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Ionic liquids in analytical chemistry

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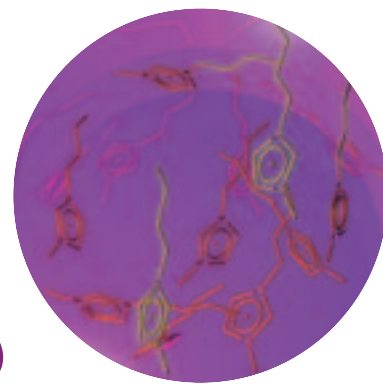Guor-Tzo Wei
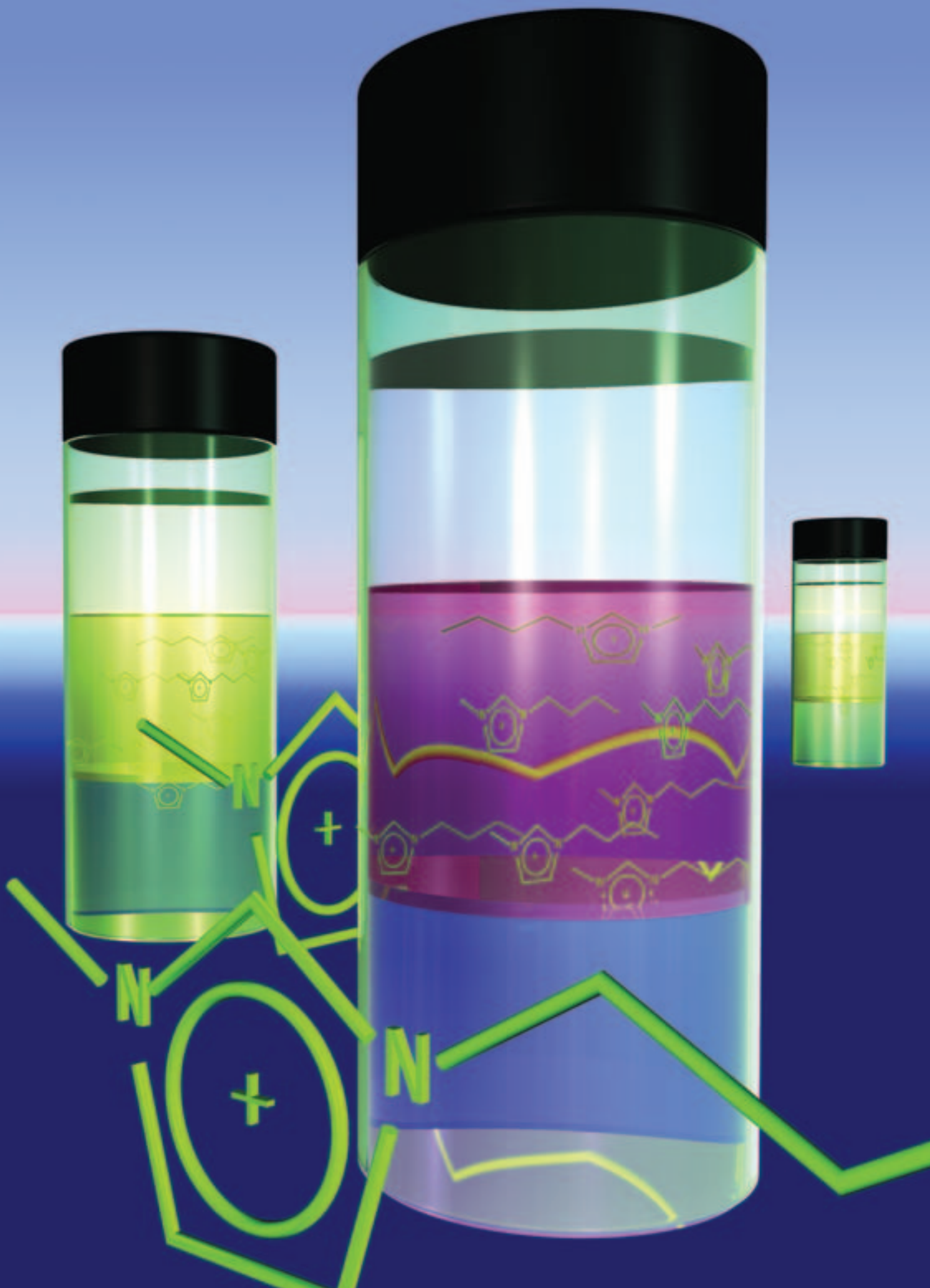
IONIC LIQUIDS
in Analytical Chemistry

Room-temperature ionic liquids have tremendous potential in organic synthesis, green chemistry, separations, MS, spectroscopy, and electrochemistry.

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Room-temperature ionic liquids (RTILs), also known as liquid organic, molten, or fused salts, are a class of nonmolecular ionic solvents with low melting points. The accepted definition of an RTIL is any salt that has a melting point lower than ambient temperature (*1*). However, "ionic liquid" (IL) is often applied to any compound that has a melting point <100 °C. Most common RTILs are composed of unsymmetrically substituted nitrogen-containing cations (e.g., imidazole, pyrrolidine, pyridine) with inorganic anions (e.g., Cl^-, PF_6^-, BF_4^-). ILs are also interesting because of their other useful and intriguing physicochemical properties. Wilkes et al. first reported ambient-temperature ILs based on the 1-alkyl-3-methylimidazolium cation in 1982 (*2*). Since then, many ILs containing a variety of cations and anions of different sizes have been synthesized to provide specific characteristics.

Over the past few years, research and applications of ILs have expanded tremendously. The initial impetuses for this expansion were organic synthesis and the growth of green chemistry. In this article, we will give an overview of the structure and properties of ILs and describe their expanding use in various applications in separations and chromatography, MS, spectroscopy, and electrochemistry.
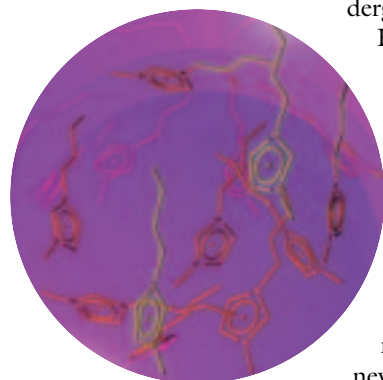
Description and properties

ILs have negligible vapor pressures at room temperature, possess a wide range of viscosities, can be custom-synthesized to be miscible or immiscible, often have high stability, and are capable of un-

FIGURE 1. Plot illustrating the magnitude of each interaction parameter at 70 °C for various ILs used in different applications.

a, hydrogen-bond basicity; *b*, hydrogen-bond acidity; *r*, interaction via nonbonding and π-electrons; *s*, dipolarity or polarizability; and *l*, dispersion forces. BMIM, 1-butyl-3-methylimidazolium; TfO, triflate; NTf$_2$, bis[(trifluoromethyl)sulfonyl]imide; sulfone-BF$_4$, butyl ethylsulfonylmethylimidazolium-BF$_4$; sulfoxide-BF$_4$, butyl ethylsulfinylmethylimidazolium-BF$_4$; NHb$_3$, tributylammonium; NHe$_3$, triethylammonium; NH$_2$m$_2$, dimethylammonium; PA, picolinate; OHPA, 2-hydroxypicolinate; Ac, acetate; CHCA, α-cyano-4-hydroxycinnamate; SA, sinapinate; vim, vinyl imidazolium; mim, methylimidazolium; mpy, methyl pyrrolidinium. Some data from Ref. 3 were used to construct this plot.

dergoing multiple solvation interactions with many types of molecules (*3*). Because the unique combination of cations and anions influences the various properties of ILs, they have been described as designer solvents (*4*). Table 1 gives the structure, physicochemical properties, and synthesis for a few selected ILs, each representative of a particular class. The range of available anion and cation combinations could provide up to 10^{18} different RTILs (*5*).

Although the relationship between the structure of ILs and their physicochemical and solvation properties is not well understood, general trends can be observed within specific classes of ILs. For example, when the densities of 1-alkyl-3-methylimidazolium cations are compared while the anion is held constant, they decrease when the alkyl group is lengthened (*6*). The viscosities of the same class of ILs (with the anion held constant) increase as the alkyl group is lengthened. Compared with typical organic solvents, ILs are much more viscous: Viscosities are in the range 35–500 cP for common ILs versus values of 0.6 cP for toluene and 0.9 cP for water. Meanwhile, the surface tension for this group of ILs decreases as the alkyl group is lengthened from two to six methylene units (*6*).

From a green-chemistry standpoint, the fact that ILs have little vapor pressure is of considerable interest because they produce few volatile organic compounds compared with traditional organic solvents (*7*; Table 2 can be found in Supporting Information at pubs.acs.org/ac). The potential for explosions is minimized because many RTILs have little or no flammability and no flash point. In many cases, products can be extracted from the RTIL after reaction, and the RTIL can be recovered and recycled. Many synthetic reactions are faster in RTILs, and this saves time and/or energy. However, other properties cannot be overlooked. Some of the more common ILs are susceptible to chemical and thermal degradation. For example, 1-butyl-3-methylimidazolium chloride (BMIM-Cl) turns from yellow to amber at 120 °C (*8*). This same IL begins to show signs of decomposition when heated to >150 °C. PF$_6^-$ undergoes hydrolysis to produce HF (*9*). This property may have severe implications if RTILs become widely used and eventually appear in watersheds.

However, producing bulkier cations (*10*) and dicationic salts (*11*) rather than monocationic salts vastly improved the thermal stability of ILs. These newer ILs appear to be stable and nonvolatile at temperatures ≥ 240 °C. The toxicity and environmental degradation of ILs must be evaluated as well. Although no system is totally green, the strength of ILs directly complements many of the weaker aspects of traditional solvent systems. Several excellent reviews demonstrating the use of achiral (*1*, *12*, *13*) and chiral (*14*) ILs as solvents are available for the interested reader.

Three general techniques exist to probe the interaction and solvation capability of RTILs and to attempt to approximate their polarity. The first technique uses an empirical solvent-polarity scale that relies on the solvatochromic behavior of various dyes (*5*, *15–18*). The second and third techniques are similar in that they both utilize inverse GC (to study the physicochemical properties of a phase, rather than to do separations). However, one technique relies on a handful of probe molecules (*19*), whereas the other depends on many probe molecules (*3*) to approximate polarity as well as to deconvolute and quantify individual solvation interactions.

The most common empirical solvent polarity scale relies on the solvatochromic behavior of various dyes in different solvent systems (*15–18*). In terms of solvent strength and selectivity, this method was also used to classify single- and mixed-solvent LC systems (*20*). All results from this approach have indicated that IL solvents have polarities close to those of short-chained alcohols. Nevertheless, it is well known that two ILs with different cation–anion combinations can have significantly different effects on reaction rates, product ratios, chromatographic retention, and extraction selectivity (*1*, *3*, *18*). This polarity-based parameter, however, provides a "weighted average" of all solvation interactions and fails to discriminate among the various properties of ILs with different cation–anion combinations.
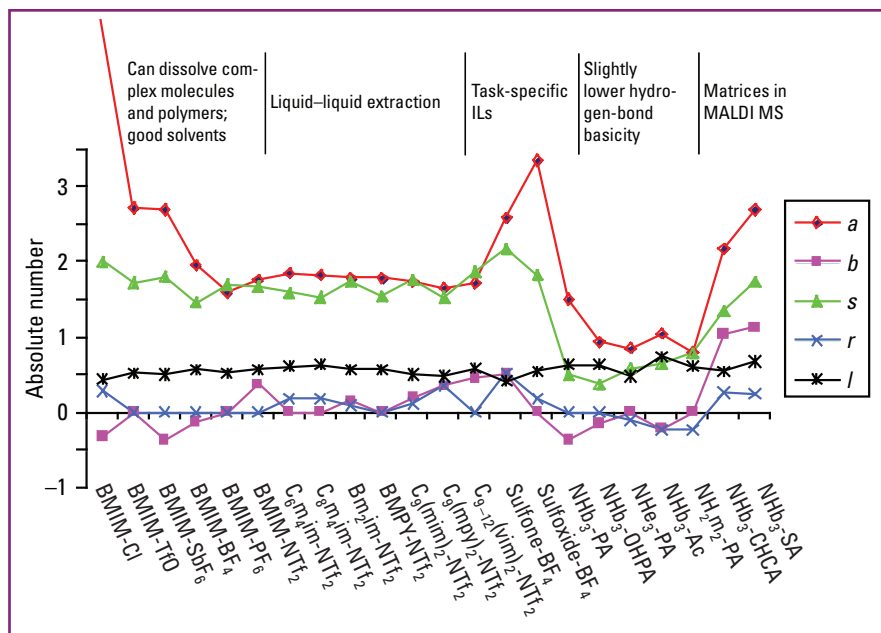
The solvation-parameter model developed by Abraham was applied to determine the individual solvation interactions of an ionic liquid (*3, 21*).

$$\ln k = c + rR_2 + s\pi_2^H + a\alpha_2^H + b\beta_2^H + l\log L$$

In this equation, *r* is the ability of the IL to interact with π- and nonbinding-electrons of the solute; *s* is a measure of the dipolarity or polarizability; *a* is the hydrogen-bond basicity (acidic solutes will interact with a basic phase); *b* is the hydrogen-bond acidity (basic solutes will interact with an acidic phase); and *l* describes dispersion forces and indicates how well the RTIL will separate members of any homologous series. These are the calculated interaction parameters; the numerical magnitude of each describes the importance of the individual interactions, thereby characterizing the RTIL. R_2 is the excess molar refraction; π_2^H is the ratio of dipolarity to polarizability; α_2^H is the hydrogen-bond acidity; β_2^H is the hydrogen-bond basicity. These are known solute descriptors that are used to interrogate the ionic liquid phase (*3, 21*). Lastly, *k* is the chromatographic retention factor; *c* contains the chromatographic phase ratio; and *L* is the solute's gas–hexadecane partition coefficient at 298 K.

The interaction parameters can then be used to individually characterize the different IL cations and anions (*3*). For example, the anion largely controls the hydrogen-bond basicity, whereas the effect of the cation is smaller and influences π–π interactions (depending on the structure) and in some cases the hydrogen-bond acidity. The interaction parameters can be used to explain the selectivity and reaction rates observed in IL-mediated organic reactions and to classify ILs and predict whether they may be useful in specific applications. Some ILs have enhanced hydrogen-bond acidity interactions, whereas task-specific ILs have enhanced hydrogen-bond basicity interactions (Figure 1). A unique combination of solvation interactions and solvent miscibility governs the types of applications in which ILs can be beneficial.

GC

To be an ideal GC stationary phase, a compound must possess specific characteristics. It must be thermally stable at high temperatures; viscous; easy to apply for immobilization on the capillary wall; and capable of providing selective, high-efficiency separations. ILs possess all of these properties, and they provide multiple solvation interactions with molecules (*3, 19*).

Early on, liquid organic salts such as ethylammonium nitrate and ethylpyridinium bromide were used as stationary phases, but they suffered from narrow liquid ranges and poor chromatographic efficiency (*22, 23*). Recently, imidazolium-based RTILs were used as stationary phases, and the retention behavior of various molecules was examined on BMIM-PF$_6$ and BMIM-Cl (*19*). The BMIM-Cl stationary phase, because of its high hydrogen-bond basicity, strongly retained molecules that were hydrogen-bond donors (e.g., acids, alcohols). Nonpolar molecules generally eluted earlier than polar molecules. RTILs possess yet another interesting property: a "dual-nature" behavior. That is, the station-
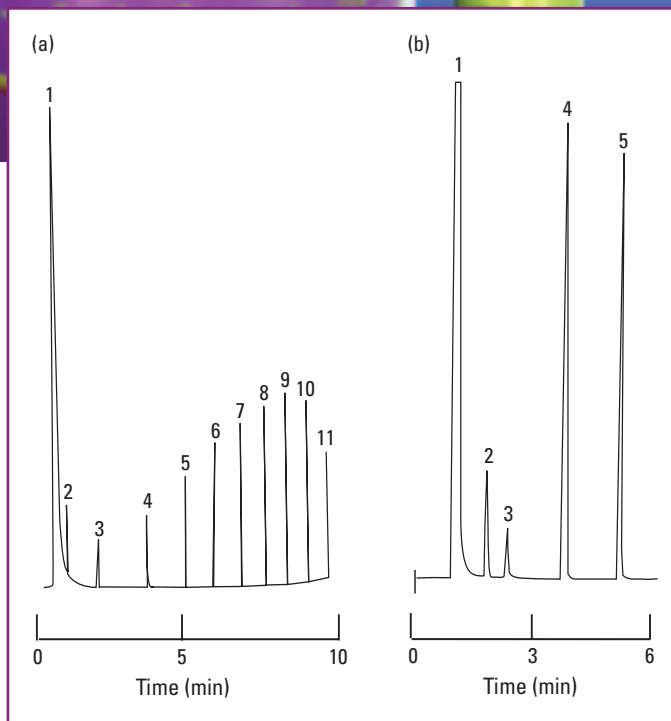

FIGURE 2. Dual-nature selectivity of a 15-m BMIM-TfO column.

(a) Homologous mix of *n*-alkanes: 1, CH$_2$Cl$_2$; 2, hexane; 3, heptane; 4, octane; 5, nonane; 6, decane; 7, undecane; 8, dodecane; 9, tridecane; 10, tetradecane; 11, pentadecane. (b) Mixture of small-chain alcohols: 1, CH$_2$Cl$_2$; 2, methanol; 3, ethanol; 4, propanol; 5, butanol. (Adapted from Ref. 3.)

ary phase separates polar molecules as if it were a polar stationary phase and separates nonpolar molecules like a nonpolar phase (*19, 24*). This is possible because ILs may be the only solvents capable of all types of intermolecular interactions. Thus, they can use their considerable dispersion interaction capabilities to separate nonpolar molecules (Figure 2a). Also, they can use any interaction—such as dipolar, hydrogen bonding, or charge interactions, singly or combined—to separate polar molecules (Figure 2b).

Although RTILs are said to possess high volatilization temperatures and stability, recent evidence indicated that the properties may have been overestimated for certain cation–anion combinations (*8, 10*). Even so, because RTILs displayed such favorable selectivity characteristics when used as GC stationary phases, an effort was undertaken to find new types of RTILs with increased stability and volatilization temperatures. Increasing the bulkiness of the cation and choosing an anion that provides acceptable peak shape (i.e., does not form strong hydrogen bonds or otherwise interact very strongly with analyte molecules) resulted in two new ILs, which were synthesized and successfully used as stationary phases at temperatures near 240 °C (*10*). More recently, partially cross-linked IL-based stationary phases have provided high-selectivity and high-efficiency separations at temperatures >250 °C (*24*). These phases could be particularly attractive for 2D GC, in which both orthogonality and thermal stability are important (Table 1).

ILs were also explored as stationary-phase solvents in enantioselective GC (*25, 26*). Methylated cyclodextrins (CDs) were dissolved in an IL and coated directly onto GC capillary columns. The separation capabilities were compared with those of commercial columns containing the same chiral selectors but dissolved in polysiloxane. The RTIL columns had much higher ef-

Table 1. Structure and physicochemical properties of selected RTILs.

Structure	Name or function	Mp (°C)	Density (g/cm³)
	1-Butyl-3-methylimidazolium chloride (BMIM-Cl)	65	1.10
	1-Butyl-3-methylimidazolium bis[(trifluoro-methyl)sulfonyl]imide (BMIM-NTf$_2$)	−4	1.43
	1-Butyl-3-methylimidazolium trifluoromethanesulfonate (BMIM-TfO)	16	1.29
	1-Butyl-3-methylimidazolium hexafluorophosphate (BMIM-PF$_6$)	−8	1.36
	1-Benzyl-3-methylimidazolium trifluoromethanesulfonate (triflate)	27	1.30 (30 °C)
	Task-specific IL	−17.4 glass transition	NA
	Task-specific IL	NA	NA
	MALDI matrices Methylimidazolium α-Cyano-4-hydroxycinnamate	NA	NA
	MALDI matrix 2,5-Dihydroxybenzoic acid butylamine	NA	NA
	C$_6$(mim)$_2$-NTf$_2$	>−14, <−4	1.52
	C$_6$(mpy)$_2$-NTf$_2$	>−8, <0	1.41
	Unnamed	NA	1.47
	1-Butyl-3-methylimidazolium lactate	NA	NA
	N,N-Dimethylephedrinium NTf$_2$	54	Solid

Refractive index	Viscosity (cP)	Conductivity (S/m)	Comments	Ref.
Solid	Solid	Solid	Supercooled liquid; soluble in water; can dissolve up to 15% by wt. of cellulose; starting material for other BMIM ILs	3, 8, 70
1.427	52 (20 °C)	0.39	Immiscible with water; produces some tailing peaks when used as GC stationary phase	3, 8
1.438	90 (20 °C)	0.37	Miscible in water; produces most-symmetrical peaks when used as GC stationary phase	3, 8
1.411	312 (20 °C)	0.14	Immiscible with water; not as green; hydrolysis of anion produces HF	3, 8, 9
NA	NA	NA	Highly stable, high-temperature GC stationary phase	10
NA	964 (25 °C)	NA	Immiscible with water; extracts Hg^{2+} and Cd^{2+} from aqueous soln.	28
NA	NA	NA	Reacts reversibly with CO_2 to sequester gas as carbonate salt; does not need water to function	71
NA	NA	NA	Liquid MALDI matrix that produces ion intensity signals for biomolecules; can form homogeneous mixture with analyte and improve shot-to-shot reproducibility	40
NA	NA	NA	Enhanced shot-to-shot reproducibility and MALDI-induced fragmentation; used for oligosaccharides and polymers	44
1.441	362 (25 °C)	NA	Geminal dicationic ILs with high thermal stability at 350–400 °C; used as high-temperature GC stationary phases and ion pairing agents in MS	11
1.436	502 (25 °C)	NA		
1.457	NA	NA	Geminal dicationic IL that cross-links to produce partially and completely cross-linked polymer beads and GC stationary phases	11
NA	NA	NA	Chiral IL used as chiral solvent in organic synthesis	14
Solid	Solid	Solid	First chiral IL to exhibit enantioselectivity when used as a chiral stationary phase in GC; also used as a chiral solvent in organic synthesis	14, 26

ficiencies than the commercial columns (*25*). A potential new class of chiral stationary phases involves *N,N*-dimethylephedrinium-based ILs that exhibit enantioselective retention for four different classes of analytes (*26*)—chiral alcohols (including diols), chiral sulfoxides, some chiral epoxides, and acetylated amines (Table 1). In addition, a reversal of enantiomeric elution order occurred when diastereomeric versions of the ILs were used.

In another unique application, RTILs were examined as solvents for headspace GC (*27*). The compounds 2-ethyl-hexanoic acid, formamide, and tri-*n*-butylamine are examples of acidic, neutral, and basic analytes, respectively, that were dissolved in 1-*n*-butyl-3-methylimidazolium hydrogen sulfate and 1-*n*-butyl-2,3-dimethylimidazolium dicyanamide. When the proper IL was chosen, all analytes could be determined with detection and quantitation limits in the low-parts-per-million range. This work has tremendous potential in the quantitation of compounds with low vapor pressure, for which traditional headspace GC is limited.

Extractions

A distinct advantage of RTILs is that they can be custom-synthesized to be either water- or hexane-immiscible, and this makes them useful for liquid–liquid extractions. The choice of the anion (and in some cases, the structure and functionality of the cation) controls the water solubility of the RTIL. Most water-immiscible RTILs contain either PF_6^- or bis[(trifluoromethyl)sulfonyl]imide anion (Table 1).

The functionality of the cations was manipulated to coordinate Hg^{2+} and Cd^{2+} and extract them from water (*28*). These task-specific ILs incorporate urea-, thiourea-, and thioether-substituted alkyl groups into the imidazolium parent compound, and then this cation is combined with PF_6^- to form the water-immiscible RTIL (Table 1). The cations containing thiourea and urea yielded the highest distribution ratios for the two metal ions. These task-specific ILs can also be mixed with less expensive ILs, such as 1:1 BMIM-PF_6, to obtain similar distribution ratios.

Dicyclohexyl-18-crown-6 (DC18C6) crown ether was dissolved in ILs, which were used as extraction solvents to achieve very large distribution ratios for Sr^{2+} (*29*). Additionally, an investigation into the extraction of aqueous solutions of alkali metal chlorides with DC18C6 demonstrated that as the 1-alkyl group in 1-alkyl-3-methylimidazolium PF_6 was lengthened, the extraction efficiency decreased (*30*).

ILs that also acted as Lewis and Bronsted acids or bases were used as extraction media in the deep desulfurization of diesel fuels (*31*). ILs that had larger anions demonstrated significantly better extraction of dibenzothiophene than smaller anions, regardless of the cation used. In another study, BMIM-BF_4 and BMIM-PF_6 were used to remove sulfur-containing compounds from light oils with a combination of chemical oxidation and solvent extraction (*32*). With BMIM-PF_6, a unique three-phase extraction system of oil (top), H_2O_2 plus water (middle), and IL (bottom) was formed. This allowed extraction of the sulfur compounds from oil to the IL phase and their oxidation to the corresponding sulfones by H_2O_2. The high-polarity oxidized sulfones mainly partition to the IL phase. This leads to continued extraction of the sulfur compounds from oil and results in much higher desulfurization compared with mere extraction of light oil with an IL (*32*).

The partitioning behavior of acidic, basic, and neutral molecules in BMIM-PF_6/water and octanol/water also was examined (*8*). Generally, basic analytes partitioned more to BMIM-PF_6 than to octanol, whereas the reverse was true for acidic analytes. Neutral molecules and ionizable compounds with both basic and acidic functionalities exhibited similar distribution behavior in both systems. When the pH of the extraction system was controlled, heavy-metal ions could be extracted, separated, and preconcentrated with a biphasic BMIM-PF_6/aqueous phase and a dithizone chelator (*33*). RTILs containing calixarenes were used to extract cesium ions (*34*) and silver ions (*35*) from aqueous solutions. Monoaza-substituted crown ethers also were used as extractants for the separation of Sr^{2+} and Cs^{2+} from aqueous solutions (*36*). The quantitative phase transfer of unmodified gold nanoparticles and gold nanorods from aqueous solutions to the BMIM-PF_6 IL was demonstrated (*37*). The sizes and shapes of the nanoparticles and nanorods were not affected by the phase transfer. Water-immiscible ILs were also used as extraction solvents in direct-immersion and headspace liquid-phase microextraction (*38*). Compared with 1-octanol, the ILs provided higher extraction efficiencies and enrichment factors because larger drop volumes are required.

The IL 1-octyl-3-methylimidazolium (OMIM) PF_6 was used as a disposable liquid absorbent for solid-phase microextraction

(SPME) studies of benzene, toluene, ethylbenzene, and xylenes (BTEX) from paints (*39*). Compared with commercially available SPME fibers, the IL-SPME fiber provided a much lower cost per determination, similar reproducibility, and no detectable carryover. The detection limits for the BTEX compounds ranged from 0.1 to 0.8 mg/mL with RSDs of ~3–10%. Recent work has focused on the use of IL-SPME fibers to extract a wide range of analytes, from polar compounds to biomolecules. Changing the cation–anion combination makes ILs especially useful in producing both coated and immobilized absorbents.

MS

MALDI MS is a powerful technique for determining high-molecular-weight compounds, especially biopolymers. Inherent to MALDI MS is its ability to provide an intact molecular ion because of its soft ionization. To be effective, the matrix must contain a chromophore to absorb laser light and promote ionization of the analyte. Of equal importance, the matrix must also be nonvolatile so that it can exist under high-vacuum conditions. The ideal matrix should also dissolve the analyte and minimize the chemical and thermal degradation of the sample. Because RTILs can meet many of these requirements, they were examined as a new class of liquid matrices (*40*).

The distinct advantages ILs have over solid matrices are that analytes can be more easily dissolved and the matrix–analyte solution is more homogeneous; this allows for better shot-to-shot reproducibility. Homogeneity is not observed with traditional solid MALDI matrices; instead, one must search for appropriate "hot spots" to do an analysis. Unfortunately, the traditional imidazolium-based ILs provided no analyte signals for proteins (*40*). The customary IL anions, in particular, did not promote analyte ion formation. However, when ILs of traditional MALDI matrices (α-cyano-4-hydroxycinnamic and sinapinic acids) were formed, ion peak intensities as high as or higher than those obtained with solid matrices were achieved and the detection limits were equivalent or lower (Figure 3).

Quantification and molecular-weight determination of DNA oligomers, oligonucleotides, peptides, and small proteins can also be performed with IL matrices (*41*, *42*). The improved precision and homogeneity also lead to good calibration curves over broad concentration ranges (*42*). Furthermore, the slopes of the calibration curves correlated with the inverse of peptide molecular weights. Thus, predicting relative sensitivities of related analytes is possible (*42*).

IL matrices also were used for phospholipids to produce higher signal intensities, smaller spot sizes, improved spot homogeneity, better signal reproducibility, and better detection limits than with crystalline matrices (*43*). The compound 2,5-dihydroxybenzoic acid butylamine offers the broadest applicability to a wide range of biomolecules. IL MALDI matrices were demonstrated as co-solvents for enzymatic reactions with fast, direct screening of the reaction mixture (*44*).
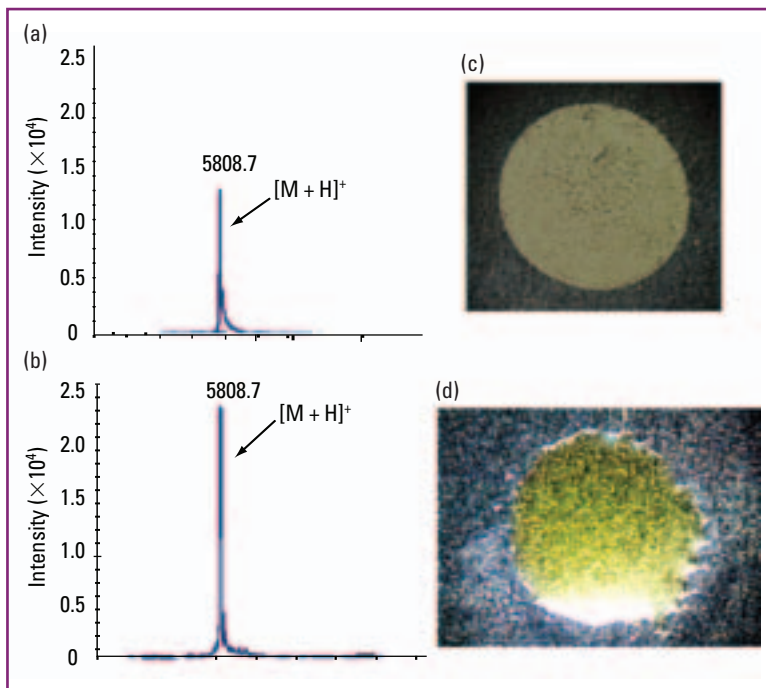

FIGURE 3. MALDI mass spectra of insulin in the matrices (a) CHCA and (b) an IL. A significant enhancement in the intensity of the molecular ion is observed in the IL matrix. (c) MALDI plate of CHCA containing cracks, crystals, and numerous incongruities often found in solid matrices. (d) IL in which the analyte is dissolved and homogeneous throughout.

(a) and (b) were obtained from www.chemistry.wustl.edu/~msf/ASMS2002/Ying_Li_Abstract.pdf; (c) and (d) were reprinted from Ref. 40.

IL solvents containing immobilized catalysts were examined by ESI MS (*45*). When the IL–catalyst mixture is diluted in an appropriate solvent, charged catalysts can be observed at concentrations 4 orders of magnitude more dilute than the IL. In cases for which the IL and/or catalyst are water- or solvent-reactive, ESI MS of undiluted ILs was successfully demonstrated (*46*). However, RTILs can cause substantial pollution of MS sources. Recently, detection of perchlorate at the parts-per-trillion level was facilitated by using a series of imidazolium- and pyrrolidinium-based dicationic ILs as ion-association reagents in ion chromatography/ion-association ESI MS analyses (*47*). In addition to enhancing sensitivity, this approach minimized interference from other anions.

Spectroscopy

NIR was used with great success to determine association and binding constants between phenol and α-, β-, and γ-CD dissolved in BMIM-Cl (*48*). The results demonstrated that the binding constants observed in the RTIL are much lower than those in D_2O, and this confirms the predominance of external adsorption as the main interaction between phenols and CDs in an IL solvent. An NIR spectroscopic technique also was developed for sensitive and direct determination of critical micelle concentration values of various nonionic surfactants in RTILs (*49*). The NIR approach appeared to be sensitive, universal, and nonintrusive, and no additives were needed. Preliminary results indicated that NIR can be used to characterize the aggregates in RTILs, monitor the kinetics of reactions, and identify reaction products.
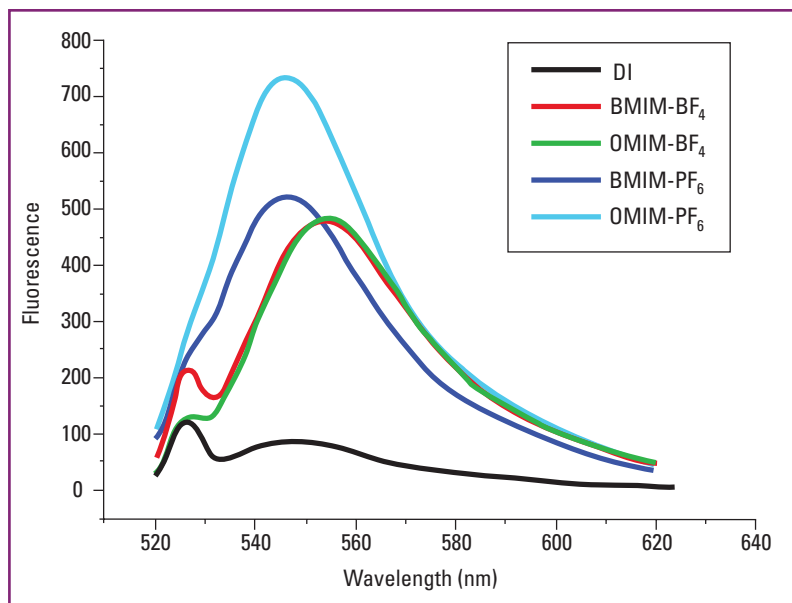
FIGURE 4. Fluorescence spectra of Rhodamine 6G dye in 4 different IL solvents and deionized water (DI).

Distinct and obvious fluorescence enhancements were observed in all IL solutions compared with DI. The highest fluorescence enhancement was observed for OMIM-PF$_6$ (8.6) followed by BMIM-PF$_6$ (6.1); identical enhancements were observed for BMIM-BF$_4$ and OMIM-BF$_4$ (5.6). Each solution was prepared at a concentration of 0.5 ppm and was excited at 526 nm.
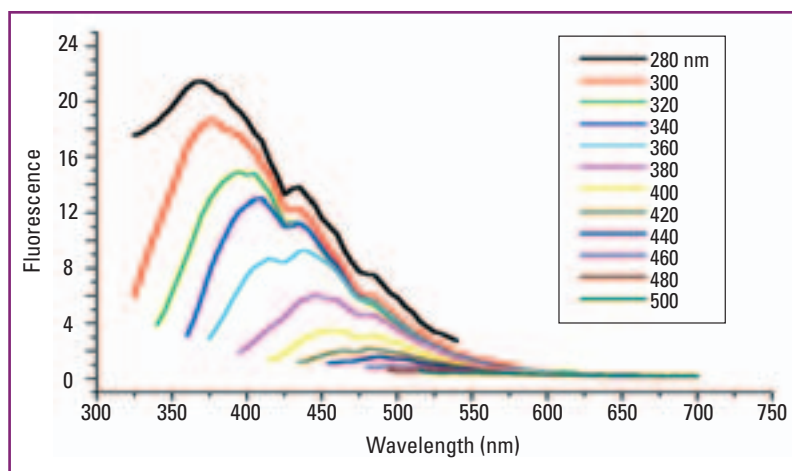

FIGURE 5. Spectra of purified, neat BMIM-PF$_6$, demonstrating the fluorescence of the IL as a function of excitation wavelength. The highest background fluorescence was observed at an excitation wavelength of 280 nm, whereas the background dropped significantly at excitation wavelengths >450 nm (55).

Time-resolved fluorescence spectroscopy was used to measure the dynamics of solvation of coumarin 153 (50, 51) and 4-aminophthalimide (52) in RTILs with various cations and anions. The results indicated that for the imidazolium-based ILs, the solvation dynamics occur in two separate time regimes consisting of ultrafast (5–55 ps) and slow (nanoseconds) components. A study suggested that the polarizability of the cation plays a role in the initial ultrafast component of solvation, whereas the relative diffusional motions of the cations and anions contribute to the slower component (51).

When the spatial resolution of confocal Raman spectroscopy was exploited, the molecular interactions between RTILs and a membrane made of Nafion could be interrogated. The results indicated that, when in contact with such polymers, RTILs behave like electrolytes rather than solvents (53). Recently, solutions of cellulose and cellulose oligomers dissolved in BMIM-Cl were studied with NMR spectroscopy (54).

Most recently, researchers discovered that up to a 6-fold fluorescence enhancement can be achieved when Rhodamine 6G dye molecules are excited in 4 different ILs and deionized water (55; Figure 4). The highest fluorescence enhancement was observed in OMIM-PF$_6$, whereas BMIM-BF$_4$ and OMIM-BF$_4$ demonstrated the smallest enhancements. Preliminary data suggest that the viscosity and solvation effects of ILs contribute to the fluorescence enhancements of dyes (55). An unexpected complication occurs when fluorescence is measured in IL solvents: the background fluorescence of impurities or the ILs themselves when excited at 280–430 nm (55; Figure 5). Although the origin of this background fluorescence has not yet been explained, the intensity is enough to interfere with many luminescence studies. Future work will undoubtedly reveal the origin of this fluorescence and possibly explain how to minimize its influence in spectroscopic measurements.

Electrochemistry

Ideal electrolytes should possess high ionic conductivity ($>10^{-4}$ S/cm), large electrochemical windows (>1 V) over which the electrolyte is neither reduced nor oxidized, fast ion mobility during redox reactions ($>10^{-14}$ m^2/V·s), and low volatility (56). Indeed, ILs exhibit many of these properties and characteristics. Many early electrochemical studies performed by Osteryoung were conducted on mixtures of aluminum chloride and 1-alkylpyridinium chlorides that were reported to be molten at or near room temperature (57). Wilkes et al. later introduced chloroaluminate melts based on dialkylimidazolium cations (2). Early studies of this interesting class of aprotic solvents focused on equilibria, how the electrochemistry varied depending on the acid–base character of the melt, the use of electroanalytical approaches to analyze water and oxide impurities, and the use of polypyrrole- and polyvinylferrocene-coated electrodes (57). Some studies suggested that ILs might be useful as electrolytes in batteries, photoelectrochemical cells, and electroplating (2, 57).

Carrier ions (Li$^+$, Na$^+$, H$^+$, I$^-$) are required to compose the electrochemical cell; this is problematic because IL electrolyte ions also migrate along the potential gradient. Typical ILs have conductivities of $>10^{-2}$ S/cm and are often useless as target ions (2, 57, 58). ILs possessing a zwitterionic structure in which the cation and anion are tethered (and therefore not expected to migrate with the potential gradient) were examined (58). They showed much lower ionic conductivities in the 10^{-5}–10^{-7} S/cm range.

The fact that ILs possess much higher viscosities than normal electrochemical supporting electrolytes has an impact on the observed diffusion coefficients. The diffusion coefficients of Li^+ (1.9×10^{-8} cm^2/s), Na^+ (1.4×10^{-8} cm^2/s), and K^+ (4.5×10^{-8} cm^2/s) in BMIM-PF$_6$ were determined (59). A comparative study was done of the diffusion coefficients of a neutral molecule and the radical cation or dication products generated after an electrochemical reaction in an IL and acetonitrile. The diffusion coefficient of the radical cation was consistently about half that of the neutral molecule (60). In contrast, in acetonitrile, the ratio of the diffusion coefficients was nearly 60% higher, an indication that viscosity and charge have considerable effects on the transport of diffusing species in IL solutions.

When IL-based electrolyte solutions were used, π-conjugated polymers (polyaniline, polypyrrole, and polythiophene) were reported to have long periods of stability and robustness for electrochemical mechanical actuators, electrochromic windows, and numeric displays (56). Slower ion insertion kinetics and gradual deswelling were observed for poly[3-(4-fluorophenyl)thiophene] when this electroactive polymer was produced in a pure IL rather than tetraethylammonium tetrafluoroborate and acetonitrile (61). As a result of a study with ac impedance, different conductivity mechanisms were proposed for hybrid materials of multiwall carbon nanotubes and mesocarbon microbeads when each was combined with the BMIM-PF$_6$ IL, (62). BMIM-PF$_6$-coated microperoxidase-modified gold and glassy carbon electrodes demonstrated efficient electron transfer between the electrode and the protein, resulting in high activity and catalysis toward H_2O_2. Recently, the electrochemical stability of self-assembled monolayers (SAMs) of alkanethiols on gold surfaces was enhanced in an IL, and nearly double the stable potential window of SAMs resulted compared with conventional aqueous or organic solvents (63). In addition, the background currents in ILs were much smaller than in other solvents in all cases.

By attaching short polyether chains to crystalline redox moieties, Murray and co-workers introduced a class of highly viscous molecular melts that exhibit electron transport properties (64, 65). The initial hybrid redox melts were based on cobalt(II/I) and iron(III/II) bipyridines and exhibited large "inner-sphere"-like energy barriers whose size depended on the length of the attached polyether chain (64). A series of polyether-tailed counterions for ruthenium hexamine, metal trisbipyridines, metal trisphenanthrolines, and ionic forms of aluminum quinolate, anthraquinone, phthalocyanine, and porphyrins were introduced to extend the number of hybrid redox polyether melts (65). These melts generally exhibited ionic conductivities in the range 7×10^{-5} to 7×10^{-10} S/cm.
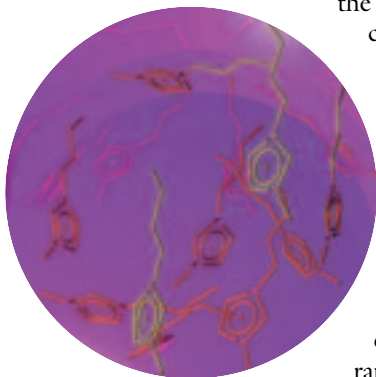
Miscellaneous uses

RTILs were used as additives for CE and HPLC separations. In the electrophoretic method, the IL modifier was added in concentrations of 2–90 mM to the run buffer, and good reproducibility of migration time and high selectivity was demonstrated. IL-modified run buffers were demonstrated in the achiral separations of polyphenols from grape seed extracts (66) and in achiral and chiral separations of alkyl aryl ketones, phenols, and chiral binaphthyl derivatives with polymeric surfactants as chiral selectors (67).

Imidazolium-based ILs were also used as mobile-phase additives in HPLC to separate amines. The structure of the IL, especially the length of the alkyl chain, and the concentration in the mobile phase influenced selectivity and efficiency, respectively (68). Many of the observed effects of IL additives in HPLC and CE stem from their chaotropic nature (69).

Future directions

Although we have highlighted many recent innovations in analytical chemistry, IL research has expanded into all areas of chemistry. ILs in analytical chemistry are still in their infancy, and many areas could benefit from them. Two general approaches are likely to emerge: novel and interesting applications of pre-existing ILs and the development of new, optimized ILs for specific applications. Classification and prediction of physicochemical properties and characteristics of ILs according to their cation and anion combination are desperately needed. Thoroughly characterizing new and pre-existing ILs will be necessary to accomplish this. The solvents will also need to be free of impurities known to affect the physicochemical and solvation properties of ILs.

Commercial GC stationary phases will become available within the year. Solid-phase extraction and SPME research will experience great development. IL solvents are replacing many reaction systems, and new ILs will be created specifically for MALDI MS and ESI MS. These developments will nicely complement the efforts of many who are studying enzyme-mediated reactions. Spectroscopic applications, which were slow to develop, should accelerate. The potential for electrochemical studies continues to be considerable.

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