A greener, halide-free approach to ionic liquid synthesis*

Jamie L. Ferguson[1,2], John D. Holbrey[1], Shieling Ng[1],
Natalia V. Plechkova[1], Kenneth R. Seddon[1], Alina A. Tomaszowska[1],
and David F. Wassell[1,‡]

[1]The QUILL Research Centre, School of Chemistry and Chemical Engineering,
The Queen's University of Belfast, Belfast, Northern Ireland, BT9 5AG, UK;
[2]Centre for Catalysis Research and Innovation, Department of Chemistry,
University of Ottawa, 10 Marie Curie, Ottawa, Ontario K1N 6N5, Canada

Abstract: Conventionally, ionic liquids with anions generated from simple organic acids are prepared following a metathetic procedure from a halide salt, usually a chloride. Here, we describe an efficient means of generating hydroxide solutions of the cations of interest, allowing many ionic liquids to be produced by simple acid–base reactions, completely avoiding the use of halides.

Keywords: barium; green synthesis; ionic liquids; metathesis; strontium.

INTRODUCTION

Ionic liquids have now been established as viable alternatives to organic solvents for a number of industrial processes, including synthesis, catalysis, and extraction, and applications, including thermal fluids, lubricants, or electrolytes [1–3]. This is largely due to their unique property sets, such as inherent conductivity, negligible vapour pressure, and their ability to be tuned for specific applications [4]. The negligible vapour pressure and conventional non-flammability of these materials decreases the chance of fugitive emissions [5], making them suitable as environmentally friendly substitutes for the traditional organic solvents used in industrial processes [1]. It must be stressed, however, that ionic liquids are not intrinsically green, despite many claims to the contrary (both fallacious in concept and completely ignoring the source of the ionic liquid), but may be designed to be green [6–9]. The conventional routes to ionic liquids are illustrated in eqs. 1 and 2. These processes involve the use of chloroalkanes, isolation of intermediate chloride ionic liquids, eq. 1, and then followed by a metathetic reaction with either an acid, HY, with concomitant generation of waste hydrogen chloride, eq. 2a, or with MY (M = Group 1 metal), with concomitant generation of waste metal chloride, eq. 2b. Clearly, any synthesis based around eqs. 2 will lead, inevitably, to an ionic liquid product with chloride contamination.

$$L + RCl \rightarrow [LR]Cl \tag{1}$$

$$[LR]Cl + HY \rightarrow [LR]Y + HCl \tag{2a}$$

$$[LR]Cl + MY \rightarrow [LR]Y + MCl \tag{2b}$$

(where M is usually Li, Na, or K)

Indeed, a recent assessment of the "greenness" of the synthetic routes to 1-butyl-3-methylimidazolium chloride has been published [6]. In terms of green chemistry, one of the issues with the use of ionic liquids involves their synthesis, particularly the metathetic step, which often generates stoichiometric amounts of halide salts or hydrogen chloride and large volumes of waste organic solvents [6]. Thus, most of the current synthetic protocols for the preparation of ionic liquids still struggle with elaborate synthetic schemes and complex purification, and result in ionic liquids with significant chloride contamination [10]. The presence of chloride can not only deactivate catalysts, but is also a source of corrosion [11,12]. Here, we describe a new route to ionic liquids, completely eliminating the use of halide ions and reducing significantly the usage of organic solvents. The new procedure involves the generation of aqueous hydroxide solutions of organic cations, which are then neutralised with organic acids, the by-product being water. This is particularly important to access systems with carboxylates, and other organic anions, which can rarely be introduced directly by alkylation [13]. The hydroxide solution is generated by hydrolysis of an intermediate alkyl sulfate salt, followed by reaction with an aqueous Group 2 metal hydroxide or oxide, resulting in the generation of Group 2 metal sulfate wastes; Group 2 metal sulfates are found as natural ores [14]. Variants included in the development of the optimised procedure are also discussed.

EXPERIMENTAL

Materials

1-Methylimidazole (99.9 %), bromoalkanes (≥97 %), chloroalkanes (≥97 %), diethyl sulfate (98 %), dimethyl sulfate (≥99.0 %), 1-butylpyrrolidine (98 %), dimethylbutylamine (99.0 %), 1-butyl-3-methylimidazolium hydrogensulfate (95 %), 1-ethyl-3-methylimidazolium hydrogensulfate (95 %), tributylamine (≥99.0 %), strontium hydroxide octahydrate (98 %), barium hydroxide octahydrate (98 %), calcium oxide (99.9 %), potassium hydroxide (99.99 %), methanoic acid (≥98 %), ethanoic acid (≥99 %), propanoic acid (≥99 %), butanoic acid (≥99 %), 2-methylpropanoic acid (≥99 %), hexanoic acid (≥98 %), octanoic acid (≥98 %), L-(+)-lactic acid (~98 %), hydroxyethanoic acid (99 %), malonic acid (99 %), D-(+)-galacturonic acid monohydrate (97 %), succinic acid (99.0 %), xanthine (98 %), L-(+)-glutamine (≥99 %), L-(+)-alanine (≥98 %), β-(±)-phenylalanine (≥98 %), α-L-(+)-phenylalanine (≥98 %), tributylmethylammonium hydroxide (20 % solution in water), sulfamic acid (99 %), 2-aminomethanesulfonic acid (97 %), 4-morpholineethanesulfonic acid (≥99 %), sulfanilic acid (≥99 %), 4-morpholinepropanesulfonic acid (≥99.5 %), 2-[(2-hydroxy-1,1-bis(hydroxymethyl)ethyl)amino]ethanesulfonic acid (≥99 %), N-(2-acetamido)-2-aminoethanesulfonic acid (≥99 %), and taurine (≥99 %) were purchased from Aldrich and used without further purification. Tributylphosphine (50 % in toluene), tripentylphosphine, trihexylphosphine, trioctylphosphine, and trihexyl(tetradecyl)phosphonium chloride were donated by Cytec Canada and used without further purification. Amberlite IRN-78 resin (Supelco) was washed several times with deionised water prior to use, until the smell of the residual amine from the manufacturing process disappeared. Toluene, deionised water, ultrapure water, ethanol (industrial methylated spirits), absolute ethanol, and sulfuric acid were used as received.

Ionic liquids were dried under high vacuum at 48 h at 80 °C prior to analysis.

Equipment

All NMR spectra (unless otherwise stated) were recorded on either a Bruker Avance DPX 300 or DRX 500 spectrometer (25 °C). Chemical shifts are reported in δ (ppm) with reference to external tetramethylsilane. Deuterated solvents were all used as purchased from Sigma-Aldrich. Electrospray ionisation mass spectra were recorded on a Waters LCT Premier mass spectrometer. C, H, N, and S contents (wt %) were determined using a Perkin-Elmer Series II CHNS/O 2400 CHN Elemental Analyser

(ASEP). Metal contents were determined on a Perkin Elmer Optima simultaneous ICP instrument. Samples were analysed 4–5 times, and the result (estimated ±0.5 % relative error) was averaged (ASEP). Halides were determined with the use of the oxygen combustion method, whereby a weighed sample is burned in a pure oxygen atmosphere, followed by titration with mercury(II) nitrate (ASEP). Water content was determined by Karl-Fischer analysis with the use of a GR Scientific Cou-Lo Aquamax KF moisture meter, with analyses determined in triplicate.

Hydroxide solution synthesis

Ion-exchange column, method {A}

Generic synthetic method
For comparative purposes, an established resin-exchange method for the production of hydroxide solutions of ionic liquid cations was performed [15]. To a glass chromatography column (length 70 cm, inner diameter 1.9 cm), fitted with a glass wool filter at the lower end, a slurry of Amberlite IRN-78 ion-exchange resin in deionised water was added (Fig. 1). The column was preconditioned by flushing with deionised water (500 cm^3), ensuring that the final water level was always above the resin. The eluant pH was tested for neutrality by Universal pH paper, and halide content was tested by addition of 1 drop acidic aqueous silver(I) nitrate (0.30 M Ag[NO$_3$] in 1.0 M HNO$_3$) to verify that the eluant was neutral and free of halides. The column was then sealed with a punctured rubber septum, through which the drainage end of a separating funnel had been forced. A halide salt of the cation of interest (0.007–0.3 mmol) was weighed into a clean dry beaker and dissolved in deionised water (200–1300 cm^3). The resulting solution was poured into the separating funnel reservoir atop the column. The stopcock of the separating funnel and column were first opened fully and then adjusted such that the solution eluted at a rate of ca. 1 drop per every 20–30 s. The column was allowed to elute for 16–18 h, until the solution had drained to just above the top of the resin. The column was then flushed with deionised water (100 cm^3), using the same elution rate. A small sample (5.0 cm^3) of the eluant was titrated with aqueous hydrochloric acid (0.10036 M) to determine its concentration. The colourless,

Internal diameter (1.9 cm)

Glass column length (70 cm)
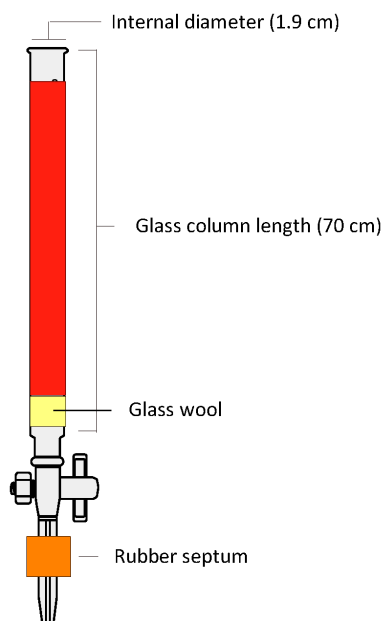
Glass wool

Rubber septum

Fig. 1 Ion-exchange column.

highly basic hydroxide solution generated from the procedure was then neutralised to its specific equivalence point with the conjugate acid of the anion of interest. Hydroxide solutions of imidazolium cations are unstable, and must be maintained at low temperatures and low concentration before use; they should be used as soon as possible after generation. The pH at equivalence was determined by use of the general pK_a equation and concentration of the basic solution formed above. This pH was conveniently found by the use of the CurTiPot freeware program [16]. Water was initially removed with a rotary evaporator, and then any remaining traces of water were removed under high vacuum for 15 h at 80 °C.

Synthesis of 1-butyl-3-methylimidazolium ethanoate

$[C_4mim]Br$ (13.878 g, 0.07 mol) was dissolved in deionised water (200 cm^3) and loaded into the separating funnel atop the column. The stopcock of the separating funnel and column were opened fully and then adjusted such that the solution eluted at a rate of ca. 1 drop per every 30 s. The column was allowed to elute for 16 h, until the solution had drained to the top of the resin. The column was then flushed with deionised water (100 cm^3), using the same elution rate. A sample of the eluant (5.0 cm^3) was titrated with aqueous hydrochloric acid (0.10036 M) to determine its concentration. The colourless eluant collected was titrated using ethanoic acid to the calculated end point of pH 8.4 with the help of a pH meter. Water was then removed under vacuum with the use of a rotary evaporator. The remaining viscous liquid was then dried under high vacuum at 80 °C for 15 h. The product was obtained as a clear yellowish viscous liquid. Yield 78.52 %. Elemental analysis for $C_{10}H_{18}N_2O_2$ % calc. (% found): C 60.58 (56.03), H 9.15 (8.74) N 14.13 (11.73) S 0.00 (<0.30); <0.5 wt % Br.

Sulfate metathesis

The sulfate metathesis methodology requires a hydrogensulfate (or bisulfate) salt of the cation of interest. These were obtained by two general methods; (I) metathesis of a chloride salt with sulfuric acid (included here for completeness), or (II) reaction of a trialkylamine or trialkylphosphine with a dialkyl sulfate alkylating agent (typically dimethyl sulfate), followed by hydrolysis of the resulting alkyl sulfate salt. The salts $[C_2mim][HSO_4]$ and $[C_4mim][HSO_4]$ were purchased from Aldrich, and used as received.

Chloride salt metathesis, method (Ia)

Tetraalkylphosphonium chloride (0.100 mol) was weighed and placed in a clean dry round-bottomed flask (250 cm^3) equipped with a stirring bar. An equivalent amount of concentrated sulfuric acid (0.100 mol) was added slowly with stirring. The round-bottomed flask was fitted with a stopcock, the other end of which was connected to an open tube packed with NaOH pellets. The flask was stirred for 4 h at room temperature, after which the open end of the NaOH packed tube was connected to a small diaphragm pump. The mixture was then heated up to 90 °C and was left to stir for 15 h under vacuum. The tetraalkylphosphonium hydrogensulfate thus produced was used in further reactions described later.

Nonaqueous chloride salt metathesis, method (Ib)

The chloride salt of the tetraalkylphosphonium cation of interest (0.100–0.193 mol) was added to a clean, dry round-bottomed flask equipped with a magnetic stirring bar and stopcock. Concentrated H_2SO_4 (0.110–0.304 mol) was slowly added, and the stopcock was connected to a low vacuum water pump to remove the generated hydrogen chloride. After the visible evolution of HCl had ceased, the flask was connected to an NaOH pre-trap, and the outlet of the NaOH pre-trap was connected to high vacuum and evacuated at 70 °C for 12 h. The viscous liquid obtained was then dissolved in toluene (100 cm^3) and washed with dilute aqueous H_2SO_4 (up to 450 cm^3 total volume, 5 M, at least 3 portions), then with deionised water (5–8 portions of 50–150 cm^3 each). The pH of the final deionised water wash was then tested for neutrality (Universal pH paper), and halide content was tested by addition of one drop of acidic aqueous silver(I) nitrate (0.30 M Ag[NO_3] in 1.0 M HNO_3) to verify that the final wash was neutral and free of halides. The toluene was then removed under vacuum (rotary evap-

orator) and the residual liquid dried in vacuo at 80–90 °C overnight. The tetraalkylphosphonium hydrogensulfate product was obtained as a clear viscous liquid.

Methyl sulfate hydrolysis, method (IIa)
The methyl sulfate salt of the cation of interest (0.10–0.3 mol) was placed in a clean dry beaker (1000 cm^3) with deionised water added (200–400 cm^3) to form a 2 M solution. Concentrated sulfuric acid (4–9 g, 98 mol %) was added to the beaker. The solution was heated to, and maintained at, 100 °C in an open beaker to allow for the loss of the generated methanol. Reaction progress was monitored via ^{1}H NMR spectroscopy by observing the loss of the singlet due to the methyl group of the anion at 3.59 ppm (D$_2$O solvent). The water level in the beaker was kept constant with the addition of deionised water as required (ca. 50 cm^3 every 30 min). Hydrolysis was complete after 6 h.

1-Ethyl-3-methylimidazolium ethyl sulfate hydrolysis, method (IIb)
A two-necked flask was fixed under a Vigreux column, to the top of which was attached a distillation head, leading down to a receiving flask. A vacuum line was attached to the distillation head. Concentrated sulfuric acid (98 %, 3.00 g; 1.8 cm^3; 0.0300 mol) was diluted with water (118.2 cm^3) and transferred to the flask. The solution was brought to reflux, and then [C$_2$mim][EtSO$_4$] (36.68 g; 30 cm^3; 0.1552 mol) was added to it. The reaction solution was stirred under reflux (4 d). A low vacuum was then applied (ca. 230 mbar), while the solution was maintained under reflux (5.5 h), causing some liquid to distil into the receiving flask. Vacuum was released, and the reaction mixture continued stirring under reflux (15 h). Again, a low vacuum was applied while the solution was maintained under reflux (1.5 h), causing a very small amount of liquid to distill. Solvent was removed from the product in vacuo (90 °C), and the product was obtained quantitatively as a clear, slightly yellow liquid containing a total of 30 mmol of sulfuric acid.

On obtaining the hydrogensulfate salt of interest, a metathetic route utilising one of four metals *M*, one from Group 1 (viz. potassium) and three from Group 2 (viz. calcium, strontium, and barium) was investigated.

Potassium hydroxide metathesis, method {B}

Generic synthetic method
A sample of solid KOH was dissolved in ultra-pure water and titrated against a standard aqueous hydrochloric acid solution (0.10036 M); the true hydroxide concentration was noted.

KOH (1.5–30 g) was added to a clean, dry round-bottomed flask and dissolved in a 9:1 v/v ethanol/water solution (20–250 cm^3). The hydrogensulfate salt of the cation of interest (0.01–0.2 mol) was weighed into a clean, dry round-bottomed flask and dissolved in the ethanol/water solution (30–250 cm^3), and then transferred to the previously prepared KOH solution with additional ethanol/water rinses. The resulting suspension was stirred at room temperature for 2 h, removed from stirring, sealed, and cooled (4 °C, 1 d), whence a white precipitate settled from the clear yellow solution and was removed via vacuum filtration (P4 sintered glass funnel), washed with absolute ethanol, and discarded. The colourless, highly basic hydroxide solution generated from this procedure was then neutralised to its specific equivalence point with the conjugate acid of the anion of interest.

Synthesis of 1-butyl-3-methylimidazolium ethanoate
A sample of solid KOH was dissolved in ultra-pure water and titrated against a standard aqueous hydrochloric acid solution (0.10036 M); the true hydroxide concentration was noted.

KOH (17.62 g; 0.2619 mol) was added to a clean, dry round-bottomed flask and dissolved in a 9:1 v/v ethanol/water solution (140 cm^3). [C$_4$mim][HSO$_4$] (31.003 g; 0.1312 mol) was separately dissolved in a 9:1 v/v ethanol/water solution (105 cm^3) in a round-bottomed flask at room temperature. The [C$_4$mim][HSO$_4$] solution was transferred to the potassium hydroxide solution, along with two ethanol/water rinses (9:1 v/v; 60 cm^3 each). The resulting suspension was stirred at room temperature for 2 h, removed from stirring, sealed, cooled (4 °C, 1 d), whence a white precipitate settled from the

clear yellow solution and was removed via vacuum filtration (P4 sintered glass funnel), washed with absolute ethanol (40 cm^3), and discarded. A portion of the [C$_4$mim][OH] solution (300.0 cm^3) generated from the procedure was then neutralised with ethanoic acid to pH 8.6 with the use of a pH meter to produce [C$_4$mim][CH$_3$CO$_2$] (19.714 g, 0.099 mol). Yield = 98.6 %. Elemental analysis for C$_{10}$H$_{18}$N$_2$O$_2$ % calc. (% found): C 60.58 (57.93), H 9.15 (9.21), N 14.13 (13.44), S 0.00 (<0.3); halide (Br + Cl) = 0.40 wt %; K = 78.0 mg kg^{-1}.

Calcium oxide metathesis, method {C}

Synthesis of tributylmethylammonium ethanoate
[N$_{1444}$][HSO$_4$] obtained from hydrolysis (0.321 mol, containing 2 wt % of a 40 mol % H$_2$SO$_4$ solution) was placed in a round-bottomed flask (1000 cm^3), and CaO (30.25 g, 0.539 mol) in deionised water was added (800 cm^3) and stirred for 16 h. Ethanoic acid was then slowly added to the slurry to pH = 12.70, with the aid of a pH meter. The slurry was then filtered and another portion of ethanoic acid was added to the filtrate to a pH value of 8.00. Water was removed under vacuum, and the residue was dissolved in ethanol (100 cm^3). The precipitate formed was removed by filtration and discarded. The filtrate was transferred to a clean, dry round-bottomed flask, and solvent was again removed under vacuum. The resulting pale yellow liquid was dried under high vacuum at 65 °C over 16 h to produce [N$_{1444}$][CH$_3$CO$_2$] (54.2 g, 0.209 mol). Yield = 65 %. Elemental analysis for C$_{15}$H$_{33}$NO$_2$ % calc. (% found): C 69.44 (67.10), H 12.82 (11.74), N 5.39 (4.91), S 0.00 (<0.3); Ca 700 ppm.

Strontium hydroxide metathesis, method {D}

Generic aqueous synthesis, method {Da}
The hydrogensulfate salt of the cation of interest (0.100 mol) was weighed into a clean, dry round-bottomed flask, and dissolved in hot deionised water (95–100 °C, 100 cm^3). Strontium hydroxide octahydrate (0.120 mol) was weighed into a conical flask and dissolved in hot deionised water (95–100 °C, 200 cm^3). The previously prepared cation hydrogensulfate salt solution was transferred to the same conical flask, and the round-bottomed flask was rinsed with hot, deionised water (95–100 °C, 2 × 50 cm^3) with the rinses transferred into the conical flask as well. This cloudy reaction mixture was stirred, open, with an overhead stirrer and allowed to cool (4 °C, 16 h). The white precipitate was removed via vacuum filtration (P4 glass sintered funnel with a 0.5 cm silica gel layer), washed with water (ca. 20 °C, 2 × 25 cm^3), and discarded. The colourless, highly basic hydroxide solution generated from the procedure was then neutralised to its specific equivalence point with the conjugate acid of the anion of interest. The pH at equivalence was determined by use of the general pK_a equation and approximate concentration of the basic solution formed above. This pH was conveniently found by the use of CurTiPot [16]. Water was removed under vacuum (rotary evaporator), and ethanol (100 cm^3) was added to the filtrate, resulting in a small amount of fine white precipitate, which was again removed by filtration. The ethanol and any remaining traces of water were then removed from the filtrate under vacuum (rotary evaporator followed by high vacuum).

Synthesis of 1-butyl-3-methylimidazolium ethanoate
[C$_4$mim][HSO$_4$] (11.82 g; 0.05 mol) was weighed into a clean, dry round-bottomed flask, and dissolved in hot deionised water (95–100 °C, 100 cm^{-3}). Strontium hydroxide octahydrate (19.09 g; 0.072 mol) was weighed into a conical flask and dissolved in hot deionised water (95–100 °C, 200 cm^3). The previously prepared [C$_4$mim][HSO$_4$] solution was quantitatively transferred to the conical flask, rinsing with hot, deionised water (95–100 °C, 2 × 50 cm^3). This cloudy reaction mixture was stirred, open, with an overhead stirrer and allowed to cool (4 °C, 16 h). The white precipitate was removed via vacuum filtration (P4 glass sintered funnel with a 0.5 cm silica gel layer), washed with water (ca. 20 °C, 2 × 25 cm^3), and discarded. The colourless, highly basic [C$_4$mim][OH] solution generated from the procedure was then neutralised to equivalence with ethanoic acid to pH 8.6 with the use of a pH meter. Water was removed under vacuum (rotary evaporator), and ethanol (100 cm^3) was added to the filtrate, result-

ing in a small amount of fine white precipitate, which was again removed by filtration. The ethanol and any remaining traces of water were then removed under vacuum (rotary evaporator followed by high vacuum). $[C_4mim][CH_3CO_2]$ Yield = 98 %, Elemental analysis % calc. for $C_{10}H_{18}N_2O_2$ (% found): C 60.58 (56.98), H 9.15 (9.23), N 14.13 (13.33), S 0.00 (<0.3); Sr = 193 mg kg^{-1}.

Generic nonaqueous synthesis, method {Db}
The hydrogensulfate salt of the cation of interest (0.050 mol) was weighed into a clean dry conical flask and dissolved in methanol (100 cm^3). A slight excess of strontium hydroxide (0.060 mol) was weighed into a clean dry conical flask and dissolved in methanol (100 cm^3). The methanolic cation hydrogen-sulfate solution was then transferred to the strontium hydroxide solution, with subsequent methanol rinses (2 × 50 cm^3), immediately generating a white slurry. The reaction mixture was then heated to 50 °C, and the flask loosely sealed to limit evaporation, stirred for 30 min, then allowed to cool to room temperature (at this point, it is possible to isolate the methanolic solution of the hydroxide salt of the cation of interest. In this case, enough methanol is added to double the volume. The solution is then allowed to settle under centrifugation, and the supernatant is decanted and stored for future use). An excess of the acid form of the anion of interest was then added, and the methanol removed under vacuum generating a cloudy white viscous liquid. Deionised water (100 cm^3) was added to the white paste, and the resultant slurry was transferred to a separating funnel. The flask was rinsed with trichloromethane (2 × 150 cm^3), and the rinses were transferred to the separating funnel in order to extract the prepared ionic liquid from the mixture. Strontium sulfate (white precipitate) and unreacted strontium hydroxide remained as a suspension in the aqueous layer. The trichloromethane layer (bottom layer) was then collected, and the solvent removed under vacuum. The ionic liquid generated was later dried under high vacuum at 80 °C for 15 h.

Synthesis of tetrahexylphosphonium ethanoate
$[P_{6\,6\,6\,6}][HSO_4]$ (23.455 g; 0.050 mol) was weighed and dissolved in 100 cm^3 methanol. A slight excess of strontium hydroxide octahydrate (15.948 g; 0.060 mol) was weighed in a conical flask and dissolved in methanol (100 cm^3). The methanolic $[P_{6\,6\,6\,6}][HSO_4]$ solution was then added to the conical flask containing the strontium hydroxide solution, with subsequent methanol rinses (2 × 50 cm^3), immediately producing a white suspension. The reaction mixture was then heated to 50 °C, and the flask loosely sealed to limit evaporation, stirred for 30 min, then allowed to cool to room temperature. An excess of ethanoic acid (>0.050 mol) was then added, and the methanol removed under vacuum generating a cloudy white viscous liquid. Deionised water (100 cm^3) was added to the white paste, and then transferred to a separating funnel. The flask was rinsed with trichloromethane (2 × 150 cm^3), and the rinses were transferred to the separating funnel in order to extract the prepared $[P_{6\,6\,6\,6}][CH_3CO_2]$ from the mixture. Strontium sulfate (white precipitate) and unreacted strontium hydroxide remained as a suspension in the aqueous layer. The trichloromethane layer (bottom layer) was then collected, and the solvent removed under vacuum. The $[P_{6\,6\,6\,6}][CH_3CO_2]$ produced was then dried under high vacuum at 80 °C for 15 h. $[P_{6\,6\,6\,6}][CH_3CO_2]$ Yield = 89.9 %; Elemental analysis for $C_{26}H_{55}PO_2$, % found (% calc.): C 70.98 (72.51), H 12.86 (12.87); 0.62 % Cl$^-$; Sr <10 mg kg^{-1}.

Barium hydroxide metathesis, method {E}

Generic synthetic method
The hydrogensulfate salt of the cation of interest (0.100 mol) was weighed into a clean, dry round-bottomed flask, and dissolved in hot deionised water (95–100 °C, 100 cm^3). Barium hydroxide octahydrate (0.120 mol) was weighed into a conical flask and dissolved in hot deionised water (95–100 °C, 200 cm^3). The previously prepared cation hydrogensulfate salt solution was transferred to the same conical flask, and the round-bottomed flask was rinsed with hot, deionised water (95–100 °C, 2 × 50 cm^3) with the rinses transferred into the conical flask as well. This cloudy reaction mixture was stirred, open, with an overhead stirrer and allowed to cool to room temperature, then refrigerated (4 °C, 16 h). The white solid precipitate was removed via vacuum filtration (P4 glass sintered funnel with a 0.5 cm silica

gel layer), washed with water (ca. 20 °C, 2 × 25 cm^3), and discarded. The colourless, highly basic hydroxide solution generated from the procedure was then neutralised to its specific equivalence point with the conjugate acid of the anion of interest. The pH at equivalence was determined by use of the general pK_a equation and approximate concentration of the basic solution formed above. Water was removed under vacuum (rotary evaporator), and ethanol (100 cm^3) was added to the filtrate resulting in a small amount of fine white precipitate, which was again removed by filtration. The ethanol and any remaining traces of water were then removed under vacuum (rotary evaporator followed by high vacuum).

Synthesis of 1-butyl-3-methylimidazolium ethanoate
[C$_4$mim][HSO$_4$] (23.63 g; 0.10 mol) was weighed into a round-bottomed flask and dissolved in hot water (100 °C, 100 cm^3). Barium hydroxide octahydrate (37.860 g; 0.12 mol) was weighed into a conical flask and dissolved in hot deionised water (100 °C, 200 cm^3). The hydrogensulfate solution was poured into it, followed by rinsing of the flask with hot deionised water (100 °C, 2 × 50 cm^3) into the reaction mixture. The mixture was stirred, unsealed, at 100 °C (1 h), and then was cooled to room temperature. The white solid precipitate was removed via vacuum filtration (P4 sintered glass funnel with a 0.5 cm silica gel layer), washed with water (ca. 20 °C, 2 × 25 cm^3), and discarded. Ethanol (100 cm^3) was added to the filtrate resulting in a white precipitate, which was again removed by filtration. The colourless, highly basic [C$_4$mim][OH] solution generated from the procedure was then neutralised with ethanoic acid to pH 8.6 with the use of a pH meter. [C$_4$mim][CH$_3$CO$_2$] Yield = 98 %; Elemental analysis % calc. for C$_{10}$H$_{18}$N$_2$O$_2$ (% found): C 60.58 (57.05), H 9.15 (9.27), N 14.13 (13.23), S 0.00 (<0.3); Sr = 79 mg kg^{-1}, Ba = 279 mg kg^{-1}.

RESULTS AND DISCUSSION

General

Although there are some relatively "green" methods of generating ionic liquids, such as the reaction of imidazole carbenes with the conjugate protic acid of the anion of interest [17], alkylation with a trifluoroethanoic acid ester followed by recovery of the trifluoroethanoic acid [13], as well as synthesis of the cation via alkylation with dimethyl carbonate followed by reaction of the intermediate methyl carbonate ionic liquid with the conjugate protic acid on the anion of interest [18], these methods have certain drawbacks. The carbene method is only relevant for imidazolium cations and can generally only be used to produce very small amounts of the ionic liquid of interest, albeit highly pure. Trifluoroethanoic acid esters are quite expensive, and the acid product is toxic, shows poor biodegradability, and is an ecotoxin. The dimethyl carbonate method, while more widely applicable, requires high temperature, long reaction times, and regular access to an autoclave of reasonable size (impossible for some research groups) if larger amounts of the ionic liquid are required. Direct purchase of hydroxide or hydrogen carbonate solutions of useful cations is possible in some cases, but cation selection is limited and the solutions are usually unstable. The need for the development of a simple method to produce relatively large amounts (hundreds of grams) of a wide array of ionic liquids is apparent.

Inspiration for the development of this family of methodologies came from the known low solubility of calcium sulfate in water and potassium sulfate in ethanol/water mixtures. Initial trials showed that both methods are feasible. However, in the case of the calcium method, very large volumes of solvent are required due to the low concentration required to force the synthesis to completion, and the potassium method requires large volumes of ethanol for it to work at all. A review of the solubility of metal hydroxides and sulfates shows why these problems occur, while also pointing to improved alternatives (Table 1).

Table 1 Aqueous solubility of selected potassium, calcium, strontium, and barium salts [19].

Compound		Solubility/g $(100\ cm^3)^{-1}$	
		Cold (T/°C)	Hot (T/°C)
Potassium	ethanoate	253 (*20*)	492 (*62*)
	carbonate	112 (*20*)	156 (*100*)
	hydroxide	107 (*15*)	178 (*100*)
	sulfate	12 (*25*)	24 (*100*)
Calcium	ethanoate	37.4 (*0*)	29.7 (*100*)
	carbonate	0.0014 (*25*)	0.0018 (*75*)
	hydroxide	0.185 (*0*)	0.077 (*100*)
	oxide	0.131 (*10*)	0.07 (*80*)
	sulfate	0.209 (*30*)	0.1619 (*100*)
Strontium	ethanoate	36.9 (*NA*)	36.4 (*97*)
	carbonate	0.0011 (*18*)	0.065 (*100*)
	hydroxide octahydrate	0.9 (*0*)	47.71 (*100*)
	oxide	0.69 (*30*)	22.85 (*100*)
	sulfate	0.0113 (*0*)	0.014 (*30*)
Barium	ethanoate	58.8 (*0*)	75 (*100*)
	carbonate	0.0022 (*18*)	0.0065 (*100*)
	hydroxide octahydrate	5.6 (*15*)	94.7 (*78*)
	oxide	3.48 (*20*)	90.8 (*100*)
	sulfate	0.000246 (*25*)	0.000413 (*100*)

For comparison, the previously reported ion-exchange column methodology for the preparation of [C$_2$mim]-based ionic liquids with various amino acid anions, was also used to prepare a sample of [C$_4$mim][CH$_3$CO$_2$] [15]. The concentration of selected contaminants in 1-butyl-3-methylimidazolium ethanoate produced by the column exchange, potassium hydroxide, strontium hydroxide, and barium hydroxide synthetic methods as described above are included in Table 2.

Table 2 Selected contaminants[a] in 1-butyl-3-methylimidazolium ethanoate from four ionic liquids synthetic methods.

Method		K/mg kg^{-1}	Sr/mg kg^{-1}	Ba/mg kg^{-1}	Cl+Br/ wt %
Exchange column	{A}	65.0	<10	<10	0.47
Potassium hydroxide	{B}	78.0	<10	<10	0.40
Strontium hydroxide	{Da}	33.0	193	<10	0.37
Barium hydroxide	{E}	<10.0	79	279	0.45

[a]All sulfur content in ionic liquids synthesised are below detection limit.

Note that because the calcium method required an extremely high level of dilution to go to completion, it was abandoned immediately upon development of the strontium method and full characterisation of the few ionic liquids, produced by the method, was not carried out. All the methods summarised in Table 2 generated reasonably pure samples of [C$_4$mim][CH$_3$CO$_2$]. However, when a much greater range of ionic liquids were prepared (see Table 3), the route via potassium hydroxide consistently produced ionic liquids with too high a level of metal contamination. As barium salts are relatively toxic compared to strontium salts (oral rat LD$_{50}$ = 118 mg kg^{-1} for barium chloride compared to 2250 mg kg^{-1} for strontium chloride), it was decided to pursue the strontium method for synthesis of

Table 3 Example ionic liquids prepared by column, potassium, strontium, and barium metathesis methods with analysis.

Ionic liquid (abbreviation)	Method	% C (Theo)	% H (Theo)	% N (Theo)	% S (Theo)	Halide/wt %	Metal/mg kg⁻¹	% Yield
[C₂mim][HCO₂]	{A}	52.70 (53.83)	7.55 (7.74)	16.21 (17.94)		Br; 0.97		99
[C₂mim][HCO₂]	{Da}	52.18 (53.83)	7.38 (7.74)	16.86 (17.94)			Sr; 80.6	84
[C₂mim][HCO₂]	{E}	52.44 (53.83)	7.93 (7.74)	16.85 (17.94)			Ba; <10	78
[C₂mim][CH₃CO₂]	{A}	55.65 (56.45)	8.01 (8.29)	15.91 (16.46)		Br; 0.97		84
[C₂mim][CH₃CO₂]	{Da}	55.12 (56.45)	8.50 (8.29)	15.28 (16.46)			Sr; 70.2	78
[C₂mim][CH₃CO₂]	{E}	54.97 (56.45)	8.07 (8.29)	15.55 (16.46)			Ba; <10	80
[C₂mim][C₂H₅CO₂]	{A}	57.23 (58.67)	8.39 (8.75)	14.91 (15.20)		Br; 0.36		78
[C₂mim][C₂H₅CO₂]	{Da}	57.02 (58.67)	8.05 (8.75)	14.88 (15.20)			Sr; 74.0	80
[C₂mim][C₂H₅CO₂]	{E}	57.58 (58.67)	7.86 (8.75)	15.36 (15.20)			Ba; <10	85
[C₂mim][C₃H₇CO₂]	{A}	59.05 (60.58)	9.12 (9.15)	13.82 (14.13)		Br; 0.24		80
[C₂mim][C₃H₇CO₂]	{Da}	59.13 (60.58)	8.52 (9.15)	13.59 (14.13)			Sr; 145	85
[C₂mim][C₃H₇CO₂]	{E}	58.41 (60.58)	8.68 (9.15)	13.77 (14.13)			Ba; <10	85
[C₂mim][C₅H₁₁CO₂]	{A}	62.51 (63.69)	8.94 (9.80)	11.98 (12.38)		Br; 0.94		85
[C₂mim][C₅H₁₁CO₂]	{Da}	62.25 (63.69)	9.44 (9.80)	12.47 (12.38)			Sr; <10	85
[C₂mim][C₅H₁₁CO₂]	{E}	62.37 (63.69)	9.97 (9.80)	12.90 (12.38)			Ba; 20.3	81
[C₂mim][C₇H₁₅CO₂]	{A}	65.67 (66.11)	10.25 (10.30)	10.88 (11.01)		Br; 0.27		85
[C₂mim][C₇H₁₅CO₂]	{Da}	65.91 (66.11)	9.46 (10.30)	10.88 (11.01)			Sr; 99.7	81
[C₂mim][C₇H₁₅CO₂]	{E}	65.41 (66.11)	9.50 (10.30)	11.75 (11.01)			Ba; 16.4	94
[C₂mim][Me₂CHCO₂]	{A}	58.86 (60.58)	8.86 (9.15)	14.29 (14.13)		Br; 0.54		81
[C₂mim][Me₂CHCO₂]	{Da}	59.28 (60.58)	8.45 (9.15)	14.22 (14.13)			Sr; 32.6	94
[C₂mim][Me₂CHCO₂]	{E}	59.50 (60.58)	8.71 (9.15)	14.10 (14.13)			Ba; <10	79
[C₂mim][MeCH(OH)CO₂]	{A}	51.49 (53.99)	7.85 (8.05)	13.10 (13.99)		Br; 0.20		94
[C₂mim][MeCH(OH)CO₂]	{Da}	52.39 (53.99)	7.46 (8.05)	13.77 (13.99)			Sr; 34.9	79
[C₂mim][MeCH(OH)CO₂]	{E}	52.90 (53.99)	8.28 (8.05)	13.72 (13.99)			Ba; <10	97
[C₂mim][HOCH₂CO₂]	{A}	50.91 (51.60)	7.57 (7.58)	15.03 (15.04)		Br; 0.45		79
[C₂mim][HOCH₂CO₂]	{Da}	50.91 (51.60)	7.00 (7.58)	14.95 (15.04)			Sr; 74.4	97
[C₂mim][HOCH₂CO₂]	{E}	50.88 (51.60)	7.30 (7.58)	15.12 (15.04)			Ba; <10	93

(continues on next page)

Table 3 (*Continued*).

Ionic liquid (abbreviation)	Method	% C (Theo)	% H (Theo)	% N (Theo)	% S (Theo)	Halide/wt %	Metal/mg kg^{-1}	% Yield
$[C_1C_4pyr][HCO_2]$	{Da}(IIa)	63.78 (64.13)	10.79 (11.30)	7.07 (7.48)	<0.50		Sr; 171	85
$[C_1C_6pyr][HCO_2]$	{Da}(IIa)	65.67 (66.93)	10.80 (11.70)	6.43 (6.50)	<0.50		Sr; 186	90
$[C_1C_8pyr][HCO_2]$	{Da}(IIa)	68.85 (69.09)	11.77 (12.01)	5.00 (5.75)	<0.50		Sr; 168	90
$[C_1C_{10}pyr][HCO_2]$	{Da}(IIa)	69.58 (70.80)	11.13 (12.25)	4.37 (5.16)	<0.50		Sr; 232	83
$[C_1C_4pyr][CH_3CO_2]$	{Da}(IIa)	64.30 (65.63)	10.82 (11.52)	6.59 (6.96)	<0.50		Sr; 178	90
$[C_1C_6pyr][CH_3CO_2]$	{Da}(IIa)	67.98 (68.08)	11.28 (11.87)	5.86 (6.11)	<0.50		Sr; 343	89
$[C_1C_8pyr][CH_3CO_2]$	{Da}(IIa)	58.94 (59.99)	12.25 (12.14)	5.22 (5.44)	<0.50		Sr; 265	85
$[C_1C_{10}pyr][CH_3CO_2]$	{Da}(IIa)	70.35 (71.53)	11.79 (12.36)	4.23 (4.91)	<0.50		Sr; 198	79
$[N_{4\,4\,4\,1}][HCO_2]$	{Da}(IIa)	67.63 (68.52)	12.43 (12.73)	5.33 (5.71)			Sr; 80.4	90
$[N_{4\,4\,4\,1}][CH_3CO_2]$	{Da}(IIa)	68.48 (69.45)	11.73 (12.82)	4.96 (5.40)			Sr; 173	82
$[N_{4\,4\,4\,1}][C_2H_5CO_2]$	{Da}(IIa)	69.69 (70.28)	13.07 (12.90)	5.08 (5.12)			Sr; 49.7	84
$[N_{4\,4\,4\,1}][C_3H_7CO_2]$	{Da}(IIa)	70.36 (71.02)	11.55 (12.97)	4.59 (4.87)			Sr; 107	89
$[N_{4\,4\,4\,1}][C_5H_{11}CO_2]$	{Da}(IIa)	71.27 (72.32)	12.05 (13.10)	4.11 (4.44)			Sr; 142	90
$[N_{4\,4\,4\,1}][C_7H_{15}CO_2]$	{Da}(IIa)	73.06 (73.41)	12.85 (13.20)	3.95 (4.08)			Sr; 33.8	92
$[N_{4\,4\,4\,1}][Me_2CHCO_2]$	{Da}(IIa)	70.64 (71.02)	11.77 (12.97)	4.54 (4.87)			Sr; 154	90
$[N_{4\,4\,4\,1}][MeCH(OH)CO_2]$	{Da}(IIa)	65.03 (66.39)	12.14 (12.19)	4.31 (4.87)			Sr; 152	82
$[N_{4\,4\,4\,1}][HOCH_2CO_2]$	{Da}(IIa)	64.12 (65.41)	11.87 (12.08)	4.76 (5.09)			Sr; 29.6	91
$[P_{4\,4\,4\,4}][HCO_2]$	{Da}(Ia)	66.45 (67.07)	12.82 (12.25)			Cl; 0.21	Sr; 224	91
$[P_{4\,4\,4\,6}][HCO_2]$	{Da}(Ia)	67.70 (68.63)	11.51 (12.43)			Cl; 0.84	Sr; 67.2	87
$[P_{4\,4\,4\,8}][HCO_2]$	{Da}(Ia)	68.21 (69.95)	13.56 (12.58)			Cl; 1.30	Sr; 85.2	94
$[P_{4\,4\,4\,10}][HCO_2]$	{Da}(Ia)	70.75 (71.09)	13.32 (12.71)			Cl; 0.26	Sr; 209	94
$[P_{4\,4\,4\,12}][HCO_2]$	{Da}(Ia)	71.20 (72.07)	13.45 (12.82)			Cl; 0.26	Sr; 43.6	89
$[P_{4\,4\,4\,14}][HCO_2]$	{Da}(Ia)	71.69 (72.92)	13.55 (12.92)			Cl; 0.16	Sr; 65.7	87

Table 3 (*Continued*).

Ionic liquid (abbreviation)	Method	% C (Theo)	% H (Theo)	% N (Theo)	% S (Theo)	Halide/wt %	Metal/mg kg^{-1}	% Yield
[P$_{5\,5\,5\,5}$][HCO$_2$]	{Da}(Ia)	69.23 (69.95)	12.85 (12.58)			Cl; 0.47	Sr; 43.4	82
[P$_{6\,6\,6\,6}$][HCO$_2$]	{Db}(Ib)	71.12 (72.07)	12.55 (12.82)			Cl; 0.48	Sr; <10	91
[P$_{8\,8\,8\,8}$][HCO$_2$]	{Db}(Ib)	73.29 (74.94)	12.10 (13.15)			Cl; 0.45	Sr; 32.2	80
[P$_{4\,4\,4\,4}$][CH$_3$CO$_2$]	{Da}(Ia)	66.40 (67.88)	12.95 (12.34)			Cl; 0.22	Sr; 77.6	94
[P$_{4\,4\,4\,6}$][CH$_3$CO$_2$]	{Da}(Ia)	68.38 (69.32)	11.37 (12.51)			Cl; 0.66	Sr; 235	86
[P$_{4\,4\,4\,8}$][CH$_3$CO$_2$]	{Da}(Ia)	69.64 (70.54)	13.36 (12.65)			Cl; 1.14	Sr; 286	90
[P$_{4\,4\,4\,10}$][CH$_3$CO$_2$]	{Da}(Ia)	70.96 (71.59)	11.11 (12.77)			Cl; 0.10	Sr; 332	94
[P$_{4\,4\,4\,12}$][CH$_3$CO$_2$]	{Da}(Ia)	71.12 (72.51)	12.10 (12.87)			Cl; 0.17	Sr; 237	91
[P$_{4\,4\,4\,14}$][CH$_3$CO$_2$]	{Da}(Ia)	72.66 (73.31)	12.91 (12.96)			Cl; 0.10	Sr; 261	85
[P$_{5\,5\,5\,5}$][CH$_3$CO$_2$]	{Da}(Ia)	69.88 (70.54)	13.17 (12.65)			Cl; 0.36	Sr; 59.2	87
[P$_{6\,6\,6\,6}$][CH$_3$CO$_2$]	{Db}(Ib)	70.98 (72.51)	12.86 (12.87)			Cl; 0.62	Sr; <10	90
[P$_{8\,8\,8\,8}$][CH$_3$CO$_2$]	{Db}(Ib)	74.83 (75.22)	13.13 (13.18)			Cl; 0.52	Sr; 25.2	96
[P$_{4\,4\,4\,1}$][HCO$_2$]	{Da}(IIa)	62.98 (64.09)	10.77 (11.91)				Sr; 173	84
[P$_{4\,4\,4\,1}$][CH$_3$CO$_2$]	{Da}(IIa)	63.84 (65.18)	11.43 (12.03)				Sr; 562	88
[P$_{4\,4\,4\,1}$][C$_2$H$_5$CO$_2$]	{Da}(IIa)	65.85 (66.17)	11.20 (12.15)				Sr; 227	92
[P$_{4\,4\,4\,1}$][C$_3$H$_7$CO$_2$]	{Da}(IIa)	66.59 (67.07)	11.19 (12.25)				Sr; 157	82
[P$_{4\,4\,4\,1}$][C$_5$H$_{11}$CO$_2$]	{Da}(IIa)	67.58 (68.43)	11.66 (12.69)				Sr; 165	91
[P$_{4\,4\,4\,1}$][C$_7$H$_{15}$CO$_2$]	{Da}(IIa)	68.42 (69.95)	12.15 (12.58)				Sr; 335	91
[P$_{4\,4\,4\,1}$][Me$_2$CHCO$_2$]	{Da}(IIa)	66.23 (67.07)	11.92 (12.25)				Sr; 141	92
[P$_{4\,4\,4\,1}$][MeCH(OH)CO$_2$]	{Da}(IIa)	61.99 (62.72)	10.39 (11.51)				Sr; 114	88
[P$_{4\,4\,4\,1}$][HOCH$_2$CO$_2$]	{Da}(IIa)	60.20 (61.62)	11.27 (11.38)				Sr; 192	81
[P$_{8\,8\,8\,4}$][HCO$_2$]	{Db}(Ib)	72.84 (73.68)	13.28 (13.01)			Cl; 0.33	Sr; 44.8	89
[P$_{8\,8\,8\,6}$][HCO$_2$]	{Db}(Ib)	73.57 (74.34)	13.58 (13.08)			Cl; 0.50	Sr; < 10	90
[P$_{8\,8\,8\,10}$][HCO$_2$]	{Db}(Ib)	74.47 (75.48)	12.78 (13.21)			Cl; 0.54	Sr; 32.3	96
[P$_{8\,8\,8\,12}$][HCO$_2$]	{Db}(Ib)	74.47 (75.97)	14.00 (13.27)			Cl; 1.11	Sr; 13.0	88
[P$_{8\,8\,8\,14}$][HCO$_2$]	{Db}(Ib)	75.68 (76.41)	13.03 (13.32)			Cl; 0.56	Sr; <10	90

Table 3 (*Continued*).

Ionic liquid (abbreviation)	Method	% C (Theo)	% H (Theo)	% N (Theo)	% S (Theo)	Halide/wt %	Metal/mg kg⁻¹	% Yield
[P₈₈₈₄][CH₃CO₂]	{Db}(Ib)	73.66 (74.02)	13.20 (13.04)			Cl; 0.66	Sr; 19.0	88
[P₈₈₈₆][CH₃CO₂]	{Db}(Ib)	73.88 (74.65)	12.57 (13.12)			Cl; 0.35	Sr; <10	74
[P₈₈₈₁₀][CH₃CO₂]	{Db}(Ib)	75.02 (75.73)	12.84 (13.24)			Cl; 0.26	Sr; <10	87
[P₈₈₈₁₂][CH₃CO₂]	{Db}(Ib)	75.61 (76.19)	13.30 (13.29)			Cl; 0.21	Sr; 12.0	90
[P₈₈₈₁₄][CH₃CO₂]	{Db}(Ib)	75.27 (76.62)	13.44 (13.34)			Cl; 0.41	Sr; 15.4	95
[P₆₆₆₁₄][HCO₂]	{Db}(Ib)	73.02 (74.94)	12.78 (13.15)			Cl; 0.38	Sr; < 10	83
[P₆₆₆₁₄][CH₃CO₂]	{Db}(Ib)	74.21 (75.22)	13.36 (13.18)			Cl; 0.44	Sr; 13.9	86
[P₆₆₆₁₄][C₂H₅CO₂]	{Db}(Ib)	74.08 (75.48)	12.58 (13.21)			Cl; 0.29	Sr; 150	91
[P₆₆₆₁₄][C₃H₇CO₂]	{Db}(Ib)	74.62 (75.73)	12.88 (13.24)			Cl; 0.45	Sr; 191	97
[P₆₆₆₁₄][C₅H₁₁CO₂]	{Db}(Ib)	75.02 (76.19)	13.13 (13.29)			Cl; 0.24	Sr; 115	96
[P₆₆₆₁₄][C₇H₁₅CO₂]	{Db}(Ib)	76.17 (76.62)	12.81 (13.34)			Cl; 0.37	Sr; 154	93
[P₆₆₆₁₄][Me₂CHCO₂]	{Db}(Ib)	75.52 (75.73)	12.47 (13.24)			Cl; <0.10	Sr; 225	97
[P₆₆₆₁₄][MeCH(OH)CO₂]	{Db}(Ib)	73.35 (73.37)	12.06 (12.84)			Cl; <0.10	Sr; 171	83
[P₆₆₆₁₄][HOCH₂CO₂]	{Db}(Ib)	73.22 (73.07)	12.91 (12.80)			Cl; 0.54	Sr; 180	74
[C₂mim][H₂NC₂H₄SO₃]	{A}	40.17 (40.84)	7.90 (7.28)	17.57 (17.86)	13.34 (13.63)	Br; 0.14, Cl; 1.02		75
[C₃mim][H₂NC₂H₄SO₃]	{A}	42.92 (43.36)	6.93 (7.68)	16.26 (16.85)	11.87 (12.86)			73
[C₄mim][H₂NC₂H₄SO₃]	{A}	44.66 (45.61)	7.23 (8.04)	12.48 (15.96)	12.18 (12.48)		Sr; <100	75
[C₆mim][H₂NC₂H₄SO₃]	{A}	47.56 (49.46)	7.47 (8.65)	11.83 (14.42)	10.26 (11.00)	Br; 0.30, Cl; 0.39	Sr; <100	79
[C₇mim][H₂NC₂H₄SO₃]	{A}	50.30 (51.12)	8.93 (8.91)	13.39 (13.76)	10.10 (10.50)			74
[C₈mim][H₂NC₂H₄SO₃]	{A}	54.36 (52.64)	10.07 (9.15)	13.57 (13.15)	10.06 (10.04)			78
[C₁₀mim][H₂NC₂H₄SO₃]	{A}	53.22 (55.30)	9.86 (9.57)	10.68 (12.09)	8.69 (9.23)			76
[C₁₂mim][H₂NC₂H₄SO₃]	{A}	57.06 (57.56)	9.86 (9.93)	11.22 (11.19)	8.24 (8.54)			60
[C₁₄mim][H₂NC₂H₄SO₃]	{A}	60.34 (59.52)	9.48 (10.24)	10.48 (10.41)	6.83 (7.94)			61
[C₁₆mim][H₂NC₂H₄SO₃]	{A}	61.34 (61.21)	11.08 (10.51)	8.87 (9.73)	7.05 (7.43)			79
[C₁₈mim][H₂NC₂H₄SO₃]	{A}	61.95 (62.70)	10.48 (10.74)	8.53 (9.14)	6.82 (6.97)			67
[N₁₁₁₄][H₂NC₂H₄SO₃]	{Da}(IIa)	42.43 (44.97)	9.86 (10.06)	10.86 (11.65)	13.14 (13.34)		Sr; <100	91
[N₄₄₄₁][H₂NC₂H₄SO₃]	{Da}(IIa)	53.94 (55.52)	8.69 (11.18)	8.58 (8.63)	9.95 (9.88)		Sr; <100	79
[C₁C₄pyr][H₂NC₂H₄SO₃]	{Da}(IIa)	48.53 (49.59)	10.09 (9.84)	10.11 (10.52)	12.43 (12.04)	Br; 0.16, Cl; 1.02	Sr; 1300	92
[P₆₆₆₁₄][H₂NC₂H₄SO₃]	{Db}(Ib)	67.29 (67.61)	9.54 (11.68)	2.11 (2.32)	5.46 (5.31)		Sr; 500	41*

(continues on next page)

Table 3 (*Continued*).

Ionic liquid (abbreviation)	Method	% C (Theo)	% H (Theo)	% N (Theo)	% S (Theo)	Halide/wt %	Metal/mg kg^{-1}	% Yield
[C$_2$mim][NH$_2$SO$_3$]	{Da}	32.04 (34.77)	6.19 (6.32)	19.07 (20.27)	17.27 (15.74)	Br; 0.17, Cl; 0.19	Sr; <100	95
[C$_4$mim][NH$_2$SO$_3$]	{Da}	38.27 (40.84)	6.98 (7.28)	16.35 (17.86)	13.30 (13.63)	Br; 0.18, Cl; 0.26	Sr; <100	83
[N$_{1\,1\,1\,4}$][NH$_2$SO$_3$]	{Da}(IIa)	36.41 (39.60)	8.53 (9.50)	12.94 (13.19)	16.48 (15.10)		Sr; 100	83*
[C$_2$mim][MES]	{Da}	49.99 (47.20)	6.81 (7.59)	12.52 (13.76)	9.95 (10.50)		Sr; 200	82
[C$_2$mim][MOPS]	{Da}	47.23 (48.88)	7.69 (7.89)	12.67 (13.15)	10.06 (10.04)		Sr; 4600	79
[C$_4$mim][MES]	{Da}	49.34 (50.43)	8.01 (8.16)	12.35 (12.60)	9.33 (9.62)		Sr; <100	95
[C$_4$mim][MOPS]	{Da}	50.22 (51.85)	7.07 (8.41)	11.70 (12.09)	9.61 (9.23)		Sr; 2900	94
[C$_4$mim][AMS]	{Da}	44.30 (43.36)	7.70 (7.68)	13.79 (16.85)	13.54 (12.86)		Sr; <100	86
[C$_4$mim][sulf]	{Da}	52.33 (54.00)	6.53 (6.80)	13.32 (13.49)	10.41 (10.30)		Sr; <100	74
[C$_4$mim][ACES]	{Da}	44.35 (44.98)	6.89 (7.55)	13.98 (17.49)	13.31 (10.01)		Sr; <100	89
[C$_4$mim][TES]	{Da}	44.41 (45.76)	7.51 (7.95)	11.07 (11.44)	8.92 (8.72)		Sr; <100	80
[C$_4$C$_4$pyr][MeCH(OH)CO$_2$]	{A}	60.95 (59.97)	10.23 (10.90)	5.35 (5.83)		Cl; <0.05		83
[C$_4$C$_4$pip][MeCH(OH)CO$_2$]	{A}	59.33 (63.64)	9.98 (11.09)	5.18 (5.71)		Br; 0.12		79
[C$_8$ 3mpy][(+)-galac]	{A}	55.58 (55.16)	7.85 (8.56)	4.68 (3.22)		Cl; <0.05		66
[C$_8$mim][xan]	{A}	59.39 (58.94)	8.58 (7.56)	23.16 (24.26)		Cl; <0.05		75
[C$_4$mim][(+)-ala]	{Da}	55.57 (58.12)	9.45 (9.31)	17.25 (18.49)		Cl; <0.10	Sr; 1123	67
[C$_4$mim][(+)-Hglu]	{Da}	52.13 (54.72)	8.18 (8.12)	13.94 (14.73)			Sr; 3252	56
[C$_4$mim][xan]	{Da}	53.58 (53.78)	6.64 (6.25)	27.11 (28.95)		Cl; <0.10	Sr; 91	87
[C$_2$mim][(+)-galac]	{B}	46.54 (48.90)	5.46 (7.26)	7.92 (8.77)	0.70 (0.00)		K; 3600	69
[C$_2$mim][BF$_4$]	{B}	36.57 (36.40)	5.46 (5.60)	13.06 (14.15)	B 5.50 (5.50)		K; 1900	64
[C$_4$mim][(+)-Htart]	{B}	47.93 (49.99)	7.07 (6.99)	6.33 (9.72)	<0.5 (0.00)		K; 1100	82
[C$_4$mim][Hmal]	{B}	50.10 (52.93)	7.20 (7.40)	10.49 (10.29)	<0.5 (0.00)		K; 13400	73
[P$_{6\,6\,6\,14}$][Hsucc]	{B}(Ib)	71.78 (71.95)	13.14 (12.24)	<0.3 (0.00)			K; 50	52

C$_x$mim = 1-alkyl-3-methylimidazolium (alkyl chain x carbon atoms long), C$_x$C$_y$pyr = dialkylpyrrolidinium (alkyl chains x and y carbon atoms long), P$_{w\,x\,y\,z}$ = tetraalkylphosphonium, alkyl chains w, x, y, and z carbon atoms long (as with N$_{w\,x\,y\,z}$), C$_x$C$_y$pip = dialkylpiperidinium (alkyl chains x and y carbon atoms long), C$_x$ 3mpy = alkyl-3-methylpyridinium (alkyl chain x carbon atoms long), MeCH(OH)CO$_2$ = lactate, HOCH$_2$CO$_2$ = glycolate, H$_2$NC$_2$H$_4$SO$_3$ = taurinate, NH$_2$SO$_3$ = sulfamate, MES = 4-morpholine ethanesulfonate, MOPS = 4-morpholine propanesulfonate, AMS = 2-aminomethane sulfonate, sulf = 4-aminophenol sulfate, ACES = N-(2-acetamido)-2-aminoethanesulfonate, TES = 2-[(2-hydroxy-1,1-bis-(hydroxymethyl)ethyl)amino]ethanesulfonate, (+)-galac = D-(+)-galacturonate, xan = xanthinate, (+)-ala = L-(+)-alaninate, (+)-Hglu = L-(+)-glutamate, (+)-Htart = (+)-tartrate, Hmal = malate, Hsucc = succinate.
*Yield calculated based on initial starting material prior to hydrogensulfate synthesis.

many more ionic liquids. Elemental analyses for some of the ionic liquids produced in our laboratory using this method are included in Table 3, as well as the previously generated ionic liquids utilising the column method and the potassium series. To readily distinguish between combined methodologies, identification of the methods used is based on the headings developed in the synthetic section. Therefore, in Table 3, synthesis of all ionic liquids utilising the column method starting with a halide salt are denoted {A}, synthesis of all ionic liquids utilising the strontium method starting with water-soluble purchased hydrogensulfate salts are denoted {Da}, all ionic liquids utilising a water-soluble hydrogensulfate that itself was formed by the hydrolysis of a methyl sulfate are denoted {Da}(IIa), and so on.

Halide contamination is similar and significant for all samples in Table 2, and is present for all commercially sourced cations in Table 3 as well. To establish the source of contamination, the commercial 1,3-dialkylimidazolium hydrogensulfates, 1-ethyl-3-methylimidazolium hydrogensulfate and 1-butyl-3-methylimidazolium hydrogensulfate, were analysed and found to contain 0.23 wt % halide and 0.14 wt % halide, respectively. This implies that production of halide-free ionic liquids requires the synthesis of the parent cation from halide-free starting materials, such as the dimethyl sulfate route, and avoidance of commercial material.

In addition, the analysis in Table 2 shows anomalous amounts of metal contamination in some cases, such as high levels of strontium in the synthesis utilising barium hydroxide. To establish the source of this contamination, the metal hydroxides were analysed for potassium, strontium, barium, and halide. The results are presented in Table 4 below.

Table 4 Selected contaminants in the metal hydroxide starting materials utilised in this study.

Metal hydroxide	K/mg kg^{-1}	Sr/mg kg^{-1}	Ba/mg kg^{-1}	Cl+Br/wt %
Potassium hydroxide	–	<10	<10	<0.01
Strontium hydroxide octahydrate	186	–	<10	0.09 Br
Barium hydroxide octahydrate	397	3460	–	<0.01

Impurity levels in some of these hydroxides are rather high; particularly noticeable is the amount of strontium impurity seen in the barium hydroxide sample. This is reflected in the strontium contamination level seen in the [C$_4$mim][CH$_3$CO$_2$] generated using barium hydroxide.

Ion-exchange column {A}

The column method is well established, and has been used to generate hydroxide solutions from halide salts of ionic liquid cations for the production of amino acid anion ionic liquids previously [15]. We have found that fresh resin must be rinsed with large volumes of water to remove residual amine, as failing to do so results in contaminated, highly odiferous ionic liquids. Column pre-conditioning requires large volumes of water, and halide salts must be very dilute to prevent flooding of the exchange sites. The overall yield using this method could be quite good, but yields were inconsistent and were often in the 60–80 % range. Solvent use was estimated to be as high as 0.33 litres per gram of product, and generally less than 10 g of ionic liquid produced per synthesis. The method is extremely tedious, producing small samples of ionic liquids somewhat contaminated with various metal halide salts. The method invariably requires the use of halide starting materials.

Hydrogensulfate metathesis

Hydrogensulfate production

Chloride salt metathesis, (Ia) and (Ib)

Although this publication is focused on halide-free synthesis methodologies, the production of the required hydrogensulfate salt starting from chloride salts is included to demonstrate the flexibility of the methodology. Overall, two separate procedures were followed based on water solubility. For water-soluble chloride salts, one equivalence of sulfuric acid was slowly added to the chloride salt of the cation of interest, heated and stirred under vacuum. For purposes of both safety and equipment maintenance, the evolved hydrogen chloride gas may be conveniently trapped by a base column. For those salts that are insoluble in water, it was found that the above method resulted in ionic liquids highly contaminated with chloride ions. Therefore, this procedure was followed by dissolution of the mixture in toluene, several washes with dilute aqueous sulfuric acid, and then several washes with water. In the case of water-insoluble ionic liquids the entire procedure results in low yields (ca. 50 %) due to the extensive number of extractions required.

In summary, none of the procedures used resulted in chloride-free ionic liquids, and low yields were also observed

Alkyl sulfate hydrolysis, (IIa) and (IIb)

Production of ionic liquid cations by the quaternisation of trialkylamine, trialkylphosphine, and similar bases with dialkyl sulfate alkylating agents lies at the heart of this method. These alkylations are fast, clean, and simple, and result in quaternised salts essentially free of halides [20]. The acid-catalysed hydrolysis reaction to generate the hydrogensulfate anion is well known [21]. Here, the hydrolysis was performed under the bench scale conditions used for bulk synthesis. It was found that a 40 mol % sulfuric acid solution added to a 2 M solution of the methyl sulfate salt of the cation of interest (about 10 wt % of the acid solution to the methyl sulfate solution), when maintained at 100 °C for 5 h, was sufficient to completely hydrolyse the methyl sulfate to the hydrogensulfate. This hydrolysis can be conveniently monitored by observing the loss of the methyl signal of the methyl sulfate by ^{1}H NMR spectroscopy. The hydrolysis reaction is performed simply by heating the combined acid/methyl sulfate solution in an open beaker in a fume hood. Alternatively, the generated alcohol may be captured by applying a weak vacuum in a sealed system with a side trap, as was performed with the ethyl sulfate example. In both cases, the reaction proceeds much more quickly if the alcohol generated is removed from the parent solution. As this reaction is performed at around 100 °C, care must be taken to ensure that any lost water is replaced as the reaction proceeds.

Metal sulfate metathesis, {B}, {C}, {D}, or {E}

The overall approach reported here includes the quaternisation of a tertiary amine (or phosphine), including trialkylamine or alkylimidazole, with dimethyl sulfate (or, more generally, dialkyl sulfate) to produce a methyl sulfate salt of the cation of interest. This is followed by hydrolysis of the methyl sulfate anion to hydrogensulfate, and metathesis with a Group 1 or Group 2 metal oxide or hydroxide. This produces a hydroxide solution of the cation of interest and the solid sulfate salt of the metal (see, e.g., Fig. 2).

The initial step, alkylation of the tertiary amine, is a well-established procedure that has previously been shown to generate a series of ionic liquids, the alkyl sulfates [20,22]. The procedure is extremely simple, generating alkyl sulfate ionic liquids in high yield. Because these alkyl sulfates are known to be susceptible to hydrolysis, the longer chain analogues have been produced via transesterification by heating with an acid catalyst [23]. Where possible, dimethyl sulfate was used as the alkylating agent, due to the fast hydrolysis rate of its anion.

Once the hydrogensulfate salt of the preferred cation is obtained, the final step of this reaction sequence is dependent upon the specific metal hydroxides (or oxides) chosen.
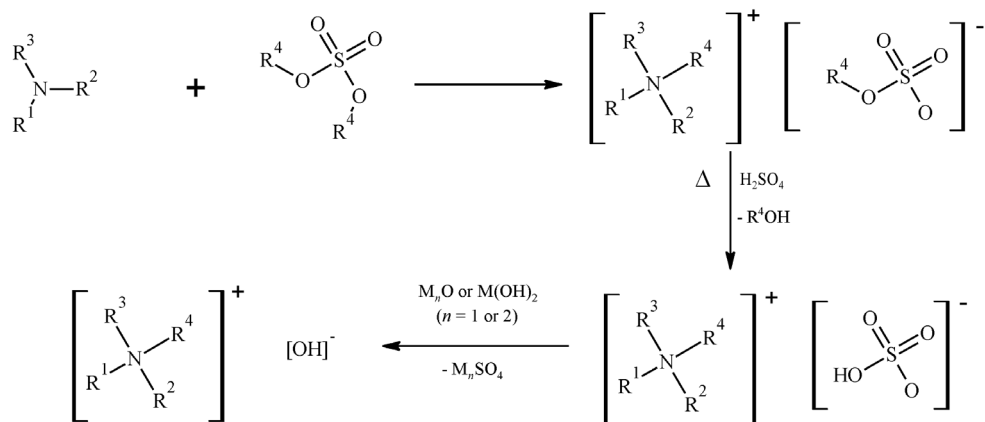
Fig. 2 Generic reaction scheme for generation of tetraalkylammonium hydroxides.
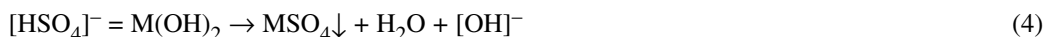
Potassium {B}

Potassium hydroxide shows good solubility in ethanol (4 wt %) and aqueous ethanol, whereas the potassium sulfate shows a poorer value in aqueous ethanol (1.2 wt % at 0.4 mole fraction ethanol in water, 25 °C) [23], and even lower under basic conditions. This suggests the following reaction scheme with the generated hydrogensulfate anion (eq. 3):

$$[HSO_4]^- + 2KOH \rightarrow K_2[SO_4]\downarrow + H_2O + [OH]^- \tag{3}$$
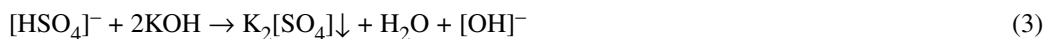
With some care, and treatment of the final ionic liquid with absolute ethanol, the potassium hydroxide synthetic method does indeed produce the desired ionic liquids. However, the resultant ionic liquid is often contaminated with quite high levels of potassium. In addition, the method requires large volumes of ethanol.

Group 2 metal oxides/hydroxides, {C}, {D}, and {E}

Group 2 metal oxides react with water to form hydroxides, or the hydroxides may be obtained commercially. Although calcium hydroxide shows low solubility in water, both strontium and barium hydroxides show excellent solubility in hot water in the octahydrate form. The sulfates of all three metals show extremely poor solubility in water (see Table 1), indicating that a reaction scheme similar to that for the Group 1 metal hydroxides may proceed (eq. 4):

$$[HSO_4]^- = M(OH)_2 \rightarrow MSO_4\downarrow + H_2O + [OH]^- \tag{4}$$

As in the case with potassium, the hydroxide solution of a cation of interest can be generated efficiently with the concomitant production of a sulfate salt.

Calcium {C}

Calcium hydroxide was initially chosen to develop this methodology as it was thought that adding the hydrogensulfate solution to a calcium hydroxide suspension in cold water, then heating, would drive the reaction to completion and precipitate out residual calcium hydroxide and carbonate. The methodology works, but the similarity in the solubility of the hydroxide and sulfate salt required the use of very dilute solutions. The addition of the conjugate acid of the anion of interest may in some cases be used to drive the reaction to completion; however, this limits the applicability of this method.

Strontium {D}

Ultimately, strontium hydroxide was chosen for this reaction due to its high solubility in hot water, low solubility in cold water, the low solubility of the sulfate salt in cold water, and the low toxicity of stron-

tium [25]. Also, solubility of strontium carbonate, a common contaminant due to absorption of atmospheric carbon dioxide, is the lowest of all the Group 2 metals.

Barium {E}

The use of barium hydroxide generated hydroxide solutions much more efficiently than the previous calcium hydroxide experiments, but a perusal of Table 1 indicates that excess barium hydroxide may contaminate the final solution, and the health risks associated with barium salts preclude their regular use.

With the use of any Group 2 hydroxide, it should be noted that contamination of glassware with the carbonate is endemic. For the production of high-purity ionic liquids, the glassware should be regularly cleaned with a dilute nitric acid solution between uses.

The synthetic method utilising strontium hydroxide described above allows the production of a solution of the hydroxide salt of the cation of interest. Hydroxide solutions may, in turn, be neutralised to the respective equivalence point by any selected acid generating an ionic liquid consisting of the cation of interest paired with the anion of interest in an aqueous solution with minimal contamination.

This synthetic strategy, utilising the strontium hydroxide method, allows flexible design capabilities in ionic liquid synthesis. Careful design of the cation synthetic procedure often allows the pathway to be halide free as well. Many ionic liquids with different cations and anions can be synthesised. Examples including imidazolium, ammonium, pyridinium, pyrrolidinium, and phosphonium cations with both carboxylic acid and amino acid-based anions have been produced in our laboratories utilising this technique (Table 4).

In addition, an entire synthetic cycle may be envisioned, whereby all basic materials used in the ionic liquid synthesis are regenerated (Fig. 3). In this cycle, alkylimidazole (or trialkylamine or trialkylphosphine) is first reacted with dimethyl sulfate to form the methyl sulfate salt. Although laboratory synthetic schemes often require the use of a haloalkane to form the starting alkylimidazole, trialkylamine, or trialkylphosphine, industrial processes typically do not use them for this step. The remaining steps to produce the hydroxide solution and strontium sulfate remain as outlined previously. The methanol released by the hydrolysis of methyl sulfate may be readily captured and reacted with sulfuric acid (recovered from strontium sulfate as described later) to regenerate dimethyl sulfate, which then may be used again for the methylation of 1-alkylimidazole [20]. The generated strontium sulfate is effectively the main ore of strontium, celestine [14]. An aqueous suspension of strontium sulfate may be treated with ammonium carbonate, precipitating out strontium carbonate and leaving ammonium sulfate in solution [26]. The generated strontium carbonate may then be heated to drive off carbon dioxide to produce strontium oxide (indeed, this is the main industrial method of doing so) [14]. Ammonium sulfate may be decomposed to generate ammonia and sulfuric acid [27]. The regenerated sulfuric acid may be cycled back by reaction with the methanol produced by hydrolyses to re-form dimethyl sulfate. The ammonia may be reacted with the carbon dioxide produced by heating strontium carbonate, to regenerate the ammonium carbonate [28]. Strontium oxide, suspended in water, produces the strontium hydroxide required for the production of the hydroxide solution of the cation of interest. All steps in the cycle are known in either the academic literature or the patent literature.

The methodology is also shown to be superior to the use of ion-exchange resins, which require far higher volumes of solvent, produces hydroxide solutions contaminated with resin impurities, and results in spent resin that must either be discarded or regenerated using yet more solvent.
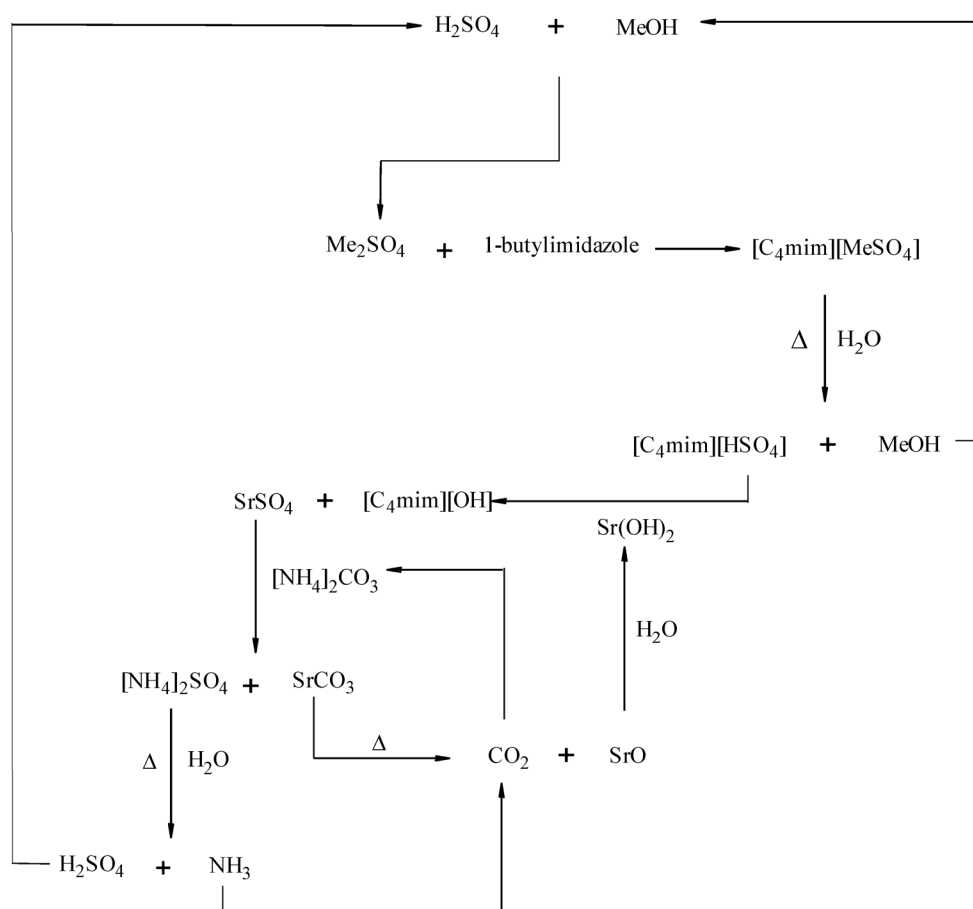
Fig. 3 Potential reaction cycle, regenerating all starting materials involved in the synthesis of hydroxide solutions for ionic liquid synthesis.

SUMMARY AND CONCLUSIONS

During ionic liquid synthesis, traditionally quaternisation is achieved by alkylation with a haloalkane followed by anion metathesis. Ionic liquids obtained in this process are frequently contaminated with the halide salt due to incomplete ion exchange, which is undesirable, especially for some applications (e.g., electrochemistry, catalysis) [29]. In addition, concerns about potential toxicity and environmental issues have resulted in attempts to reduce the use of haloalkanes, and an authoritative review of the natural chlorine cycle has been published [30].

The relative value of this synthetic method rests largely with the scale and scope of the intended use of the final ionic liquid. We find that on the bench scale, this methodology is well suited to the production of clean ionic liquid batches of about one kilogram, or less. At industrial scale, this may represent the only viable economic route to chloride-free ionic liquids.

The synthetic techniques involving metathesis of the hydrogensulfate anion ionic liquids to generate hydroxide solutions based on differential solubility are summarised in Fig. 4. The ionic liquids produced by simple acid–base neutralisation of the hydroxide solution show high purity and in principle contain no halide impurities. The preferred route, in our hands, utilises strontium hydroxide, but routes using potassium hydroxide or barium hydroxide are also viable, and may be optimised for spe-
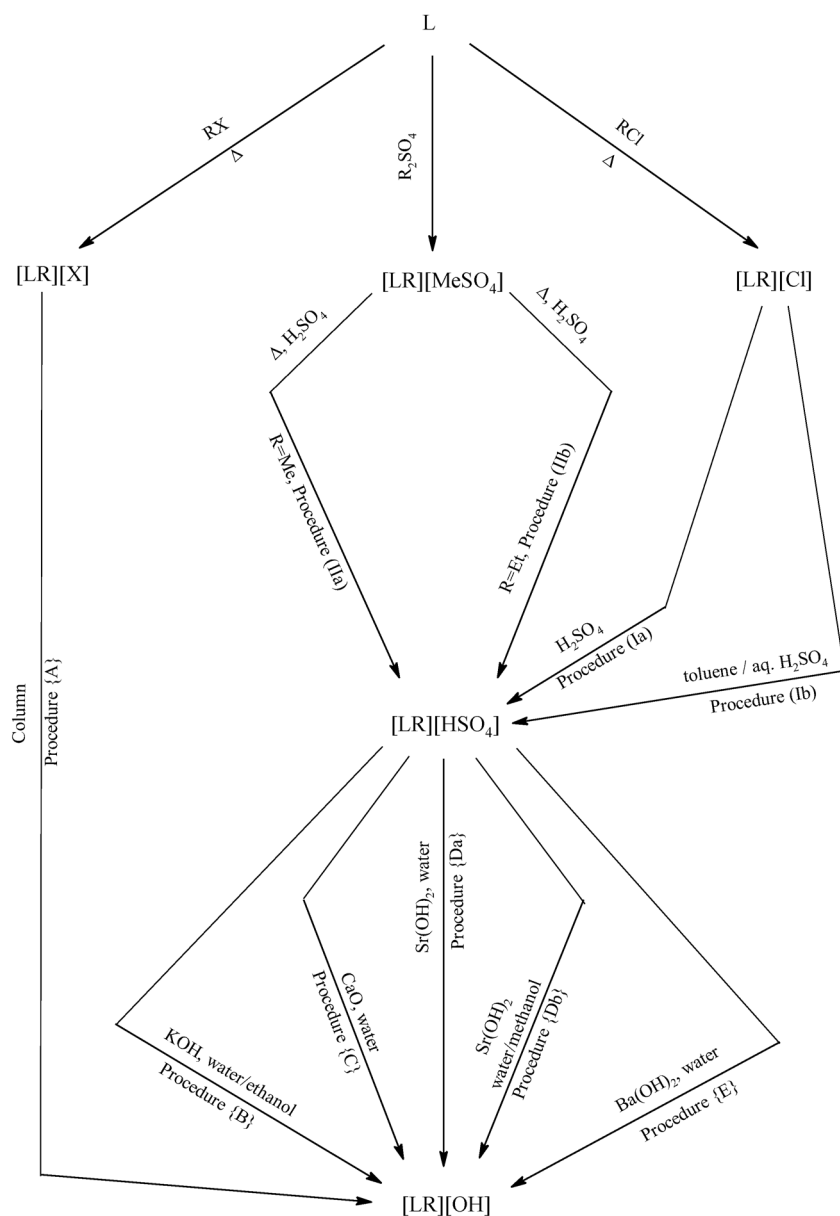
Fig. 4 Schematic outlining the novel synthetic techniques.

cific cations. This methodology is extremely versatile, giving access to ionic liquids based on the conjugate bases of very weak acids that are difficult to prepare by any other route. In the QUILL laboratories, this now represents our preferred synthetic route for many ionic liquids which we had previously prepared via chloride intermediates.

ACKNOWLEDGMENTS

ADDENDUM

On performing due diligence after submission, the authors noted the presence of a BASF patent (WO2005070896) outlining the use of barium hydroxide in a manner quite similar to that described in this article. Three subsequent patents by the same company refer to it (WO2007057403, WO2008135482, and WO2009087184). The initial patent is later referenced in the academic literature [31], although there is no discussion relevant to the metathesis.

REFERENCES

1. N. V. Plechkova, K. R Seddon. *Chem. Soc. Rev.* **37**, 123 (2008).
2. M. Grätzel. *Acc. Chem. Res.* **42**, 1788 (2009).
3. J. D. Holbrey. *Chim Oggi—Chem. Today* **25**, 24 (2007).
4. M. Freemantle. *An Introduction to Ionic Liquids*, RSC Publications, Cambridge, UK (2010).
5. N. V. Plechkova, K. R. Seddon. "Ionic liquids: 'Designer' solvents for green chemistry", in *Methods and Reagents for Green Chemistry: An Introduction*, P. Tundo, A. Perosa, F. Zecchini (Eds.), pp. 105–130, John Wiley, New York (2007).
6. M. Deetlefs, K. R. Seddon. *Green Chem.* **12**, 17 (2010).
7. (a) M. Petkovic, J. L. Ferguson, H. Q. N. Gunaratne, R. Ferreira, M. C. Leitao, K. R. Seddon, L. P. N. Rebelo, C. S. Pereira. *Green Chem.* **12**, 643 (2010); (b) H. Garcia, R. Ferreira, M. Petkovic, J. L. Ferguson, M. C. Leitao, H. Q. N. Gunaratne, K. R. Seddon, L. P. N. Rebelo, C. S. Pereira. *Green Chem.* **12**, 367 (2010).
8. M. Deetlefs, K. R. Seddon. *Chim Oggi—Chem. Today* **24**, 16 (2006).
9. D. R. MacFarlane, K. R. Seddon. *Aust. J. Chem.* **60**, 3 (2007).
10. K. R. Seddon, A. Stark, M. J. Torres. *Pure Appl. Chem.* **72**, 2275 (2000).
11. H. Olivier-Bourbigou, L. Magna, D. Morvan. *Appl. Catal., A* **373**, 1 (2010).
12. K. Marczewska-Boczkowska, M. Kosmulski. *Mater. Manuf. Proc.* **24**, 1173 (2009).
13. A. J. Carmichael, M. Deetlefs, M. J. Earle, U. Fröhlich, K. R. Seddon. "Ionic liquids: Improved syntheses and new products", in *Ionic Liquids as Green Solvents: Progress and Prospects*, R. D. Rogers, K. R. Seddon (Eds.), ACS Symposium Series, Vol. 856, pp. 14–31, American Chemical Society, Washington, DC (2003).
14. P. Patnaik. *Handbook of Inorganic Chemicals*, p. 890, McGraw-Hill, New York (2002).
15. K. Fukumoto, M. Yoshizawa, H. Ohno. *J. Am. Chem. Soc.* **127**, 2398 (2005). Adjustments to the reported procedure provided by Dr. N. V. Plechkova, personal communication.
16. I. G. R. Gutz. CurTiPot pH and Acid–Base Titration v. 3.3.2 for Excel, Release: 10/March/2008; <http://www2.iq.usp.br/docente/gutz/Curtipot_.html>
17. M. J. Earle, K. R. Seddon. Preparation of Imidazole Carbenes and the Use Thereof for the Synthesis of Ionic Liquids, World Patent, WO 0177081 (2001).
18. J. D. Holbrey, R. D. Rogers, S. S. Shukla, C. D. Wilfred. *Green Chem.* **12**, 407 (2010).
19. D. R. Lide (Ed.). *CRC Handbook of Chemistry and Physics*, 72nd ed. (Special Student Edition), Section 4, CRC Press, Boston (1991–1992).
20. J. D. Holbrey, W. M. Reichert, R. P. Swatloski, G. A. Broker, W. R. Pitner, K. R. Seddon, R. D. Rogers. *Green Chem.* **4**, 407 (2002).
21. For example: B. D. Batts. *J. Chem. Soc. B* 551 (1966).

22. W. B. McCormack, B. C. Lawes. "Sulfuric and sulfurous esters", in *Kirk Othmer Encyclopedia of Chemical Technology*, 4th ed., John Wiley, New York, **23**, 409 (1997).
23. S. Himmler, S. Hormann, R. van Hal, P. S. Schulza, P. Wasserscheid. *Green Chem*. **8**, 887 (2006).
24. J. Mydlarz, A. G. Jones. *Chem. Eng. Data*. **35**, 214 (1990).
25. V. V. Cole, B. K. Harned, R. Hafkesbring. *J. Pharmacol. Exp. Ther*. **71**, 1 (1941).
26. F. de Buda. Method for Recovery and Conversion of Strontium Sulfate to Strontium Carbonate from Low and Medium Grade Celestite Ores, U.S. Patent 4666688 (to Excel-Mineral Company).
27. M. Curren, B. Foody, J. Tolan. Process for Producing Ammonia and Sulfuric Acid from a Stream Comprising Ammonium Sulfate, U.S. Patent 7632479B2 (to Iogen Energy Corporation).
28. I. Mavrovic. Process and Apparatus for the Production of Ammonium Carbonate, U.S. Patent 3310367 (to Chemical Construction Company).
29. J. H. Davis Jr., C. M. Gordon, C. Hilgers, P. Wasserscheid. "Synthesis and purification of ionic liquids", in *Ionic Liquids in Synthesis*, T. Welton, P. Wasserscheid (Eds.), 7 (2003).
30. N. Winterton. *Green Chem.* **5**, 173 (2000).
31. E. Kuhlmann, S. Himmler, H. Giebelhaus, P. Wasserscheid. *Green Chem.* **9**, 233 (2007).