

This document is confidential and is proprietary to the American Chemical Society and its authors. Do not copy or disclose without written permission. If you have received this item in error, notify the sender and delete all copies.

Can COSMOthermX Predict a Salting in Effect?

Journal:	<i>The Journal of Physical Chemistry</i>
Manuscript ID	jp-2017-04847m.R1
Manuscript Type:	Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Toivola, Martta; University of Helsinki, Department of Chemistry Prisle, Nønne; University of Oulu, Nano and Molecular Systems Research Unit Elm, Jonas; University of Helsinki, Physics Waxman, Eleanor; University of Colorado Boulder, Department of Chemistry and Biochemistry; NIST, Applied Physics Division Volkamer, Rainer; University of Colorado, Chemistry and Biochemistry Kurtén, Theo; University of Helsinki, Department of Chemistry

SCHOLARONE™
Manuscripts

Can COSMOthermX Predict a Salting in Effect?

Martta Toivola^a, Nønne L. Prisle^b, Jonas Elm^c,
Eleanor M. Waxman^d, Rainer Volkamer^e, and Theo
Kurtén*^a

^aDepartment of Chemistry, P.O. Box 55, FI-00014 University of Helsinki, Finland

^bNano and Molecular Systems Research Unit, University of Oulu, Finland, P. O. Box 3000,
FI-90014 University of Oulu, Finland

^c Department of Physics, University of Helsinki, P.O. Box 64, FI-00014 University of Helsinki,
Finland

^dDepartment of Chemistry and Biochemistry, University of Colorado Boulder, CO, USA, now at
Applied Physics Division, NIST, Boulder, CO, USA

^e Department of Chemistry and Biochemistry & CIRES, University of Colorado at Boulder, CO,
USA

1
2
3 ABSTRACT: We have used COSMO-RS, a method combining quantum chemistry with
4 statistical thermodynamics, to compute Setschenow constants (K_S) for a large array of organic
5 solutes and salts. The studied systems comprise both atmospherically relevant organic solutes
6 and salts, as well as aromatic species and tetraalkylammonium salts for which experimental data is
7 available. In agreement with previous studies on single salts, the Setschenow constants predicted
8 by COSMO-RS (as implemented in the COSMOTermX program) are generally too large
9 compared to experimental values. COSMOTermX overpredicts the salting out effect (positive
10 K_S), and/or underpredicts the salting in effect (negative K_S). For ammonium and sodium salts, K_S
11 values are larger for oxalates and sulfates, and smaller for chlorides and bromides. For chloride
12 and bromide salts, K_S values usually increase with decreasing size of the cation, along the series
13 $\text{Pr}_4\text{N}^+ < \text{Et}_4\text{N}^+ < \text{Me}_4\text{N}^+ \leq \text{Na}^+ \approx \text{NH}_4^+$. Of the atmospherically relevant solute-salt systems
14 studied, salting in is predicted only for oxalic acid in sodium and ammonium oxalate, as well as
15 in sodium sulfate, solutions. COSMOTermX was thus unable to replicate the experimentally
16 observed salting in of glyoxal (and/or its hydrates) in sulfate solutions, likely due to the
17 overestimation of salting out effects. In contrast, COSMOTermX does qualitatively predict the
18 experimentally observed salting in of multiple organic solutes in solutions of alkylammonium salts.

44 INTRODUCTION

45
46
47
48
49 The physical and chemical properties of secondary aerosol particles determine their
50 ability to act as cloud condensation nuclei, which in turn affect cloud properties and thus the
51 global climate.¹ While sulfuric acid and nitrogen-containing bases may be required for the first
52 steps of atmospheric new-particle formation, organic compounds in various states of oxidation
53
54
55
56
57
58
59
60

1
2
3 dominate their growth processes,² and have been observed to explain a remarkable part of the
4 total aerosol mass.³ The partitioning of an organic compound between the gas phase and the
5 aerosol particles depends on the solubility of the compound. Atmospheric aerosol particles may
6 in general contain coexisting solid and liquid phases, and the latter may be either aqueous or
7 organic. In this study, we focus on the solubility of organic compounds in the aqueous phase.
8 Solvation of organic compounds plays a critical role in secondary organic aerosol formation^{4,5}
9 and cloud droplet activation⁶ in the atmosphere. For example, Prisle *et al.*⁵ showed how SOA
10 formation from uptake to an aqueous salt phase was much more modest than predicted from
11 absorptive partitioning under the assumption of ideal (i.e. assuming that the activity of each
12 component equals its mole fraction) aqueous phase mixing behavior of the organics.⁴ Bilde and
13 Svenningsson⁶ demonstrated how cloud droplet activation is significantly impacted by small
14 amounts of salt altering the balance of droplet growth and organic aerosol solubility threshold in
15 the aqueous droplet phase.

16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35 Atmospheric aerosol particles contain a mixture of both organic and inorganic
36 components, and the aqueous aerosol phase may contain high concentrations of various ionic
37 solutes, in particular salts such as sulfates, nitrates or chlorides. Due to non-ideality (non-
38 vanishing mixing effects resulting from solute-solute or solute-solvent interactions), the
39 solubility of organic molecules in such solutions may be very different from that in pure water. A
40 decrease in the solubility of organics upon the addition of a salt is known as a salting out effect.
41 Conversely, an increase in solubility is known as salting in. The change of solubility of neutral
42 organic solutes in salt water can be described using the Setschenow relationship

$$\log\left(\frac{S_0}{S}\right) = K_S c_S \quad (1)$$

1
2
3 where S_0 and S are the solubilities of the solute in pure water and salt solution, respectively, and
4
5 c_s is the salt concentration (which can be expressed in terms of either molarities, moles of solute
6
7 per liter of solution, or molalities, moles of solute per kilogram of solvent). Positive values of the
8
9 Setschenow constant K_S indicate a salting out effect, i.e. the salt lowers the solubility of the
10
11 organics, while negative values indicate salting in. Equation 1 may be written also in terms of
12
13 partition coefficients, as shown by Endo *et al.*⁷
14
15

16
17 Both experimental and theoretical studies on salting effects have been carried out.
18
19 Experimentally, both salting in and salting out have been observed, with the latter tending to be
20
21 more common for atmospherically relevant combinations of salts and organic
22
23 solutes.^{7,8,9,10,11,12,13,14} A possible explanation for this is that salting out is caused by a general
24
25 competition for solvation between neutral organic and ionic solutes, while salting in is related to
26
27 more specific favorable interactions between pairs of solutes (e.g. a neutral organic and a certain
28
29 anion or cation). Currently available empirical models for predicting Setschenow constants are
30
31 unable to simultaneously predict both salting in and salting out effects, possibly due to lacking
32
33 descriptions of the specific favorable interactions behind salting in, or to the very different
34
35 chemical characteristics between the molecules that salt in, and the molecules the empirical
36
37 models are typically trained with.^{10,15,16,17}
38
39
40
41
42

43
44 The combination of quantum chemistry - based modeling of molecular interactions with
45
46 statistical thermodynamics offers a possibility to study equilibrium properties, such as salting
47
48 effects, efficiently for large number of systems. The most advanced method of this type currently
49
50 available is called COSMO-RS (The CONductor-like Screening Model for Real Solvents).^{18,19}
51
52 COSMOthermX^{20,21} is a commercial program based on the COSMO-RS method. Previous
53
54 studies of Setschenow constants in $(\text{NH}_4)_2\text{SO}_4$ ¹⁰ and NaCl ⁷ solutions show a moderately good
55
56
57
58
59
60

1
2
3 correlation between experimental K_S values and COSMOthermX predictions, but with a few
4
5 outliers, notably caffeine in NaCl.⁷
6
7

8 In this work we have calculated salt - solute - pair specific Setschenow constants for the
9
10 following organic solutes: benzaldehyde, benzene, benzoic acid, 1,2-dimethylbenzene, 1,3-
11
12 dimethylbenzene, 1,4-dimethylbenzene, glycerol, glyoxal, glyoxal dihydrate, glyoxal
13
14 monohydrate, 1,2-ISOPOOH (isoprene hydroxyl hydroperoxide), 3,4-ISOPOOH, isoprene epoxy
15
16 diol, malonic acid, methylglyoxal dihydrate, 2-methyl tetraol, 1-naphthol, 2-naphthol,
17
18 naphthalene, nitrobenzene, oxalic acid, phenol, succinic acid and toluene. These organic
19
20 molecules are chosen for two reasons: they are either known or suggested to participate in
21
22 atmospheric aerosol processes^{22, 23} or/and experimental salting constant values are available for
23
24 them.^{7,8,9,11,12,13} The selection of salt solutions is similarly motivated both by atmospheric
25
26 relevance, and by the availability of experimental results. We have studied solutions of singly-
27
28 (Cl^- , Br^-) and doubly charged (SO_4^{2-} , $\text{C}_2\text{O}_4^{2-}$) anions with small singly charged cations (Na^+ ,
29
30 NH_4^+). (In acidic solutions, SO_4^{2-} , $\text{C}_2\text{O}_4^{2-}$ co-exist with their conjugate bases HSO_4^- and HC_2O_4^- -
31
32 these were not included in the present study.) Additionally, we have studied the chloride and
33
34 bromide salts of organic tetraalkylaminium cations: Et_4NCl , Et_4NBr , Me_4NCl , Me_4NBr , Pr_4NCl
35
36 and Pr_4NBr (where $\text{Me} = \text{CH}_3$, $\text{Et} = \text{CH}_3\text{CH}_2$, and $\text{Pr} = \text{CH}_3\text{CH}_2\text{CH}_2$). While experimental data is
37
38 only available for some solute - salt pairs, we have here computed Setschenow constants for all
39
40 combinations of the solutes and salts described above.
41
42
43
44
45
46
47
48
49

50 **METHODS**

51
52
53
54
55
56
57
58
59
60

1
2
3 We evaluated Setschenow constants using the COSMO-RS method, which is based on an
4 electrostatic theory of locally interacting molecular surface descriptors and statistical
5 thermodynamics.¹⁸ We used COSMOthermX version C30_1501.^{20,21} The advantage of this
6 method is that no system-specific experimental parameters are needed (though when available
7 these can be incorporated into some property calculations, and may improve the accuracy of
8 results).²⁴ The only pre-existing information needed for the modeling are the energetically
9 favored structures (conformations) of the studied molecules. For flexible molecules, a
10 representative set of conformations is needed (they are then treated in COSMOthermX using
11 their Boltzmann-weighted populations). Accounting for multiple conformers is important mainly
12 when the polarities of different conformers are very different, resulting in potentially large free
13 energy differences between the gas phase and the aqueous phase.²⁵ Thermodynamical properties
14 of liquid systems are calculated from quantum chemistry-based molecular interactions.

15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32 The most time-consuming step of COSMO-RS modeling is creating the molecule-
33 specific cosmo-files using density functional theory calculations. This step is done only once for
34 each of the molecules in this study. The cosmo-files of molecules contain information on the
35 screening charge distribution on a molecular conductor-like screening model surface, the σ -
36 surface, and the energy. For benzene, phenol, nitrobenzene, toluene, benzaldehyde, benzoic acid,
37 the dimethylbenzenes, naphthalene, Na^+ , NH_4^+ and Cl^- , the input files for the COSMOthermX
38 calculations are taken from the library of the COSMOthermX program suite. (Note that all these
39 systems have a very limited number of conformers – often only one.) For the other cases,
40 conformer generation was first performed using the MMFF force-field, and the systematic
41 conformer generation tool of the Spartan '14 program.²⁶ When the total number of conformers
42 was on the order of 100 or more (this was the case for 1,2-ISOPOOH, 3,4-ISOPOOH, Pr_4N^+ and
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 Et₄N⁺), B3LYP/6-31+G(d) calculations were performed in Spartan on the MMFF structures, and
4
5 a representative set of several tens of low-energy conformers was selected from these. For the
6
7 ISOPOOH isomers with multiple possible intramolecular hydrogen bonds, several different
8
9 hydrogen-bonding patterns were included in the conformer set, including also structures without
10
11 intramolecular hydrogen bonds even when these were significantly higher in (gas-phase
12
13 B3LYP/6-31+G(d)) energy.
14
15

16
17 The geometry optimizations were then performed in Turbomole²⁷ at the BP-RI-
18
19 DFT/TZVP level (where BP refers to B88-VWN-P86).²⁸ Gas phase single point-energies and
20
21 cosmo-files were finally computed at the TZVPD-FINE level, which refers to BP-RI-
22
23 DFT/TZVPD, with the molecular surface cavity constructed using the fine grid marching
24
25 tetrahedron algorithm. TZVPD-FINE is the highest-quality calculation method currently
26
27 available for COSMO-RS simulations, and it is recommended especially for secondary and
28
29 tertiary aliphatic amines and polyether compounds.²⁴ For the flexible molecules, the TZVPD-
30
31 FINE and the subsequent COSMOTermX calculations were performed using the 20 lowest
32
33 energy conformers optimized by Turbomole (at the BP-RI-DFT/TZVP level, with COSMO-RS
34
35 solvation) for the neutral organics, and the 10 lowest for the cations. Test calculations on 3,4-
36
37 ISOPOOH indicates that our conformational sampling approach is sufficient for most of the
38
39 systems studied here, but may severely underestimate the K_S values for the ISOPOOH isomers
40
41 with sulfate and oxalate salts.
42
43
44
45
46
47
48
49
50

51 RESULTS AND DISCUSSION

52
53
54
55
56
57
58
59
60

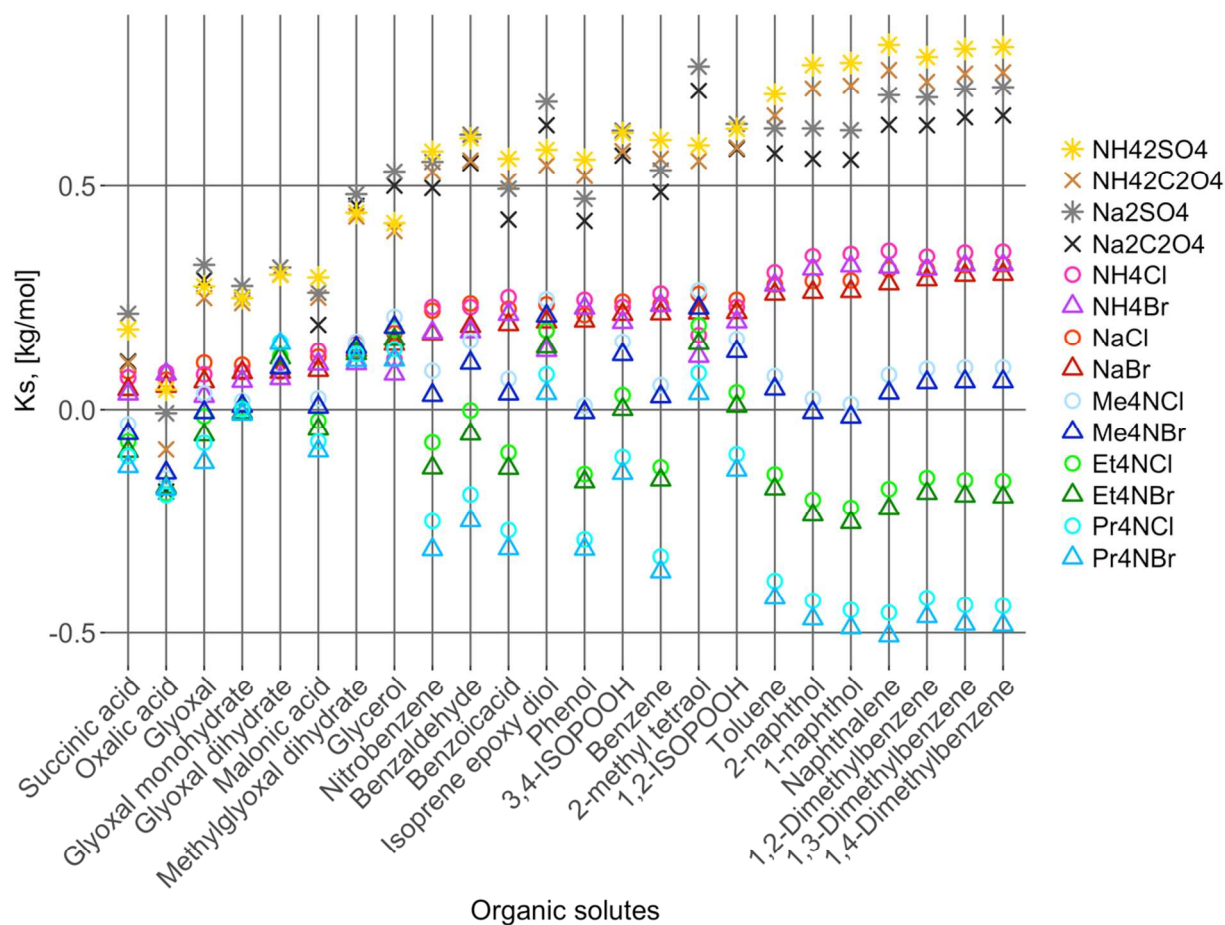
1
2
3 We evaluated the Setschenow constants using four different salt mole fractions (with
4 respect to the total solution composition, i.e. moles of salt per moles of water and salt): 0.09,
5 0.009, 0.0009, and 0.00009. Solutions with a salt mole fraction of 0.009 were then studied in
6 more detail. A salt mole fraction of 0.009 is approximately equivalent to a salt concentration of
7 0.5 mol/l, which is a typical seawater salt concentration, and also in line with the concentrations
8 used by Endo *et al.*⁷ Salt concentrations in atmospheric aerosols and cloud droplets can be much
9 higher or lower than this, depending especially on the size of the aerosol particle or droplet and
10 ambient relative humidity.
11
12
13
14
15
16
17
18
19
20
21

22 The Setschenow constants obtained for the studied organic-salt-pairs in salt solution with
23 a salt mole fraction of 0.009 are presented in Figure 1, with numerical values given in Table S1
24 of the Supporting Information. Setschenow constants are reported in units of inverse molality;
25 kg/mol. The reason for using molality rather than molarity is that the former does not require
26 knowledge of the exact liquid densities. The variation in the Setschenow constants depending on
27 the salt concentration used in the calculations is illustrated using error bars in Figure S1 in the
28 Supporting Information (with numerical values given in Tables S2-S4). For 80% of the systems,
29 the variation in the Setschenow constant across the range of studied salt mole fractions is less
30 than 0.2 kg/mol, and for 97% it is less than 0.3 kg/mol. These variations are not negligible given
31 that the absolute values of the computed Setschenow constants are all between -0.6 and 1.0
32 kg/mol. In other words, the concentration dependence of the solubility predicted by
33 COSMOTermX does not exactly match that of the original Setschenow equation.
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49

50 The majority of the studied systems (solute – salt pairs) salt out, as expected from
51 previous studies.^{7,8,11,12,13} COSMOTermX was unable to replicate the experimentally observed
52 salting in of glyoxal (in practice, glyoxal hydrates)⁹ or succinic acid²⁹ in sulfate solutions.
53
54
55
56
57
58
59
60

However, systems containing large organic cations, Pr_4N^+ or Et_4N^+ , are predicted to salt in most of the organics studied here. Also, oxalic acid is predicted by COSMOTermX to salt in into sodium and ammonium oxalate, as well as sodium sulfate solutions.

Some clear trends can also be discerned from the data. For the chloride and bromide salts, the K_S values usually (with a few exceptions) increase along the cation series $\text{Pr}_4\text{N}^+ < \text{Et}_4\text{N}^+ < \text{Me}_4\text{N}^+ \leq \text{Na}^+ \approx \text{NH}_4^+$. For the ammonium and sodium salts, $\text{C}_2\text{O}_4^{2-}$ and SO_4^{2-} anions salt out most organics more strongly than Cl^- and Br^- anions. Furthermore, the organics that salt in most strongly in Pr_4N^+ or Et_4N^+ - containing solutions also salt out most strongly in $\text{C}_2\text{O}_4^{2-}$ and SO_4^{2-} -containing solutions.



1
2
3 **Figure 1.** Values of the Setschenow constants at 25°C for the studied solute-salt-pairs, computed
4
5
6 at a salt mole fraction of 0.009.
7
8
9

10
11 Experimental values for Setschenow constants are reported either in units of kg/mole
12 (inverse molality), or in units of l/mol (inverse molarity). Kampf *et al.* demonstrated that using
13 molality rather than molarity gives a consistent picture of salting effects in both pure inorganic
14 and mixed inorganic/organic aerosol seed particles.⁹ In other words, the Setschenow constants
15 obtained for pure and mixed seed particles were found to be identical when using molality units,
16 while the value of K_S depended on the seed when using molarity units.
17
18
19
20
21
22
23
24

25
26 For a semi-quantitative comparison of COSMO-RS and experimental results,^{7,8,9,11,12,13}
27 we here assume that the density of the salt solution is the unit density of pure water, 1 kg/l, and
28 convert molarities into molalities using this density. Density variations of aqueous salt solutions
29 are often unknown, and may be on the order of tens of percent. The resulting comparison is
30 shown in Figure 2 (where only the Setschenow constants for which experimental values could be
31 found are plotted).
32
33
34
35
36
37
38
39

40
41 COSMOthermX has previously been reported to overestimate the salting out effect in
42 sodium chloride and ammonium sulfate solutions.^{7,10} Our calculations indicate that this
43 observation applies also to other salt solutions. As seen from Figure 2, COSMOthermX generally
44 gives an upper limit for K_S – the experimental value is never significantly higher than the
45 computed K_S , but is often significantly lower. Predictions for Na_2SO_4 , NaCl and NaBr salts are
46 in reasonable agreement with experiments, while the largest disagreements are found for some of
47 the ammonium salts, and for Pr_4NBr and Et_4NBr . This might indicate problems in the
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 quantitative treatment of NH_4^+ H-bonds on one hand, and of the interactions of neutral organic
4 solutes with the large alkylammonium cations on the other. The assumption of unit density may
5 also be the most problematic for solutions containing the larger cations. Earlier studies on single
6 salts^{7,9} have found that the predictive power of COSMOTermX can be improved by multiplying
7 the computed K_S values by a correction factor. For our dataset including multiple salts, we were
8 unable to significantly improve the predictive power of COSMOTermX either by a constant
9 offset or by a multiplicative factor. Fortunately, as seen from Figure 2, the sign of K_S is correctly
10 predicted for most cases, with a few cases of COSMOTermX predicting salting out while
11 experiments indicate salting in, and no examples of the opposite misprediction.
12
13
14
15
16
17
18
19
20
21
22
23
24

25 The general overestimation of K_S by COSMOTermX is likely the reason for the
26 incorrect prediction of salting out for glyoxal hydrates in sulfate solutions. It can be seen from
27 Figure 1 that the Setschenow constants for glyoxal hydrates in sulfate solutions (Na_2SO_4 and
28 $(\text{NH}_4)_2\text{SO}_4$) are lower than those of most other organic solutes. Thus, COSMOTermX may be
29 able to predict the relative ordering of Setschenow constants (for the same solute in different
30 salts, or for different solutes in the same salt) reasonably, despite the absolute values being
31 overestimated.
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

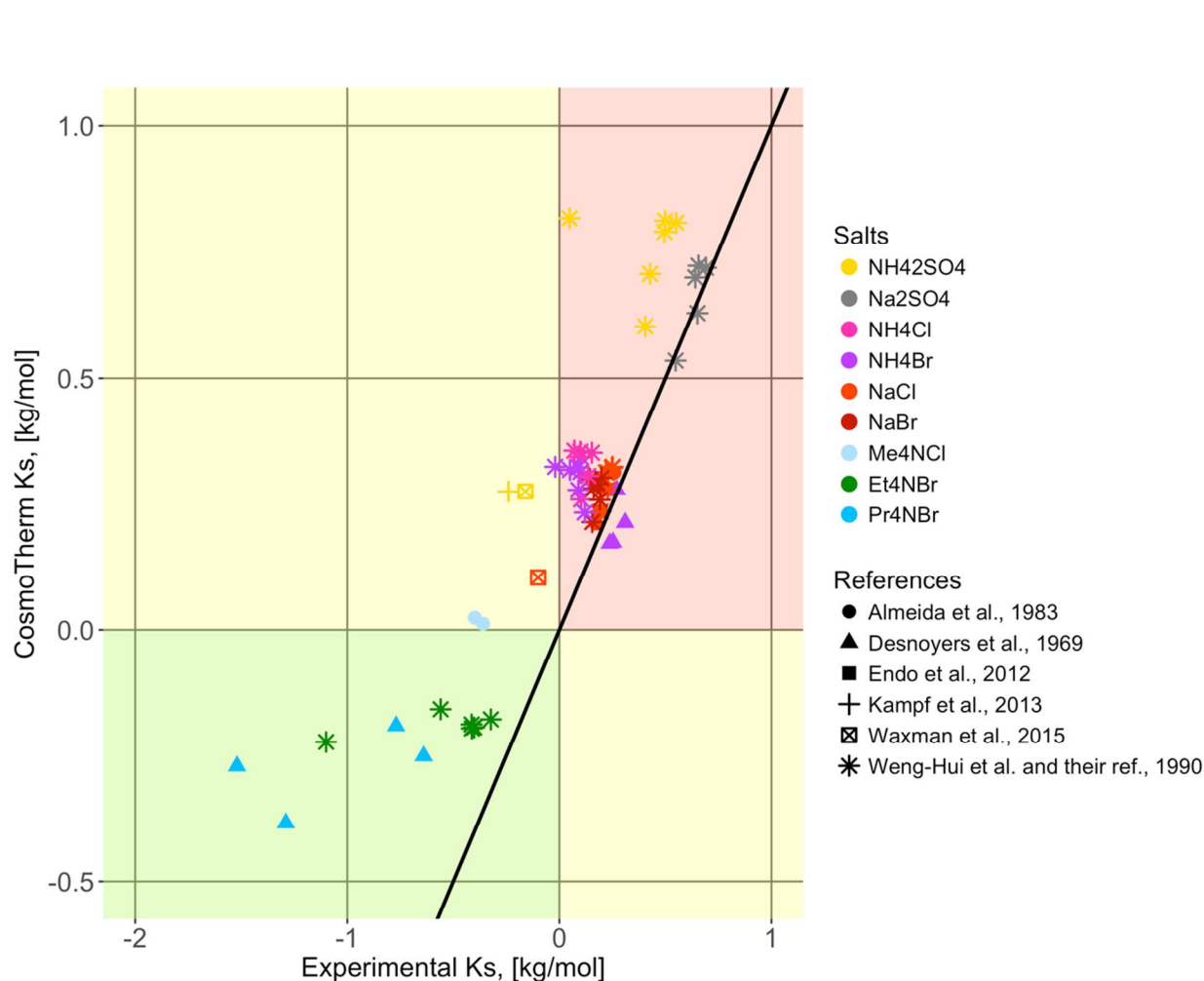


Figure 2. Setschenow constants predicted by COSMOTermX (at 25°C, computed at a salt mole fraction of 0.009) plotted against the experimental values (converted from molarities into molalities where necessary by assuming a unit density). The data points in the green shaded area correspond to systems for which both COSMOTermX and experiments yield salting in, while those in the red shaded area correspond to systems for which both yield salting out. The data points in the yellow shaded areas correspond to systems for which COSMOTermX and experiments disagree on the sign of K_S . Experimental data from Almeida *et al.*,¹¹ Desnoyers *et al.*,¹² Endo *et al.*,⁷ Kampf *et al.*,⁹ Waxman *et al.*,⁸ and Weng-Hui *et al.*,¹³ (and references therein).

1
2
3 The molecular-level mechanisms behind salting in/out phenomena can be described in
4 terms of changes in the environment of a solute molecule between pure water and a salt solution.
5
6 Endo et al.⁷ explained the salting out effect by an increase in the cohesion energy of water when
7 salt was added. This would then weaken the interaction of the organic solute with the water, and
8 increase the work of cavity creation, leading to decreased solubility. This explanation can be
9 connected to the structural effects on water of different ions, especially anions: structure-making
10 “kosmotropes” have been suggested to salt neutral solutes out,³⁰ while structure-breaking
11 “chaotropes” could salt them in. If this structural effect were the main or sole interaction behind
12 salting effects, salting in or out should depend mainly on the salt, with the identity of the neutral
13 organic solute playing little or no role. Clearly, this is not the case either experimentally (Figure
14 2) or according to our modeling (Figure 1): the degree and even the sign of the salting effect
15 depends almost as much on the neutral solute as on the salt. For example, our results indicate that
16 alkylammonium salts may cause either strong salting in (e.g. for dimethylbenzenes) or moderate
17 salting out (e.g. for the glyoxal hydrates), while oxalate salts may cause either strong salting out
18 (e.g. for aromatics), or weak salting in (for oxalates). Furthermore, both the predicted and the
19 experimentally observed salting effects disagree with the predictions from the “structure” theory
20 of ions. According to the classification in the review article by Marcus,³¹ Pr_4N^+ is a structure-
21 making ion, Na^+ and Et_4N^+ are borderline cases, and all the other ions in our study are structure-
22 breaking. Yet by far the strongest salting-in effects are seen (both theoretically and
23 experimentally) for the structure-making Pr_4N^+ salts, while the strongest salting-out effects are
24 seen (again both theoretically and experimentally) for sulfate salts, which according to Marcus³¹
25 should be structure-breaking. Salting, and especially salting in, must therefore involve specific
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 interactions between the neutral and ionic solutes - as acknowledged even in studies generally
4
5 subscribing to the kosmotrope/chaotrope – analysis of salting phenomena.³⁰
6
7

8 The COSMO-RS method is based on pairwise interacting surface charges, and
9
10 intermolecular interactions are determined by the probability distributions of the screening
11
12 charges (σ -profiles) of the individual molecules embedded in a virtual conductor. The σ -profile
13
14 is computed separately for each individual molecule. COSMOTermX then treats interactions
15
16 between all the different components of a system (in our cases consisting of water, a cation, an
17
18 anion, and an organic solute). Thus, both direct interactions between neutral and ionic solutes, as
19
20 well as indirect water-mediated interactions, are modelled.
21
22
23
24

25 Comparison of the σ -profiles of two molecules or ions can be used to visualize their
26
27 possible interactions. For example, Schröder et al.¹⁶ studied the salting effect of
28
29 hexafluorobenzene in several salt solutions. They found that a salting out effect was observed
30
31 when no interactions between the organic solute and water molecules could be identified from
32
33 the σ -profiles. Conversely, salting in is associated with complementary parts in the σ -profiles of
34
35 solute and solvent molecules, indicating attractive interactions. (Two σ -profiles peaks are
36
37 “complementary” when they are located at opposite sides of the origin, at approximately equal
38
39 distances from it.) In our study, the organics that clearly salt in into Pr_4N^+ salt solutions ($K_s < -0,1$)
40
41 are characterized by σ -profiles that are relative narrow, and have a probability peak that is
42
43 complementary with the σ -profile for Pr_4N^+ . Conversely, the σ -profiles of these organics are not
44
45 at all complementary with those of the dianions (sulfate and oxalate), leading to large salting out
46
47 in their solutions. This explains the large spread between different salts of the K_s values for the
48
49 compounds on the right-hand side of Figure 1.
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4 σ -profiles for the solvent water molecule and for the ionic solutes driving salting in/out of
5
6 the neutral organic are shown in Figure 3. Profiles for the organic solutes themselves are not
7
8 shown for simplicity. σ -profiles for two representative organic solutes (naphthalene and oxalic
9
10 acid) are shown in Figure S2 in the Supporting Information (and additional σ -profiles can be
11
12 visualized from the cosmo files provided in a separate zip archive in the Supporting
13
14 Information). The order of K_s values for organic solutes with NH_4^+ and Na^+ salts with different
15
16 anions follows the order of the σ -profile peaks of the anions, as shown in Figure 3 ($\text{Br-Cl-C}_2\text{O}_4$ -
17
18 SO_4). In other words, the more polar anions, with σ -profile peaks further from the origin, cause
19
20 greater salting out. This is in agreement with recent experimental observations by Wang *et al.*¹⁴,
21
22 who report stronger salting out for a large variety of organic solutes in sodium and ammonium
23
24 sulfate salts than in sodium and ammonium chloride (or nitrate) salts. For cations, the σ -profiles
25
26 of Pr_4N^+ , Et_4N^+ and Me_4N^+ are wider and closer to the origin compared to those of NH_4^+ and
27
28 Na^+ , and they partly complement the σ -profiles of weakly polar or non-polar organic molecules
29
30 (not shown), leading in some cases to salting in as shown in Figure 1.
31
32
33
34
35
36

37 NH_4^+ may form a hydrogen bond with the oxygen atom of a water molecule, which
38
39 increases the cohesion energy as suggested by Endo *et al.*,⁷ and could lead to stronger salting out
40
41 for NH_4^+ salts than for the corresponding Na^+ salts. This pattern is predicted for many of the
42
43 organic solutes studied here, though the differences between sodium and ammonium salts with
44
45 the same anion are generally small. However, the recent measurements by Wang *et al.*¹⁴ report
46
47 the opposite trend, with sodium sulfate and chloride salting out all the organic solutes in their
48
49 study more strongly than ammonium sulfate and chloride, respectively. COSMOTermX
50
51 predicts stronger salting out for sodium sulfate and oxalate salts compared to ammonium sulfate
52
53 and oxalate salts for the following organic solutes: glycerol, glyoxal, glyoxal dihydrate, glyoxal
54
55
56
57
58
59
60

1
2
3 monohydrate, isoprene epoxy diol, methylglyoxal dihydrate and 2-methyl tetraol. These organic
4 solutes are all able to act as H-bond acceptors, forming H-bonds with both water and NH_4^+ . This
5
6 may lead to relatively weaker salting out of these organic solutes by ammonium oxalate and
7
8 sulfate compared to sodium oxalate and sulfate. However, the COSMOThermX predictions
9
10 disagree with experimental observations⁸ for methylglyoxal hydrates, for which salting out has
11
12 been found to be stronger for NH_4^+ salts than for Na^+ salts.
13
14
15
16
17
18
19
20
21
22

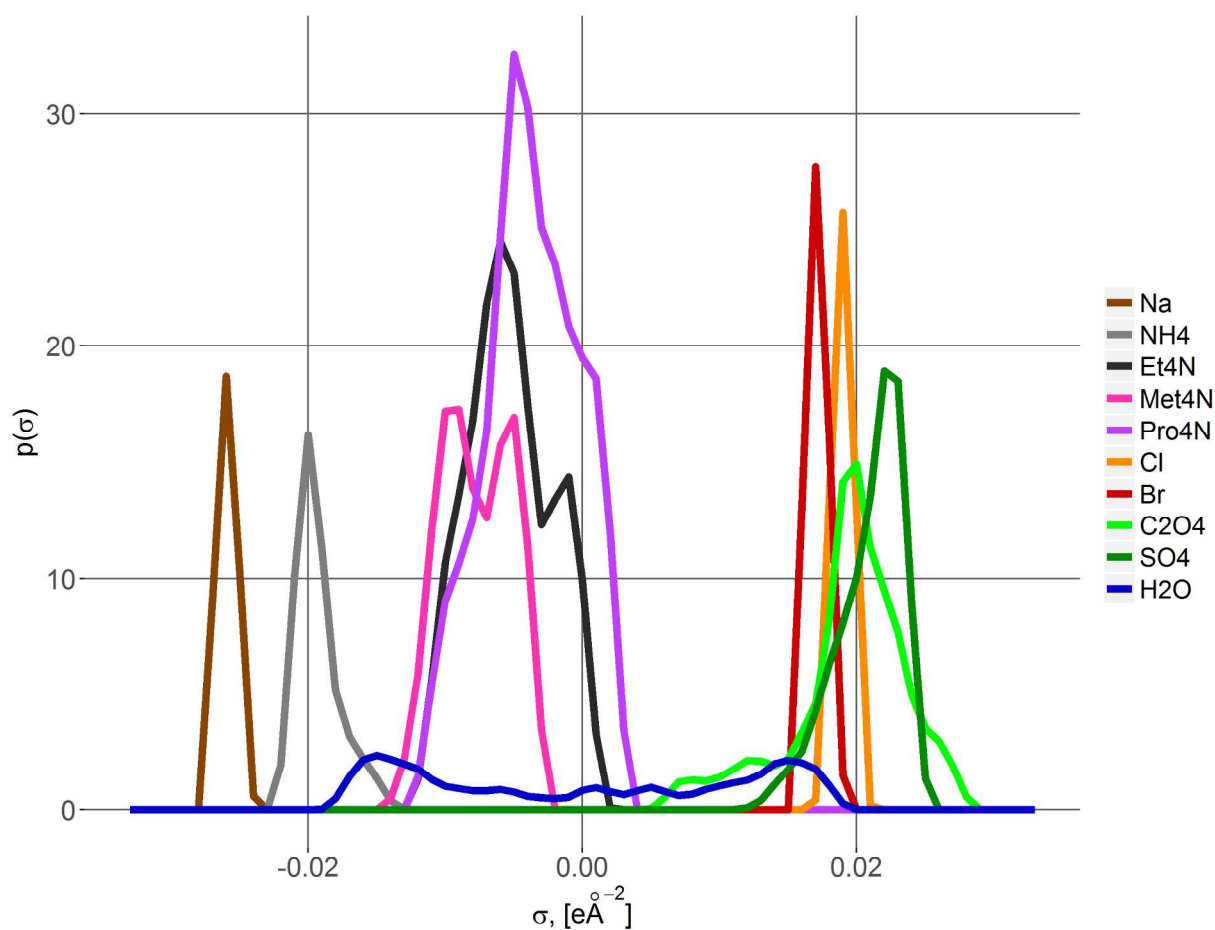


Figure 3. σ -profiles for the water molecule and for the various ions included in this study

1
2
3 Oxalic acid is an interesting exception among the studied organics. It is the only molecule
4 for which COSMOTermX predicts salting in also by salts composed only of small inorganic
5 ions. While oxalic acid can in principle act as both an H-bond acceptor and an H-bond donor,
6 the latter characteristic is dominant (as usual for acids), and oxalic acid therefore interacts
7 favorably with strong H-bond acceptors such as $\text{C}_2\text{O}_4^{2-}$ and SO_4^{2-} anions. This leads to salting in
8 by Na^+ salts of these anions. The reason for larger Setschenow constants (greater salting out /
9 lesser salting in) of oxalic acid in NH_4^+ solutions ($(\text{NH}_4)_2\text{SO}_4$, $(\text{NH}_4)_2\text{C}_2\text{O}_4$) might be a result of
10 stronger interactions between NH_4^+ and water molecules, which tends to favor salting out as
11 discussed above. Strong hydrogen bonding between glyoxal hydrates and the sulfate anion were
12 suggested by Kurtén et al.³² as the reason for the experimentally observed^{8,9} salting in of glyoxal
13 in sulfate solutions. While COSMOTermX was unable to predict the experimentally observed
14 behavior for glyoxal (in practice, its hydrates), the negative K_S predicted for oxalic acid in some
15 sulfate and oxalate solutions indicates that the general mechanism of salting in due to strong
16 specific hydrogen bonds between an organic solute and a dianion is at least qualitatively
17 described by the COSMO-RS method.

18
19
20 We further compared the computed K_S values with the three different interaction energy
21 components reported by COSMOTermX for each of the neutral organic molecules: the misfit
22 energy, the H-bond energy and the van der Waals (vdW) energy. While the main interaction
23 partner for the neutral organic molecules is likely (in all but the most concentrated salt solutions)
24 the solvent water, salting effects are related to differences in the interactions of neutral solutes
25 between pure water and salt solutions. In other words, the absolute magnitude of the solute –
26 water interaction is largely irrelevant to the salting phenomenon, as only differences in
27 interactions matter. We thus plotted the K_S values against the differences in each interaction
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 energy component between the pure water and the salt solution (at a salt mole fraction of 0.009).
4
5 These differences contain contributions from both direct interactions between neutral organic
6
7 and ionic solutes, as well as water-mediated interactions such as differences in the work of cavity
8
9 creation.
10

11
12 The misfit energy $E(\text{misfit})$ is a measure of the energy cost of embedding the molecule in
13
14 a real solution instead of a perfect conductor continuum,¹⁹ and differences in the misfit energy
15
16 between pure water and a salt solution are thus at least qualitatively related to the effect of the
17
18 salt on the work of cavity creation around the neutral solute. Figure 4 shows a linear relationship
19
20 between the calculated K_S values and the difference in misfit energies between pure water and
21
22 the salt solution ($\Delta E(\text{misfit})$). However, the correlation is quite weak in Et_4NBr , $\text{Na}_2\text{C}_2\text{O}_4$ and
23
24 Na_2SO_4 solutions. An organic molecule salts in if its misfit energy in salt solution is lower, or
25
26 just slightly higher, than in the water solution. In contrast, a large Setschenow constant (strong
27
28 salting out) indicates a high misfit energy in salt solution. Somewhat surprisingly, clear
29
30 correlations between the Setschenow constants of all the studied systems and the H-bond or
31
32 vdW-energy differences were not observed (see Figures 5 and 6). However, the predicted
33
34 Setschenow constants for the carbonate and sulfate salts, which form strong hydrogen bonds, do
35
36 correlate weakly with the H-bond energy difference (see Figure 5). Similarly, the predicted
37
38 Setschenow constants for the alkylaminium salts, which interact with neutral organic solutes
39
40 mainly via van der Waals forces, correlate weakly with the vdW – energy difference (see Figure
41
42 6).
43
44
45
46
47
48
49

50
51 Especially for atmospherically relevant solute-salt combinations, salting out seems to be
52
53 the general rule, and salting in the exception. This can be understood in terms of the mechanisms
54
55 discussed by both Schröder *et al.*¹⁶ and Endo *et al.*⁷: small anions and cations tend to interact
56
57
58
59
60

1
2
3 strongly with solvent water molecules, and thus by default decrease the solubility of neutral
4 organics - unless some strong and specific favorable interactions of the neutral solute
5 counteracts this effect. The general increase in Setschenow constants along the series $\text{Pr}_4\text{N}^+ <$
6 $\text{Et}_4\text{N}^+ < \text{Me}_4\text{N}^+ \leq \text{Na}^+ \approx \text{NH}_4^+$ reflects the strength of the favorable interaction between the
7 cations and water: the smaller and more polar cations interact more strongly with water
8 molecules, leading (on average) to greater salting out of neutral organic solutes. The analogous
9 increase in the Setschenow constants in NH_4^+ and Na^+ salts along the anion series $\text{Br}^- < \text{Cl}^- <$
10 $\text{C}_2\text{O}_4^{2-} < \text{SO}_4^{2-}$ is another example of the same mechanism: more polar (smaller or more highly
11 charged) anions cause stronger salting out.

12
13
14
15
16
17
18
19
20
21
22
23
24
25 The salting in encountered in the systems studied here can be divided into two subgroups,
26 corresponding to two very different types of attractive interactions: that of a large, hydrophobic
27 (typically aromatic) molecule with a large alkylammonium cation, and that of a small, extremely
28 polar hydrogen-bond donor with a doubly charged anion (sulfate or oxalate). As illustrated in
29 Figure 1 and Table S1, COSMOTermX is in principle able to describe both of these types of
30 salting in, which have also been observed in the literature. The data in Figures 5 and 6 also
31 support the hypothesis that van der Waals interactions between the organic solute and the
32 alkylammonium cations drive salting in in the former case, while hydrogen bonding between the
33 organic solute and the dianion drives salting in in the latter case. However, the latter type of
34 salting in is predicted only for oxalate, likely related to the general overestimation of K_s .

35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
COSMOTermX has recently been suggested to overestimate the effect of intramolecular
hydrogen bonds on vapor pressures of conformationally flexible polyfunctional molecules.³³ A
similar overestimation of the strengths of the hydrogen bonds between water molecules and
anions and/or cations, relative to those between the organic solutes and dianions, could be a

possible explanation for the misprediction of K_S for example for glyoxal hydrates in sulfate solutions. However, this mechanism would not explain the overestimation of K_S observed also for solutes without hydrogen-bonding groups.

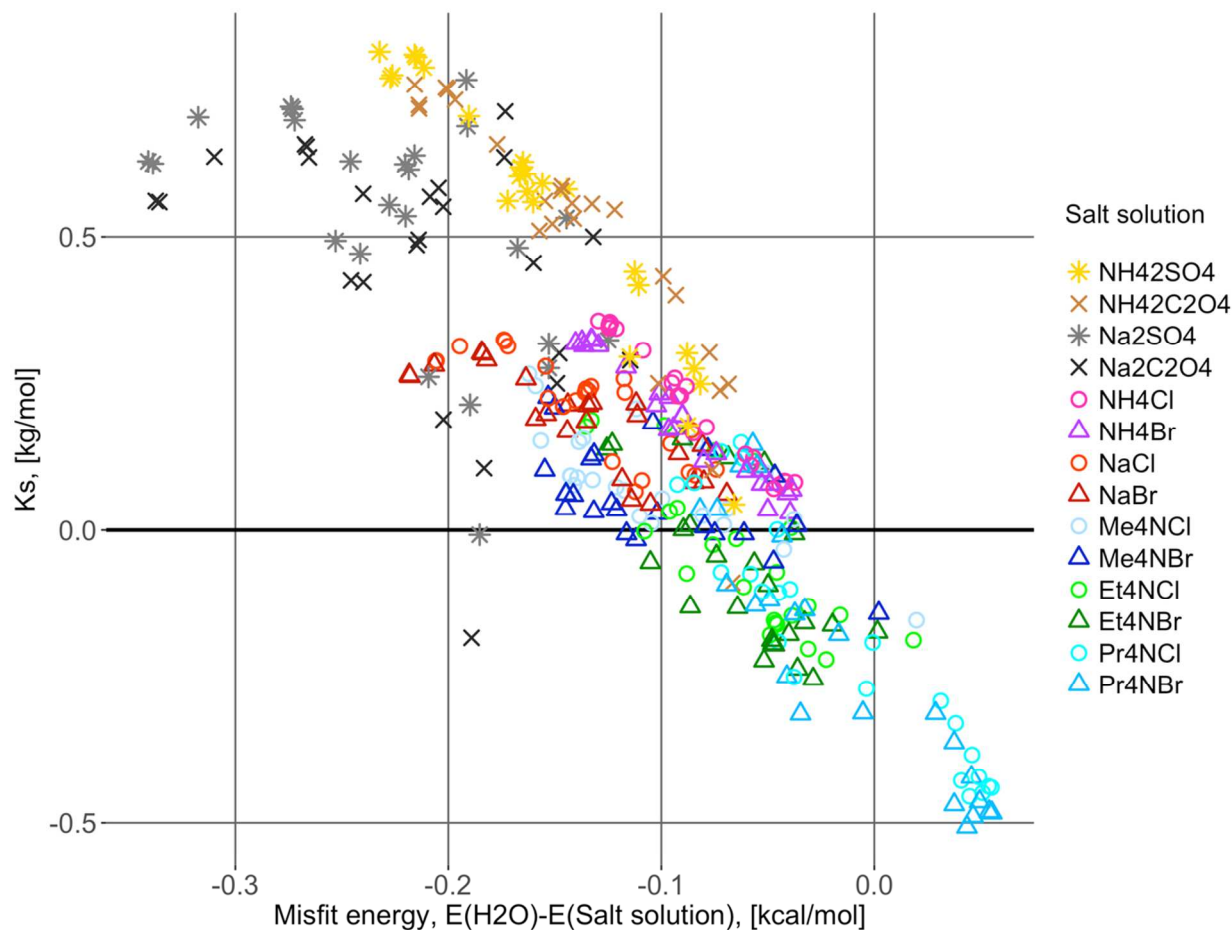


Figure 4. Setschenow constants plotted as a function of the difference in misfit energies between pure water and the salt solution, at 25 C and using a salt mole fraction of 0.009.

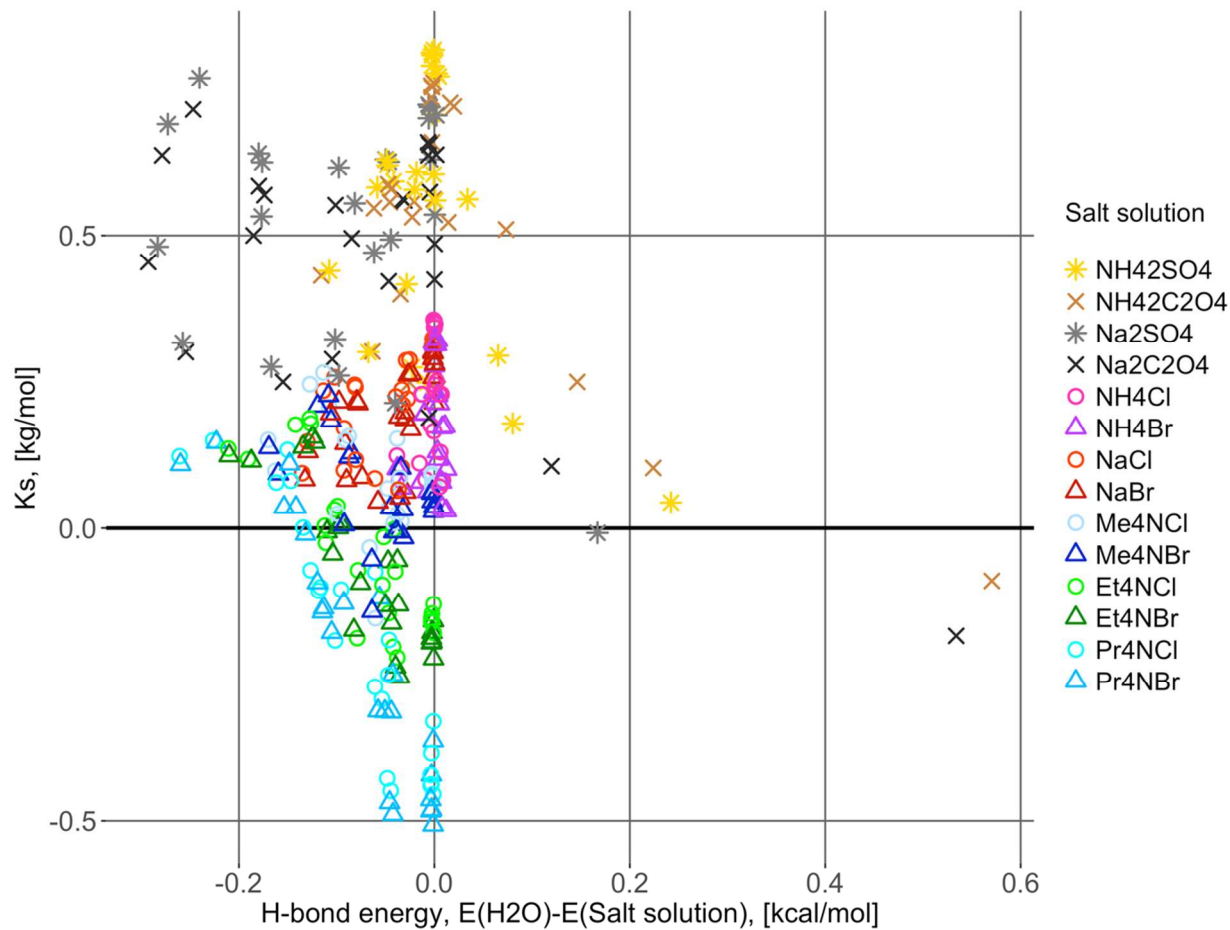


Figure 5. Setschenow constants plotted as a function of the difference in H-bond energies between pure water and the salt solution, at 25 °C and using a salt mole fraction of 0.009.

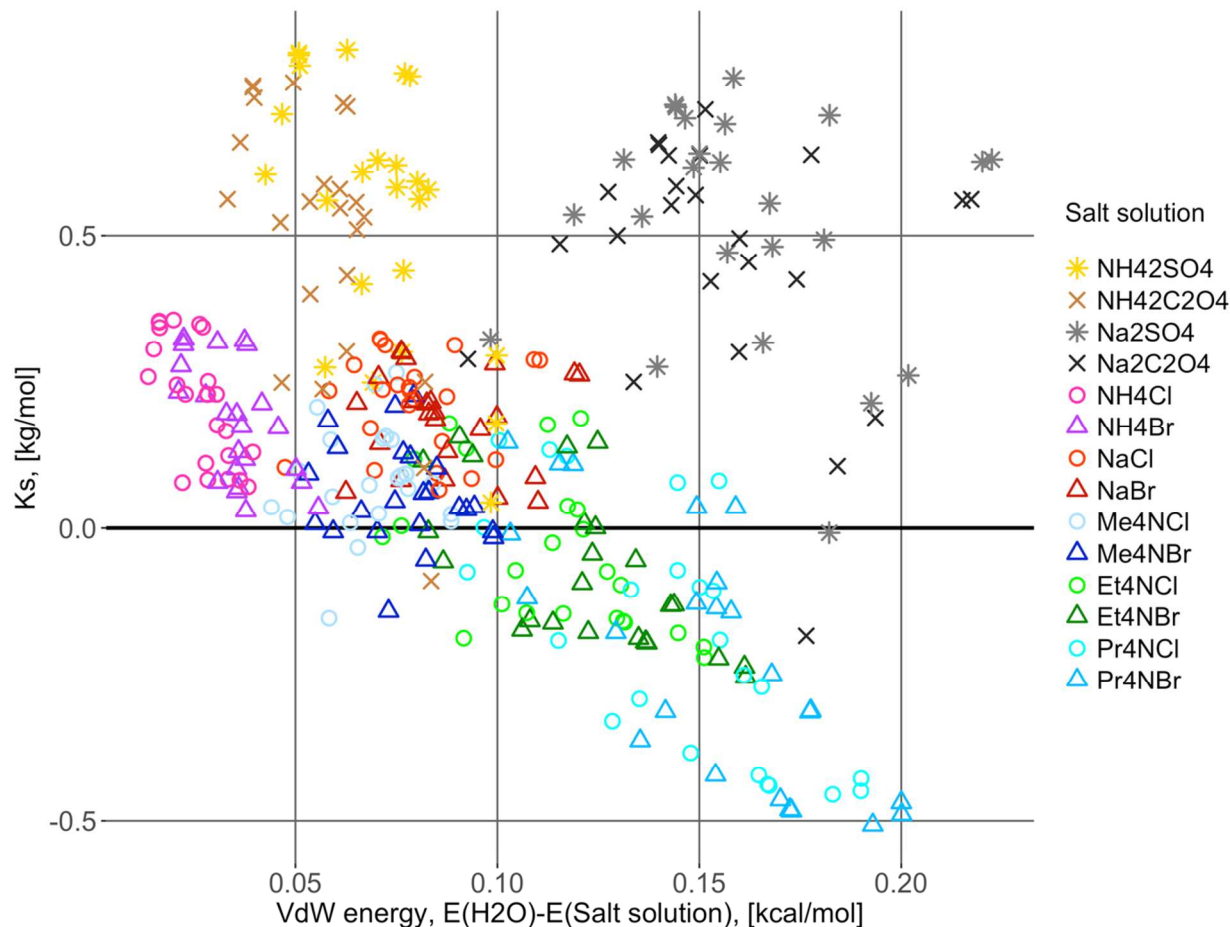


Figure 6. Setschenow constants plotted as a function of the difference in van der Waals energies between pure water and the salt solution, at 25 C and using a salt mole fraction of 0.009.

CONCLUSIONS

We have computed Setschenow constants for a large set of organic solute-salt pairs, containing both atmospherically relevant compounds and salts, as well as systems for which salting in has been experimentally observed. Qualitatively, COSMOTermX is able to predict salting in (negative Setschenow constants) for two very different types of systems: large aromatic molecules with salts containing large alkylammonium cations, and small polar H-bond

1
2
3 donors with salts containing doubly charged anions (sulfate and oxalate). However, Setschenow
4 constants are almost always overestimated by COSMOTermX (by up to 1.5 kg/mol for some
5 aromatics in alkylammonium salts), possibly due to an overestimation of the relative strength of the
6 general interactions leading to salting out (e.g. competition for solvent molecules) compared to
7 the more specific favorable interactions between neutral solutes and ions which are responsible
8 for salting in. For example, we speculate that COSMOTermX may overestimate the relative
9 strengths of the hydrogen bonds between water and dianions compared to those between polar
10 organics and dianions. For this reason, the only atmospherically relevant compound for which
11 COSMOTermX is able to predict salting in is oxalic acid – e.g. the behavior of glyoxal in
12 sulfate solutions is incorrectly predicted. We suggest that COSMOTermX can nevertheless be
13 used to evaluate relative Setschenow constants of different solutes in the same salt, or the same
14 solute in different salts. Furthermore, despite the exact drivers behind the overestimate being
15 unclear, the systematic nature of the errors in the predicted K_S mean that COSMOTermX can
16 be used as a quick qualitative test for salting in: if COSMOTermX predicts a negative
17 Setschenow constant for a given system, then it is very likely to display (significant) salting in.
18 Similarly, large positive Setschenow constants likely indicate an absence of salting in, though
19 they should not necessarily be taken as an indication of strong salting out. The ability to at least
20 qualitatively predict salting effects using a relatively simple computational tool such as
21 COSMOTermX represents a great advantage for atmospheric aerosol systems, which typically
22 comprise water, salt, and a vast amount of different organic solute. It is virtually impossible to
23 perform systematic experimental analysis for all the possible composition combinations of such
24 aerosol systems. There is a need to better understand the drivers for the observed bias in
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 predicting K_S in order to more quantitatively complement experimental data and fill the gaps in
4
5 atmospheric models.
6
7
8
9
10

11 12 ASSOCIATED CONTENT

13
14
15
16 **Supporting Information.** Tables S1-S4. Setschenow constants computed using salt mole
17 fraction of 0.009, 0.09, 0.0009 and 0.00009, respectively. Figure S1. Dependence of the
18 Setschenow constants on the salt mole fraction. Figure S2. σ -profiles for the lowest-energy
19 conformers of naphthalene, oxalic acid, Pr_4N^+ and $\text{C}_2\text{O}_4^{2-}$. (PDF) .cosmo and .energy files for all
20 structures not found in the COSMOTermX library. (ZIP)
21
22
23
24
25
26
27
28
29
30

31 32 AUTHOR INFORMATION

33 34 **Corresponding Author**

35
36 Theo Kurtén

37
38 Department of Chemistry, University of Helsinki,

39
40 P.O. Box 55,

41
42 FI-00014 University of Helsinki, Finland

43
44
45
46 theo.kurten@helsinki.fi
47
48
49
50

51 52 **Author Contributions**

53
54 The manuscript was written through contributions of all authors. All authors have given approval
55 to the final version of the manuscript.
56
57
58
59
60

ACKNOWLEDGMENT

We thank prof. Ilona Riipinen for helpful discussions, and Noora Hyttinen for help with test calculations. We thank the Academy of Finland for funding and the CSC IT Center for Science for computer time. This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 717022), and U.S. National Science Foundation (AGS1649147). E.W. is recipient of a NRC fellowship. J. E. thanks the Carlsberg Foundation for financial support.

REFERENCES

¹ Stocker, T. F.; Quin, D.; Plattner, G.-K.; Tignor, M. M. B.; Allen, S. K.; Boschung, J.; Nauels, A.; Xia, X.; Bex, V.; Midgley, P. M. (eds). *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: New York, U.S.A., **2013**.

² Tröstl, J.; Chuang, W. K.; Gordon, H.; Heinritzi, M.; Yan, C.; Molteni, U.; Ahlm, L.; Frege, C.; Bianchi, F.; Wagner, R.; *et al.* The role of low-volatility organic compounds in initial particle growth in the atmosphere. *Nature* **2016**, 533, 527-531.

³ Jimenez, J. L.; Canagaratna, M.R.; Donahue, N. M.; Prevot, A. S. H.; Zhang, Q.; Kroll, J. H.; DeCarlo, P. F.; Allan, J. D.; Coe, H.; Ng, N. L.; *et al.* Evolution of Organic Aerosols in the Atmosphere. *Science* **2009**, 326, 1525-1529.

⁴ Pankow, J. F.; Chang, E. I. Variation in the Sensitivity of Predicted Levels of Atmospheric

1
2
3
4
5 Organic Particulate Matter (OPM). *Environ. Sci. Technol.* **2008**, 42, 7321-7329.
6
7
8
9

10
11 ⁵ Prisle, N. L.; Engelhart, G. J.; Bilde, M.; Donahue, N. M. Humidity influence on gas-particle
12 phase partitioning of α -pinene + O₃ secondary organic aerosol. *Geophys. Res. Lett.* **2010**, 37,
13 L01802.
14
15
16
17

18
19 ⁶ Bilde, M.; Svenningsson, B. CCN activation of slightly soluble organics: the importance of
20 small amounts of inorganic salt and particle phase. *Tellus* **2004**, 56B, 128-134.
21
22
23
24

25
26 ⁷ Endo, S.; Pfennigsdorff, A.; Goss, K.-U. Salting-Out Effect in Aqueous NaCl Solutions:
27 Trends with Size and Polarity of Solute Molecules. *Environ. Sci. Technol.* **2012**, 46, 1496–1503.
28
29
30

31
32 ⁸ Waxman, E. M.; Elm, J.; Kurtén, T.; Mikkelsen, K. V.; Ziemann, P. J.; Volkamer R. Glyoxal
33 and Methylglyoxal Setschenow Salting Constants in Sulfate, Nitrate, and Chloride Solutions:
34 Measurements and Gibbs Energies. *Environ. Sci. Technol.* **2015**, 49, 11500-11908.
35
36
37

38
39 ⁹ Kampf, C. J.; Waxman, E. M.; Slowik, J. G.; Dommen, J.; Pfaffenberger, L.; Praplan, A.
40 P.; Prévôt, A. S. H.; Baltensperger, U.; Hoffmann, T.; Volkamer, R. Effective Henry's Law
41 Partitioning and the Salting Constant of Glyoxal in Aerosols Containing Sulfate *Environ. Sci.*
42 *Technol.* **2013**, 47, 4236– 4244.
43
44
45
46
47

48
49 ¹⁰ Wang, C.; Duan Lei, Y.; Endo, S.; Wania, F. Measuring and Modeling the Salting-out Effect
50 in Ammonium Sulfate Solutions. *Environ. Sci. Technol.* **2014**, 48, 13238–13245.
51
52
53

54
55 ¹¹ Almeida, M. B.; Alvarez, A. M.; De Miguela, E. M.; Del Hoyo, S.E. Setschenow
56 Coefficients for Naphthols by Distribution Method. *Can. J. Chem.* **1983**, 61, 244.
57
58
59
60

1
2
3
4
5 ¹² Desnoyers, J. E.; Ichhaporia, D. F. M. Salting-In and Salting-Out of Polar Nonelectrolytes.
6
7
8 *Can. J. Chem.* **1969**, 47, 4639-.

9
10
11 ¹³ Wen-Hui, X.; Jing-Zhe. S.; Xi-Ming, X. Studies on the Activity Coefficient of Benzene and
12
13 its Derivatives in Aqueous Salt Solutions. *Thermochimica Acta* **1990**, 169 271-286.

14
15
16
17 ¹⁴ Wang, C.; Lei, Y. D.; Wania, F. The Effect of Sodium Sulfate, Ammonium Chloride,
18
19 Ammonium Nitrate and Salt Mixtures on Aqueous Phase Partitioning of Organic Compounds.
20
21 *Environ. Sci. Technol.* **2016**, 50, 12742-12749.

22
23
24
25 ¹⁵ Wang, C.; Goss, K.-U.; Duan Lei, Y.; Abbatt, J. P. D.; Wania, F. Calculating Equilibrium
26
27 Phase Distribution During the Formation of Secondary Organic Aerosol Using COSMOthermX.
28
29 *Environ. Sci. Technol.* **2015**, 49, 8585–8594.

30
31
32
33 ¹⁶ Schröder, B.; Freire, M. G.; Varanda F. R.; Marrucho, I. M.; Santos, L. M.; Coutinho, J. A.
34
35 Aqueous solubility, effects of salts on aqueous solubility, and partitioning behavior of
36
37 hexafluorobenzene: Experimental results and COSMO-RS predictions. *Chemosphere* **2011**, 84,
38
39 415–422.

40
41
42
43 ¹⁷ Wania, F.; Lei, Y. D.; Wang, C.; Abbatt, J. P. D.; Goss, K.-U. Novel methods for predicting
44
45 gas–particle partitioning during the formation of secondary organic aerosol. *Atmos. Chem. Phys.*
46
47 **2014**, 14, 13189-13204.

48
49
50
51 ¹⁸ Klamt, A.; Schüürmann, G. J. COSMO: a new approach to dielectric screening in solvents
52
53 with explicit expressions for the screening energy and its gradient. *J. Chem. Soc., Perkin Trans.*
54
55 **1993**, 3, 799-805.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

¹⁹ Klamt, A. Conductor-like Screening Model for Real Solvents: A New Approach to the Quantitative Calculation of Solvation Phenomena. *J. Phys. Chem.* **1995**, *99*, 2224–2235.

²⁰ Eckert, F.; Klamt, A. Fast solvent screening via quantum chemistry: COSMO-RS approach. *AIChE Journal* **2002** *48*, 369–385.

²¹ Eckert, F.; Klamt, A. COSMOthermX, Version C3.0, Release 15.01; COSMOlogic GmbH & Co. KG, Leverkusen, Germany, **2014**.

²² Bilde, M.; Barsanti, K.; Booth, M.; Cappa, C. D.; Donahue, N. M.; Emanuelsson, E. U.; McFiggans, G.; Krieger, U. K.; Marcolli, C.; Topping, D.; *et al.* Saturation Vapor Pressures and Transition Enthalpies of Low-Volatility Organic Molecules of Atmospheric Relevance: from Dicarboxylic Acids to Complex Mixtures. *Chem. Rev.* **2015**, *115*, 4115–4156.

²³ St Clair, J. M.; Rivera-Rios, J. C.; Crouse, J. D.; Knap, H. C.; Bates, K. H.; Teng, A. T.; Jørgensen, S.; Kjaergaard, H.G.; Keutsch, F.N.; Wennberg P. O. Kinetics and Products of the Reaction of the First-Generation Isoprene Hydroxy Hydroperoxide (ISOPOOH) with OH. *J. Phys. Chem. A* **2016**, *120*, 1441–1451.

²⁴ Klamt, A.; Eckert, F.; Arlt, W. COSMO-RS: an alternative to simulation for calculating thermodynamic properties of liquid mixtures. *Annu. Rev. Chem. Biomol. Eng.* **2010**, *1*, 101-22.

²⁵ Eckert, F. COSMOTerm reference manual; Cosmologic GmbH: **2015**. Available online at: http://www.cosmologic.de/files/downloads/manuals/COSMOTerm_Manual.pdf.

²⁶ Spartan'14; Wavefunction Inc: Irvine CA, **2014**.

1
2
3
4
5 ²⁷ TURBOMOLE V7.0 2015, a development of University of Karlsruhe and
6
7
8 Forschungszentrum Karlsruhe GmbH, 1989-2007, TURBOMOLE GmbH, since 2007; available
9
10 from <http://www.turbomole.com>.

11
12
13 ²⁸ Schäfer, A.; Klamt, A.; Sattel, D.; Lohrenz, J. C. W.; Eckert, F. COSMO implementation in
14
15 TURBOMOLE: *Extension of an efficient quantum chemical code towards liquid systems*. *Phys.*
16
17 *Chem. Chem. Phys.* **2000**, 2, 2187-.

18
19
20
21 ²⁹ Yli-Juuti, T.; Zardini, A. A.; Eriksson, A.C.; Hansen, A. M. K.; Pagels, J. H.; Swietlicki, E.;
22
23 Svenningsson, B.; Glasius, M.; Worsnop, D. R.; Riipinen, I.; *et al.* Volatility of Organic
24
25 Aerosol: Evaporation of Ammonium Sulfate/Succinic Acid Aqueous Solution Droplets. *Environ.*
26
27 *Sci. Technol.* **2013**, 47, 12123-12130.

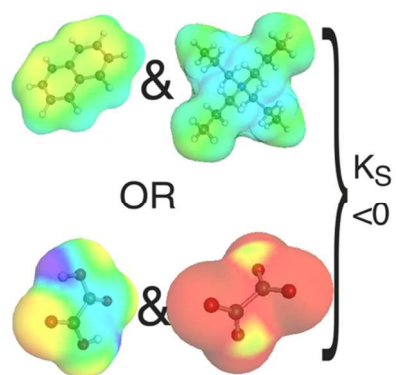
28
29
30
31 ³⁰ Zhang, Y.; Furyk, S.; Bergbreiter, D. E.; Cremer, P. S. Specific Ion Effects on the Water
32
33 Solubility of Macromolecules: PNIPAM and the Hofmeister Series. *J. Am. Chem. Soc.* 2005,
34
35 127, 14505-14510.

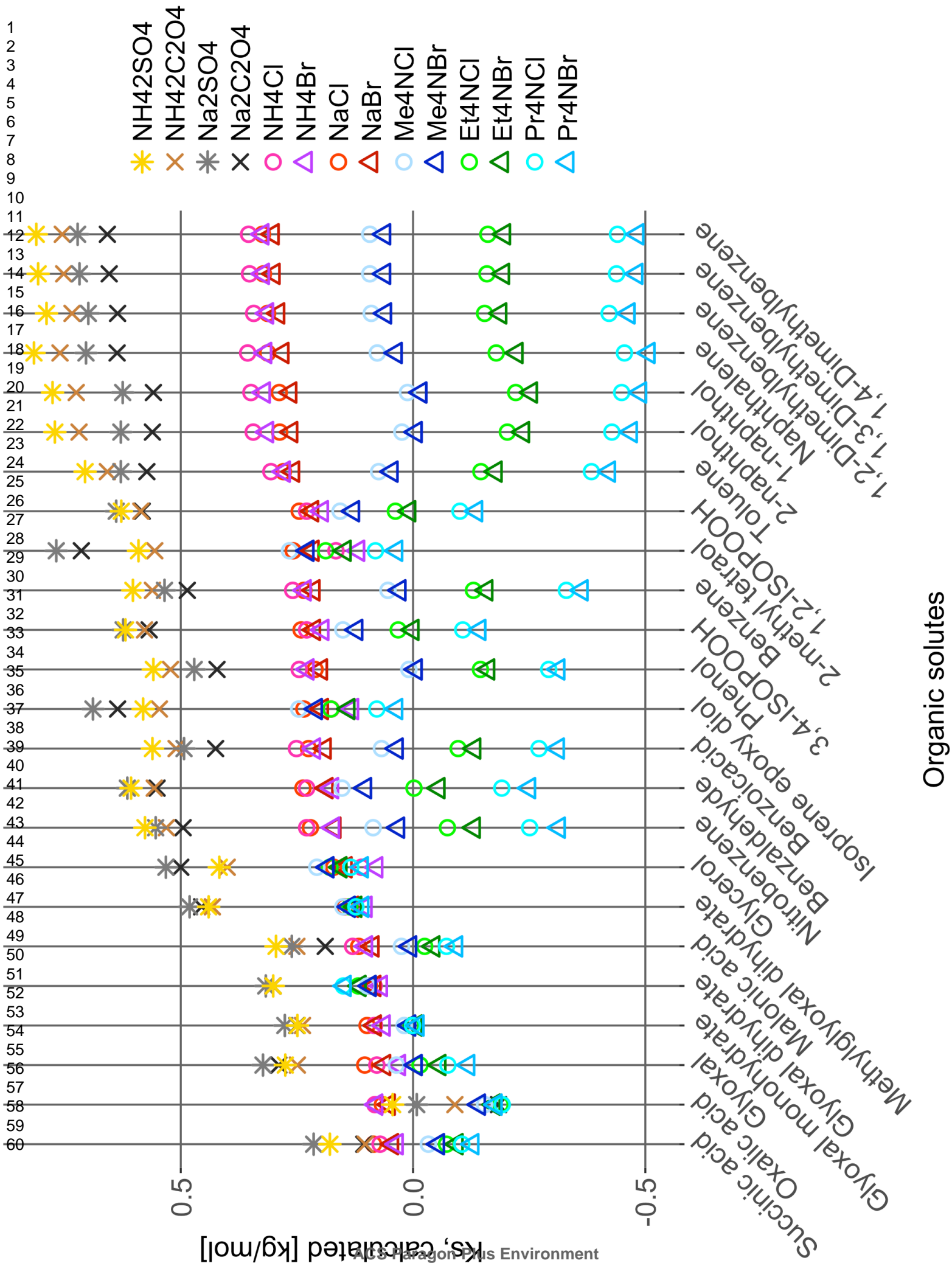
36
37
38
39 ³¹ Marcus, Y. Effect of Ions on the Structure of Water: Structure Making and Breaking. *Chem.*
40
41 *Rev.* **2009**, 109, 1346–1370

42
43
44
45 ³² Kurtén, T.; Elm, J.; Prisle, N. L.; Mikkelsen, K. V.; Kampf, C. J.; Waxman, E. M.;
46
47 Volkamer, R. Computational Study of the Effect of Glyoxal–Sulfate Clustering on the Henry’s
48
49 Law Coefficient of Glyoxal. *J. Phys. Chem. A* **2015**, 119, 4509–4514.

1
2
3
4
5 ³³ Kurtén, T.; Tiusanen, K.; Roldin, P.; Rissanen, M.; Luy, J.-N.; Boy, M.; Ehn, M.; Donahue,
6
7 N. M. α -Pinene Autoxidation Products May Not Have Extremely Low Saturation Vapor
8
9 Pressures Despite High O:C Ratios. *J. Phys. Chem. A* **2016**, 120, 2569-2582.
10
11
12
13
14
15

16 **TOC IMAGE**



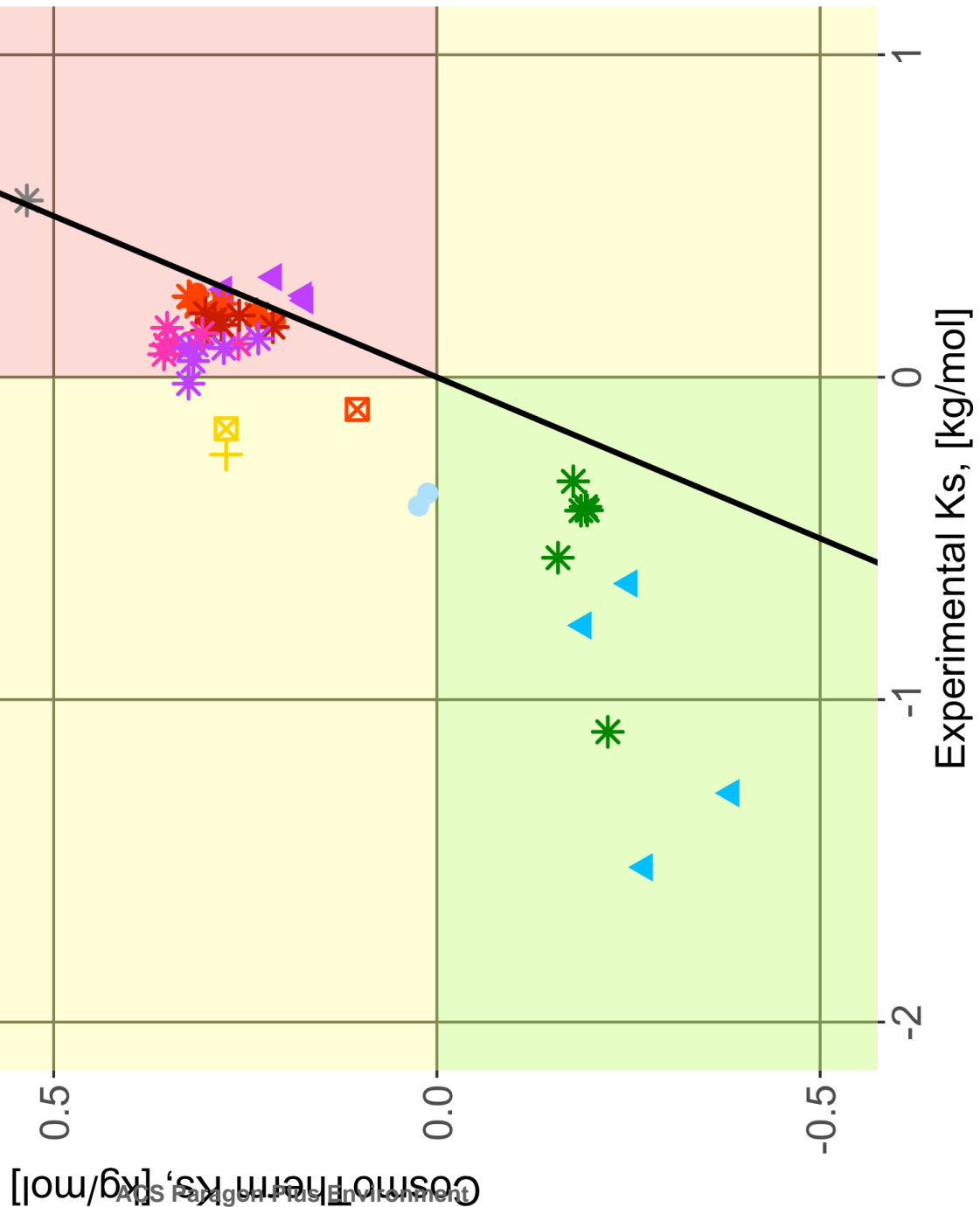


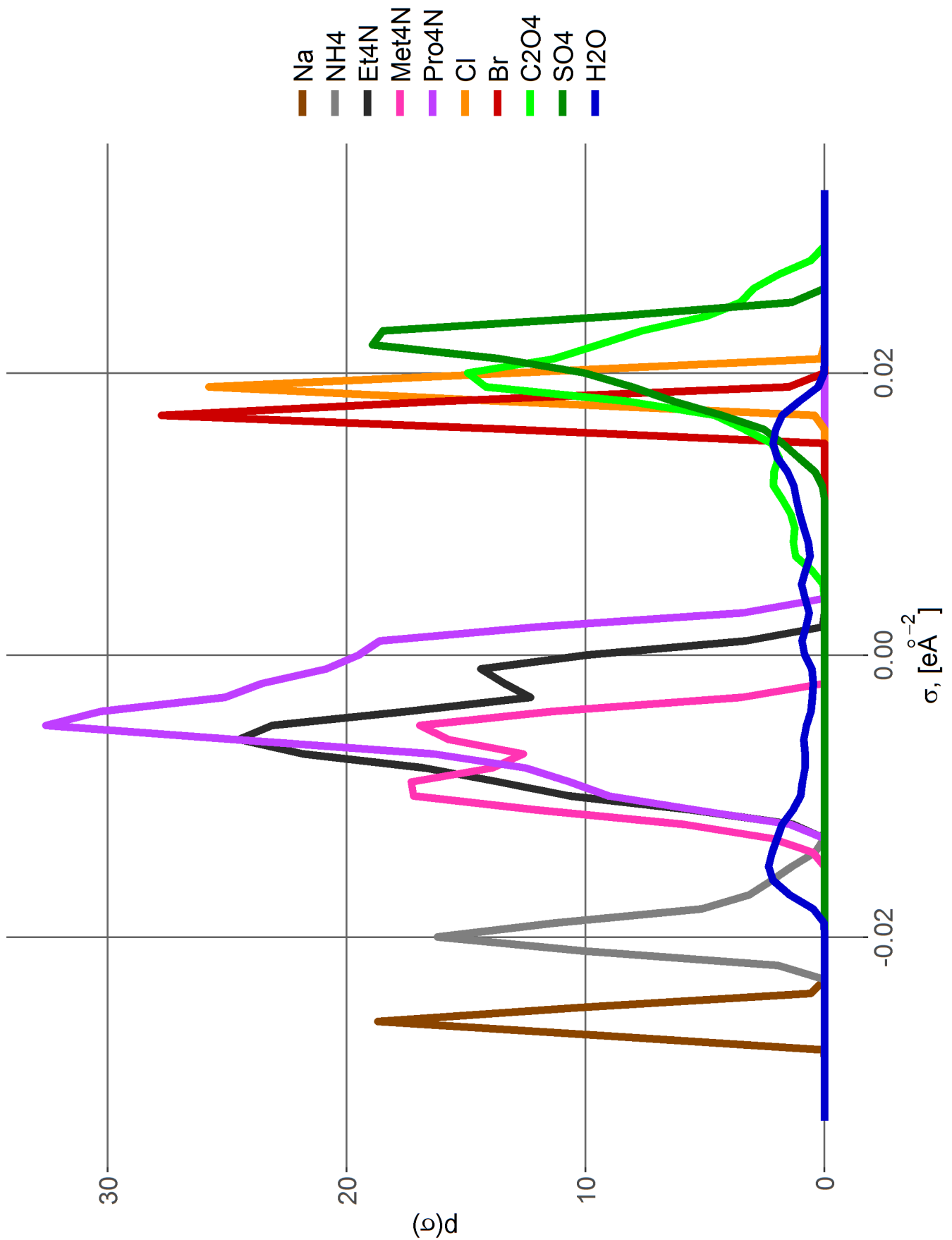
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- Salts**
- NH₄2SO₄ (Yellow circle)
 - Na₂SO₄ (Grey circle)
 - NH₄Cl (Pink circle)
 - NH₄Br (Purple circle)
 - NaCl (Orange circle)
 - NaBr (Red circle)
 - Me₄NCl (Light blue circle)
 - Et₄NBr (Green circle)
 - Pr₄NBr (Blue circle)

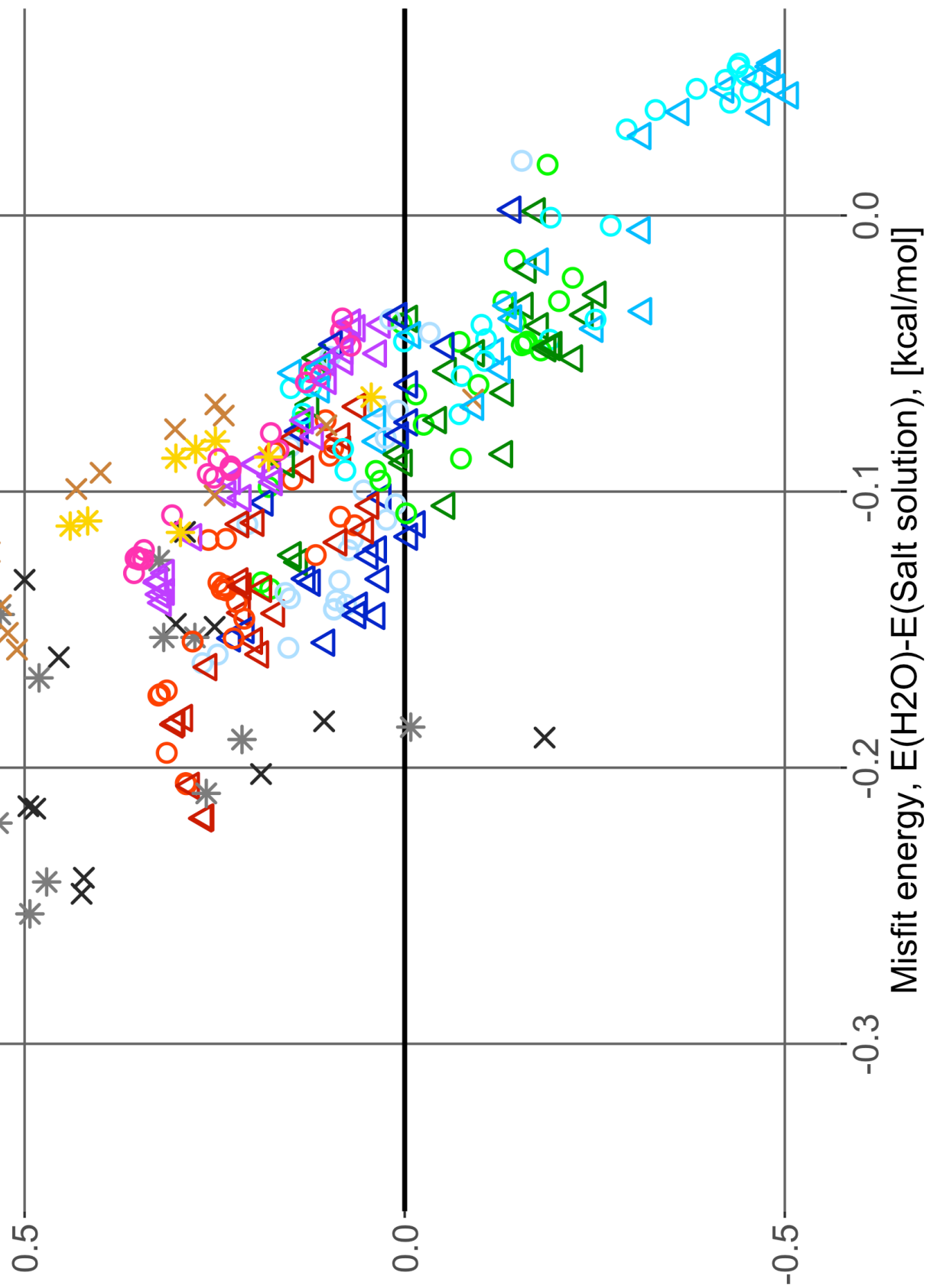
References

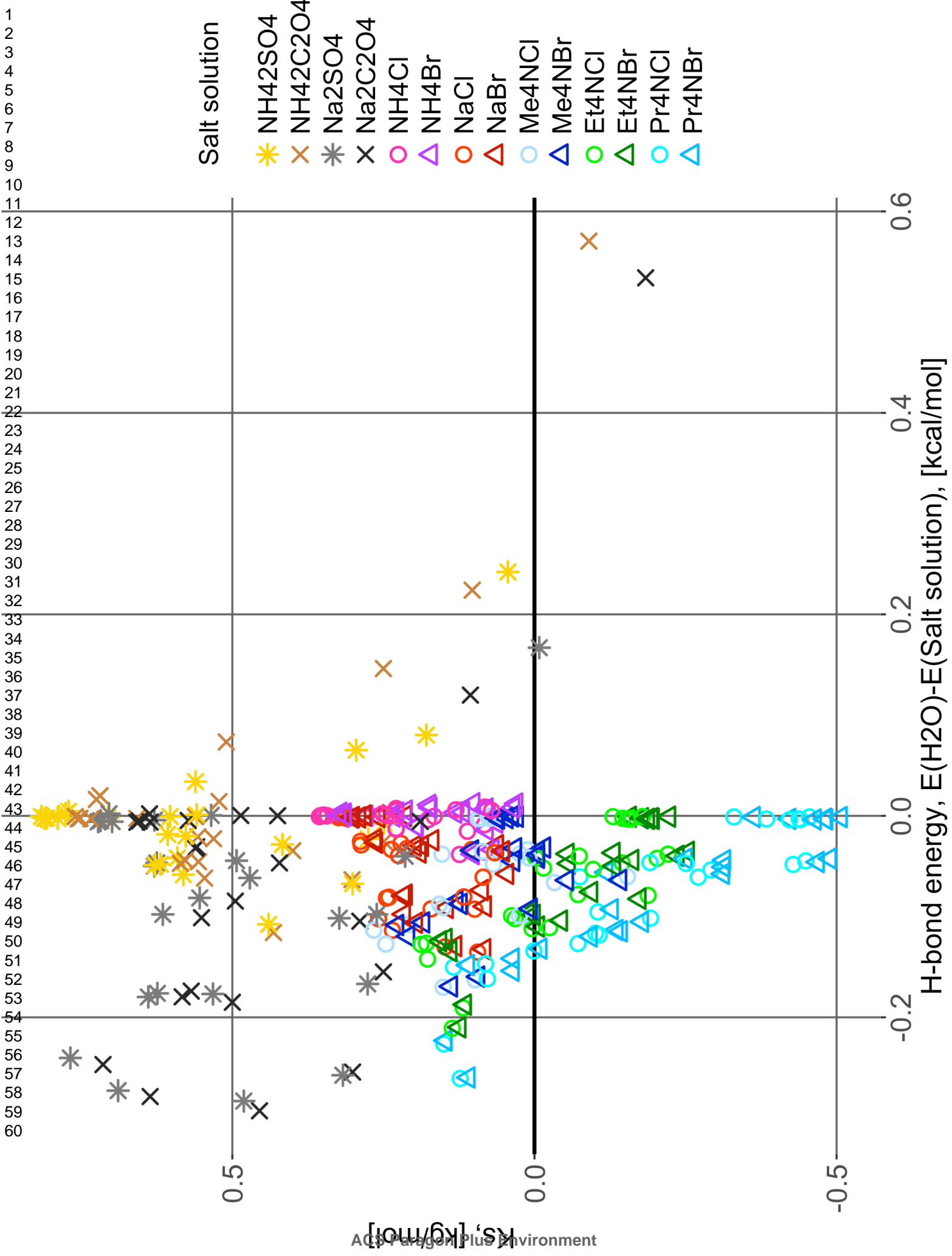
- Almeida et al., 1983 (Black circle)
- Desnoyers et al., 1969 (Black triangle)
- Endo et al., 2012 (Black square)
- Kampf et al., 2013 (Black plus)
- Waxman et al., 2015 (Black square with X)
- Weng-Hui et al. and their ref., 1990 (Black asterisk)



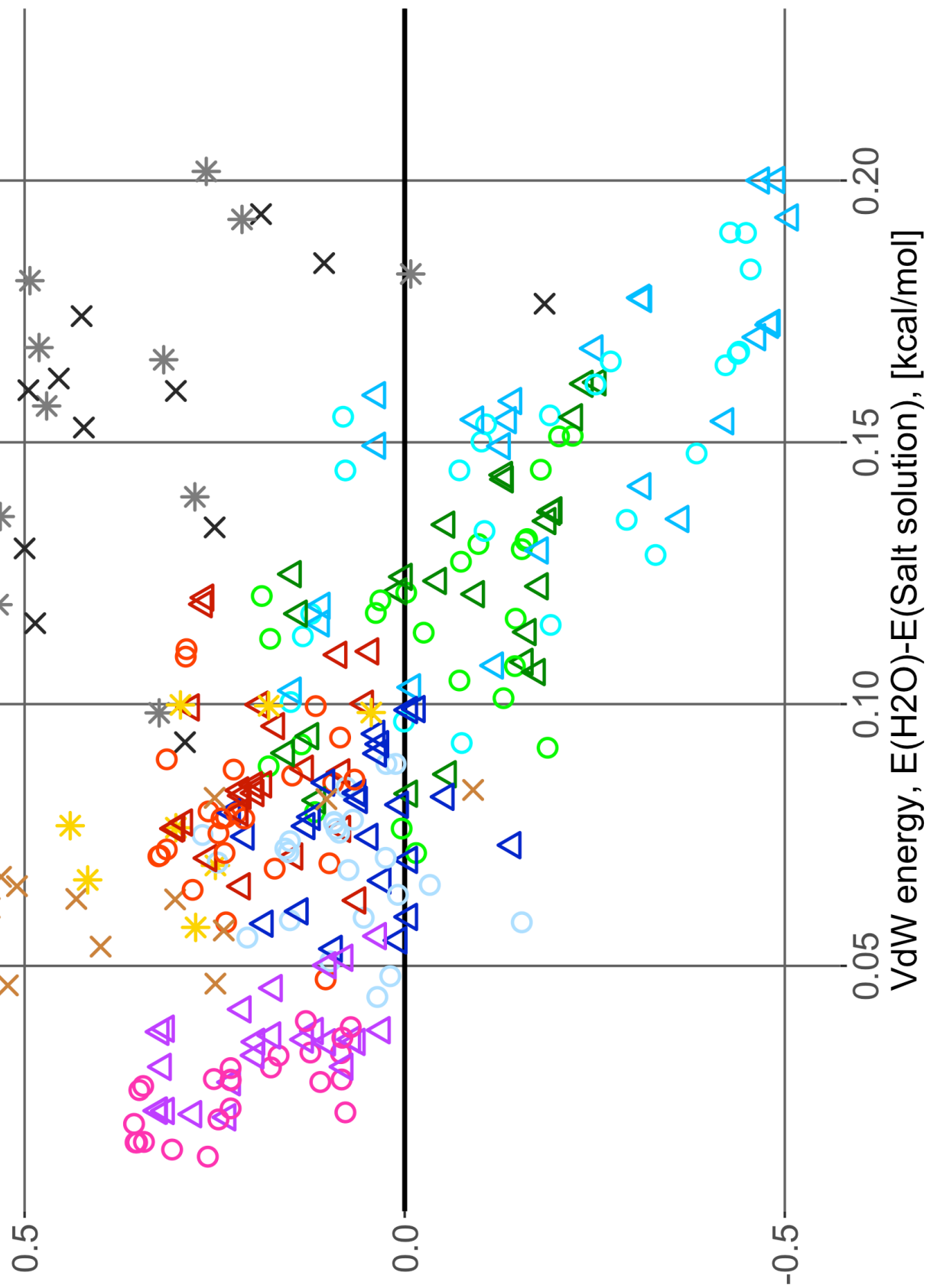
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

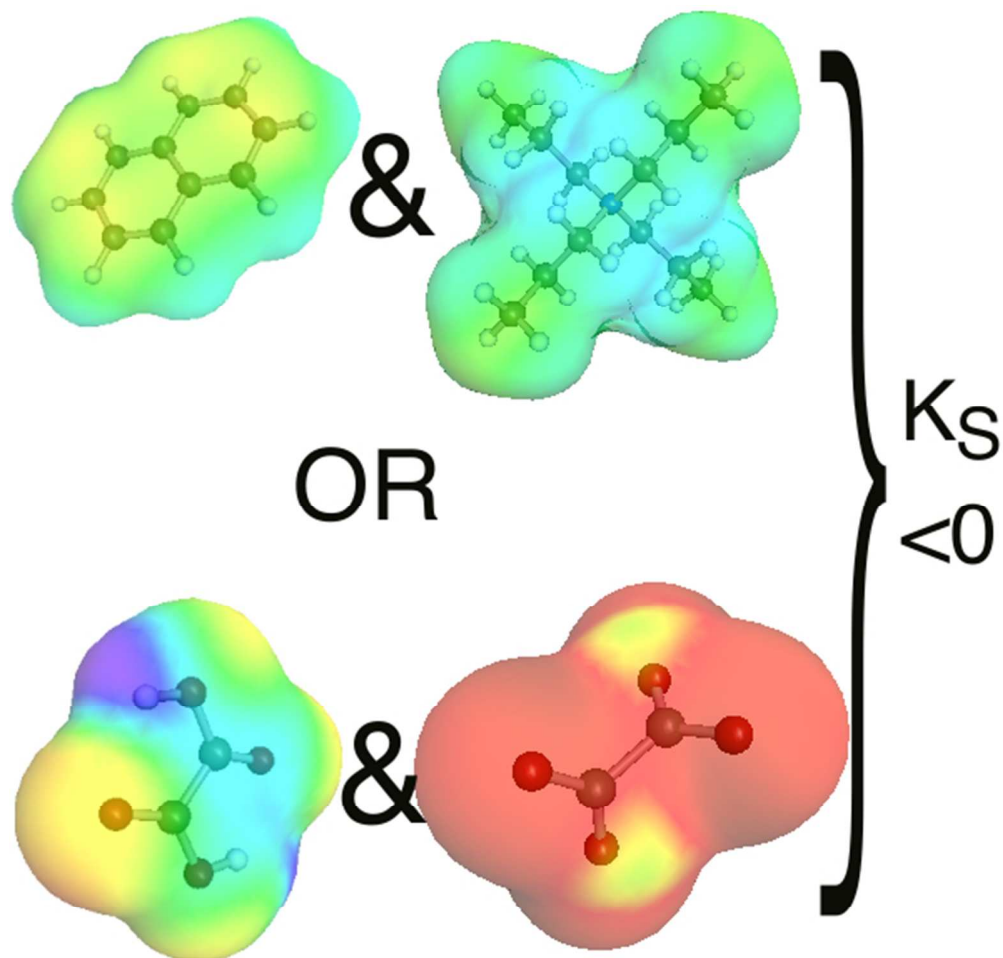
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60





1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60





TOC image

50x50mm (300 x 300 DPI)