

Deep eutectic solvents: a structural point of view on the role of the anion

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Abstract

The structural properties of four deep eutectic solvents (DESs), namely a 1:2 mixture of choline chloride and urea, and three analogous DESs containing different anions in place of chloride, namely fluoride, nitrate or acetate, were investigated by using Molecular Dynamics. The order of the DES melting points was found not to correlate with the strength of urea-anion hydrogen bonds. However, the DES low melting points are related to the anion ability to build favourable networks of interactions with both choline and urea, in such a way as to maximize the hydrogen bonds among all the different moieties of the system.

Keywords:

deep eutectic solvents, reline, choline acetate urea, choline fluoride urea, choline nitrate urea

1. Introduction

One of the key principles of green chemistry is to use safer solvents. In this respect, ionic liquids (ILs) have been introduced as green alternatives to hazardous organic solvents and their application has increased extensively in the last years in different areas of research and industry.[1] ILs have thus received tremendous attention in the literature [2, 3, 4, 5, 6, 7] but, unfortunately, their large-scale applications have been limited by their cost. A new generation of solvents, named deep eutectic solvents (DESs), has emerged at the beginning of this century as more inexpensive alternatives to typical ILs while still showing similar peculiar properties.[8] DESs are eutectic mixtures most often consisting of a quaternary ammonium salt and a hydrogen-bond donor, and they are very interesting systems in that the components of the mixture have high melting points in their pure state and become liquid at room temperature after they are mixed.[9, 10, 11] Due to their exceptional properties, DESs can be used in many applications such as in extraction processes, catalysis, electrochemistry and synthesis.[12] Moreover, DESs can dissolve a wide range of solutes including metal oxides that are insoluble in most molecular solvents and this is essential in several processes such as metal extraction, waste recycling, and catalyst preparation.[13, 14]

With the rise in popularity and potential applications of DESs, a fundamental molecular-level understanding of their structure and dynamic nature takes on great importance. Several experimental and theoretical investigations have attempted to shed light into the origin of the unusual properties of this new class of solvents.[15, 16, 17, 18, 19, 20, 21, 22, 23] MD simulations by Sun et al. on DESs involving choline chloride and urea in different ratios revealed a disruption of the long-range ordering of choline chloride by urea and a significant

moderation in urea-urea and choline-chloride interaction energies, which resulted in a significant melting point depression for the DES mixture.[17] The effect of water on DES characteristics has been also investigated by combining MD and densities, viscosities and conductivities measurements of choline chloride/urea aqueous solutions, showing that in the presence of water the anion is preferentially hydrated as compared to urea or the cation.[18] Similarly, Perkins et al. made observations using MD simulations and infrared spectroscopy that suggested the presence of strong hydrogen bonding interactions between chloride and urea, leading to the low-melting nature of this DES.[19]

One of the major open questions about DESs is the origin of the very large melting point depression that takes place when the DES constituents are mixed together to form the DES. The key physical driving force for the formation of DESs has been related by some authors to the charge delocalization process resulting from the intermolecular hydrogen bonding.[20, 21, 22] This view has been disputed by Zahn and co-workers, whose *ab initio* MD simulations of DES systems show negligible charge transfer from the chloride ion to the hydrogen bond donor molecule.[23] On the other hand, Abbot et al. stated that the melting point depression upon mixing choline chloride with hydrogen bond donors rises from the interaction between the hydrogen bond donor molecules and the chloride ion, with additional effects such as cation molecular symmetry.[8] However, in our recent MD study on two DESs with different cations, namely a 1:2 mixture of choline chloride and urea (reline) and a 1:2 mixture of butyltrimethylammonium chloride and urea (UBTMAC), we have shown that even if reline shows a larger melting point depression as compared to UBTMAC, the hydrogen bond interactions between chloride ions and urea molecules are more favorite in UBTMAC.[24] This result suggests that the formation of anion-urea hydrogen bonds cannot be the only factor at the origin of the large melting point depression observed

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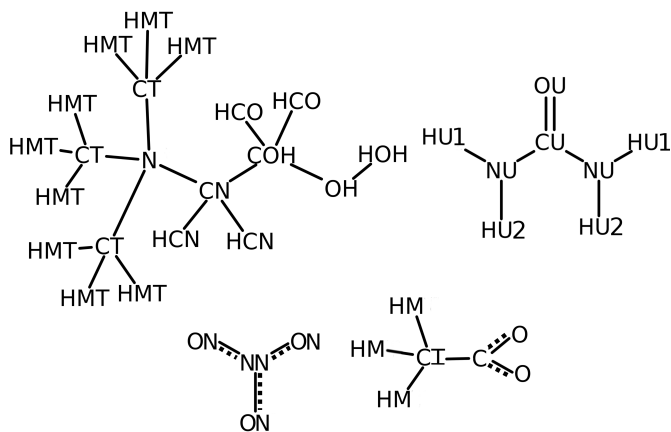


Figure 1: Atom labeling used in this work for the choline cation (top left), urea molecule (top right), nitrate anion (bottom left) and acetate anion (bottom right).

in DESs and a more complex picture has to be considered in which a variety of different hydrogen bonds exist.[24]

It is clear that, despite a recent intense research activity, the origin of the peculiar behaviour of DESs is still a topic of intense debate. In this work we use the MD technique, which has been profitably employed to characterize the structure of many liquid systems,[25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36] to explore the interactions in DESs in order to gain a more thorough understanding of their peculiar properties. In particular, we investigate and compare the structural properties of the most studied DES, namely reline, with three analogous DESs containing different anions in place of chloride, namely fluoride, nitrate and acetate. All of these DESs are liquid at room temperature,[37, 38] and investigating the modifications of the DES properties that take place when the salt anion is changed can be very important. Indeed, the peculiar characteristics of these solvents are strongly related to the formation of hydrogen bonds between the anion and the hydrogen bond donor (urea), and it is thus very useful to investigate systems containing anions with different ability to form hydrogen bonds.

2. Molecular Dynamics details

MD simulations of four different DES systems have been carried out, namely 1:2 mixtures of choline chloride and urea (ChCl-urea), choline fluoride and urea (ChF-urea), choline nitrate and urea (ChNO₃-urea) and choline acetate and urea (ChACE-urea). All of the MD simulations were performed using the GROMACS software package.[39] The force fields used in the simulations were taken from Canongia Lopes and Padua and from OPLS. In particular, the force field parameters of cholinium, chloride, fluoride, nitrate, acetate and urea can be found in Refs. 40, 41, 42, 43, 44 and 45, respectively. Note that the Lopes-Padua force field is the most widely used force field in MD simulations of ILs and has been built on the OPLS one. The simulated systems were composed of 350 salt and 700 urea molecules placed in a cubic box. The simulations were performed in the NVT ensemble at 300

K using the Nosé-Hoover thermostat [46] with a relaxation constant of 0.5 ps and a timestep of 1 fs. Initial configurations were obtained by generating a low density cubic box that was then compressed in the NPT ensemble. The box edge length to be used in the production phase was then determined by equilibrating the system in the NPT ensemble at 1 atm and 300 K for about 5 ns with the exception of ChCl-urea for which the system was simulated at the experimental density (1.197 g cm⁻³). The systems were then equilibrated in the NVT ensemble at 300 K for 10 ns and the final production time in the NVT ensemble was of 100 ns, in which the configurations were saved every 100 timesteps. Intermolecular interactions were evaluated explicitly inside a 12 Å cutoff, while electrostatic long-range effects were treated with the Particle Mesh Ewald method.[47] All stretching vibrations involving hydrogen atoms were constrained by means of the LINCS algorithm. The atom names of the different species used throughout the paper are shown in Figure 1.

3. Results

To develop new understanding of DES behavior, we have carried out MD simulations of four DES systems containing different anions, namely ChCl-urea, ChF-urea, ChNO₃-urea and ChACE-urea, and we have analyzed and compared their structural properties. As a first remark, we would like to point out that we have recently compared the structural results obtained from the MD simulation of ChCl-urea with the findings of a neutron diffraction and EPSR modelling study [48] and the good agreement found allowed us to assess the ability of the employed force fields to properly reproduce the DES structural properties. As concerns the other investigated DESs, to the best of our knowledge an accurate experimental determination of their liquid structural properties has not yet been carried out in the literature. However, since the force fields employed in the simulations are part of the same generalized force field developed by Canongia Lopes-Padua and integrated and based on the OPLS one, we are confident in their ability to properly reproduce also the structural properties of ChF-urea, ChNO₃-urea and ChACE-urea.

In the first step of this investigation, we have calculated several molecularly centered radial distribution functions $g(r)$'s among different species in the mixtures (Figure 2). We also computed a series of coordination numbers, N , by integration of the $g(r)$'s up to a cutoff distance chosen as the position of the first minimum of the corresponding $g(r)$. The structural parameters of all the molecularly centered $g(r)$'s are listed in Table 1. Molecular centers are defined as the CN atom of the cation, CU atom of urea, C atom of acetate and NN atom of nitrate (see Figure 1). The strongest interaction is that between the anions and the urea molecules in all the DES systems (Figure 2A). Very interestingly, two different behaviours are found depending on the monoatomic or polyatomic nature of the anion. Indeed both chloride-urea and fluoride-urea are characterized by the presence of a very intense single peak indicating strong first shell interactions between anions and urea molecules. The first shell

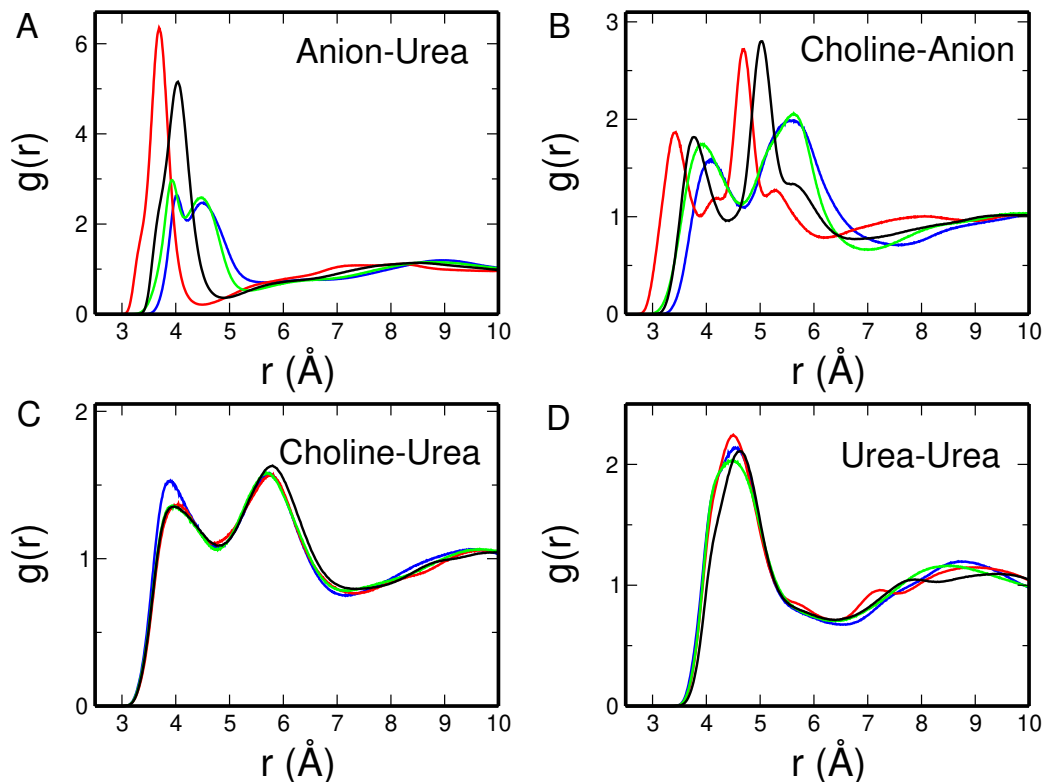


Figure 2: Molecularly centered radial distribution functions calculated from the MD simulations of ChCl-urea (black line), ChF-urea (red line), ChNO₃-urea (green line) and ChACE-urea (blue line). Molecular centers are defined as the CN atom of the cation, CU atom of urea, C atom of acetate and NN atom of nitrate (see Figure 1).

distance is shorter in the case of fluoride and the $g(r)$ shows a higher intensity as compared to chloride, following the decrease of atomic weight. On the other hand, the anion-urea coordination number is slightly higher in the chloride based DES: on average each anion is coordinated by 3.6 and 3.2 urea molecules in ChCl-urea and ChF-urea, respectively. At variance with this result, the nitrate-urea and acetate-urea $g(r)$'s are characterized by two peaks that are much less intense than the halide ones. These two peaks can be ascribed to the presence of two main different coordination modes of the polyatomic anions with respect to the urea molecules: a sort of "bridge interaction" in which two oxygen atoms coordinate two HU2 hydrogen atoms of the urea molecule, which gives rise to the $g(r)$ low distance peak, and a monodentate coordination in which the anion and the urea molecule interact via a single hydrogen atom, producing the $g(r)$ second peak. On average, each anion forms at least one "bridge interaction" with one urea molecule as shown by the anion-urea "bridge interacting" coordination number which is 1.4 and 1.0 for nitrate and acetate, respectively. Interestingly, if we consider the total anion-urea coordination number obtained by integrating both the first and second $g(r)$ peak, we find that both nitrate and acetate anions are coordinated by an average number of 4.2 urea molecules.

Besides interacting with the urea molecules, the anions interact with the choline cations and also in this case different trends can be observed depending on the nature of the anion (Figure 2B). The choline-chloride and choline-fluoride $g(r)$'s show sev-

eral intense low-distance peaks due to interactions with different cationic groups: in particular the most intense peaks at 5.02 Å and 4.70 Å for chloride and fluoride, respectively, are due to anions interacting either with the choline hydroxyl group or with the cationic core via the methyl groups. Choline and anions interact via the hydroxyl group or via the cationic core also in the ChNO₃-urea and ChACE-urea DESs, and these contributions give rise to the $g(r)$ second peaks centered at 5.62 Å. If we compare the $g(r)$ intensity, we can see that also in this case the functions involving halides are more intense than those related to nitrate or acetate, showing the presence of stronger interactions.

While several differences have been evidenced in the anion-urea and choline-anion interactions due to the different nature of the anion involved, the choline-urea and urea-urea interactions formed in the four DES systems are very similar to each other, thus showing that the nature of the anion does not have a significant impact on this kind of interactions. Looking at the choline-urea $g(r)$'s we see that they are less intense than those involving the anions. As a general result, the urea molecules do not form hydrogen bonds with the hydroxyl group but rather interact with the methyl substituents on the ammonium nitrogen atoms: these contributions give rise to the broad peak at about 5.80 Å, while urea molecules directly interacting with the HCN atoms bonded to CN generate the first shell peak at shorter distances. In all the investigated DESs, the urea molecules form hydrogen bonds with other urea molecules and these interac-

g(r)	System	atom A	atom B	R (Å)	N	cutoff (Å)	
Anion-Urea	ChCl-urea	Cl	CU	4.04	3.6	4.91	
	ChF-urea	F	CU	3.69	3.2	4.50	
	ChNO ₃ -urea I ^a	NN	CU	3.93	1.4	4.18	
		NN	CU	4.48	2.8	5.36	
	ChACE-urea I ^a	C	CU	4.02	1.0	4.21	
		C	CU	4.50	3.2	5.66	
	ChCl-urea	Cl	HU1	2.06	1.8	2.94	
		Cl	HU2	2.05	2.4	2.94	
	ChF-urea	F	HU1	1.70	1.6	2.55	
		F	HU2	1.70	2.0	2.55	
	ChNO ₃ -urea	ON	HU1	1.67	0.7	2.37	
		ON	HU2	1.65	0.9	2.27	
	ChACE-urea	O	HU1	1.78	0.8	2.66	
		O	HU2	1.76	1.3	2.40	
	Choline-Anion	ChCl-urea	CN	Cl	3.77	0.7	4.40
		ChF-urea	CN	F	3.43	0.5	3.87
ChNO ₃ -urea		CN	NN	3.93	1.0	4.66	
ChACE-urea		CN	C	4.08	0.8	4.69	
ChCl-urea		HOH	Cl	1.98	0.9	3.24	
ChF-urea		HOH	F	1.63	0.9	2.75	
ChNO ₃ -urea		HOH	NN	1.61	0.8	2.22	
ChACE-urea		HOH	C	1.70	0.9	2.38	
Choline-Urea	ChCl-urea	CN	CU	3.97	1.9	4.81	
	ChF-urea	CN	CU	4.05	2.0	4.75	
	ChNO ₃ -urea	CN	CU	3.93	1.9	4.78	
	ChACE-urea	CN	CU	3.90	1.8	4.76	
	ChCl-urea	HMT	OU	2.72	1.0	3.64	
		N	OU	4.48	6.5	6.33	
	ChF-urea	HMT	OU	2.69	0.9	3.58	
		N	OU	4.46	6.8	6.30	
	ChNO ₃ -urea	HMT	OU	2.69	0.9	3.60	
		N	OU	4.46	6.4	6.42	
	ChACE-urea	HMT	OU	2.69	0.9	3.64	
		N	OU	4.48	6.1	6.40	
	Urea-Urea	ChCl-urea	CU	CU	4.62	5.4	6.40
		ChF-urea	CU	CU	4.50	6.3	6.40
ChNO ₃ -urea		CU	CU	4.50	5.5	6.37	
ChACE-urea		CU	CU	4.54	5.4	6.49	
ChCl-urea		HU1	OU	1.92	0.4	2.78	
		HU2	OU	1.94	0.2	2.70	
ChF-urea		HU1	OU	1.91	0.4	2.78	
		HU2	OU	1.94	0.3	2.71	
ChNO ₃ -urea		HU1	OU	1.91	0.4	2.76	
		HU2	OU	1.94	0.2	2.67	
ChACE-urea		HU1	OU	1.91	0.4	2.79	
		HU2	OU	1.96	0.2	2.66	

Table 1: Structural parameters of the radial distribution functions $g(r)$'s calculated from the MD simulations of ChCl-urea, ChF-urea, ChNO₃-urea and ChACE-urea systems. R is the position of the $g(r)$ first peak and N is the coordination number calculated by integration of the $g(r)$ up to the listed cutoff distances. ^a $g(r)$ first peak ^b $g(r)$ second peak

tions give rise to a sharp urea-urea $g(r)$ first peak. The urea-urea coordination is more favored in the ChF-urea DES as shown by the higher urea-urea coordination number which is 6.3 as compared to the value found in ChCl-urea, ChF-urea, ChNO₃-urea (5.4-5.5).

In order to better characterize the specific interactions taking place in the DESs, we have calculated from the MD trajectories the site-site $g(r)$'s of a significant subset of atoms (Figure 3). The structural parameters of all the $g(r)$'s are listed in Table 1. The X-HU1 and X-HU2 $g(r)$'s reported in Figure 3A (where X is either Cl, F, ON or O for ChCl-urea, ChF-urea,

ChNO₃-urea and ChACE-urea, respectively) show that strong anion-urea hydrogen bonds are formed in all the investigated DESs. The intensity of the $g(r)$'s decreases in the order ChF-urea>ChCl-urea>ChACE-urea>ChNO₃-urea, while the hydrogen bond distances follow the trend ChNO₃-urea<ChF-urea<ChACE-urea<ChCl-urea.

Since the DES melting point depression has been ascribed to the hydrogen bond interactions between the hydrogen bond donor and acceptor,[8] it is interesting to relate these results to the trend of the DES melting points that are 1°C, 4°C, 12°C and 18°C for ChF-urea, ChNO₃-urea, ChCl-urea and ChACE-urea, respectively.[37, 38] It has been suggested that this trend can correlate with the hydrogen bond strength,[8] but looking at our results we see that this is not the case. Indeed, if we take as an index of hydrogen bond strength the degree of structuring of the interactions, which is related to the $g(r)$ intensity, we see that the order of melting points and intensities is not the same, with the exception of ChF-urea system which shows the lowest melting point and highest $g(r)$ intensity. On the other hand, if we consider that usually, for nonbonding interactions, the shorter is the distance the stronger the interaction, (as long as the distance is beyond Pauli's repulsive region), we see once again that the order of melting points does not correspond to the order of the hydrogen bond distances. Note that the melting point trend cannot be related even to the number of hydrogen bonds formed by the anions.

UV/vis absorption titrations were recently used to investigate the formation of H-bonded complexes between anionic H-bond acceptors and neutral H-bond donors in organic solvents and the ranking of the anions on the basis of their ability to accept hydrogen bonds was found to be acetate>chloride>nitrate showing that, among the anions considered in the present study, acetate is the strongest H-bond acceptor.[49] Such ranking of the anions is the opposite of the order found in the DESs melting points. Altogether our results show that the melting point trend found in ChCl-urea, ChF-urea, ChNO₃-urea and ChACE-urea is not related to the strength of the hydrogen bonds formed between the anions and urea.

If we compare the hydrogen bond interactions formed by the anions with HU1 and HU2 within the same DES, we can see that the X-HU1 and X-HU2 $g(r)$'s are similar, with a similar position of the first peak and a preference for the HU2 atom that is very pronounced in the ChACE-urea system. A similar preference for the HU1 urea atom was previously shown for ChCl-urea by a combined MD and IR investigation.[19]

Besides interacting with the urea molecules, the anions form strong hydrogen bonds with the hydroxyl group of the choline cation, as evidenced by the high intensity peak found in the HOH-X $g(r)$ (Figure 3B) and the order of the $g(r)$ intensities and hydrogen bond distances resembles those found for anion-urea hydrogen bond interactions. Each hydroxyl group of the choline cation forms almost one hydrogen bond with one anion in all the investigated DESs. As concerns reline, it was previously shown that the hydrogen bond interaction present in the choline chloride crystal structure, where each chloride ion interacts with one hydroxyl group,[50] is preserved also when

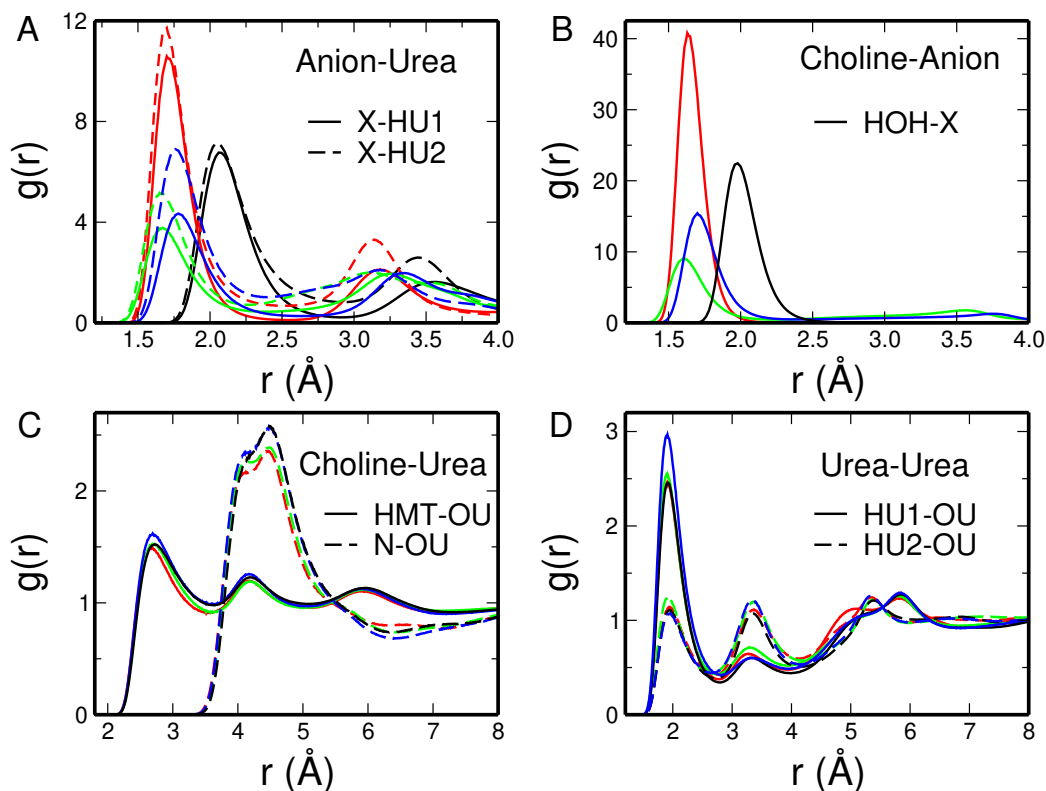


Figure 3: Site-site radial distribution functions calculated from the MD simulations of ChCl-urea (black line), ChF-urea (red line), ChNO₃-urea (green line) and ChACE-urea (blue line). Solid and dotted lines are referred to different interactions as shown in the legends. X is defined as the Cl, F, ON and O atom for the ChCl-urea, ChF-urea, ChNO₃-urea and ChACE-urea systems, respectively.

the DES reline is formed.[24] Very interestingly, according to our present results this hydrogen bond interaction is present in all the investigated DESs, independently on the nature of the anion.

At variance with urea-anions and choline-anions interactions whose strength and distance strongly depend on the DES anion, choline-urea and urea-urea specific interactions are similar to each other in all DES systems and their $g(r)$'s are much less intense and more unstructured than those involving the anions. In particular, instead of forming hydrogen bonds with the oxygen atom of the hydroxyl group, urea prefers to interact with the cationic core, as shown by the presence of a low distance peak in the HMT-OU $g(r)$ and by the high coordination number found for the N-OU interactions (Figure 3C and Table 1). On the other hand, urea forms hydrogen bonds with other urea molecules (Figure 3D) and these interactions are preferentially formed between OU and HU1: the HU1-OU $g(r)$'s are indeed much more intense than the HU2-OU ones and the value of the coordination number is about twice as high.

We have seen that it is not possible to find a simple correlation between the order of DES melting points and the strength of the urea-anion hydrogen bonds formed in the systems. However, besides the small differences in the melting point values, all of the DES investigated in this work share the important properties to be DES and to be liquid at ambient temperature. The origin of the low melting point of DESs has to be looked for in some common features of these solvents and according to

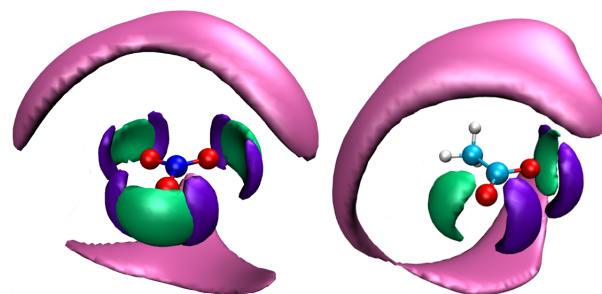


Figure 4: Spatial distribution functions (SDFs) of the urea HU1 and HU2 atoms (violet surfaces), choline H atoms (green surfaces) and choline N atom (mauve surfaces) around nitrate in ChNO₃-urea (left panel) and around acetate in ChACE-urea (right panel). The carbon, nitrogen, hydrogen and oxygen atoms are colored cyan, blue, white and red, respectively.

our results it can be related to the ability of the hydrogen bond acceptors (the anions in our case) to build a favourable network of hydrogen bond interactions with the other components of the system (choline and urea) in such a way to maximize the hydrogen bonds between all the different moieties.

To understand how nitrate and acetate are able to build such hydrogen bond network we can calculate from the MD simulations the spatial distribution functions (SDFs) of urea and choline around the anions. Note that these functions have been calculated in an internal reference system integral with the an-

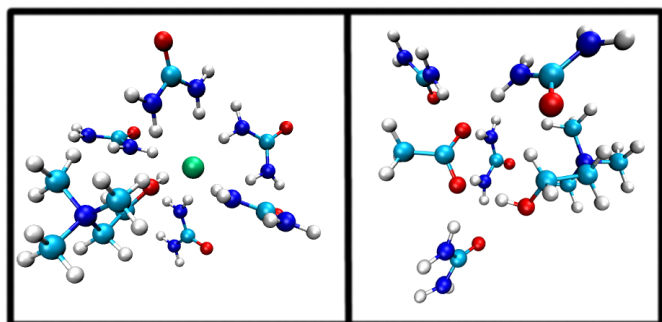


Figure 5: Simulation snapshots showing choline and urea molecules surrounding the chloride ion in ChCl-urea (left panel) and acetate in ChACE-urea (right panel). The chlorine, carbon, nitrogen, hydrogen and oxygen atoms are colored green, cyan, blue, white and red, respectively.

ion plane and, in order to properly compare the results, SDFs with the same ratio density/maximum density have been shown. For ChCl-urea and ChF-urea it is not possible to carry out such analysis because we cannot build an internal reference system on a monoatomic anion. As concerns nitrate (left panel of Figure 4), the hydrogen atom of the choline hydroxyl interacts with the anion oxygen atoms by positioning itself in front of the nitrate ON atom, along the NN-ON direction. Conversely, the hydrogen atoms of urea molecules prefer to interact with ON laterally, forming open torus-shaped distributions around the nitrate anions. Besides these hydrogen bond interactions, choline cations can approach nitrate via their cationic core, by forming electrostatic anion-cation interactions and the choline cationic core tends to occupy regions of space which are not occupied by urea, namely above and below the nitrate plane.

Also in the case of acetate (left panel of Figure 4) the anion-cation and anion-urea interactions are clearly driven by hydrogen bonds, but in this case neither the urea nor the choline hydrogen atoms are located along the C-O direction. The SDFs of the urea HU1 and HU2 atoms show torus-shaped distributions around the C-O directions with a high probability in the region between the two O atoms of acetate, while the hydrogen atoms of choline hydroxyl have a higher probability to be positioned on the opposite side, towards the methyl group. However, it is important to stress that in lowering the SDF isovalues both distributions close themselves on the other side by filling the entire toroid. The driving force for the formation of these peculiar structural arrangement is once again the maximization of favourable interactions among the different species in the mixtures.

To provide visual insights, two representative snapshots of the environment seen by the anion in ChCl-urea and ChACE-urea are shown in Figure 5, as examples. Typical neighborhoods composed of urea molecules and one choline cation interacting with the anions via hydrogen bonds can be observed. In all DES systems, urea molecules and choline cations arrange themselves in the vicinity of the anions in such a way to maximize the hydrogen bond interactions. In the acetate case, it can be seen one urea molecule forming with acetate the above mentioned "bridge interaction". Moreover, urea and choline arrangements on the lateral side of the C-O direction leading

to the toroid distribution previously shown can be clearly observed.

4. Conclusions

Here, we present a structural characterization of four DES systems having different anions, namely ChCl-urea, ChF-urea, ChNO₃-urea and ChACE-urea, carried out by means of the MD technique. Strong hydrogen bond interactions between the anions and urea molecules are found in all the systems, but the order of DES melting points is not related to the strength of urea-anion hydrogen bonds. Indeed, the hydrogen bond strength was found to decrease in the order ChF-urea > ChCl-urea > ChACE-urea > ChNO₃-urea, while the hydrogen bond distances increases as follows ChNO₃-urea < ChF-urea < ChACE-urea < ChCl-urea and neither trends correspond to the order of DES melting points (ChF-urea < ChNO₃-urea < ChCl-urea < ChACE-urea). However, besides small differences in the melting point values, all of the investigated DESs share the important properties to be DESs and to be liquid at ambient temperature. According to our results, the origin of the low melting point of DESs can be related to the ability of the hydrogen bond acceptors (the anions in our case) to build a favourable network of hydrogen bond interactions with the other components of the system (choline and urea) in such a way to maximize the hydrogen bonds between all the different moieties. Indeed, besides interacting with urea molecules, each anion forms almost one hydrogen bond with the hydroxyl group of the choline cation in all the investigated systems, thus showing that such cation-anion hydrogen bond interaction is a common structural characteristics of this class of DESs, independently on the nature of the anion. Therefore, in DESs a complex network of interactions is formed in which the anions try to maximize their hydrogen bond interactions with the other components of the system. The specific way in which each anion achieves this goal depends on the nature of the anion: as an example, we have shown that polyatomic anions such as nitrate and acetate, besides interacting with urea molecules via a single hydrogen atom, are able to form "bridge interactions" in which they bind simultaneously two HU2 atoms of urea. This work represents a step forward in the rationalization of DES behavior based on the structure at a molecular level, which can be of great help to design DES for specific applications.

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