; \blacklozenge - 7th carbon.

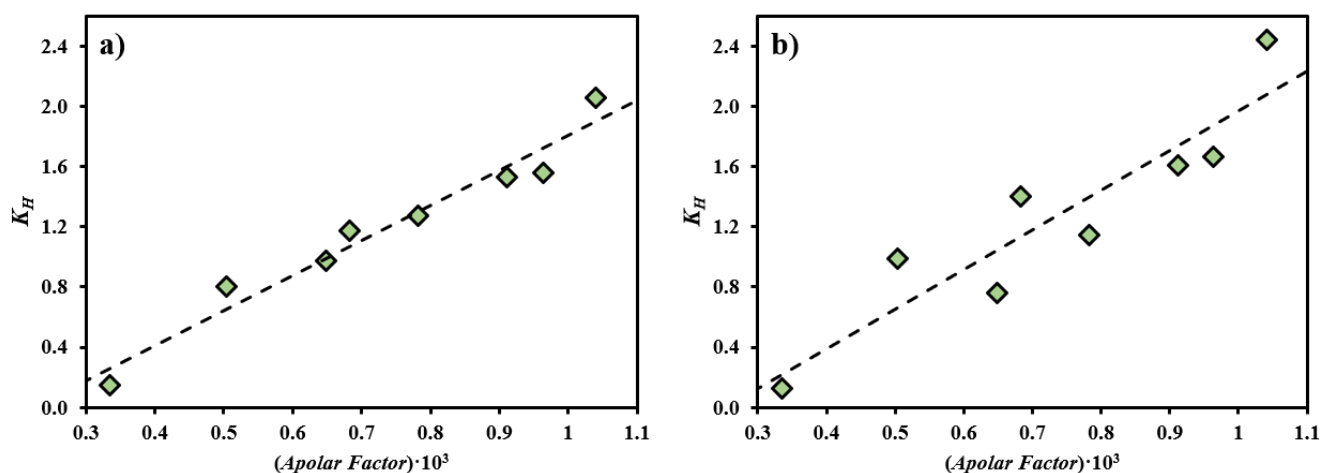


Figure 2. Setschenow constants for a) gallic acid or b) syringic acid in glycerol ether-based hydrotropic solutions as a function of the apolar factor of the hydrotrope. The dashed line is the straight line fitted to the data using the least squares method.

Having provided direct, experimental evidence for the hydrotrope-solute aggregation, let us now address its driving force. As a quantitative measure for the apolarity of a molecule, the unnormalized σ -profile framework of COSMO-RS has been adopted^[15]. This is a histogram representing the amount of molecular surface with a given polarization charge-density, σ . The unnormalized σ -profile framework should prove advantageous for the study of hydrotrophy since it can quantify the apolarity of both hydrotrope and solute. Moreover, the geometry and polarity of molecules optimized within the COSMO solvation model should more closely resemble that which is found in a real aqueous solution than molecules optimized in the gas phase. The optimization details of the solute and hydrotrope molecules herein studied are given in supporting information.

To study the relationship between apolarity and hydrotrophy using the σ -profile framework, an apolar factor was defined:

$$\int_{-0.0082}^{+0.0082} p(\sigma) \cdot (0.0082 - |\sigma|) \cdot d\sigma \quad (1.1)$$

This factor is a measure of the area under the curve of the apolar region, with the apolar/polar frontier being defined as $\sigma = -0.0082 \text{ e}/\text{\AA}^2$ and $\sigma = 0.0082 \text{ e}/\text{\AA}^2$, in line with previous studies^[15,16]. The amount of apolar surface area, $p(\sigma)$, is weighted by the actual polarity of the surface, with regions near the apolar/polar frontier being progressively penalized by the term $(0.0082 - |\sigma|)$ in Equation 1. To test this novel measure of apolarity, the Setschenow constant (the ratio between solubility enhancement and hydrotrope concentration in the dilute region) of several hydrotropic systems previously reported in the literature was correlated against the apolar factor. Table S2 of the supporting information contains the apolar factors of these hydrotropes while the correlations obtained are reported in Figure 2 for the glycerol ether systems herein studied and Figure S4 for other systems. The results obtained show that, for the same family of hydrotropes, the solubility enhancement of the solute positively correlates with the apolar factor of the hydrotrope. This supports the view of water-mediated aggregation of hydrotrope around the solute and supports the idea of hydrotrope apolarity as the driving force of hydrotrophy.

Shimizu and Matubayasi^[17] derived a hydrotrophy model based on cooperative water-mediated hydrotrope-solute aggregation using statistical thermodynamics. When regressed against experimental solubility curves, this model returns the average number of hydrotrope molecules in the vicinity of the solute (*m parameter*). Since this model has been previously applied to the systems herein studied^[14], Figure 3 depicts this parameter plotted against the apolar factor of the corresponding hydrotrope. The resulting plot shows that the *m parameter* reaches a maximum for both gallic acid and syringic acid. Surprisingly, this maximum is located at the apolar factor of the solute. As described above, solute-hydrotrope interactions are established between their apolar moieties, resulting in strong and favourable interactions only due to the presence of water. However, there is no distinction between apolar moieties of solute and hydrotrope. Consequently, a hydrotrope that is more apolar than the solute will tend to agglomerate with itself more promptly than with the solute. Put differently, in terms of apolar contacts, it is as if there are three different forms of hydrotrope present in the system: free hydrotrope, hydrotrope associated with solute and hydrotrope associated with itself.

Figure 3 shows that hydrotropes that are more apolar than the solute will tend to aggregate less around it. This does not translate, however, into a maximum on the solubility enhancement (Figure 2), which is rationalized by taking into account that even though the most apolar hydrotropes may statistically possess less molecules around the solute, they are able to cover more of its apolar area due to their larger size. In fact, this suggests that the product between the apolar factor of a hydrotrope (a measure of its apolar area) and the *m parameter* of the system may be an exceptional descriptor for the solubility enhancement due to hydrotrophy.

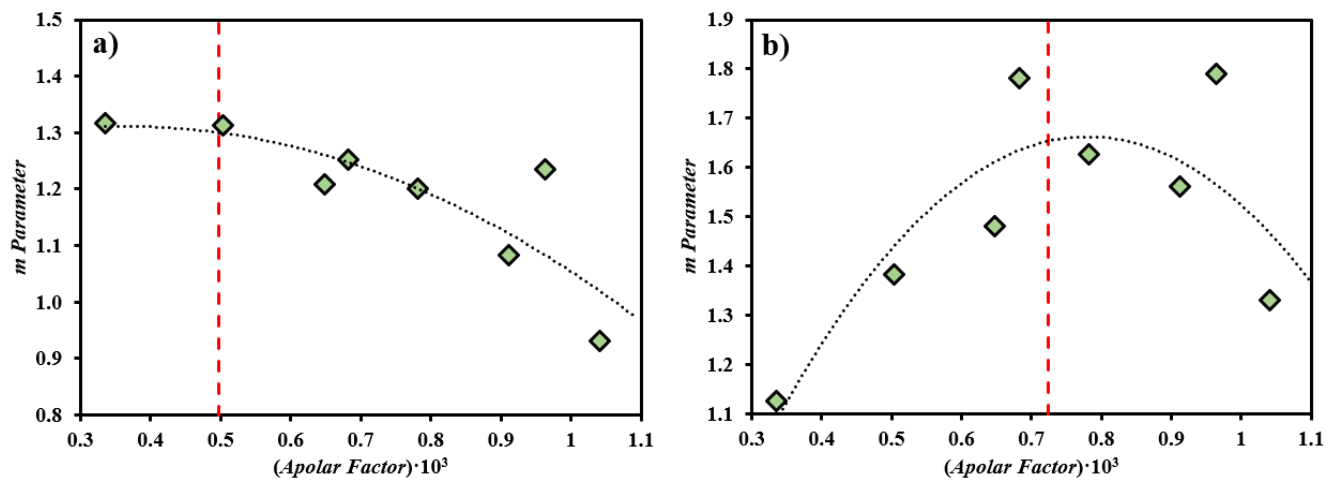


Figure 3. Number of hydrotrope molecules (*m* Parameter) in the vicinity of the solute, estimated using the Shimizu and Matubayasi^[17] model, for a) gallic acid and b) syringic acid in aqueous solutions of glycerol ethers^[14], plotted against the apolar factor of the corresponding hydrotrope. The black dashed line is a visual guide whilst the red dashed line represents the apolar factor of the solute.

In conclusion, experimental evidence was reported for the first time showing that hydrotrope molecules aggregate around the solute, which support previous cooperativity theories of hydrotrophy. Moreover, it was shown that apolarity is the driving force of hydrotrophy, with strong solute-hydrotrope interactions arising in the presence of water. These interactions are statistical and are established between apolar moieties of both solute and hydrotrope. These water-mediated interactions are, however, not exclusive to solute-hydrotrope pairs and the number of hydrotropes aggregated around the solute is maximum when the apolarity of hydrotrope and solute is the same. The results reported in this work are, thus, of the utmost importance in the understanding of the water-mediated hydrotrope-solute interactions hypothesis and provide the necessary theoretical background to tailor new hydrotrope molecules for specific applications.

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