Highly Active Families of Catalysts for the Ring-Opening Polymerization of Lactide: Metal Templated Organic Hydrogen Bond Donors Derived from 2-Guanidinobenzimidazole

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Contents

DETAILS OF SYNTHESES

General. Reactions were conducted under N_2 using standard Schlenk techniques. Work-ups were carried out in air. Chemicals were treated as follows: CH_2Cl_2 and toluene (2 × Fisher Scientific; for reactions), dried and degassed using a Glass Contour solvent purification system; CH_2Cl_2 (EMD Chemicals; for chromatography/workups), hexanes (Macron Chemicals), MeOH (BDH), $CDCl_3$, DMSO-d_6 and acetone-d_6 (3 × Cambridge Isotope Laboratories), 2-guanidinobenzimidazole (GBI), $CoCl_2 \cdot 6H_2O$, $CyNMe_2$, NEt_3, 1,2,2,6,6-pentamethylpiperidine (PMP), $Me_2N(CH_2)_2NMe(CH_2)_2NMe_2$ (PMDETA), 4-phenylbenzyl alcohol (InOH), and DL-lactide (6 × Sigma Aldrich) were used as received. [(η^5-C_5H_5)Ru(CO)(GBI)](BAr$_f$) (**2**$^+$ BAr$_f^-$; BAr$_f$ = B(3,5-$C_6H_3(CF_3)_2)_4$) was prepared as described previously.[s1]

NMR spectra were recorded on Varian NMRS 500 MHz or Bruker (cryoprobe) 500 MHz spectrometers at ambient probe temperatures and referenced as follows (δ/ppm): ^{1}H, residual internal $CHCl_3$ (7.26), DMSO-d_5 (2.50), or acetone-d_5 (2.04); ^{13}C, internal $CDCl_3$ (77.20), DMSO-d_6 (40.45) or acetone-d_6 (205.87 and 30.60). IR spectra were recorded using a Shimadzu IRAffinity-1 spectrometer with a Pike MIRacle ATR system (diamond/ZnSe crystal). UV-vis spectra were recorded using a Shimadzu UV-1800 spectrophotometer. Microanalyses were conducted by Atlantic Microlab.

Size Exclusion Chromatography (SEC) was performed on a Waters instrument equipped with a model 1515 isocratic HPLC pump, an inline degasser, and a model 2414 differential refractometer using four PLgel polystyrene-co-divinylbenzene gel columns (Polymer Laboratories, Inc.) connected in series (THF eluent, 1.00 mL/min flow rate, 35 °C). Data were analyzed using the program Breeze (version 3.30, Waters). The concentrations of all polymer solutions were ca. 3 mg/mL. Analyses were conducted with the program Discovery32 (Precision Detectors, Inc.) using a system calibration curve generated by plotting molecular weight as a function of retention time for a series of broad polydispersity polystyrene standards.

MALDI−TOF MS experiments were performed on a Voyager DE-STR mass spectrometer (Applied Biosystems) under optimized conditions in positive linear mode. Ions were generated

by a pulsed nitrogen laser at 337 nm and accelerated through 25 kV. A total of 100 laser shots were used per spectrum. The matrix *trans*-3-indoleacrylic acid (IAA) and cationization agent NaI were employed. The sample and matrix were separately dissolved in THF (10 mg/mL) and the solutions mixed (volume ratio 1:1). About 0.5 μL of this solution was deposited on a stainless steel sample holder, which was air dried prior to MALDI-TOF MS analysis.

$[Co(GBI)_3](Cl)_3 \cdot 3H_2O$. (**$1^{3+}$** $3Cl^-$).[s2] A round bottom flask was fitted with a condenser and charged with a purple solution of $CoCl_2 \cdot 6H_2O$ (0.206 g, 1.60 mmol) in methanol (20 mL). Then a solution of GBI (0.839 g, 4.79 mmol, 3 equiv) in methanol (30 mL) was added with stirring. The red mixture was refluxed. After 24 h, the sample was cooled. After 24 h, the precipitate was collected by filtration and dried by oil pump vacuum to give **1^{3+}** $3Cl^-$ as a red solid (0.707 g, 1.02 mmol, 64%), mp (capillary) 237-238 °C.

NMR (DMSO-d_6 δ/ppm): ^{1}H (500 MHz)[s3] 7.24, 6.96 (2 m, 2(2H) of 3 *o*-$C_6\underline{\mathbf{H}}_4$), 7.17, 7.09, 5.57 (3 m, 3(1H) of 3 *o*-$C_6\underline{\mathbf{H}}_4$), 6.94-6.78 (m, 3H of 3 *o*,*m*-$C_6\underline{\mathbf{H}}_4$), 6.64 (apparent s, 1H of 3 *m*-$C_6\underline{\mathbf{H}}_4$), 6.38-6.27 (m, 7H,[s3] 1H of 3 *m*-$C_6\underline{\mathbf{H}}_4$ and overlapping N**H** signals), 4.81, 4.52, 4.06 (3 br s, 3(2H), 3 N$\underline{\mathbf{H}}_2$), 3.17 (br s, 6H, 3 $\underline{\mathbf{H}}_2$O); ^{13}C{^{1}H} (125 MHz) 159.3, 156.9, 156.7 (3 s, 3 N=$\underline{\mathbf{C}}(NH)_2$), 153.2, 152.5, 150.2 (3 s, 3(NH=$\underline{\mathbf{C}}NH_2$)), 141.1, 140.7, 140.3 (3 s, 3 HNCCH-CHCHCH$\underline{\mathbf{C}}$N), 138.2, 137.4, 135.9 (3 s, 3 HN$\underline{\mathbf{C}}$CHCHCHCHCN), 120.7, 120.3, 119.3, 119.0 (4 s (two peaks obscured or overlapping), 3 NCCH$\underline{\mathbf{C}}$H$\underline{\mathbf{C}}$HCHCN), 115.4, 113.9, 112.2, 112.0, 111.8, 111.2 (6 s, 3 NC$\underline{\mathbf{C}}$HCHCH$\underline{\mathbf{C}}$HCN). The preceding NMR assignments were confirmed by the 2D spectra depicted below and agreed with those given earlier.[s2a,s3]

IR (thin film, cm^{-1}): 3214 (m, ν_{N-H}), 1668 (s, $\nu_{C=N}$), 1602 (s, $\nu_{C=C}$), 1566 (s, $\nu_{C=C}$), 1462 (m, $\nu_{C=C}$), 1455 (m, δ_{NH}), 1208 (s, ν_{CN}), 1050 (s, ν_{CCN}), 754 (s, δ_{CH}). UV-vis (DMSO): λ_{max} 516 nm (ε 343 mol^{-1} dm^3 cm^{-1}).

$[Co(GBI)_3](BAr_f)_3 \cdot xH_2O$ (**1^{3+}** $3BAr_f^-$), x = 14 ± 1. A round bottom flask was charged with a solution of $AgBAr_f$ (2.91 g, 2.99 mmol, 3 equiv)[s4] in CH_2Cl_2 (25 mL). Then a solution of **1^{3+}** $3Cl^-$ (0.690 g, 0.927 mmol) in water (20 mL) was added, the picture in Figure 1s was taken, and the mixture vigorously stirred.. After 15 min, the stirring was stopped (see Figure 2s), the red

CH_2Cl_2 phase was separated from the aqueous phase, and the CH_2Cl_2 was allowed to evaporate in a hood overnight to give $\mathbf{1}^{3+}$ $3BAr_f^-$ as a red powder (2.70 g, 0.850 mmol, 85%), mp (capillary) 118-119 °C. Anal. Calcd. for $C_{120}H_{91}B_3CoF_{72}N_{15}O_{14}$ (3425.17): C, 45.41; H, 2.65; N, 6.62. Found: C, 45.33; H, 2.65; N, 6.61.

Figure S1. Biphasic mixture after gentle addition of CH_2Cl_2 solution of $AgBAr_f$ (14.1×10^{-2} M, 40 mL) to aqueous solution of $\mathbf{1}^{3+}$ $3Cl^-$ (3.25 M, 40 mL).

Figure S2. Biphasic mixture 2 h after stirring was halted.

NMR (acetone-d_6 δ/ppm):^{1}H (500 MHz) BAr_f at 7.78 (s, 24H, *o*), 7.67 (s, 12H, *p*); 7.51, 7.45, 7.38, 7.30, 7.20, 5.83 (6 d, J = 10 Hz, 6(1H), 3 *o*-$C_6\underline{\mathbf{H}}_4$), 7.18, 7.09, 7.05, 7.01, 6.86, 6.64, (6 t, J = 10 Hz, 6(1H), 3 *m*-$C_6\underline{\mathbf{H}}_4$), 6.79, 6.44, 6.37 (3 br s, 3(1H), 3 CN**H**C(NH)=NH_2), 5.51, 5.10, 4.60 (3 br s, 3(2H),[s5] 3 N$\underline{\mathbf{H}}_2$), 3.57 (br s, ca. 28H, 14 $\underline{\mathbf{H}}_2$O); ^{13}C{^{1}H} (125 MHz) BAr_f at 163.1 (q, $^1J_{CB}$ = 50 Hz, *i*-$\underline{\mathbf{C}}_6H_3(CF_3)_2$), 135.5 (s, *o*-$\underline{\mathbf{C}}_6H_3(CF_3)_2$), 130.1 (q, $^2J_{CF}$ = 31.3 Hz, *m*-$C_6H_3(\underline{\mathbf{C}}F_3)_2$), 128.6 (q, $^1J_{CF}$ = 271.3 Hz, $\underline{\mathbf{C}}F_3$), 118.4 (s, *p*-$\underline{\mathbf{C}}_6H_3(CF_3)_2$); 160.2, 158.0, 157.5 (3 s, 3 N=$\underline{\mathbf{C}}(NH)_2$), 151.4, 151.0, 148.4 (3 s, 3 NH=$\underline{\mathbf{C}}NH_2$), 140.2, 140.1, 139.4 (3 s, 3 HNCCH-CHCHCH$\underline{\mathbf{C}}$N), 134.5, 134.4, 134.0 (3 s, 3 HN$\underline{\mathbf{C}}$CHCHCHCHCN), 124.1, 123.6, 122.9, 122.8, 122.7, 122.4 (6 s, 3 NCCH$\underline{\mathbf{C}}$H$\underline{\mathbf{C}}$HCHCN), 117.3, 115.9, 113.7, 112.7, 112.4, 111.7 (6 s, 3 NC-$\underline{\mathbf{C}}$HCHCH$\underline{\mathbf{C}}$HCN).

IR (thin film, cm^{-1}): 3420, 3380 (m, ν_{N-H}), 1681 (s, $\nu_{C=N}$), 1568, 1525, 1463 (m, $\nu_{C=C}$), 1354 (s, ν_{CF_3}), 1275 (vs, ν_{CF}), 1112 (vs, ν_{CN}), 1103 (vs, ν_{C-C}), 837 (m, $\nu_{1,3,5\text{-trisubs. benzene}}$), 745

and 690 (s, δ_{CH}). UV-Vis (CH_2Cl_2): λ_{max} 548 nm (ε 387 mol^{-1} dm^3 cm^{-1}).

Polymerizations. A (Table 1).[s6] A Schlenk tube was successively charged with DL-lactide (0.072 g, 0.50 mmol), $\mathbf{1}^{3+}$ $3BAr_f^-$ or $\mathbf{2}^+$ BAr_f^- (HBD, 1 or 3 mol%), 4-phenylbenzyl alcohol (InOH, 1 or 3 mol%), dry CH_2Cl_2 (0.5 mL), the H-bond acceptor (HBA, 1 or 3 mol%), and activated 4Å molecular sieves (5 beads), and charged with N_2. The mixture was stirred for 24 h at room temperature. Then benzoic acid (1 or 3 mol%) was added to quench the polymerization. The mixture was filtered and concentrated *in vacuo*. The conversion was calculated by integrating the NMR signals of the Me**H**(C=O) methine protons in the residual monomer and polymer (δ/ppm 5.03 (q, J = 6 Hz) and 5.19 (m); Figure s25 below). Molar masses and dispersities of the crude polymers were measured by SEC. **B** (Table 2).[s6] A Schlenk tube was successively charged with DL-lactide (0.072 g, 0.50 mmol), $\mathbf{1}^{3+}$ $3BAr_f^-$ or $\mathbf{2}^+$ BAr_f^- (2 or 4 mol%), 4-phenylbenzyl alcohol (2 or 4 mol%), dry CH_2Cl_2 (0.5 mL), the H-bond acceptor (2 or 4 mol%) and activated 4Å molecular sieves (5 beads), and charged with N_2. The mixture was stirred for 24 h at room temperature. After 24 h and again after 48 h, the same quantity of DL-lactide was added. After 72 h, benzoic acid (2 or 4 mol%) was added. The mixture was filtered, concentrated *in vacuo*, and analyzed as in **A**.

MALDI-TOF SPECTRA

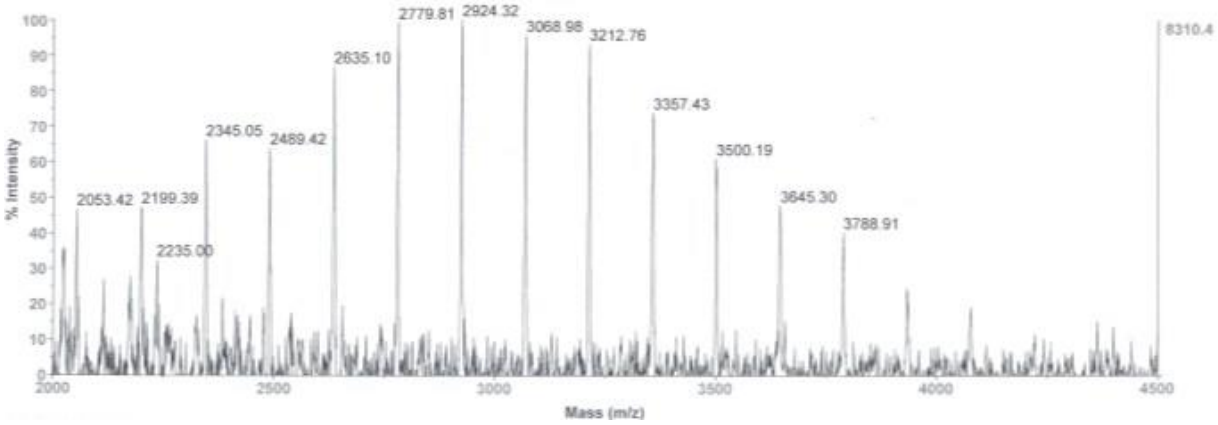


Figure S3. MALDI-ToF mass spectrum of polylactide obtained under the general conditions of Table 1 using DL-lactide, $\mathbf{1}^{3+}$ $3BAr_f^-$, PMP, and InOH (100:2:2:2).

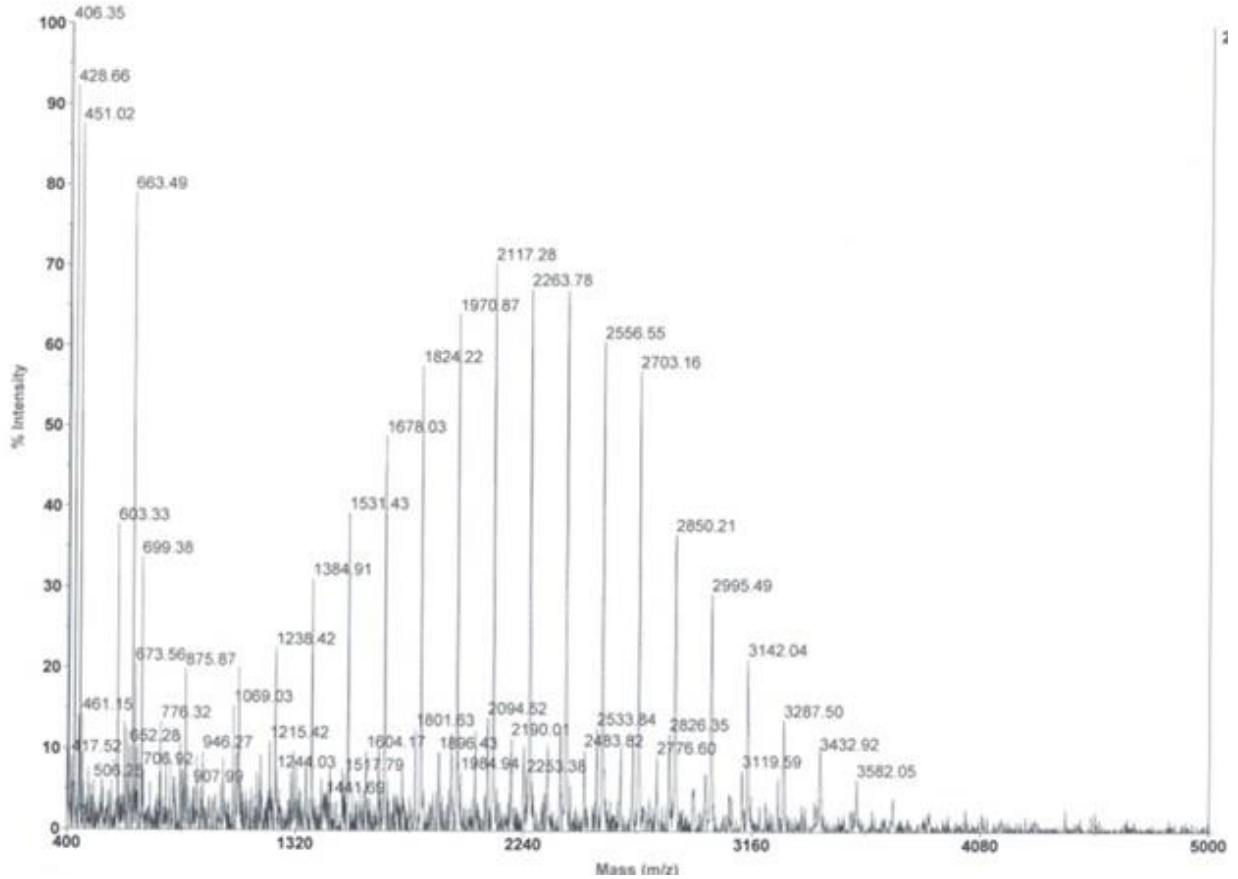


Figure S4. MALDI-ToF mass spectrum of polylactide obtained from entry 14 of Table 2 (DL-lactide, $\mathbf{1}^{3+}$ $3BAr_f^-$, PMP, InOH, 50:4:4:4).

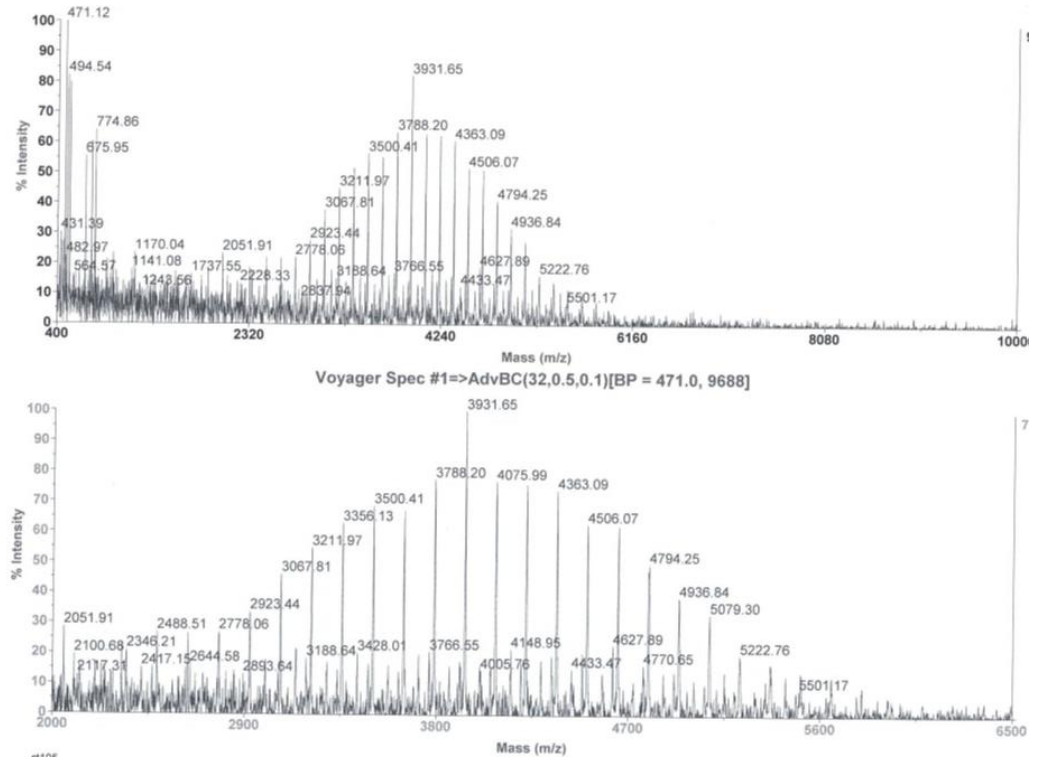


Figure S5. MALDI-ToF mass spectrum of polylactide obtained from entry 15 of Table 2 (DL-lactide, $\mathbf{1}^{3+}$ 3BAr$_f^-$, PMP, InOH, 100:4:4:4).

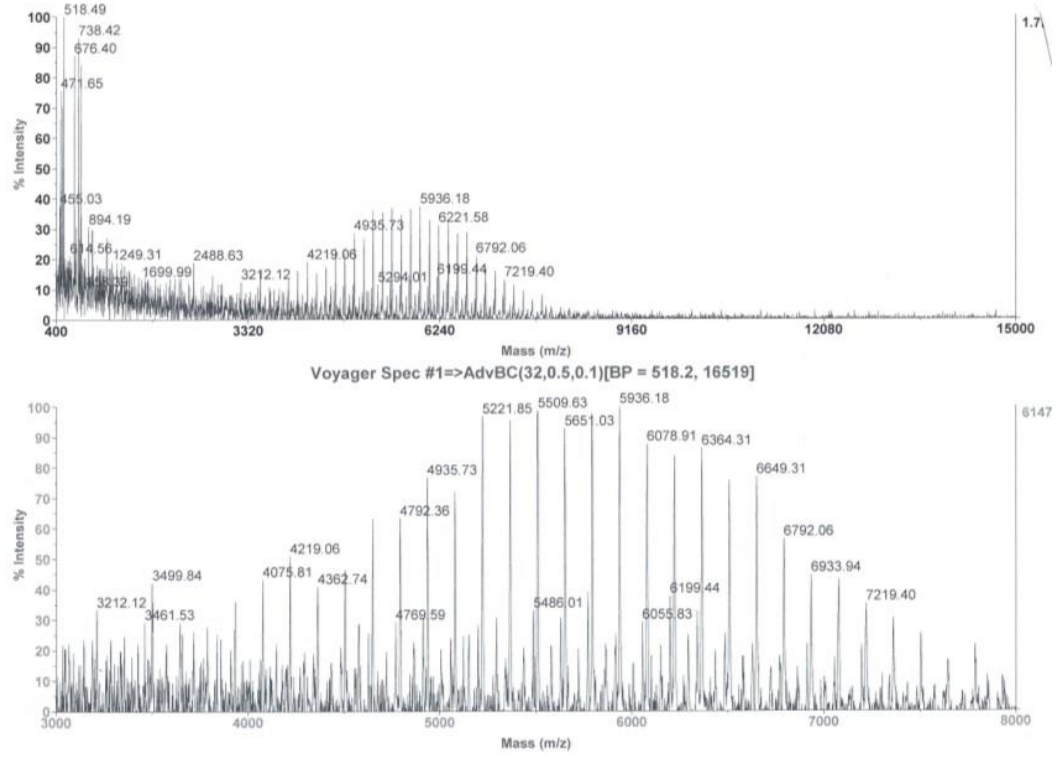


Figure S6. MALDI-ToF mass spectrum of polylactide obtained from entry 16 of Table 2 (DL-lactide, $\mathbf{1}^{3+}$ 3BAr$_f^-$, PMP, InOH, 150:4:4:4).

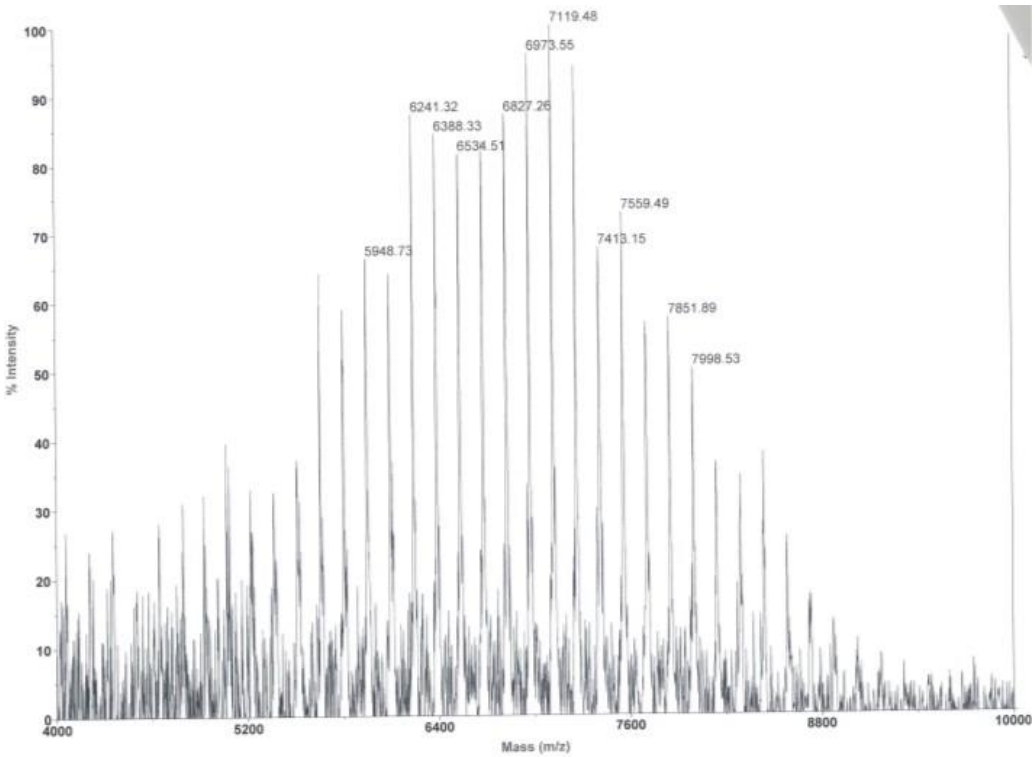


Figure S7. MALDI-ToF mass spectrum of polylactide obtained from entry 9 of Table 1 (DL-lactide, $\mathbf{2}^{+}$ BAr_f^{-}, PMP, InOH, 100:1:1:1).

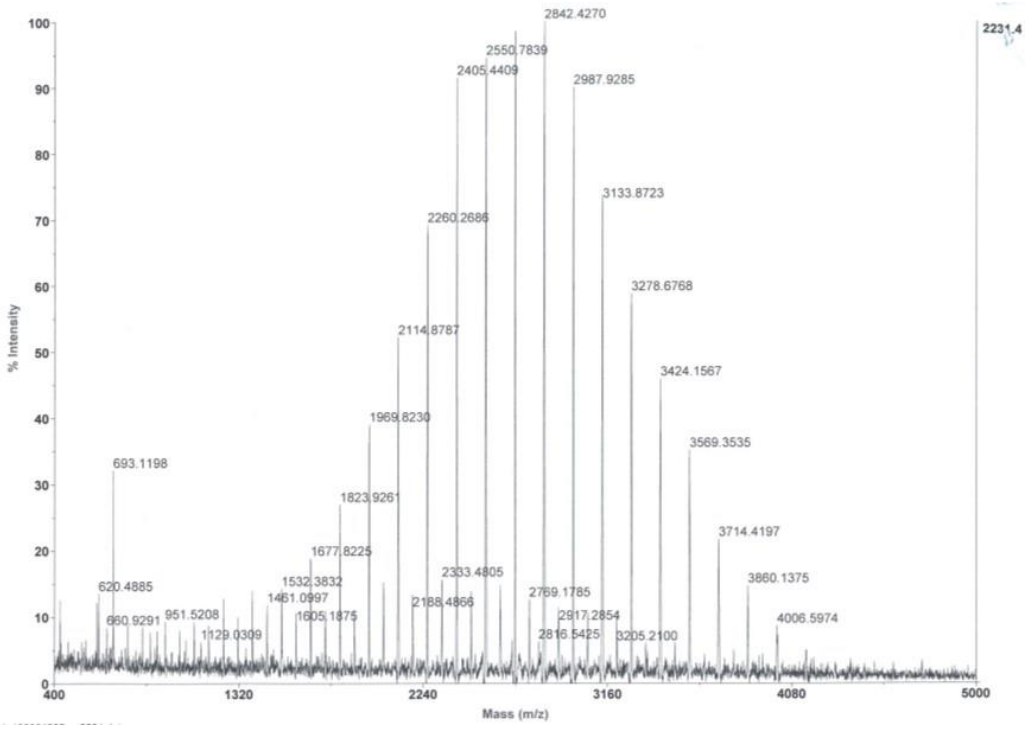


Figure S8. MALDI-ToF mass spectrum of polylactide obtained from entry 17 of Table 2 (DL-lactide, $\mathbf{2}^{+}$ BAr_f^{-}, PMP, InOH, 50:2:2:2).

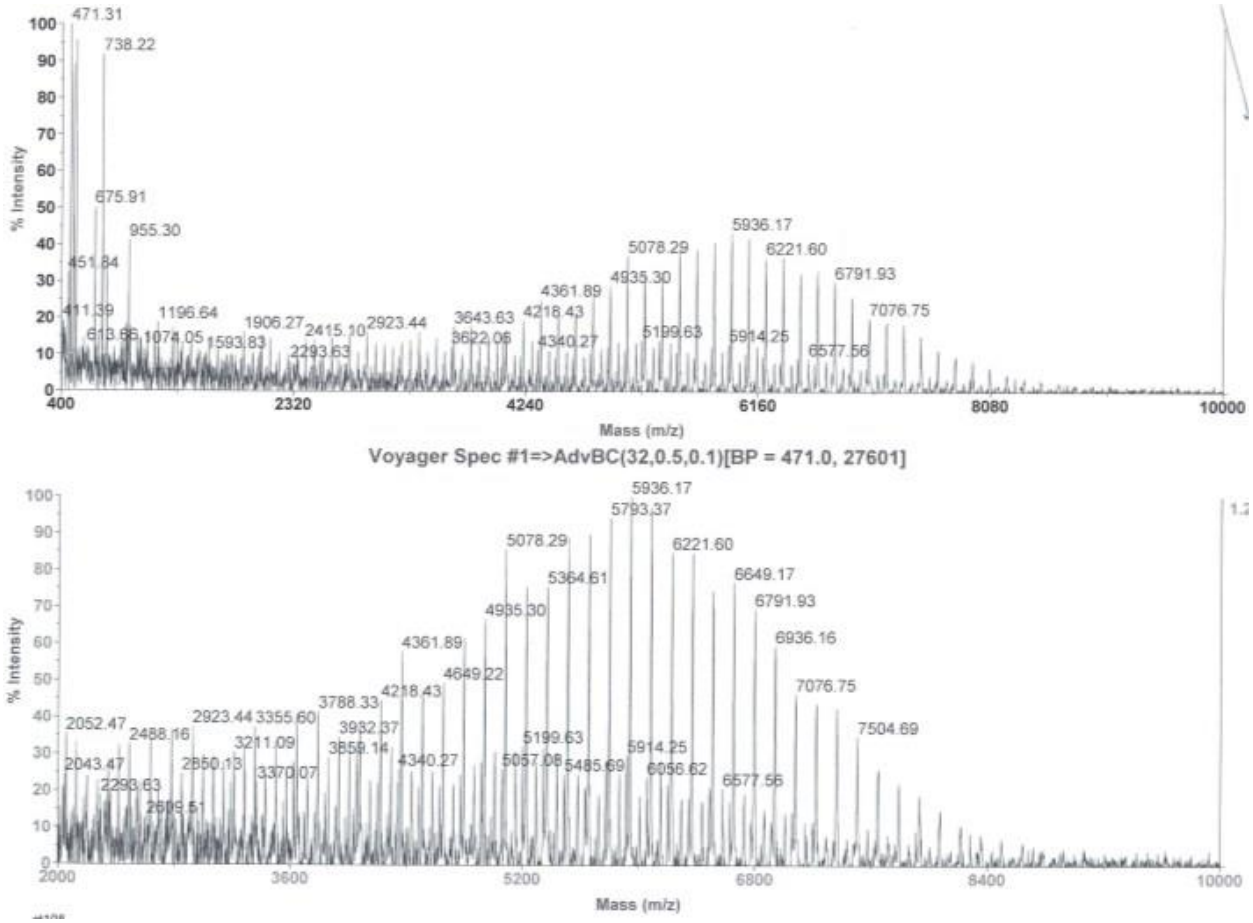


Figure S9. MALDI-ToF mass spectrum of polylactide obtained from entry 18 of Table 2 (DL-lactide, $\mathbf{2}^{+}$ BAr_f^{-}, PMP, InOH, 100:2:2:2).

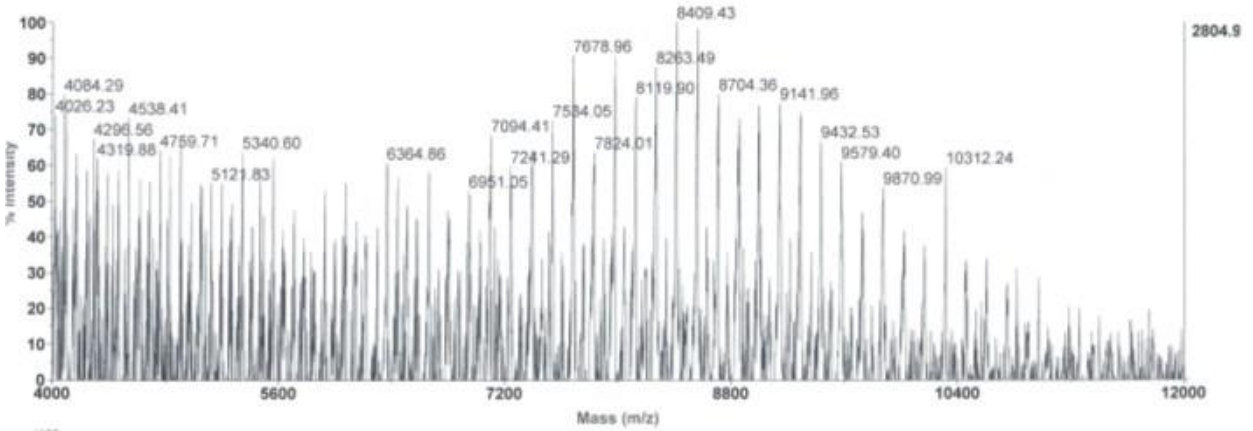


Figure S10. MALDI-ToF mass spectrum of polylactide obtained from entry 19 of Table 2 (DL-lactide, $\mathbf{2}^{+}$ BAr_f^{-}, PMP, InOH, 150:2:2:2).

SIZE EXCLUSION CHROMATOGRAPHY (SEC)

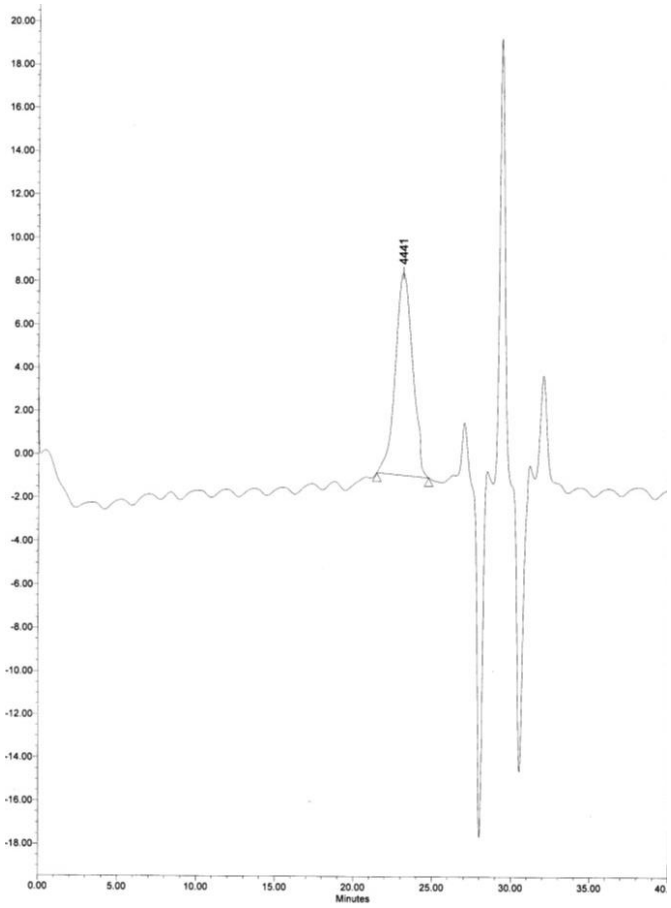


Figure S11. SEC trace of polylactide obtained from entry 4 of Table 1.

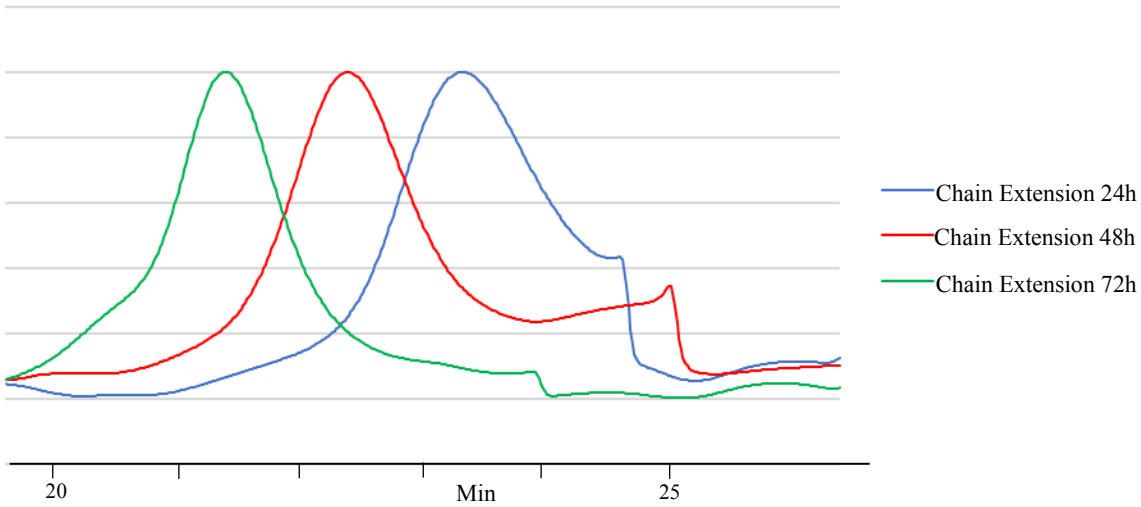


Figure S12. SEC trace of polylactides obtained from entries 15-17 of Table 2

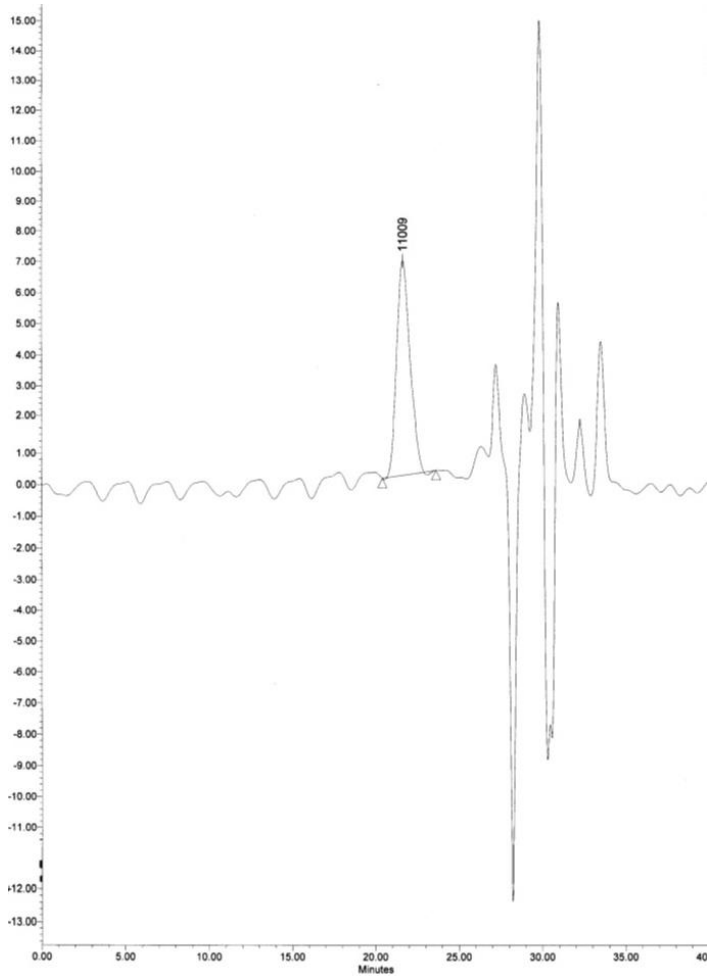


Figure S13. SEC trace of polylactide obtained from entry 10 of Table 1.

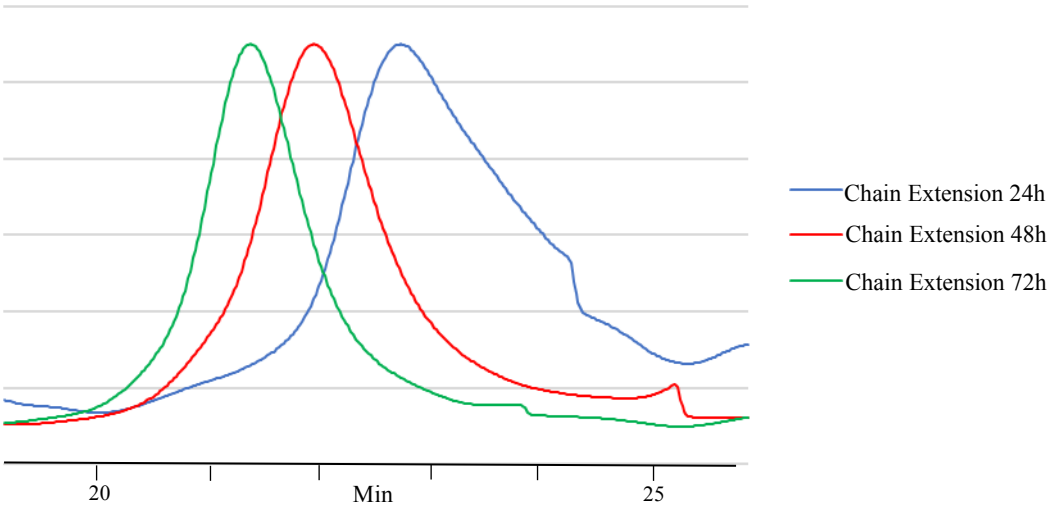


Figure S14. SEC trace of polylactides obtained from entries 18-20 of Table 2.

RATE MONITORING

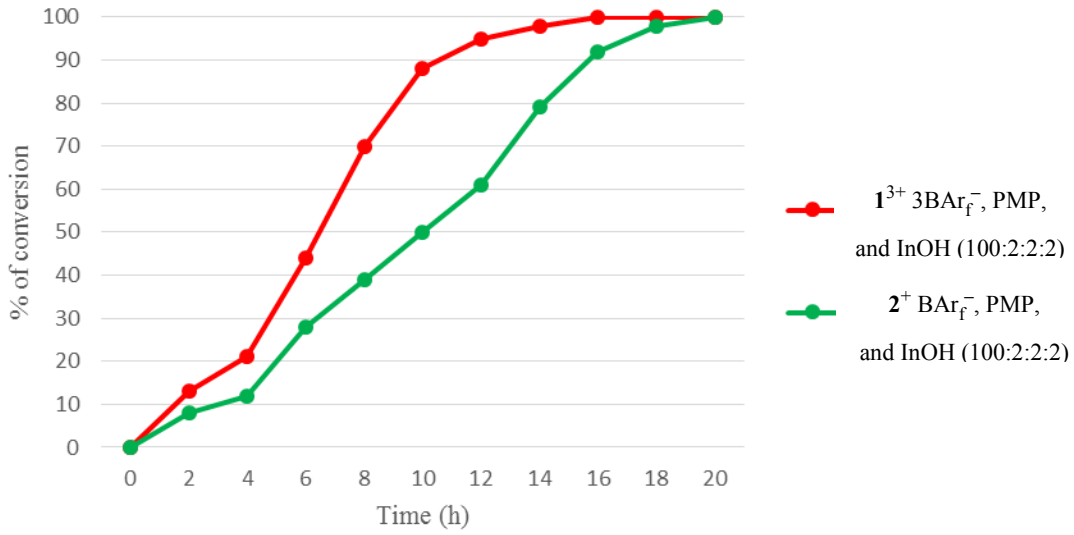


Figure S15. Rate profile for the reaction of DL-lactide, $\mathbf{1}^{3+}$ $3BAr_f^-$, PMP, and InOH (100:2:2:2) (red line) and $\mathbf{2}^{+}$ BAr_f^-, PMP, and InOH (100:2:2:2) (green line) under conditions similar to those used in Table 1.

NMR SPECTRA

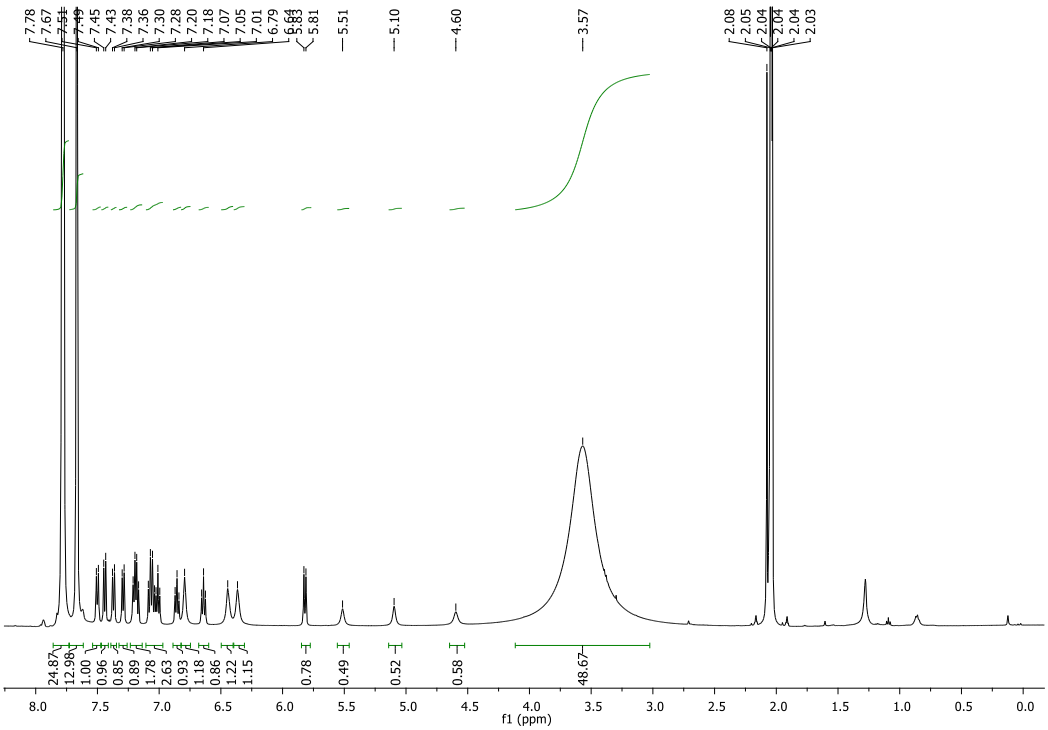


Figure S16. ^{1}H NMR spectrum of $\mathbf{1}^{3+}$ 3BAr$_f^-$ in acetone-d_6.

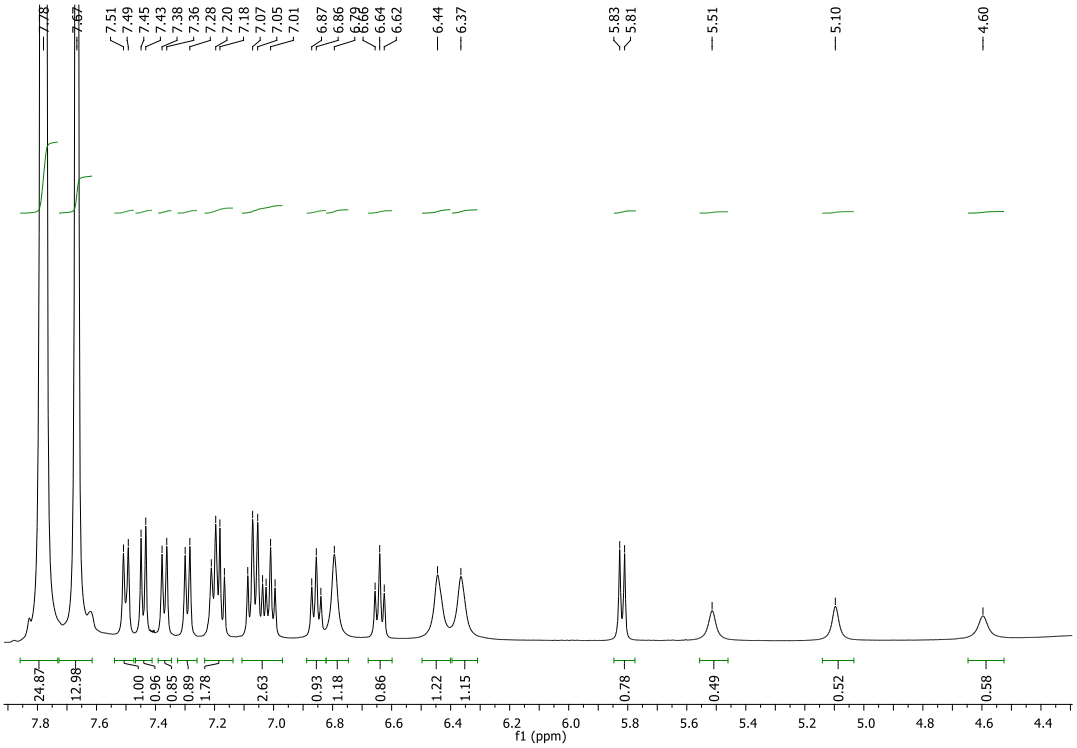


Figure S17. ^{1}H NMR spectrum of $\mathbf{1}^{3+}$ 3BAr$_f^-$ in acetone-d_6 (zoom).

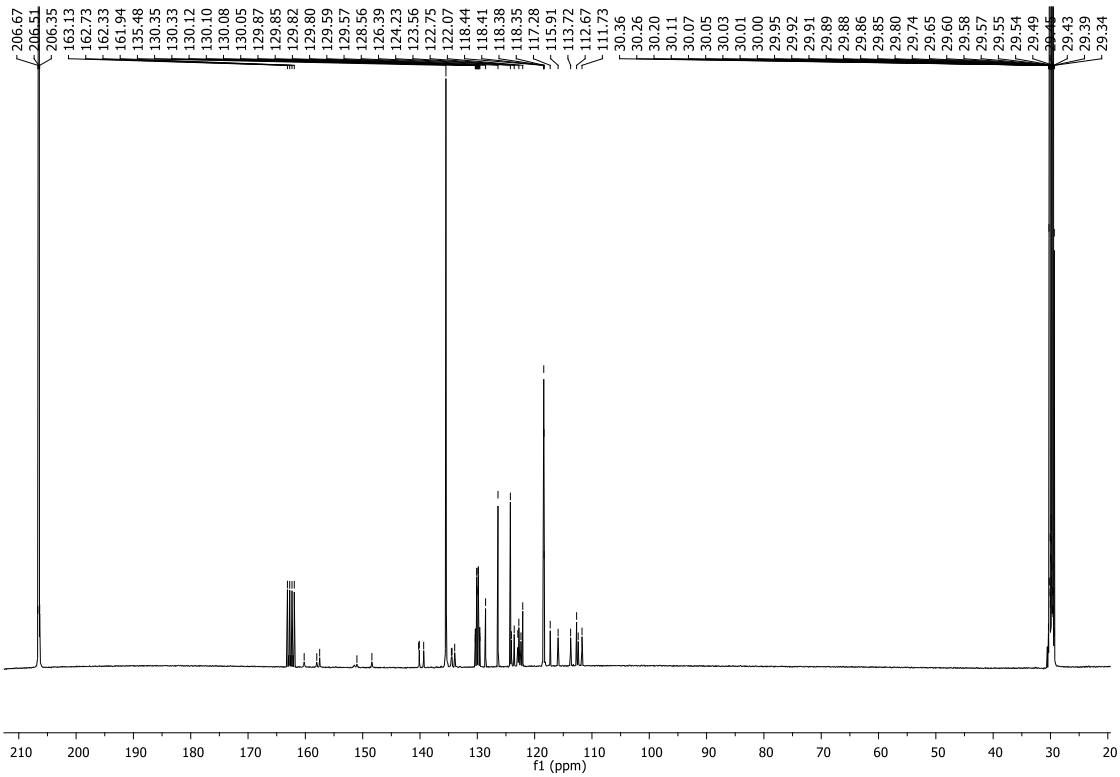


Figure S18. $^{13}C\{^{1}H\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6.

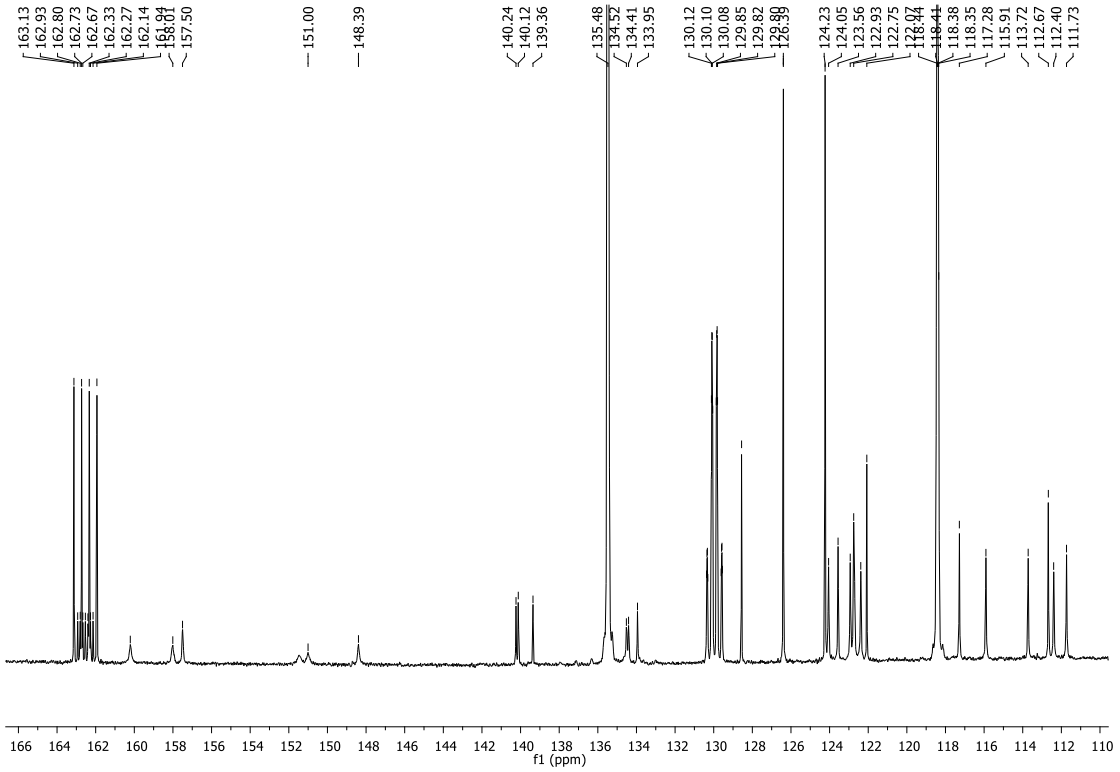


Figure S19. $^{13}C\{^{1}H\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6 (zoom).

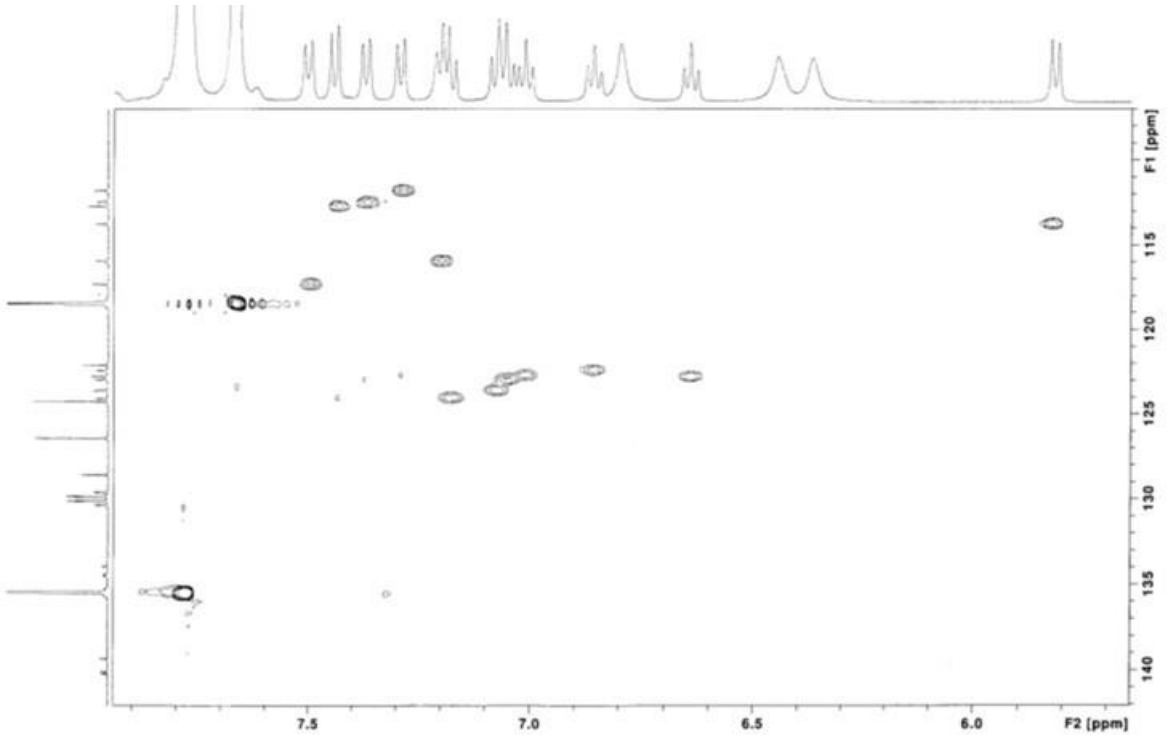


Figure S20. HSQC $\{^{1}H,^{13}C\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6.

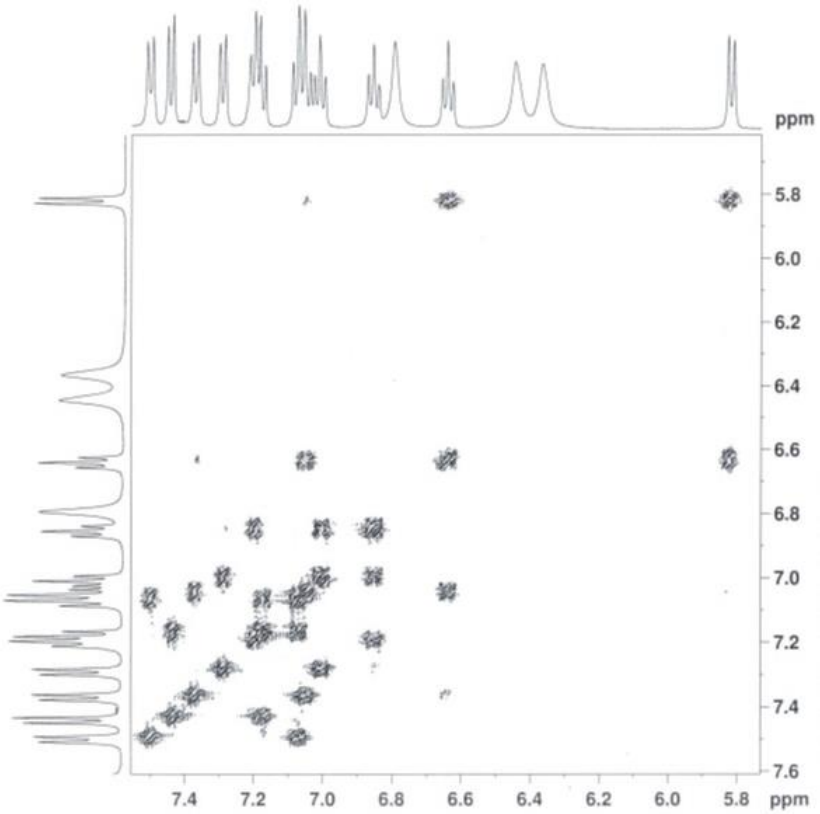


Figure S21. COSY $\{^{1}H,^{1}H\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6.

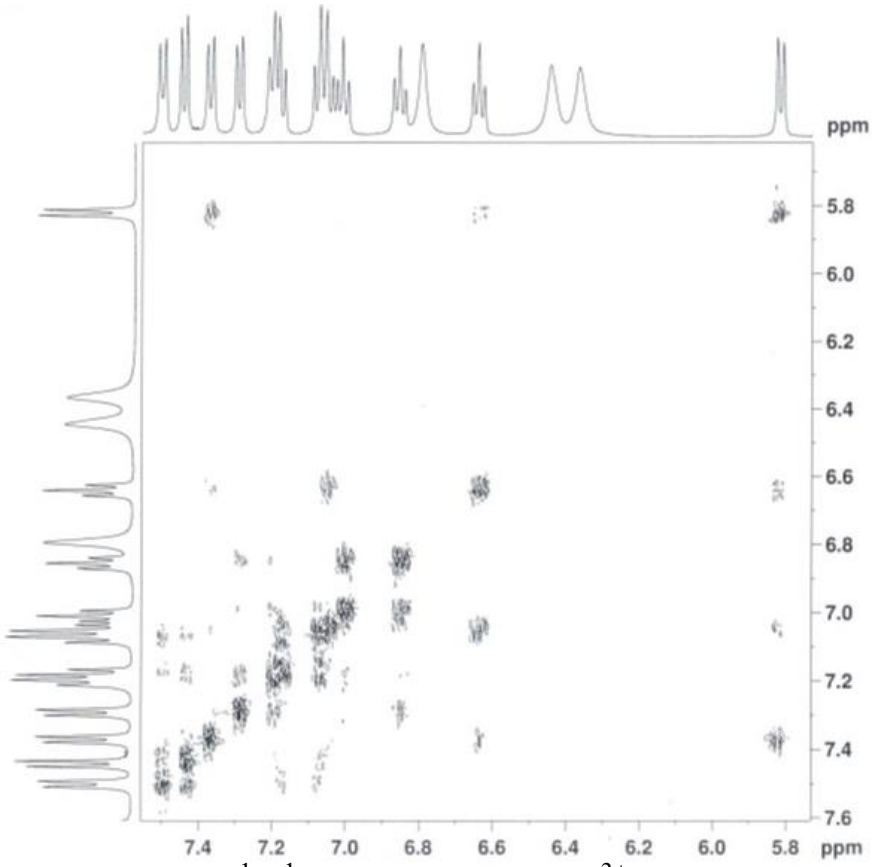


Figure S22. HMBC $\{^{1}H,^{1}H\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6.

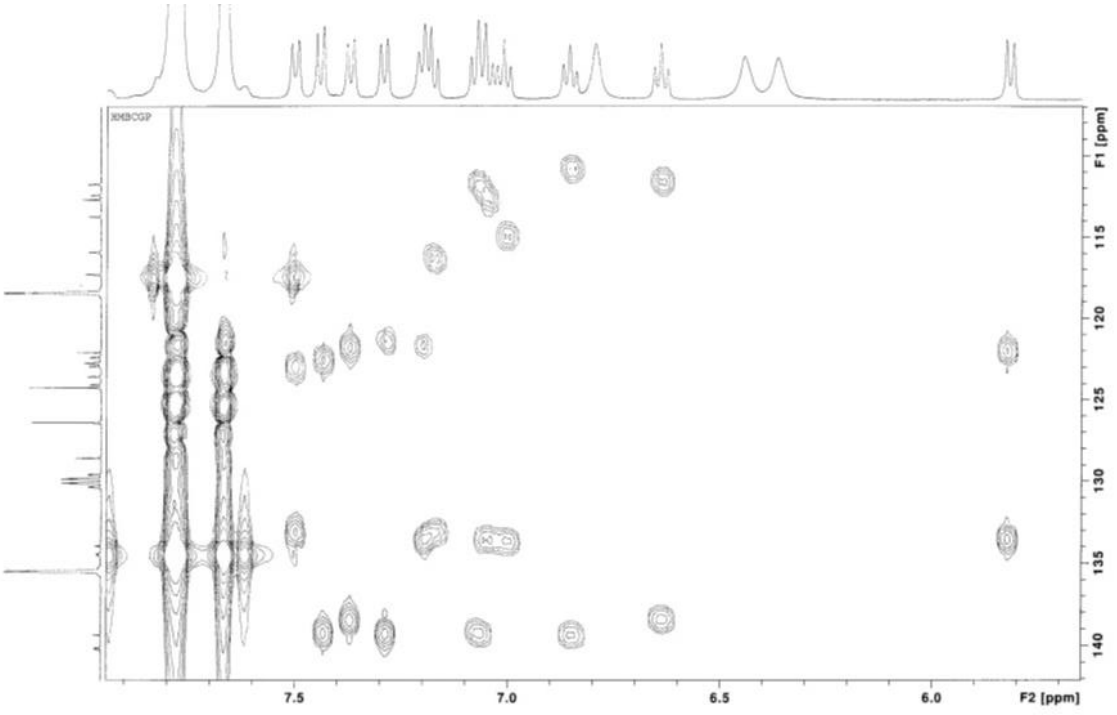
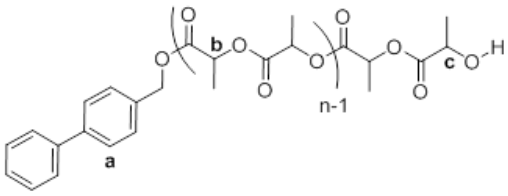


Figure S23. TOCSY $\{^{1}H,^{13}C\}$ NMR spectrum of $\mathbf{1}^{3+}$ $3BAr_f^-$ in acetone-d_6.

Polylactide: 

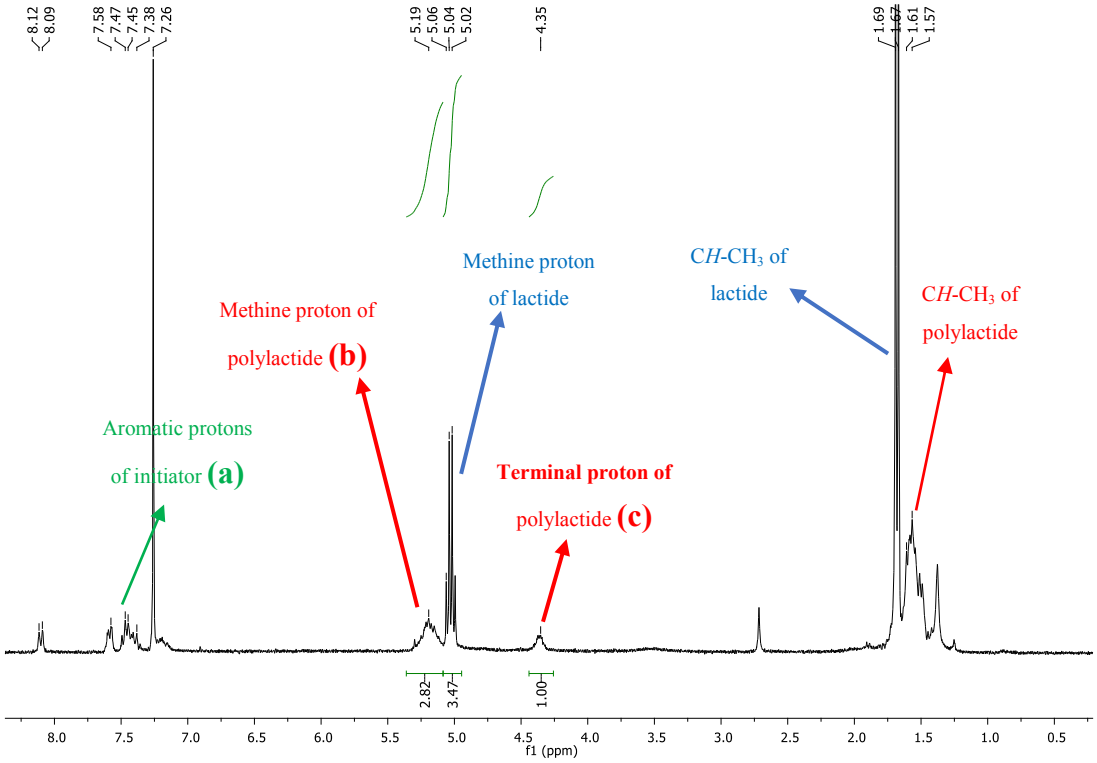


Figure S24. ^{1}H NMR spectrum of polylactide at 45% conversion in $CDCl_3$.

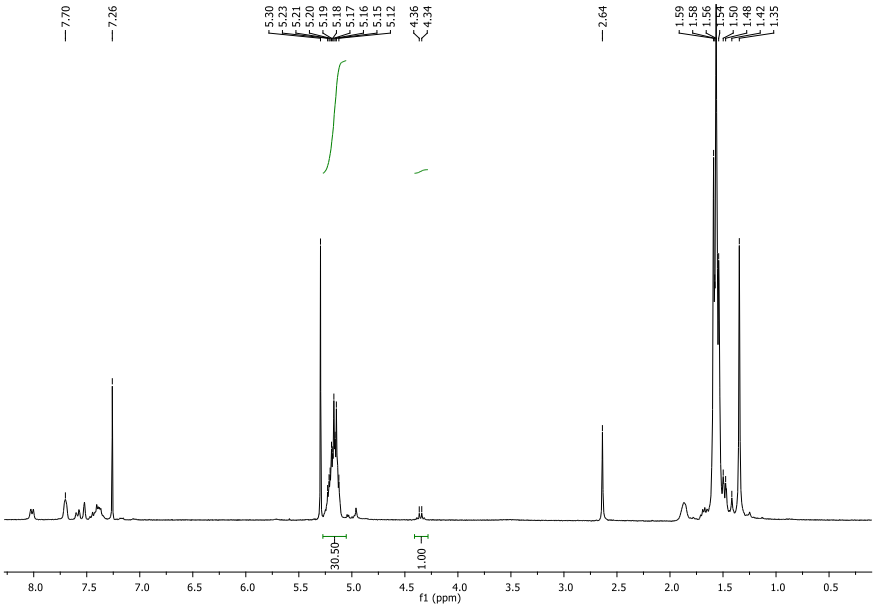


Figure S25. ^{1}H NMR spectrum of polylactide at >99% conversion in $CDCl_3$.

TITRIMETRIC EXPERIMENTS

UV-visible. A cuvette (1 cm × 1 cm) was charged with 4.0 mL of a freshly prepared 0.010 M CH_2Cl_2 solution of $\mathbf{1}^{3+}$ $3BAr_f^-$ (0.126 g, 0.040 mmol). Then neat DL-lactide was added in eleven increments of 5.0×10^{-5} g (3.5×10^{-4} mmol). UV-visible spectra were recorded after every increment. Data: Table S1 and Figures S26, S27 and S28.

NMR. An NMR tube was charged with 0.500 mL of a freshly prepared 0.050 M $CDCl_3$ solution of InOH (0.0046 g, 0.025 mmol). Then neat PMP was added in seven increments of 0.005 mL (0.0250 mmol). NMR spectra were recorded after every increment. Data: Table S2 and Figures S29 and S30.

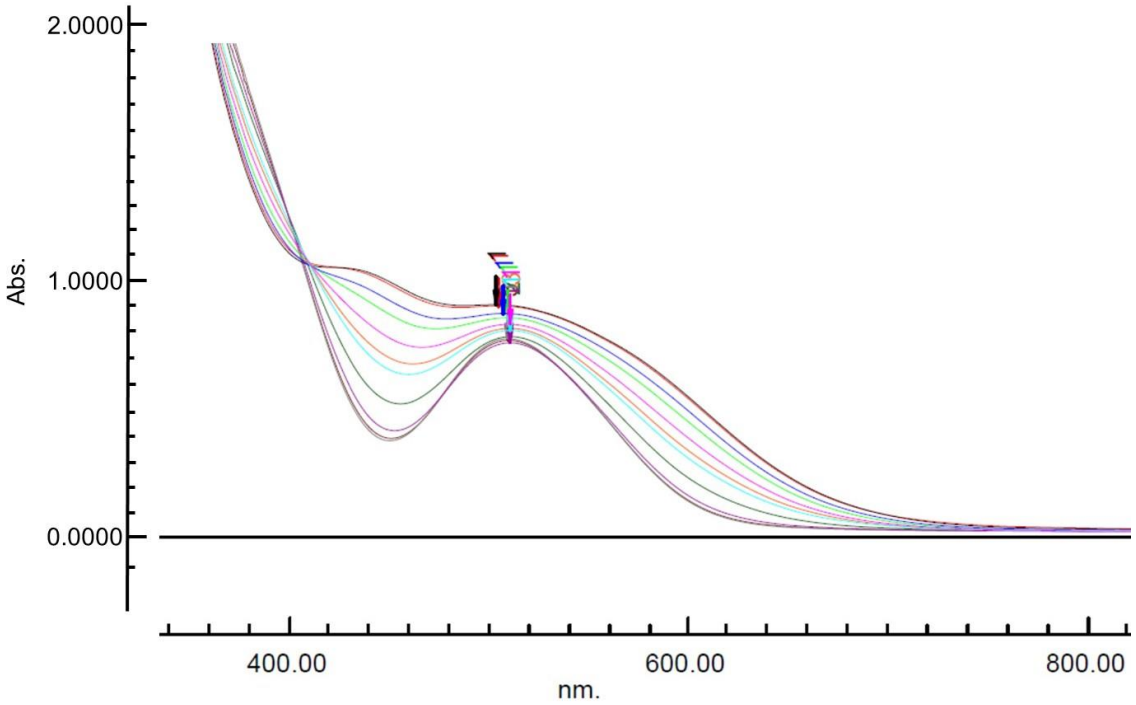


Figure S26. UV-visible spectra: addition of DL-lactide to $\mathbf{1}^{3+}$ $3BAr_f^-$ in CH_2Cl_2 as detailed above.

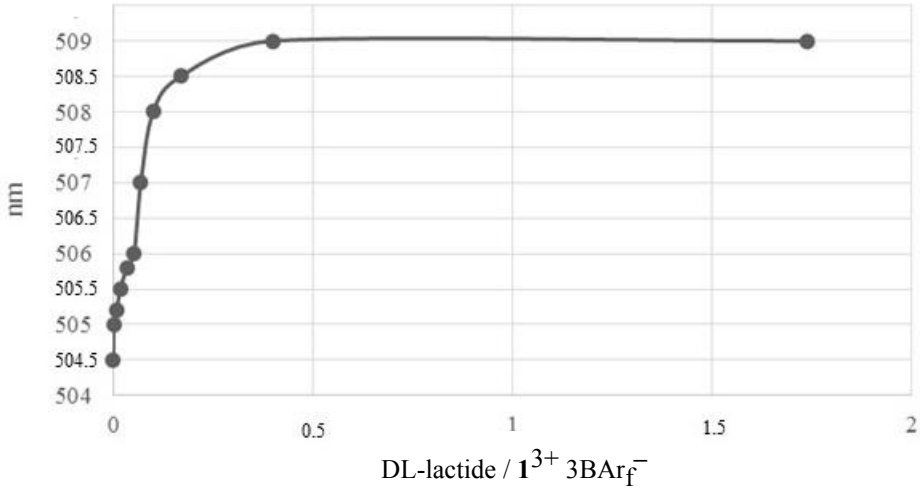


Figure S27. Variation of λ_{max} during the experiment in Figure S26.

Table S1. Data for the UV-visible spectra in Figure S26.

UV spectrum	DL-lactide (mol)	Conc. DL-lactide M	HBD (mol)	Conc. HBD M	DL-lactide/ HBD	λ_{max} (nm)
1	0	0	4.0×10^{-5}	1.0×10^{-2}	0	504.5
2	6.8×10^{-8}	1.7×10^{-5}	4.0×10^{-5}	1.0×10^{-2}	1.7×10^{-3}	505
3	3.5×10^{-7}	8.8×10^{-5}	4.0×10^{-5}	1.0×10^{-2}	8.8×10^{-3}	505.2
4	6.8×10^{-7}	1.7×10^{-4}	4.0×10^{-5}	1.0×10^{-2}	1.7×10^{-2}	505.5
5	1.4×10^{-6}	3.5×10^{-4}	4.0×10^{-5}	1.0×10^{-2}	3.5×10^{-2}	505.8
6	2.1×10^{-6}	5.3×10^{-4}	4.0×10^{-5}	1.0×10^{-2}	5.3×10^{-2}	506
7	2.8×10^{-6}	6.9×10^{-4}	4.0×10^{-5}	1.0×10^{-2}	7.0×10^{-2}	507
8	4.0×10^{-6}	1.0×10^{-3}	4.0×10^{-5}	1.0×10^{-2}	1.0×10^{-1}	508
9	6.8×10^{-6}	1.7×10^{-3}	4.0×10^{-5}	1.0×10^{-2}	1.7×10^{-1}	508.5
10	1.0×10^{-6}	4.0×10^{-3}	4.0×10^{-5}	1.0×10^{-2}	4.0×10^{-1}	509
11	6.8×10^{-4}	1.7×10^{-2}	4.0×10^{-5}	1.0×10^{-2}	1.7	509

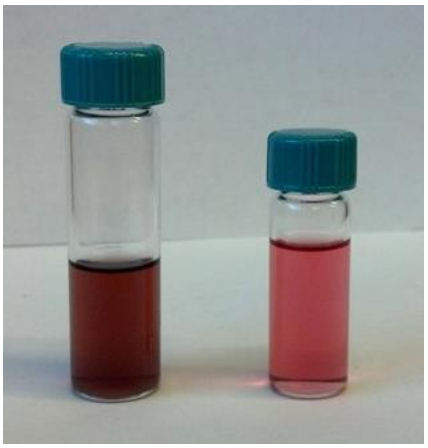


Figure S28. A CH_2Cl_2 solution that is 1.0×10^{-2} M in $\mathbf{1}^{3+}$ $3BAr_f^-$ (left) and a CH_2Cl_2 solution that is 1.0×10^{-2} M in $\mathbf{1}^{3+}$ $3BAr_f^-$ and 1.7×10^{-2} M in DL-lactide (right, corresponding to spectrum 11 in Table S1)

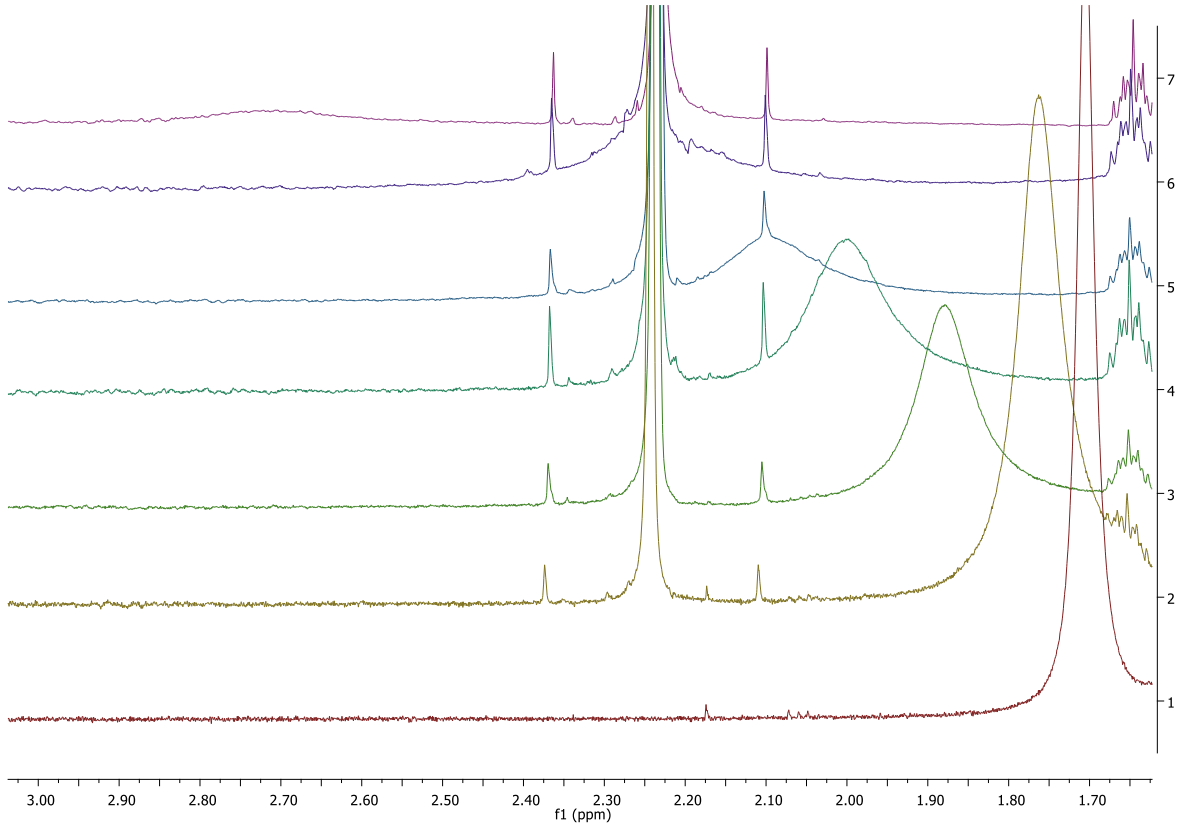


Figure S29. ^{1}H NMR spectra: addition of PMP to InOH in $CDCl_3$ as described above.

Table S2. Data for the NMR spectra in Figure S30.

^{1}H NMR spectrum	PMP (mol)	Conc. PMP M	InOH (mol)	Conc. InOH M	PMP/InOH	δ (ppm) OH
1	0	0	2.5×10^{-5}	5.0×10^{-2}	0	1.71
2	2.5×10^{-5}	5.0×10^{-2}	2.5×10^{-5}	5.0×10^{-2}	1	1.76
3	7.5×10^{-5}	1.5×10^{-1}	2.5×10^{-5}	5.0×10^{-2}	3	1.88
4	1.3×10^{-4}	2.5×10^{-1}	2.5×10^{-5}	5.0×10^{-2}	5	2.00
5	1.8×10^{-4}	3.5×10^{-1}	2.5×10^{-5}	5.0×10^{-2}	7	2.10
6	2.5×10^{-4}	5.0×10^{-1}	2.5×10^{-5}	5.0×10^{-2}	10	2.24
7	5.0×10^{-4}	1.0	2.5×10^{-5}	5.0×10^{-2}	20	2.76

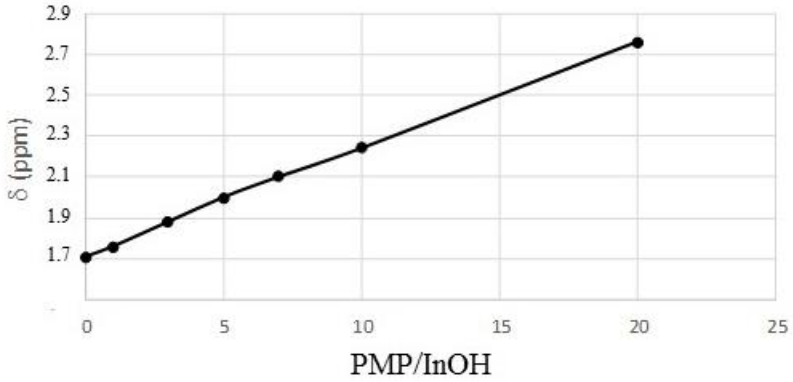


Figure S30. Variation of the ^{1}H NMR chemical shift of the OH proton of InOH during the experiment in Figure S29 ($\Delta\delta$ (ppm) = 1.05).

REFERENCES

(**s**1) (a) Scherer, Alex, Doctoral Dissertation, Universität Erlangen-Nürnberg, 2010. (b) Scherer, A.; Mukherjee, T.; Hampel, F. Gladysz, J. A. manuscript in preparation.

(**s**2) Ceniceros-Gómez, A. E.; Barba-Behrens, N.; Bernès, S.; Nöth, H.; Castillo-Blum, S. E. *Inorg. Chim. Acta* **2000**, *304*, 230–236.

(**s**3) For detailed ^{1}H and ^{13}C NMR analyses of this compound, including two additional salts of the same trication, see reference **s**2. The multiplet at 6.38-6.27 in our ^{1}H spectrum integrates somewhat higher than the theoretical intensity.

(**s**4) The $AgBAr_f$ was prepared as previously described: Miller, K. J.; Kitagawa, T. T.; Abu-Omar, M. M. *Organometallics*, **2001**, *20*, 4403–4412.

(**s**5) This corresponds to the theoretical number of protons for this signal, the assignment of which is supported by the 2D NMR experiments and literature data for related salts.[s2,s3] In practice, the observed integration is commonly less, which is provisionally attributed to H/D exchange with the solvent. One NH signal was not observed.

(**s**6) Thomas, C.; Milet, A.; Peruch, F.; Bibal, B. *Polym. Chem*. **2013**, *4*, 3491–3498.