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Universal Scaling Behavior of Entropy and Conductivity in Ionic Liquids

S. Cheng¹, M. Musial^{1*}, Z. Wojnarowska¹, K. L. Ngai², J. Jacquemin^{3,4,5}, M. Paluch^{1*}

 ¹Institute of Physics, University of Silesia in Katowice, Silesian Center for Education and Interdisciplinary Research, 75 Pułku Piechoty 1A, 41–500 Chorzów, Poland
 ²CNR-IPCF, Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, I-56127, Pisa, Italy
 ³QUILL Research Centre, School of Chemistry and Chemical Engineering, Queen's University Belfast, David Keir Building, Belfast, Northern Ireland BT9 5AG, United Kingdom
 ⁴Laboratoire PCM2E, Université de Tours, Parc de Grandmont 37200 Tours, France
 ⁵ Materials Science and Nano-Engineering, Mohammed VI Polytechnic University, Lot 660-Hay Moulay Rachid, Ben Guerir, Morocco

Corresponding author: malgorzata.musial@smcebi.edu.pl; marian.paluch@us.edu.pl

ABSTRACT: The density scaling behavior of dynamics and thermodynamics is investigated in ionic liquids. By comparing the scaling exponent of different dynamic quantities (dc-conductivity, viscosity, and diffusion) of a series of homologous ionic liquids, we discover that longer alkyl chain in the cation provides lower scaling value. Additionally, a systematic study on the entropy scaling behavior is carried out based on various samples within different structures and strength of interactions between anions and cations. Interestingly, for all tested samples, a linear relationship between Grüneisen parameter (scaling exponent) and entropy was obtained, and more importantly, the generated slope shows a close relation to the typical interactions (van der Waals and Coulomb forces, and *H*-bonds). Therefore, we establish a new correlation for this group of compounds.

INTRODUCTION

A century has passed since the discovery of the first ionic liquid (IL) by Walden in 1914. The ionic liquids (ILs) research field continues to grow as more families of ILs are synthesized and developed. ILs are composed of discrete cations and anions that can be individually customized, allowing the design of ILs with tunable physical, chemical, and biological properties suitable for various applications, including green chemistry, energy storage, and pharmaceutical industry [1,2,3,4].

Because of their excellent glass-forming ability and superior thermal stability, ILs offer new opportunities to investigate long-standing problems i.e. the dynamics and thermodynamics of glass transition, as well as the corresponding ion transport properties, over extreme broad temperature and pressure ranges. For this reason, many studies on the dynamic and mechanical properties (*e.g.* structural and conductivity relaxation times, conductivity, and viscosity) of these unique materials have been carried out under different thermodynamic conditions. However, so far there is no generally accepted model and theory to either fully explain these properties or predict the key variables over the range from simple dynamics at high temperatures to complex dynamics at lower temperatures approaching T_g . An alternative solution to this problem can be offered by the concept of density scaling:

$$x = f(TV^{\gamma_x}) \tag{1}$$

where x represents any of the physical variables such as the structural relaxation time quantifying the molecular dynamics, V is the specific volume, T is the temperature, and γ_x is the scaling exponent.

This approach assumes that dynamic quantities including viscosity, conductivity, relaxation time or diffusion coefficient can be scaled onto a single master-curve when plotted versus TV^{γ_x} [5,6,7].The magnitude of the parameter γ_x reflects the steepness of the repulsive part of the effective short-range intermolecular potential [8] and thus it is a material constant directly related to the structure of a given material. If the thermodynamic scaling is satisfied for a given system one can predict the dynamic properties at any temperature and pressure conditions. Thermodynamic scaling has been already confirmed for many van der Waals liquids and polymers [9,10]. Very recently, our group studied the density scaling of dc-conductivity on two ILs: 1-butyl-2,3-dimethylimidazolium bis(trifluoromethylsulfonyl)imide ([BMMIm][TFSI]) and 1-butyl-3-methylimidazolium acetate ([BMIm][OAc]) [11]. For these ILs differing significantly in the strength of the interactions between the ionic species, the thermodynamic scaling law has been successfully verified over a broad density range with a state-point-independent value of γ_{σ} (scaling exponent for dc-conductivity, σ_{dc}).

By using a revised entropy model of the glass transition dynamics originally proposed by Avramov [12], the authors of ref. [13] suggested that the entropy, S, for a supercooled liquid satisfies under some approximations a scaling law,

$$S(T,V) = f(TV^{\gamma_G}), \tag{2}$$

where the scaling exponent γ_G is the thermodynamic Grüneisen parameter [14,15]. The entropy calculated from experimental data of molecular glass-formers under different *T* and *V* has confirmed approximately Eq.(2) [16,17,18,19]. Generally, for any model in which the relaxation time is a function of the entropy, the scaling exponent γ_x in Eq.(1) should be equal to γ_G according to the analysis presented in Refs. [13,16]. However, the value of the exponent γ_G is significantly smaller than the parameter γ_x . Therefore, Grzybowska *et al.* [19] suggested that the system entropy *S* is not sufficient to govern the structural relaxation time τ of molecular glassformer. It has been also reported that the entropy of IL (1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide [BMIm][TFSI]) conforms to density scaling, with the scaling exponent identified with the Grüneisen parameter [19]. Nevertheless, the calculations of *S* were made over a narrow range corresponding to temperature and pressure ranges of ΔT =30 K, ΔP =200 MPa. The data of *S* collapsed to a single master curve with relatively low precision by using a constant value of the scaling exponent [19].

In this work, we investigate the density scaling behavior of dc-conductivity and entropy of 1-ethyl-3-methylimidazolium diethylphosphate ([EMIm][DEP]) over a broad range of T, P, and V. We find that density scaling exponent of dc-conductivity is state-point independent. It fluctuates around the average of 2.15 ± 0.03 when the volume changes of 13%. We also find a relationship between the Grüneisen parameter and the entropy for the studied IL, from which a single master curve can be constructed. Furthermore, due to the wealth of *PVT* data for ILs in the

literature [20], we have selected 15 additional systems to investigate the density scaling of entropy. In this way, the effects of strength of various intermolecular interactions between cations and anions can be systematically analyzed and a general conclusion may be drawn from the results.

METHODS

Materials.

Anhydrous solvents, such as *N*-methylimidazole (CAS number: 616-47-7; purity: 99%+), triethyl phosphate (CAS number: 78-40-0; purity: 99.8%), dimethyl sulfoxide-d₆ (CAS number: 2206-27-1; purity: 99%+ with 99.96 atom %D), diethyl ether (CAS number: 60-29-7; purity: 99.7%+), were supplied by Sigma Aldrich and used directly as received.

Synthesis of the [EMIM][DEP]. 1-Ethyl-3-methylimidazolium diethylphosphate (CAS number 848641-69-0; purity >98%) was synthesized at QUILL (*Queen's University Ionic Liquid Laboratories*) by following the methodology reported below which is comparable to that reported originally in the literature [21,22].

Briefly, *N*-methylimidazole (8.2 g, 0.1 mol) and an equimolar amount of triethyl phosphate (18.2 g, 0.1 mol) were added to a Carius tube and flushed with nitrogen. After sealing and covering in aluminium foil the tube was then heated to 373.15 K for 24 hrs. The resulting liquid was washed with diethyl ether $(3\times20 \text{ cm}^3)$ at room temperature followed by drying under reduced pressure (1 Pa) at 353 K overnight to remove starting materials and solvent residues. After washing and drying the ionic liquid resulting yield was 21.9 g, 83%. Before measurements, the sample was again dried and degassed under low pressure (1 Pa) at temperatures not exceeding 373 K. IL was kept under a nitrogen atmosphere and then used without any further purification. The purity of the sample was firstly estimated by considering the water level in the sample (lower than 0.01 wt/wt% (or 100 ppm) by Karl Fischer Coulometric titration using an 899 Coulometer, Metrohm) and by comparing ¹H and ¹³C NMR spectra recorded at 293 K on a Bruker Avance DPX spectrometer at respectively 300 MHz and 75 MHz with those published by either Kuhlmann *et al.* [22] or Hiraga *et al.* [23] as shown in the Figs S1 and S2 of the supporting information (SI).

The purity of the sample was then assessed by comparing systematically density (ρ), speed of sound (c), viscosity (η) and molar isobaric heat capacity (C_p) datasets collected during this work at 0.1 MPa with those available in the literature reported in the Tables S1-S4 of the SI.

Density, speed of sound, and viscosity measurements. The density and the speed of sound of the [EMIm][DEP] were simultaneously determined from 293.15 to 363.15 K (u(T) = 0.01 K) at atmospheric pressure using a DSA 5000 M from Anton Paar. An extended calibration of this equipment was done by following the recommendations of the manufacturer with dry air and redistilled water. Furthermore, great care was also given during the interpretation of speed of sound data [24], as the [EMIm][DEP] was reported as a nondispersive media for temperature

higher than 308.15 K (*i.e.* with a similar transducer operating at a frequency of 3 MHz) [25]. The uncertainty of each property and stated conditions, reported in the footnote of Tables S1-S2 in SI, were determined by the following advice reported in the literature [26].

The viscosity of the IL was measured using a Bohlin Gemini Rotonetic Drive 2 cone and plate rheometer (\pm 1% repeatability) from 293.15 to 373.15 K (u(*T*) = 0.01 K) at atmospheric pressure. The rheometer was calibrated using ultra-pure water and an oil viscosity standard (ASTM Oil Standard S600, Cannon, 1053 mPa·s at 298.15 K). From this study, the relative uncertainty of the reported viscosity measurements, u_r(η) did not exceed 3%.

Conductivity Measurements. The dielectric measurements at ambient pressure for [EMIm][DEP] series were carried out in a nitrogen atmosphere over a frequency range from 10^{-1} Hz to 10^7 Hz using Novo-Control GMBH Alpha dielectric spectrometer. At the beginning of measurements each sample was equilibrated in active sample cell (two stainless steel electrodes of diameter, d = 15 mm separated by quartz ring; distance between plates of the capacitor was constant and equal to 0.08 mm) for 1 h at 373 K. Then, the material was cooled down to the glassy state. The applied cooling rate was 5 K·min⁻¹. The temperature was controlled by the Novo-control Quattro system with a nitrogen gas cryostat. The temperature stability was within ±0.1 K. The errors from calibration, temperature (u(T) = 0.1 K), and pressure (u(p) = 2 kPa) control yield an uncertainty of 5% of dc-conductivity determined herein.

High-pressure conductivity measurements. The conductivity measurements under highpressure conditions were carried out with the use of capacitor $\Phi = 10$ mm, filled with the studied sample. The capacitor was hermetically closed and placed in the high-pressure chamber. Compression was achieved by using the silicone oil, however without any contact between sample and oil. The pressure was measured by the Unipress setup with the pressure resolution of 1 MPa. The temperature was stabilized by means of a Weiss fridge with an error of 0.1 K. The errors from calibration, temperature (u(T) = 0.1 K), and pressure (u(p) = 1 MPa) control yield an uncertainty of 7% of dc-conductivity determined herein.

Temperature Modulated Differential Scanning Calorimetry (TMDSC). Calorimetric experiments were performed by a Mettler Toledo DSC1STAR System equipped with a liquid nitrogen cooling accessory and an HSS8 ceramic sensor with 120 thermocouples. Enthalpy and temperature calibrations were performed using indium and zinc standards. During these measurements, the tested samples (about 25mg) were placed in aluminum crucibles with a 40 μ L volume and the flow of nitrogen was 60 mL·min⁻¹. The measurements were performed in the temperature range from 220 to 373 K with a heating rate of 0.5 K·min⁻¹ and the temperature amplitude of the pulses equal to 1 K.

RESULTS AND DISCUSSION

Density scaling of dynamic quantities

The conductivity of [EMIm][DEP] under isobar 0.1 MPa and five isotherms were studied by means of broadband dielectric spectroscopy (see Methods for details). Representative dielectric spectra collected in the frequency interval ranging from 10^{-1} to 10^{6} Hz are demonstrated in the conductivity formalism, $\sigma'(f)$ in Fig. S3 of the SI. Three distinctly visible regions can be observed in spectra *i.e.*, *i.* a low-frequency deviation from the plateau attributed to the polarization effect, typical for ion-conducting materials; *ii.* a frequency-independent region known as the dc-conductivity, σ_{dc} ; and *iii.* the power-law behavior observed at higher frequencies. The key quantity considered in this work is dc-conductivity.

For our purpose to present the dc-conductivity as a function of T and V, the modified Tait-equation (Eq. 3) is applied to analyze the high-pressure density dataset reported in Ref. [23].

$$V(T,P) = (A_0T^2 + A_1T + A_2) \left\{ 1 - C \times ln \left[1 + \frac{P}{b_0 exp(-b_1T)} \right] \right\}$$
(3)

where A_0 , A_1 , A_2 , C, b_0 , and b_1 are parameters. According to the determined parameters of Eq. 3, the requested *PVT* data were extrapolated to the same *T* and *P* conditions as those applied during dc-conductivity measurements. Consequently, we have transformed the $\sigma_{dc}(T,P)$ data determined in this work to *T-V* representation. The results are shown in a 3D plot (Fig. S4A in SI). These data cover both the supercooled and normal liquid states of [EMIm][DEP]. As a result, the ion dynamics represented by σ_{dc} can be followed over 13 orders of magnitude corresponding to volume fluctuations of 13%. As seen from Fig. S3 in SI, the σ_{dc} data decrease with either isobaric cooling or isothermal compression.

Different approaches to determine the dc-conductivity scaling parameter are reported in the literature [18, 27,28]. Herein, we employed a model-independent procedure [29]. Namely, based on the experimental $-\log_{10}\sigma_{dc}(T, V)$ data presented in Fig. S4A in SI, we have determined a set of $\log_{10}T(-\log_{10}V)$ dependences at each constant $-\log_{10}\sigma_{dc}$ (*i.e.*, $-\log_{10}\sigma_{dc}=3,4,5,...,13$). It can be seen in the inset of Fig. S4A that each obtained iso-conductivity $\log_{10}T(-\log_{10}V)$ dependence can be well described by s simple linear fit. According to Eq.1, the yielding slope is equal to the scaling exponent γ_{σ} . In Fig. S4A in SI, two planes perpendicular to the $-\log_{10}\sigma_{dc}$ axis are chosen to show the method as examples. By following this methodology, the averaged γ_{σ} coefficient is close to 2.15±0.03 for the tested IL. By using this value, a superposed single master curve is obtained by plotting $\sigma_{dc} vs$. $TV^{\gamma_{\sigma}}$ with high precision (Fig. S4B in SI).

Interestingly, it has been reported that other dynamic quantities of ILs, such as viscosity, relaxation times, and diffusion coefficient, also satisfied this density scaling law, *i.e.* the scaling exponent is a state-point-independent parameter. Herein, we collect the scaling exponents of various ILs [11,30,31,32] having different strength of interionic interactions (Fig. 1).



Fig. 1. The density scaling exponents of dynamic properties (dc-conductivity, viscosity, and diffusion coefficient) of several ILs having different dominant interactions. Data are taken from: ref. [11] ([BMMIm][TFSI] and [BMIm][OAc]); ref. [30] ([BMIm][BF₄], [HMIm][BF₄], [OMIm][BF₄], [BMIm][PF₆], [HMIm][PF₆], [OMIm][PF₆], and [HMIm][TFSI]); ref. [32] ([OMIm][TFSI]; ref. [30] ([BMIm][TFSI]); visocosity and diffusion coefficient); ref. [31] ([BMIm][TFSI]-dc-conductivity).

As seen from Fig. 1, the exponents obtained from scaling of different dynamic quantities within the single ionic liquid are not the same. However, at the same time, the ratio of $\gamma_{\sigma}/\gamma_{\eta}$ (where γ_n is the scaling exponent of viscosity) is close to unity which results from the coupling between ion transport dynamics and structural relaxation in aprotic ionic liquids. Interestingly, in each homologous series, a clear decrease of dynamic scaling exponent with an increase of alkyl chain length is observed. To explain this result, we return to the relationship between scaling exponent and intermolecular potential. In general, the intermolecular potential is composed of an attractive part and a repulsive part represented by a two-body power law [8,33,34] and the scaling exponent is determined by the steepness of the resultant intermolecular potential at a short distance where the repulsive part dominates. From this point of view, the effect of the attractive part on the scaling exponent cannot be ignored, especially, in terms of ILs where electrostatic attractions are dominated. Moreover, based on the analysis of the single-component Lennard-Jones system, the attractive term increases the steepness of the effective repulsive part, and thus increases the power-law exponent [35]. For imidazolium-based ILs, longer alkyl chain attached onto the imidazolium ring is more effective in screening the electrostatic forces and then results in weaker attractive interaction which contributes to a lower value of the power-law exponent.

Density scaling of entropy and its relation to the structure of ILs

Based on the *PVT* data, we can investigate the total entropy under different thermodynamic conditions by using the well-known thermodynamic relation,

$$S(T,P) = S_{\rm r} + \int_{T_{\rm r}}^{T} C_p(T,P_{\rm r}) \, dlnT - \int_{P_{\rm r}}^{P} (\partial V(T,P)/\partial T)_P dP \tag{4}$$

where S_r is the entropy under the reference condition. The C_p is the molar isobaric heat capacity at 0.1 MPa obtained from the Temperature Modulated Differential Scanning Calorimetry (TM-DSC).



Fig. 2. A) The isothermal and isobaric values of S- S_r of [EMIm][DEP] plotted in a 3D plane in terms of T and V. **B**) Density scaling plots of S- S_r of [EMIm][DEP]. **Inset of A**: the results from the horizontal crossing of the S- S_r data of [EMIm][DEP]. **Inset of B**: the linear variation of the entropy scaling exponent for [EMIm][DEP] calculated from the slope of the lines in the inset of **A**.

Moreover, it has been derived that the entropy can be well represented by:

$$S(T,V) = S_r + C_V \ln(TV^{\gamma_s})$$
⁽⁵⁾

where C_V is the molar isochoric heat capacity which could be easily calculated using the thermodynamic relationship between C_p and C_V . However, the scaling exponent γ_s for *S* is different from γ_σ for conductivity [11] and γ_s is supposed to be γ_G defined as Grüneisen parameter and given by [13]

$$\gamma_G = \frac{V_m \alpha_P}{C_V \kappa_T} \tag{6}$$

where $V_{\rm m}$ is the molar volume, α_p the isobaric thermal expansion, and κ_T the isothermal compressibility. According to the definition of γ_G , one can anticipate that its value should change with the thermodynamic conditions since the thermodynamic variables ($V_{\rm m}$, α_p , and κ_T) are in general functions of temperature and pressure. Therefore, the collapse of all data into a single curve cannot be achieved using a constant value of γ_G .

Having the generated *PVT* data in the same wide density regime as dc-conductivity, we calculated the values of S(T,P) using Eq. 4 with the C_p from TMDSC. For our purpose, we converted S(T,P) to S(T,V) and determined the values of γ_G applying the same method as in the case of dc-conductivity *i.e.*, the model-independent procedure. Based on the S(T,V) data presented in Fig. 2A, we chose six different values of entropy covering all the investigated thermodynamic range. Two of them are presented in Fig. 2A as examples. Consequently, six $\log_{10}T(-\log_{10}V)$ dependencies are determined. It can be seen in the inset of Fig. 2A that each of them can be well described by simple linear fit with a slope yielding the exponent γ_G , and it is

denoted herein by $\gamma_G(S)$ to indicate that Grüneisen parameter is a function of entropy. A monotonic decrease of $\gamma_G(S)$ with increasing *S*-*S*_r was obtained. This simple change of $\gamma_G(S)$ with entropy draws our attention to assume that there may be a linear relationship between these two quantities. Therefore, we plotted $\gamma_G(S)$ as a function of *S*-*S*_r. As expected, we obtained a linear function with high precision. The results are shown in the inset of Fig. 2B. But now the question is whether the $\gamma_G(S)$ obtained in this way can satisfy the density scaling of entropy in ILs? How it works in practice is illustrated in Fig. 2B. It is evident that all isothermal and isobaric curves can be collapsed into a perfect master curve using a $\gamma_G(S)$ as a function of *S*-*S*_r.

Importantly, we have chosen more ionic liquids with various combinations of anions and cations to confirm the behaviour pattern reported above. Specifically, a reasonably good scaling curve *S*-*S*_r *vs.* $TV^{\gamma_G(S)}$ can be obtained for each selected IL over a broad thermodynamic range with $\gamma_G(S)$ being a linear function of *S*-*S*_r. The entropy scaling results of these ILs are present in Fig. 3A and 3B. The data of *PVT* data and *C*_p at ambient pressure for these ILs are taken from the literature [36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62].



Fig. 3. A) The linear relation between $\gamma_G(S)$ and S- S_r of chosen ILs having distinct compositions of ions. B) The density scaling superposed curves of entropy of the chosen ILs. The corresponding *PVT* and C_p data are taken from: a. ref. [39] and [46]; b. ref. [47] and [48]; c. ref. [39] and [49]; d. ref. [43] and [50]; e. ref. [42] and [53]; f. ref. [40] and [51]; g. ref. [41] and [52]; h. ref. [37] and [57]; i. ref. [38] and [57]; j. ref. [45] and [54]; k. ref. [55] and [55]; l. ref. [62] and [57]; m. ref. [61] and [60]; n. ref. [58] and [60]; o. ref. [56] and [60].

The chosen ILs have different ions and thus different intermolecular interactions. Consequently, the slope *k* of the linear function connecting the scaling exponent with the entropy varies in a broad range from -3.71×10^{-3} to -0.91×10^{-3} , and the absolute values are shown in Fig. 4. Interestingly, the change of these values is not random but closely related to the typical interactions: van der Waals forces, Coulomb forces, and *H*-bonds. Specifically, the slope decreases with increasing carbon chain length in anion or cation. Such behavior has been found for $[C_2SO_4]^-$ and $[C_8SO_4]^-$ (absolute value of *k* decrease from 3.35×10^{-3} to 0.91×10^{-3}), and is also

observed for [EMIm]⁺, [BMIm]⁺ and [OMIm]⁺ (Fig. 4). Thus, the slope decreases as van der Waals interactions increase with the length of the alkyl chain and Coulomb forces decrease at the same time. Additionally, we find that for ILs with TFSI anion, in which van der Waals and electrostatic forces are very similar (i.e., [BMpyr][TFSI], [BMMIm][TFSI], [N₄₁₁₁][TFSI], [BMIm][TFSI]), the slope decreases with increasing of hydrogen bonds contribution. The highest values were obtained for [BMPyr][TFSI], [BMMIm][TFSI] with negligible donoracceptor capabilities, and the lowest was determined for [BMIm][TFSI] which easily forms hydrogen bonds between cation and anion. We can also assume that strong electrostatic intermolecular interactions drive the high value of |k| e.g., for [BMIm][SCN] > [BMIm][BF₄] > [BMIm][BETI] > [BMIm][FAP] where *H*-bond contribution is small and the van der Waals forces are similar due to the same butyl chain in both structures, therefore it is possible to compare only electrostatic forces (voluminous and heavy anions only weakly interact, whereas small and light anions provide strong Coulomb interaction potential due to their higher surface charge density). The situation is more complicated for ILs in the last group in Fig. 4, as two interactions change significantly: H-bonds and Coulomb forces. Since both abovementioned contributions change in the row: $[BMIm]Cl > [BMIm][OAc] > [BMIm][PF_6] > [BMIm][TFSI]$ and as k decreases in the same way, one can think that electrostatic forces are decisive and dominant even if the [BMIm][Cl] or [BMIm][OAc] form one of the strongest hydrogen bonds between cation and anion, strong enough to disrupt the structure of cellulose [63,64].



Fig. 4. The absolute values of the slope of the linear fitting.

CONCLUSION

Summarizing, in this paper, we analyzed the density scaling of the dc-conductivity of [EMIm][DEP]. In a broad thermodynamic range, the conductivity data, covering 13 orders of magnitude, collapse onto a single master curve when plotted versus $TV^{\gamma_{\sigma}}$, with a constant scaling exponent γ_{σ} . At the same time, the density scaling of other dynamic properties, *e.g.*, viscosity, relaxation time, and diffusion, is recalled to show its general validity in the class of ILs. On the

other hand, we found that the entropy of ILs can be scaled by TV^{γ_S} well with $\gamma_S = \gamma_G(S)$, being a linear function of the entropy. From this point, the superposition of entropy data onto a single master curve was successfully demonstrated. Since ILs with various dominant interactions are investigated herein (using literature *PVT* data), the scaling behavior of entropy reported in this work should be treated as universal. Additionally, we have made a systematic investigation of the relationship between the strength of intermolecular interactions (Coulombic and van der Waals interactions, and *H*-bonds) and the obtained slope, *k*. The delicate balance between all these intermolecular interactions makes it difficult to generalize the role of each force in the obtained slope. Nevertheless, we have extracted some important information including the following. (*i*) As the contribution of electrostatic forces increases, a higher absolute value of *k* is observed. (*ii*) A decrease of |k| is detected when van der Waals and hydrogen-bonding interactions increase.

In addition to improve our knowledge on the thermodynamic and dynamics properties of ILs, this work demonstrates how their physicochemical properties can be predicted for conditions beyond those measured. This has obvious utility in the design and development of new products and applications.

Corresponding Author

* malgorzata.musial@smcebi.edu.pl; marian.paluch@us.edu.pl

ORCID

M. Musiał:0000-0002-1624-6617 Z. Wojnarowska:0000-0002-7790-2999 S. Cheng:0000-0002-5615-8646 K.L. Ngai:0000-0003-0599-4094 M. Paluch: 0000-0002-7280-8557 J. Jacquemin: 0000-0002-4178-8629

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REFERENCESDeclaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:



Journal Record

Author statement

Shinian Cheng: Writing- Original draft preparation, Visualization, Methodology, Małgorzata Musiał: Writing- Reviewing and Editing, Investigation, Data curation, Visualization, Żaneta Wojnarowska: Writing- Reviewing and Editing, Visualization, K. L. Ngai: Writing- Reviewing and Editing, Johan Jacquemin: Resources, Investigation, Writing- Reviewing and Editing, Marian Paluch: Conceptualization, Supervision.

Highlights

• Density scaling of the dc-conductivity and entropy in ionic liquids was investigated.

• Longer alkyl chain in the cation provides lower scaling value.

• Linear relationship between Grüneisen parameter (scaling exponent) and entropy was determined.

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