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Supplementary information

Synthesis of aprotic ionic liquids

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Supplementary Information

Synthesis of Aprotic Ionic Liquids

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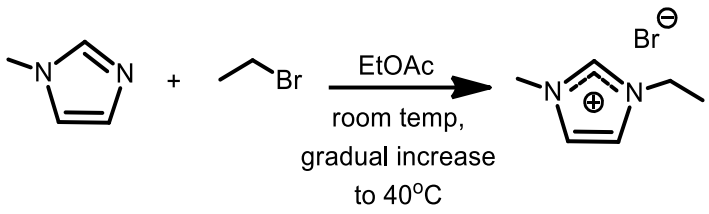
1-ethyl-3-methylimidazolium bromide [C_2C_1im]Br

One-step synthesis



Starting Materials

1-bromoethane (99%), received from Sigma-Aldrich, was extracted with conc. sulfuric acid until the acid layer remained colourless. The organic layer was neutralized with saturated aqueous solution of sodium bicarbonate, followed by washing with deionized water. The resulting liquid was dried with $MgSO_4$ overnight and then distilled under vacuum.

1-Methylimidazole was left overnight stirring over potassium hydroxide pellets and then distilled under vacuum.

Experimental procedure

The procedure was reproduced as described by Koutsoukos et al.[1] 1-bromoethane (20 mL, 268 mmol, 1.2 eq.) was added to a stirring solution of 1-methylimidazole (17.8 mL, 223.3 mmol, 1 eq.) in ethyl acetate (100 mL) in an ice bath. Once addition was completed, the solution was allowed to reach room temperature and then it was left stirring for 2 days. Then the temperature was gradually increased to 40 °C and the reaction mixture was left stirring for 2 days, monitored by ^{1}H NMR. The resulting salt was filtered and dried overnight on the Schlenk Line to yield a white solid (35.4 g, 185.3 mmol, 83 % yield).

Characterisation: [C_2C_1im]Br synthesis

^{1}H-NMR (400 MHz, $CDCl_3$): δ / ppm : 10.21 (s, 1H, imC(2)**H**), 7.59-7.54 (m, 2H, imC(4,5)**H**), 4.34 (q, J = 7.36 Hz, 2H, ethyl – C(1)**H_2**), 4.04 (s, 3H, methyl – C**H_3**), 1.53 (t, J = 7.37 Hz, 3H, ethyl – C**H_3**).

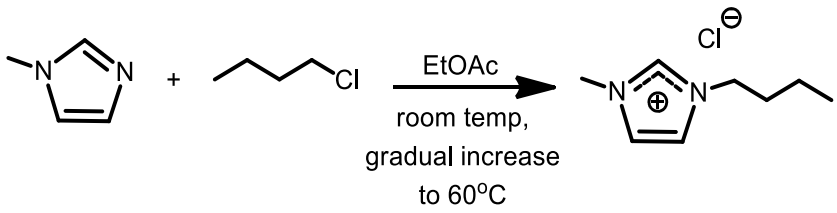
^{13}C{^{1}H}-NMR (101 MHz, $CDCl_3$): δ / ppm : 136.88 (imC(2)), 123.7 (imC(4)), 121.98 (imC(5)), 45.24 (ethyl – C(1)), 36.67 (methyl – C(1)), 15.67 (ethyl – C(2)).

ESI$^+$: m/z 111.1 (100 %, M+).

Elemental analysis (calculated): C – 36.38(37.72), H – 6.06(5.8), N – 13.77(14.66).

1-butyl-3-methylimidazolium chloride [C_4C_1im]Cl

One-step synthesis



Starting Materials

1-chlorobutane (99%), received from Sigma-Aldrich, was extracted with conc. sulfuric acid until the acid layer remained colourless. The organic layer was neutralized with saturated aqueous solution of

sodium bicarbonate, followed by washing with deionized water. The resulting liquid was dried with $MgSO_4$ overnight and then distilled under vacuum.

1-Methylimidazole was left overnight stirring over potassium hydroxide pellets and then distilled under vacuum.

Experimental procedure

The procedure was adapted from Clark et al.[2] 1-chlorobutane (340 mL, 3.26 mol, 1.1 eq) was added drop-wise to a cooled, stirred solution of 1-methylimidazole (235 ml, 2.96 mol, 1 eq) in 200 mL ethyl acetate. Whilst stirring, the reaction mixture was allowed to warm up to room temperature then continued stirring for 1 week at room temperature. The temperature was increased by 10 °C every 4 days until the reaction reached 60 °C and the reaction mixture was then held at 60 °C for 20 days, monitored by ^{1}H NMR. The reaction mixture was then cooled to -20 °C for 2 days affording white crystals. Excess solvent was decanted and the crystals washed with ethyl acetate (2 x 150 mL). Then $[C_4C_1im]Cl$ was dissolved in minimum amount of acetonitrile and was recrystallised from ethyl acetate (process repeated twice) and then dried under vaccum vacuo yielding white crystals. (295.41 g, 67 % yield).

Characterisation: $[C_4C_1im]Cl$ synthesis

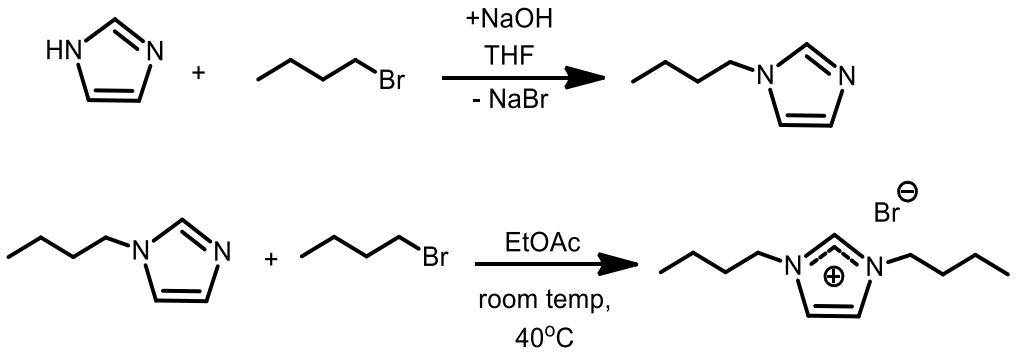
^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm : 9.61 (s, 1H, imC(2)**H**), 7.91 (m, 2H, imC(4)**H**), 7.83 (m, 2H, imC(5)**H**), 4.20 (q, J = 7.2 Hz, 2H, butyl – C(1)**H$_2$**), 3.88 (s, 3H, methyl – C**H$_3$**), 1.75 (t, J = 7.30 Hz, 3H, butyl – C(2)**H$_2$**), 1.23 (h, J = 7.3 Hz, 2H, butyl – C(3)**H$_2$**), 0.87 (t, J = 7.40 Hz, 3H, butyl – C(4)**H$_3$**).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm : 136.75 (imC(2)), 123.53 (imC(4)), 122.25 (imC(5)), 48.33 (butyl – C(1)), 36.67 (methyl – C(1)), 31.38 (butyl – C(2)), 18.74 (butyl – C(3)), 13.27 (butyl – C(4)).

Elemental analysis (calculated): C – 53.69(55.01), H – 9.14(8.66), N – 15.35(16.04).

1,3-dibutylimidazoliumbromide $[C_4C_4im]Br$

Two-step synthesis



Starting Materials

1-bromobutane (99%), received from Sigma-Aldrich, was extracted with conc. sulfuric acid until the acid layer remained colourless. The organic layer was neutralized with saturated aqueous solution of sodium bicarbonate, followed by washing with deionized water. The resulting liquid was dried with $MgSO_4$ overnight and then distilled under vacuum.

1H-imidazole, received from Sigma-Aldrich was recrystallised from ethanol before use.

Procedure: 1-butylimidazole synthesis

The procedure was adapted from Tosoni et al.[3] and Lee et al.[4]. 1H-imidazole (6.68 g, 98.12 mmol, 1.0 eq) was dissolved in a concentrated solution of NaOH (4.71 g, 117.7 mmol, 1.2 eq) in water (15 mL). Under stirring a solution of 1-bromobutane (10.54 mL, 98.1 mmol, 1.0 eq) in tetrahydrofuran (40 mL) was added dropwise. The reaction was stirred at 60 °C for a total of 11 days with continuous monitoring by ^{1}H NMR. After 4 days the ^{1}H NMR showed unconsumed 1H-imidazole and an additional 0.1 eq of 1-bromobutane was added. After 5 days the ^{1}H NMR still showed unconsumed 1H-imidazole, and an additional 0.1 eq of 1-bromobutane was added. After 6 days ^{1}H NMR showed full conversion of 1H-imidazole and the reaction was stopped. The reaction mixture was evaporated under vacuum to remove the tetrahydrofuran. The remaining liquid was dissolved in dichloromethane and washed with water (3 x 20 mL). The organic layer was dried with $MgSO_4$, filtered and solvent removed under vacuum. The resulting brown liquid was distilled to produce a viscous colourless liquid (6.5 g, 52.1 mmol, 53% yield)

Characterisation: 1-butylimidazole synthesis

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm : 0.88 (t, J_{HH} = 7.4 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**) 1.22 (h, J_{HH} = 7.4 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.67 (p, J_{HH} = 7.3 Hz, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 3.95 (t, J_{HH} = 7.1 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3),6.89 (s, 1H, im-C(5)***H***), 7.16 (s, 1H, im-C(4)***H***), 7.62 (s, 1H, im-C(2)***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm : 13.81 (N-CH_2-CH_2-CH_2-**CH_3**), 19.61 (N-CH_2-CH_2-**CH_2**-CH_3), 33.11 (N-CH_2-**CH_2**-CH_2-CH_3), 46.07 (N-CH_2-**CH_2**-CH_2-CH_3), 119.64 (im-C(5)), 128.77 (im-C(4)), 137.64 (im-C(2)).

HRMS, ESI^+: m/z found 125.1079, calc. 125.1034 ($C_8H_{20}N^+$)

Elemental analysis (calculated): C- 50.86(50.58), H- 7.95(8.10), N- 10.49(10.72)

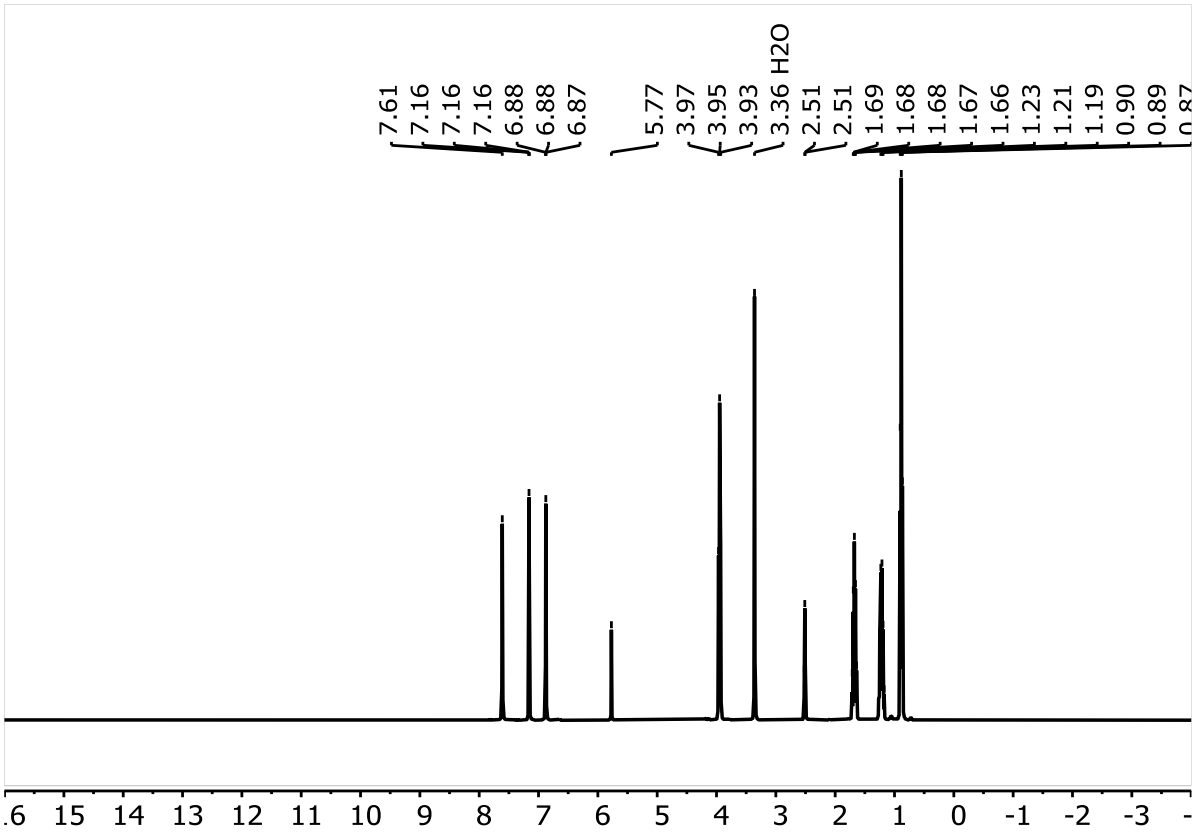


Figure S1. ^{1}H NMR of 1-butylimidazole after washing with water, before distillation.

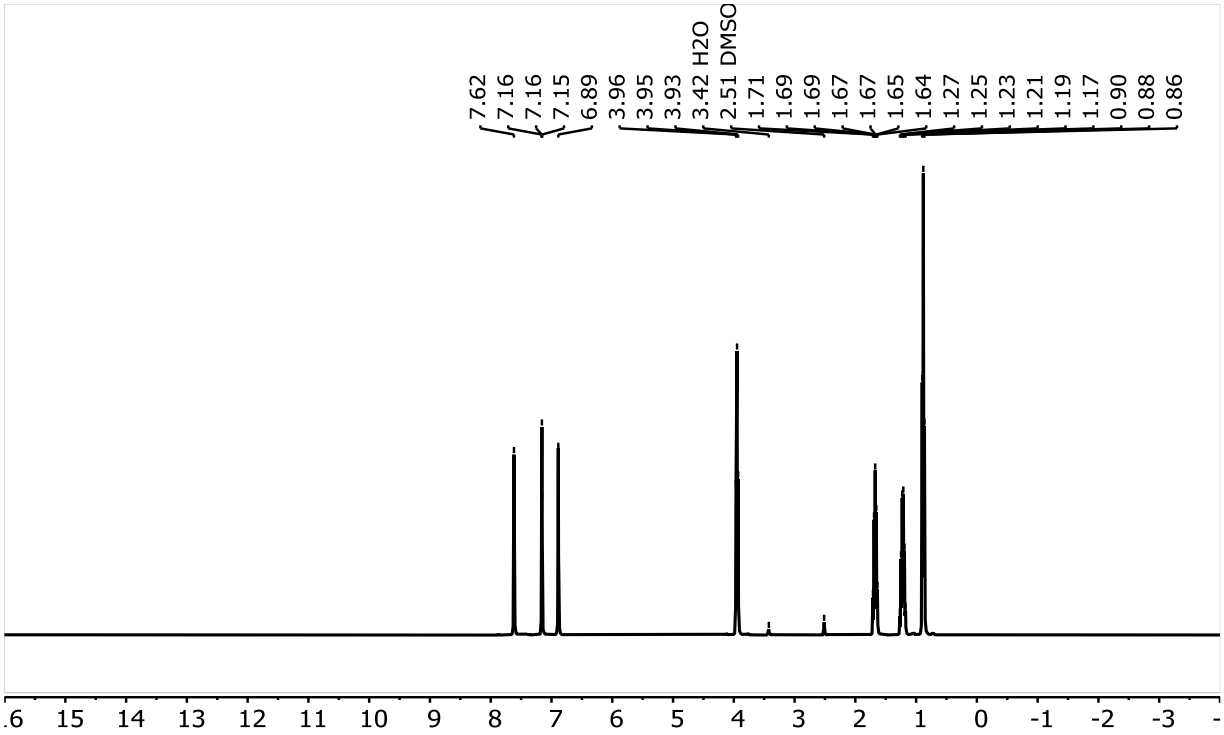


Figure S2. ^{1}H NMR of 1-butylimidazole after distillation.

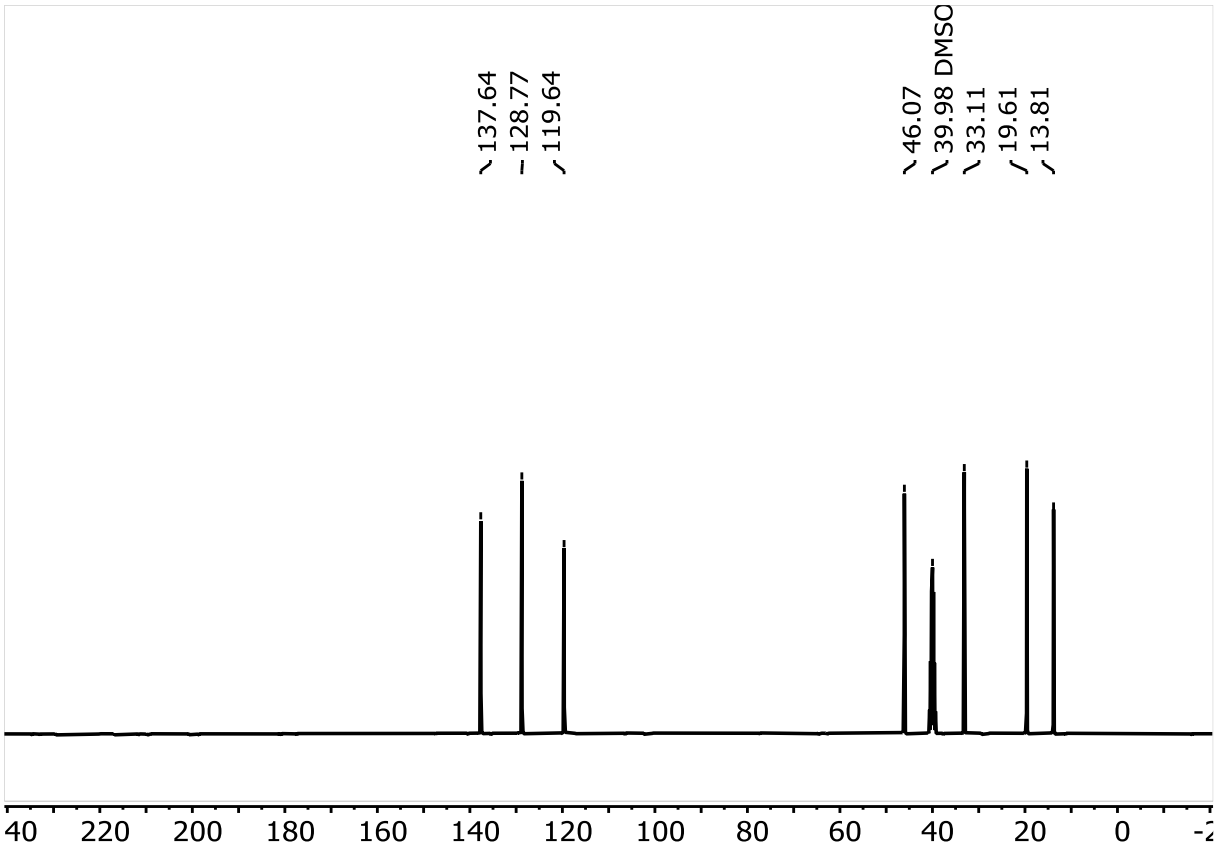


Figure S3. ^{13}C NMR of 1-butylimidazole after distillation.

Pictures: 1-butylimidazole synthesis

Figure S4. 1H-imidazole before recrystallisation.

Figure S5. 1H-imidazole after recrystallisation.

Figure S6. 1-bromobutane without purification (left) and after purification (right).

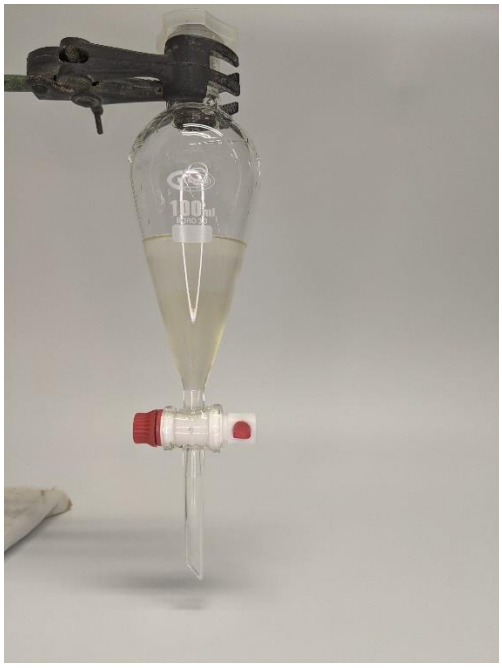


Figure S7. Washing of 1-bromobutane (top phase) with sulfuric acid (bottom phase).

Figure S8. 1-bromobutane (left) and sulfuric acid phase (right) collected in vials.

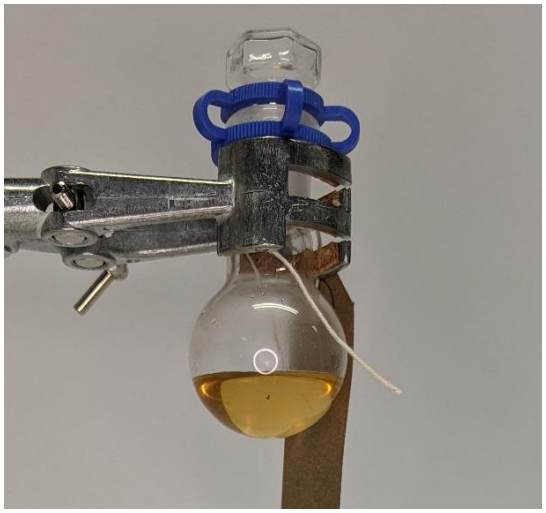


Figure S9. 1-butylimidazole after washing with water, before distillation.

Figure S10. 1-butylimidazole after distillation.

Procedure: 1,3-dibutylimidazolium bromide [C_4C_4im]Br synthesis

The procedure was adapted from Clark et al.[2] 1-butylimidazole (6.1 g, 49.1 mmol, 1 eq) was dissolved in 40 mL of ethyl acetate. 1-bromobutane (8.08 g, 58.9 mmol, 1.2 eq) was added dropwise over 30 min under vigorous stirring. The reaction was stirred at room temperature for 2 days followed by stirring at 40 °C for a further 11 days. The reaction was monitored by ^{1}H NMR and additional 0.1 equivalents of 1-bromobutane were added periodically until the 1-butylimidazole had fully reacted. The reaction mixture was evaporated, giving an oily product. The crude oil was dissolved in acetonitrile (10 mL) and precipitated from ethyl acetate (40 mL). The suspension was kept in the freezer overnight in order for the two phases to separate fully. The upper phase was decanted with a cannula and the resulting oil was dried under vacuum. The ethyl acetate (upper) phase was evaporated in order to isolate any dissolved product. The product isolated from the ethyl acetate phase was re-purified separately and then mixed. The final product was a colourless liquid (10.3 g, 39.3 mmol, 80% yield).

Characterisation: 1,3-dibutylimidazolium bromide [C_4C_4im]Br synthesis

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm : 0.88 (t, J_{HH} = 7.4 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**) 1.22 (h, J_{HH} = 7.4 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.67 (p, J_{HH} = 7.3 Hz, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 3.95 (t, J_{HH} = 7.1 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3),6.89 (s, 1H, im-C(5)***H***), 7.16 (s, 1H, im-C(4)***H***), 7.62 (s, 1H, im-C(2)***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm : 13.81 (N-CH_2-CH_2-CH_2-**CH_3**), 19.61 (N-CH_2-CH_2-**CH_2**-CH_3), 33.11 (N-CH_2-**CH_2**-CH_2-CH_3), 46.07 (N-CH_2-**CH_2**-CH_2-CH_3), 119.64 (im-C(5)), 128.77 (im-C(4)), 137.64 (im-C(2)).

HRMS, ESI$^+$: m/z found 125.1079, calc. 125.1034 ($C_8H_{20}N^+$)

MS, ESI$^-$: 78.9, 80.9 (Br^-)

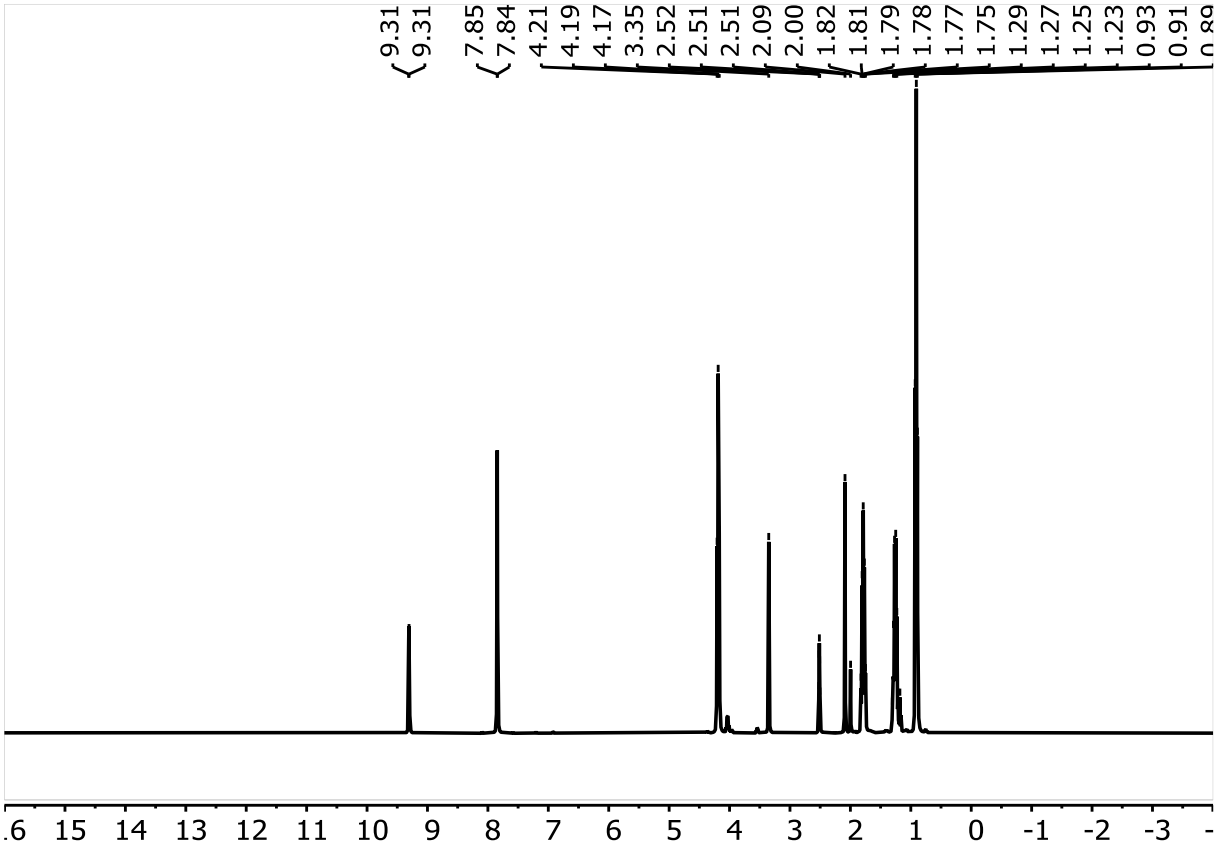


Figure S11. ^{1}H NMR of [C_4C_4im]Br before recrystallisations.

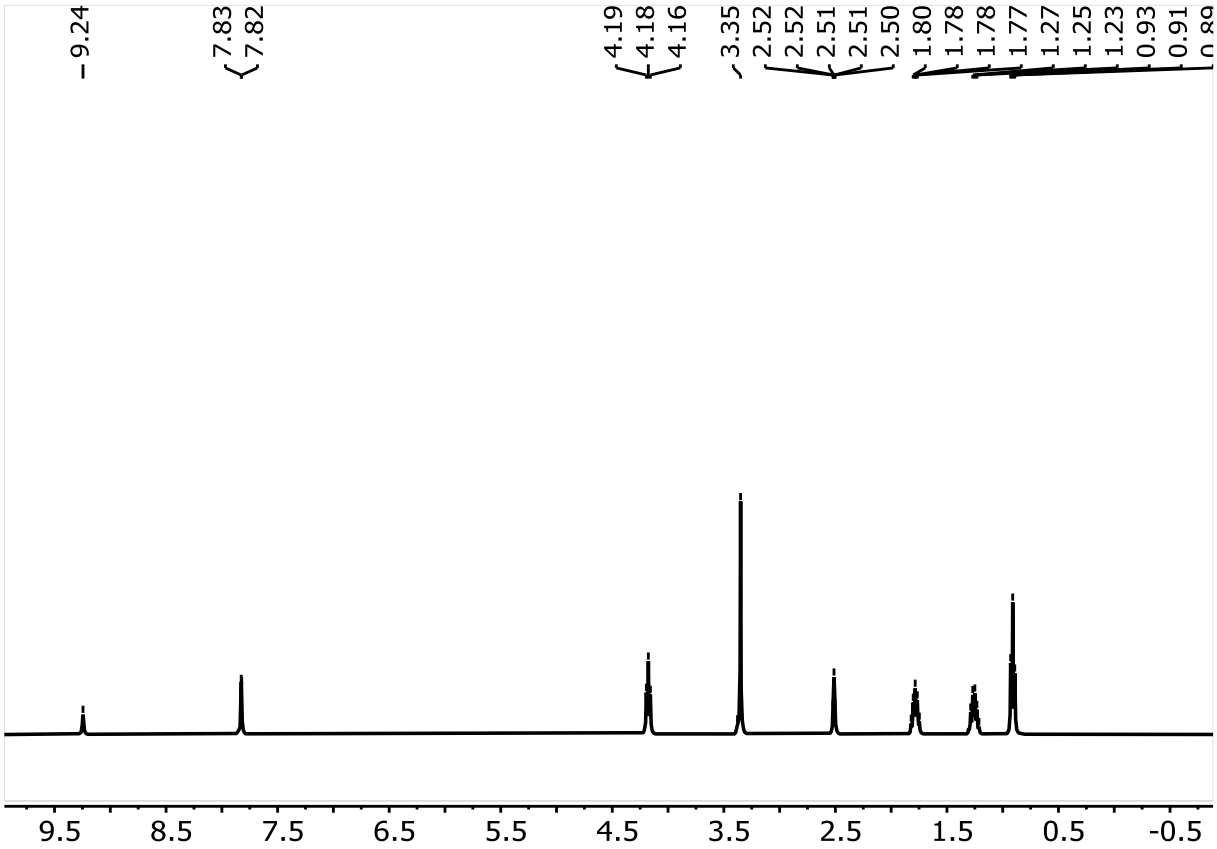


Figure S12. ^{1}H NMR of [C_4C_4im]Br after recrystallisations.

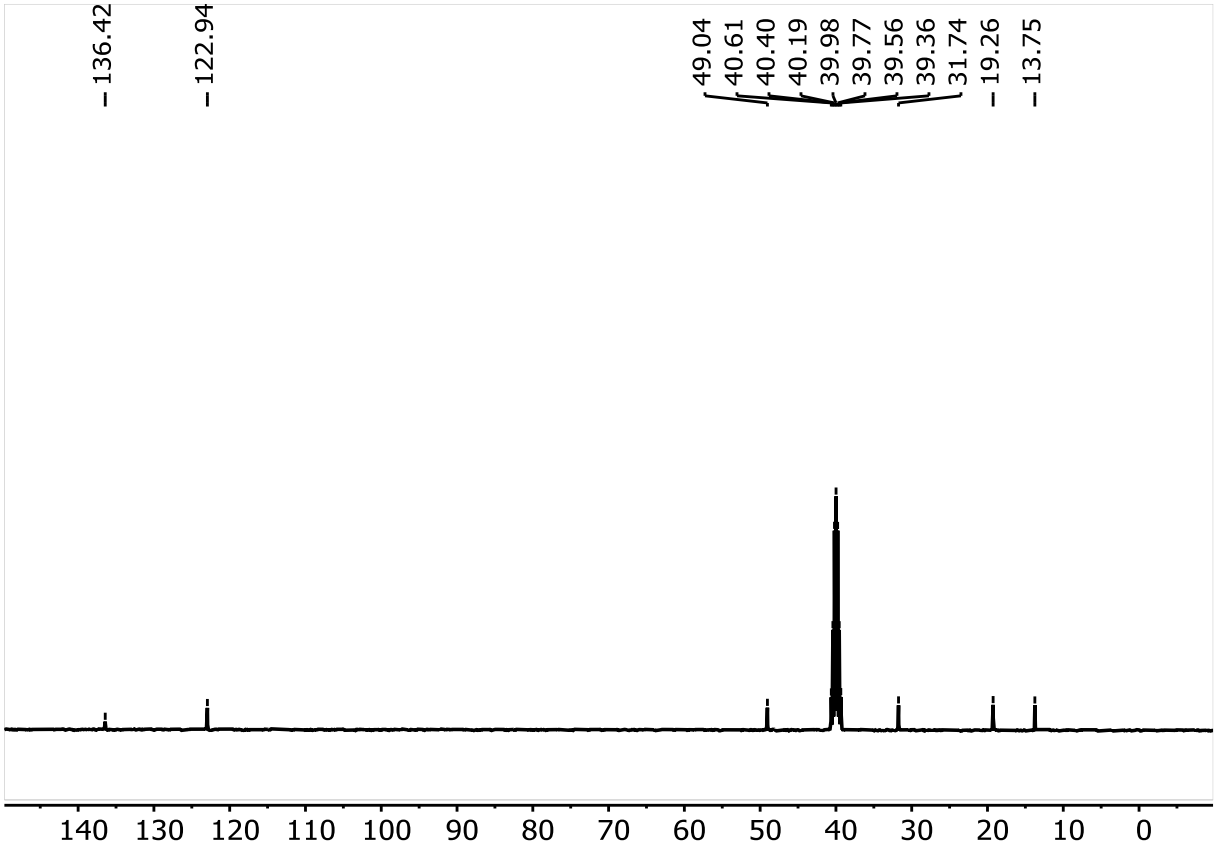
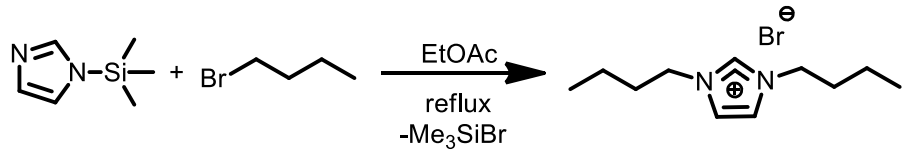


Figure S13. ^{13}C NMR of [C_4C_4im]Br after recrystallisations.

Pictures: 1,3-dibutylimidazolium bromide [C_4C_4im]Br synthesis

Figure S14. [C_4C_4im]Br after recrystallisations.

One-pot synthesis



Starting Materials

1-bromobutane was purified as described in the previous section.

N-trimethylsilylimidazole (97%), received from Acros Organics, was purified by distillation under reduced pressure.

Procedure

The procedure was adapted from Harlow et al.[5], He et al.[6] and Vygodskii et al.[7] The above syntheses were performed in toluene. We used ethyl acetate as the reaction solvent, as it is less hazardous. As a result, the reflux temperature of the crude mixture is lowered.

N-trimethylsilylimidazole (11 mL, 75.1 mmol, 1 eq) was added to a solution of 1-bromobutane (24.3 mL, 225.1 mmol, 3 eq) in ethyl acetate (25 mL). The reaction mixture was refluxed for 48 hours and monitored by ^{1}H-NMR until full conversion of N-trimethylsilylimidazole was observed. A layered mixture was produced and the ionic liquid layer (bottom layer) was separated, followed by the removal of the excess solvent. Then the crude sample was dissolved in acetonitrile and precipitated from ethyl acetate. The purification process was repeated twice to remove any impurities. The product was dried in high vacuum and the title compound was obtained as a brown viscous liquid (17.34 g, 66.4 mmol, 89% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm : 0.89 (t, J_{HH} = 7.4 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**) 1.22 (h, J_{HH} = 7.4 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.67 (p, J_{HH} = 7.3 Hz, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 3.94 (t, J_{HH} = 7.1 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3),6.89 (s, 1H, im-C(5)***H***), 7.16 (s, 1H, im-C(4)***H***), 7.62 (s, 1H, im-C(2)***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm : 13.81 (N-CH_2-CH_2-CH_2-**CH_3**), 19.60 (N-CH_2-CH_2-**CH_2**-CH_3), 33.11 (N-CH_2-**CH_2**-CH_2-CH_3), 46.07 (N-CH_2-**CH_2**-CH_2-CH_3), 119.65 (im-C(5)), 128.77 (im-C(4)), 137.64 (im-C(2)).

HRMS, ESI^+: m/z found 181.1707, calc. 181.1705 ($C_8H_{20}N^+$)

MS, ESI^-: 78.9, 80.9 (Br^-), 340.9 ($[M^+ + 2M^-]^-$)

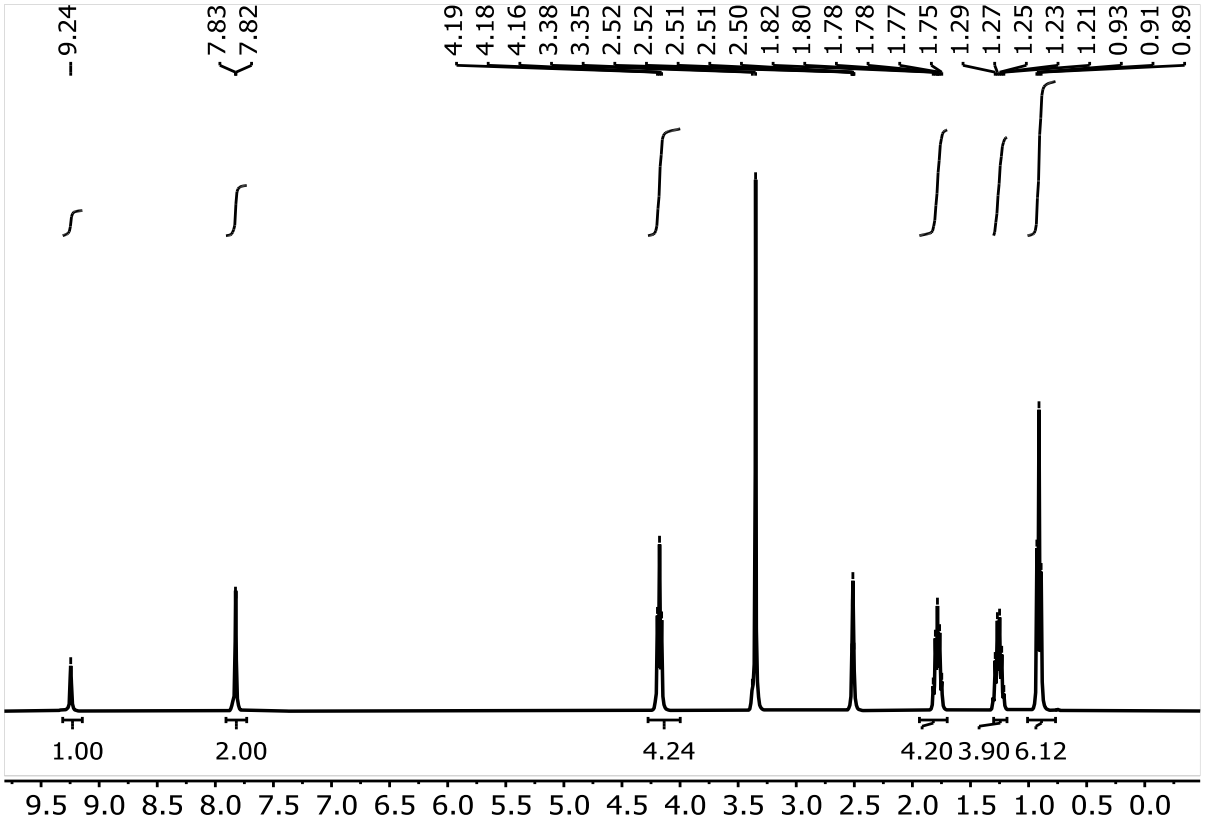


Figure S15. ^{1}H NMR of [C_4C_4im]Br before purification.

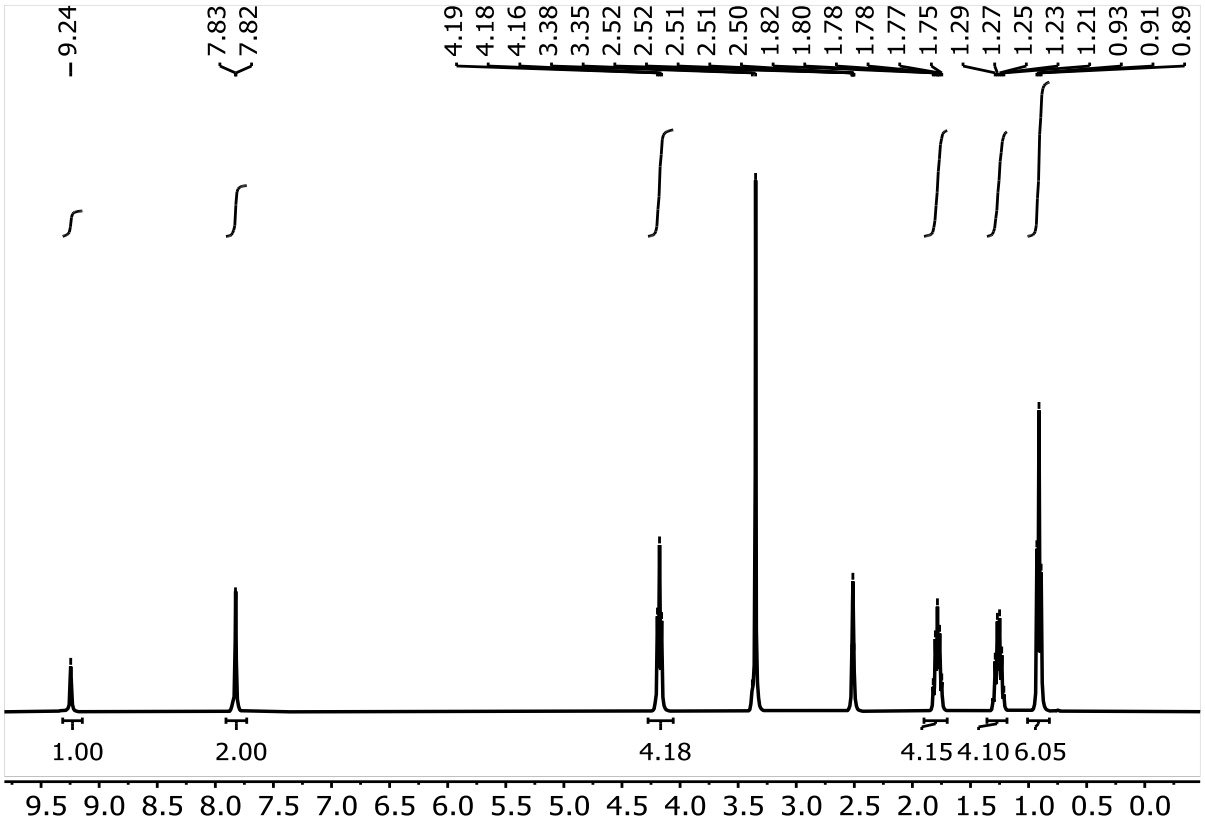


Figure S16. ^{1}H NMR of [C_4C_4im]Br after 2 recrystallisations.

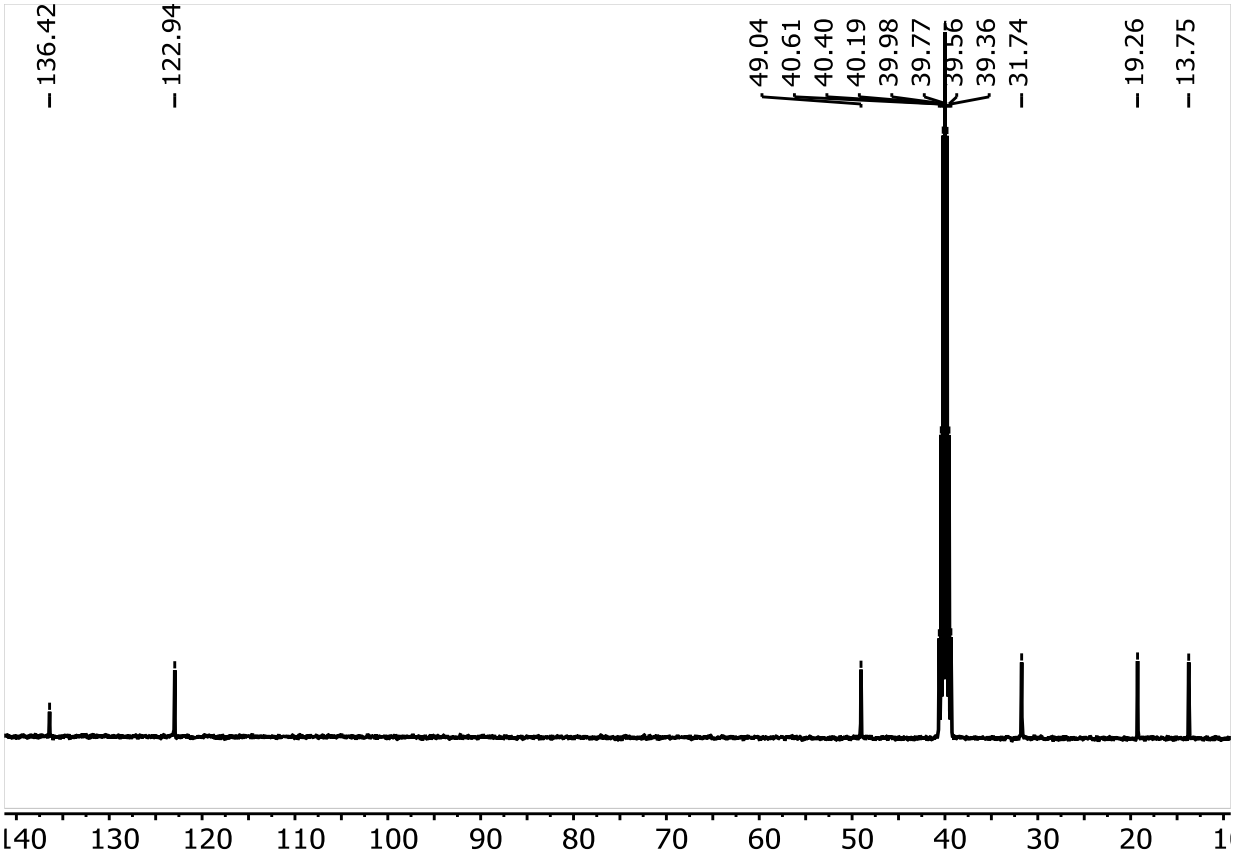


Figure S17. ^{13}C NMR of $[C_4C_4im]Br$ after 2 recrystallisations.

Pictures

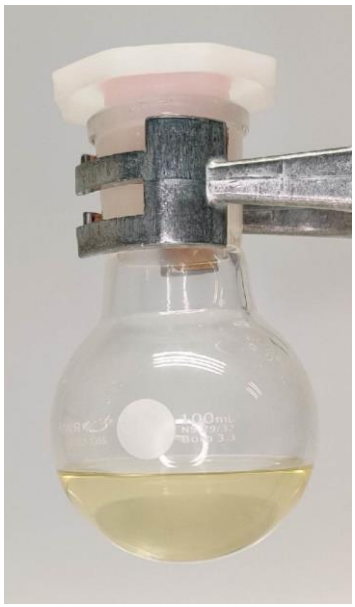


Figure S18. N-trimethylsilylimidazole before distillation.

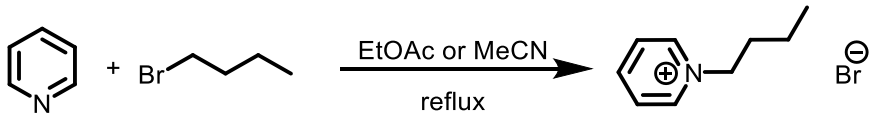
Figure S19. N-trimethylsilylimidazole after distillation.

Figure S20. Crude reaction mixture after 1 day. Top phase contains ethyl acetate and unreacted starting materials, while bottom phase contains $[C_4C_4im]Br$.

Figure S21. Crude [C_4C_4im]Br before purification.

N-butylpyridinium bromide [C_4Py]Br

Slow reaction, controlled temperature



Starting Materials

Pyridine (99.8%), received from Sigma Aldrich, was stirred with potassium hydroxide overnight, followed by distillation under reduced pressure.

1-bromobutane was purified as described in the previous section.

Procedure

The procedures were adjusted from Królikowska et al.[8] and Takao et al.[9] Two reactions, one conducted in ethyl acetate and one in acetonitrile as solvents were set up separately.

1-bromobutane (8.18 g, 6.5 mL, 57.4 mmol, 1.1 eq) was added into a solution of pyridine (4.15 g, 4.2 mL, 52.2 mmol, 1 eq) in the corresponding solvent (20 mL, ethyl acetate or acetonitrile) dropwise in an ice bath. The mixture was allowed to reach room temperature and was stirred for 24 hours. Then the temperature was slowly increased up to the boiling point of the solvent over several hours and the mixture was refluxed in an oil bath for 72 hours under nitrogen atmosphere.

Acetonitrile reaction. The final product is soluble in acetonitrile, therefore no phase separation is observed in this case. The excess solvent and reagent were removed in a rotary evaporator. The resulting solid was re-dissolved in acetonitrile (10 mL) and recrystallised from ethyl acetate (40 mL). Then the excess solvent was removed and the white solid product was obtained and further dried under vacuum (10.29 g, 47.5 mmol, 91% yield).

Ethyl acetate reaction. The final product is not soluble in ethyl acetate and as a result it forms a separate phase. The ethyl acetate phase was removed with a cannula and the product was dried under

vacuum. The solid was re-dissolved in acetonitrile (10 mL) and recrystallised from ethyl acetate (40 mL). The final product was obtained as white powder (10.62 g, 49.1 mmol, 94% yield).

Characterisation

Acetonitrile reaction

^{1}H-NMR (400 MHz, DMSO-d_6) δ / ppm : 0.91 (t, J_{HH} = 7.5 *Hz*, 3H, N-CH_2-CH_2-CH_2-C***H*$_3$**), 1.28 (tq, J_{HH} = 7.5 *Hz*, 2H, N-CH_2-CH_2-C***H*$_2$**-CH_3), 1.90 (tt, J_{HH} = 7.5 *Hz*, 2H, N-CH_2-C***H*$_2$**-CH_2-CH_3), 4.62 (t, J_{HH} = 7.5 *Hz*, 2H, N-C***H*$_2$**-CH_2-CH_2-CH_3), 8.17 (t, *J* = 7.0 *Hz*, 2H, CH-C***H***-CH-C***H***-CH), 8.61 (t, *J* = 8.0 *Hz*, 1H, CH-CH-C***H***-CH-CH), 9.12 (d, J_{HH} = 6.0 *Hz*, 2H, C***H***-N-C***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6) δ / ppm : 13.32 (N-CH_2-CH_2-CH_2-C***H*$_3$**), 18.74 (N-CH_2-CH_2-C***H*$_2$**-CH_3), 32.67 (N-CH_2-C***H*$_2$**-CH_2-CH_3), 60.48 (N-C***H*$_2$**-CH_2-CH_2-CH_3), 128.09 (CH-C***H***-CH-C***H***-CH), 144.77 (CH-CH-C***H***-CH-CH), 145.49 (C***H***-N-C***H***).

HRMS, ESI^{+}: m/z found 136.1128, calc. 136.1126 ([$C_9H_{14}N_1$]$^{+}$).

MS, ESI^{-}: 78.9, 80.9 (Br^{-})

Elemental analysis (calculated): C- 50.44(50.02), H- 6.75(6.53), N- 6.33(6.48)

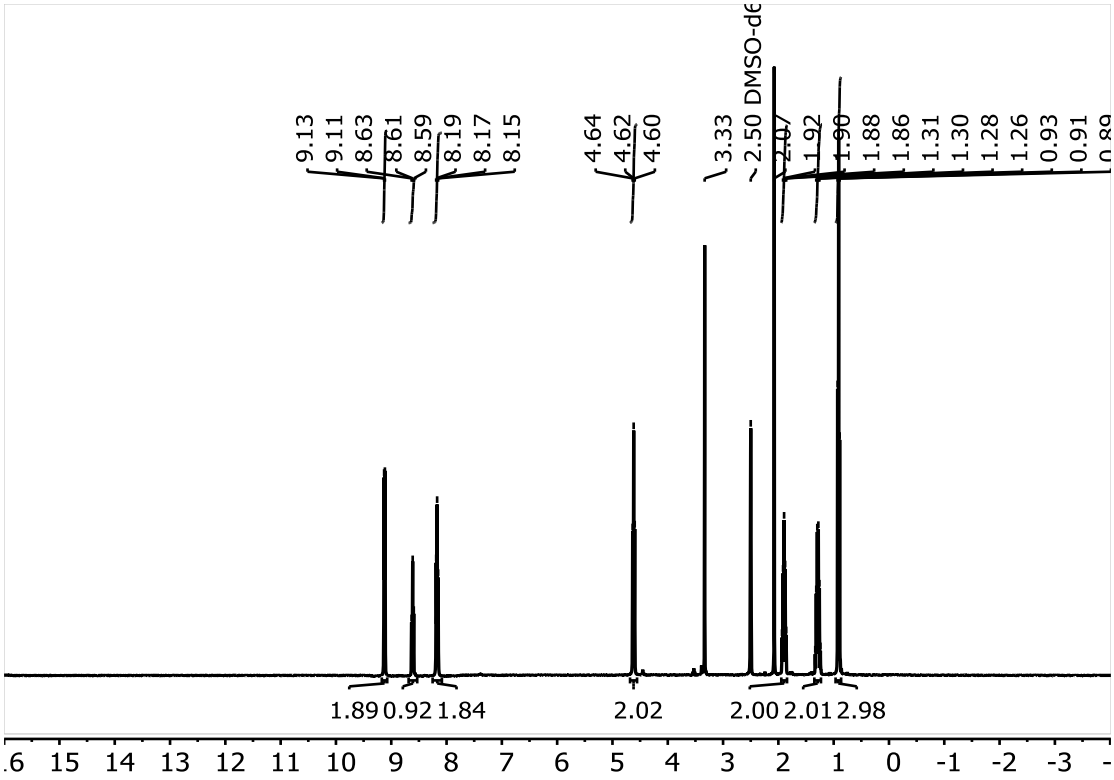


Figure S22. ^{1}H NMR of [C_4Py]Br from the reaction using acetonitrile as solvent.

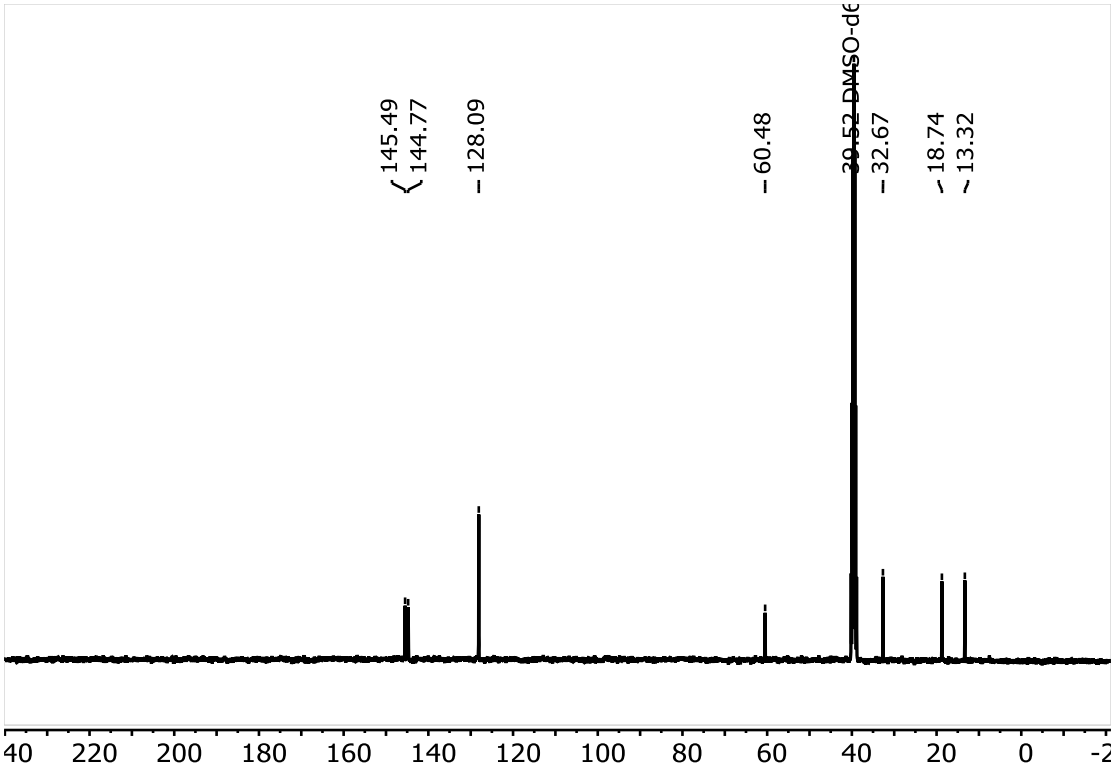


Figure S23. ^{13}C NMR of [C_4Py]Br from the reaction using acetonitrile as solvent.

Ethyl acetate reaction

^{1}H-NMR (400 MHz, DMSO-d_6) δ / ppm : 0.91 (t, *J* = 7.5 *Hz*, 3H, N-CH_2-CH_2-CH_2-C***H*$_3$**), 1.28 (tq, *J* = 7.5 *Hz*, 2H, N-CH_2-CH_2-C***H*$_2$**-CH_3), 1.90 (tt, *J* = 7.5 *Hz*, 2H, N-CH_2-C***H*$_2$**-CH_2-CH_3), 4.63 (t, *J* = 7.5 *Hz*, 2H, N-C***H*$_2$**-CH_2-CH_2-CH_3), 8.17 (t, *J* = 7.0 *Hz*, 2H, CH-C***H***-CH-C***H***-CH), 8.62 (t, *J* = 8.0 *Hz*, 1H, CH-CH-C***H***-CH-CH), 9.14 (d, *J* = 5.5 *Hz*, 2H, C***H***-N-C***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6) δ / ppm : 13.34 (N-CH_2-CH_2-CH_2-C***H*$_3$**), 18.75 (N-CH_2-CH_2-C***H*$_2$**-CH_3), 32.68 (N-CH_2-C***H*$_2$**-CH_2-CH_3), 60.47 (N-C***H*$_2$**-CH_2-CH_2-CH_3), 128.10 (CH-C***H***-CH-C***H***-CH), 144.77 (CH-CH-C***H***-CH-CH), 145.49 (C***H***-N-C***H***).

HRMS, ESI$^+$: m/z found 136.1125, calc. 136.1126 ([$C_9H_{14}N_1$]$^+$)

MS, ESI$^-$: 78.9, 80.9 (Br^-)

Elemental analysis (calculated): C- 49.57(50.02), H- 6.75(6.53), N- 6.31(6.48)

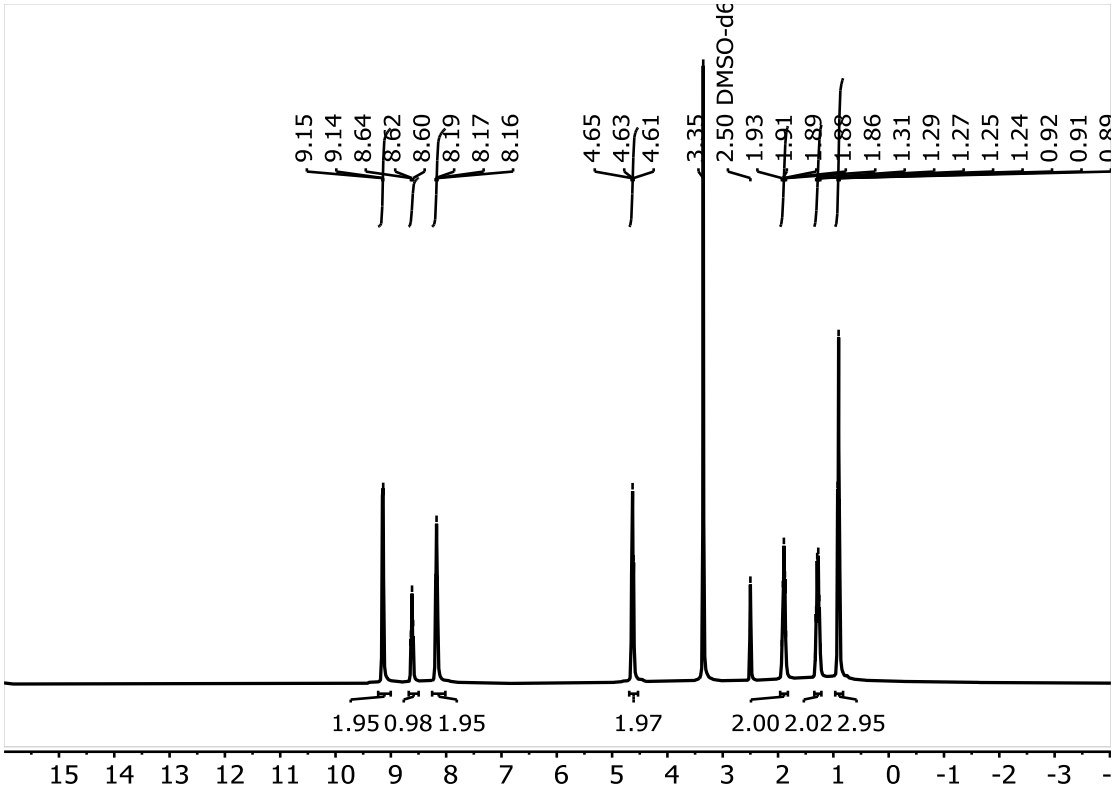


Figure S24. ^{1}H NMR of [C_4Py]Br from the reaction using ethyl acetate as solvent.

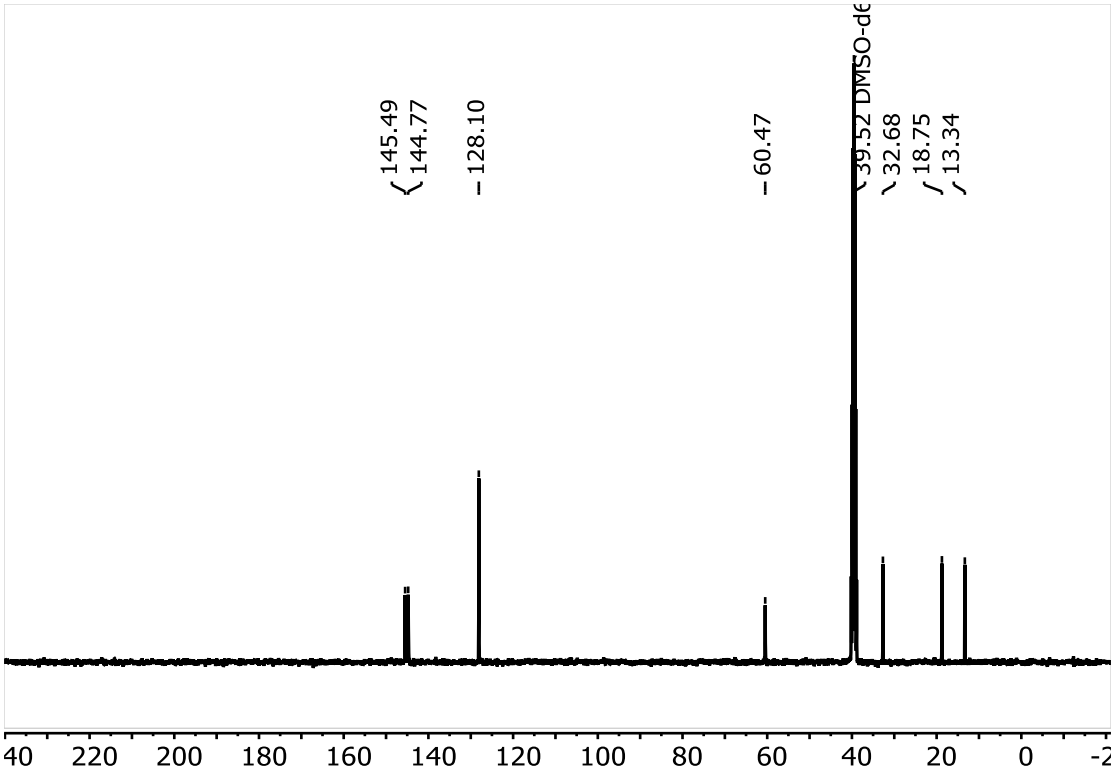


Figure S25. ^{13}C NMR of [C_4Py]Br from the reaction using ethyl acetate as solvent.

Pictures

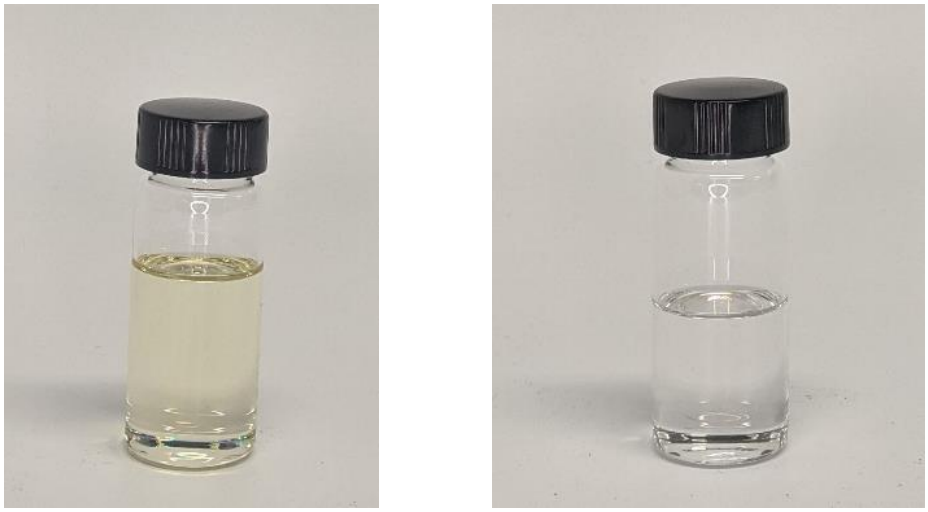
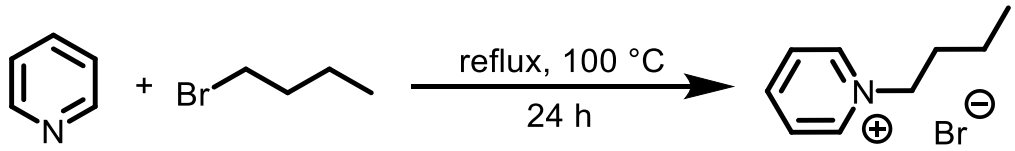


Figure S26. Pyridine before (left) and after (right) purification.

Figure S27. Crude reaction mixtures after 1 day of stirring. Left is the reaction using acetonitrile (homogeneous solution), while right is the reaction using ethyl acetate (white precipitate starts forming).

Figure S28. Crude reaction mixtures after completion of the reaction. Left is the reaction using acetonitrile (homogeneous solution), while right is the reaction using ethyl acetate (white precipitate has formed).

Fast synthesis, solvent-free



Starting materials

1-bromobutane (99%) and pyridine (99.8%) were received from Sigma-Aldrich and used without any purification.

Procedure

The procedure was adapted from Scammels et al.[10] and Tzedakis et al.[11] Pyridine (4.07 g, 51.3 mmol, 1.0 eq) and bromobutane (8.45 g, 61.6 mmol, 1.2 eq) were mixed at room temperature, then heated to 100 °C and stirred for 24 h. The reaction was allowed to cool to room temperature affording the crude product as a brown solid. This was dissolved in minimum acetonitrile (20 mL) and purified via recrystallisation using ethyl acetate (30 mL). The supernatant was removed using a syringe and the excess solvent was removed under reduced pressure, at room temperature. This recrystallisation procedure was performed twice. The resulting solid was dried under high vacuum for 24 h. The title compound was obtained as a light-brown solid (9.82 g, 45.5 mmol, 89% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.90 (t, $^{3}J_{H,H}$ = 7.4 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**), 1.28 (h, $^{3}J_{H,H}$ = 7.3 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.89 (p, $^{3}J_{H,H}$ = 7.6 Hz, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 4.64 (t, $^{3}J_{H,H}$ = 7.4 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3), 8.17 (t, $^{3}J_{H,H}$ = 7.0 Hz, 2H, Py-HC3/HC5), 8.62 (t, $^{3}J_{H,H}$ = 7.8 Hz, 1H, Py-HC4), 9.17 (d, $^{3}J_{H,H}$ = 5.2 Hz, 2H, Py-HC2/HC6).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 12.93 (N-CH_2-CH_2-CH_2-**CH_3**), 18.75 (N-CH_2-CH_2-**CH_2**-CH_3), 32.70 (N-CH_2-**CH_2**-CH_2-CH_3), 59.28 (N-**CH_2**-CH_2-CH_2-CH_3), 127.04 (Py-C3/C5), 144.78 (Py-C4), 145.51 (Py-C2/C6).

HRMS, ESI^+: m/z found 136.1126, calc. 136.1121 ($C_9H_{14}N^+$)

MS, ESI^-: m/z found 78.9, 80.1 (Br^-)

Elemental analysis (calculated): C- 50.09 (50.02), H- 6.61 (6.53), N- 6.51 (6.48)

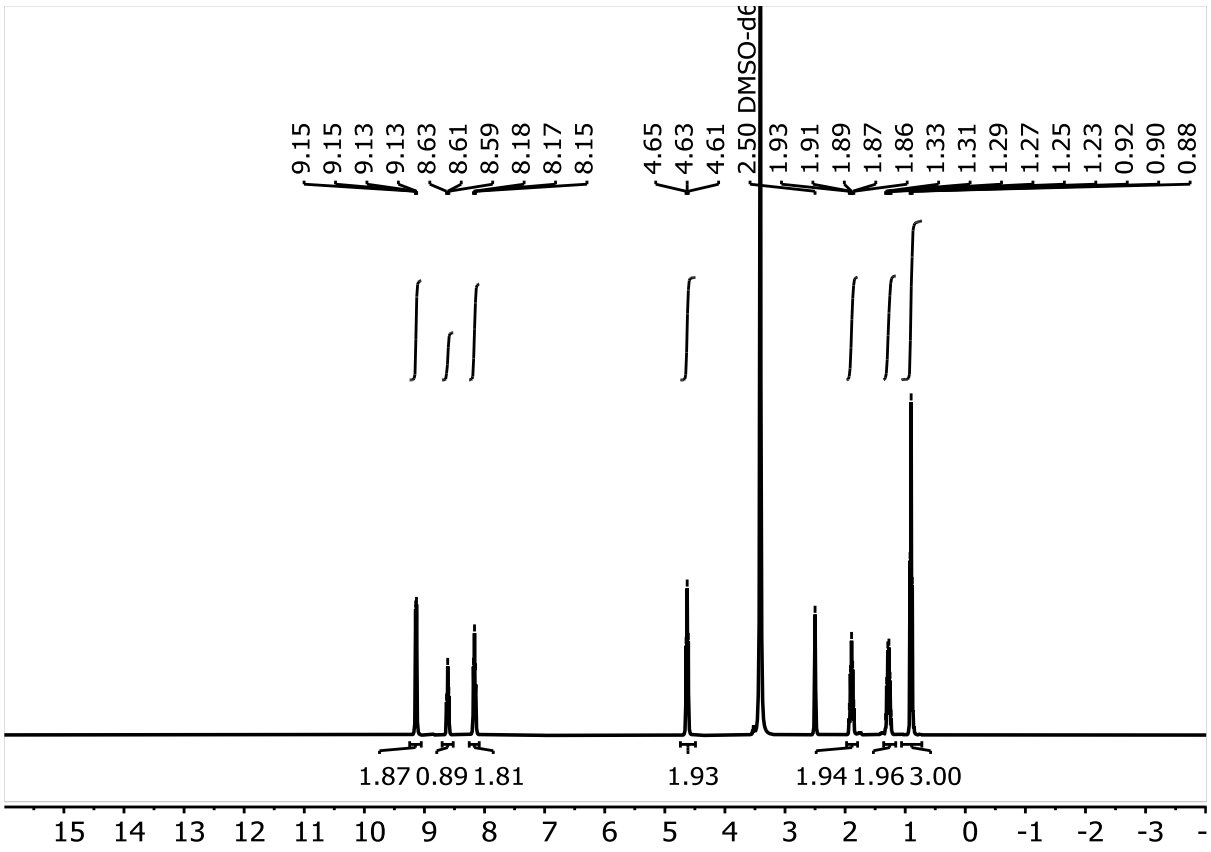


Figure S29. ^{1}H NMR of [C_4Py]Br before recrystallisations.

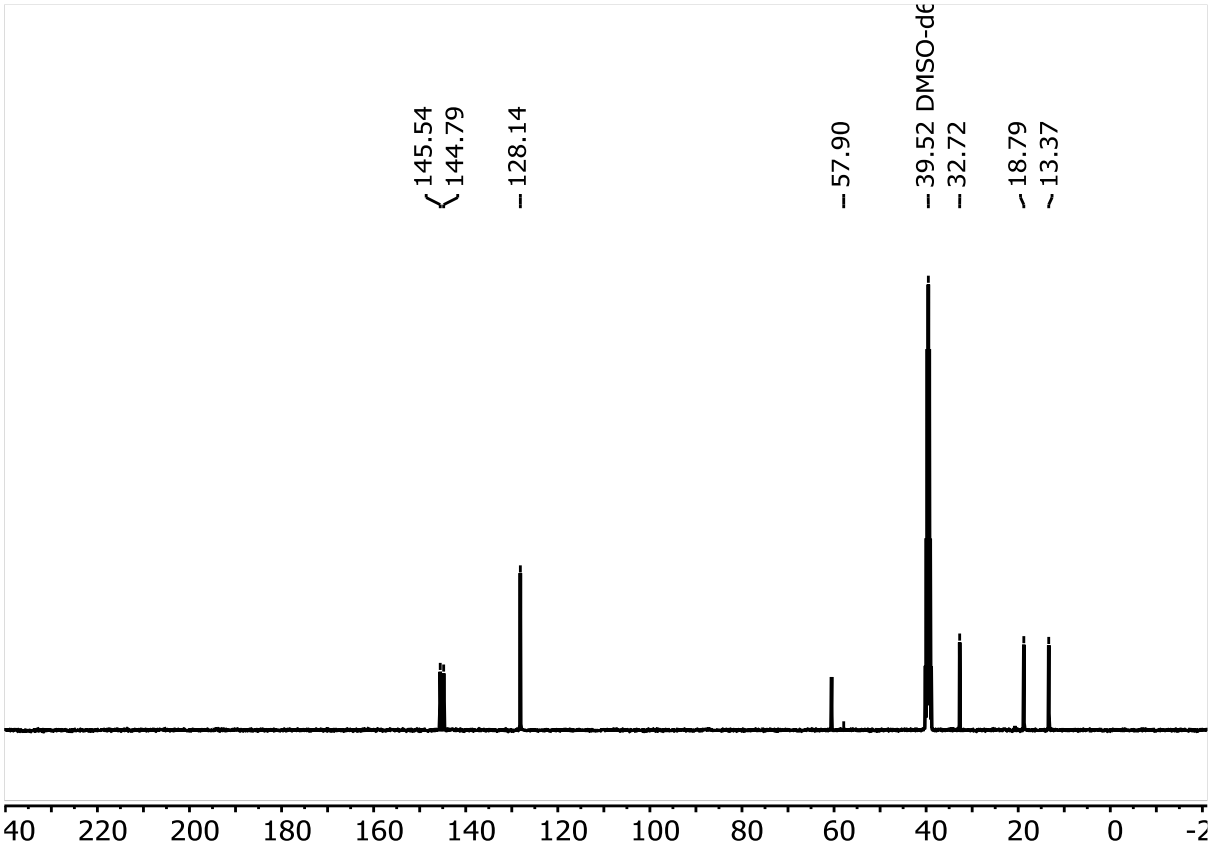


Figure S30. ^{13}C NMR of [C_4Py]Br before recrystallisations.

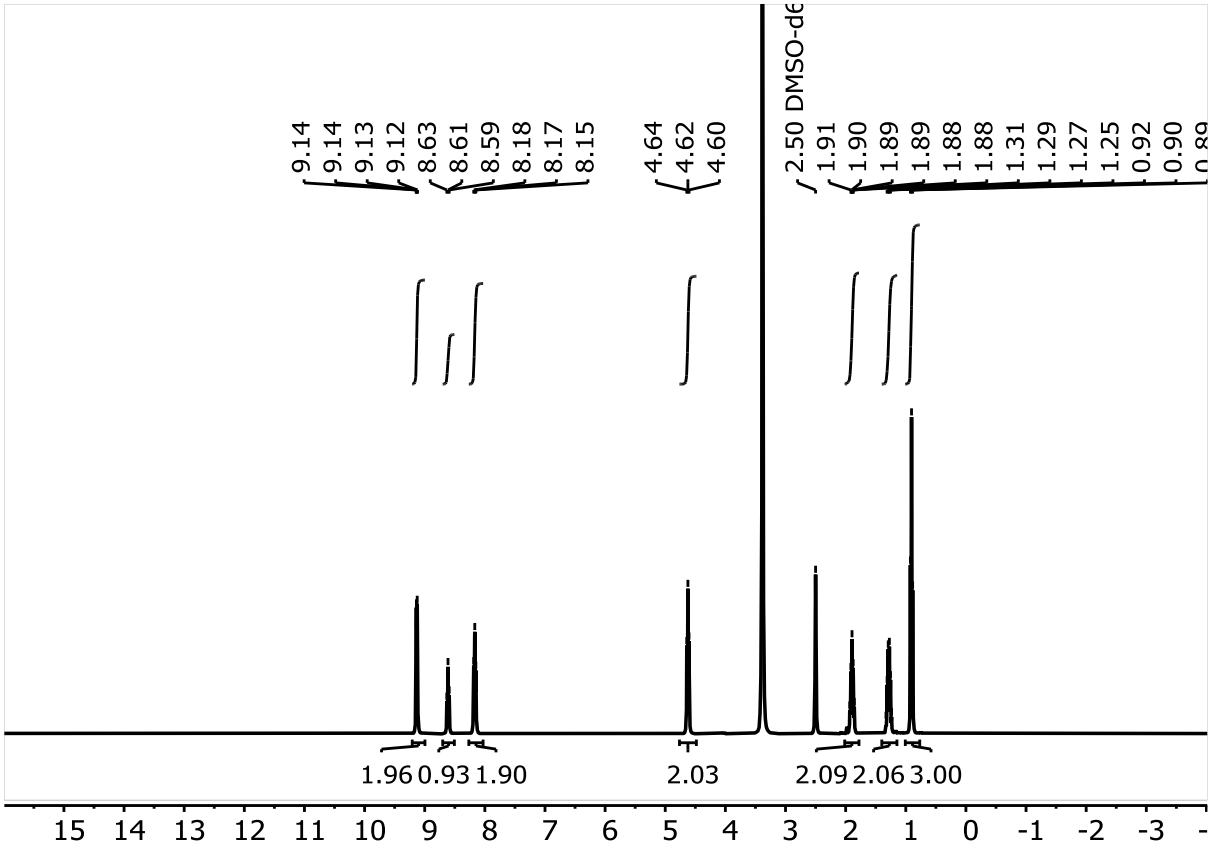


Figure S31. ^{1}H NMR of [C_4Py]Br after one recrystallisation.

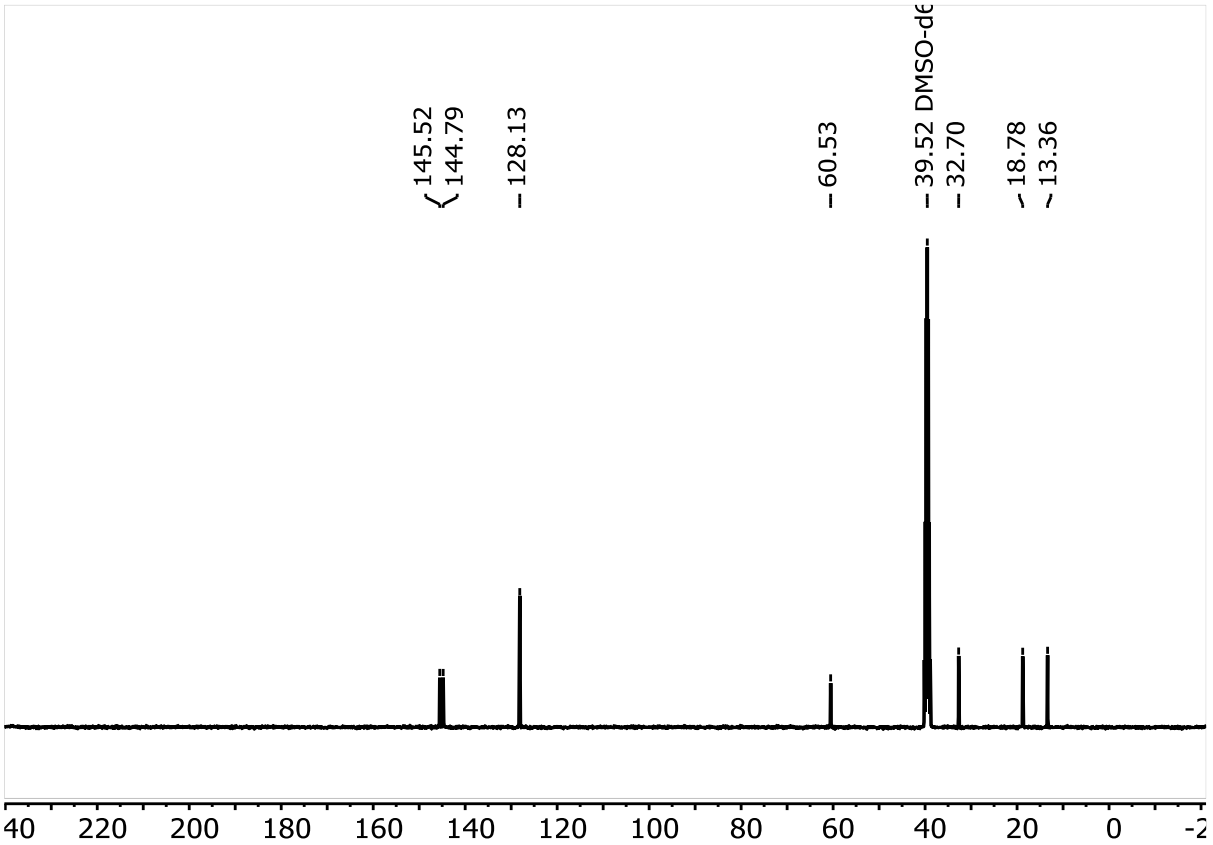


Figure S32. ^{13}C NMR of [C_4Py]Br after one recrystallisation.

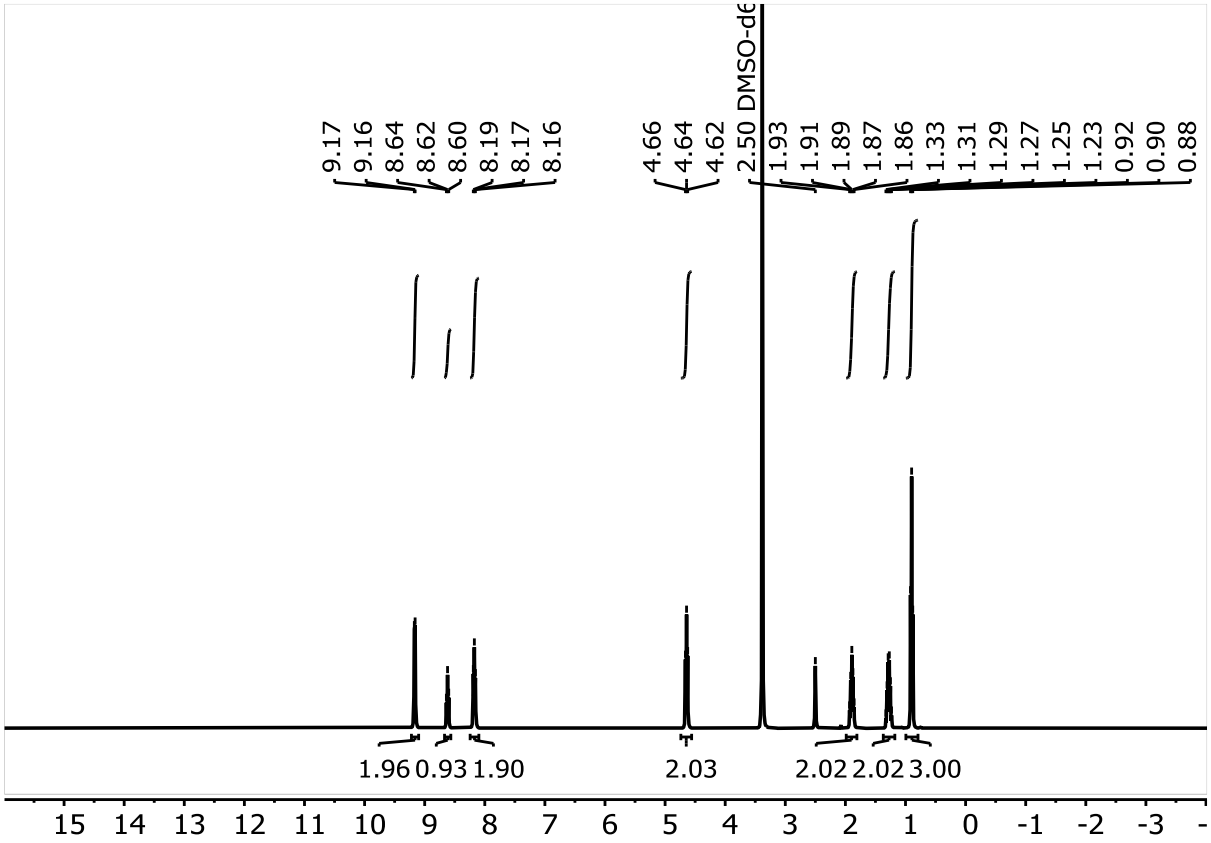


Figure S33. ^{1}H NMR of [C_4Py]Br after two recrystallisations.

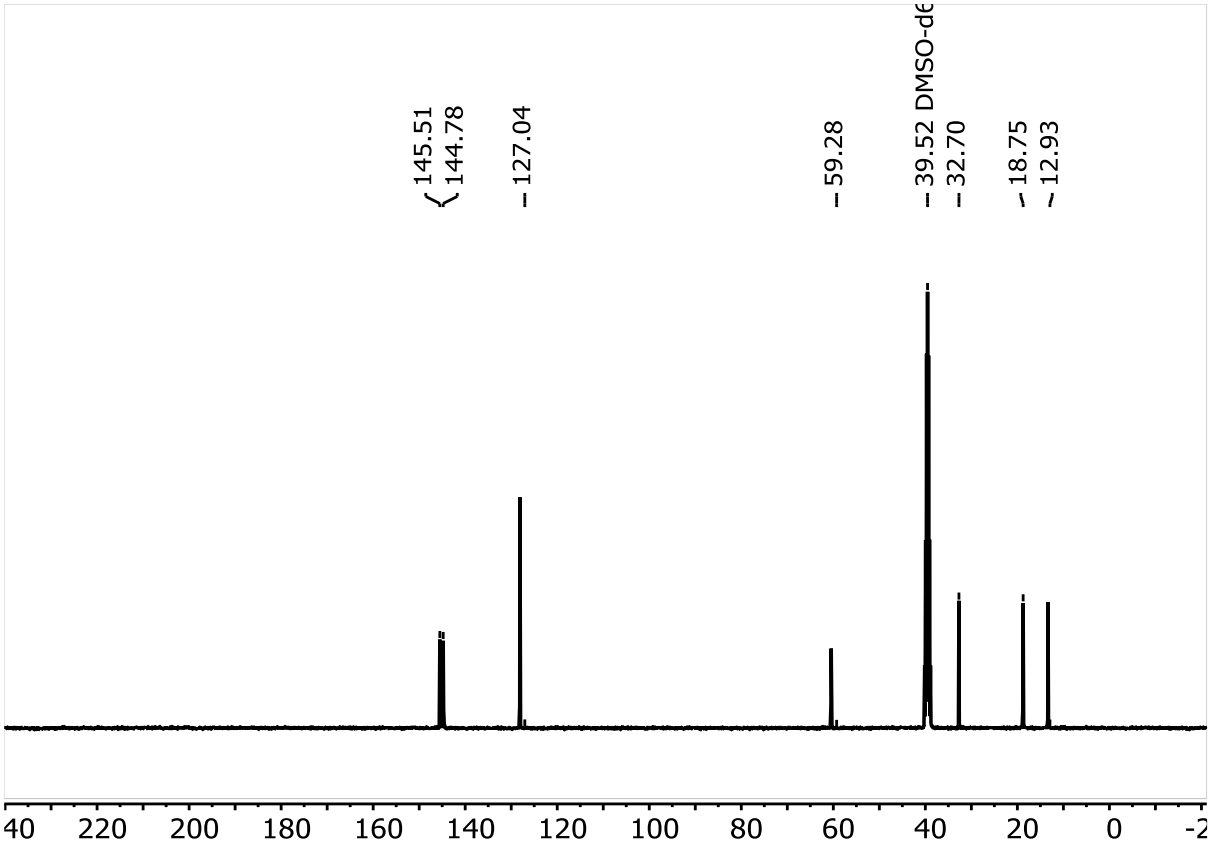


Figure S34. ^{13}C NMR of [C_4Py]Br after two recrystallisations.

Pictures

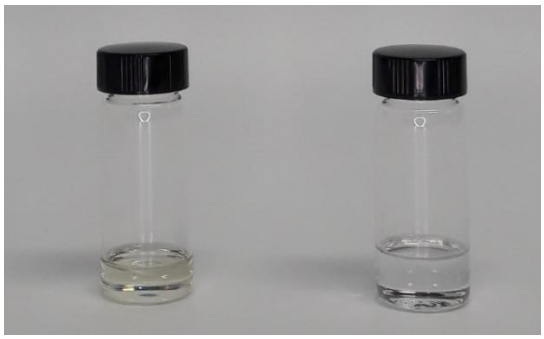


Figure S35. Starting materials, without any purification: pyridine (left), bromobutane (right).

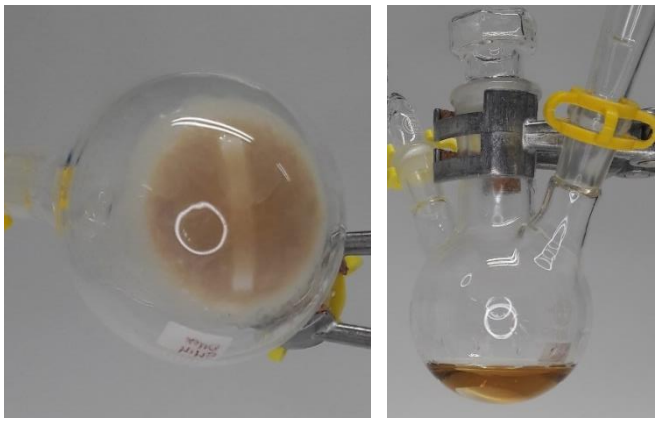


Figure S36. Crude $[C_4Py]Br$, before purification: solid (left), dissolved in acetonitrile (right). The solid compound is off-white, but the solution is brown.

Figure S37. First recrystallisation of $[C_4Py]Br$.

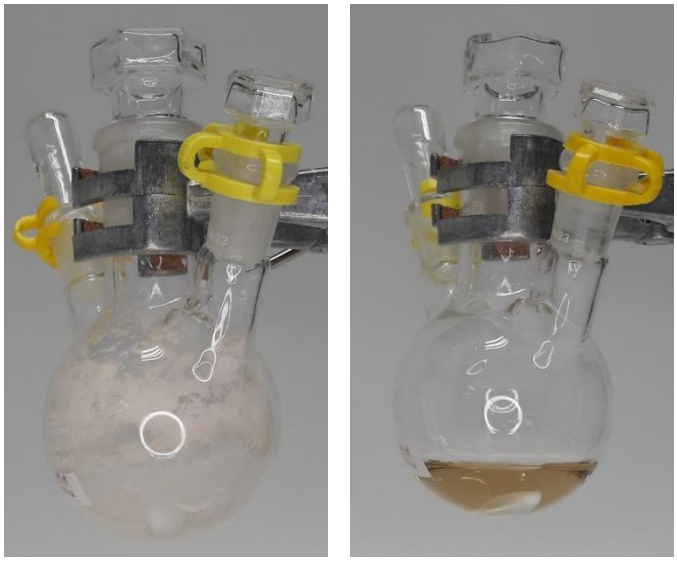


Figure S38. [C_4Py]Br after one recrystallisation: solid (left), dissolved in acetonitrile (right). The solid powder looks off-white, but the solution is yellow.

Figure S39. Second recrystallisation of [C_4Py]Br.

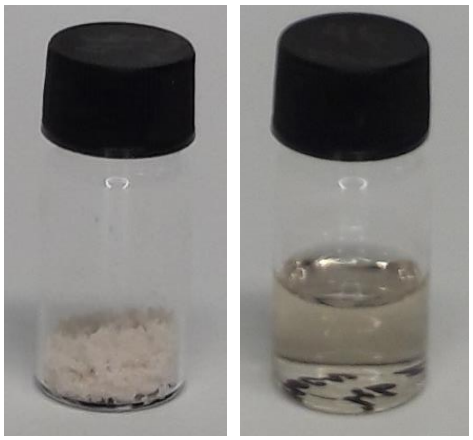


Figure S40. [C_4Py]Br after two recrystallisations: solid (left), dissolved in acetonitrile (right). The solid powder is off-white and the solution slightly yellow.

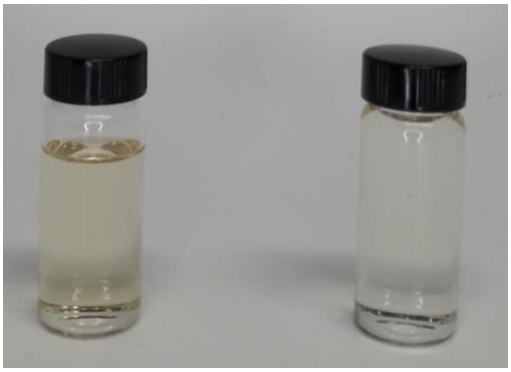


Figure S41. Ethyl acetate phases recovered from the first (left) and second (right) recrystallisations.

Figure S42. Comparison of [C_4Py]Br before recrystallising (left), after one recrystallisation (middle) and after two recrystallisations (right).

US-assisted synthesis

Starting Materials

Pyridine (99.8%), received from Sigma Aldrich, was stirred with potassium hydroxide overnight, followed by distillation under reduced pressure.

1-bromobutane was purified as described in the previous section.

Procedure

The procedure was adapted from Namboodiri and Varma.[12] Ice bath cooling was added to counteract the heating of the reaction during sonication. This was included to safeguard the equipment and ensure no reagents evaporated from the open reaction vial during the sonication period. The reaction time was extended from 2 hours to 4 hours to account for slower reaction rate due to reduced temperature.

A sonicator vial (25 mL) was charged with pyridine (5.11 mL, 63.2 mmol, 1.0 eq) and 1-bromobutane (6.92 mL, 64.5 mmol, 1.02 eq). The open reaction vessel was connected to a VCX 750 ultrasonics processor (Sonics & Materials INC) equipped with a ½ inch diameter sonicator horn and placed in an ice bath for cooling. The reaction was sonicated at 20% amplitude for 4 hours under continuous refreshing of the ice bath when necessary. After 4 hours the solid product had precipitated and the reaction was stopped. The resulting suspension was dissolved in acetonitrile (10 mL) and was recrystallised from ethyl acetate (40 mL). The solid was then filtered, washed with ethyl acetate, dried under vacuum and analysed by ^{1}H NMR. The recrystallisation process was performed twice to remove any impurities. The final product was isolated as an off-white powder (6.6 g, 25.3 mmol, 40% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.92 (t, J_{HH} = 7.4 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**), 1.30 (h, J_{HH} = 7.4 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.97 – 1.85 (m, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 4.64 (t, J_{HH}= 7.4 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3), 8.19 (t, J_{HH} = 7.0 Hz, 2H, (m, 2H, py-HC3/HC5), 8.63 (m, 1H, py-HC4), 9.16 (m, 2H, py-HC2/HC6).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 13.81 (N-CH_2-CH_2-CH_2-**CH_3**), 19.22 (N-CH_2-CH_2-**CH_2**-CH_3), 33.15 (N-CH_2-**CH_2**-CH_2-CH_3), 60.94 (N-**CH_2**-CH_2-CH_2-CH_3), 128.57 (py-C3/C5), 145.25 (py-C4), 145.96 (py-C2/C6).

HRMS, ESI^+: m/z found 136.1125, calc. 136.1121 ($C_9H_{14}N^+$)

MS, ESI^-: 78.9, 80.9 (Br^-)

Elemental analysis (calculated): C- 50.02(50.02), H- 6.88(6.53), N- 6.93(6.48)

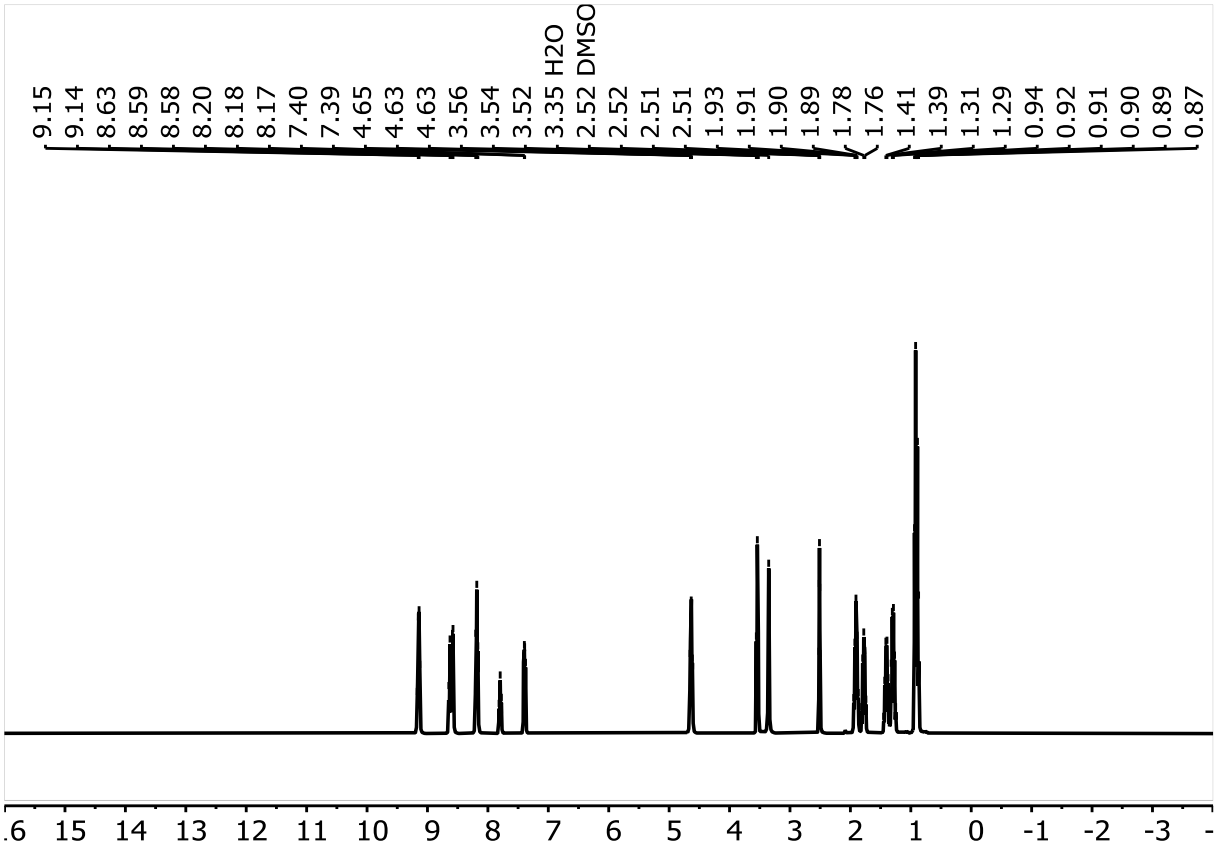


Figure S43. ^{1}H NMR of crude reaction mixture, unreacted pyridine still exists in the system.

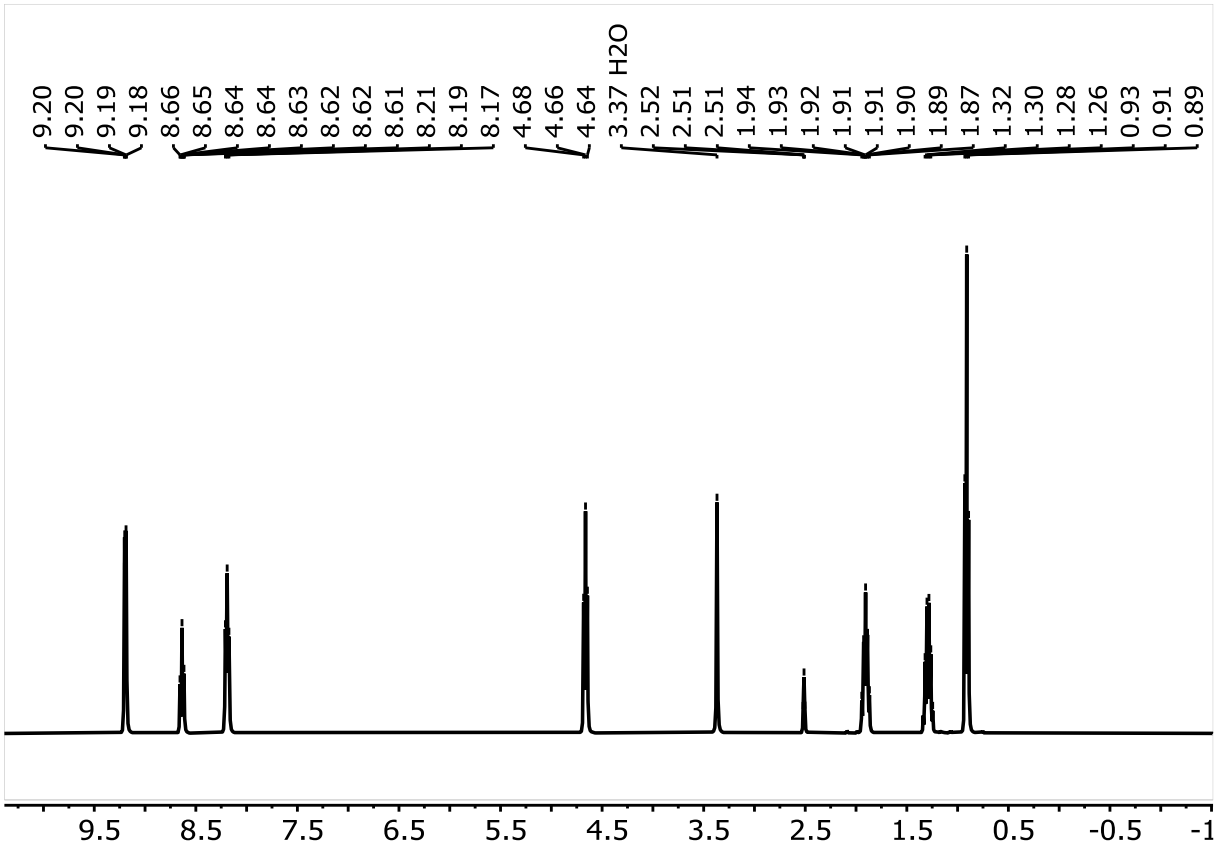


Figure S44. ^{1}H NMR of [C_4Py]Br after the first recrystallisation. Unreacted pyridine has been removed.

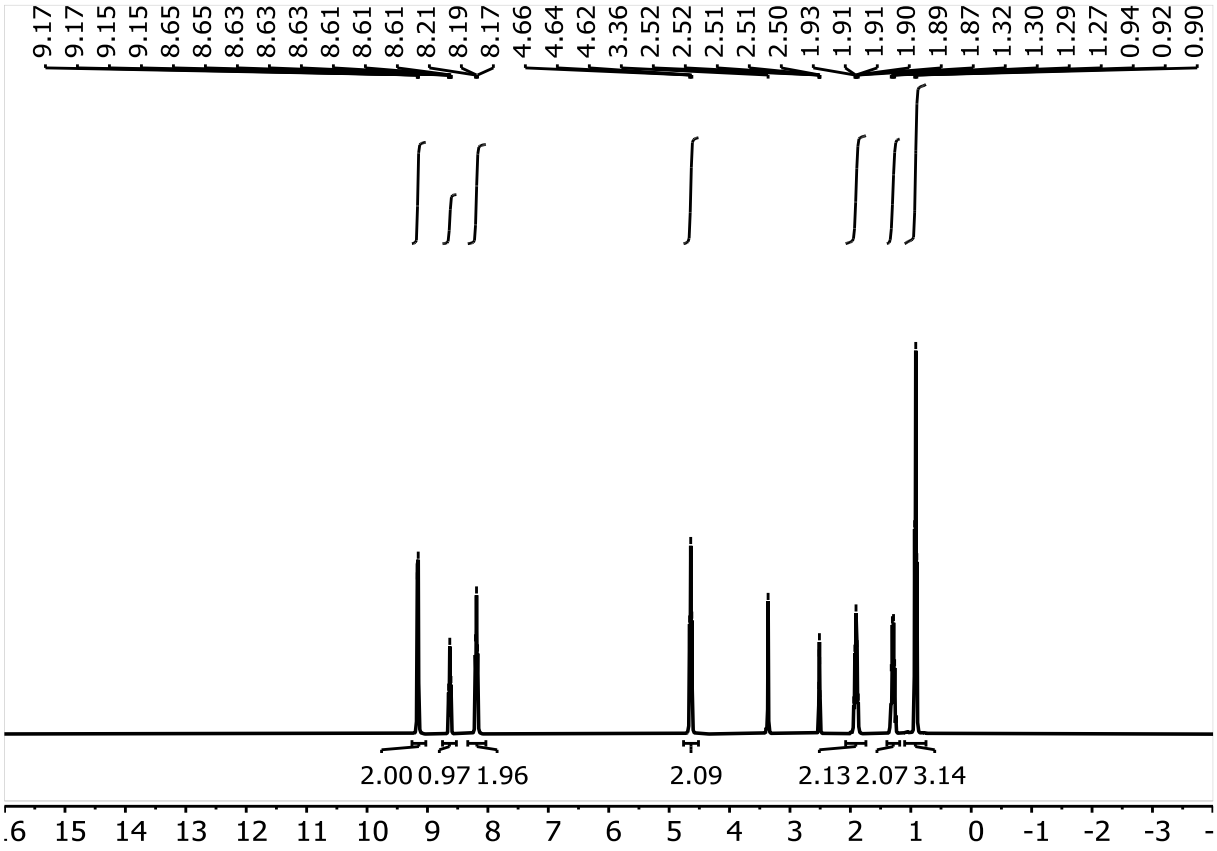


Figure S45. ^{1}H NMR of [C_4Py]Br after the second recrystallisation.

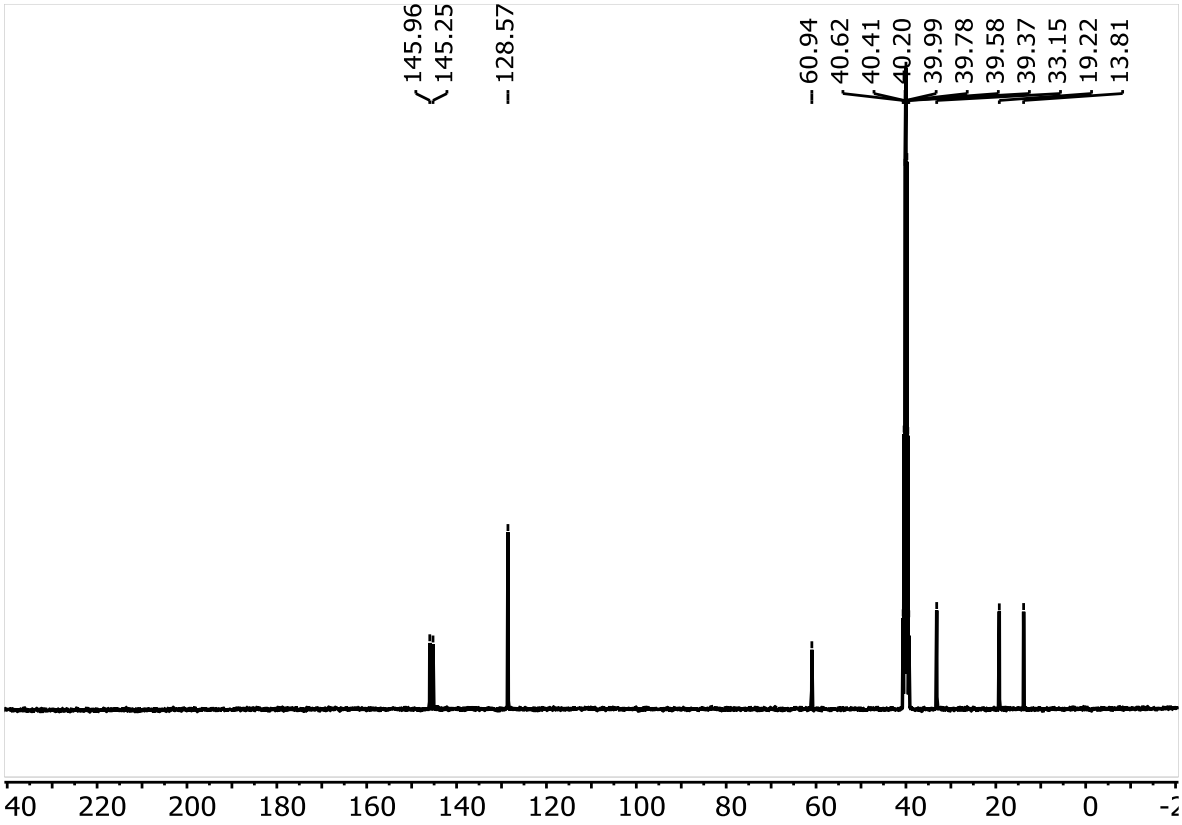


Figure S46. ^{13}C NMR of $[C_4Py]Br$ after the second recrystallisation.

Pictures

Figure S47. Thick-walled reaction vial. Suitable for sonication probe.

Figure S48. Vial containing crude reaction mixture after 4 hours of sonication.

Figure S49. First recrystallisation of [C_4Py]Br.

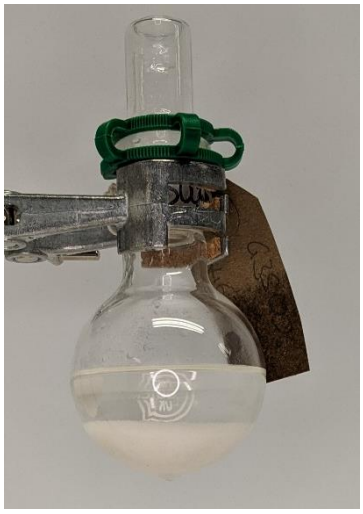


Figure S50. Second recrystallisation of [C_4Py]Br.

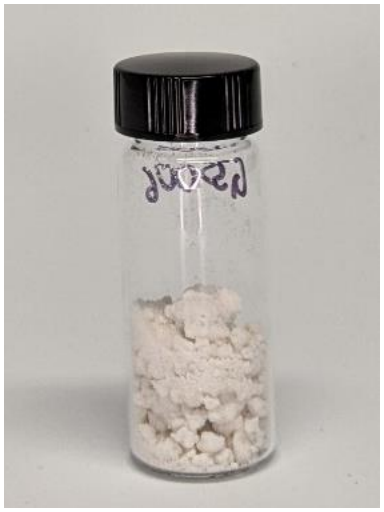


Figure S51. Final product, [C_4Py]Br received from US-assisted synthesis.

MW-assisted synthesis

Starting Materials

Pyridine (99.8%), received from Sigma Aldrich, was stirred with potassium hydroxide overnight, followed by distillation under reduced pressure.

1-bromobutane was purified as described in the previous section.

Procedure

The reaction procedure was adapted from Deetlefs and Seddon.[13] The literature procedure calls for a reactor time of 30 min at 130 °C and at 240 °C. In practice these conditions proved to be too harsh, the reaction was completed in less than 1 minute, with pressure and temperature spikes of 180 °C and 15 bar. Due to safety concerns the procedure was therefore altered to include a gentle ramp from 60 to 95 °C over 10-15 min, followed by a 30 min plateau at 95 °C.

A microwave reaction vial (30 mL) equipped with a magnetic stirrer bar was charged with pyridine (4.09 mL, 50.6 mmol, 1.0 eq) and 1-bromobutane (5.54 mL, 51.6 mmol, 1.02 eq). The reaction was conducted in a "Biotage Initiator" microwave reactor. The reaction was heated to 60 °C for 5 min, then raised to 80 °C for 5 min and finally to 95 °C for 30 min. The crude reaction mixture was then let to cool down and was dissolved in acetonitrile (10 mL) and recrystallized from ethyl acetate (40 mL). The solid was filtered, washed with ethyl acetate, dried under vacuum and analysed by ^{1}H NMR. The recrystallisation process was repeated once more in order to remove the impurities. The final product was dried under vacuum and was collected as an off-white powder (7.13 g, 27.3 mmol, 54% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.92 (t, *J* = 7.3 Hz, 3H, N-CH_2-CH_2-CH_2-**CH_3**), 1.30 (h, *J* = 7.4 Hz, 2H, N-CH_2-CH_2-**CH_2**-CH_3), 1.91 (p, *J* = 7.6 Hz, 2H, N-CH_2-**CH_2**-CH_2-CH_3), 4.63 (t, *J* = 7.4 Hz, 2H, N-**CH_2**-CH_2-CH_2-CH_3), 8.18 (t, *J* = 6.9 Hz, 2H, py-HC3/HC5), 8.67 – 8.58 (m, 1H, py-HC4), 9.13 (d, *J* = 5.9 Hz, 2H, py-HC2/HC6).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 13.81 (N-CH_2-CH_2-CH_2-**CH_3**) 19.23 (N-CH_2-CH_2-**CH_2**-CH_3), 33.14 (N-CH_2-**CH_2**-CH_2-CH_3), 60.98 (N-**CH_2**-CH_2-CH_2-CH_3), 128.57 (py-C3/C5), 145.24 (py-C4), 145.96 (py-C2/C6).

HRMS, ESI$^+$: m/z found 136.1125, calc. 136.1121 ($C_9H_{14}N^+$)

MS, ESI^-: 78.9, 80.9 (Br^-)

Elemental analysis (calculated): C- 50.30(50.02), H- 6.49(6.53), N- 6.13(6.48)

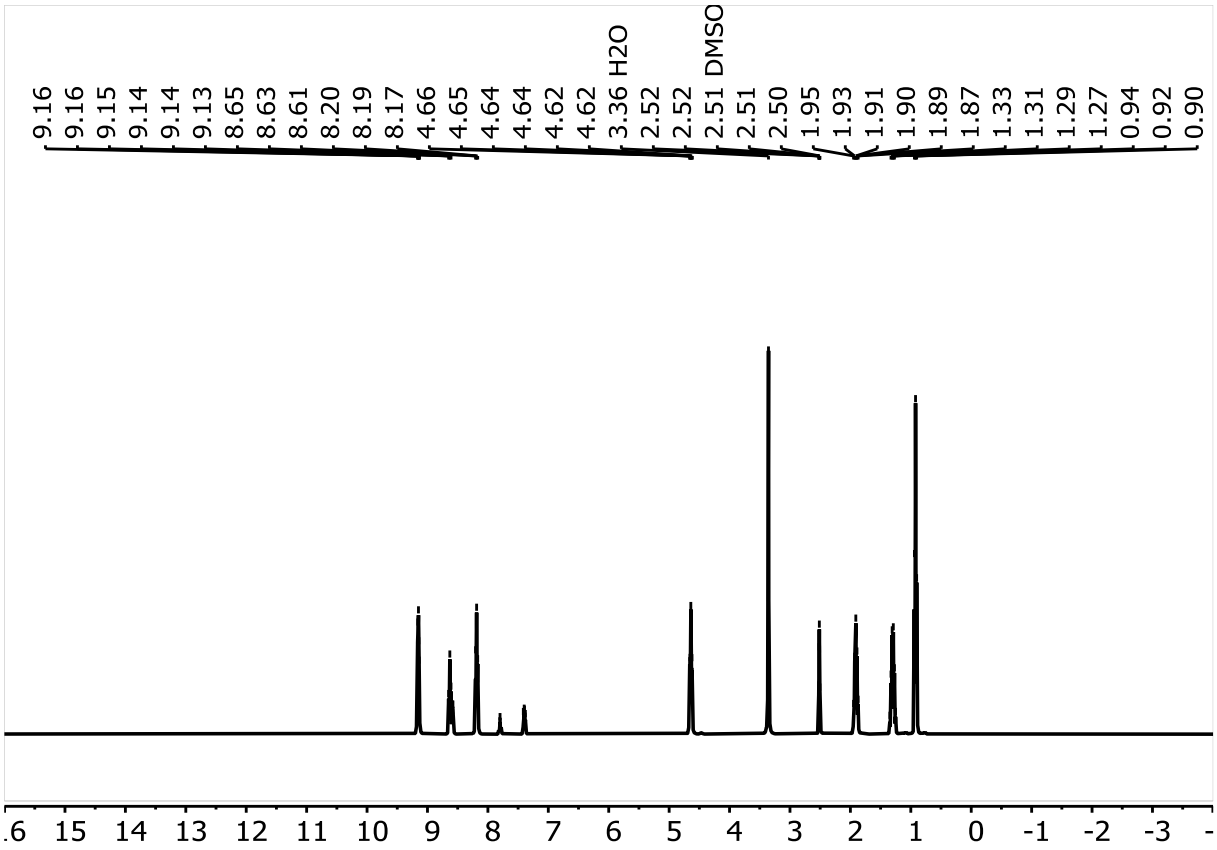


Figure S52. ^1H NMR of crude reaction mixture. Unreacted pyridine still exists in the system.

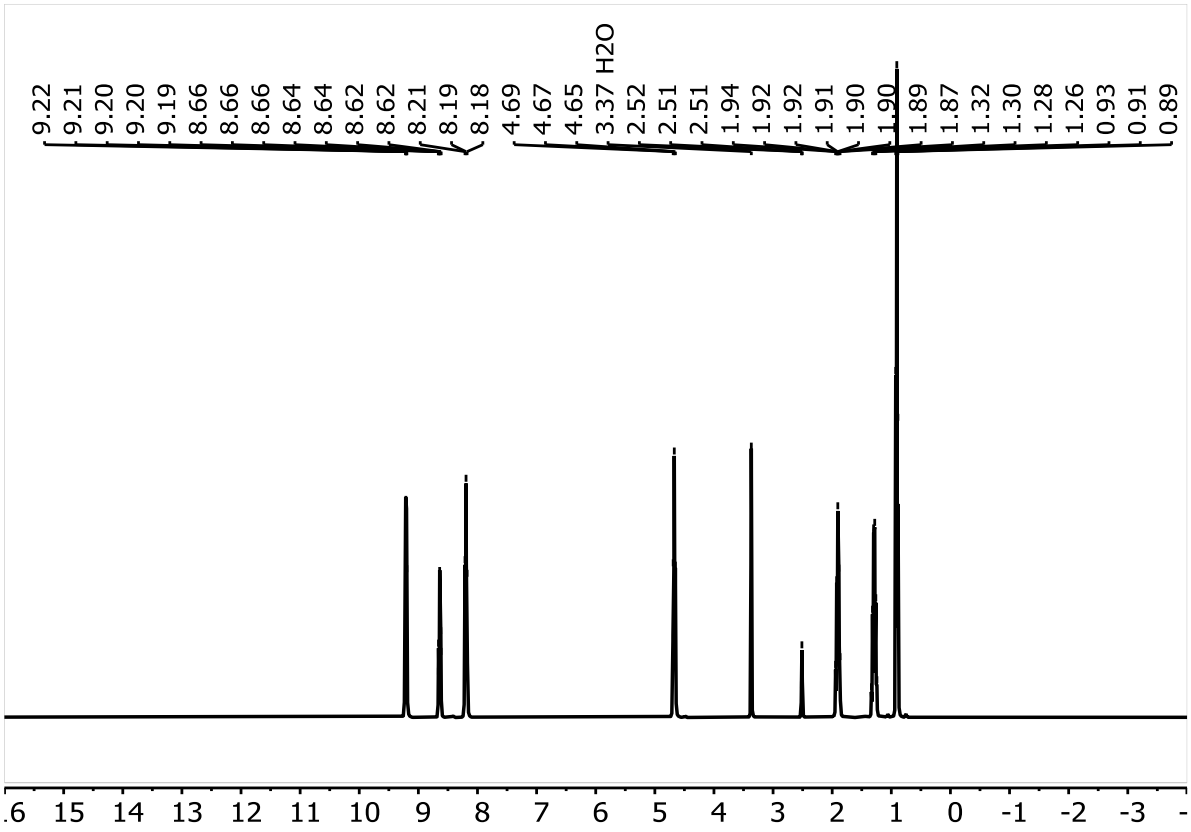


Figure S53. ^{1}H NMR of [C_4Py]Br after the first recrystallisation.

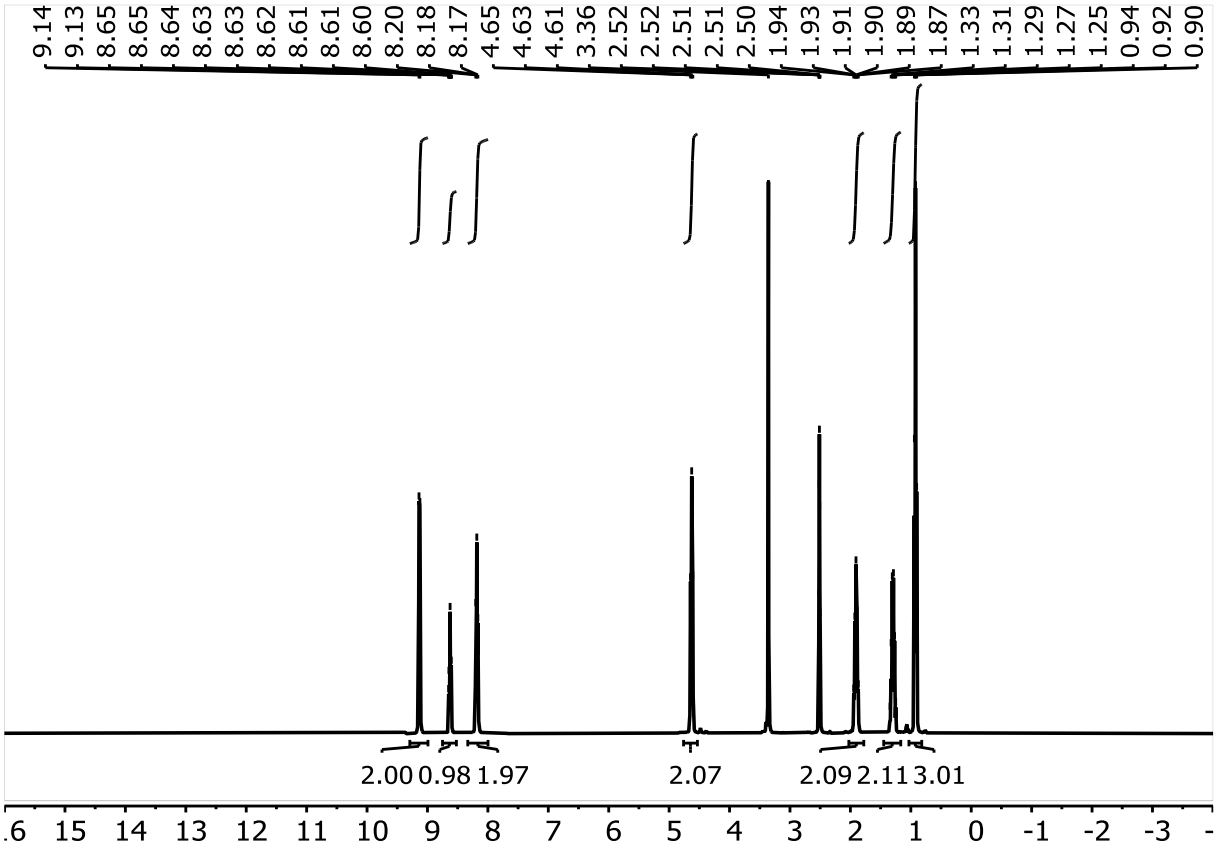


Figure S54. ^{1}H NMR of [C_4Py]Br after the second recrystallisation.

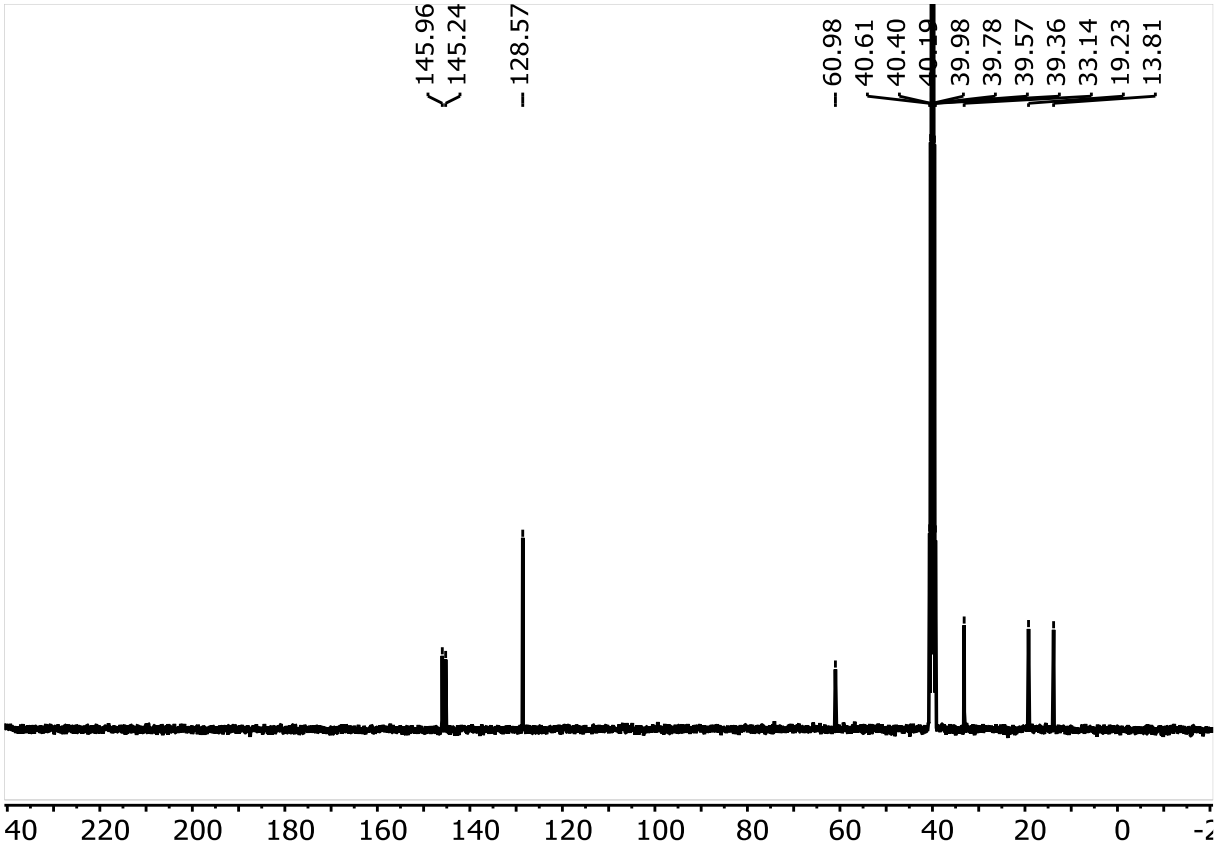


Figure S55. ^{13}C NMR of $[C_4Py]Br$ after the second recrystallisation.

Pictures

Figure S56. Thick-walled vial with sealed cap, suitable for the microwave reactor.

Figure S57. Vial containing crude reaction mixture after 40 min of MW irradiation.

Figure S58. First recrystallisation of [C_4Py]Br.

Figure S59. Second recrystallisation of [C_4Py]Br.

Figure S60. Final product, [C_4Py]Br.

Figure S61. Comparison between the product of controlled (left) and uncontrolled (right) MW-assisted reaction.

Tributylphosphine purification

Starting Materials

Tributylphosphine (97%, mixture of isomers, Sigma 247049, used as received)

Procedure

Under Schlenk conditions / exclusion of oxygen, a distillation kit was charged with ground sodium hydroxide and tributylphosphine. The tributylphosphine was distilled under reduced pressure at a bath temperature of ≈80-90°C.

Characterisation

The NMR spectrum below is a comparison of [P_{444}] before (red) and after (black) the distillation. Before, the purity of the phosphine is about 80%, as determined by (inverse gated decoupled) ^{31}P NMR. Distillation removes all undesired phosphorus species apart from the side chain isomers. Solvent is C_6D_6.

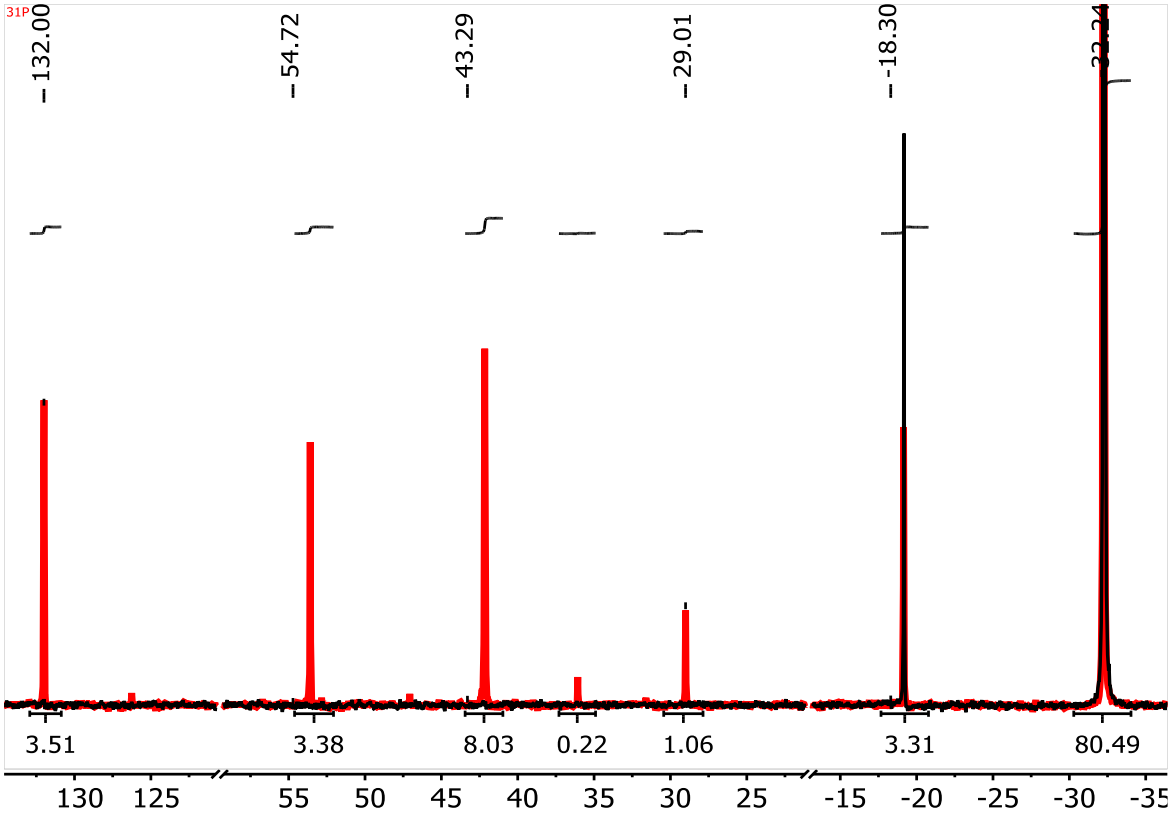


Figure S62. ^{31}P NMR, comparison between the non-purified (red) and purified (black) [P_{444}].

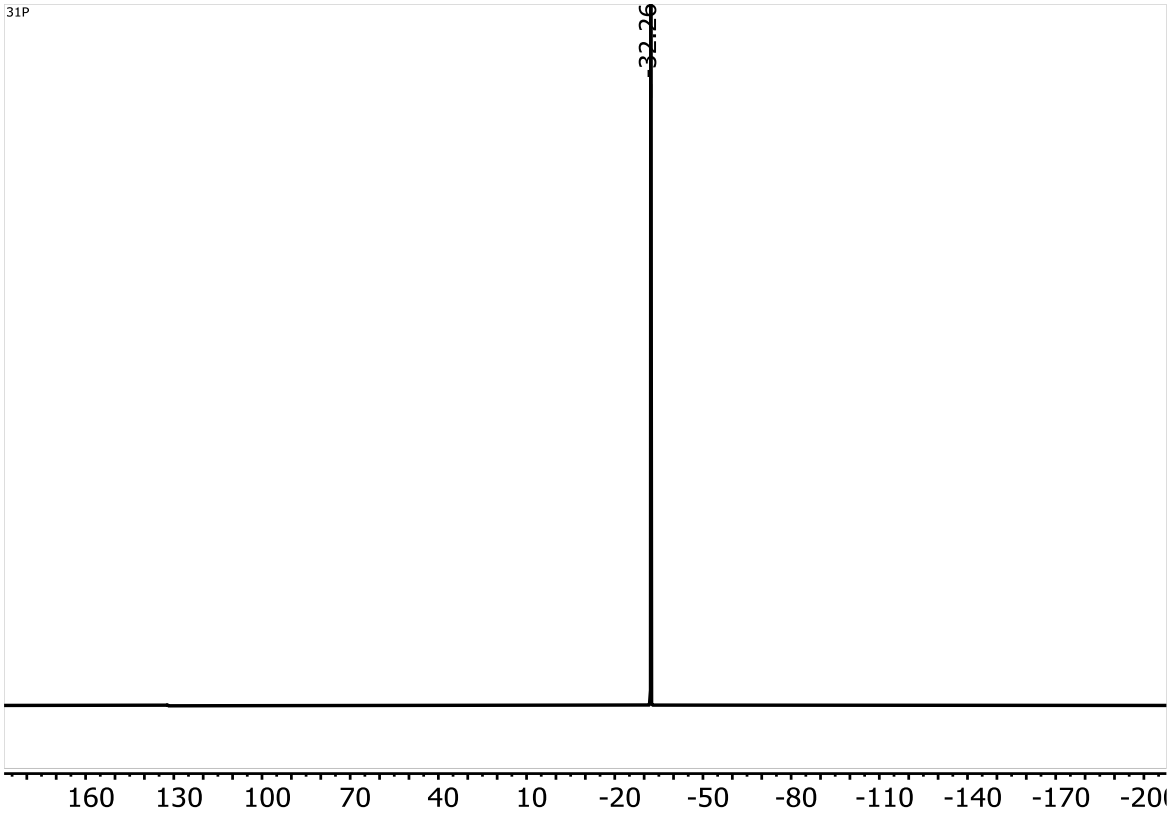


Figure S63. ^{31}P NMR of pure [P_{444}] (99%, commercially available), NMR was prepared in a glovebox, solvent is C_6D_6.

Pictures

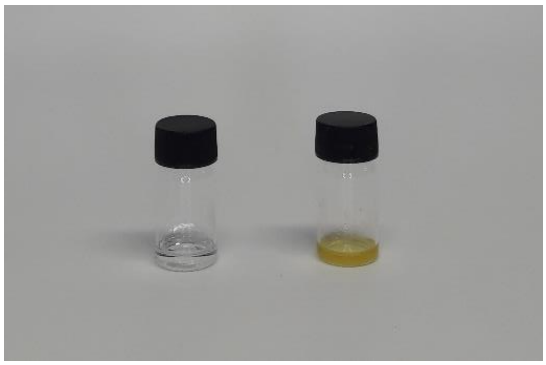
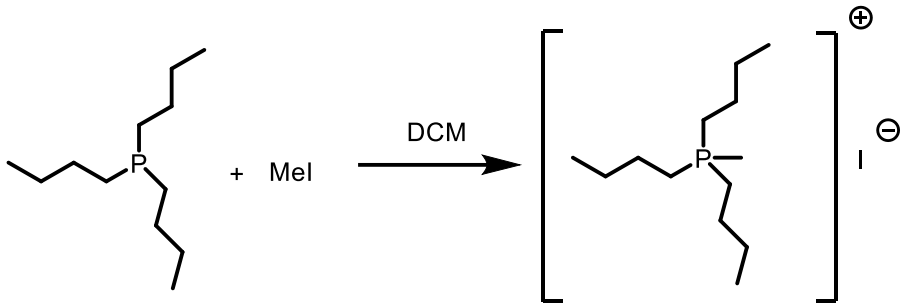


Figure S64. left: tributylphosphine, mixture of isomers, as received. Right: residue after distillation.

Tributylmethylphosphonium iodide [P_{4441}]I

Alkylation in DCM

Route adapted from Philippi et al.[14] We also direct the readers to the work of Bradaric et al.[15]



Starting materials

Iodomethane (purum ≥99.0%) was obtained from Sigma-Aldrich and was purified as described below.

Tributylphosphine (99%, single isomer, Sigma 731374) was purified as described in the previous section.

Dichloromethane (GPR Rectapur, stab. with 0.2 % ethanol).

Procedure

30 mL Methyl iodide were washed with 20 mL aqueous $Na_2S_2O_3$ 5% (w/v), 20 mL water, 20 mL aqueous Na_2CO_3 5% (w/v), and again 20 mL water. The Methyl iodide was then stirred over P_4O_{10} and distilled from fresh P_4O_{10} under Schlenk conditions using N_2 as inert gas.

Tributylphosphine (35 mL, 28.7 g, 142.1 mmol, 1.00 eq) was dissolved in 100 mL dichloromethane in a Schlenk flask inside a glovebox. The flask was then transferred to a Schlenk line and cooled to 0°C in an ice bath. Freshly purified methyl iodide (12 mL, 27.4 g, 193.1 mmol, 1.36 eq) was added slowly over 30 min. The reaction mixture was then stirred at room temperature for 3 h, and the solvent removed under reduced pressure. The product tends to form a voluminous solid foam when crystallising on the rotary evaporator. Once this occurs, the product is dried on a Schlenk line, frequently breaking up large pieces of product with a spatula. The desired product was obtained a white powder (47.05 g, 137 mmol, 96%).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.90 (t, $^{3}J_{H-H}$ = 7.1 Hz, 9H, CH_2-C***H₃***), 1.30-1.57 (m, 12H, (C***H₂***)$_2$-CH_3), 1.82 (d, $^{2}J_{H-P}$ = 14.0 Hz, 3H, P-C***H₃***), 2.08-2.32 (m, 6H, P-C***H₂***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 3.34 (d, $^{1}J_{H-P}$ = 51.3 Hz, P-***C***H_3), 13.25 (s, ***C***H_3), 18.96 (d, $^{1}J_{H-P}$ = 49.1 Hz, CH_2-***C***H_3), 22.57 (d, $^{2}J_{H-P}$ = 4.4 Hz, ***C***H_2-CH_2-CH_3), 23.25 (d, $^{3}J_{H-P}$ = 16.0 Hz, CH_2-***C***H_2-CH_3)

^{31}P{^{1}H}-NMR (162.1 MHz, DMSO-d_6): δ / ppm = 32.37 (s).

HRMS, ESI^+: m/z found 217.2077, calc. 217.2085 ($C_{13}H_{30}P^+$).

Elemental analysis (calculated): C- 46.58 (45.36), H- 8.98 (8.78), N- 0 (0)

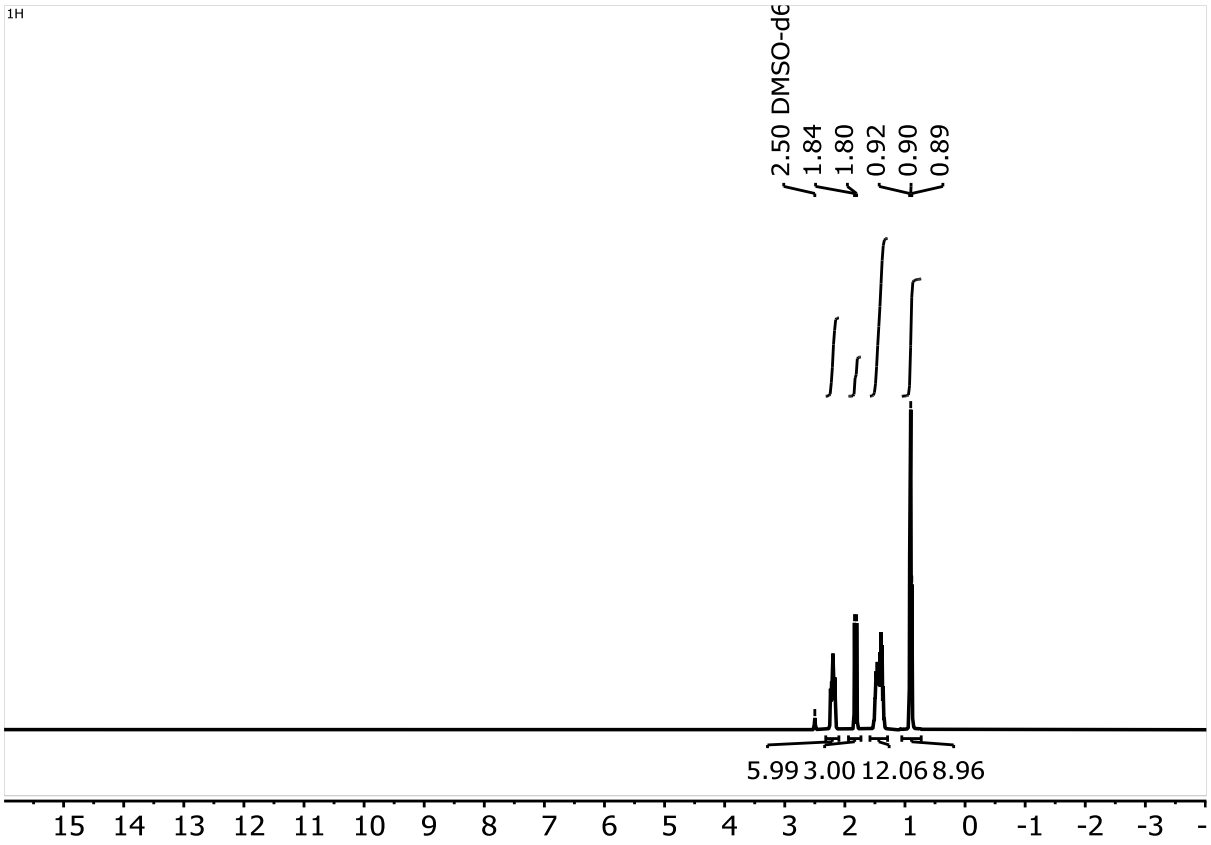


Figure S65. ^{1}H NMR of the purified [P_{4441}]I.

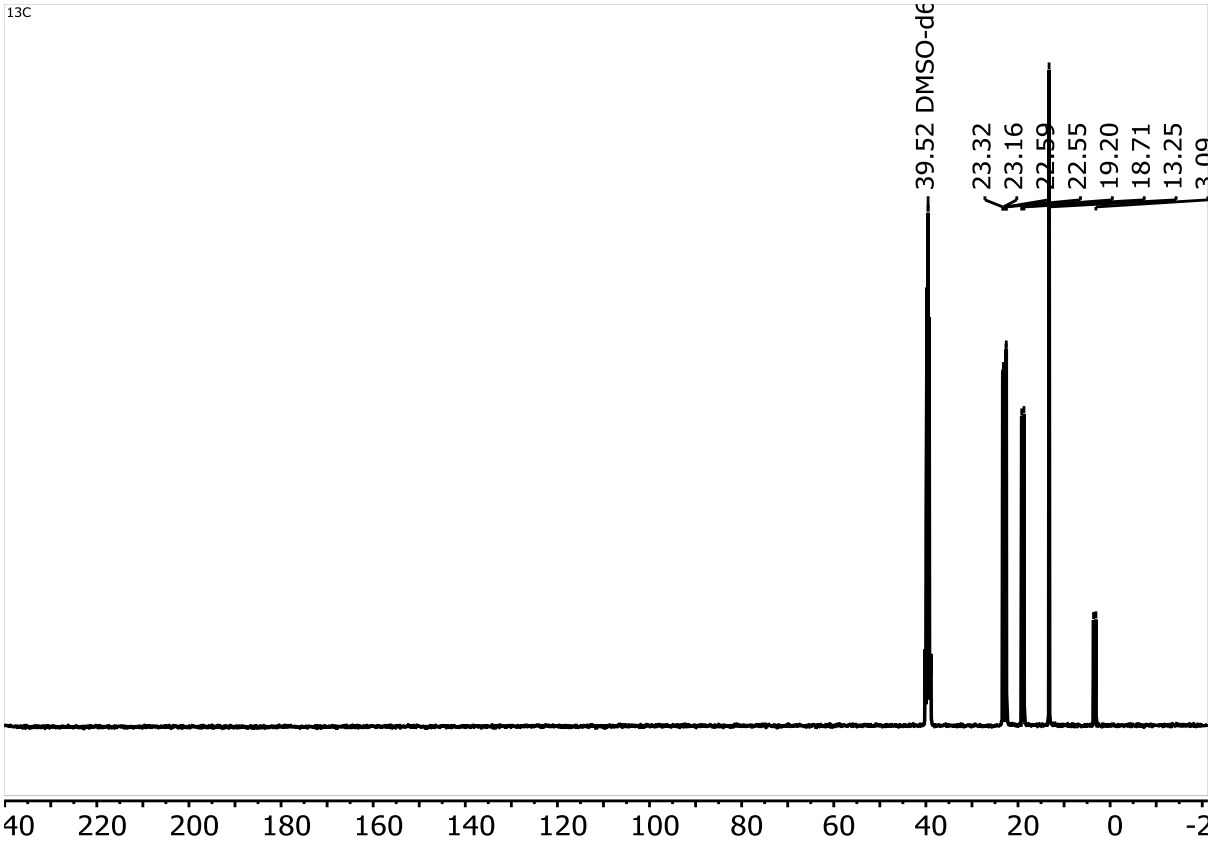


Figure S66. ^{13}C NMR of the purified $[P_{4441}]I$.

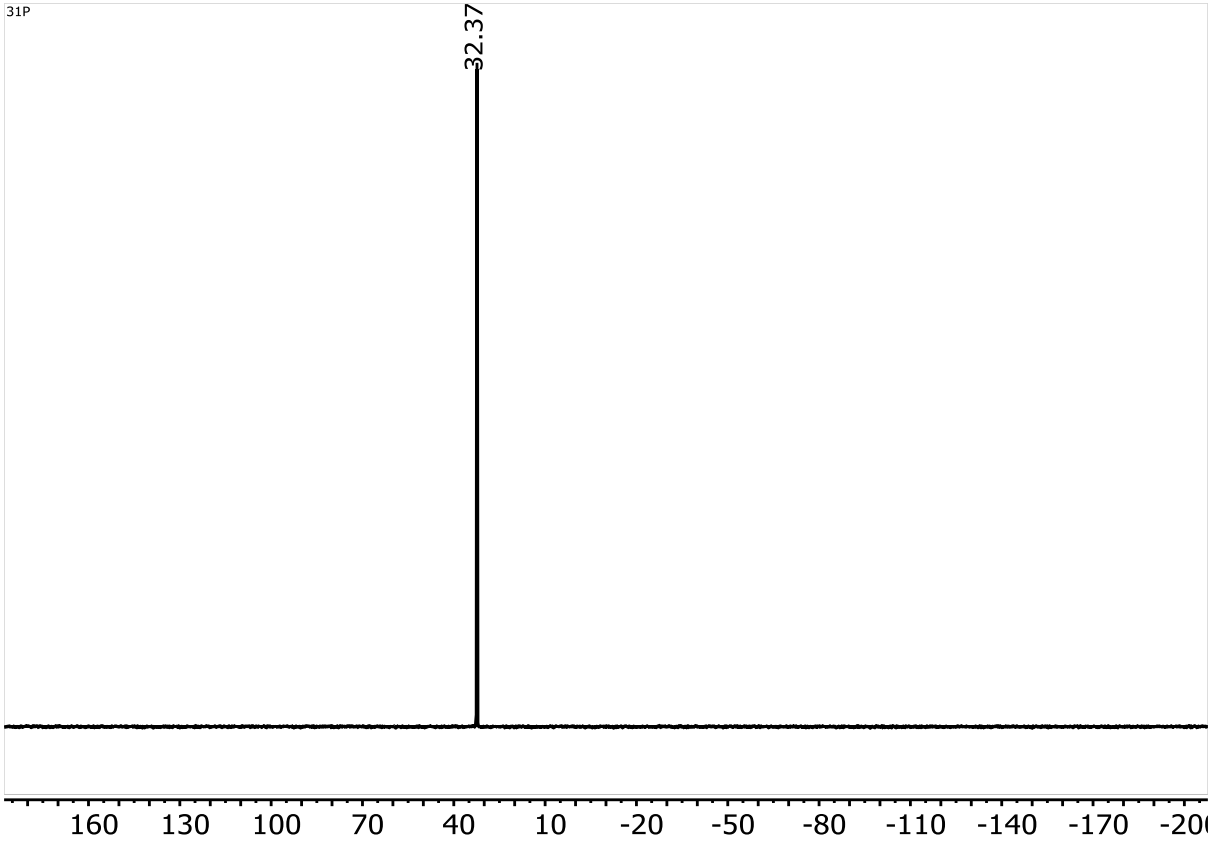


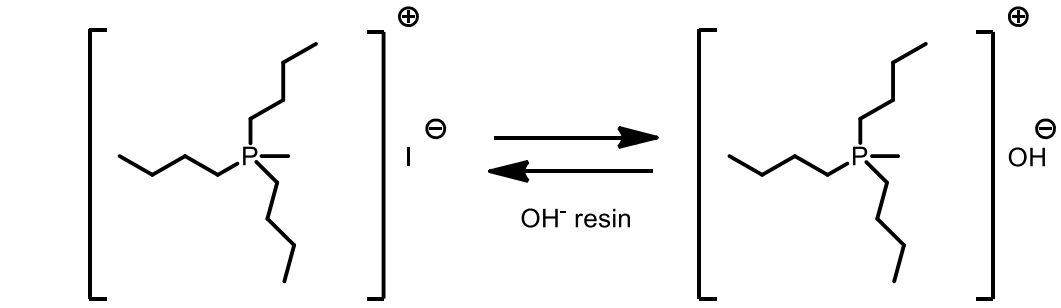
Figure S67. ^{31}P NMR of the purified $[P_{4441}]I$.

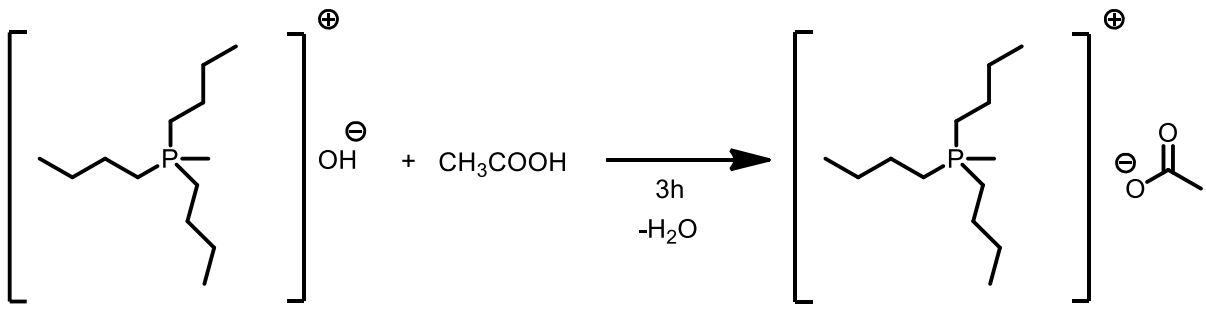
Pictures

Figure S68. Purified final product, $[P_{4441}]I$.

Tributylmethylphosphonium acetate

Ion exchange from halide precursor





Starting Materials

$[P_{4441}]I$ was synthesised and purified as described in the previous section.

Amberlyst™ A26, OH-form, ion-exchange resin was obtained from ACROS Organics. After use, the ion-exchange resin was regenerated by washing with 5% aqueous NaOH solution and then with deionised water until the pH of the eluent is 7.

Acetic acid (CH_3COOH, 99.8%) was purchased from Sigma Aldrich and used without further purification.

Procedure

The procedure was adapted from Clough et al.[16]

A solution of $[P_{4441}]I$ (5.1 g, 14.8 mmol, 1.0 eq) in 20 mL water was slowly passed through a chromatography column packed with Amberlyst™ A26, OH-form. All eluent with pH ≥ 7 (1000 mL), containing $[P_{4441}][OH]$, was collected. To this, acetic acid (0.85 mL, 14.8 mmol, 1.0 eq) was added dropwise and the mixture was stirred for 2 hours. The resulting aqueous ionic liquid of $[P_{4441}][OAc]$ was dried under vacuum to yield a colourless viscous liquid (2.86 g, 10.3 mmol, 69%).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.91 (t, $^3J_{H-H}$ = 7.0 Hz, 9H, CH_2-C***H*****$_3$**), 1.33-1.50 (m, 12H, (C***H*****$_2$**)$_2$-CH_3), 1.53 (s, 3H, C***H*****$_3$**COO^-), 1.79 (d, $^2J_{H-P}$ = 14.0 Hz, 3H, P-C***H*****$_3$**), 2.10-2.22 (m, 6H, P-C***H*****$_2$**)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 3.13 (d, $^1J_{H-P}$ = 51.4 Hz, P-***C***H_3), 13.31 (s, ***C***H_3), 18.90 (d, $^1J_{H-P}$ = 49.2 Hz, CH_2-***C***H_3), 22.60 (d, $^2J_{H-P}$ = 4.4 Hz, ***C***H_2-CH_2-CH_3), 23.33 (d, $^3J_{H-P}$ = 16.0 Hz, CH_2-***C***H_2-CH_3), 25.92 (s, ***C***H_3COO^-), 172.47 (s, CH_3***C***OO^-)

^{31}P{^{1}H}-NMR (162.1 MHz, DMSO-d_6): δ / ppm = 32.42 (s).

HRMS, ESI^+: m/z found 217.2088, calc. 217.2085 ($C_{13}H_{30}P^+$).

MS, ESI^-: 58.9 ($[CH_3COO]^-$)

Elemental analysis (calculated): C- 62.07 (65.18), H- 12.13 (12.03), N- (0)

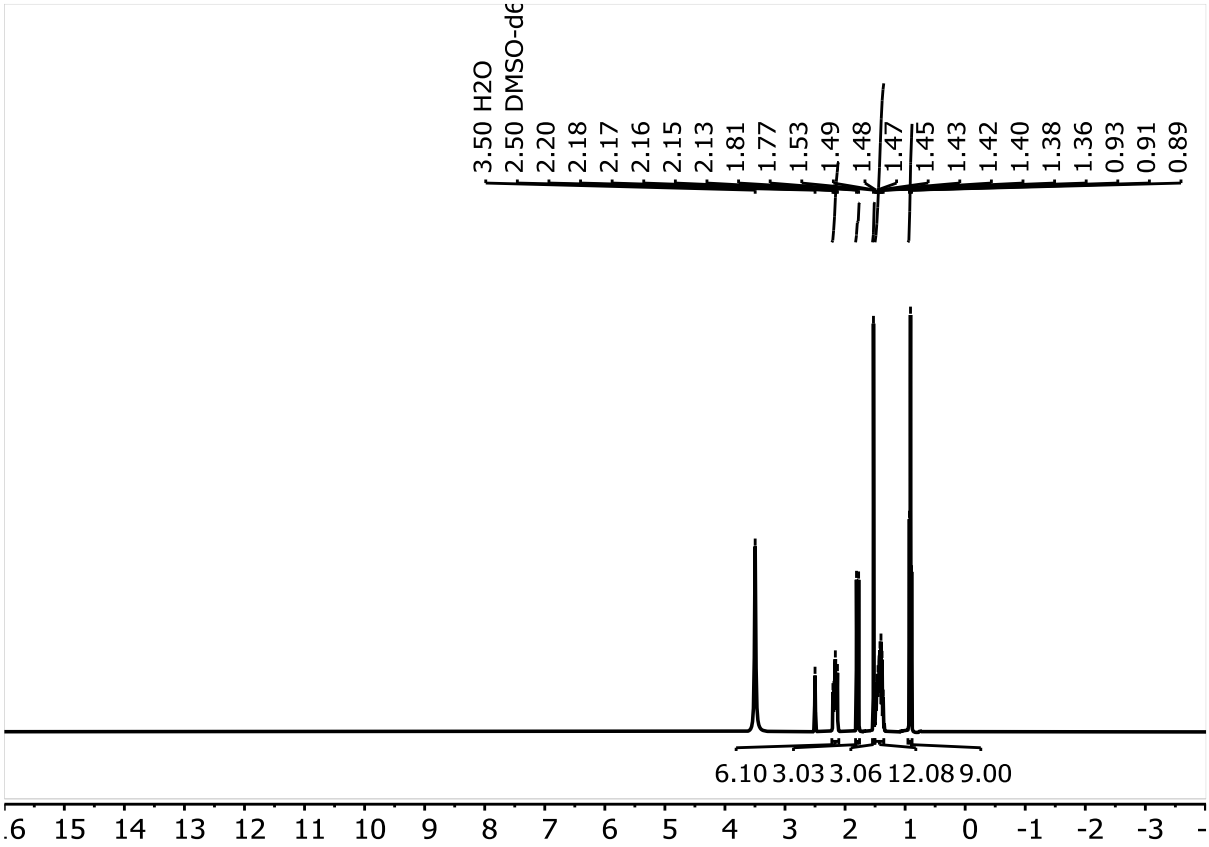


Figure S69. ^{1}H NMR of dried [P_{4441}][OAc] (ion exchange route).

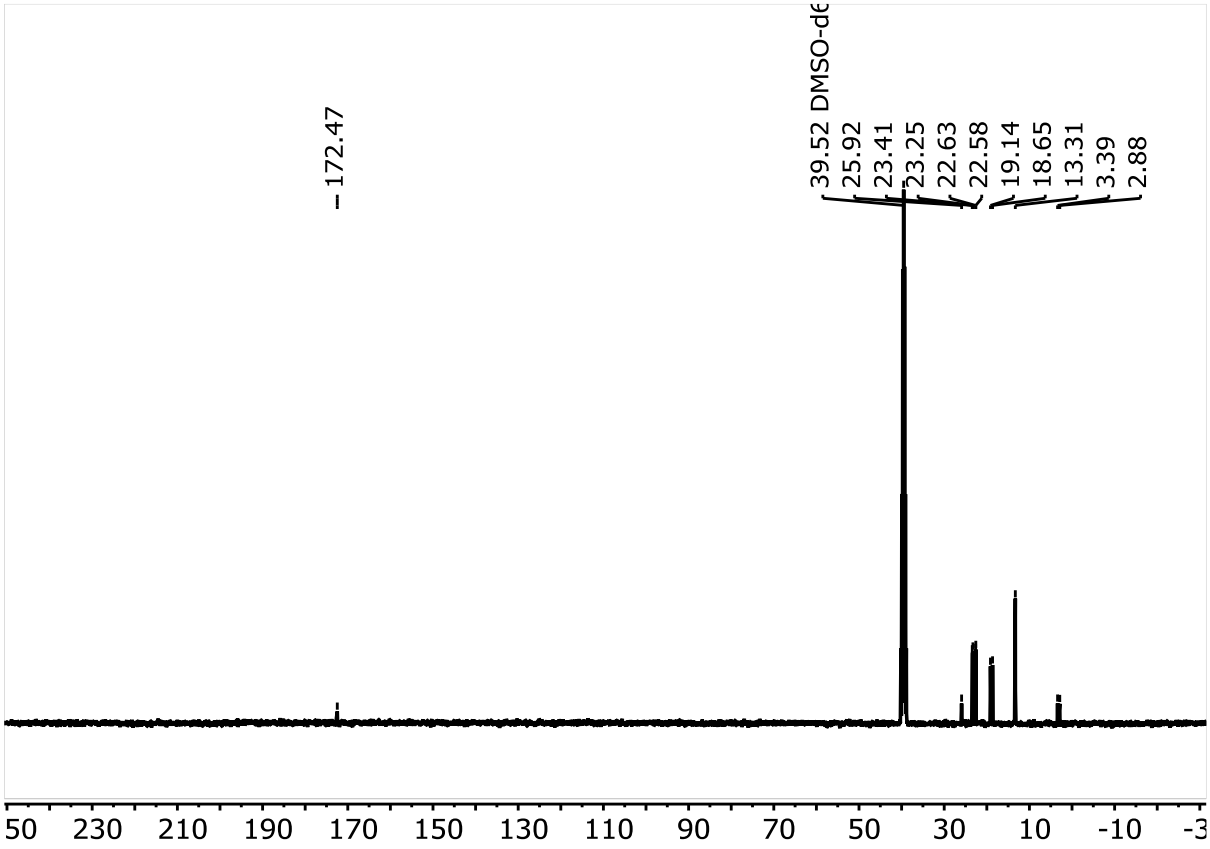


Figure S70. ^{13}C NMR of dried [P_{4441}][OAc] (ion exchange route).

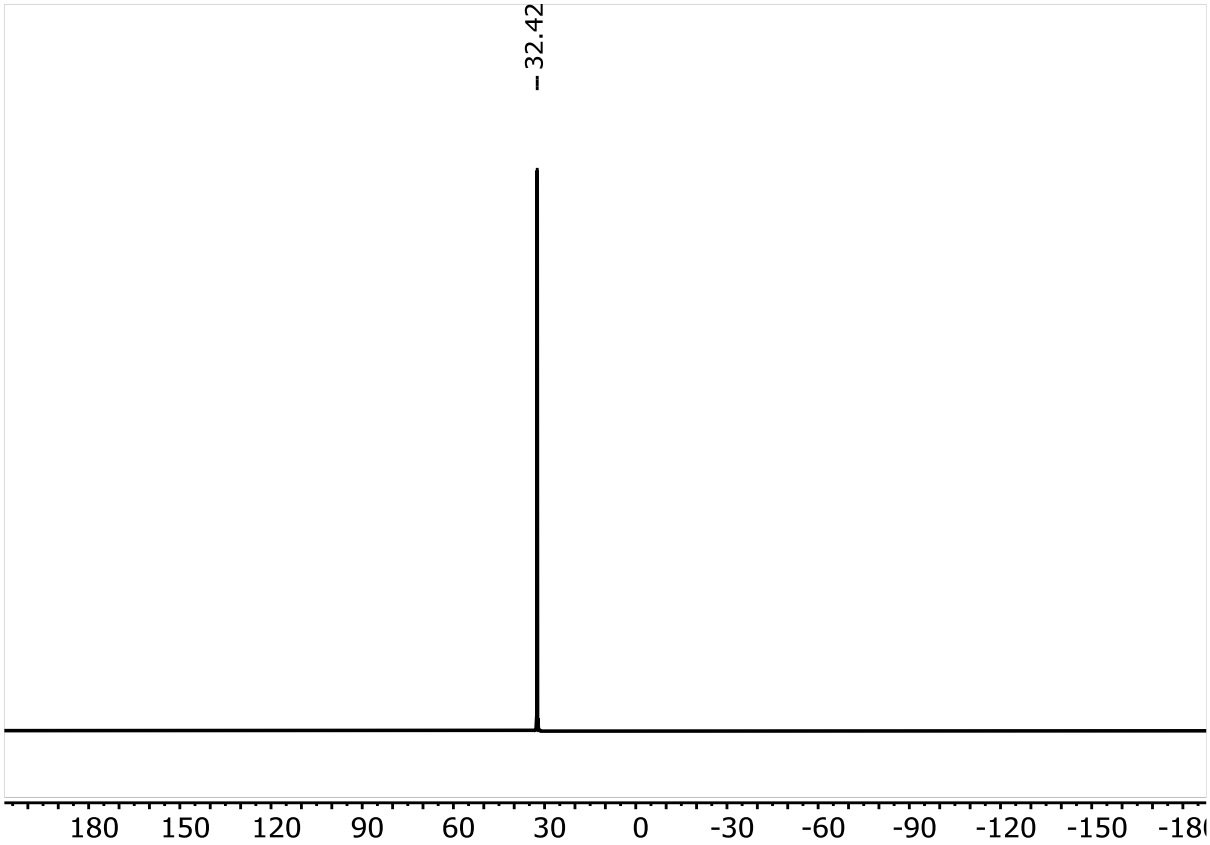


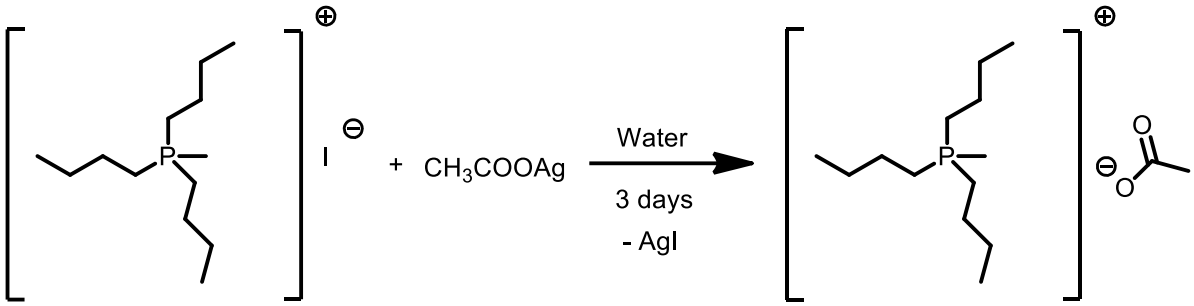
Figure S71. ^{31}P NMR of dried $[P_{4441}][OAc]$ (ion exchange route).

Pictures

Figure S72. Aqueous eluent of the ion-exchange chromatography column containing $[P_{4441}][OAc]$.

Figure S73. Final purified and dried [P_{4441}][OAc].

Metathesis with silver(I) acetate



Starting Materials

[P_{4441}]I was synthesised and purified as described in the previous section.

CH_3I (≥99.0%) was obtained from Sigma-Aldrich and used without further purification.

Silver(I) acetate (CH_3CO_2Ag) was purchased from Fluorochem and used without further purification.

Procedure

The procedure was adapted from Clough et al.[16]

CH_3CO_2Ag (2.48 g, 14.8 mmol, 1.0 eq) was dissolved in 20 mL of water and was added dropwise to a solution of [P_{4441}]I (5.12 g, 14.8 mmol, 1.0 eq) in 20 mL water. The reaction mixture was left stirring in the dark for 3 days. The bright yellow precipitate of AgI was filtered and aqueous ionic liquid was collected. The aqueous solution was tested for residual halides with 0.3 M $AgNO_3$ in 1 M HNO_3 and for residual silver ions with 1 M HCl. Both tests were negative, showing complete consumption of the starting materials. The resulting aqueous ionic liquid of [P_{4441}][OAc] was dried under vacuum giving a colourless viscous liquid (2.78 g, 10.1 mmol, 68% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.91 (t, $^3J_{H\text{-}H}$ = 7.1 Hz, 9H, CH_2-C***H₃***), 1.32-1.53 (m, 12H, (C***H₂***)$_2$-CH_3), 1.48 (s, 3H, C***H***$_3COO^-$), 1.80 (d, $^2J_{H\text{-}P}$ = 14.0 Hz, 3H, P-C***H₃***), 2.11-2.24 (m, 6H, P-C***H₂***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 3.12 (d, $^1J_{H\text{-}P}$ = 51.6 Hz, P-***C***H_3), 13.29 (s, ***C***H_3), 18.88 (d, $^1J_{H\text{-}P}$ = 49.1 Hz, CH_2-***C***H_3), 22.61 (d, $^2J_{H\text{-}P}$ = 4.4 Hz, ***C***H_2-CH_2-CH_3), 23.34 (d, $^3J_{H\text{-}P}$ = 15.9 Hz, CH_2-***C***H_2-CH_3), 26.37 (s, ***C***H_3COO^-), 172.21 (s, CH_3***C***OO^-)

$^{31}P\{^{1}H\}$-NMR (162.1 MHz, DMSO-d_6): δ / ppm = 32.45 (s).

HRMS, ESI^+: m/z found 217.2088, calc. 217.2085 ($C_{13}H_{30}P^+$).

MS, ESI^-: 58.9 ($[CH_3COO]^-$)

Elemental analysis (calculated): C- 63.13 (65.18), H- 11.49 (12.03), N- 0.12 (0)

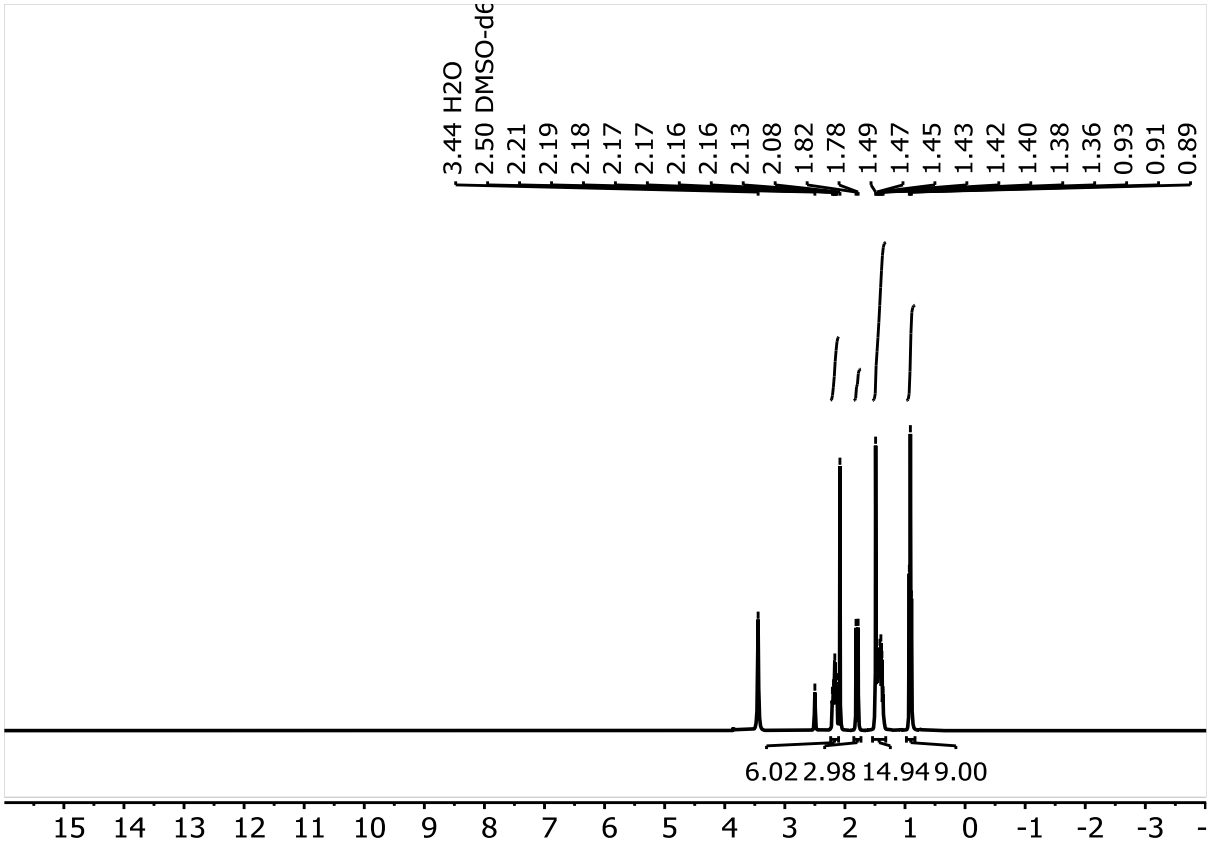


Figure S74. ^{1}H NMR of dried $[P_{4441}][OAc]$ (metathesis with silver acetate route).

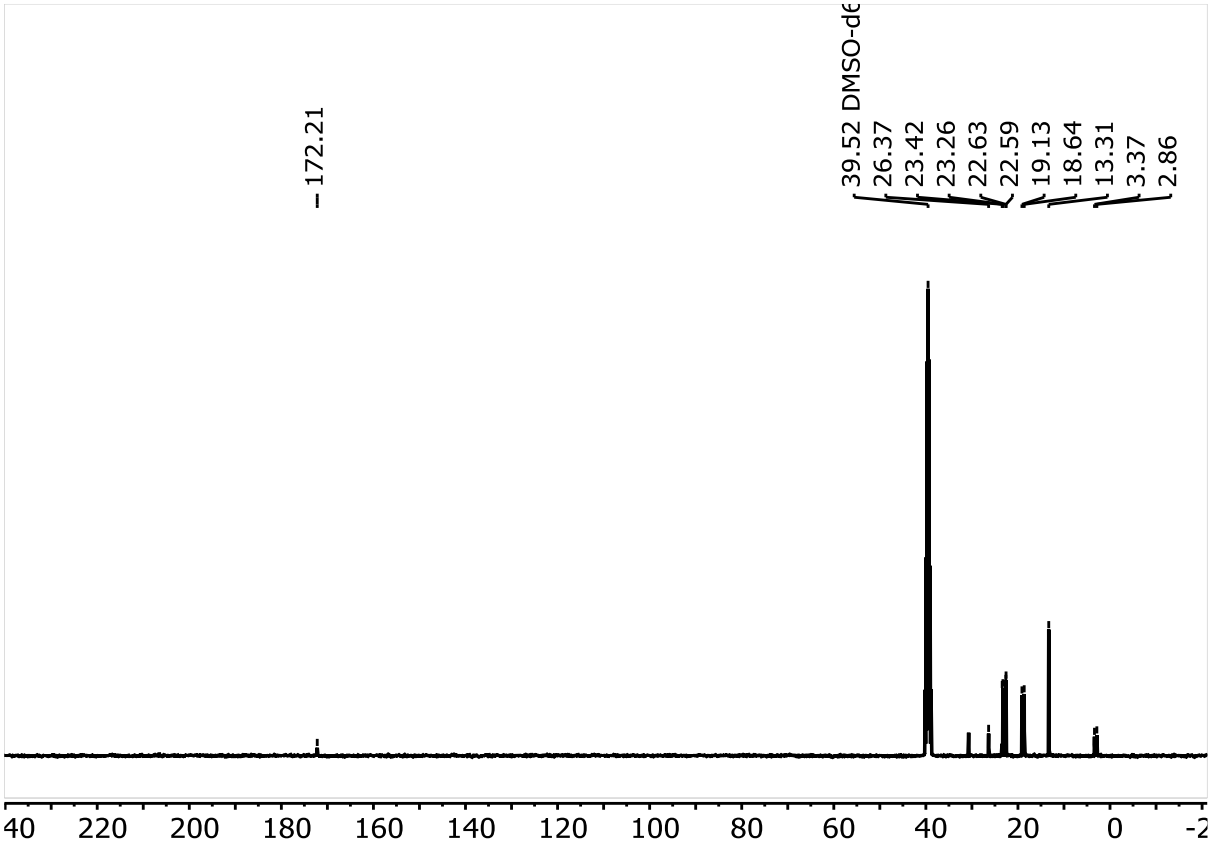


Figure S75. ^{13}C NMR of dried $[P_{4441}][OAc]$ (metathesis with silver acetate route).

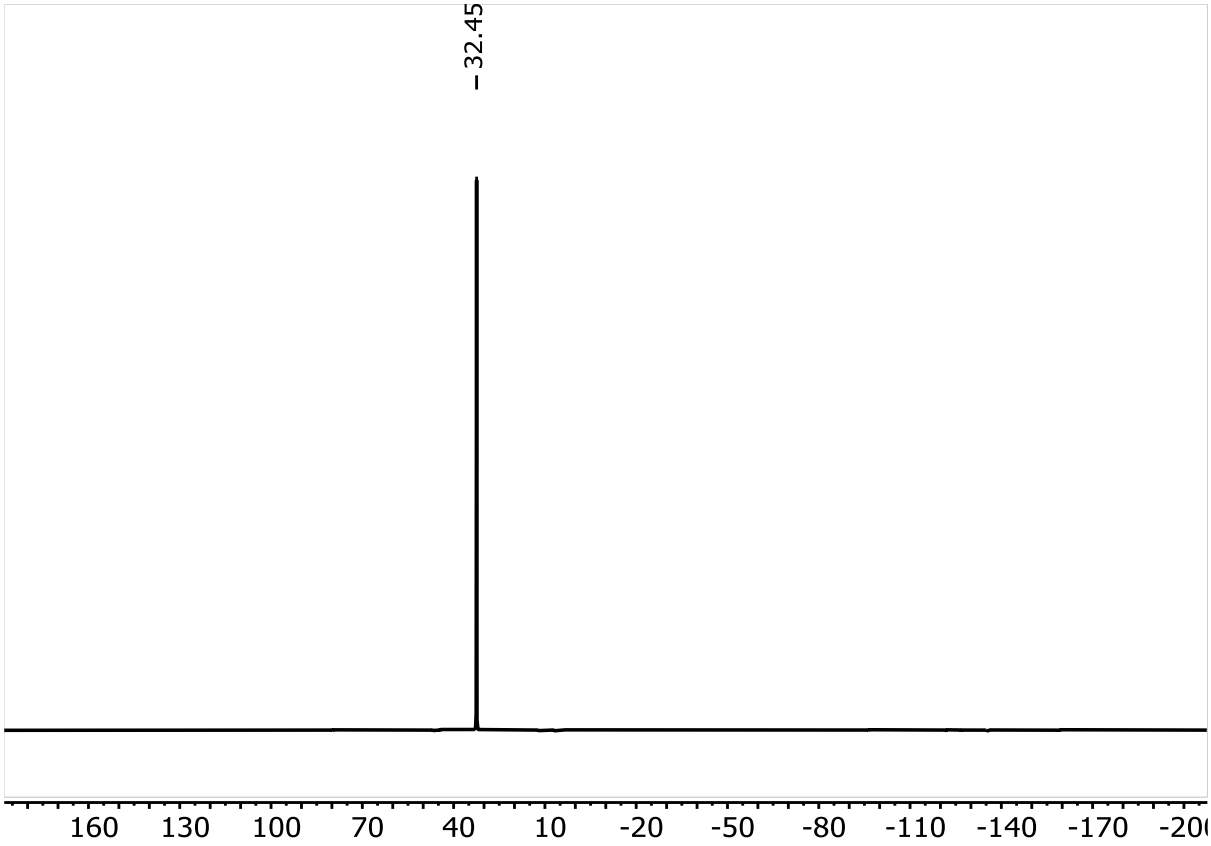


Figure S76. ^{31}P NMR of dried $[P_{4441}][OAc]$ (metathesis with silver acetate route).

Pictures

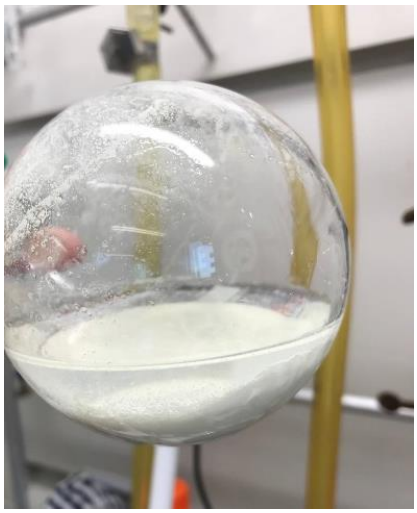


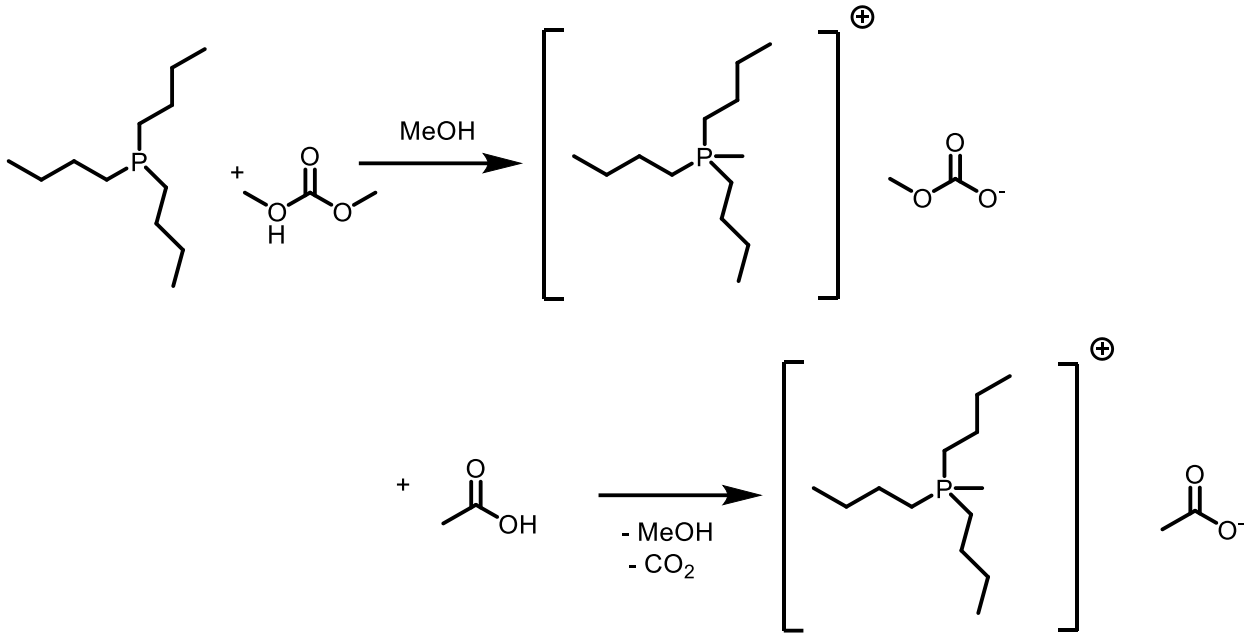
Figure S77. $[P_{4441}][OAc]$ aqueous solution with silver(I) iodide precipitate.

Figure S78. Final purified and dried $[P_{4441}][OAc]$.

Methyl carbonate route – mixture of isomers

The methyl carbonate route was repeated twice, with different purities of tributylphosphine. The first time we use tributylphosphine which is commercially bought as a mixture of isomers (lower price), while the "clean phosphine" has a purity of 99%+ (significantly higher price).

For a general procedure towards phosphonium methylcarbonates and the neutralisation, see the work of Selva et al,[17] as well as the works of Kalb et al.[18, 19]



Starting Materials

Dimethyl carbonate (anhydrous >99% sigma)

Methanol (99.8%, anhydrous)

Tributylphosphine (mixture of isomers, freshly distilled from sodium hydroxide)

Procedure

Inside a glovebox, a 20 mL pressure tube (Ace Glass, Vineland, USA) with silicone seal (Ace Glass, Vineland, USA) was charged with tributylphosphine (5 mL, 4.11 g, 20.3 mmol, 1.00 eq), dimethyl carbonate (3 mL, 3.22 g, 35.8 mmol, 1.76 eq) and 5 mL methanol. The pressure tube was then immersed in an oil bath and heated to 111 °C for 44 h. After cooling to room temperature, glacial acetic acid (1.22 g, 20.3 mmol, 1.00 eq) was added and the resulting mixture stirred for 30 min. The solvent was removed under reduced pressure and the product dried under high vacuum, giving a white powder (5.40 g, 19.5 mmol, 96% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.90 (t, $^{3}J_{H-H}$ = 7.1 Hz, 9H, CH_2-C***H₃***), 1.31-1.53 (m, 12H, (C***H₂***)$_2$-CH_3), 1.49 (s, 3H, C***H***$_3$COO$^-$), 1.83 (d, $^{2}J_{H-P}$ = 14.1 Hz, 3H, P-C***H₃***), 2.12-2.30 (m, 6H, P-C***H₂***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 3.03 (d, $^{1}J_{H-P}$ = 51.3 Hz, P-***C***H_3), 13.29 (s, ***C***H_3), 18.82 (d, $^{1}J_{H-P}$ = 49.2 Hz, CH_2-***C***H_3), 22.63 (d, $^{2}J_{H-P}$ = 4.4 Hz, ***C***H_2-CH_2-CH_3), 23.34 (d, $^{3}J_{H-P}$ = 16.1 Hz, CH_2-***C***H_2-CH_3), 26.33 (s, ***C***H_3COO$^-$), 172.05 (s, CH_3***C***OO$^-$)

^{31}P{^{1}H}-NMR (162.1 MHz, DMSO-d_6): δ / ppm = 32.57 (s), 37.24 (s).

HRMS, ESI$^+$: m/z found 217.2080, calc. 217.2085 ($C_{13}H_{30}P^+$).

Elemental analysis (calculated): C- 62.42 (65.18), H- 11.85 (12.03), N- 0.46 (0)

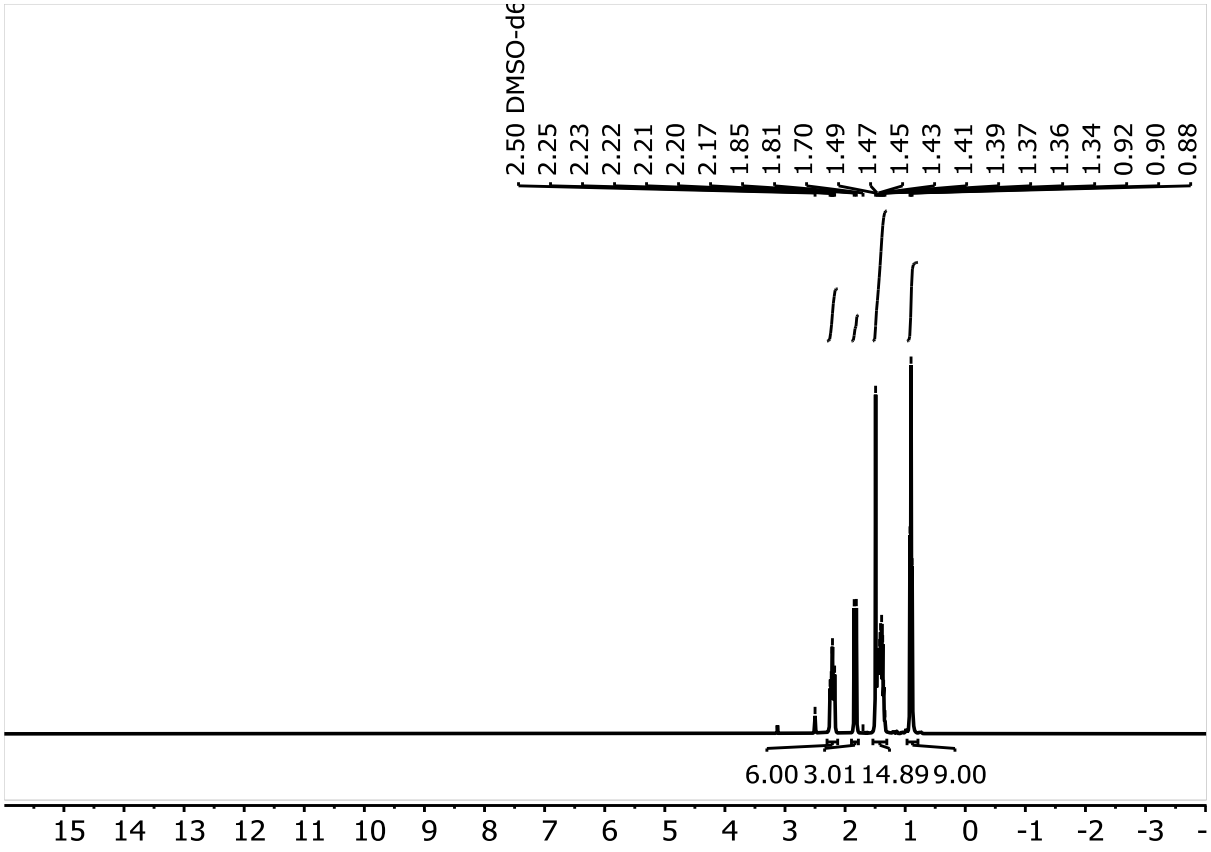


Figure S79. ^{1}H NMR of dried [P_{4441}][OAc] (mixture of phosphine isomers).

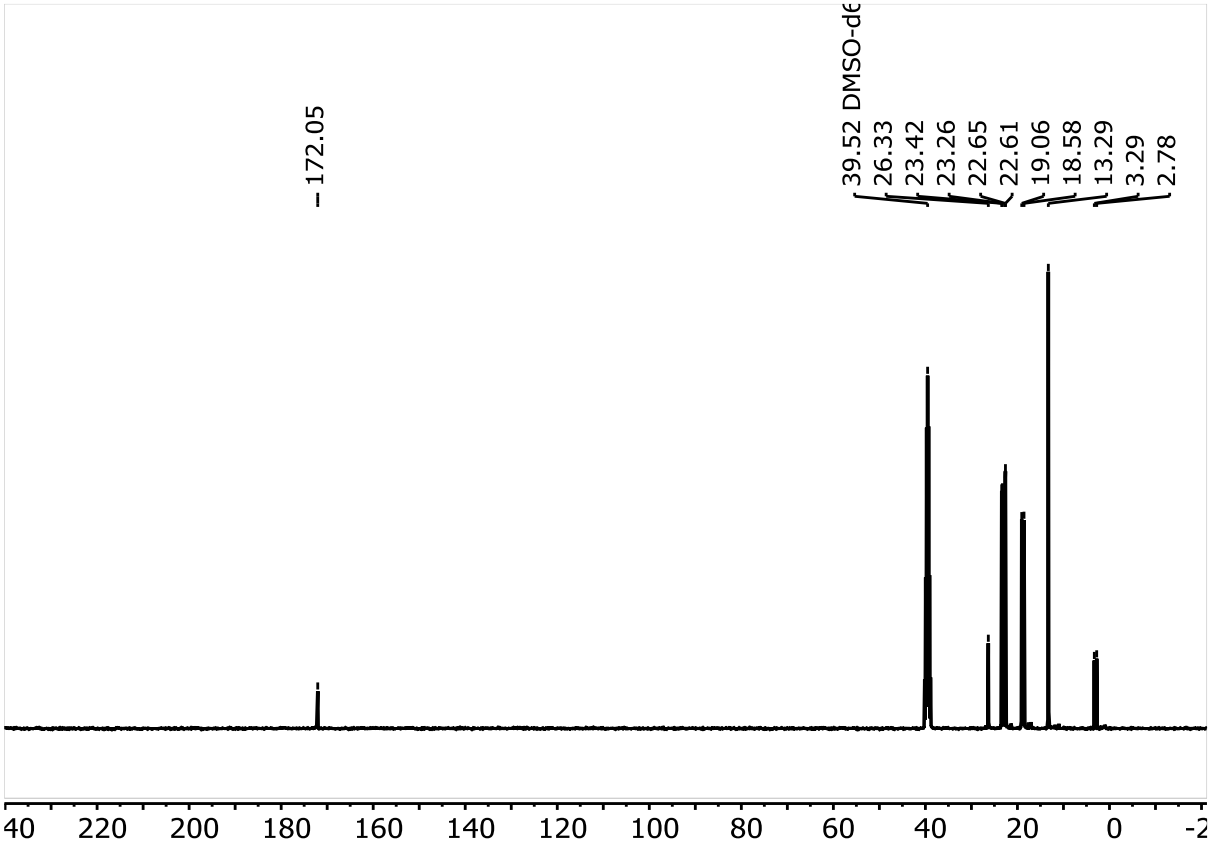


Figure S80. ^{13}C NMR of dried [P_{4441}][OAc] (mixture of phosphine isomers)

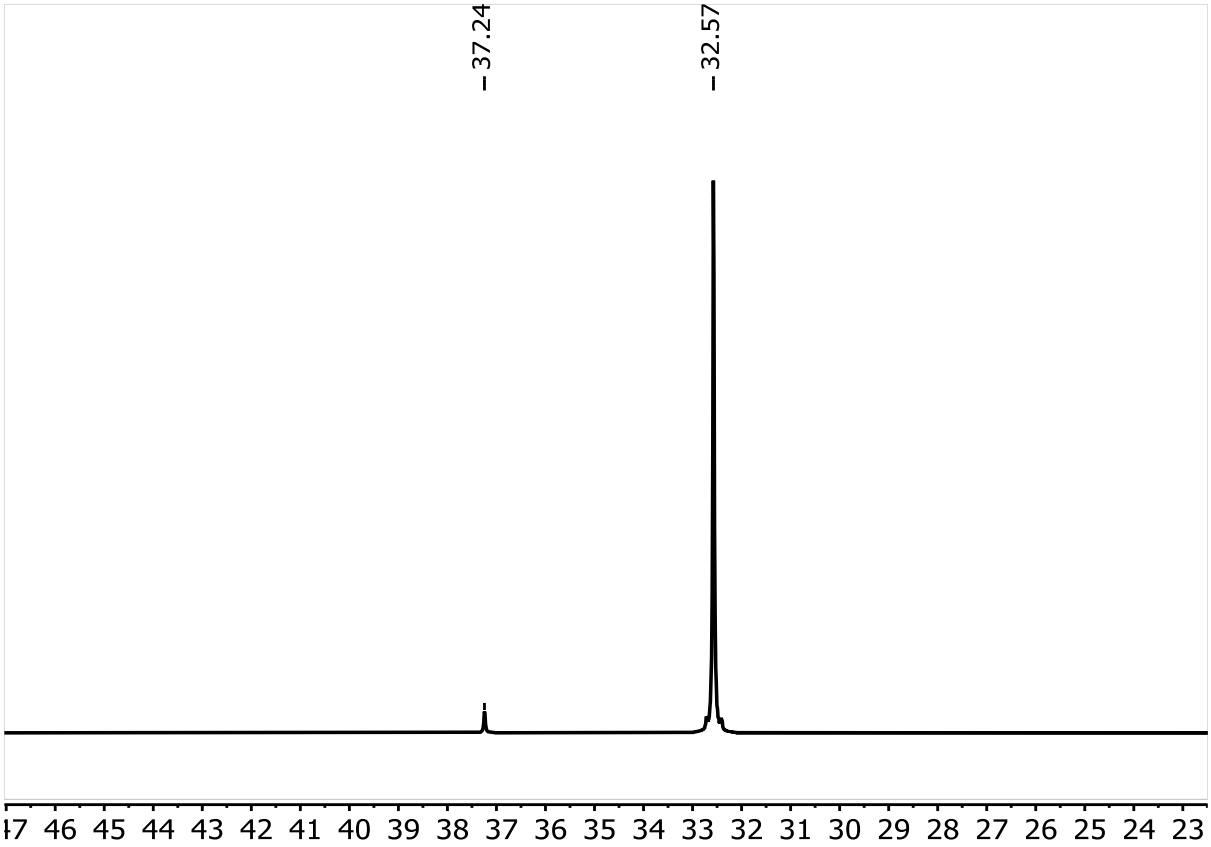


Figure S81. ^{31}P NMR of dried $[P_{4441}][OAc]$ (mixture of phosphine isomers)

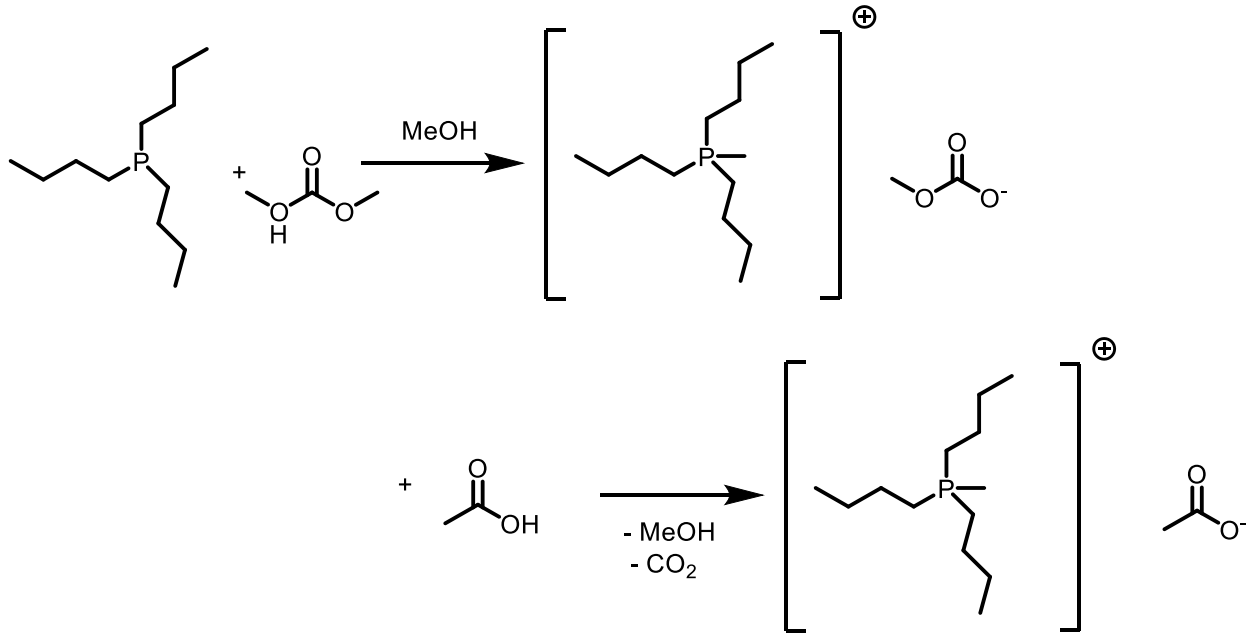
Pictures

Figure S82. Starting mixture of tributylphospine, dimethyl carbonate and methanol.

Figure S83. Reaction mixture after 24 h at 111 °C.

Figure S84. Dried [P_{4441}][OAc] (mixture of phosphine isomers)

Methylcarbonate route – clean Phosphine



Starting Materials

Tributyl phosphine (99%, single isomer, Sigma 731374)

Dimethyl carbonate (anhydrous ≥99% sigma sigma 51712-7)

Methanol (AnalaR Normapur)

Procedure

Inside a glovebox, a 20 mL pressure tube (Ace Glass, Vineland, USA) with silicone seal (Ace Glass, Vineland, USA) was charged with tributylphosphine (with 4.07 g, 20.1 mmol, 1.00 eq), dimethyl carbonate (3.20 g, 35.6 mmol, 1.77 eq) and 5 mL methanol. The pressure tube was then immersed in an oil bath and heated to 111 °C for 40 h. After cooling to room temperature, glacial acetic acid (1.21 g, 20.1 mmol, 1.00 eq) was added and the resulting mixture was stirred for 30 min. The solvent was removed under reduced pressure and the product dried under high vacuum, giving a white powder (5.40 g, 19.5 mmol, 97% yield).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.90 (t, $^{3}J_{H-H}$ = 7.1 Hz, 9H, CH_2-C***H₃***), 1.31-1.53 (m, 12H, (C***H₂***)$_2$-CH_3), 1.48 (s, 3H, C***H***$_3$$COO^-$), 1.83 (d, $^{2}J_{H-P}$ = 14.1 Hz, 3H, P-C***H₃***), 2.12-2.30 (m, 6H, P-C***H₂***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 3.04 (d, $^{1}J_{H-P}$ = 51.4 Hz, P-***C***H_3), 13.29 (s, ***C***H_3), 18.83 (d, $^{1}J_{H-P}$ = 49.3 Hz, CH_2-***C***H_3), 22.63 (d, $^{2}J_{H-P}$ = 4.4 Hz, ***C***H_2-CH_2-CH_3), 23.34 (d, $^{3}J_{H-P}$ = 16.1 Hz, CH_2-***C***H_2-CH_3), 26.48 (s, ***C***H_3COO^-), 171.97 (s, CH_3***C***OO^-)

^{31}P{^{1}H}-NMR (162.1 MHz, DMSO-d_6): δ / ppm = 32.57 (s).

HRMS, ESI^+: m/z found 217.2088, calc. 217.2085 ($C_{13}H_{30}P^+$).

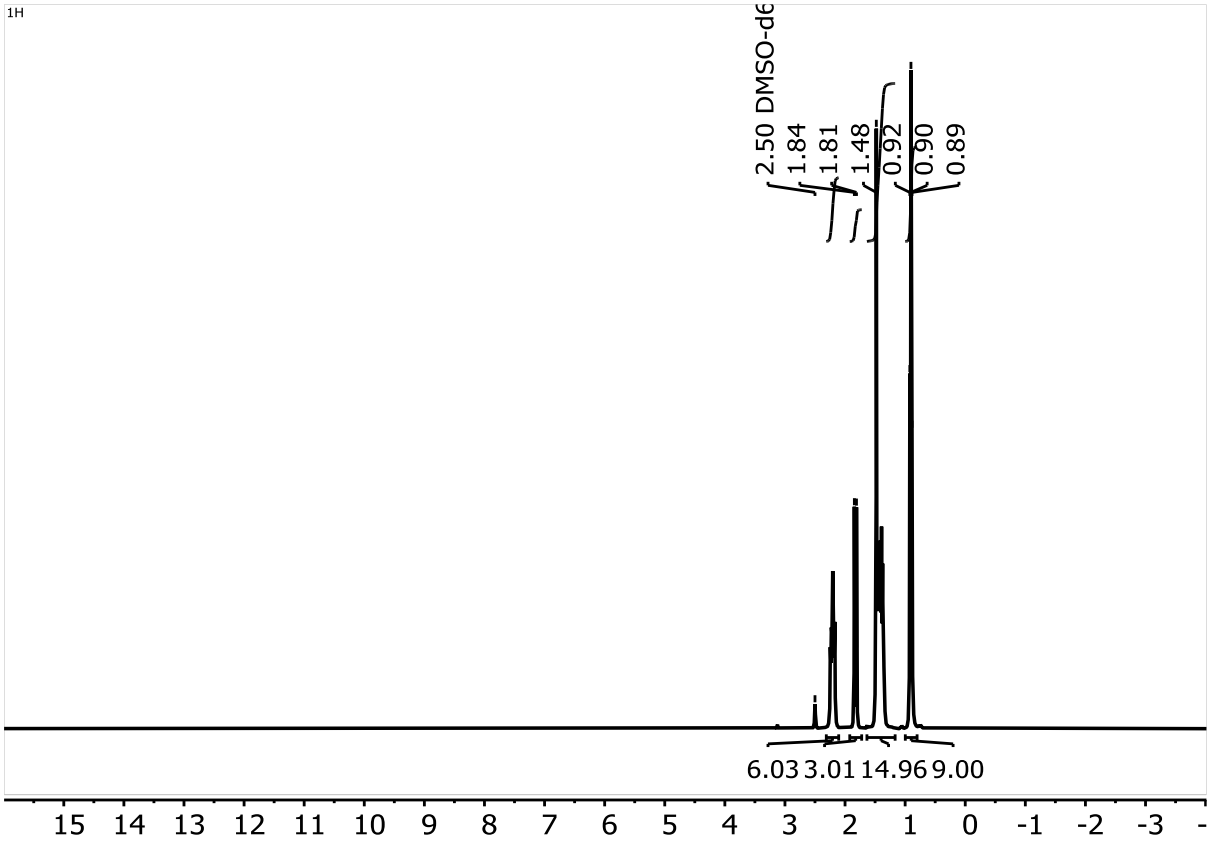


Figure S85. ^{1}H NMR of dried [P_{4441}][OAc].

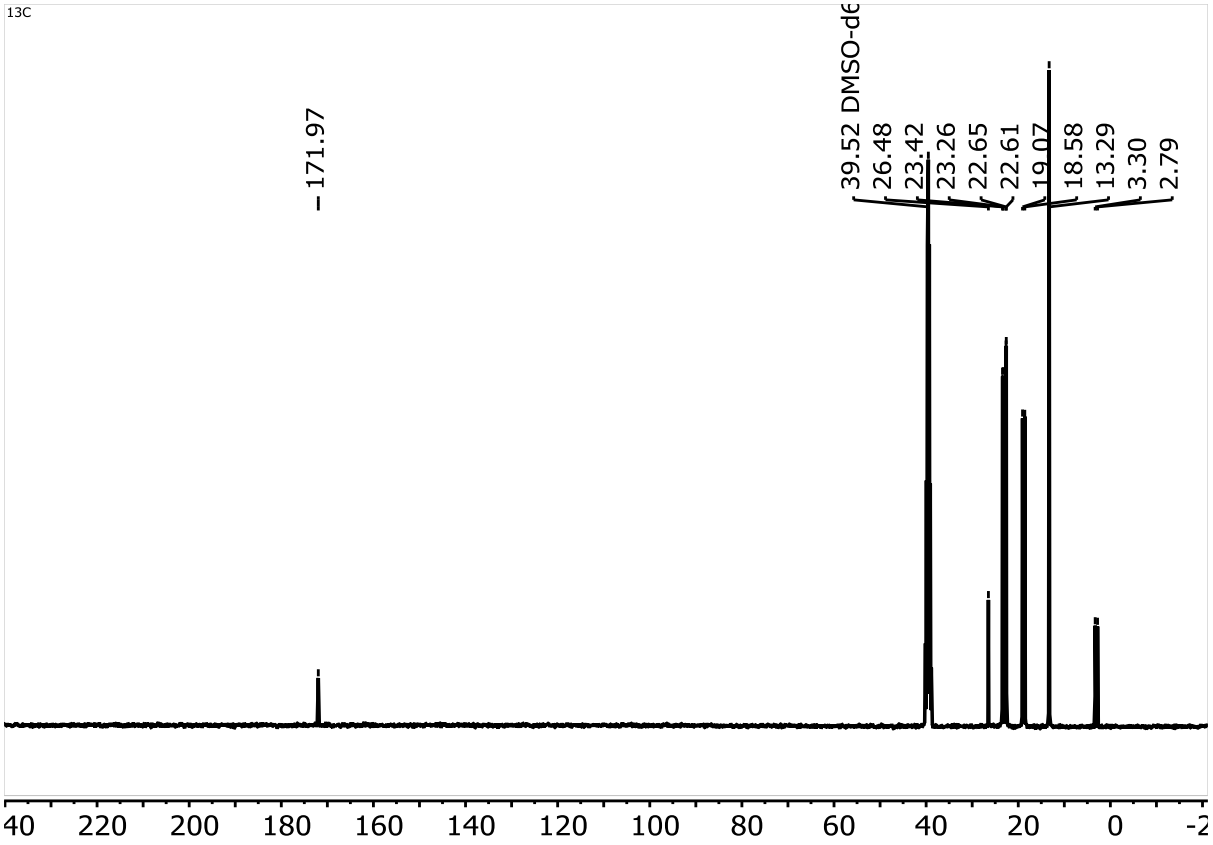


Figure S86. ^{13}C NMR of dried $[P_{4441}][OAc]$.

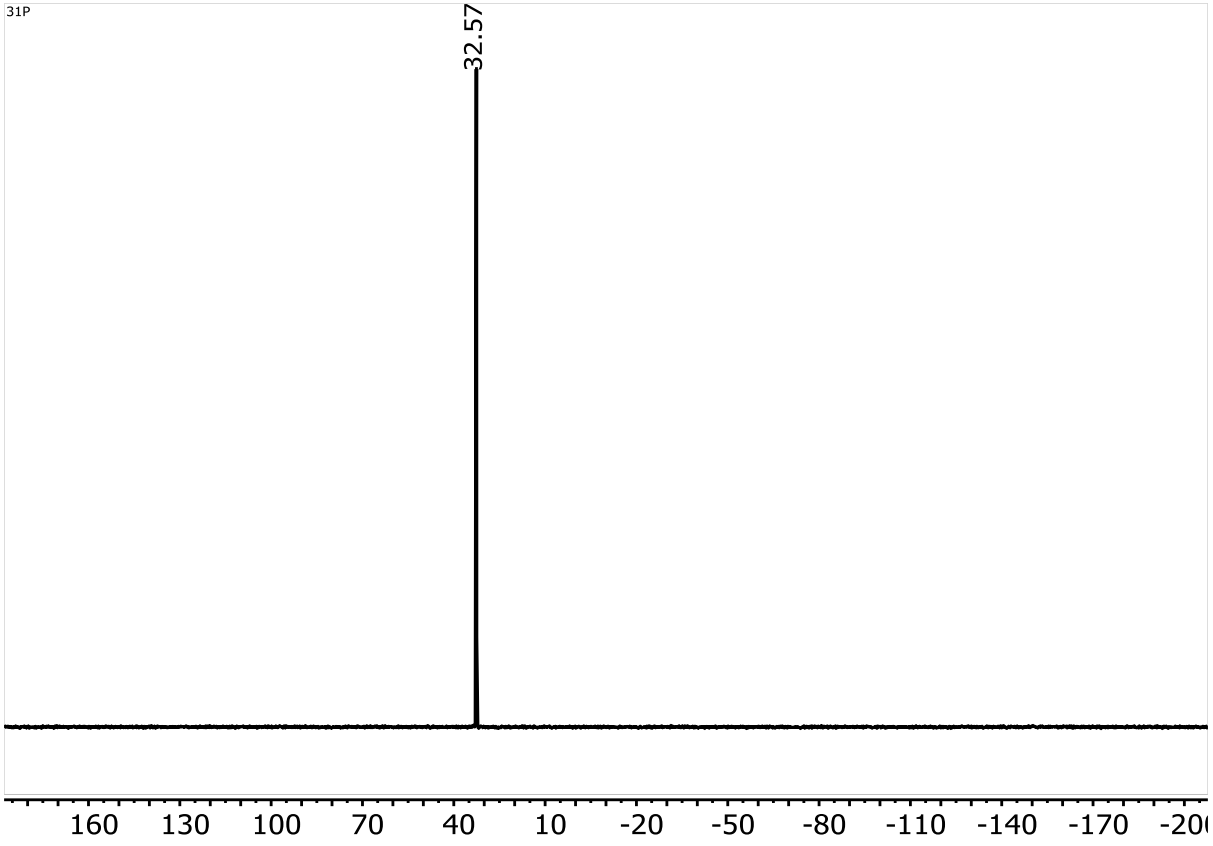


Figure S87. ^{31}P NMR of dried $[P_{4441}][OAc]$.

Pictures

Figure S88. Starting materials before reaction, inside the high-pressure tube.

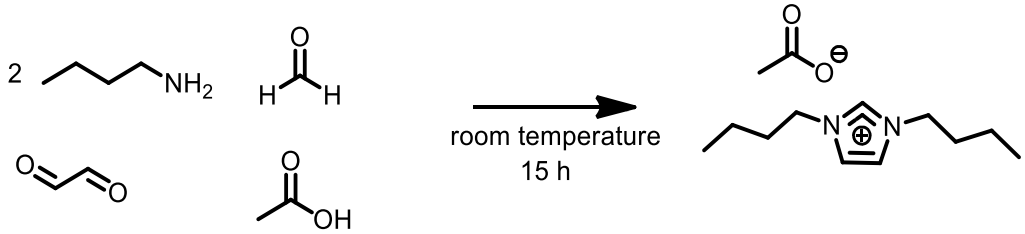
Figure S89. Starting materials after the reaction, inside the high-pressure tube.

Figure S90. Final, dried, [P_{4441}][OAc].

1,3-dibutylimidazolium acetate

Debus-Radziszewski

Route adapted from Depuydt et al.[20] See also the work of Damilano et al.[21]



Starting materials

Butylamine (≥99.0%, Merck 8.01539.1000)

Formaldehyde (37 % w/w in H_2O, stabilised with 5-15% MeOH, ACROS ORGANICS 119690010)

Glyoxal (40% w/w in H_2O, Fluorochem 094007)

Acetic acid (99.8 - 100.5%, Sigma Aldrich 27225-1L-M)

All starting materials were used as received, without further purification.

Procedure

Butylamine (25 mL, 18.23 g, 249.0 mmol) was cooled to 0 °C in an ice bath, and a pre-cooled mixture of aqueous formaldehyde 37% w/w (9 mL, 10.08 g, 124.1 mmol) and glacial acetic acid (10.7 mL, 11.25 g, 187.0 mmol) was added slowly over 30 min, keeping the temperature below 10°C. The resulting mixture was stirred at 0 °C for 1 h, after which aqueous glyoxal 40% w/w (14 mL, 18.24 g, 126 mmol) was added. The reaction mixture was stirred at ambient temperature for 15 h and then washed 7 times with diethyl ether, 20 mL each. The product was dried under vacuum at 50 °C overnight to give the desired product as a red viscous liquid (29.59 g, 123.0 mmol, 99% yield). The

acetate peak in the ^{1}H NMR integrates to 3.6 instead of 3.0, which is likely due to contamination with excess acetic acid.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.87 (t, $^{3}J_{H\text{-}H}$ = 7.4 Hz, 6H, C***H₃***), 1.22 (h, $^{3}J_{H\text{-}H}$ = 7.4 Hz, 4H, C***H₂***-CH_3), 1.65 (s, 3.6H, C***H₃***COO^-), 1.76 (p, $^{3}J_{H\text{-}H}$ = 7.3 Hz, 4H, C***H₂***-CH_2-CH_3), 4.20 (t, $^{3}J_{H\text{-}H}$ = 7.2 Hz, 4H, N-C***H₂***), 7.90 (s, 2H, ***H***C=C***H***), 10.09 (s, 1H, N-C***H***-N)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 13.24 (s, ***C***H_3), 18.78 (s, ***C***H_2-CH_3), 24.83 (s, ***C***H_3COO^-), 31.38 (s, ***C***H_2-CH_2-CH_3), 48.35 (s, N-***C***H_2), 122.41 (s, H***C***=***C***H), 137.24 (s, N-***C***H-N), 173.19 (s, CH_3***C***OO^-).

HRMS, ESI^+: m/z found 181.1705, calc. 181.1705 ($C_{11}H_{21}N^+$).

Elemental analysis (calculated): C- 62.30 (64.97), H- 9.78 (10.07), N- 10.74 (11.66)

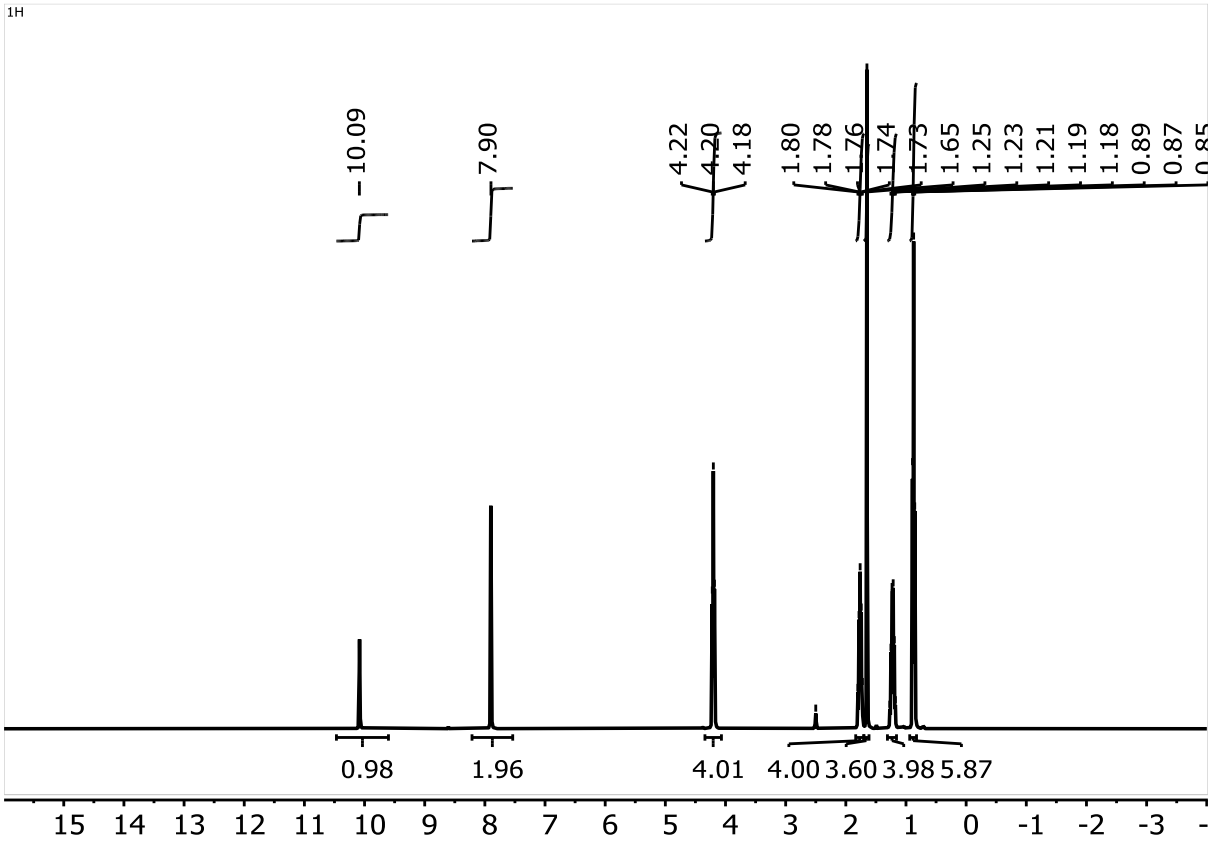


Figure S91. ^{1}H NMR of [C_4C_4im][OAc].

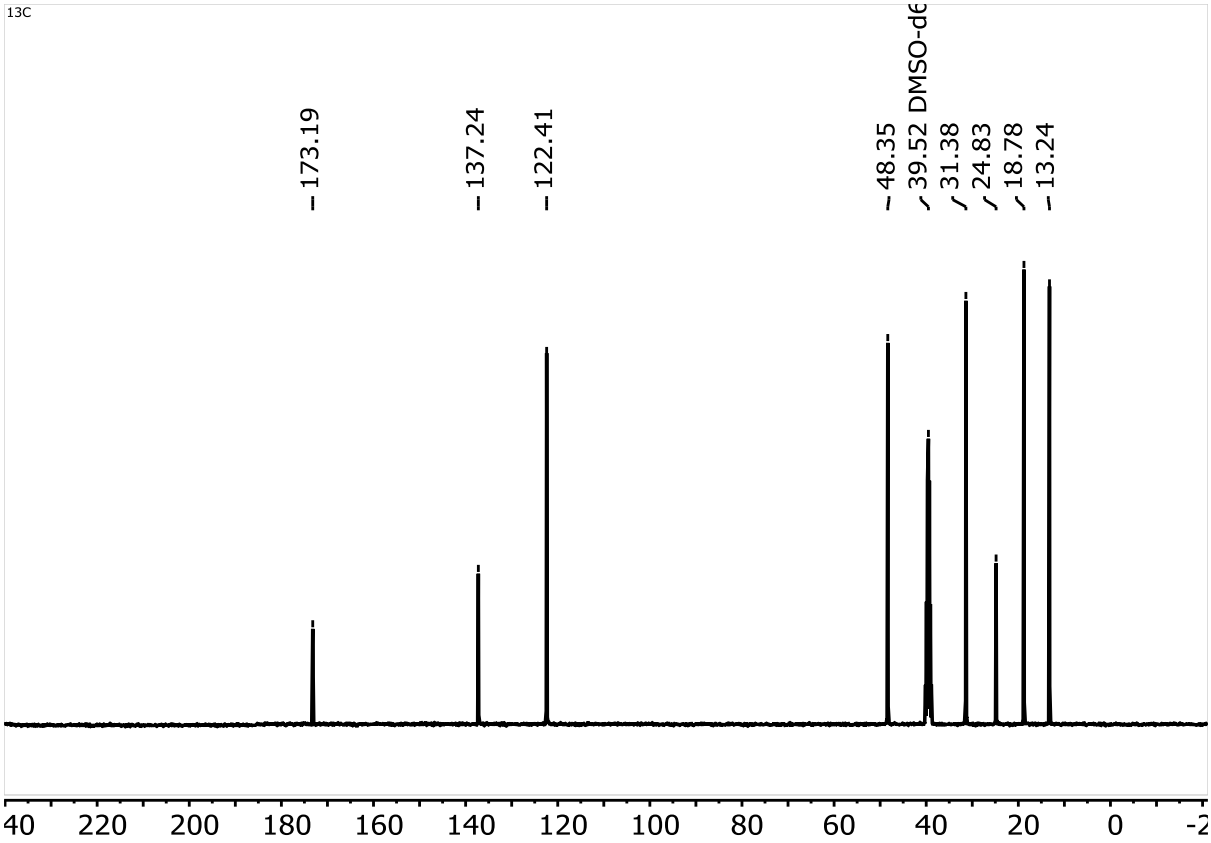


Figure S92. ^{13}C NMR of $[C_4C_4im][OAc]$.

Pictures

Figure S93. Crude reaction mixtures, before any purification.

Figure S94. First ether wash of the reaction mixture. Top layer: ether phase, bottom layer: IL phase.

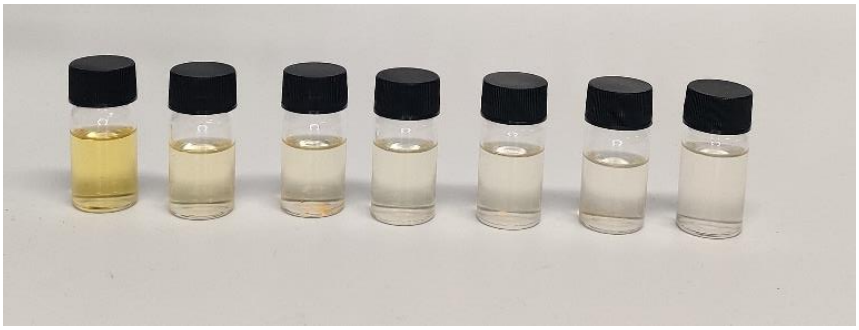


Figure S95. Ether layers from the washes of IL. Left: first wash, right: seventh wash.

Figure S96. Final dried product, $[C_4C_4im][OAc]$.

1,3-dibutylimidazolium halide

Metathesis with HX

Adapted from Damilano et al.[21] The reaction failed, probably because the shorter chain dibutylimidazolium doesn't separate well – they used dioctylimidazolium and longer.

Starting Materials

HCl (37% aqueous ACS reagent Sigma 258148)

HBr (48% aqueous purum p.a. Fluka 18730)

Procedure

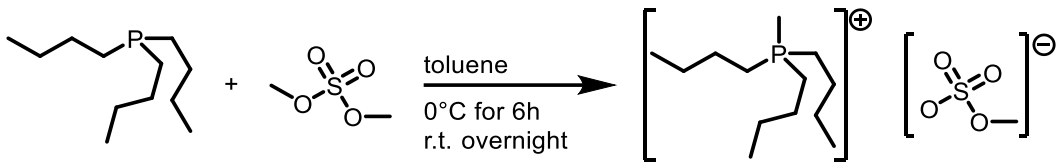
To $[C_4C_4im][OAc]$ (2.65 g, 11.0 mmol) was added HCl 37% (22 mL). In a separate flask, to $[C_4C_4im][OAc]$ (5.17 g, 21.5 mmol) was added HBr 48% (20 mL). Both mixtures remained as one homogeneous phase, no phase separation occurred. According to the literature reference the formed $[C_4C_4im]X$ should salt out, form a separate phase.

Pictures

Figure S97. $[C_4C_4im][OAc]$ with HBr (left) and with HCl (right.

Tributylmethylphosphonium methylsulfate $[P_{4441}][C_1SO_4]$

Methylation of $[P_{444}]$ with dimethyl sulfate



Starting Materials

$[P_{444}]$ was purified as described in the previous section.

Dimethyl sulfate ($C_1C_1SO_4$) (≥ 99.8%) was obtained from Sigma-Aldrich, stirred for 24 h over NaOH, and distilled under reduced pressure.

Toluene and $C_1C_1SO_4$ were dried and degassed via three freeze-pump-thaw cycles each, in order to remove any traces of dissolved oxygen that will oxidise $[P_{444}]$.

Procedure

The procedure was adapted from Clough et al.[22]

Inside a glovebox, [P_{444}] (6.16 g, 30.4 mmol, 1 eq) was mixed with toluene (20 mL). The [P_{444}] solution was cooled with an ice bath and a solution of $C_1C_1SO_4$ (4.09 g, 32.4 mmol, 1.07 eq) in toluene (20 mL) was added dropwise over a 6 h period, under N_2 atmosphere. Afterwards, the reaction mixture was allowed to warm up to room temperature overnight. A two-layer system had developed which was separated. The ionic liquid/bottom layer was extracted with toluene (3 x 10 mL). Any volatiles were removed under reduced pressure at room temperature. The title compound (7.61 g, 23.2 mmol, 76% yield) was obtained as a colourless solid.

Characterisation

^{1}H-NMR (400 MHz, DCM-d_2): δ / ppm = 0.98 (t,$^3J_{H,H}$ = 6.9 Hz, 9H, P-$(CH_2)_3$-***CH_3***), 1.46 – 1.57 (m, 12H, P-CH_2-***$(CH_2)_2$***-CH_3), 1.86 (d, $^2J_{H,P}$ = 13.4 Hz, 3H, P-***CH_3***), 2.17 – 2.24 (m, 6H, P-***CH_2***-$(CH_2)_2$-CH_3), 3.60 (s, 3H, SO_4-***CH_3***).

^{13}C{^{1}H}-NMR (101 MHz, DCM-d_2): δ / ppm = 4.26 (d, $^1J_{C,P}$ = 53.5 Hz, P-***C***H_3), 13.49 (s, P-$(CH_2)_3$-***C***H_3), 20.12 (d, $^1J_{C,P}$ = 49.5 Hz, P-***C***H_2-$(CH_2)_2$-CH_3), 23.79 (d, $^2J_{C,P}$ = 5.1 Hz, P-CH_2-***C***H_2-CH_2-CH_3), 24.16 (d, $^3J_{C,P}$ = 15.1 Hz, P-$(CH_2)_2$-***C***H_2-CH_3), 54.05 (s, SO_4-***C***H_3).

^{31}P{^{1}H}-NMR (162 MHz, DCM-d_2): δ / ppm = -31.84 (s, ***P***$_{4441}$).

HRMS, ESI^+: *m/z* found 217.2087, calc. 217.2080 ($C_{13}H_{30}P^+$).

MS, ESI^-: *m/z* found 110.0, calc. 110.1 ($CH_3O_4S^-$).

Elemental analysis (calculated): C- 50.99 (51.20), H- 9.87 (10.13), N- 0.35 (0)

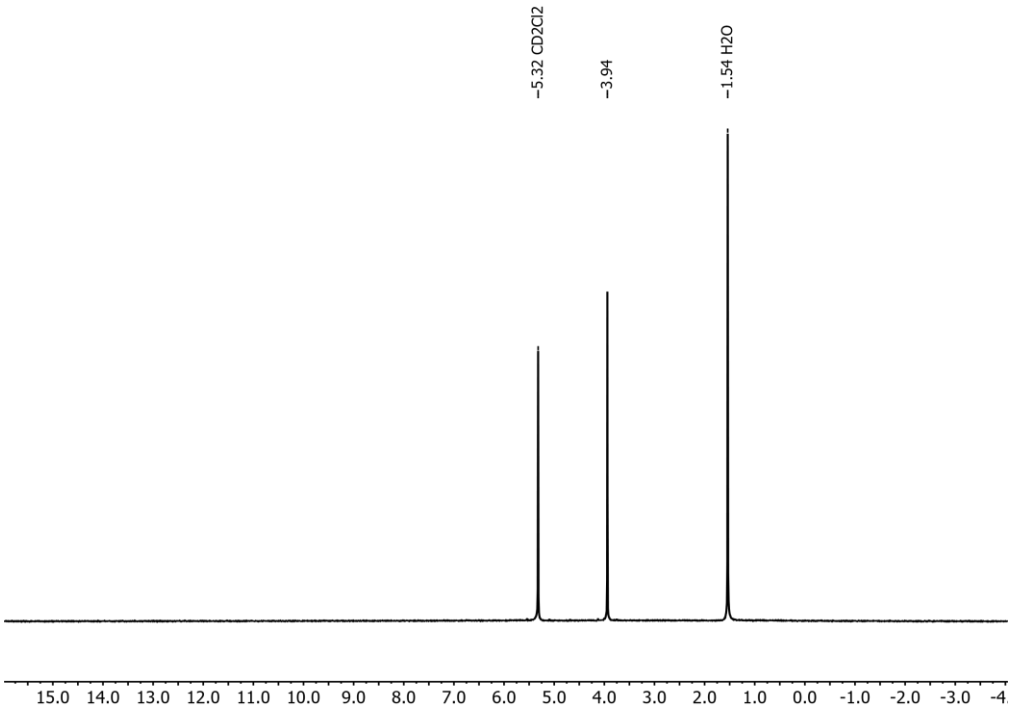


Figure S98. ^{1}H NMR of dimethyl sulfate, before any purification.

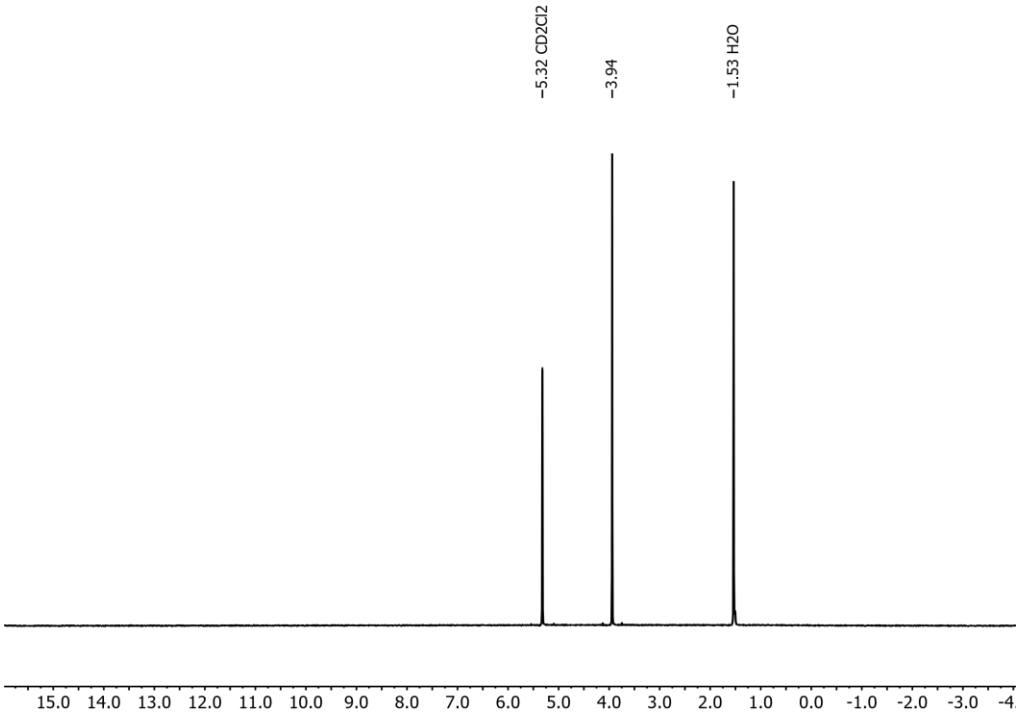


Figure S99. ^{1}H NMR of dimethyl sulfate after the purification steps. No difference is observed between the NMR spectra of the purified and non-purified material.

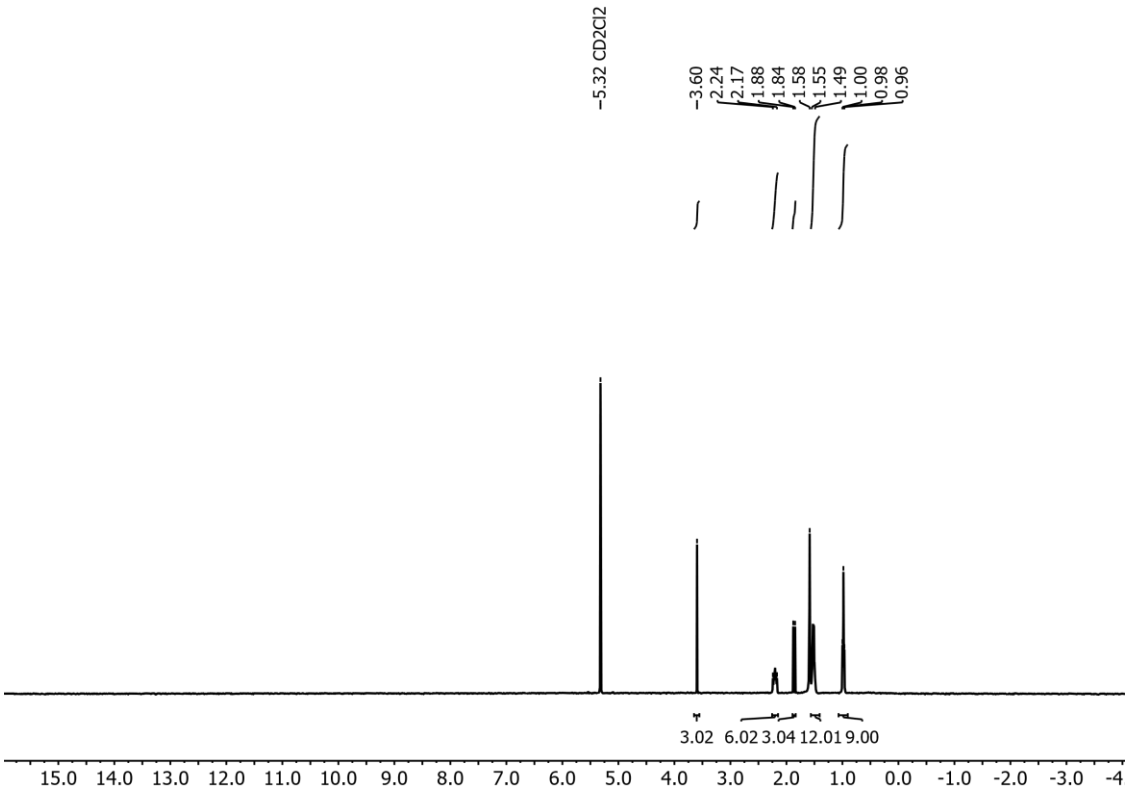


Figure S100. ^{1}H NMR of purified and dried $[P_{4441}][C_1SO_4]$.

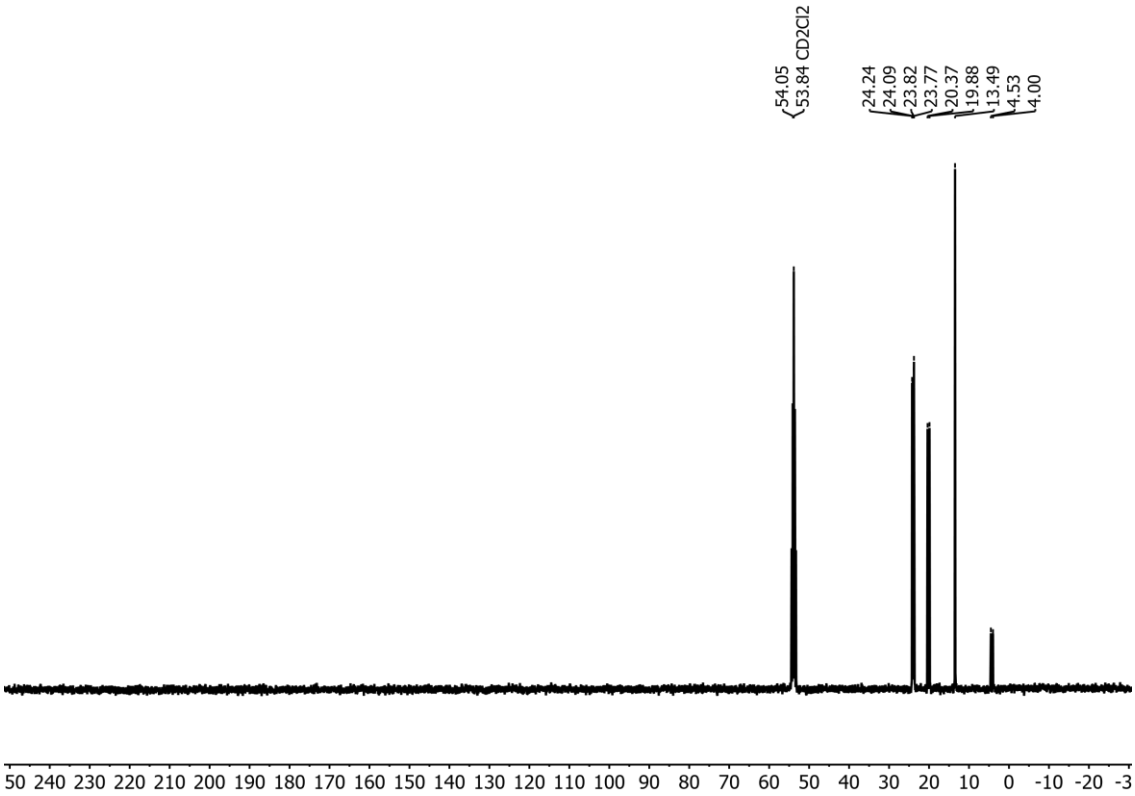


Figure S101. ^{13}C NMR of purified and dried $[P_{4441}][C_1SO_4]$.

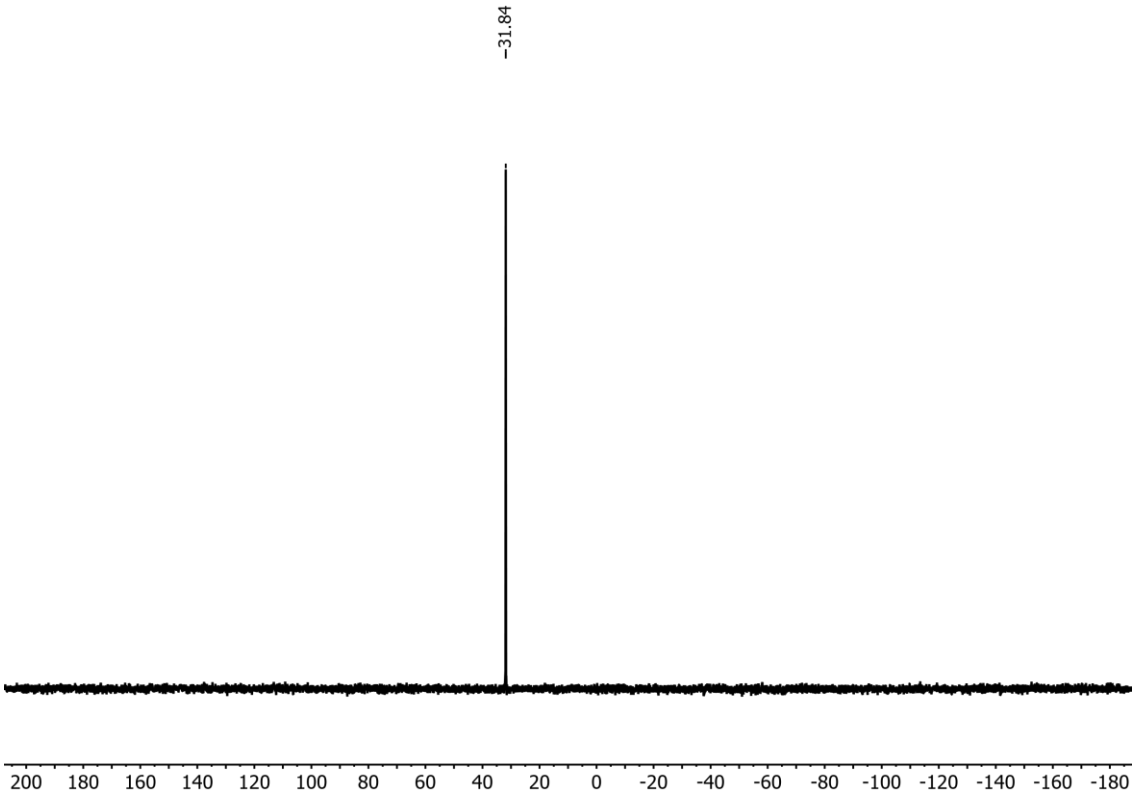


Figure S102. ^{31}P NMR of purified and dried $[P_{4441}][C_1SO_4]$.

Pictures

Figure S103. Dimethyl sulfate, as received from the bottle. Brown colouration indicates decomposition.

Figure S104. Dimethyl sulfate after stirring over NaOH pellets for 24 h.

Figure S105. Dimethyl sulfate after distillation. The received liquid is completely transparent.

Figure S106. Two-layer system indicating the formation of $[P_{4441}][C_1SO_4]$.

Figure S107. Final purified $[P_{4441}][C_1SO_4]$ in the round-bottom flask (left) and in a vial (right).

Tributylmethylphosphonium hydrogen sulfate $[P_{4441}][HSO_4]$

Starting Materials

$[P_{4441}][C_1SO_4]$ was prepared and purified as discussed in the previous section.

Sulfuric acid (H_2SO_4) was bought from Sigma Aldrich.

Procedure

The procedure was adapted from Brandt et al.[23]

$[P_{4441}][C_1SO_4]$ (3.03 g, 9.2 mmol, 1 eq) was dissolved in water (10 mL). One drop of 95% H_2SO_4 was added to the solution. The solution was heated to reflux until the ^{1}H NMR resonance of the methyl group on the $[C_1SO_4]^-$ anion was not detectable anymore (6 days). All volatiles were removed under reduced pressure. The crude product (a transparent solid) was dissolved in ~20 mL acetonitrile and stirred with activated charcoal overnight to remove any remaining acid. The charcoal was removed by filtration. All volatiles were removed under reduced pressure and the title compound (2.78 g, 8.8 mmol, 96%) was obtained as a colourless solid.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.91 (t,$^{3}J_{H,H}$ = 7.1 Hz, 9H, P-$(CH_2)_3$-***CH_3***), 1.35 – 1.51 (m, 12H, P-CH_2-***$(CH_2)_2$***-CH_3), 1.78 (d, $^{2}J_{H,P}$ = 14.0 Hz, 3H, P-***CH_3***), 2.11 – 2.19 (m, 6H, P-***CH_2***-$(CH_2)_2$-CH_3), 3.43 (bs, SO_4-***H***).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d6): δ / ppm = 3.09 (d, $^{1}J_{C,P}$ = 51.7 Hz, P-***C***H_3), 13.32 (s, P-$(CH_2)_3$-***C***H_3), 18.87 (d, $^{1}J_{C,P}$ = 49.4 Hz, P-***C***H_2-$(CH_2)_2$-CH_3), 22.64 (d, $^{2}J_{C,P}$ = 4.4 Hz, P-CH_2-***C***H_2-CH_2-CH_3), 23.33 (d, $^{3}J_{C,P}$ = 16.1 Hz, P-$(CH_2)_2$-***C***H_2-CH_3).

^{31}P{^{1}H}-NMR (162 MHz, DMSO-d6): δ / ppm = -32.40 (s, ***P***$_{4441}$).

HRMS, ESI^{+}: *m/z* found 217.2087, calc. 217.2080 ($C_{13}H_{30}P^{+}$).

MS, ESI^{-}: *m/z* found 110.0, calc. 110.1 (HO_4S^{-}).

Elemental analysis (calculated): C- 50.00 (49.66), H- 9.67 (9.94), N- 0 (0)

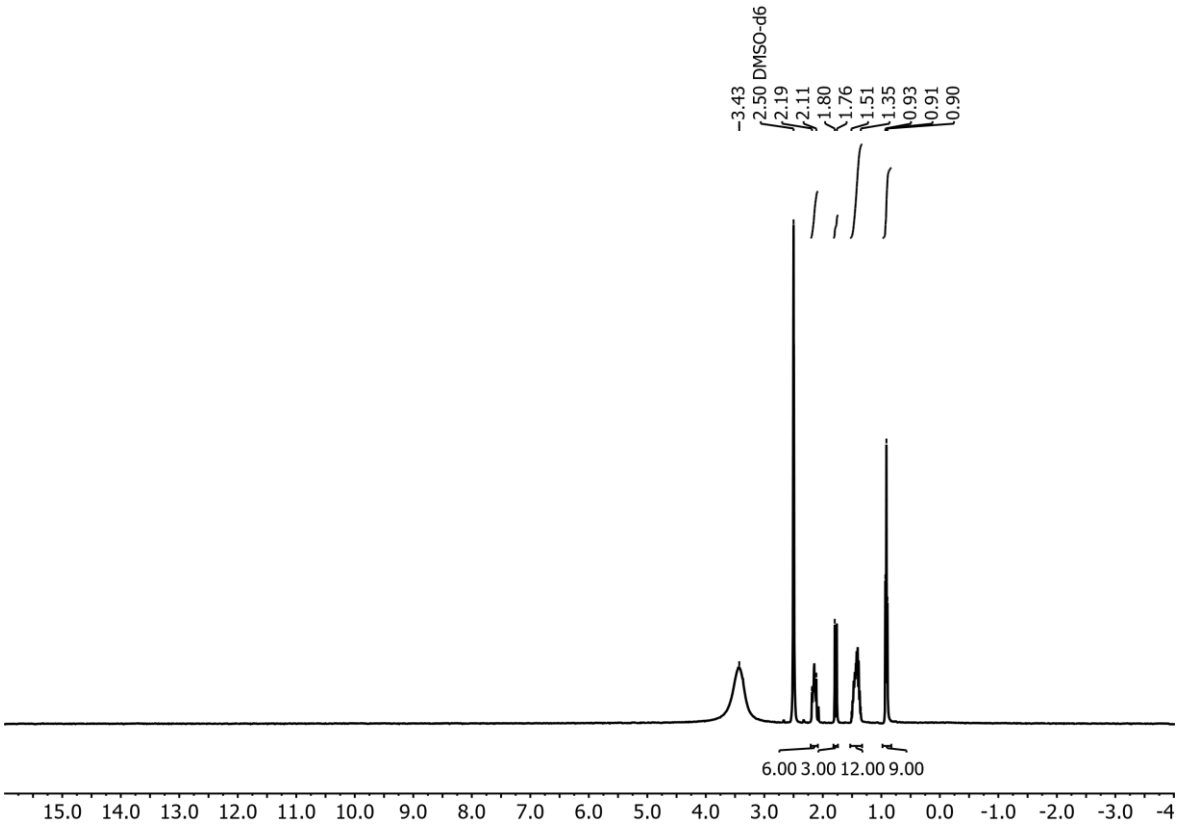


Figure S108. ^{1}H NMR of purified and dried [P_{4441}][HSO_4].

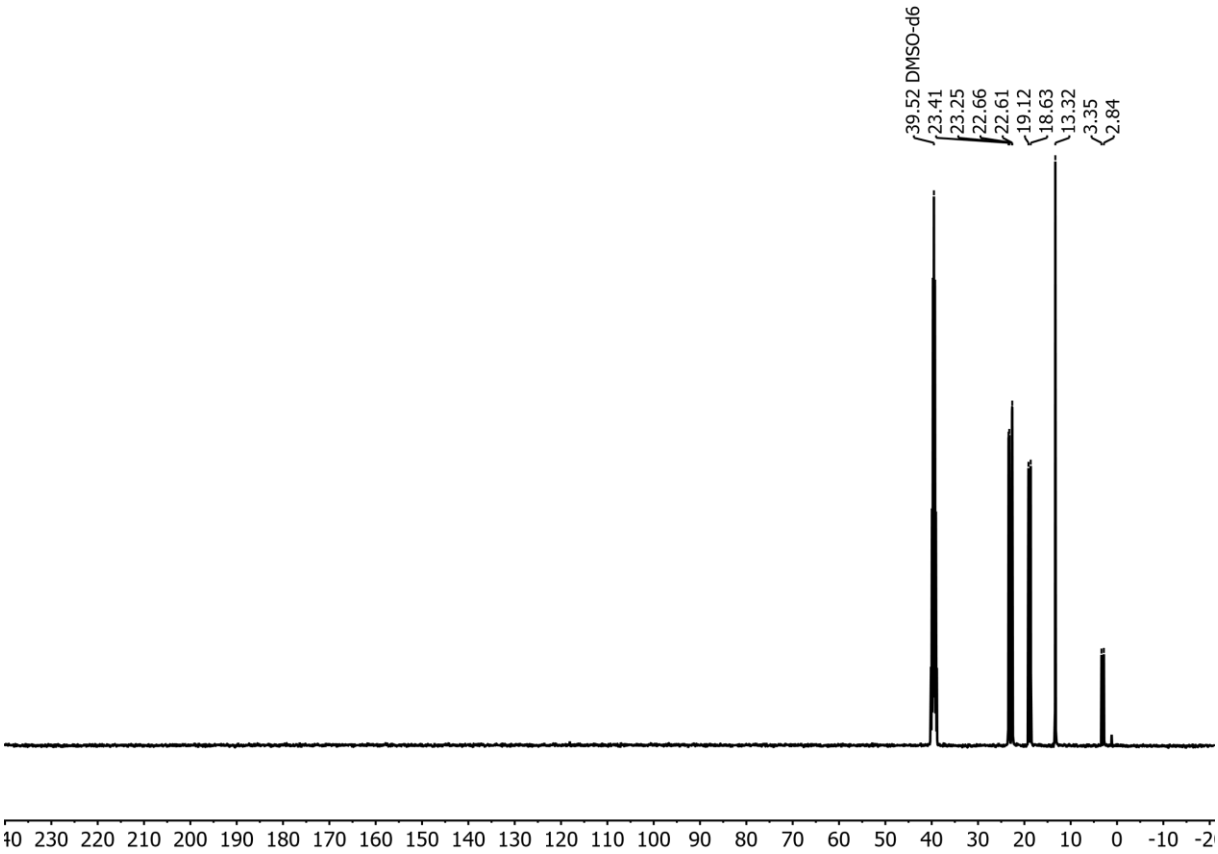


Figure S109. ^{13}C NMR of purified and dried $[P_{4441}][HSO_4]$.

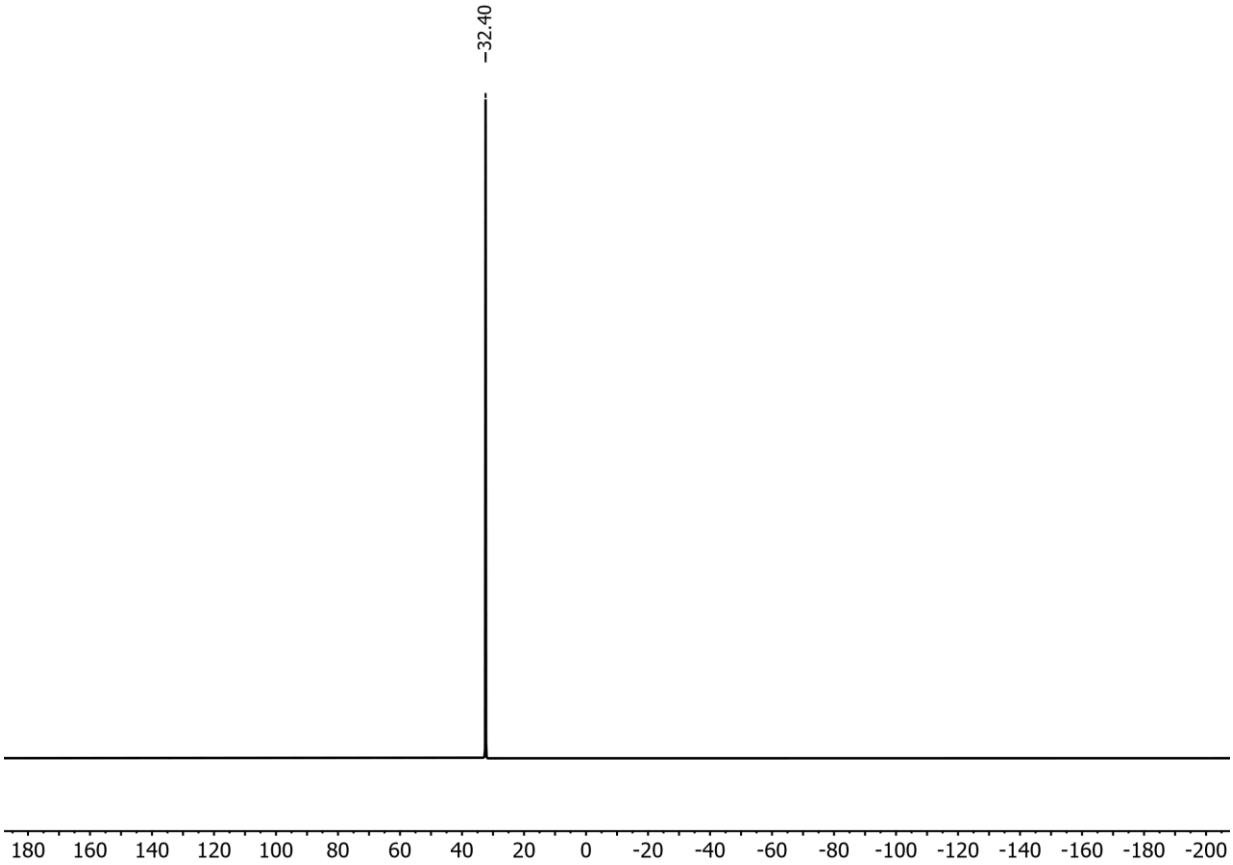


Figure S110. ^{31}P NMR of purified and dried $[P_{4441}][HSO_4]$.

Pictures

Figure S111. $[P_{4441}][C_1SO_4]$ and sulfuric acid in water, before reflux.

Figure S112. $[P_{4441}][C_1SO_4]$ and sulfuric acid in water, after reflux.

Figure S113. Crude $[P_{4441}][HSO_4]$, before treatment with activated charcoal.

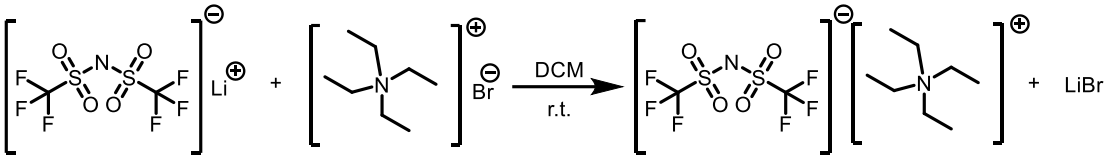
Figure S114. $[P_{4441}][HSO_4]$ in acetonitrile with activated charcoal.

Figure S115. $[P_{4441}][HSO_4]$ in acetonitrile after removal of activated charcoal.

Figure S116. Final purified and dried $[P_{4441}][HSO_4]$.

Tetraethylammonium bis(trifuolomethylsulfonyl)imide [N_{2222}][NTf_2]

Anion metathesis with Li salt



Starting Materials

[N_{2222}][Br] (99%), received from Sigma Aldrich, was dried under vacuum overnight.

Lithium bis(trifluoromethylsulfonyl)imide (99%) was used as received from Iolitec.

Procedure

The procedure was adapted from Seddon et al.[24], Clark et al.,[2] and Philippi et al.[14]

Lithium bis(trifluoromethylsulfonyl)imide (10.0 g, 34.0 mmol, 1 eq) was added into a solution of [N_{2222}][Br] (7.14 g, 34.0 mmol, 1 eq) in 50 mL dichloromethane. The solution was stirred for 24 h at room temperature. Then precipitated white solid was dissolved upon the addition of deionized water (10 mL). The layered reaction mixture was separated (ionic liquid layer: lower layer). The ionic liquid layer was washed with deionized water (6 x 10 mL) until no halide was observed, tested with acidic $AgNO_3$ solution (0.3 M $AgNO_3$ in 1 M HNO_3). The residual solvent was removed in a rotary evaporator, followed by drying under vacuum. The target product [N_{2222}][NTf_2] (12.53 g, 30.6 mmol, 90% yield) was obtained as a white solid.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6) δ / ppm = 1.15 (t, $^{3}J_{HH}$ = 7.2 *Hz*, 12H, CH_2-C***H*****$_3$**), 3.20 (q, $^{3}J_{HH}$ = 7.2 *Hz*, 8H, C***H*****$_2$**-CH_3).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6) δ / ppm = 7.07 (N-(CH_2-***C***H_3)$_4$), 51.37 (N-(***C***H_2-CH_3)$_4$).

^{19}F-NMR (377 MHz, DMSO-d_6) δ / ppm = -78.73 (s, 6F, C***F*****$_3$**).

HRMS, ESI^+: m/z found 130.1595, calc. 130.1596; ESI^-: m/z found 279.9173, calc. 279.9173 ($[NTf_2]^-$)

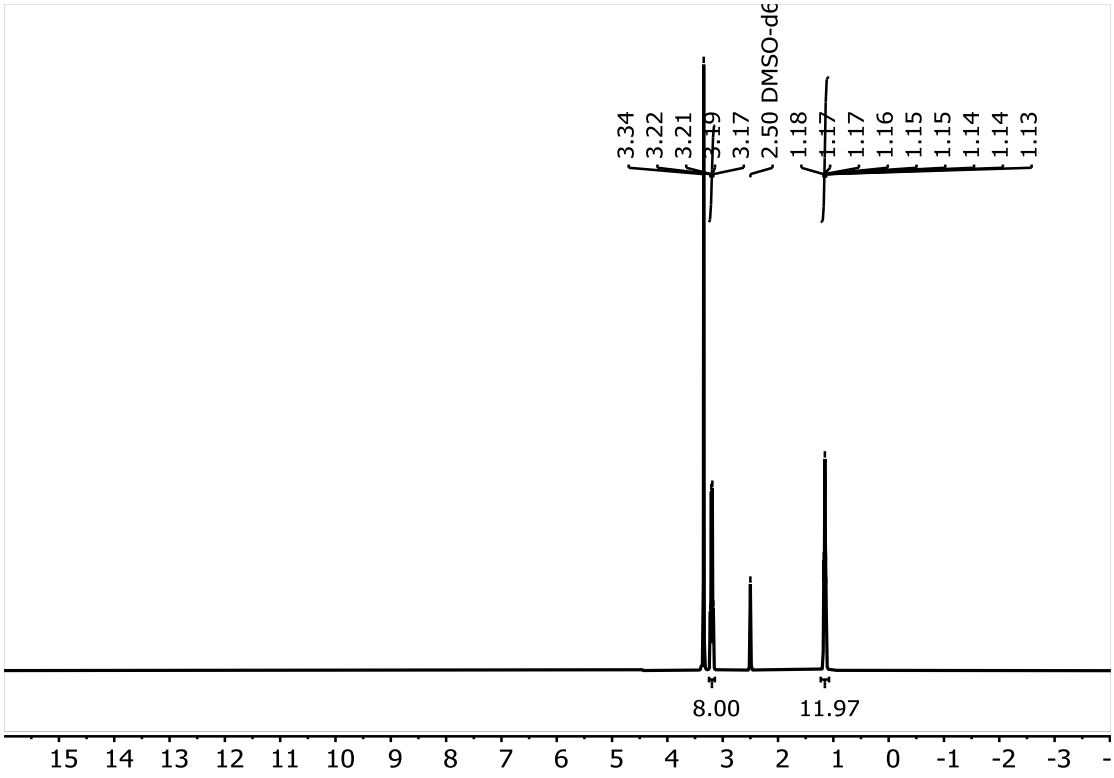


Figure S117. ^{1}H NMR of purified and dried [N_{2222}]Br.

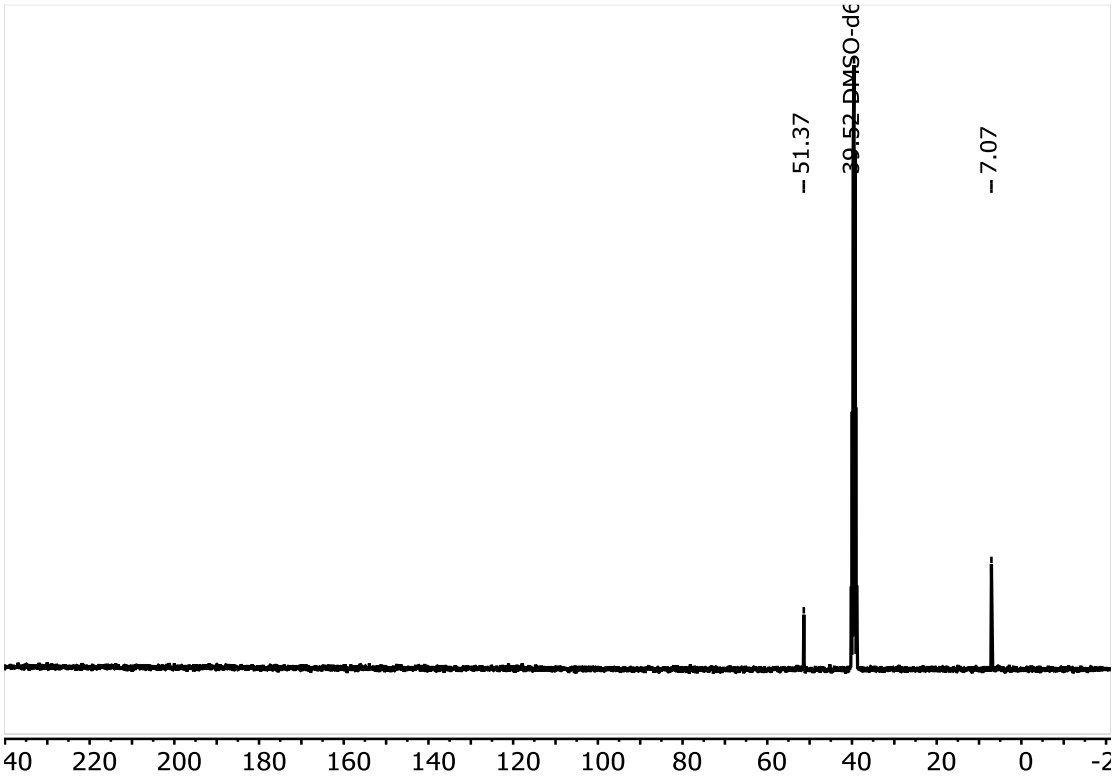


Figure S118. ^{13}C NMR of purified and dried [N_{2222}]Br.

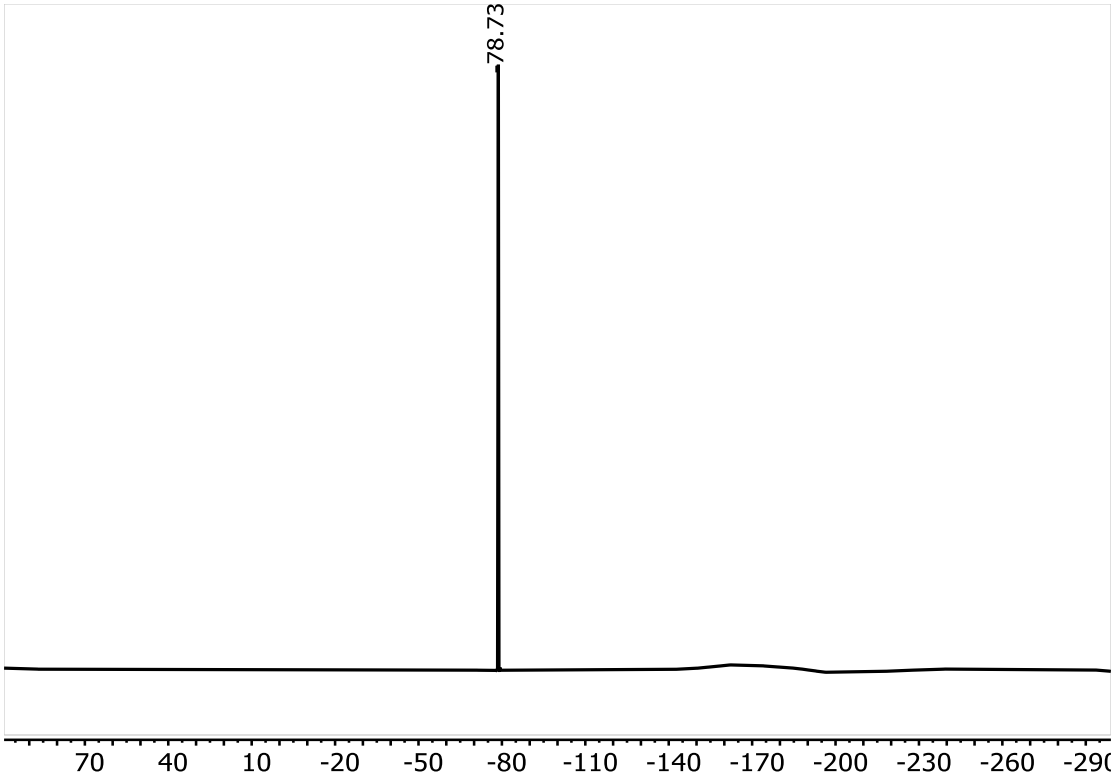


Figure S119. ^{19}F NMR of purified and dried $[N_{2222}]Br$.

Pictures

Figure S120. Commercial $[N_{2222}]Br$ after drying under vacuum.

Figure S121. White solid precipitated in the crude mixture after 24-h stirring at room temperature.

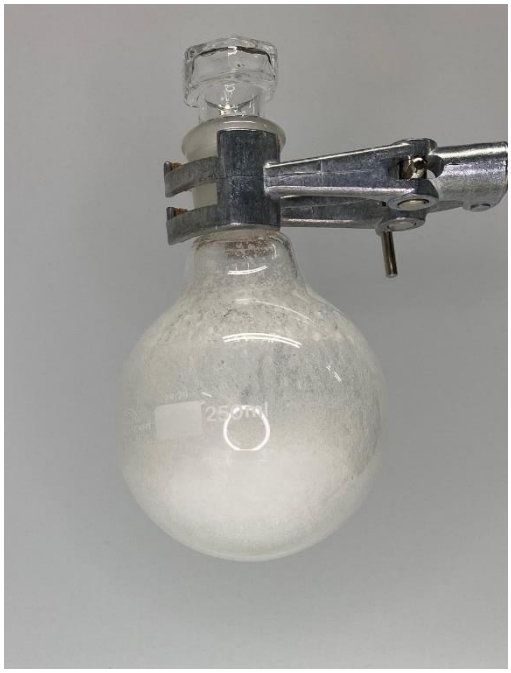
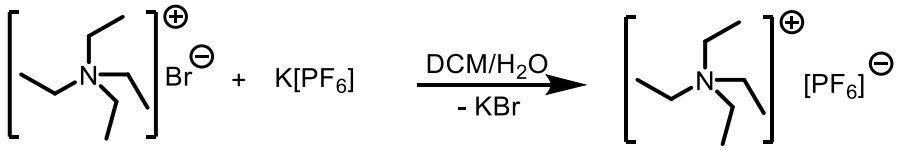


Figure S122. Final $[N_{2222}][NTf_2]$ received as white powder.

Tetraethylammonium hexafluorophosphate $[N_{2222}][PF_6]$

Anion metathesis with K salt



Starting Materials

$K[PF_6]$ (98%) and $[N_{2222}]Br$ (99%) were used as received from Aldrich.

Procedure

The procedure was adapted from Bresien et al.[25]

[N_{2222}]Br (7.64 g, 41.5 mmol, 1.0 eq) was dissolved in ~80 mL DCM and K[PF_6] (8.72 g, 41.5 mmol, 1.0 eq) was dissolved in deionised water. The two solutions were mixed at room temperature and stirred vigorously overnight. The two layers were allowed to separate. The organic phase was washed with deionised water (4 x 25 mL) until the water washings were halide-free (halide test with 0.3 M $AgNO_3$ in 1 M HNO_3). The organic phase was dried over $MgSO_4$, filtered, and any volatiles were removed under reduced pressure at room temperature. The title compound (8.91 g, 32.4 mmol, 78% yield) was obtained as a colourless solid.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 1.15 (tt, $^{3}J_{H,H}$ = 7.2 Hz, $^{2}J_{H,N}$ = 1.7 Hz, 12H, N-CH_2-***CH_3***), 3.20 (q, $^{3}J_{H,H}$ = 7.2 Hz, 8H, N-***CH_2***-CH_3).

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 7.1 (N-CH_2-***C***H_3), 51.5 (N-***C***H_2-CH_3). **^{19}F-NMR** (377 MHz, DMSO-d6): δ / ppm = -70.13 (d, $^{1}J_{F,P}$ = 712.5 Hz, P***F_6***).

^{31}P{^{1}H}-NMR (162 MHz, DMSO-d_6): δ / ppm = -144.2 (sept, $^{1}J_{P,F}$ = 712.5 Hz, ***P***F_6).

HRMS, ESI^+: *m/z* found 130.1592, calc. 130.1590 ($C_8H_{20}N^+$).

HRMS, ESI^-: *m/z* found 144.9652, calc. 144.9647 (F_6P^-).

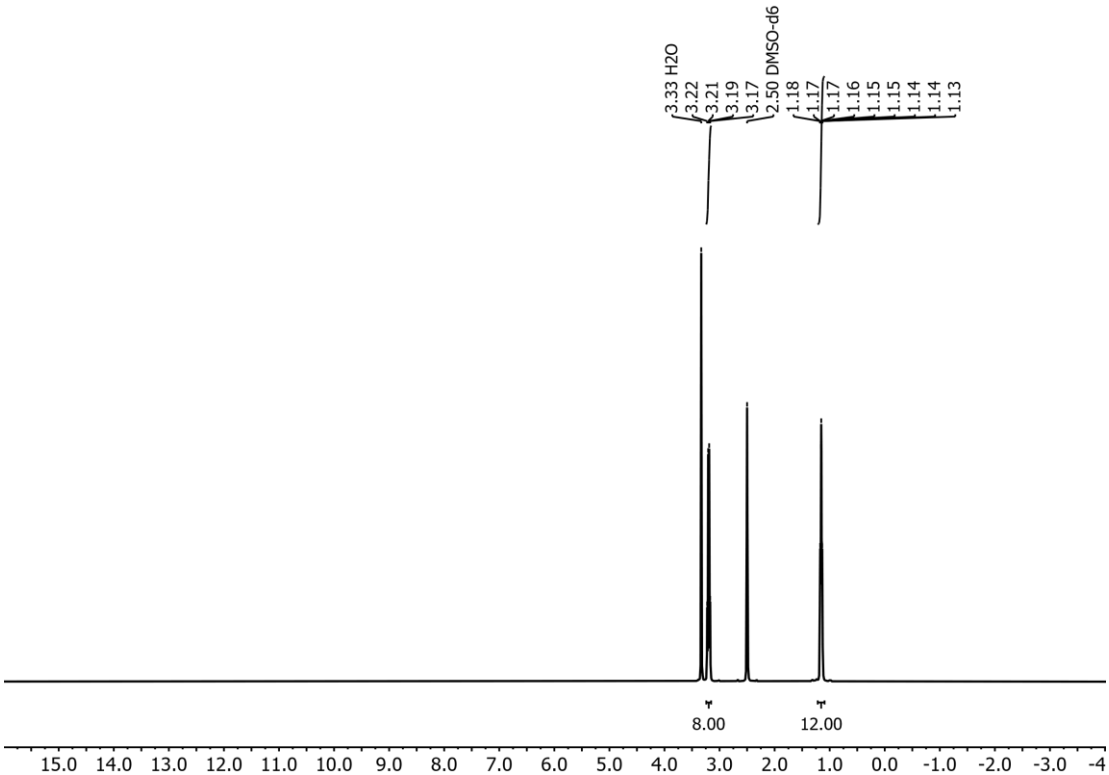


Figure S123. ^{1}H NMR of purified and dried [N_{2222}][PF_6].

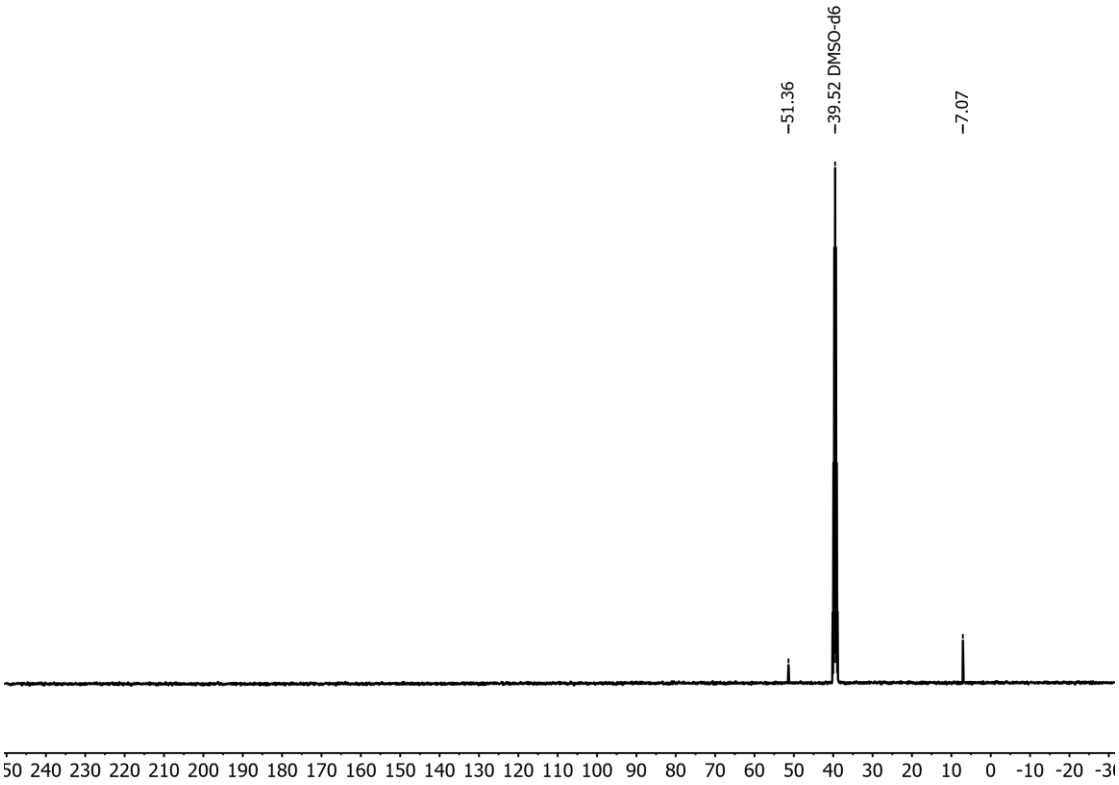


Figure S124. ^{13}C NMR of purified and dried $[N_{2222}][PF_6]$.

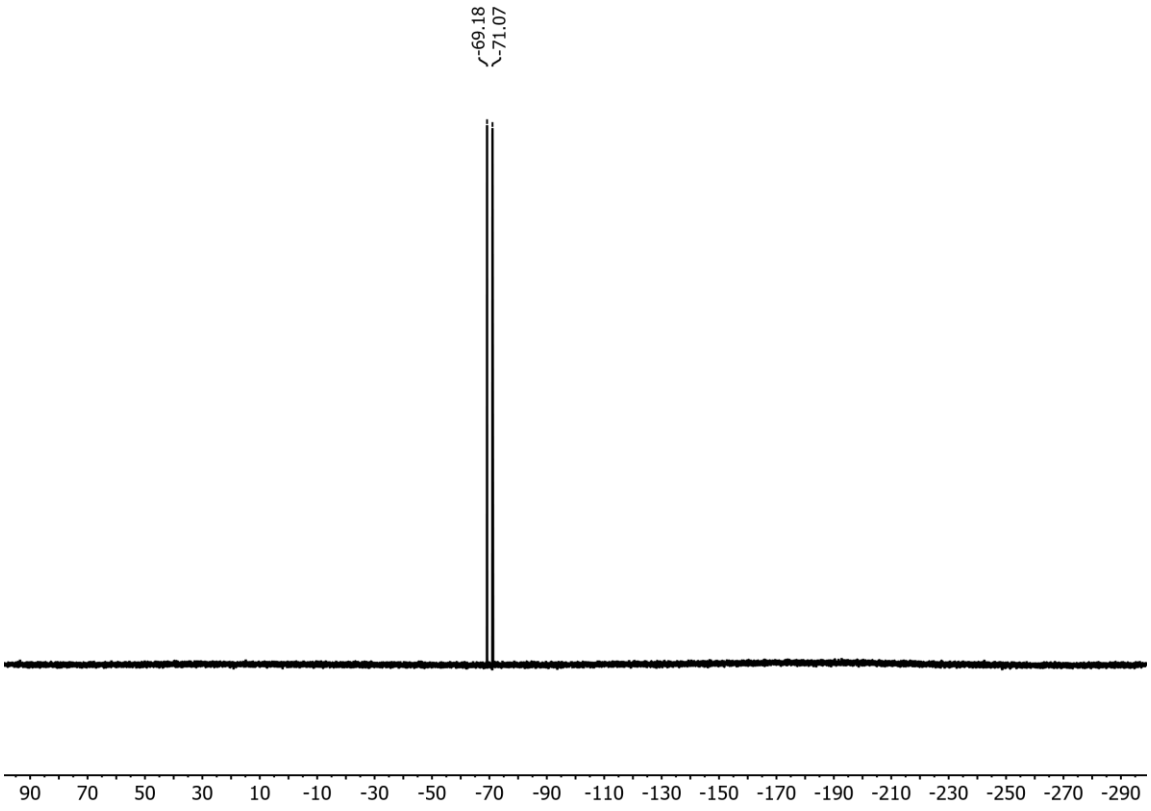


Figure S125. ^{19}F NMR of purified and dried $[N_{2222}][PF_6]$.

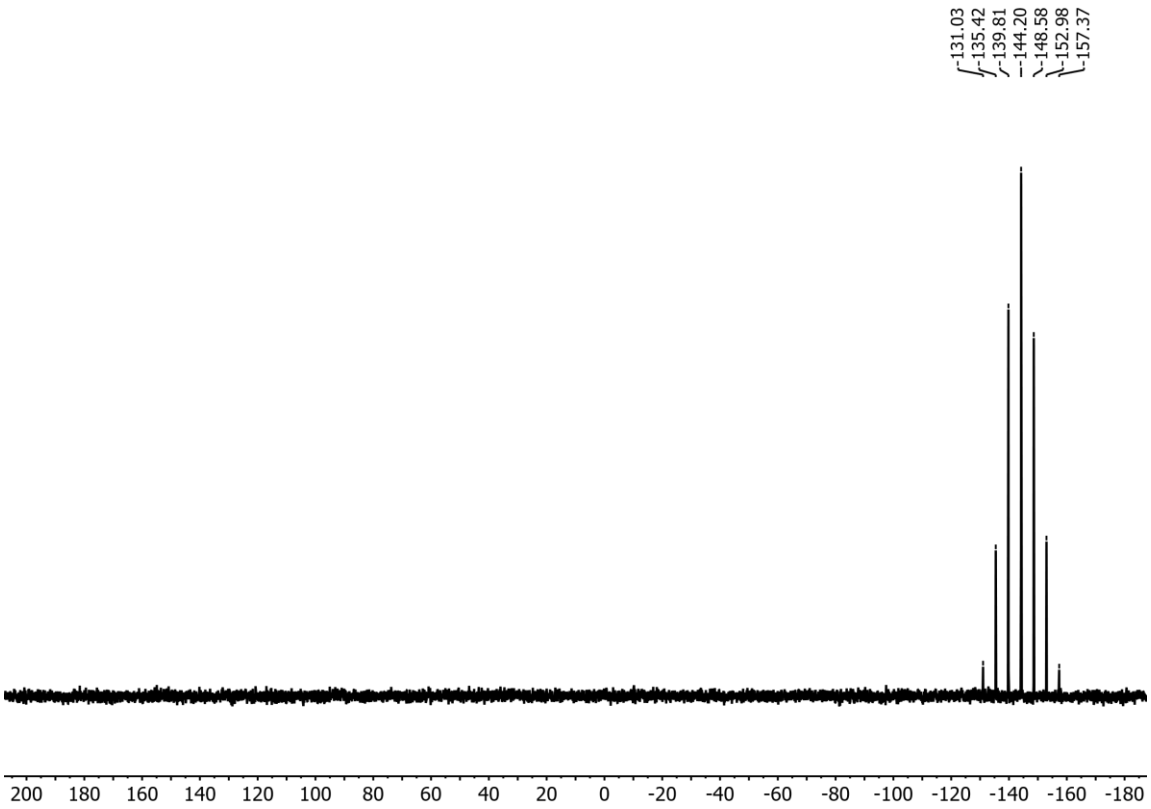


Figure S126. ^{31}P NMR of purified and dried $[N_{2222}][PF_6]$.

Pictures

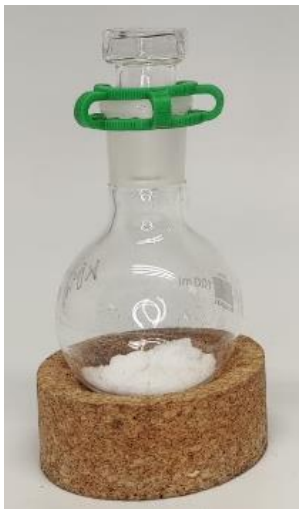


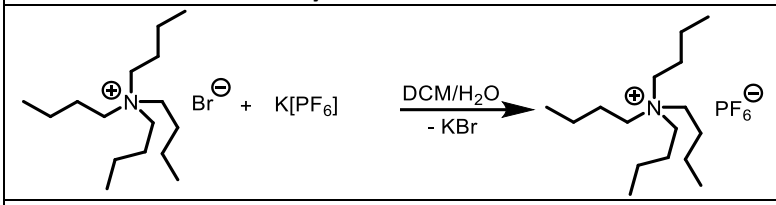
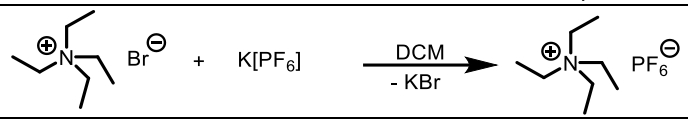
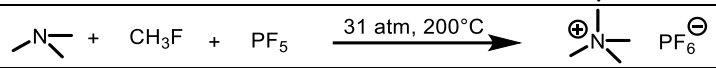
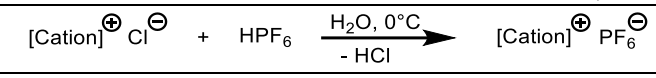
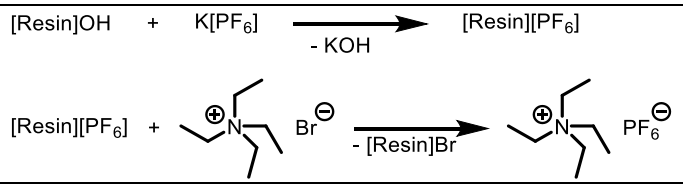
Figure S127. $K[PF_6]$.

Figure S128. Two-phase system after overnight mixing of solutions.

Figure S129. DCM phase after washing with water.

Figure S130. Final purified and dried $[N_{2222}][PF_6]$.

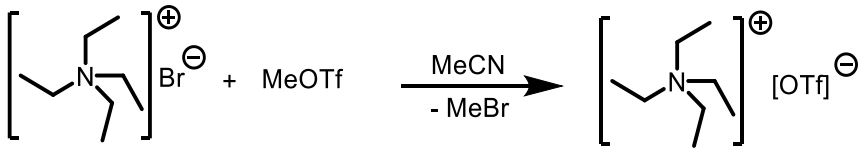
Alternative synthesis routes for $[PF_6]^-$ ionic liquids

Synthetic Route	Reference
	25
	26
	27
	28
	29

Tetraethylammonium triflate $[N_{2222}][OTf]$

Solvent free

Route adapted from Ignat'ev et al.[30] According to this method, the methyl triflate will methylate the bromide anion, producing bromomethane which will evaporate from the reaction vessel. This procedure was performed successfully for ionic liquids with more than four carbons on the side chains.



Starting Materials

Methyl triflate (≥98%, Aldrich 164283-10g ampoule)[31]

Tetraethylammonium bromide ($[N_{2222}]Br$) (99% ReagentPlus, Aldrich 241059-50g)

All the starting materials were used as received, without further purification.

Procedure

$[N_{2222}]Br$ (1.74 g, 8.3 mmol, 1.00 eq) was dried in a Schlenk flask under high vacuum. To the solid, methyl triflate (1.8 mL, 16.5 mmol, 1.99 eq) was added, and the resulting suspension was stirred for 30 min at room temperature. The reaction mixture was dried in high vacuum overnight, giving the final product as a white solid (1.99 g, 7.1 mmol, 86% isolated yield). The silver nitrate test was positive, indicating that there is remaining bromide in the system. The solid was washed two times with 10 mL diethyl ether each in order to remove unreacted methyl triflate, followed by drying in high vacuum.

Characterisation of the product showed incomplete conversion of $[N_{2222}]Br$, as the silver nitrate halide test indicated high bromide content. Taking a closer look to the initial work by Ignat'ev et al.,[30] we can see a key factor of the success of the neat reaction is the formation of a liquid final product, which dissolves the starting material and drives the reaction to completion. Since in this case both $[N_{2222}]Br$

and $[N_{2222}][OTf]$ are solid (and insoluble in methyl triflate), the reaction is not led to completion. Repeating the neat reaction with $[N_{4444}]Br$ led to full conversion of the starting material, as $[N_{4444}][OTf]$ is liquid.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 1.15 (tt, $^{3}J_{H\text{-}H}$ = 7.3 Hz, $^{2}J_{H\text{-}N}$ = 1.8 Hz, 12H, N-C***H₂***-CH_3), 3.22 (q, $^{3}J_{H\text{-}H}$ = 7.2 Hz, 8H, N-CH_2-C***H₃***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 7.13 (s, N-CH_2-***C***H_3), 51.41 (t, $^{1}J_{C\text{-}N}$ = 3.1 Hz, N-***C***H_2-CH_3), 120.65 (q, $^{1}J_{C\text{-}F}$ = 322.3 Hz, ***C***F_3)

^{19}F-NMR (377 MHz, DMSO-d_6): δ / ppm = -77.77 (s, C***F₃***).

HRMS, ESI^+: m/z found 130.1591, calc. 130.1596 ($C_8H_{20}N^+$); ESI^-: m/z found 148.9536, calc. 148.9520 ($CO_3F_3S^-$).

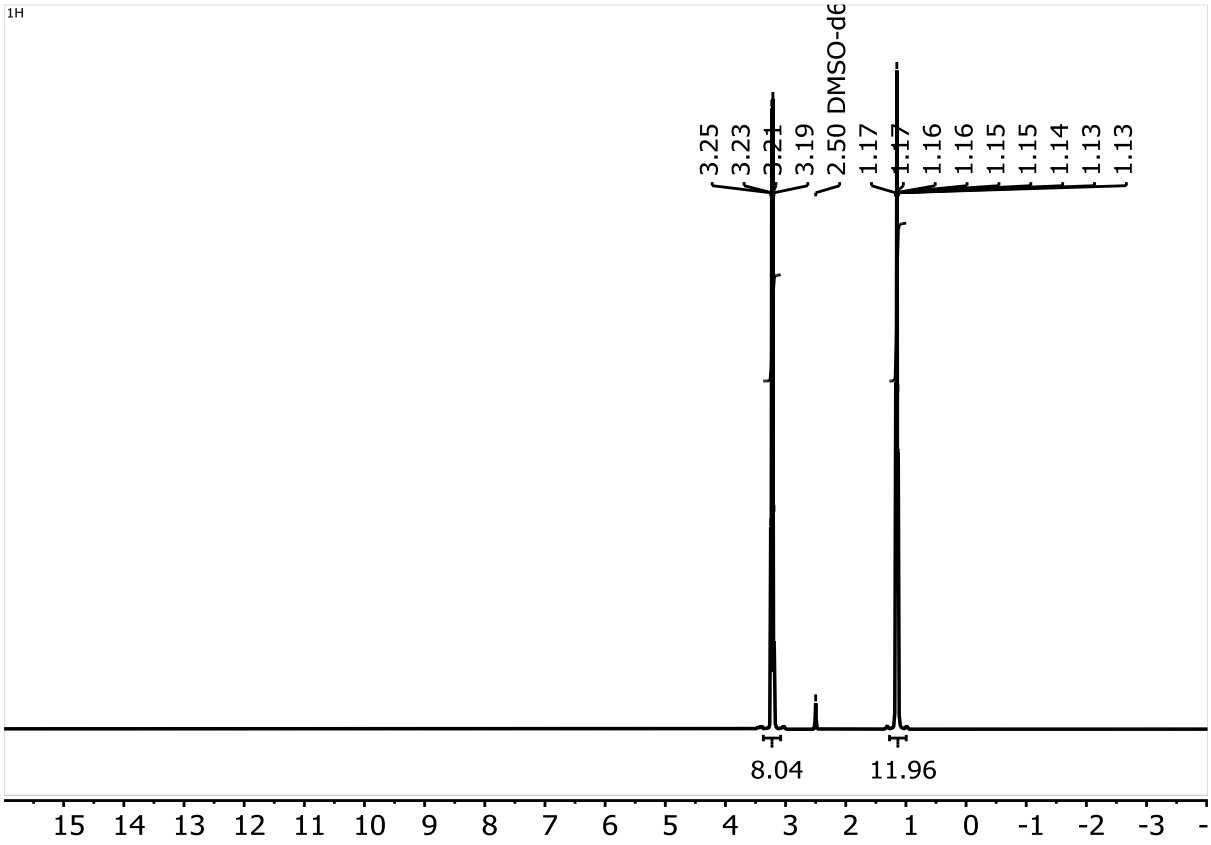


Figure S131. ^{1}H NMR of the reaction product.

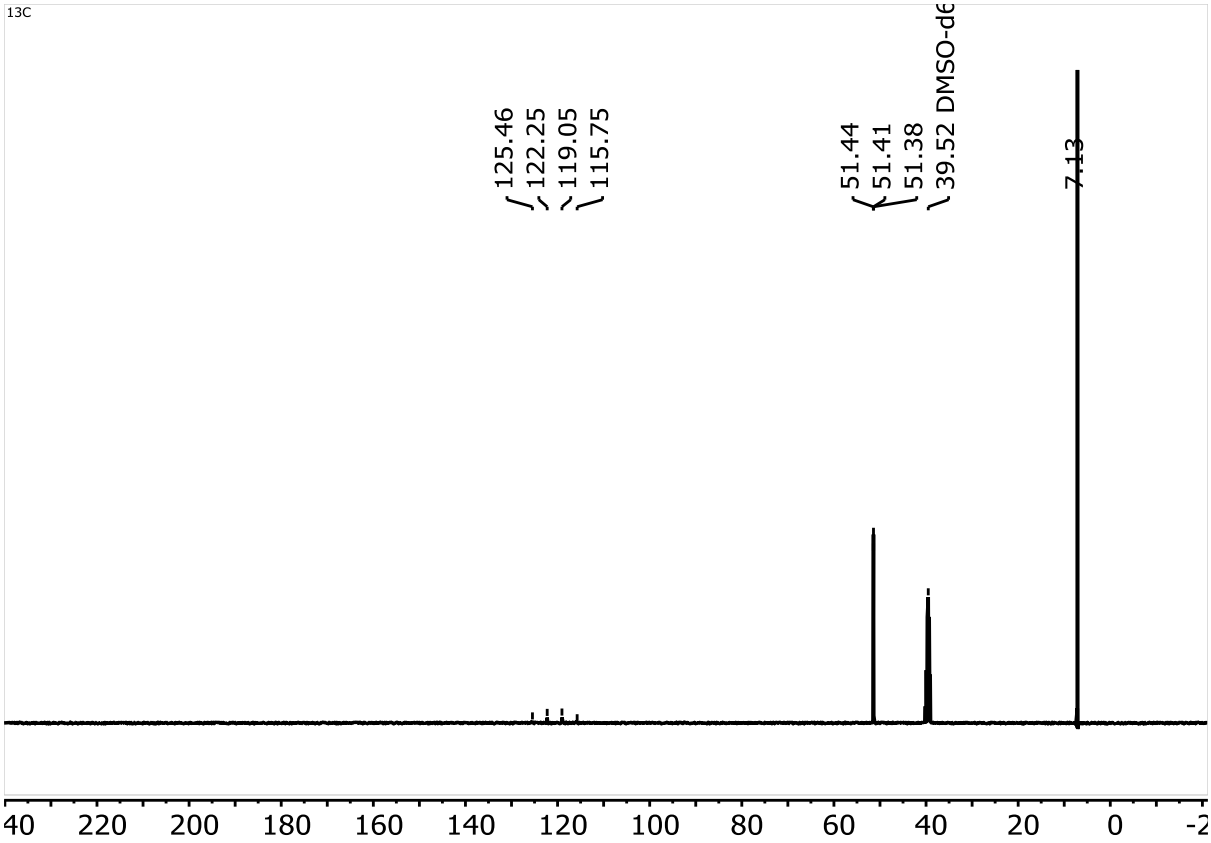


Figure S132. ^{13}H NMR of the reaction product. We observe extremely low intensity of the $[OTf]^-$ signals.

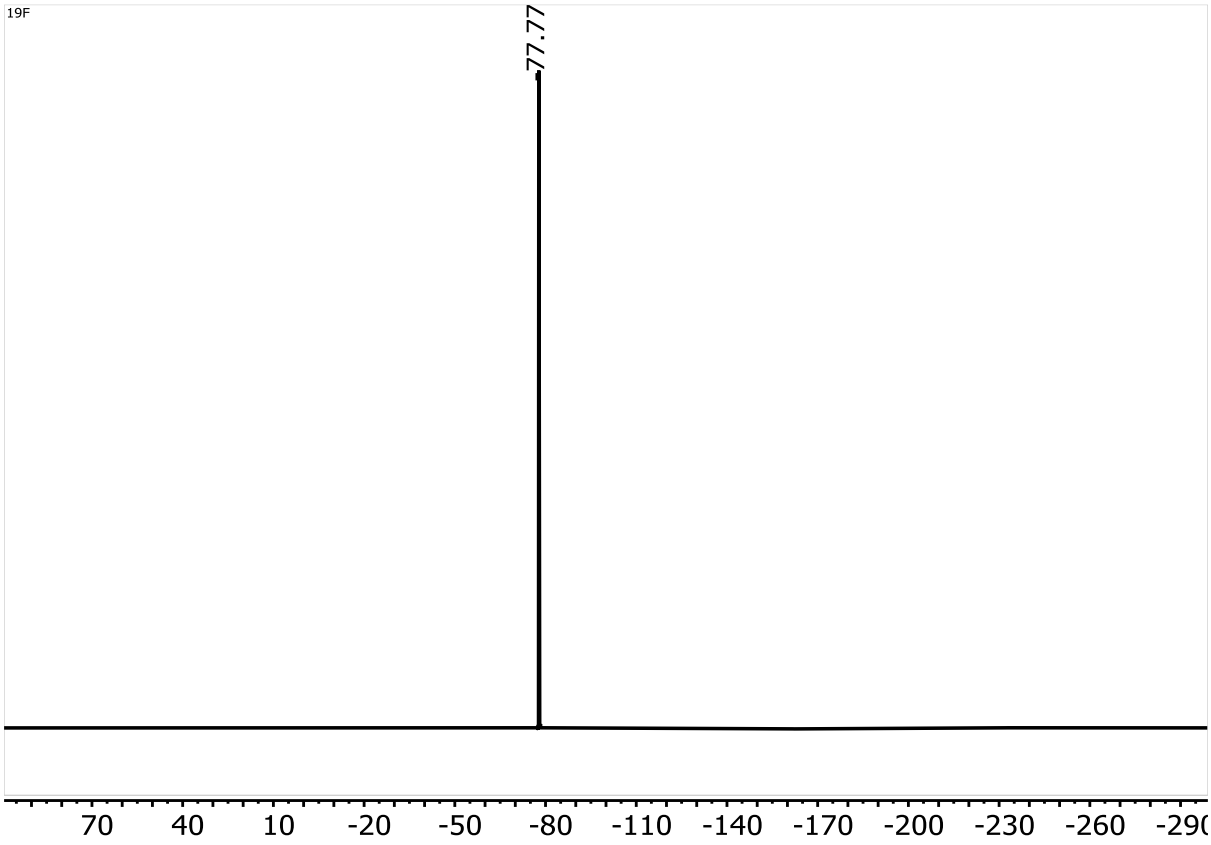


Figure S133. ^{19}F NMR of the reaction product.

Pictures

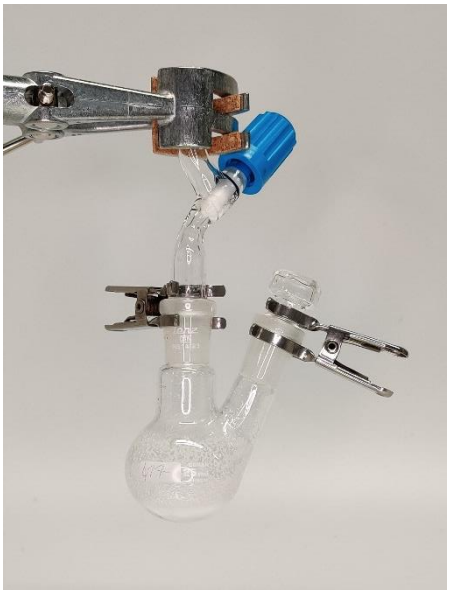
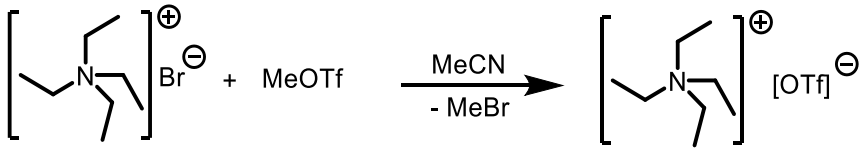


Figure S134. Reaction mixture after the addition of methyl triflate and stirring for 30 minutes.

Figure S135. Product after drying in high vacuum.

In Acetonitrile

After the failed first attempt, we followed the route adapted from the work of Szpecht et al.[32] They use acetonitrile as their solvent of choice, claiming full conversion of the starting material.



Starting Materials

Methyl triflate (≥98%, Aldrich 164283-10g ampoule)

Tetraethylammonium bromide ([N_{2222}]Br) (99% ReagentPlus, Aldrich 241059-50g)

Acetonitrile HPLC grade

All the starting materials were used as received, without further purification.

Procedure

[N_{2222}]Br (1.01 g, 4.8 mmol, 1.00 eq) was dried in a Schlenk flask under high vacuum and subsequently dissolved in acetonitrile (dried over molecular sieves before use). Methyl triflate (0.65 mL, 5.9 mmol, 1.2 eq) was added, and the resulting clear solution was stirred for 30 min. The reaction mixture was dried in high vacuum overnight, giving the final product as a white powder (1.43 g, 5.11 mmol, 106% isolated yield). The silver nitrate test was negative; however impurities were visible in the NMR spectra. Further purification was achieved by washing the solid two times with 10 mL diethyl ether each, followed by drying in high vacuum.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 1.16 (tt, $^{3}J_{H\text{-}H}$ = 7.3 Hz, $^{2}J_{H\text{-}N}$ = 1.8 Hz, 12H, N-C***H₂***-CH_3), 3.20 (q, $^{3}J_{H\text{-}H}$ = 7.2 Hz, 8H, N-CH_2-C***H₃***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 7.05 (s, N-CH_2-***C***H_3), 51.40 (t, $^{1}J_{C\text{-}N}$ = 3.1 Hz, N-***C***H_2-CH_3), 120.71 (q, $^{1}J_{C\text{-}F}$ = 322.3 Hz, ***C***F_3)

^{19}F-NMR (377 MHz, DMSO-d_6): δ / ppm = -77.78 (s, C***F₃***).

HRMS, ESI^+: m/z found 130.1598, calc. 130.1596 ($C_8H_{20}N^+$); ESI^-: m/z found 148.9520, calc. 148.9520 ($CO_3F_3S^-$).

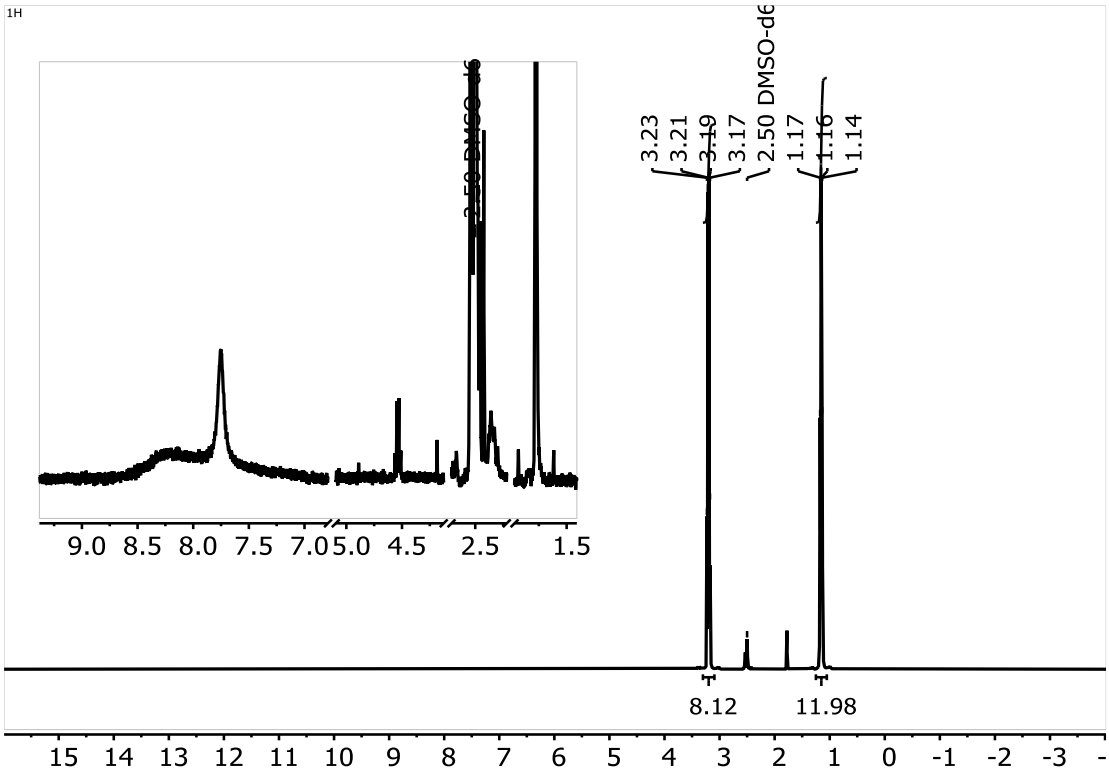


Figure S136. ^{1}H NMR of the obtained product. Zoomed in: the impurities caused due to the use of acetonitrile as the reaction solvent.

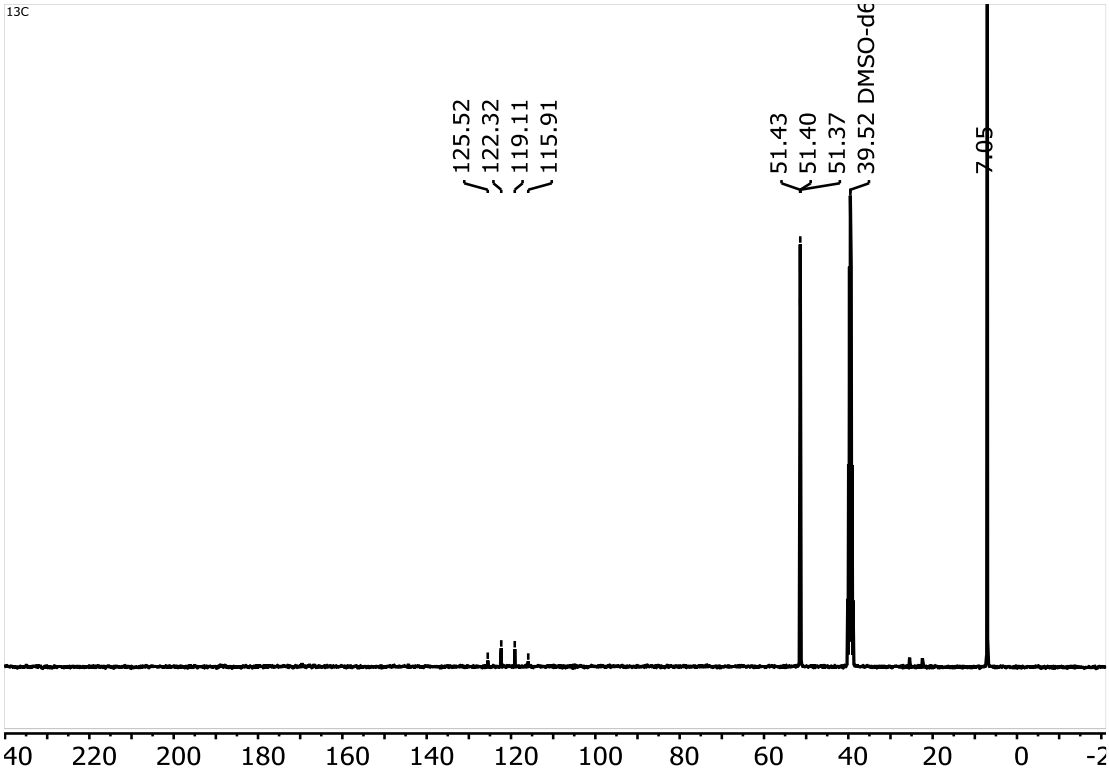


Figure S137. ^{13}C NMR of the obtained product.

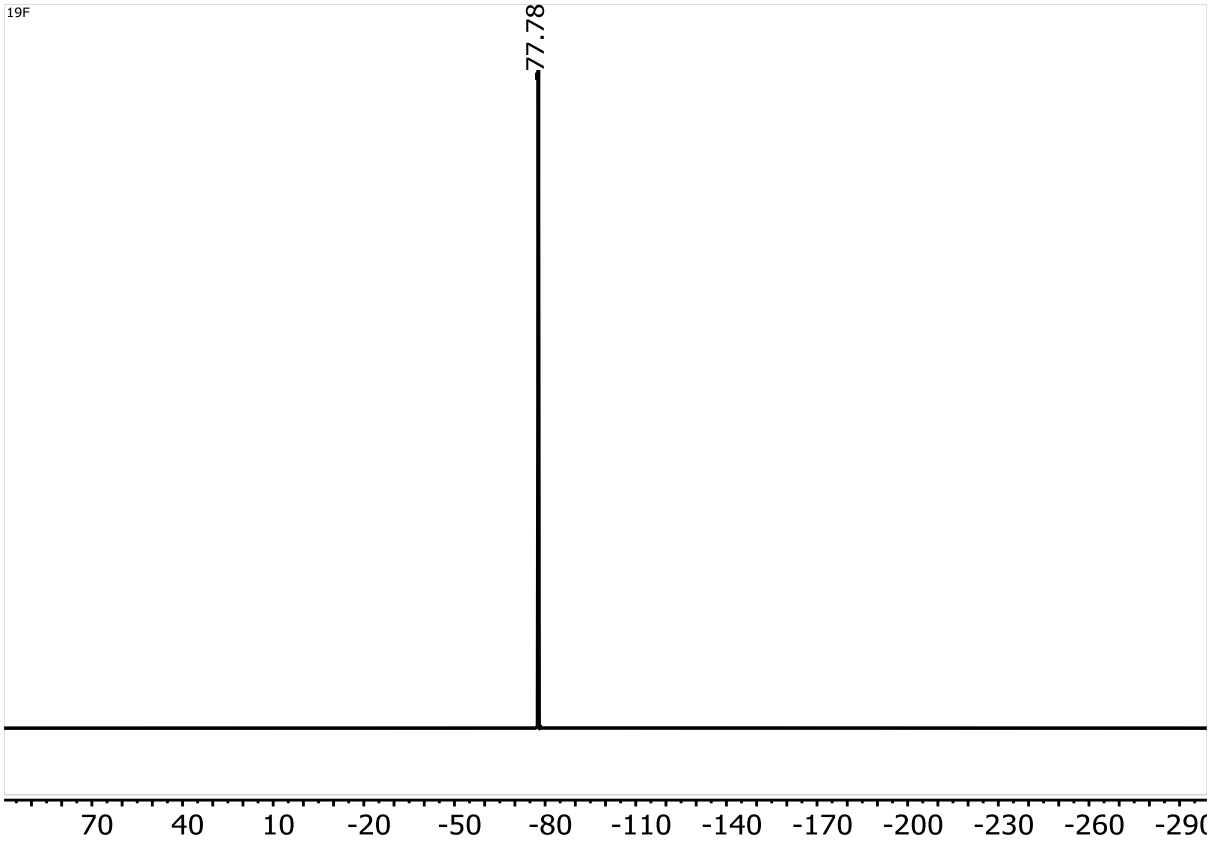


Figure S138. ^{19}F NMR of the obtained product.

Pictures

Figure S139. $[N_{2222}]Br$ dissolved in acetonitrile

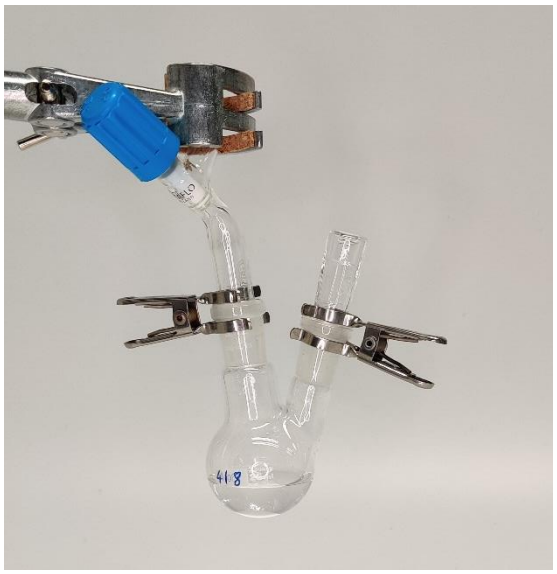
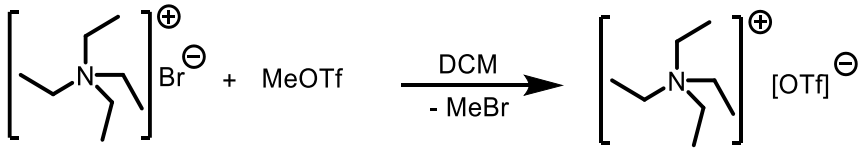


Figure S140. Crude product after reaction with methyl triflate

Figure S141. Final product after purification and drying in high vacuum.

In dichloromethane

The previous method resulted in full conversion of the starting $[N_{2222}]Br$, but also produced undesired by-products. This is expected as acetonitrile is not considered the optimum solvent for these types of reactions, since it can also react with methyl triflate.[31] Therefore, the procedure was repeated once again, this time using dichloromethane as the solvent, as this is considered sufficiently inert.



Starting Materials

Methyl triflate (≥98%, Aldrich 164283-10g ampoule)

Tetraethylammonium bromide ($[N_{2222}]Br$) (99% ReagentPlus, Aldrich 241059-50g)

Dichloromethane (GPR Rectapur, stabilised with 0.2 % ethanol)

All the starting materials were used as received, without further purification.

Procedure

The procedure was adapted from Szpecht et al.[32] and Yamaguchi et al.[31]

$[N_{2222}]Br$ (1.04 g, 4.9 mmol, 1.00 eq) was dissolved in 10 mL dichloromethane. Methyl triflate (1 mL, 1.50 g, 9.1 mmol, 1.85 eq) was added dropwise over 10 min, and the resulting clear solution was stirred at room temperature for 30 min. The solvent and excess methyl triflate were removed in high vacuum, and the product dried in high vacuum overnight. 1.46 g product were obtained, containing approximately 14 mol% or 8 % (w/w) triflic acid, as determined via ^1H NMR. The yield of the title compound is thus 1.35 g (4.8 mmol, 98% yield).

The target ionic liquid is well-soluble in water, which is also the reason why the dichloromethane / water metathesis route does not work well for $[OTf]^-$ ionic liquids. To demonstrate this, 0.7298 g of the raw product were dissolved in 10 mL dichloromethane and 3 mL water. After vigorous stirring and separation, the organic phase was washed again with 3 mL water. Then, the organic phase was

separated, and the solvent removed under reduced pressure. Thus, only 50 mg of the ionic liquid (free from HOTf) could be isolated via this method.

To remove HOTf, 0.54 g of the raw product were suspended in 5 mL diethyl ether, and after stirring for 5 min, the ether was decanted via cannula. This washing step was repeated with another 5 mL of diethyl ether, and the resulting solid dried in high vacuum. Thus, 0.45 g of acid-free ionic liquid were obtained (16% total weight loss).

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 1.16 (tt, $^{3}J_{H\text{-}H}$ = 7.3 Hz, $^{2}J_{H\text{-}N}$ = 1.9 Hz, 12H, N-C***H₂***-CH_3), 3.20 (q, $^{3}J_{H\text{-}H}$ = 7.3 Hz, 8H, N-CH_2-C***H₃***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 7.04 (s, N-CH_2-***C***H_3), 51.38 (t, $^{1}J_{C\text{-}N}$ = 3.0 Hz, N-***C***H_2-CH_3), 120.70 (q, $^{1}J_{C\text{-}F}$ = 322.2 Hz, ***C***F_3)

^{19}F-NMR (377 MHz, DMSO-d_6): δ / ppm = -77.78 (s, C***F₃***).

HRMS, ESI^{+}: m/z found 130.1595 calc. 130.1596 ($C_8H_{20}N^{+}$); ESI^{-}: m/z found 148.9526 calc. 148.9520 ($CO_3F_3S^{-}$).

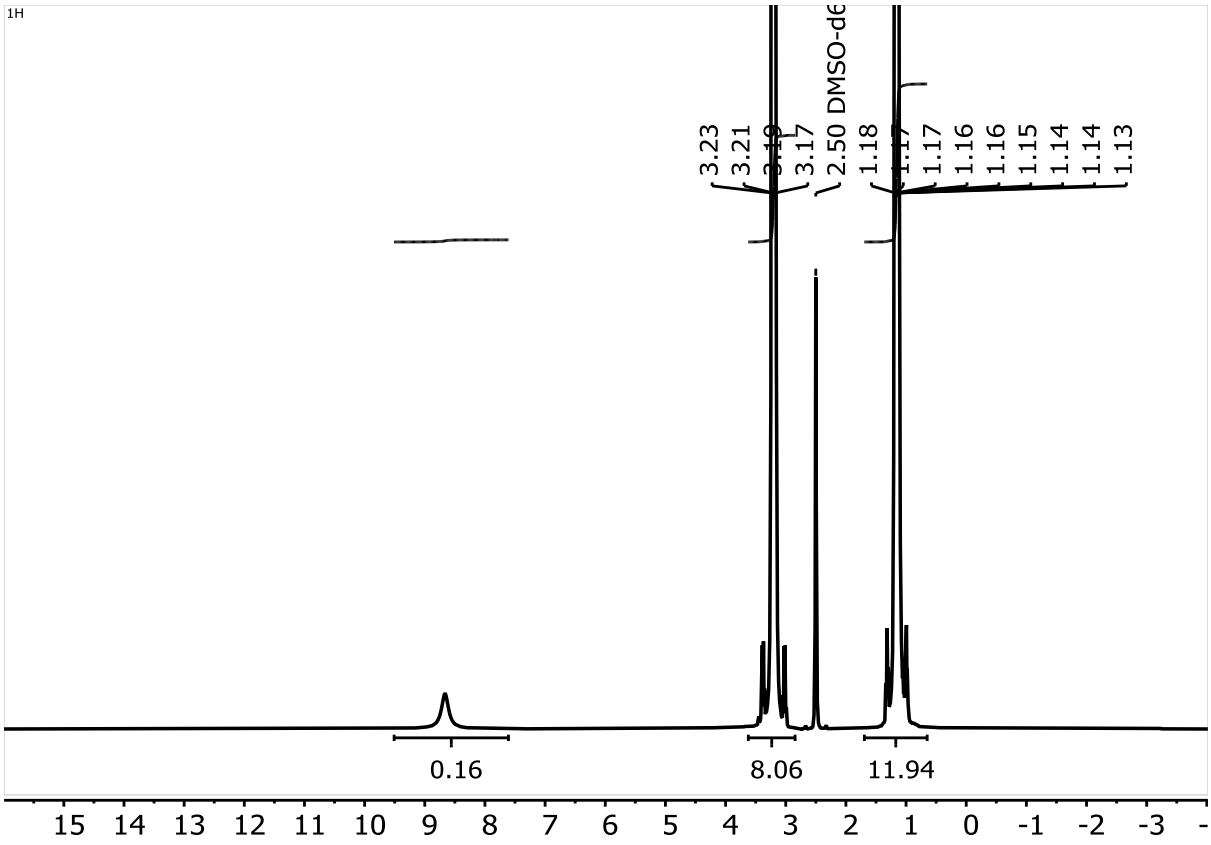


Figure S142. ^{1}H NMR of the raw product contaminated with free acid.

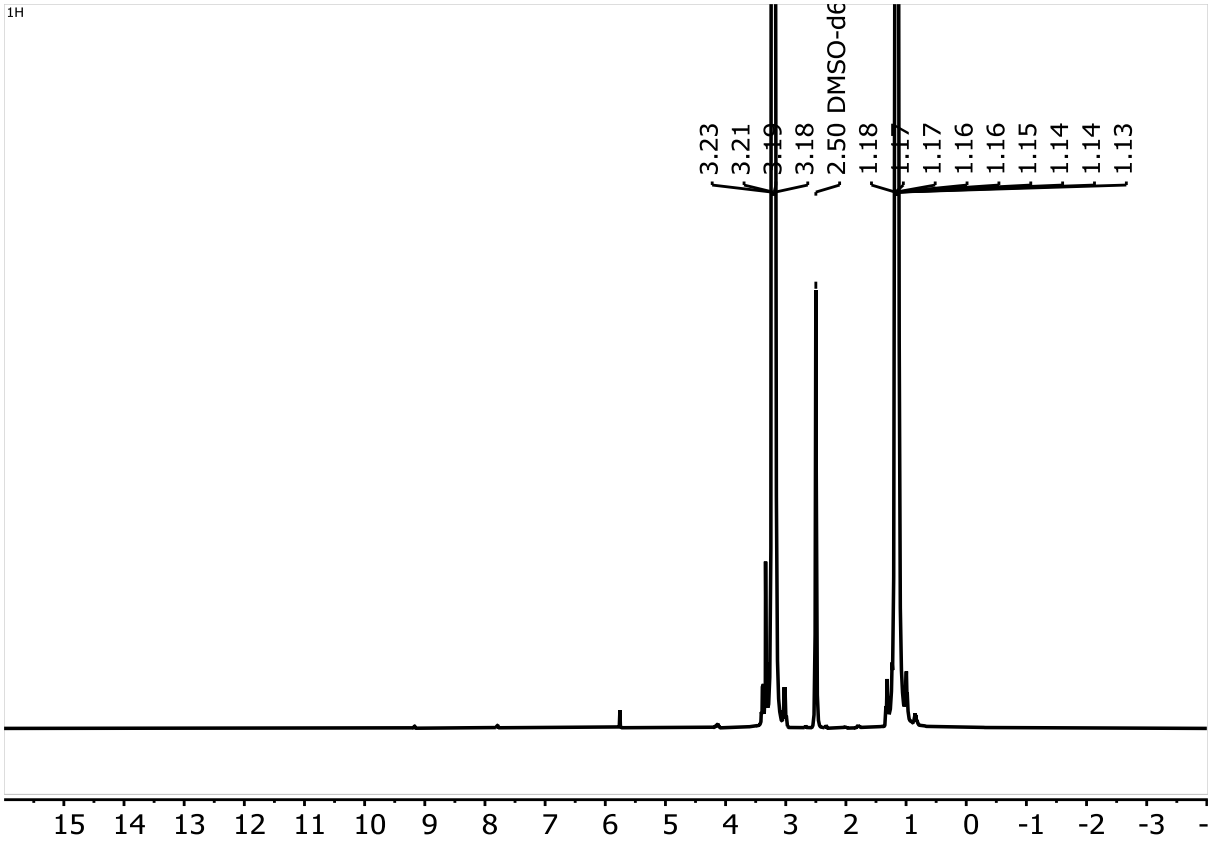


Figure S143. ^{1}H NMR of the product after washes with DCM – the acid is removed, but only under considerable losses.

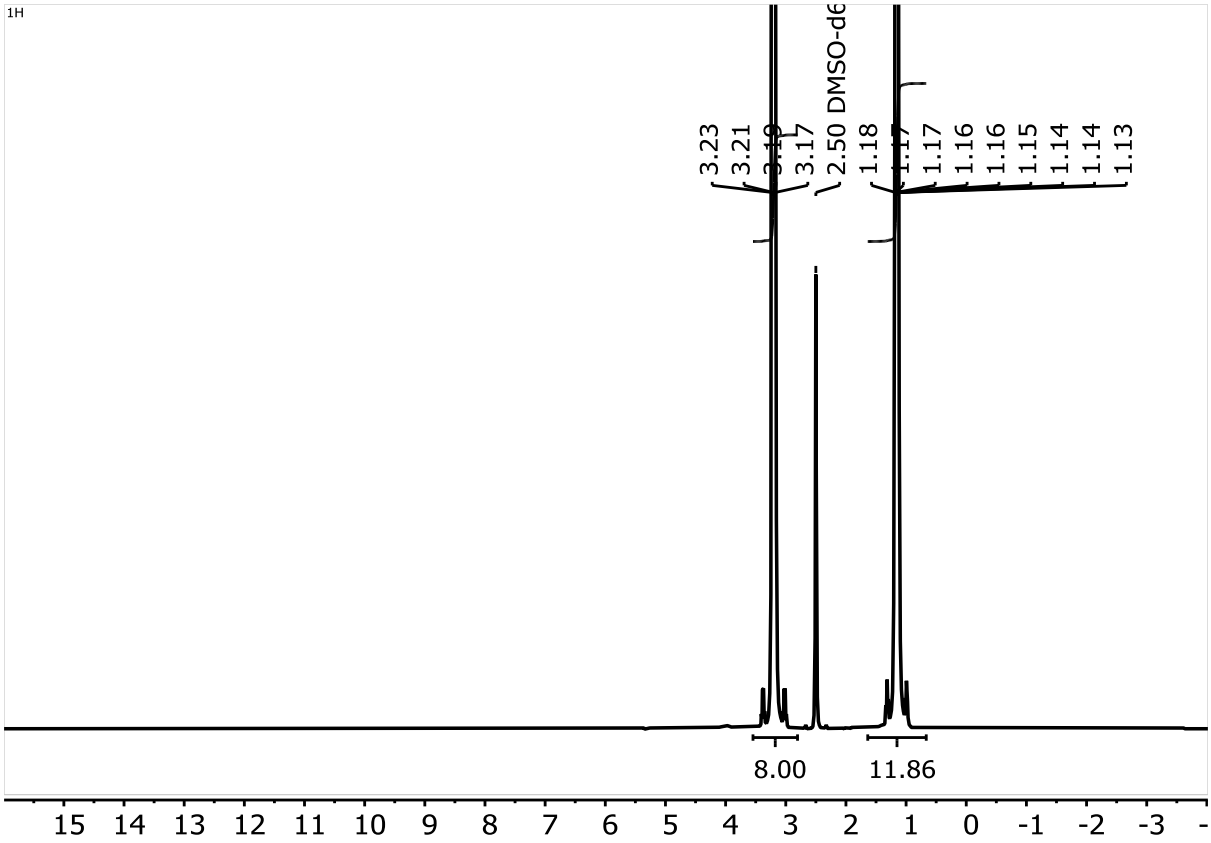


Figure S144. ^{1}H NMR of the product after the washes with ether.

Pictures

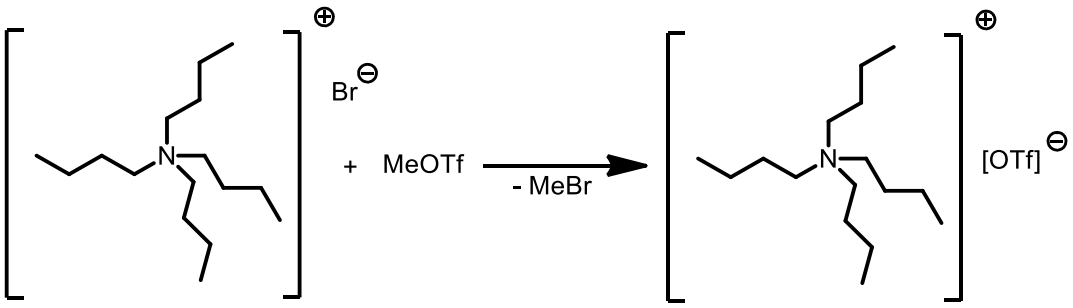
Figure S145. The reaction mixture

Figure S146. The raw product.

Tetrabutylammonium triflate [N_{4444}][OTf]

Solvent free

Route adapted from Ignat'ev et al.[30] This reaction was performed in order to demonstrate that alkyl chain length and liquefaction of the final product are crucial for the full completion of the reaction. Indeed, in this case the reaction was completed without the formation of any by-products with full conversion of the starting materials.



Starting Materials

Methyl triflate (≥98%, Aldrich 164283-10g ampoule)[31]

Tetrabutylammonium bromide ([N_{4444}]Br) (99% ReagentPlus, Aldrich 241059-50g)

All the starting materials were used as received, without further purification.

Procedure

[N_{4444}]Br (2.04 g, 6.3 mmol, 1.0 eq) was dried in a Schlenk flask under high vacuum. Methyl triflate (2.2 mL, 20.1 mmol, 3.2 eq) was added to the solid, and the resulting mixture was stirred for 40 min. During stirring, all solids were dissolved after approximately 10 min. The reaction mixture was dried in high vacuum overnight, giving a colourless viscous liquid (2.35 g, 6.0 mmol, 95% yield). The silver nitrate test was negative. Further purification was achieved by washing the solid two times with 10 mL diethyl ether each, followed by drying in high vacuum.

Characterisation

^{1}H-NMR (400 MHz, DMSO-d_6): δ / ppm = 0.93 (t, $^{3}J_{H-H}$ = 7.3 Hz, 12H, C***H₃***), 1.31 (h, $^{3}J_{H-H}$ = 7.3 Hz, 8H, C***H₂***-CH_3), 1.66-1.48 (m, 8H, C***H₂***-CH_2-CH_3), 3.25-3.05 (m, 8H, N-C***H₂***)

^{13}C{^{1}H}-NMR (101 MHz, DMSO-d_6): δ / ppm = 13.44 (s, ***C***H_3), 19.19 (s, ***C***H_2-CH_3), 23.05 (s, ***C***H_2-CH_2-CH_3), 57.52 (t, $^{1}J_{C-N}$ = 2.7 Hz, N-***C***H_2), 120.70 (q, $^{1}J_{C-F}$ = 322.6 Hz, ***C***F_3)

^{19}F-NMR (377 MHz, DMSO-d_6): δ / ppm = -77.81 (s, C***F₃***).

HRMS, ESI^+: m/z found 242.2833, calc. 242.2848 ($C_{16}H_{36}N^+$); ESI^-: m/z found 148. 9529, calc. 148.9520 ($CO_3F_3S^-$).

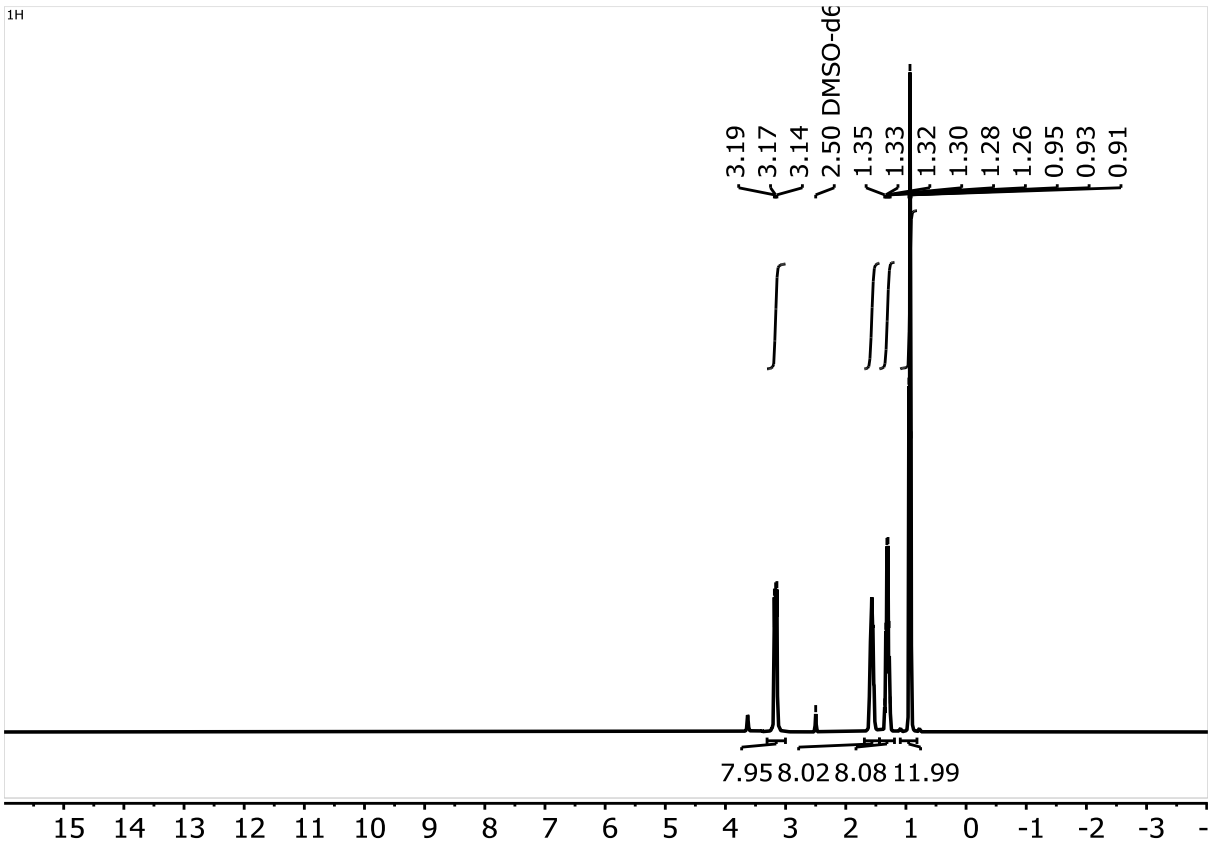


Figure S147. ^{1}H NMR of the obtained final product.

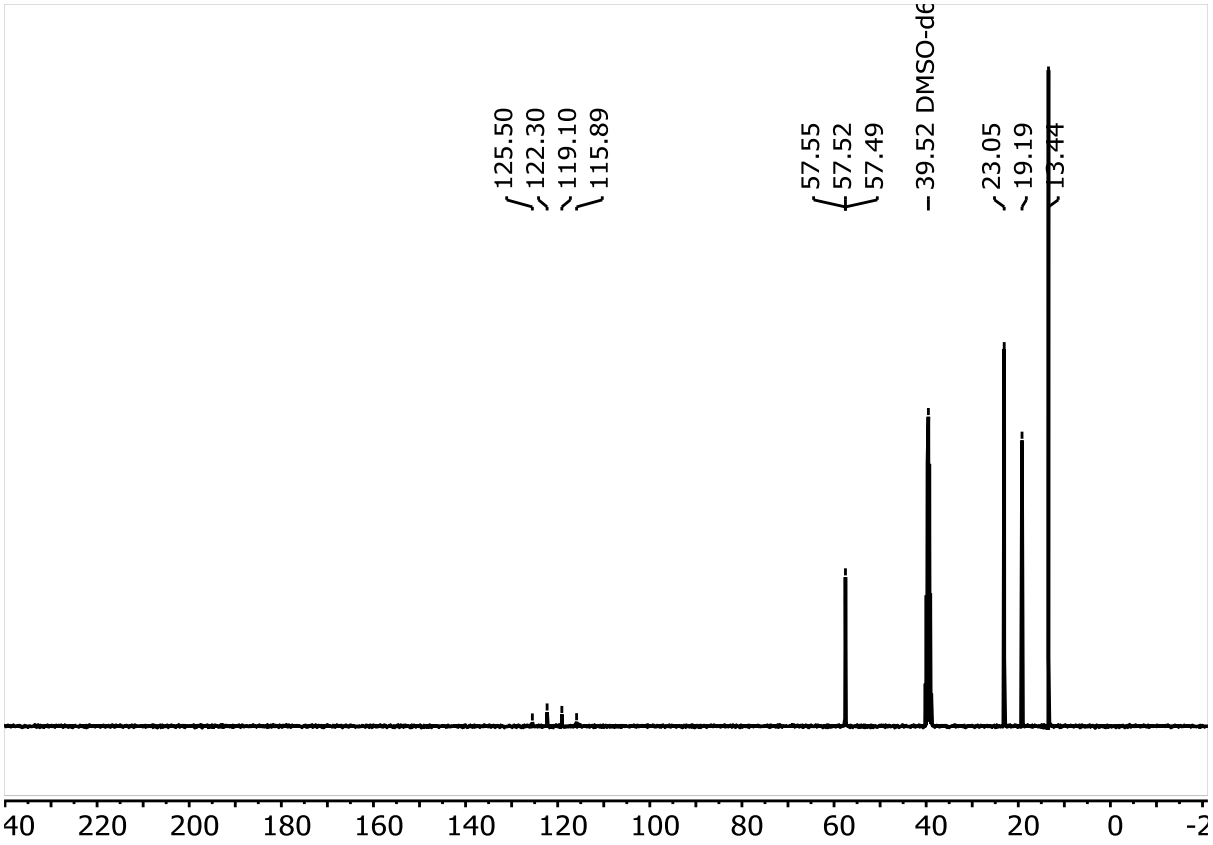


Figure S148. ^{13}C NMR of the obtained final product.

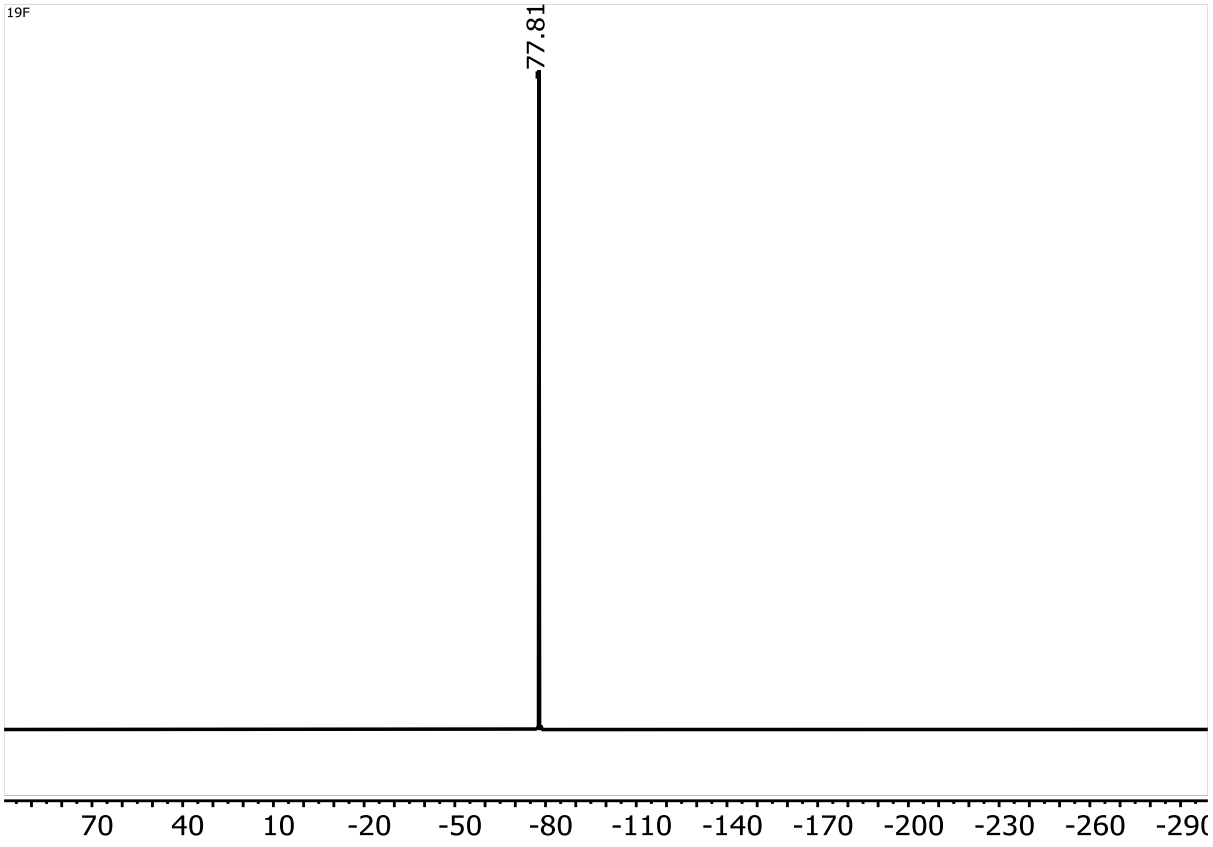


Figure S149. ^{19}F NMR of the obtained final product.

Pictures

Figure S150. Commercially bought $[N_{4444}]Br$ after drying.

Figure S151. Commercially bought methyl triflate ampule.

Figure S152. Homogeneous reaction mixture after addition of methyl triflate and stirring.

Acknowledgements

FP acknowledges funding from the President's PhD scholarship. AD thanks GlaxoSmithKline (GSK) and the Engineering and Physical Sciences Research Council (EPSRC) for funding her PhD studies. GJS thanks the National Institute for Health Research (NIHR) for funding his PhD studies. JB thanks the Defence Science and Technology Laboratory (Dstl) for funding his PhD studies.

NMR spectra were recorded at the NMR facility of Imperial College London.

The authors thank Dr. Lisa Haigh for performing the mass spectrometry measurements.

The authors thank Mr. Tommaso Costantini and Prof. Milo Shaffer (Imperial College London) for giving us access to their ultrasonic processor.

The authors thank Dr. Archie Wall and Prof. Edward Tate (Imperial College London) for giving us access to their microwave reactor.

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