Modelling room temperature ionic liquids

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Received (in Cambridge, UK) 31st March 2008, Accepted 29th April 2008
First published as an Advance Article on the web 11th June 2008
DOI: 10.1039/b805384g

Room temperature ionic liquids (IL) composed of organic cations and inorganic anions are already being utilized for wide-ranging applications in chemistry. Complementary to experiments, computational modelling has provided reliable details into the nature of their interactions. The intra- and intermolecular structures, dynamic and transport behaviour and morphologies of these novel liquids have also been explored using simulations. The current status of molecular modelling studies is presented along with the prognosis for future work in this area.

Introduction

Chemical reaction media have traditionally been divided into two classes: polar and non-polar. While liquids such as water, dimethyl sulfoxide, *etc.*, fall into the former, organic compounds such as carbon tetrachloride, acetone, benzene and a host of other volatile organic solvents constitute the latter category. Molten salts, composed of ions, possess properties that can be chemically tuned to either of these two extremes. Salts comprising purely inorganic components melt at high temperatures and their liquid state structure was extensively studied through computer simulation molecular dynamics (MD) calculations in the 1970s[1] using the inter-ionic potentials developed by Tosi and Fumi.[2] However, salts consisting of molecular (organic) ions melt at lower temperatures and can even be present in the liquid state under ambient conditions. Despite some early work on such salts, these systems were not extensively explored until relatively recently.[3–6] Possessing interesting properties with scope for industrial applications, these liquids have attracted much interest among the research community.[4,7–9] Computer simulations in general and MD in particular have complemented these experimental observations on room temperature (RT) ILs by offering a microscopic picture of the structure, dynamic processes and other phenomena.[10–12] The MD simulation technique, with its unique capability for the study of molecular liquids is also well-suited to the study of ILs. In this *feature article*, we review the progress made in the application of MD simulations to ILs, focusing on the specific challenges that ILs pose to the modelling community, and offer our thoughts on future problems that lie in this area.

An important role for computer simulations in the area of ILs is the prediction of physical properties starting from the molecular structure of the ions. This so-called structure–property relationship drives most of the theoretical studies. Among the many properties of interest, viscosity, electrochemical window, morphology, catalysis, and solubility are of importance. These quantities exhibit a complex dependence on the electronic, molecular, and intermolecular structure. Hence accurate predictions require a combination of several theoretical approaches. Cation–anion interactions and preferred geometries can be obtained using quantum chemical calculations in the gas phase. Such calculations are also routinely employed to characterize intramolecular interaction potentials (for example, angle bending and torsions) as well as charges on interacting sites on the ions. Atomistic simulations with empirical force fields are used to study the liquid state structure and dynamic properties. Gibbs ensemble Monte Carlo simulations offer a way to calculate solubility of gases in ILs. Coarse graining of intramolecular degrees of freedom and the use of resulting softer intermolecular interactions enable one



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to study large length- and time-scale phenomena and thus the intrinsic morphology of ILs. These are of chief interest in biphasic systems and in ILs exhibiting liquid crystalline phases.

Apart from the above, the *ab initio* molecular dynamics (AIMD) method, which combines electronic structure calculations with conventional MD, provides an accurate picture of ion–ion interactions in a time evolving configuration of the liquid state. Such simulations are based on quantum density functional theory and are quite demanding of CPU time to perform. The length and time scales that can be explored using current day computers with AIMD are around 1–2 nm and tens of ps, respectively. Despite this limitation, knowledge gained from such limited simulations is immense. It is the only technique able to predict the intermolecular structure (and vibrational dynamics) of ILs under specific thermodynamic conditions, from first principles. Hence AIMD simulations will continue to have great relevance.

The most studied ILs contain the dialkylimidazolium moiety as the cation and an inorganic anion. Therefore, we limit ourselves to modelling studies of such systems in this review. These liquids exhibit large viscosities, relative to, say, liquid water. At ambient conditions, the latter has a viscosity of around 1 cP, while typical ILs exhibit an order of magnitude (or more) larger viscosities. Consequently, structural relaxation times of ILs are large, and the duration of the MD trajectory that one generates needs to be much longer compared to that for conventional liquids, in order to achieve a comparable sampling of the configuration space. It is thus crucial that a simulator understands the limits of a specific computational technique and employs appropriate methods to obtain different properties of the liquid. A systematic hierarchical approach in modelling ILs is likely to be efficient and successful in obtaining a holistic picture of these systems. A schematic of this approach is shown in Fig. 1. This review will also detail one such effort from our group.

Various aspects of modelling room temperature ILs have been reviewed in the recent literature.[10–16] Apart from reviewing many computational studies on ILs ranging from gas phase quantum calculations to coarse grained MD simulations, we emphasize the utility of a hierarchical modelling approach, details of which will be provided in this article.

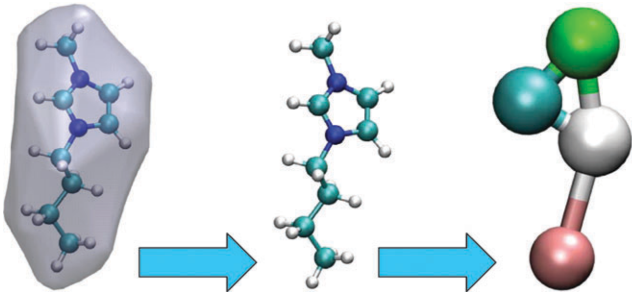

Fig. 1 In a hierarchical modelling approach, the pair correlation function between sites is used as a reference to build the parameters of the interaction model. Figure depicts the representation of an imidazolium cation in *ab initio*, atomistic and coarse grain MD simulations (left to right).

Quantum chemical calculations

To aid further discussion, we provide a schematic of the 1-*n*-butyl-3-methylimidazolium cation in Fig. 2; this is usually denoted as [bmim], or [C_4mim]. Here, b stands for butyl.

In ILs containing short to medium length alkyl tails on the cation, the dominant interaction is electrostatic. In ILs whose cations possess longer alkyl tails (say, C_7 or higher) dispersion or van der Waals interactions compete with electrostatic effects. In the former category, quantum chemical calculations using Hartree–Fock (HF) and extended methods, MP2 level perturbation calculations, and density functional theory (DFT) have been carried out on individual ions and on ion pairs. Such gas phase calculations have been employed to obtain details on the ion pair stability, intramolecular geometry, preferred orientations of ions in the pair, to understand the significance of hydrogen bonding, and the degree of charge transfer between ions. So far, very few higher level *ab initio* calculations, say, using the coupled cluster technique have been reported. The cations in particular are reasonably large entities and thus such calculations are CPU intensive.

One of the earliest work is that of Singer and co-workers[17] who carried out HF and MP2 level calculations on ion pairs with cations containing alkyl tails of varying lengths (ranging between methyl and butyl). The stabilization energy was found to decrease with increasing length of the alkyl group for bromide and iodide anions; however, the trend was just the opposite in the case of chloride. The stabilization energies of the ion pairs were found to be correlated with the melting points of the compounds. These calculations were also able to rationalize the decrease in the melting point on changing the anion from chloride to iodide through bromide, keeping the cation fixed as 1-butyl-3-methylimidazolium. A similar correlation between the association energy of the ion pair complexes and the melting point of the compounds or the shear viscosity of the melt has been obtained by Hunt *et al.*[18]. Carrying out DFT calculations using the B3LYP exchange–correlation functional on larger basis sets, Li and co-workers[19] obtained optimized geometries of many ion pairs containing either the chloride or bromide anion. The cation was [emim] (1-ethyl-3-methylimidazolium) and various positions for the anion around the cation were explored. Four stable locations were identified, all of them exhibiting a possibility for the formation of a cation–anion hydrogen bond. The most stable of these is near the acidic hydrogen, H(C2). This hydrogen is the most acidic since the deprotonated cationic state (carbene) is stabilized by the two adjacent nitrogens. The computed stabilization energies range from 300 to 500 kJ mol^{-1}, and help rationalize the high viscosity values and low vapour pressure, respectively of the liquid.

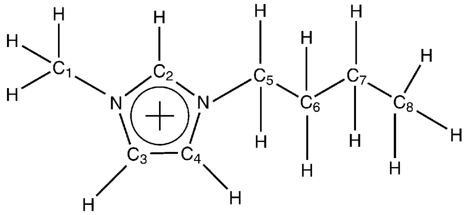

Fig. 2 Schematic of the 1-*n*-butyl-3-methylimidazolium cation with atom numbering.

Interestingly, the authors found evidence for a conformational transition of the alkyl tail upon ion pair formation when the anion approaches the acidic proton of the cation. However, the presence of an additional anion near the H(C3) or H(C4) site prevented the conformational change. The influence of the anion on the rotational barriers of the alkyl group on the cation has also been studied by Hunt and Gould.[20]

Based on DFT calculations of numerous ion pairs, Gutowski *et al*.[21] prescribed a minimum value of -54 kJ mol^{-1} for the enthalpy of reaction between an imidazole and an alkyl halide for them to form a salt. Such an approach obviates the need to conduct many synthesis experiments. The importance of hydrogen bonding between the ion pair has attracted much attention in quantum calculations.[22] Monatomic anions such as halides, form only one hydrogen bond with the cation, while molecular anions such as tetrafluoroborate or hexafluorophosphate, form multiple hydrogen bonds with the same cation. In the latter complexes, the fluorines form hydrogen bonds with both H(C2) as well as with the hydrogen atoms belonging to the methylene or methyl groups on the cationic side chain. Note however, that monatomic anions can form multiple hydrogen bonds if more than one cation is present in the complex. Such complexes have not been studied yet in the gas phase, although *ab initio* MD results on the liquid state provide the evidence (see later). Ludwig and co-workers examined optimized geometries of [emim][Tf_2N] (1-ethyl-3-methylimidazolium bis(trifluoromethylsufonyl)imide) ion pairs and dimers of ion pairs (*i.e.*, two cations and anions each) within DFT.[23] Spectroscopic signatures to identify the two categories of cations—one in which all the three ring hydrogens were hydrogen bonded to anions and another in which only one of the ring hydrogens was hydrogen bonded were provided. These calculations were able to explain their observations on the C–H (ring carbon–ring hydrogen) stretching mode vibrations through infrared spectroscopy on the bulk liquid. Hunt and Gould have examined in detail the vibrational spectroscopic signatures of multiple hydrogen bonds between the ions.[20]

Tsuzuki and co-workers have investigated cation–anion complexes using high quality quantum chemical calculations, *i.e.*, MP2 and coupled cluster including triple excitations, CCSD(T).[24] Complexes of the [emim] cation with various anions were examined and trends in interaction strengths were obtained. Conversely for the BF_4^- anion, stabilization energies with several different cations were also obtained. These energies were compared with experimentally obtained ionic conductivities, as the dissociation of the dimer/complex is an essential part of ion transport and mobility. The partitioning of the total energy into various contributions showed that electrostatics is the most dominant. By a clever substitution of the acidic hydrogen with a methyl group, the authors were able to estimate the contribution of hydrogen bonding to the stability of the complex. They concluded that the hydrogen bond contribution to the stabilization energy was small. However, this observation does not negate the presence of a C–H$\cdots$anion hydrogen bond in either the complex or in the liquid state. The effect of chemical substitution of the acidic hydrogen by a methyl group on the electronic structure has also been studied by Hunt.[25] Interestingly, the butyl side chain in the methyl substituted compound exhibits a larger barrier for rotation compared to the native compound. The resultant reduction in entropy makes the methyl substituted liquid more viscous, despite the fact that the anion cannot make hydrogen bonds with the cation in that compound. These studies show the immense power of quantum chemical calculations in helping to rationalize liquid state properties, even though they are performed in the gas phase. In another study, Tsuzuki *et al*. showed[26] that the C2–H(C2)–F hydrogen bond in imidazolium–BF_4 complex is not linear and hence is not important for ion pair formation. Unlike conventional hydrogen bonds, which exhibit a strong orientation dependence between the donor and the acceptor, that formed between H(C2) and this anion shows only a weak directionality.

In an elaborate and systematic study, Hunt *et al*. characterized the electronic structure of [bmim][Cl] in the gas phase using both DFT and MP2 level calculations with very large basis sets.[27] Relative acidities of different sites on the cation ring were investigated to find out their hydrogen bonding abilities. They have also been able to calculate site charges in the complex through a natural atomic orbital analysis. A molecular orbital picture of the electronic states in the complex has been obtained. Evidence for a small amount of charge transfer from the anion to the atoms constituting the ring of the cation has also been seen. The magnitude of charge transfer from the chloride is estimated to be $0.165e$, which is non-negligible. Our work on modelling the liquid [bmim][PF_6] has demonstrated the importance of accounting for this charge transfer in classical MD force fields.[28] The LUMO of the ion pair was found to be the antibonding LUMO of the cation. This naturally disfavours the acceptance of electrons by the complex and hence the large electrochemical window of ILs can be understood. This profound observation should spur further theoretical work on the properties of ILs.

To summarize, gas phase quantum calculations concur on the multiple energy minima for an anion around the imidazolium cation. The presence of the anion appears to significantly influence the barrier for butyl rotation, thus affecting the transport properties of the liquid state. Although the existence of a hydrogen bond between the cation and the anion is undoubted, its relevance to the stability of the ion pair is not unambiguous. The character of the hydrogen bond too appears to be different from that of a traditional hydrogen bond, in its apparent lack of directionality.

Ab initio molecular dynamics

As noted above, significant insights into the nature of interactions have come through accurate quantum chemical calculations performed in the gas phase on single ions, ion pairs and ion-pair dimers. Another approach to study the liquid state structure and possibly dynamics is through *ab initio* MD simulations. AIMD simulations, based on density functional theory[29–32] offer the possibility of examining intermolecular structural correlations at a temperature and density corresponding to experimental conditions. However, most AIMD simulations based on DFT lack the effects of dispersion interactions which could be crucial in ILs containing medium to long alkyl groups. However, see recent work by Röthlisberger and co-workers on this issue where one way of handling dispersion within DFT based simulations is presented.[33] As the dominant interaction in ILs with short tails is electrostatic in nature, DFT-based simulations are likely to be more realistic in representing the liquid. On the other hand, AIMD simulations, being very expensive, are constrained by small sizes of the system and short trajectory lengths. Typical values are around 400 to 500 atoms and about 10–20 ps. These simulations are typically started from liquid state configurations which are equilibrated by classical MD using empirical interaction potentials. Within the short trajectories explored by AIMD simulations, the ions cannot be expected to move even beyond their nearest neighbours. AIMD simulations are thus unable to predict structural correlations that are vastly different from classical MD. On the contrary, their utility is in being able to allow for local or short range structural adjustments based on the potential energy surface provided by DFT. The premise in such simulations is that DFT could perform better than the empirical potential, given the fact that in the former (i) there are no adjustable parameters, in principle and (ii) the pseudopotentials are largely transferable.

AIMD simulations on ILs have been reported on the following systems: 1,3-dimethylimidazolium chloride ([mmim][Cl])[34–37] 1-butyl-3-methylimidazolium hexafluorophosphate,[38] and on one [emim][Cl] ion pair present within bulk $AlCl_3$ liquid.[39] For [mmim][Cl], the system sizes ranged from 8 to 41 ion pairs, and the temperature of the simulations was 425 K. The radial distribution (pair correlation) functions (RDFs), in particular the cation–anion g(r), obtained from the three independent simulations agreed remarkably well. While the simulations of Del Pópolo *et al.* employed a localized basis set, that of Bühl *et al.* and of Bhargava and Balasubramanian used a plane wave basis set. The latter two simulations employed norm conserving pseudopotentials and gradient corrected exchange correlation functionals—one of the BP variety[40] and another of the BLYP kind.[40a,41] The fact that all three simulations agreed, despite many differences in the inputs, shows the robustness of the methodology and the results. One of the central results of these studies is the identification of a hydrogen bond between H(C2) and the chloride ion. X-Ray scattering experiments conducted by Hardacre and co-workers[42] have clearly shown the presence of this hydrogen bond in [mmim][Cl]. However, classical MD simulations with early force fields failed to exhibit the same feature. The hydrogen bond was present in the results of all three AIMD simulations, although each of them was started from configurations equilibrated with different classical potentials. In Fig. 3, we show the evolution of the H(C2)–Cl pair correlation function in the DFT simulation, relative to the result obtained from a classical MD simulation.[36] $t = 0$ represents the g(r) obtained from classical MD, while the later time values are the same g(r) calculated at different times from the AIMD trajectory. The rapidity with which the g(r) evolves to exhibit the hydrogen bond is striking. These data show that despite the short trajectories generated in AIMD, they are capable of differing significantly from the predictions of classical MD models in the intermolecular structure at short range.

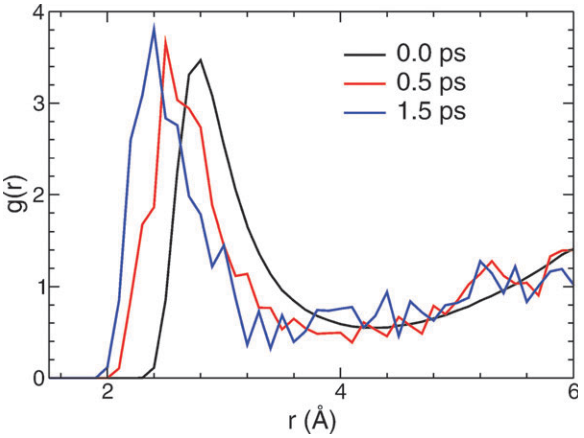

Fig. 3 Time evolution of H(C2)–Cl radial distribution function, g(r), from AIMD simulations of liquid [mmim][Cl] at 425 K, calculated at different stages of the trajectory. The system was equilibrated using classical MD simulations prior to the AIMD run. The curve for t = 0.0 ps corresponds to the data from classical MD simulations.

The pair correlation function does not discriminate between different orientations of the anion with respect to the C2–H(C2) bond. One needs to calculate the spatial distribution function in order to identify the location of the anions with respect to a central cation. This function, calculated from the AIMD trajectory is compared with that obtained from the classical MD simulation in Fig. 4. This figure shows the probability density of finding an anion around a cation, at a specific isosurface value. The classical MD result lacks anions along the C2–H(C2) bond vector, while the function for AIMD shows the dominant presence of anions along that vector, implying the formation of a strong, linear hydrogen bond. Thus, these AIMD calculations throw light on precise deficiencies in the classical potential model(s) and provide clues on their further refinement. In the absence of scattering data on liquids, the AIMD derived g(r) can form a reference against which the g(r) from classical MD simulations can be compared or benchmarked. This specific approach delineated above has been carried out by us in modelling [bmim][PF_6].[28,38]

We now review our AIMD studies.[38] Two different AIMD simulations were performed, one of pure [bmim][PF_6] at 300 K and another of carbon dioxide dissolved in [bmim][PF_6] at a mole fraction of 70%. The prospective use of ILs as a medium for storing CO_2 was the motivation for the latter study. The intermolecular structure was characterized in terms of pair correlations and spatial distribution functions. In Fig. 5, we compare the intermolecular pair correlation function obtained from our AIMD simulations[38] with X-ray scattering data.[8] The agreement is quite good, despite the small system size employed in the former study. The simulations demonstrated the presence of a weak hydrogen bond between the fluorines of the anion and the ring hydrogens of the cation. Consistent with the quantum chemical studies discussed in the previous section,[22] we observed evidence for the anion's participation in the formation of multiple hydrogen bonds (see Fig. 6 for a snapshot from the AIMD trajectory depicting this feature). Another significant observation is the preference for anions to approach closer to each other in AIMD simulations, relative to predictions from classical models, due to their highly polarizable nature. The electronic wave functions obtained from such AIMD simulations can be analyzed using the localized Wannier orbital method which associates regions

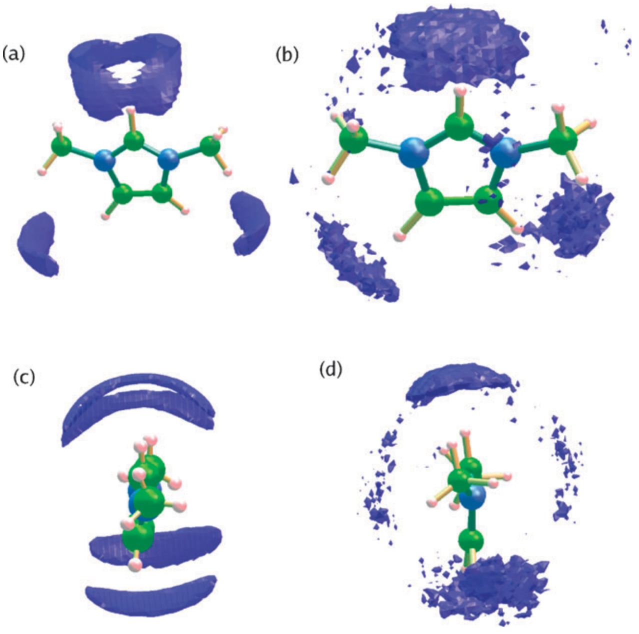

Fig. 4 Spatial distribution of chloride ions[36] around the [mmim] cation in the IL [mmim][Cl], at an isosurface value of 0.0375 $Å^{-3}$. (a) Top view from classical MD; (b) top view from AIMD; (c) side view from classical MD; (d) side view from AIMD. Reproduced with permission from Elsevier.

of electron density to individual molecules/ions. Using this approach, the polarization of the ions in the liquid state has been demonstrated by the calculation of dipole moments by Lynden-Bell and co-workers in [mmim][Cl][34,43] and by us in [bmim][PF_6].[38] The estimated cation polarization-induced dipole is about 0.7 debye. The authors have also studied the transport of a proton in this IL for its possible application in fuel cells.[37]

In the AIMD simulation study of the CO_2–[bmim][PF_6] solution,[38] CO_2 molecules were found to be proximal to the anion rather than to the cation. CO_2 molecules which are present near the anions or the ring hydrogen H(C2) were found to deviate farther from a linear geometry than the rest of their kind. The change in geometry arises due to Lewis acid–base (or electron donor–acceptor) interactions in the former case, and the formation of a weak hydrogen bond in the latter. The fluorine atoms (Lewis base) can donate a partial electronic charge to the carbon atom (Lewis acid) of CO_2. The deviation from a linear structure results in the lifting of degeneracy in the bending mode of CO_2, a finding which agrees qualitatively with spectroscopic experiments.[44] Thus, our results point out that, apart from the ion–quadrupole interactions that are expected between the anion and CO_2 molecules, ion-induced dipole interactions could also be important.

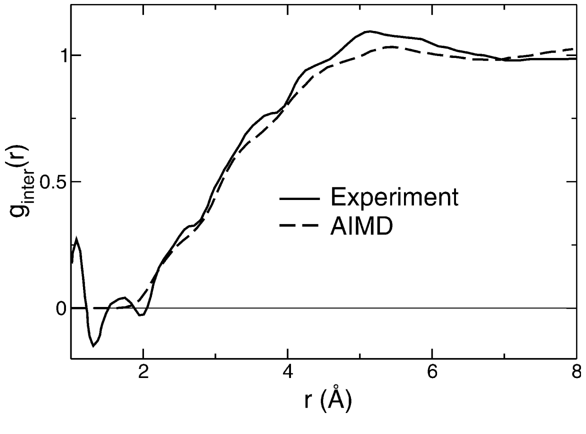

Fig. 5 Comparison of the intermolecular radial distribution functions obtained from AIMD simulations[38] with experiment,[8] for [bmim][PF_6] at 300 K.

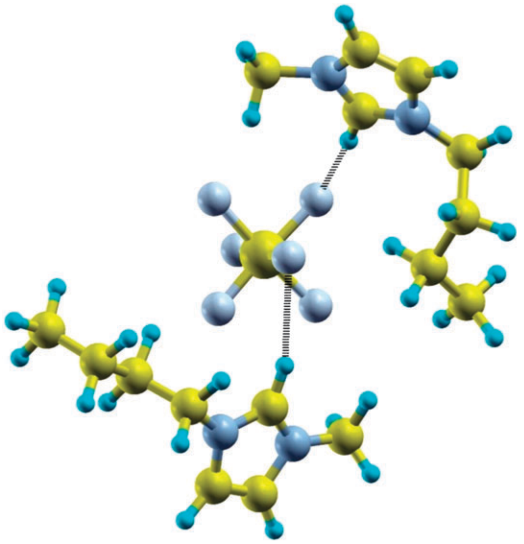

Fig. 6 Snapshot of part of a system of liquid [bmim][PF_6] from the AIMD trajectory[38] showing an anion forming two hydrogen bonds with different cations.

AIMD simulations will continue to play an incisive role in furthering our understanding of the intermolecular structure in ILs. We expect further contributions to come in the applications of such simulations to electrochemistry. The relative lack of reliable wide angle scattering data from which partial pair correlation functions could be obtained will continue to make AIMD simulations of ILs very relevant. As discussed above, such AIMD $g(r)$s have been used by us as a template for refining empirical pair potentials for use in classical MD.[28]

Force fields

One of the main requirements for the computational study of a system is the form of interaction between various particles of the system. For molecular systems including ILs, the force field is often written in the form:

$$U_{\text{tot}} = \sum_{\text{bonds}} k_b(r - r_0)^2 + \sum_{\text{angles}} k_\theta(\theta - \theta_0)^2 + \sum_{\text{dihedrals}} \sum_{n=0}^{5} k_{\psi,n} \cos^n \psi + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} 4\varepsilon_{ij} \left[\left(\frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\sigma_{ij}}{r_{ij}} \right)^{6} \right] + \sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \frac{q_i q_j}{r_{ij}}$$

which consists of so-called bonded terms including stretching, bending and torsions along with the non-bonded interactions that include the electrostatic and dispersion interactions. In the above equation, U_{tot} is the total energy, r_0 and θ_0 are equilibrium bond length and bond angle respectively, k_b and k_θ are the harmonic stretching and bending force constants respectively, ψ is the dihedral angle, ε and σ are Lennard-Jones parameters and q are the partial charges on the atoms. The interaction parameters are obtained from quantum chemical calculations in the gas phase and also by fitting the physical properties of the model liquid to experiment. Usually the stretching, bending and dispersion interactions are derived from the experimental data, while the torsional parameters and the partial charges on the atoms are computed *ab initio* from first principles calculations.

There have been several efforts by various groups towards developing and refining the force fields for ILs. The first simulations on ILs were carried out by Hanke *et al.*,[45] with a force field similar to that written above. The non-bonded interaction in this model included a repulsive term of the Buckingham type (exponential in distance). From a comparison of their united and all atom models, they concluded that the latter was superior in reproducing the dynamics in ILs, although results on the structure were similar for the two representations. This early work was followed by several groups who have come up with force fields for either specific ILs[46–48] or for an entire class of ILs.[49–51] Some of these force fields were tested[52] using spectroscopic data on imidazolium cation conformations, and found to be consistent with the information obtained from Raman experiments.

Force fields for ILs based on pyridinium, tetraalkylphosphonium, tetraalkylammonium and guanidinium based cations have also been developed[53,54] expanding the spectrum of ILs that can be studied using computational methods. Recent developments include force fields for the tetraalkylphosphonium based ILs with amino acids as anions.[55]

Many of the earlier force fields failed to predict the hydrogen bonding between the anion and the cation. Also the transport properties computed from these models have been found to deviate from experiments to a large extent. A comparison between the polarizable and non-polarizable models[56] has shown that the polarizable models score better in predicting the viscosity of these liquids.

AIMD studies on bulk ILs[34–36] have shown that empirical potential models fail to predict the hydrogen bonds between the anion and the cations, which in turn has led to the refinement of the force fields. Attempts have been made to refine force fields based on force matching to *ab initio* data.[57] Although the model predicts a structure comparable to AIMD results, the density it predicts was found to be much higher than experimental values. We have refined the force field for liquid [bmim][PF_6][28] within the framework of the model of Lopes *et al.*[50] The charges on the cation and the anion were scaled to 0.8 electronic units. Further, some of the site dispersion parameters were tuned so as to match the RDFs with AIMD data. This model predicts the diffusion of the ions over a wide range of temperatures much closer to the experimental values. The reduction in the overall charge of the ions is motivated by quantum chemical calculations of ion pairs, reported by Maginn and Morrow[58] and Hunt and co-workers[27] who observed non-negligible charge transfers from the anion to the cation.

Most of the force fields discussed above do not include effects of polarization of charge density at interacting sites, due to time varying local density or inhomogeneous fields present therein. A polarizable model for ILs has been developed[56] for [emim][NO_3] and has been found to predict transport properties closer to experiment than a non-polarizable model.

In an attempt to reduce computational costs, several groups have developed united atom models for ILs,[59,60] where the methyl and methylene groups are reduced to a single site each. United atom models for [bmim][PF_6] and [bmim][NO_3] by Micaelo *et al.*[60] which has been parameterized for the GROMOS force field predicts viscosities for these two ILs very close to the experimental values over the range of temperatures studied. Coarse grained models[61,62] have also been developed for RTILs to study their long range organization. These will be discussed in a separate section later.

Classical atomistic molecular dynamics

Although AIMD simulations provide significant insights into the atomic level interactions and intermolecular structure, their widespread application is limited due to the need for extensive computational resources. In order to study larger systems and long time processes atomistic molecular dynamics is the method of choice. Provided a suitable force field for the interaction between the particles in the system is available, the properties of the liquid can be predicted to a very good accuracy. The success of this method is mainly due to the possibility of representation of the interaction in a simple additive form and the stable integration techniques available to time evolve the system. The development and refinement of force fields for ILs has already been discussed in this review.

ILs have been studied extensively using classical atomistic MD simulations. In their pioneering computational study of liquid [mmim][Cl], Lynden-Bell and co-workers[45] treated the cation methyl and methylene groups in either an all-atom or united atom representation. Their work was aimed at obtaining the structure and the dynamics of the liquid. The necessity of using the all-atom model to obtain proper transport properties was illustrated in their studies. However, present day force fields based on the united atom representation are able to predict accurate transport properties comparable to experiments.[60] Several studies aimed at obtaining the intermolecular structure using pre-existing or new force fields for specific ILs have since been reported.[46,56,58,63,64]

By using both charged and uncharged models to represent benzene, Hanke *et al.* have studied the solubility of benzene in [mmim][Cl] and [mmim][PF_6] and have arrived at the conclusion that local electrostatic solute–solvent interactions play a role in the higher solubility of aromatic compounds in ILs.[65] The time scales and molecular processes involved in solvation of polar solutes in ILs have been examined by Kim and co-workers.[66,67] They established the existence of multiple time scales in the relaxation of the solute. Solvation dynamics in ILs and of aqueous IL solutions have also been investigated in detail by Margulis and co-workers.[68] In particular, they have been able to identify the molecular origins of the red edge effect[69,70] as due to the dynamical heterogeneity of these liquids for time scales relevant to optical spectroscopy.

The development of force fields for a wide variety of ILs by Pádua and co-workers[50–52,54] has immensely contributed to the growth of computational studies on ILs. Their model is based on the OPLS/AMBER force field and is able to predict the density of several ILs over a wide range of temperatures and pressures. The inclusion of ion polarization in the force field has also been tested by Voth and co-workers and the results are found to be superior to non-polarizable models, particularly in transport properties.[56]

Studies on the liquid–vapour interface of ILs[71] suggest that there is a region of increased density just below the interface. The polar imidazolium group was found to be facing the water rich phase in MD studies of the aqueous interface of imidazolium based ILs.[72] Computational studies of the IL–vapour interface of [bmim][PF_6] carried out by Bhargava and Balasubramanian[73] reported oscillations in the electron density profile across the interface and an ordering of the charges. This study also predicted a hydrophobic surface for [bmim][PF_6] consistent with sum frequency generation spectroscopy experiments.[74]

[bmim][PF_6]–CO_2 solutions have also been studied computationally using AIMD (discussed earlier) and atomistic MD simulations. Berne and co-workers[75] have shown that CO_2 prefers to occupy voids present in the ILs. By substituting the acidic hydrogen by a methyl group and measuring the change in the Henry's constant for the solubility of CO_2 in ILs, Maginn and co-workers have demonstrated that the cation does not play a major role in the solubility of CO_2 in ILs.[76] Further studies[38] have demonstrated that the CO_2 molecules are tangential to the PF_6 sphere and are preferentially present in the octahedral voids around PF_6.

In order to obtain improvements in intermolecular structure, in particular the cation–anion hydrogen bond and transport properties, we have refined the potential parameters[28] of the CLP (Canongia Lopes–Padua) model[50–52,54] for [bmim][PF_6], which is discussed in a later section. The effective ionic charge was chosen to be ±0.8 electron units based on the studies of Morrow and Maginn[58] where they observed a charge transfer of 0.1*e* between the anion and cation. The predicted structure of the liquid from this refined model agrees very well with that obtained from our AIMD simulations. A comparison of RDFs for the acidic hydrogen and fluorine (which showed the biggest deviation) from the CLP model (on which the refined model is based), the present (refined) model, and the AIMD results is presented in Fig. 7. It can be seen that the present model results are closer to the AIMD results, which is not surprising as the RDFs were used for the refinement of the potential model.

Importantly, the refined model was able to reproduce many of the experimentally observed properties to a good accuracy. For example, it was able to predict the densities of the liquid over a wide range of temperatures (between 300 K and 500 K) within 1.5% of experiments.[77] The variation of density with pressure is also in agreement with the experimental values,[78] being within 2%. The thermal expansion coefficient measured from vapour–liquid interfacial simulations, $6.85 \times 10^{-4}\ K^{-1}$, is in very good agreement with the experimentally reported value,[77] $6.6 \times 10^{-4}\ K^{-1}$. The most important improvement of the model is in the prediction of diffusion coefficients of the ions to within 20% of experiment in the temperature range from 300 K to 500 K, which is better than any of the previous force fields for ILs. The interesting property of faster diffusion of bulky cations over anions is also observed. The present model predicts a surface tension of 47 m Nm^{-1} against the experimental value of 42.5 m Nm^{-1} [79] which is a great improvement over the previous model's value of 72 m Nm^{-1}.[73]

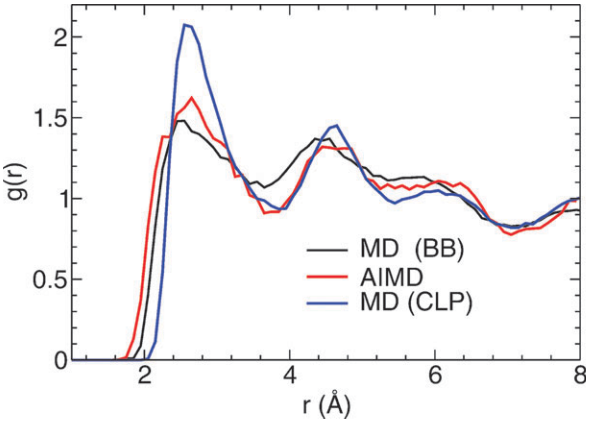

Fig. 7 H(C2)–F radial distribution function in liquid [bmim][PF_6] at 300 K as obtained from AIMD simulations,[38] compared with results of atomistic MD simulations using the CLP model[50] and the BB model.[28] Figure reproduced with permission from the American Institute of Physics.

The structure factor obtained from the refined model has been plotted along with the experimental structure factor for the liquid[80] at 200 K in Fig. 8. The figure shows the X-ray and neutron structure factor between 0.6 $Å^{-1}$ and 2.4 $Å^{-1}$ obtained from simulations and experiments at 200 K. The agreement between the simulations and experiment is evident from the figure, with the simulations predicting both the peak position and the intensity comparable to experiments.

Unlike experiments where the contribution from a pair of atoms to a certain peak in the structure factor is not readily

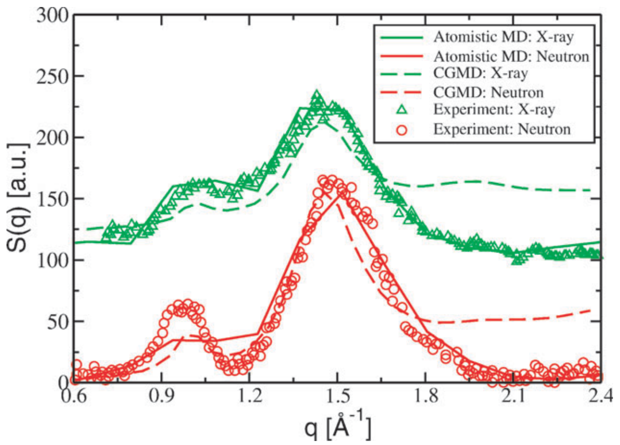

Fig. 8 Comparison of the structure factor, *S*(q) of glassy [bmim][PF_6] at 200 K, obtained from our atomistic MD simulations[28] and our coarse grained MD simulations[62] with wide angle X-ray and neutron scattering experiments.[80] The X-ray structure factors have been shifted for clarity. Copyright: (2006) American Chemical Society; (2007) AIP; (2008) Wiley-VCH.

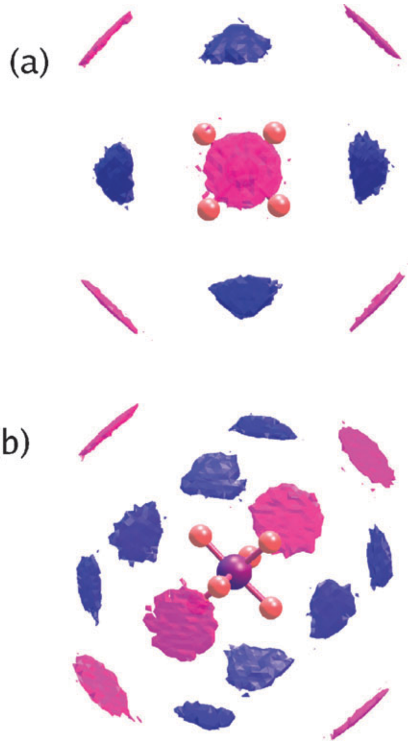

Fig. 9 (a) Spatial distribution of cations and anions present within 6.3 Å from a reference anion in liquid [bmim][PF_6]. Blue represents the cation ring centre and magenta represents the phosphorus atom of the anion. (b) Shows (a) in a different orientation. Figure reproduced with the permission of Wiley-VCH.

evident, simulations allow access to site–site partial structure factors so that the contribution of each pair to the total structure factor can be examined. This protocol allows us to assign a peak in the structure factor to a particular pair or a set of pairs in the system. Such an analysis has shown that the F–F pair and the anion–cation cross correlations mainly contribute to the 1 Å^{-1} peak in the structure factor of liquid [bmim][PF_6].

The spatial distribution of the anions and cations around an anion obtained from the refined model shown in Fig. 9 provides evidence for the local charge ordering in these liquids. The density map, which shows the favourable locations of cations and anions around an anion, clearly reveals that the most probable location of the cation is in the octahedral void of the PF_6 ion whereas anions are located along the P–F bond direction. The positions of the anion and the cation presented in the figure are only the most probable positions. Not all the probable positions depicted in the figure are occupied for every anion. A similar structural arrangement has been observed experimentally by neutron diffraction by Hardacre *et al.*[81] for the IL [mmim][PF_6].

Monte Carlo simulations

The Monte Carlo (MC) method scores over MD in terms of its versatility, particularly for small molecules.[82] As with MD, such simulations are also based on an empirical potential function. Several sampling techniques, such as importance sampling (for example, using the Metropolis algorithm) are available to generate a series of configurations consistent with the state points chosen. Shah *et al.*[47] have carried out such Monte Carlo simulations on rigid [bmim][PF_6] for various state points to compute properties of this IL. By obtaining the cohesive energy from their MC simulations and comparing it with hydrocarbons they have rationalized the low volatility of these liquids. They have also computed several thermophysical properties such as density, thermal expansion coefficient and isothermal compressibility and have compared them with experiments.

MC simulations have also been used in the study of solubilities of gases in ILs. Henry's constant, which relates the fugacity of the solute in the liquid state to its mole fraction, can be obtained from the knowledge of the excess chemical potential. This quantity can be computed in different ways. Shah and Maginn[83] have computed the Henry constant of CO_2 in ILs by using the so-called Widom test particle insertion method to obtain the excess chemical potential. Although this method is known to be subject to systematic errors in dense liquid systems with strong interactions, the extensive sampling employed by the authors is expected to provide a good estimate of the Henry constant. The values obtained by these authors were smaller by a factor of 2 compared to experiments. The use of more sophisticated methods in the calculation of excess chemical potential is desirable to obtain more precise estimates of Henry's constant. However, such calculations are tedious and even obtaining a semi-quantitative (within a factor of two of experiments) estimate is in itself a heroic effort. The derived enthalpy and entropy of absorption of CO_2 in [bmim][PF_6] from the Henry constant agree reasonably well with experiments. The estimated enthalpy was higher than experiment, due to the overestimation of the interaction energy between CO_2 and [bmim][PF_6] in the model.

The Henry constants for dissolution of several gases in [bmim][PF_6] have been investigated.[84,85] Using different methods for obtaining the excess chemical potential, Shah and Maginn have found that the expanded ensemble method predicts values close to the experiments in dense liquids with strong interactions. Expanding their investigations to include several different gases as solutes, the over estimation of interaction between these gases and ILs in the models has been identified. While dipolar and quadrupolar solutes are found to be solvated through specific interactions with the anion, the solubility of molecules such as oxygen appears to be governed by entropic contributions.

MC simulations are mainly used to study the phase behaviour of ILs with different gases and in studying the dissolution of these gases in ILs. The use of MC methods in simulating the ILs is limited due to the difficulty in applying this method to complex molecular systems. Specifically, the particle (*i.e.*, the molecule) insertion move is rather difficult for large molecules and special insertion schemes, such as the configurational bias MC approach,[86] may need to be adopted.

The advantage of using Monte Carlo simulations in predicting structural and thermodynamic properties lies in their inherent method of sampling the phase space for a particular system. Since the systems of interest have very high viscosity, proper sampling of the phase space using molecular dynamics simulations requires the generation of very long trajectories. Importance sampling allows the generation of configurations which yields proper thermodynamic quantities on averaging. We have noted the necessity of generating long trajectories in simulations of the liquid [bmim][PF_6]–vapour interface.[73] Monte Carlo scores over molecular dynamics in this aspect, but obtaining the dynamic properties is not possible due to its stochastic approach. MC simulations can be used to complement MD simulations in the investigation of phase properties of ILs and solutions and in calculations of the solubility of gases.

Coarse grain molecular dynamics

We have thus far reviewed quantum chemical, *ab initio* MD and atomistic MD simulation approaches in understanding intermolecular interactions, structure and dynamics in room temperature ILs. One of the fascinating features of ILs is that they can exhibit structural order beyond molecular distances. Such ordering is typically denoted as nanostructural order. In particular, such ordering is seen in ILs containing cations which possess long alkyl groups. Formation of self assembled structures, such as micelles, mono- or bilayers *etc*. has long been known and studied in solutions of aqueous amphiphiles.[87] Enormous progress has also been made in modelling these systems.[88] However, the organization in ILs differs distinctly from that seen in surfactant solutions. The latter are binary solutions, whereas an IL does not have a second component. The nanostructural organization in ILs exhibits a "transition" from a regime controlled by electrostatic interactions between the ions (for cations with short alkyl groups) to one where van der Waals interactions between the alkyl groups is more dominant (cations with long alkyl groups). In this respect, the imidazolium ring of the cation carrying a substantial part of the positive charge mimics the head group of an ionic surfactant and the anion plays a role similar to water (and the counterion). With this backdrop, it is not far fetched to envisage the organization of cations as the alkyl group increases in length, to behave analogously to surfactants and form micelles in water. It is known that as the size of the anion is increased, the cohesive energy of the IL decreases, leading to observable decrease in its viscosity, among other properties.[25] For instance, [bmim][Tf_2N], whose anion is larger than PF_6, is less viscous than liquid [bmim][PF_6] under ambient conditions. Based on this analogy, we also conjecture that as the size of the anion is increased, it should be more facile for the IL to order at nanometric length scales, as the dispersion energy starts to overcome the electrostatic contribution at a relatively lower alkyl tail length. Ludwig and co-workers[89] recently quantified the contribution of dispersion and electrostatic energies in Tf_2N based ILs. A schematic cartoon of the intermolecular structure in ILs containing cations with different lengths of alkyl tail is depicted in Fig. 10.

The earliest indication of long-range ordering in ILs came from the work of Urahata and Ribeiro[63] who found a weak peak in the structure factor at short wave vectors. Further evidence came from the atomistic simulations of Lopes and Pádua.[90] Experimental confirmation of the ordering was provided by the extensive work of Triolo and co-workers[91] through small angle X-ray scattering experiments on ILs of the kind, [$C_n$mim][Cl]. Modelling the organization of molecular liquids over length scales beyond intermolecular distances requires (a) system sizes that are many times the length scale of the organization one intends to study and (b) long trajectories that sample the reorganization of the ions. The latter in particular, can be excruciatingly long, due to the long relaxation times for reorientation of the cations. As the alkyl tail length increases, the molecular volume of the cations increases and the viscosity of the IL also increases. Despite the initial "successes" of atomistic MD simulations in identifying the existence of nanostructural order in pristine ILs, such approaches are unlikely to provide a quantitative comparison of the structure factor with experiment. It is in this regard that the application of coarse grained molecular dynamics assumes significance. Voth and Wang[92] have developed a coarse grained model for [emim][NO_3] to study its nanoscale ordering, in which the imidazolium ring is treated as one interaction site.

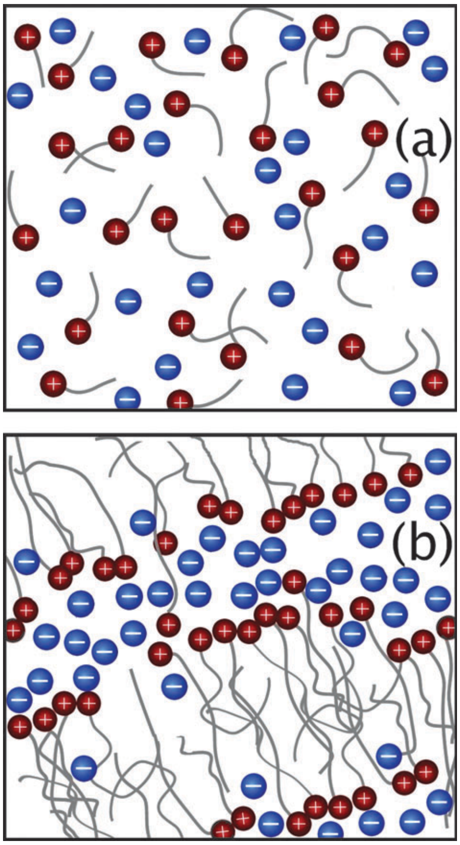

Fig. 10 Cartoon of likely intermolecular arrangement in room temperature ILs in which the cations possess (a) short alkyl chains and (b) long (C_7 or higher) alkyl groups.

The aim of coarse grained MD (CGMD) simulation is to make the problem tractable while minimally diluting chemical rigour.[93] To begin, one has to choose a specific length scale for the coarsening and then subsume all atoms present within that length scale into one united-atom or bead. The beads are then connected to one another by "bonds" to reproduce the overall architecture of the original molecule. The connected beads can interact *via* bond stretching and bending forces, and beads present within a molecule but separated from each other beyond, say, two bonds as well as beads belonging to different molecules interact *via* non-bonded interactions. The speed-up in the realization of the natural world within the CGMD approach, relative to fully atomistic MD is achieved mainly due to the many-fold reduction in the number of degrees of freedom and the use of softer interaction potentials. Typically, one creates a bead out of three heavy (*i.e.*, non-hydrogenic) atoms. Thus, in CGMD models of alkyl groups, one reduces the number of degrees of freedom by almost an order of magnitude. In an atomistic MD simulation, the time step is determined by the vibrational frequency of the stiffest bond. The time step has to be at least an order of magnitude (or more) smaller than the time period of the stiffest oscillator. This is true for the CGMD simulation as well. However, in the CGMD model, the beads represent the erstwhile atom centres that are separated by around 3 or 4 covalent bonds. Naturally, the spring constant for "bonded" beads will be much smaller than that between bonded atoms in an atomistic model. The benefit for the simulator is the flexibility to use a much larger time step than is possible in atomistic MD. Typically, one could use a factor of six to eight larger time steps in a CGMD simulation. These enhancements make CGMD simulations a powerful way to capture slow processes that occur in complex liquids.

We illustrate the CG model developed by us for modelling the family of [C$_n$mim][PF$_6$], in Fig. 11. The coarse grain model was constructed with the following principles: (i) the alkyl tail was represented in the same fashion as in Shinoda *et al.*,[94] who studied aqueous surfactant solutions; (ii) as far as possible, around three non-hydrogen atoms were coarsened into one bead, (iii) the CG model should reproduce the pair correlation functions obtained from all-atom simulations.[28] With these guiding principles, the CG prototype was constructed for [bmim][PF$_6$].[62] Apart from bond stretching and bending interactions for which the initial guesses of the parameters were obtained by Boltzmann inversion of the respective atomistic probability distributions, molecular sites in the CGMD simulation interacted *via* a 9–6 potential as well. The value of a bead's non-bonded ε parameter was obtained as the sum of the ε values of atoms which constituted that bead. The same procedure was adopted for obtaining the bead charges as well. The σ parameter was tuneable so as to reproduce the bead–bead pair correlation functions obtained from atomistic MD in the CGMD simulations.

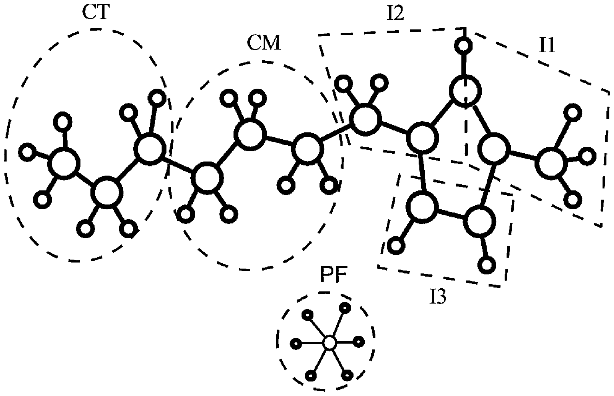

Fig. 11 Schematic of [C$_7$mim][PF$_6$] illustrating the mapping of atoms to coarse grain beads. The names of the beads are shown. Reproduced with permission from the RSC.

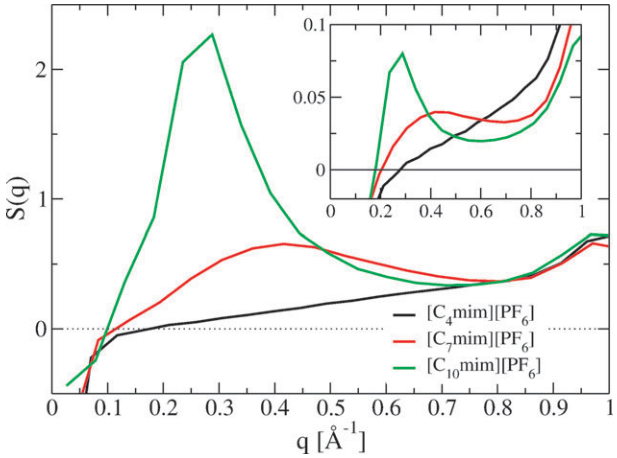

Fig. 12 Neutron (main body) and X-ray (inset) scattering structure factors, S(q) of various PF$_6$ based ILs obtained from CGMD simulations.[62] A growing correlation length is observed with increasing tail size, consistent with small angle X-ray scattering experiments.[91] Reproduced with permission from the RSC.

With these protocols, we were able to model the series of [C$_n$mim][PF$_6$] rather well. Physical properties, such as the density variation over a wide temperature and pressure range were reproduced by the CG simulations within 3.5%. It is also crucial to reproduce the surface tension of the IL. Details are provided in ref. 62. In Fig. 8, we have compared the structure factor obtained from CGMD simulations, weighted with neutron scattering lengths or by atomic form factors, against wide angle neutron and X-ray scattering data for [bmim][PF$_6$] at 200 K. The comparison is good, and proves the efficacy of the hierarchical modelling approach. Having demonstrated the predictive capabilities with [bmim][PF$_6$], we proceeded to construct CG models of this IL family with longer alkyl tails, *i.e.*, C$_7$ and C$_{10}$. This was accomplished by joining beads made of three methylene groups, whose interaction parameters were developed against atomistic simulations of *n*-alkanes and surfactants earlier by Klein and co-workers.[94] The ILs containing longer alkyl tails exhibit a strong peak in the neutron structure factor at short wave vectors (Fig. 12). The observed length scale of the correlation increases with the tail length. The calculated growing correlation length is consistent with the small angle X-ray scattering experiments of Triolo and co-workers.[91] The morphology of the IL with long alkyl tails is reminiscent of the bicontinuous phase exhibited by aqueous surfactant solutions—polar regions populated by anions and cationic rings separated by the non-polar alkyl tails of the cation.

Summary and outlook

The field of room temperature ILs has been enriched by the knowledge gained from quantum and classical computer simulations. In this area, computational research has gone hand-in-hand with experiment, the former playing second fiddle to experiments only in material synthesis. Synthesis of new compounds continues to be an experimental forte, where theory and computation has not yet played much of a role. This is true in many areas in chemistry and is applicable to ILs as well. For this situation to change, empirical potentials for atomistic MD simulations must not only be based on inputs from gas phase quantum calculations, but also from *ab initio* MD simulations. Empirical potentials derived purely from isolated molecule/complex calculations are often beset with issues of applicability to the condensed phase, due mainly to effects of polarizability. As has been demonstrated by Voth and others,[56] ILs are quite polarizable and a direct adoption of site charges from gas phase calculations is less likely to be successful in the liquid state. For instance, the presence of a net charge on the methylene or methyl groups in a long chain alkyl tail of an IL may influence the surface tension of the liquid, but may not matter much for the determination of the liquid state density. Alkyl groups orient themselves normal to the surface of an IL at a liquid–vapour interface, and directly determine the value of the surface tension. Hence any residual charge on them, however small, can possibly increase the value of the surface tension. Neutral CH_2 or CH_3 groups interacting purely *via* a Lennard-Jones interaction are likely to be suitable for predicting the surface tension properly. The moral is that despite the quantum calculations, reparameterization of the force field may be necessary for the condensed phase. The long standing difficulty in modelling liquid water testifies to this fact.

We have enunciated a hierarchical approach to develop understanding of ILs. In the case of [bmim][PF_6], this has been demonstrated in three stages: for structural correlations at length scales up to 1 nm one can depend on AIMD, on atomistic MD for a few nm, and on CGMD for larger length scales. *At each stage, it is crucial that the potential parameters are refined so that one is faithful to relevant pair correlation functions obtained through the higher level method, as well as to as many experimentally determined physical properties as possible*. As the predictive capabilities of atomistic simulations (*i.e.*, force fields) improve, it should be possible for simulations to provide significant leads to the synthesis of novel ILs as well.

As regards coarse grain simulations, these should not be equated with "toy" models. The latter are typically built in order to understand the gross properties of generic systems, and hence lack chemical detail. In order for CG models to remain relevant to chemistry, molecular level details (such as their shape, the existence of functional groups[95]) must be included. It is not clear how relevant the cation–anion hydrogen bond is to the properties of the IL. A CG model obviously neglects it, and if the model is successful, it can be concluded that ion–ion electrostatic interactions influence the liquid structure more than hydrogen bonding interactions. ILs also pose another challenge to traditional CG modelling. One of the time consuming aspects in simulations is the calculation of Coulombic interactions through the Ewald sum. Our CG model naturally includes charges; it is unclear how one could model ILs without charges! A spherical cutoff of the Coulombic interaction (with the cutoff being an additional parameter) is a possible approach; but transferability of the parameters is not guaranteed, unlike in the case of the exact, Ewald summation method. Coarse grain simulations will continue to see much activity in the near future in the modelling of pure ILs and their solutions with other solvents.

ILs exhibit several characteristics similar to supercooled liquids. Their large viscosities, and long relaxation times are similar to values encountered for supercooled, simple liquids.[96–98] Properly equilibrating ILs in simulations is necessary; Margulis *et al.*[48] adopt a strategy of starting the simulation at low densities, so that adequate mixing takes place in the liquid. Equilibrating the system at high temperature is another possible way. Due to the large structural relaxation times, it is important that simulations interested in quantitative predictions adequately sample the phase space. All properties should be averaged over many trajectories, each of which is started from independent initial configurations. The detailed mechanism of diffusion in ILs is yet to be explored, and is likely to be investigated by researchers. In particular, the faster diffusion of cations despite being heavier than anions in certain ILs demands a molecular level explanation. Computer simulations are suitably positioned to provide this insight.

Newer ILs using amino acid moieties[99] are being explored experimentally. Force fields for amino acid residues are well established in the protein literature; hence it should be possible to model these ILs in a rather straightforward manner. The ability of ILs to dissolve enzymes and impart them with higher thermostability (relative to water) is likely to increase attention in modelling these non-aqueous biological solutions.[100]

ILs are increasingly finding use in electrochemistry as electrolytes. Very few simulations have been performed on such ILs. With the predictive capabilities of several models of ILs firmly established by now, focus must be made on studies of ILs in the field of electrochemistry. Simulations of bulk IL electrolytes as well as IL–metal interfaces need to be carried out. The potential of ILs as possible storage media for gases such as CO_2 or SO_2 (flue gases) also needs to be computationally investigated.[101] Another interesting aspect of ILs is their ability to form liquid crystalline phases when the cations possess long alkyl tails.[102] These systems have not been explored in simulations yet. One should not also forget the relevance of ILs to synthetic chemists, *i.e.*, as reaction media. It appears that ILs play more than a passive role as a solvent in certain chemical reactions[4,103,104] Efforts must be made to model chemical reactions such as the Diels–Alder[105] in ILs. The time is ripe for molecular simulations to substantially contribute to all these aspects of room temperature ILs.

Acknowledgements

SB thanks the Department of Science and Technology, Government of India, and CCMS, JNCASR for support. SB also thanks Dr M. Kanakubo for interesting discussions leading to Fig. 10. MLK thanks NSF for support.

Notes and references

1. (*a*) L. V. Woodcock and K. Singer, *Trans. Faraday Soc.*, 1971, **67**, 12; (*b*) D. J. Adams and I. R. McDonald, *J. Phys. C: Solid State Phys.*, 1974, **7**, 2761.

2. M. P. Tosi and F. G. Fumi, *J. Phys. Chem. Solids*, 1964, **25**, 45.
3. K. R. Seddon, *J. Chem. Technol. Biotechnol.*, 1997, **68**, 351.
4. T. Welton, *Chem. Rev.*, 1999, **99**, 2071.
5. C. A. Angell, N. Byrne and J. Belieres, *Acc. Chem. Res.*, 2007, **40**, 1228.
6. *Electrochemical Aspects of ILs*, ed. H Ohno, Wiley-Interscience, Hoboken, 2005.
7. (*a*) M. J. Earle and K. R. Seddon, *Pure Appl. Chem.*, 2000, **72**, 1391; (*b*) K. R. Seddon, *Nat. Mater.*, 2003, **2**, 363; (*c*) R. D. Rogers and K. R. Seddon, *Science*, 2003, **302**, 792.
8. M. Kanakubo, T. Umecky, Y. Hiejima, T. Aizawa, H. Nanjo and Y. Kameda, *J. Phys. Chem. B*, 2005, **109**, 13847.
9. P. Wasserscheid and T. Welton, *ILs in Synthesis*, Wiley-VCH, Weinheim, Germany, 2003.
10. R. M. Lynden-Bell, M. G. Del Pópolo, T. G. A. Youngs, J. Kohanoff, C. G. Hanke, J. B. Harper and C. C. Pinilla, *Acc. Chem. Res.*, 2007, **40**, 1138.
11. Y. Wang, W. Jiang, T. Yan and G. A. Voth, *Acc. Chem. Res.*, 2007, **40**, 1193.
12. E. J. Maginn, *Acc. Chem. Res.*, 2007, **40**, 1200.
13. P. A. Hunt, *Mol. Simul.*, 2006, **32**, 1.
14. A. A. H. Pádua, M. F. C. Gomes and J. N. A. C. Lopes, *Acc. Chem. Res.*, 2007, **40**, 1087.
15. L. P. N. Rebelo, J. N. C. Lopes, J. M. S. S. Esperanca, H. J. R. Guedes, J. Lachwa, V. Najdanovic-Visak and Z. P. Visak, *Acc. Chem. Res.*, 2007, **40**, 1114.
16. M. G. Del Pópolo, J. Kohanoff, R. M. Lynden-Bell and C. Pinilla, *Acc. Chem. Res.*, 2007, **40**, 1156.
17. E. A. Turner, C. C. Pye and R. D. Singer, *J. Phys. Chem. A*, 2003, **107**, 2277.
18. P. A. Hunt, I. R. Gould and B. Kirchner, *Aust. J. Chem.*, 2007, **60**, 9.
19. Y. Wang, H. Li and S. Han, *J. Chem. Phys.*, 2005, **123**, 174501.
20. P. A. Hunt and I. R. Gould, *J. Phys. Chem. A*, 2006, **110**, 2269.
21. K. E. Gutowski, J. D. Holbrey, R. D. Rogers and D. A. Dixon, *J. Phys. Chem. B*, 2005, **109**, 23196.
22. K. Dong, S. Zhang, D. Wang and X. Yao, *J. Phys. Chem. A*, 2006, **110**, 9775.
23. T. Köeddermann, C. Wertz, A. Heintz and R. Ludwig, *ChemPhysChem*, 2006, **7**, 1944.
24. S. Tsuzuki, H. Tokuda, K. Hayamizu and M. Watanabe, *J. Phys. Chem. B*, 2005, **109**, 16474.
25. P. A. Hunt, *J. Phys. Chem. B*, 2007, **111**, 4844.
26. S. Tsuzuki, H. Tokuda and M. Mikami, *Phys. Chem. Chem. Phys.*, 2007, **9**, 4780.
27. P. A. Hunt, B. Kirchner and T. Welton, *Chem.–Eur. J.*, 2006, **12**, 6762.
28. (*a*) B. L. Bhargava and S. Balasubramanian, *J. Chem. Phys.*, 2007, **127**, 114510; (*b*) B. L. Bhargava, M. L. Klein and S. Balasubramanian, *ChemPhysChem*, 2008, **9**, 67.
29. R. Car and M. Parrinello, *Phys. Rev. Lett.*, 1985, **55**, 2471.
30. J. Hutter, M. Tuckerman and M. Parrinello, *J. Chem. Phys.*, 1995, **102**, 859.
31. M. Tuckerman, P. J. Ungar, T. von Rosenvinge and M. L. Klein, *J. Phys. Chem.*, 1996, **100**, 12878.
32. D. Marx and J. Hutter, *Ab initio Molecular Dynamics: Theory and Implementation*, 2000, http://www.fz-juelich.de/nic-series.
33. I.-C. Lin, M. D. Coutinho-Neto, C. Felsenheimer, O. A. von Lilienfeld, I. Tavernelli and U. Röthlisberger, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2007, **75**, 205131.
34. M. G. Del Pópolo, R. M. Lynden-Bell and J. Kohanoff, *J. Phys. Chem. B*, 2005, **109**, 5895.
35. M. Bühl, A. Chaumont, R. Schurhammer and G. Wipff, *J. Phys. Chem. B*, 2005, **109**, 18591.
36. (*a*) B. L. Bhargava and S. Balasubramanian, *Chem. Phys. Lett.*, 2006, **417**, 486; (*b*) B. L. Bhargava and S. Balasubramanian, *J. Chem. Phys.*, 2005, **123**, 144505.
37. M. G. Del Pópolo, J. Kohanoff and R. M. Lynden-Bell, *J. Phys. Chem. B*, 2006, **110**, 8798.
38. B. L. Bhargava and S. Balasubramanian, *J. Phys. Chem. B*, 2007, **111**, 4477.
39. B. Kirchner and A. P. Seitsonen, *Inorg. Chem.*, 2007, **46**, 2751.
40. (*a*) A. D. Becke, *Phys. Rev. A: At., Mol., Opt. Phys.*, 1988, **38**, 3098; (*b*) J. P. Perdew, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1986, **34**, 7406.
41. C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1988, **37**, 785.
42. C. Hardacre, J. D. Holbrey, S. E. J. McMath, D. T. Bowron and A. K. Soper, *J. Chem. Phys.*, 2003, **118**, 273.
43. C. E. R. Prado, M. G. Del Pópolo, T. G. A. Youngs, J. Kohanoff and R. M. Lynden-Bell, *Mol. Phys.*, 2006, **104**, 2477.
44. S. G. Kazarian, B. J. Briscoe and T. Welton, *Chem. Commun.*, 2000, 2047.
45. C. G. Hanke, S. L. Price and R. M. Lynden-Bell, *Mol. Phys.*, 2001, **99**, 801.
46. J. de Andrade, E. S. Boes and H. Stassen, *J. Phys. Chem. B*, 2002, **106**, 3546.
47. J. K. Shah, J. F. Brennecke and E. J. Maginn, *Green Chem.*, 2002, **4**, 112.
48. C. J. Margulis, H. A. Stern and B. J. Berne, *J. Phys. Chem. B*, 2002, **106**, 12017.
49. Z. Liu, S. Huang and W. Wang, *J. Phys. Chem. B*, 2004, **108**, 12978.
50. (*a*) J. N. C. Lopes, J. Deschamps and A. A. H. Pádua, *J. Phys. Chem. B*, 2004, **108**, 2038; (*b*) J. N. C. Lopes, J. Deschamps and A. A. H. Pádua, *J. Phys. Chem. B*, 2004, **108**, 11250.
51. J. N. C. Lopes and A. A. H. Pádua, *J. Phys. Chem. B*, 2004, **108**, 16893.
52. J. N. C. Lopes and A. A. H. Pádua, *J. Phys. Chem. B*, 2006, **110**, 7485.
53. X. Liu, S. Zhang, G. Zhou, G. Wu, X. Yuan and X. Yao, *J. Phys. Chem. B*, 2006, **110**, 12062.
54. J. N. C. Lopes and A. A. H. Pádua, *J. Phys. Chem. B*, 2006, **110**, 19586.
55. G. Zhou, X. Liu, S. Zhang, G. Yu and H. He, *J. Phys. Chem. B*, 2007, **111**, 7078.
56. T. Yan, C. J. Burnham, M. G. Del Pópolo and G. A. Voth, *J. Phys. Chem. B*, 2004, **108**, 11877.
57. T. G. A. Youngs, M. G. Del Pópolo and J. Kohanoff, *J. Phys. Chem. B*, 2006, **110**, 5697.
58. T. I. Morrow and E. J. Maginn, *J. Phys. Chem. B*, 2002, **106**, 12807.
59. Z. Liu, X. Wu and W. Wang, *Phys. Chem. Chem. Phys.*, 2006, **8**, 1096.
60. N. M. Micaelo, A. M. Baptista and C. M. Soares, *J. Phys. Chem. B*, 2006, **110**, 14444.
61. Y. Wang, S. Izvekov, T. Yan and G. A. Voth, *J. Phys. Chem. B*, 2006, **110**, 3564.
62. B. L. Bhargava, R. Devane, M. L. Klein and S. Balasubramanian, *Soft Matter*, 2007, **3**, 1395.
63. S. M. Urahata and M. C. C. Ribeiro, *J. Chem. Phys.*, 2004, **120**, 1855.
64. C. J. Margulis, *Mol. Phys.*, 2004, **102**, 829.
65. C. G. Hanke, A. Johansson, J. B. Harper and R. M. Lynden-Bell, *Chem. Phys. Lett.*, 2003, **374**, 85.
66. Y. Shim, J. Duan, M. Y. Choi and H. J. Kim, *J. Chem. Phys.*, 2003, **119**, 6411.
67. (*a*) Y. Shim, M. Y. Choi and H. J. Kim, *J. Chem. Phys.*, 2005, **122**, 044510; (*b*) Y. Shim, M. Y. Choi and H. J. Kim, *J. Chem. Phys.*, 2005, **122**, 044511.
68. H. V. R. Annapureddy, Z. Hu, J. Xia and C. J. Margulis, *J. Phys. Chem. B*, 2008, **112**, 1770.
69. Z. Hu and C. J. Margulis, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 831.
70. Z. Hu and C. J. Margulis, *Acc. Chem. Res.*, 2007, **40**, 1097.
71. R. M. Lynden-Bell, *Mol. Phys.*, 2003, **101**, 2625.
72. A. Chaumont, R. Schurhammer and G. Wipff, *J. Phys. Chem. B*, 2005, **109**, 18964.
73. B. L. Bhargava and S. Balasubramanian, *J. Am. Chem. Soc.*, 2006, **128**, 10073.
74. S. Rivera-Rubero and S. Baldelli, *J. Phys. Chem. B*, 2006, **110**, 4756.
75. X. Huang, C. J. Margulis, Y. Li and B. J. Berne, *J. Am. Chem. Soc.*, 2005, **127**, 17842.
76. C. Cadena, J. L. Anthony, J. K. Shah, T. I. Morrow, J. F. Brennecke and E. J. Maginn, *J. Am. Chem. Soc.*, 2004, **126**, 5300.
77. H. Tokuda, K. Hayamizu, K. Ishii, A. B. H. Susan and M. Watanabe, *J. Phys. Chem. B*, 2004, **108**, 16593.
78. Z. Gu and J. F. Brennecke, *J. Chem. Eng. Data*, 2002, **47**, 339.

79. (*a*) E. Sloutskin, B. M. Ocko, I. Kuzmenko, T. Gog and M. Deutsch, *J. Am. Chem. Soc.*, 2005, **127**, 7796; (*b*) E. Sloutskin, B. M. Ocko, I. Kuzmenko, T. Gog and M. Deutsch, *J. Am. Chem. Soc.*, 2005, **127**, 18333.
80. A. Triolo, A. Mandanici, O. Russina, V. Rodriguez-Mora, M. Cutroni, C. Hardacre, M. Nieuwenhuyzen, H. Bleif, L. Keller and M. A. Ramos, *J. Phys. Chem. B*, 2006, **110**, 21357.
81. C. Hardacre, S. E. J. McMath, M. Nieuwenhuyzen, D. T. Bowron and A. K. Soper, *J. Phys.: Condens. Matter*, 2003, **15**, S159.
82. D. Frenkel and B. Smit, *Understanding molecular simulation: From algorithms to applications*, Academic, New York, 1996.
83. J. K. Shah and E. J. Maginn, *Fluid Phase Equilib.*, 2004, **222–223**, 195.
84. J. K. Shah and E. J. Maginn, *J. Phys. Chem. B*, 2005, **109**, 10395.
85. I. Urukova, J. Vorholz and G. Maurer, *J. Phys. Chem. B*, 2005, **109**, 12154.
86. J. I. Siepmann, in *Computer simulations of biomolecular systems: theoretical and experimental applications*, ed. W. F. Gunsteren, P. K. Weiner and A. J. Wilkinson, Escom Science Publisher, Leiden, 1993, p. 249.
87. D. M. Small, *The physical chemistry of lipids: From alkanes to phospholipids*, Plenum, New York, 1986.
88. M. Tarek, S. Bandyopadhyay and M. L. Klein, *J. Mol. Liq.*, 1998, **78**, 1.
89. T. Köddermann, D. Paschek and R. Ludwig, *ChemPhysChem*, 2008, **9**, 549.
90. J. N. C. Lopes and A. A. H. Pádua, *J. Phys. Chem. B*, 2006, **110**, 3330.
91. A. Triolo, O. Russina, H. Bleif and E. D. Cola, *J. Phys. Chem. B*, 2007, **111**, 4641.
92. Y. Wang and G. A. Voth, *J. Am. Chem. Soc.*, 2005, **127**, 12192.
93. S. O. Nielsen, C. F. Lopez, G. Srinivas and M. L. Klein, *J. Phys.: Condens. Matter*, 2004, **16**, R481.
94. W. Shinoda, R. Devane and M. L. Klein, *Mol. Simul.*, 2007, **33**, 27.
95. S. Lee, *Chem. Commun.*, 2006, 1049.
96. M. G. Del Pópolo and G. A. Voth, *J. Phys. Chem. B*, 2004, **108**, 1744.
97. Z. Hu and C. J. Margulis, *J. Phys. Chem. B*, 2007, **111**, 4705.
98. M. S. Kelkar and E. J. Maginn, *J. Phys. Chem. B*, 2007, **111**, 4867.
99. H. Ohno and K. Fukumoto, *Acc. Chem. Res.*, 2007, **40**, 1122.
100. N. M. Micaêlo and C. M. Soares, *J. Phys. Chem. B*, 2008, **112**, 2566.
101. W. Shi and E. J. Maginn, *J. Phys. Chem. B*, 2008, **112**, 2045.
102. C. M. Gordon, J. D. Holbrey, A. R. Kennedy and K. R. Seddon, *J. Mater. Chem.*, 1998, **8**, 2627.
103. C. Chiappe and D. Pieraccini, *J. Phys. Org. Chem.*, 2005, **18**, 275.
104. J. Dupont and P. A. Z. Suarez, *Phys. Chem. Chem. Phys.*, 2006, **8**, 2441.
105. S. Tiwari and A. Kumar, *Angew. Chem., Int. Ed.*, 2006, **45**, 4824.