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Charge Transport and Glassy Dynamics in Ionic Liquids

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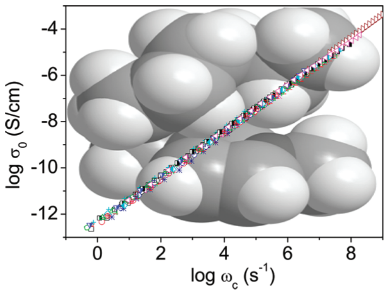

Ionic liquids (ILs) exhibit unique features such as low melting points, low vapor pressures, wide liquidus temperature ranges, high thermal stability, high ionic conductivity, and wide electrochemical windows. As a result, they show promise for use in variety of applications: as reaction media, in batteries and supercapacitors, in solar and fuel cells, for electrochemical deposition of metals and semiconductors, for protein extraction and crystallization, and many others.

Because of the ease with which they can be supercooled, ionic liquids offer new opportunities to investigate long-standing questions regarding the nature of the dynamic glass transition and its possible link to charge transport. Despite the significant steps achieved from experimental and theoretical studies, no generally accepted quantitative theory of dynamic glass transition to date has been capable of reproducing all the experimentally observed features. In this Account, we discuss recent studies of the interplay between charge transport and glassy dynamics in ionic liquids as investigated by a combination of several experimental techniques including broadband dielectric spectroscopy, pulsed field gradient nuclear magnetic resonance, dynamic mechanical spectroscopy, and differential scanning calorimetry.

Based on Einstein–Smoluchowski relations, we use dielectric spectra of ionic liquids to determine diffusion coefficients in quantitative agreement with independent pulsed field gradient nuclear magnetic resonance measurements, but spanning a broader range of more than 10 orders of magnitude. This approach provides a novel opportunity to determine the electrical mobility and effective number density of charge carriers as well as their types of thermal activation from the measured dc conductivity separately. We also unravel the origin of the remarkable universality of charge transport in different classes of glass-forming ionic liquids.

1. Introduction

Ionic liquids (ILs) are promising for manifold technological as well as fundamental applications because they exhibit unique features such as low melting points, low vapor pressures, wide liquidus ranges, high thermal stability, high ionic conductivity, and wide electrochemical windows.[1] They are under intense investigation for use as reaction media, in batteries and supercapacitors, in solar and fuel cells, for electrochemical deposition of metals and semiconductors, for protein extraction and crystallization, in nanotechnology applications, in physical chemistry, and many others. Thus, detailed knowledge of diffusion in ionic liquids is imperative for their optimal utilization in these fields. Furthermore, since ILs are also typically good glass-formers, they offer a rare opportunity to address basic questions regarding the correlation between ion conduction (translational diffusion) and the dynamic glass transition (rotational diffusion) in the broadest length- and time-scales as well as localized molecular fluctuations (secondary relaxations).[2−21] Due to its ability to measure the complex dielectric function (and consequently, the complex conductivity) over many orders of magnitude in frequency and in a wide temperature interval, broadband dielectric spectroscopy (BDS) turns out to be an ideal experimental tool for this pursuit.[22]

In this Account, we summarize recent progress in the understanding of charge transport and glassy dynamics in glass-forming ILs gained from a combination of several experimental methods including BDS, pulsed field gradient nuclear magnetic resonance (PFG NMR), differential

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scanning calorimetry (DSC), and dynamic mechanical spectroscopy (DMS). We show that the experimentally observed universality in ion conducting glasses is understood within a simple framework by considering Einstein, Stokes–Einstein, and Einstein–Smoluchowski relations. The possibility to determine diffusion coefficients in a broad range spanning more than 10 orders of magnitude from dielectric spectra is also presented.

2. Dielectric Properties of Ionic Liquids

The interaction of matter with external electromagnetic fields can be described within the framework of Maxwell's equations. Given that the response of many materials to the magnetic field is typically 4 orders of magnitude lower than the ease with which they are polarized due to electric field, molecular and collective dynamics, as well as charge transport in several classes of materials are conveniently probed using highly refined and specialized electrical techniques such as BDS.[22] At low applied electric fields, the linear response theory holds and the complex dielectric function $\varepsilon^*(\omega,T)$ as well as the complex conductivity $\sigma^*(\omega,T)$ are related by $\sigma^*(\omega,T) = i\varepsilon_0\omega\varepsilon^*(\omega,T)$, where ε_0, ω, and T denote the dielectric permittivity of free space, radial frequency, and temperature, respectively. It is readily evident that the two representations, emphasizing charge transport and molecular fluctuations of dipolar moieties, contain equivalent information. In terms of real and imaginary parts of these quantities, these can be expressed as $\sigma' = \varepsilon_0\omega\varepsilon''$ and $\sigma'' = \varepsilon_0\omega\varepsilon'$. It is worth noting that all these quantities have well-defined physical meaning; the term imaginary is only used in the mathematical sense. For instance, the imaginary part of the complex dielectric function is related to the energy dissipated by the system whereas the real part corresponds to what is usually referred to as the "dielectric permittivity" which is a measure of the energy storage in the system under investigation. Another common approach to present dielectric data of conducting amorphous materials is the electrical modulus, $M^*(\omega,T)$, which has the advantage of suppressing the contributions of mobile free charge carriers to the measured spectra. It is expressed in terms of the complex dielectric function as $M^*(\omega,T) = 1/\varepsilon^*(\omega,T)$. These three formalisms emphasize different facets of the same process. Therefore, details which are not readily evident from one approach can be recognized from the spectra in the other two representations.

Typical dielectric spectra of the ionic liquid [BMIM][BF$_4$] are presented in Figure 1. The real part of the complex conductivity σ' is characterized on the low frequency side by a plateau (the value of which directly yields the dc conductivity, σ_0) and the characteristic radial frequency, ω_c, at which dispersion sets in and turns into a power law at higher frequencies. On the other hand, the real part of the complex dielectric function ε' at $f_c = \omega_c/2\pi$ turns from the high frequency limit to the static value ε_s. At lower frequencies, it is observed that σ' decreases from σ_0 value and this is due to electrode polarization that results from the interfacial effects attributed to the slowing down of charge carriers at the electrodes.[14,15,23]

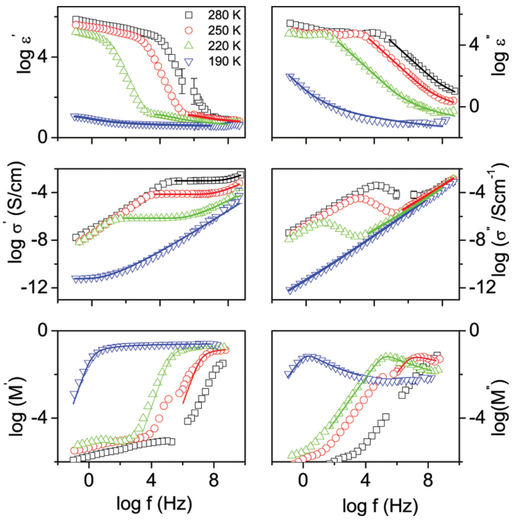

FIGURE 1. Complex dielectric, conductivity, and modulus functions for [BMIM][BF$_4$] as a function of frequency at different temperatures, as indicated. The fits are made using the analytical approximation of the random barrier model proposed by Dyre.[24] The fit parameters are as follows: for 190 K ($\sigma_0 = 8 \times 10^{-12}$ S/cm, $\tau_e = 0.09$ s); 220 K ($\sigma_0 = 8 \times 10^{-7}$ S/cm, $\tau_e = 1 \times 10^{-6}$ s); 250 K ($\sigma_0 = 5 \times 10^{-5}$ S/cm, $\tau_e = 3 \times 10^{-8}$ s); 280 K ($\sigma_0 = 1 \times 10^{-3}$ S/cm, $\tau_e = 3 \times 10^{-9}$ s) and $\varepsilon_\infty = 3 \pm 1$. The error bars are comparable to the size of the symbols, if not specified otherwise.

The dielectric response of many disordered ion-conducting solids in the charge transport-dominated regime is well described by a theoretical approach developed by Dyre.[24] Within the framework of this model, charge carriers hop in a random spatially varying potential landscape. The transport process is governed by the ability of charge carriers to overcome the randomly distributed energy barriers. The highest barrier that must be overcome to achieve an infinite cluster of hopping sites determines the onset of dc conductivity.[25] The time corresponding to the rate to overcome the highest barrier determining the dc conductivity, σ_0, is one of the characteristic parameters of the model and is denoted by τ_e. Solved within the continuous-time-random-walk approximation,[26] Dyre[24,27,28] obtained an analytical expression for the complex dielectric function as $\varepsilon^*(\omega) = \varepsilon_\infty + (\sigma_0\tau_e)/[\varepsilon_0 \ln(1 + i\omega\tau_e)]$, where ε_∞ is the (high frequency)

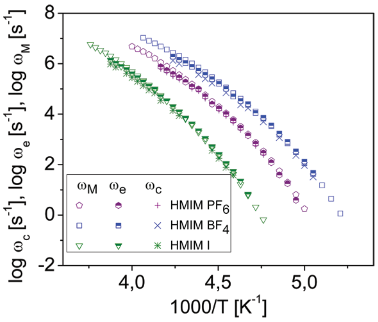

FIGURE 2. Activation plot for different characteristic electrical rates, ω_c (from σ'), ω_M (as obtained from the peak in the imaginary part of the complex modulus M'', and ω_e from the fit using the analytical equation by proposed by Dyre[24] for three different ionic liquids as indicated.[19] Reprinted with permission from *The Journal of Physical Chemistry B* **2010**, *114* (1), 382−386. Copyright 2010, American Chemical Society.

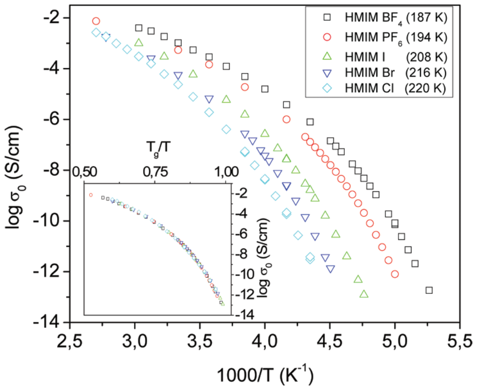

FIGURE 3. Temperature dependence of $\sigma_0(T)$ for the different ionic liquids as indicated. Inset: Scaling with respect to the calorimetric glass transition temperature (as indicated) measured by differential scanning calorimetry.[29] Reproduced by permission of the PCCP Owner Societies.

relaxed value of ε'. It can be concluded that the random barrier model quantitatively fits the experimental spectra dominated by charge transport. We have recently shown that ω_e ($= 1/\tau_e$) $\cong \omega_c$, thereby enabling the physical interpretation of ω_c within the random barrier model. The rate corresponding to the peak in the imaginary part of the complex modulus, ω_M, also practically coincides with ω_c as demonstrated in Figure 2.[19,22]

3. Universal Scaling of Charge Transport in Glass-Forming Ionic Liquids

To gain deeper insight into the dependence of charge transport on the structure and composition, ionic liquids based on the same 1-hexyl-3-methylimidazolium ([HMIM]) cation but different anions are investigated. The temperature dependence of σ_0 and ω_c, which are the main directly observable quantities characterizing charge transport (consistent with Dyre's approach), are studied. It is observed that systematic variation of the anions while maintaining the same [HMIM] cation leads to significant changes in the charge transport quantities. These changes become more pronounced as the temperature approaches the calorimetric glass transition temperature of the ionic liquid. In order to understand the role of glassy dynamics in charge transport in ionic liquids, conductivity and viscosity measurements have been made for ionic liquids with the same cation but different anions. Figure 3 shows the temperature dependence of σ_0 for the different ionic liquids. Upon scaling with respect to the calorimetric glass transition temperature, coinciding plots are obtained for the various anions studied.

Structural variation leads to differences typically exceeding 6 decades in σ_0 (between the tetrafluoroborate- and chloride-based anions). The fact that quantitative scaling is obtained with the glass transition temperature determined from differential scanning calorimetry indicates the important role played by the dynamic glass transition in charge transport in ionic liquids. In addition, viscosity, η, well-known to be directly linked to glassy dynamics, also shows a similar temperature dependence. It is evident that varying the anions leads to significant change in the viscosity and ω_c as shown in Figure 4. Further information regarding the physical meaning of the characteristic rate ω_c can be gained by comparing it to the structural relaxation rate ω_η. Due to the limited spectral range of the rheometers used in our studies, a direct comparison is only possible at low frequencies between about 0.1 and 100 Hz as presented in Figure 5. However, based on Maxwell's relation ($\eta = G_\infty/\omega_\eta$, where G_∞ denotes the

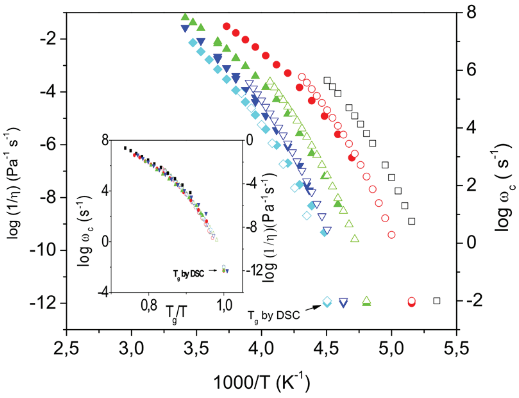

FIGURE 4. Temperature dependence of the inverse of viscosity $1/\eta(T)$ and $\omega_c(T)$ for different ionic liquids based on the same 1-hexyl-3-methylimidazolium cation (inset: scaling with respect to the calorimetric glass transition temperature measured by differential scanning calorimetry (see legend of Figure 3)). The symbols are identical to those in Figure 3 with $1/\eta(T)$ and $\omega_c(T)$ represented by full and open symbols, respectively.[29] Reproduced by permission of the PCCP Owner Societies.

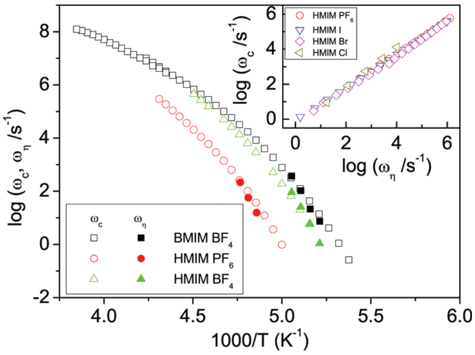

FIGURE 5. Thermal activation of the characteristic charge transport rate ω_c as well as the structural relaxation rate, ω_η, determined from direct DMS measurements for arbitrarily selected ionic liquids as indicated. The two characteristic rates practically coincide within the spectral range measured. Inset: the characteristic charge transport rate, ω_c, versus the structural relaxation rate, ω_η, determined from viscosity by applying Maxwell's relation.

instantaneous shear modulus), one can calculate the structural relaxation rate ω_η as measured by dynamic mechanical spectroscopy. This is only possible due to the experimental observation that G_∞ only varies by a factor of about 4 in the usual accessible temperature range for glass-formers. Within limits of experimental accuracy, a quantitative agreement is found for ω_η and ω_c as evident in the inset of Figure 5. Recent computational studies aimed at disentangling rotational and translational diffusion in the time scales between picoseconds and nanoseconds indicate that the characteristic time constants corresponding to the two components coincide. This finding is in accord with the results presented in Figure 5.

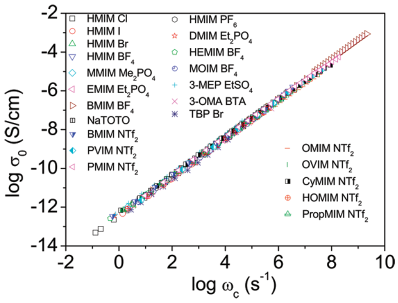

FIGURE 6. dc conductivity, σ_0, versus the characteristic frequency, ω_c, for different liquids as indicated. The data for all ionic liquids are obtained from dielectric measurements at ambient pressure. This plot experimentally demonstrates the universality of charge transport in glass-forming ionic liquids. Nomenclature employed: 1-hexyl-3-methylimidazolium chloride, [HMIM][Cl]; 1-hexyl-3-methylimidazolium bromide, [HMIM][Br]; 1-hexyl-3-methylimidazolium iodide, [HMIM][I]; 1-hexyl-3-methylimidazolium tetrafluoroborate, [HMIM][BF_4]; 1-hexyl-3-methylimidazolium hexafluorophosphate, [HMIM][PF_6]; 1-(2-hydroxyethyl)-3-methylimidazolium tetrafluoroborate, [HEMIM][BF_4]; 1-methyl-3-octylimidazolium tetrafluoroborate, [MOIM][BF_4]; 1-butyl-3-methylimidazolium tetrafluoroborate, [BMIM][BF_4]; 1,3-dimethylimidazolium dimethylphosphate, [MMIM][Me_2PO_4]; 1-ethyl-3-methylpyridinium ethylsulfate, [3-MEP][$EtSO_4$]; trioctylmethylammonium bis(trifluoromethylsulfonyl)imide, [OMA][BTA]; and tetrabutylphosphonium bromide, [TBP][Br].[21,29] Reproduced by permission of the PCCP Owner Societies.

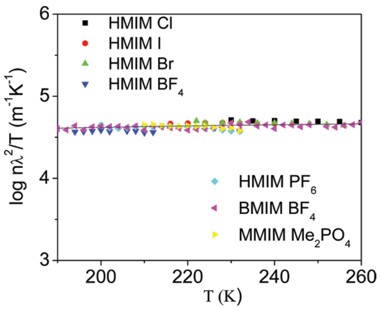

FIGURE 7. Product $(n\lambda^2)/T$ versus temperature for different ionic liquids as indicated. This plot illustrates the physical implication of the observed universality of charge transport in ionic liquids.

From electrodynamics and using the Einstein and Einstein–Smoluchowski equations, the dc conductivity can be expressed as[15,29] $\sigma_0(T) = q\mu(T)\ n(T) = n(T)[(q^2D(T))/(kT)] = n(T)[(q^2\lambda^2\omega_c(T))/(6kT)]$, where n denotes the effective number density of charge carriers contributing to charge transport in the time scale of ω_c, λ refers to the characteristic diffusion length also taken by some models as the distance characterizing the crossover from nonrandom diffusion to random diffusion,[30] D is the diffusion coefficient, and μ refers to the mobility. It is worth noting that n can be expressed as $Ng(T)$, where $g(T)$ is the proportion of mobile charge carriers at a given temperature T and N is the total number density of charge carriers available in the material. q is the elementary charge, and k denotes the Boltzmann constant. Therefore, the relation $\sigma_0 \propto \omega_c$ is experimentally established in full accord with Figure 6. It is remarkable that even though the absolute values of both the dc conductivity and the characteristic rate of charge transport vary over 11 decades depending on temperature as well as composition, a coinciding plot is obtained for all the ionic liquids investigated. The coincidence of results for *all* the glass-forming ionic liquids is not readily evident from Einstein and Einstein–Smoluchowski equations. This can only be possible if $(n\lambda^2)/T$ given by $(2k\sigma_0)/(q^2\omega_c)$ exhibits negligible temperature dependence. Since the latter consists of known quantities, the former term can be determined. Figure 7 demonstrates the practical temperature independence of $(n\lambda^2)/T$ for different ionic liquids. Studies are in progress to unravel the microscopic meaning of this finding.

4. Diffusion Coefficients from Dielectric Spectra and Its Implications

The first systematic albeit empirical studies of diffusion in ion-conducting glasses were performed by Haven and Verkerk.[31] They employed the Nernst–Einstein relation ($\sigma_0(T) = N[(q^2D(T))/(6kT)]$, where the total number density of the ions, N, is assumed to be temperature independent) to come up with the corresponding diffusion coefficient given by $D_\sigma = (6kT\sigma_0(T))/(Nq^2)$. This was then compared to the diffusion coefficient obtained from other techniques such as NMR and neutron scattering D_{NMR}. This led to the introduction of the Haven ratio, $H_{\mathrm{R}} = D_{\mathrm{NMR}}/D_\sigma$, an empirical quantity which compares the measured dc conductivity to that corresponding to the NMR diffusion coefficient.[32] It should be noted that D_σ is *calculated* from the measured dc conductivity with the assumption that all ions are mobile. The values of H_{R} are nowadays used to quantify the degree of ion–ion correlations.[32−34] For ionic liquids, a related concept called ionicity has been proposed by the research groups of Watanabe and MacFarlane.[5,35] The subtle difference between our approach and the last two lies in the initial assumptions concerning the thermal activation of the number density of charge carriers. Using our notation, the Haven ratio can be expressed as $H_{\mathrm{R}} = 1 - n/N$. Upon substitution of the typical experimental values of λ, a closer examination of the data presented in Figures 6 and 7 reveals that H_{R} values for all the ionic liquids investigated lie between 0.15 and 0.35 at lower and higher temperatures, respectively. Therefore, H_{R} can be understood as a measure of the proportion of immobile charge carriers. It is currently not clear whether these values can be entirely attributed to ion-pairing.[36] Combined experimental and theoretical effort is essential to solve this problem. From the Hall effect and other related studies, one fact is certain: both the mobility and the number density of charge carriers are in general temperature dependent quantities.[37,38]

The mobility can be determined using Einstein's relation if the diffusion coefficients are known. Estimates of the diffusion coefficients of ionic liquids can be obtained by employing the Einstein–Smoluchowski equation to analyze the dielectric data. We have experimentally established that the mean ion jump lengths in the time scale of ω_c lie typically between 0.2 and 0.3 nm. Several experimental and computational results indicate that ionic liquids are significantly heterogeneous on mesoscopic length-scales.[39−41] Nanoaggregation in ionic liquids has been observed from neutron scattering and X-ray studies for 1-alkyl-3-methylimidazolium hexafluorophosphates and confirmed by theoretical calculations. It should be noted that the length-scales of nanoaggregates exceed that of the mean ion jump distances by over an order of magnitude. The latter should be interpreted in terms of the mean displacement of the center of charge in the time-scale of structural α-relaxation. Independent measurements performed by PFG NMR (which measures the diffusion coefficient directly), together with the diffusion coefficients obtained from dielectric measurements, are shown in Figure 8. This approach yields diffusion coefficients in excellent agreement with those obtained by PFG NMR.[14,15] These calculations allow one to separate the contribution of n, the effective number density, from that of μ, the electrical mobility. It turns out that the VFT character of the conductivity originates solely from the diffusion coefficient whereas, over a broad temperature range, the number density of ions follows an Arrhenius-type temperature dependence (inset of Figure 8). Extrapolating the latter to room temperature gives a value of about 2.9×10^{27} m^{-3} for the number density of effective charge carriers in [BMIM][BF$_4$], close to 3.4×10^{27} m^{-3}, which represents the total number of ions in the system (determined from the density and the molecular weight). This implies that approximately 85% of the charge carriers participate in charge transport at room temperature. This finding is consistent with reports that not all the charge carriers participate in the conduction process.[3,5,6] The experimentally determined diffusion coefficients have

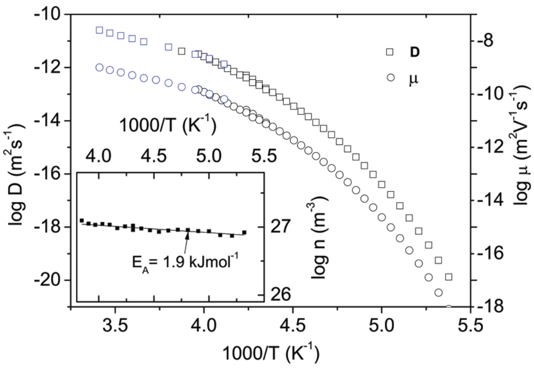

FIGURE 8. Diffusion coefficient determined by the novel approach involving application of the Einstein–Smolukowski equation, using ω_c as the characteristic hopping rate and with λ as mean ion jump length in the time scale of ω_c (typically 0.2 nm), compared with the diffusion coefficients measured by PFG NMR (blue color) for the ionic liquid [BMIM][BF$_4$].[14,15] Inset: effective number of charge carriers as a function of inverse temperature (the activation energy is as indicated). The error bars are comparable to the size of the symbols, if not specified otherwise. Log is used to refer to logarithm to base 10.

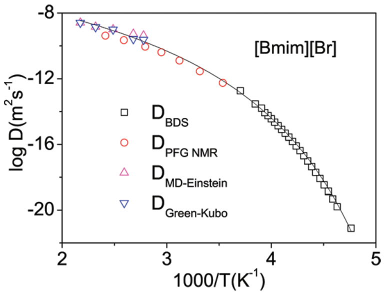

FIGURE 9. Diffusion coefficients determined by BDS for the ionic liquid [BMIM][Br] and those measured by PFG NMR. In addition, diffusion coefficients calculated by Einstein and Green–Kubo relations from quantum mechanical simulations are also shown.[45]

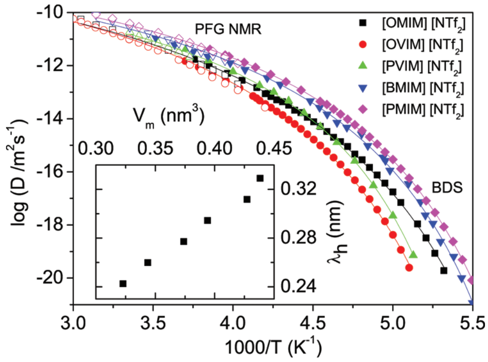

FIGURE 10. Diffusion coefficient determined from broadband dielectric spectra (open symbols) upon applying the Einstein–Smoluchowski equation using ω_c as the characteristic hopping rate for a series of ionic liquids based on the bis(trifluoromethylsulfonyl)imide anion as well as the diffusion coefficient measured by PFG NMR (filled symbols) versus inverse temperature. Inset: The mean hopping lengths (from a combination of broadband dielectric spectroscopy and PFG NMR measurements) as a function of the molecular volume (from quantum chemical calculations) of the ionic liquids investigated. The lines denote fits by the Vogel–Fulcher–Tammann equation.[21] Reproduced by permission of The Royal Society of Chemistry (RSC).

recently been shown to coincide with those found from molecular dynamics simulations through the Green–Kubo and Einstein relations as shown in Figure 9. The mean ion jump lengths are experimentally determined in the temperature regimes at which the spectral windows of BDS and PFG NMR coincide. This has been demonstrated for a series of bis(trifluoromethylsulfonyl)imide-based anions as shown in Figure 10.[21] We have recently shown that the approach holds for other conducting glass-forming systems as well.[42–44] This opens up a new field of possibilities for the application of BDS to study charge transport and glassy dynamics in glass-forming ionic liquids.

Detailed analysis of the thermal activation of the transport parameters can yield information concerning the charge transport mechanisms in ionic liquids. This is particularly attractive for technological applications such as supercapacitors, batteries, fuel cells, and other power sources and storage devices. With respect to the temperature variation, a Vogel–Fulcher–Tammann (VFT) dependence is detected for σ_0, as well as for the rate ω_c as shown in Figures 3 and 4. Since the measured σ_0 is always a product of the mobility and the number density of charge carriers participating in the conduction process, the approach to determine the diffusion coefficients discussed in the current Account enables unambiguous separation of the two and reveals that the VFT-type temperature dependence of the dc conductivity stems from a similar activation of the mobility. For electronic conductors, *Hall effect* measurements provide a similar possibility of separating n and μ but the Hall voltages associated with ionic conduction are at the nanovolt level and thus too small to be measured with any confidence.[37] This leaves BDS as the only reliable experimental method for studies in this respect.

5. Conclusions

Recent progress in the understanding of charge transport and glassy dynamics in glass-forming ionic liquids (ILs) achieved by a unique combination of experimental techniques such as broadband dielectric spectroscopy (BDS), pulsed field gradient nuclear magnetic resonance (PFG NMR), differential scanning calorimetry (DSC), and dynamic mechanical spectroscopy (DMS) is summarized. The dielectric spectra are dominated, on the low-frequency side, by electrode polarization effects, while, for higher frequencies, charge transport in a disordered matrix is the underlying physical mechanism. Whereas the absolute values of dc conductivity and viscosity vary over more than 11 decades with temperature and upon systematic structural variation of the ILs, quantitative agreement is found between the characteristic frequency of charge transport and the structural α-relaxation. This is discussed within the framework of the concept of dynamic glass transition driven hopping traced back to the Einstein, Einstein–Smoluchowski, and Maxwell relations.

A novel approach is applied to extract diffusion coefficients from BDS spectra in quantitative agreement with PFG NMR values but in a much broader range (over more than 10 decades). It becomes possible to determine from the dielectric spectra separately the number density and the mobilities of the charge carriers and the type of their thermal activation. It is shown that the observed Vogel–Fulcher–Tammann (VFT) dependence of the dc conductivity can be attributed to a similar temperature dependence of the mobility while for the number density an Arrhenius-type thermal activation is found.

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BIOGRAPHICAL INFORMATION

Joshua Sangoro completed his doctoral research on dielectric properties of ionic liquids in the year 2010 under the tutelage of Prof. Friedrich Kremer at the University of Leipzig. He was awarded his doctoral degree in Physics with grade: "very good". He is currently a postdoctoral research assistant in the laboratory of Prof. Kremer. Sangoro has coauthored more than 25 peer-reviewed articles on ionic liquids and charge transport in different classes of disordered materials within the last three years. His research interests include charge transport and molecular dynamics in bulk and confined disordered materials, liquid crystals, and experimental physics.

Friedrich Kremer is Professor and Chair of Experimental Physics at the University of Leipzig, Germany. He studied physics at the University of Munich (1968−1973) and obtained his diploma in theoretical molecular physics. Afterwards, he enrolled for additional courses in biology at the University of Freiburg i.Br. (1974) and finished his Ph.D. in the field of biological cybernetics (1977). He worked as a postdoc at the Max-Planck Institute for Solid State Physics in Stuttgart, where he developed novel spectroscopic techniques for millimeter wave and far infrared spectroscopy. During that time, he collaborated closely with Prof. Herbert Fröhlich and edited together with him the book *Coherent excitations in Biological Systems* (H. Fröhlich and F. Kremer, Eds., Springer Verlag, 1983). From 1985 to 1993, he was a senior researcher at the Max-Planck Institute of Polymer Research in Mainz, where he focused on polymer physics and materials research and developed automatic measurement systems for Broadband Dielectric Spectroscopy covering the entire range from 1 mHz to 10 GHz. In 1993, he received a call from the University of Leipzig for a chair of experimental physics. From 1998 to 2008 he was director of the Institute for Experimental Physics I, a position which was held from 1928 to 1935 by Peter Debye. Together with A. Schönhals, he edited (and wrote to a large extent) the book *Broadband Dielectric Spectroscopy* (Springer Verlag, 2003). He has coauthored more than 300 peer-reviewed research articles and edited over 5 books on topics such including broadband dielectric spectroscopy, 2D-IR spectroscopy, and experiments with optical tweezers. In 2005, he received the Karl-Heinz-Berkurts Award for his achievements in automating and promoting broadband dielectric spectroscopy and its applications. He is the current chair of the International Dielectric Society. In 2011, Kremer was awarded the Wolfgang Ostwald Prize of the German Colloidal Society.

FOOTNOTES

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