Supplementary Material (ESI) for Chemical Communications

Supplementary data

Bifunctional yttrium(III) and titanium(IV) NHC catalysts for lactide polymerisation

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Experimental

General Procedures

All manipulations were carried out under a dry oxygen-free dinitrogen atmosphere using standard Schlenk techniques or in an Mbraun Unilab glove box unless otherwise stated. The solvents used (toluene, thf, diethyl ether) were degassed and purified by passage through activated alumina towers prior to use. Benzene-d_6 was refluxed over potassium, freeze-pump-thaw degassed, and vacuum transferred prior to use. *D,L*-lactide was triply sublimed before use; other reagents were procured from Aldrich or Strem and used without further purification. Elemental analyses were determined by Mr. Stephen Boyer at London University. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AMX300 spectrometer, referenced internally to residual solvent proton resonance, and externally to TMS. Mass spectra were obtained on a Bruker Daltonics MicroTOF, and a VG autospec instrument, and the EPSRC mass spectrometry facility at Swansea. Melting points were obtained in sealed glass capillaries under dinitrogen and are reported uncorrected. Crystallographic X-ray data, were collected using Mo-Kα radiation (λ = 0.71073 Å) on a Bruker SMART1000 CCD area detector diffractometer using ωscans. Structure solution and refinement was carried out using the SHELXTL suite of programs.[1] The preparation of **1a** is described elsewhere.[2]

1 Bruker, 1997, SHELXTL 5.10. Bruker AXS Inc., Madison, Wisconsin, USA. G. M. Sheldrick, Acta Cryst A, 1990, 46, 467. G. M. Sheldrick, 1997, SHELXL97, University of Goettingen, Germany.

2 "Titanium(IV) alkoxy-N-heterocyclic carbenes; structural preferences of alkoxide and bromide adducts" Shaheed A. Mungur, Alexander J. Blake, Claire Wilson, Jonathan McMaster, and Polly L. Arnold, manuscript submitted.

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Preparations

Synthesis of $Ti(L^O)(OPr^i)_3$ 1

A Schlenk flask was charged with a mixture of KL^O (7.40 g, 36.2 mmol) and $TiCl(OPr^i)_3$ (14.71 g, 36.2 mmol) and cooled to -80 ºC, then charged with THF (50 ml). The solution was allowed to warm to room temperature with stirring. After 15 hours, the solution had become orange in colour and a colourless solid, KCl, had precipitated. The solution was filtered through a bed of celite, and the volatiles removed under reduced pressure to yield an orange oil. Analytically pure $Ti(OPr^i)_3L^O$ was obtained as a waxy colourless solid by sublimation, (80 ºC, 10^{-3} mbar), in 26 % yield (3.81 g). Anal. Calcd. for $C_{19}H_{38}N_2O_4Ti$: C, 56.15; H, 9.42; N, 6.89. Found: 45.46; H, 9.30; N, 6.73. Apparently, the compound forms carbide and so combustion analyses are returned with low calculated carbon values. ^{1}H-NMR (C_6D_6, 300 MHz): δ ppm 6.41, 6.13 (d, 1H, NC*H*CHN), 5.79 (sept, 1H, OC*H* (ax)) 5.22 (sept, 2H, OC*H* (eq)) 4.64 (sept, 1H, NC*H*) 3.46 (s, 2H, NCH_2) 1.54 (d, 12H, CH_3 (eq)) 1.35 (d, 6H, CH_3 (ax)) 1.35 (d, 6H, NCCH_3) 1.27 (2 × s, 6H, 2 × CH_3, OCCH_3). (C_5D_5N, 300 MHz): δ ppm 7.00 (d, 1H, ^{3}J=1.5 Hz, NC*H*CHN) 6.96 (d, 1H, ^{3}J=1.5 Hz, NCHC*H*N) 4.95 (sept, ^{3}H, 3J= 6.1 Hz, OC*H*$(CH_3)_2$) 4.00 (s, 3H, NCH_3) 3.86 (s, 2H, NCH_2) 1.32 (d, 18H, ^{3}J=6.1 Hz, [OCH(CH_3)$_2$]$_3$) 1.22 (s, 6H, C$(CH_3)_2$). ^{13}C{^{1}H}-NMR (C_6D_6, 75 MHz): δ ppm 189.5 (N*C*N) 119.2 (N*C*CN) 113.2 (NC*C*N) 76.2 (*C*(CH_3)) 76.0 (N*C*H$(CH_3)_2$) 75.8 (O*C*H$(CH_3)_2$) 60.9 (N*C*H_2) 50.0 (NC*C*H_3) 28.6 (C(*C*$H_3)_2$) 26.9 (OCH(*C*$H_3)_2$) (ax) 23.4 (OCH(*C*$H_3)_2$) (eq). (C_5D_5N, 75 MHz): δ ppm 190.0 (N*C*N) 120.4 (N*C*CN) 120.1 (NC*C*N) 76.8 (*C*$(CH_3)_2$) 75.3 (O*C*H$(CH_3)_2$) 61.0 (N*C*H_2) 37.0 (NCH_3) 28.7 (C(*C*$H_3)_2$) 27.0 (OCH(*C*$H_3)_2$).

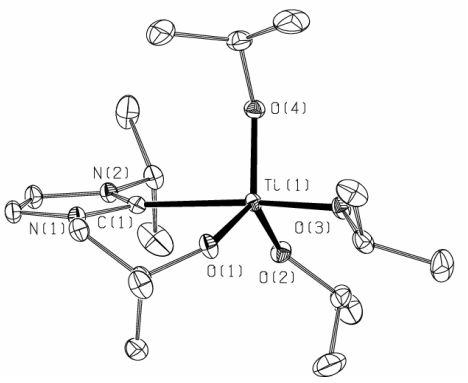

Fig. 12 Displacement ellipsoid drawing of **1** (50% probability). Selected distances (Å) and angles (°):Ti(1)-C(1) 2.293(2), Ti(1)-O(1) 1.8577(15), Ti(1)-O(2) 1.8364(14), N(1)-C(1) 1.365(3), C(1)-Ti(1)-O(1) 81.33(7), N(1)-C(1)-N(2) 103.49(17).

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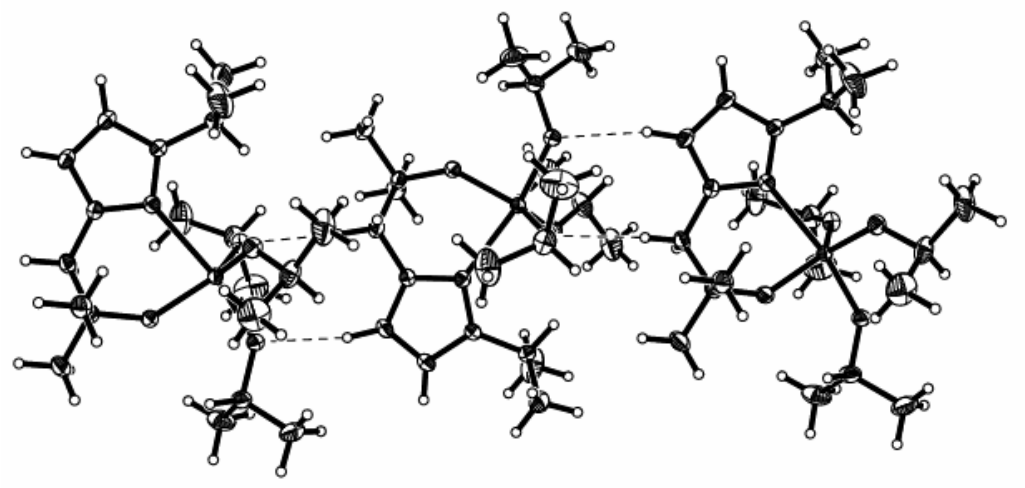


The 21 screw axis in the structure

Reaction of Ti(L^O)(OPr^i)$_3$ 1 with *D,L*-lactide

Treatment of **1** with a single equivalent of lactide monomer affords an oily dark orange material which is not identifiable:

To a benzene solution of **1** (222.3 mg, 0.1825 mmol, 0.5 ml) was added a benzene solution of *D,L*-lactide (26.3 mg, 1.825 mmol, 0.5 ml) with stirring. The solution darkened to a red-orange colour over ten minutes. Removal of volatiles under reduced pressure afforded a dark orange oil from which no identifiable products could be isolated or identified in the ^{1}H NMR spectrum.

Reaction of Ti(L^O)(OPr^i)$_3$ with Ph_3PO (test of exchange, for comparison with Y(L^N)N"$_2$:

To a C_6D_6 solution of **1** (0.081 g, 0.2 mmol, 0.55 ml) Ph_3PO (0.055 g, 0.2 mmol, 1 eq.) was added and heated (100 ºC) for 16 hours. ^{1}H-NMR (C_6D_6, 300 MHz) spectroscopy indicates no reaction.

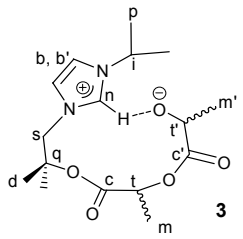
Reaction of HL^O B with *D,L*-lactide

A cold (-80 ºC) toluene solution of *D,L*-lactide (0.59 g, 4.1 mmol, 40 mL) was added slowly to a cold (-80 ºC) toluene solution of HL^O (0.75 g, 4.1 mmol, 10 mL). The yellow solution was allowed to warm to room temperature slowly with stirring for 16 hours. After this time, an orange oily precipitate had formed. The solvent was removed under reduced pressure to yield an orange oily solid, which was identified as a mixture of two products by spectroscopy.

The reaction was repeated in thf and pyridine; in each case, the same products were observed in the same ratios, identified as the two insertion products **3** and **4** according to ^{1}H NMR spectroscopy.

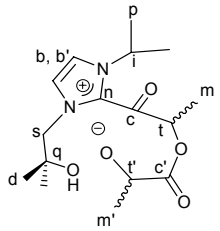
The ES mass spectrometry of dry acetonitrile solutions show extensive fragmentation. Reduction of the source dry temperature from 200 to 100 ºC, and of the transfer capillary exit voltage from 100 to 60 V showed a small decrease in fragmentation: 253.157 $[L^{O}.COCHMeO]^{+}$ (calc. 253.16), 239 $[HL^{O}.COCHO]^{+}$, 183 $[HL^{O}]^{+}$.

^{1}H-NMR (C_5D_5N, 300 MHz):



3

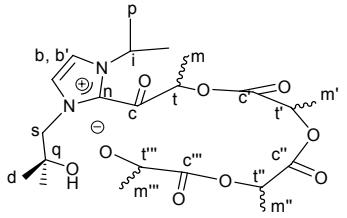
minor product **3**: δ ppm 7.77, 7.62 (d, 1H, b,b') , 6.16 (q, 1H, t'), 5.52 (sept, 1H, i), 4.85 (s, 2H, s) 3.63 (q, 1H, t), 1.82, 1.78 (d, 3H, m, m'), 1.70 (d, 6H, p), 1.33 (s, 6H, d). OH not seen. $^{13}C\{^{1}H\}$-NMR (pyridine-d_5, 75 MHz): δ ppm 172.1, 168.9 (c, c'), 143.9 (n), 138.6, 116.0 (b, b'), 69.2 (t'), 58.5 (s), 51.1 (i), 27.6 (d), 27.5 (t), 25.5 (q), 23.0, 18.1 (m', m), 18.9 (p).



4

major product **4**: δ ppm 10.85 (br s, 1H, OH) 7.77, 7.71 (d, 1H, b,b') , 5.99 (q, 1H, t'), 4.63 (sept, 1H, i), 4.53 (s, 2H, s), 4.61 (q, 1H, t), 1.38, 1.30 (d, 3H, m, m'), 1.37 (d, 6H, p), 1.33 (s, 6H, d). $^{13}C\{^{1}H\}$-NMR (pyridine-d_5, 75 MHz): δ ppm 179.6, 171.0 (c, c'), 160.0 (n), 124.3, 119.1 (b, b'), 68.2 (t'), 59.4 (s), 52.7 (i), 27.1 (d), 25.6 (q), 22.7 (t) 22.6 (p), 23.0, 21.1 (m', m).

The addition of further equivalents of *D,L*-lactide to a sample of **3** and **4** as made in a Young's tap-equipped NMR tube afforded incremental insertion products, characterised by ^{1}H NMR spectroscopy:



+ 2 equivalents:

δ ppm 10.69 (br s, 1H, OH) 7.87, 7.78 (d, 1H, b,b') , 5.73 (q, 1H, t'''), 5.44 (br m, 3H, t, t', t''), 4.63 (sept, 1H, i), 4.53 (s, 2H, s) 1.50 (br m, 12H, m, m', m'', m'''), 1.39 (d, 6H, p), 1.33 (s, 6H, d).

+ 3 equivalents:

δ ppm 10.50 (br s, 1H, OH) 7.87, 7.80 (d, 1H, b,b') , 5.74 (q, 1H, $t^{5'}$), 5.40 (br m, 5H, t, t', t'', t''', t''''), 4.63 (sept, 1H, i), 4.50 (s, 2H, s) 1.62 (br m, 18H, m – $m^{5'}$), 1.44 (d, 6H, p), 1.37 (s, 6H, d).

+ 5 equivalents:

δ ppm 10.60 (br s, 1H, OH) 7.85, 7.78 (d, 1H, b,b') , 5.71 (q, 2H, $t^{9'}$, $t^{10'}$), 5.42 (br m, 8H, t – $t^{8'}$), 4.65 (sept, 1H, i), 4.50 (s, 2H, s) 1.59 (br m, 30H, m – $m^{10'}$), 1.41 (d, 6H, p), 1.33 (s, 6H, d).

Reaction of HL^N C with *D,L*-lactide

To a benzene solution of **C** (223.2 mg, 0.1825 mmol, 0.75 ml) was added a benzene solution of *D,L*-lactide (26.3 mg, 1.825 mmol, 0.75 ml) with stirring. The colourless solution darkened to a red-orange colour over ten minutes, and an orange oil separated out of the solution which lightened to pale orange. Removal of volatiles under reduced pressure afforded a dark orange oil, which was dissolved in d_5-pyridine and identified as containing one product, **5** by ^{1}H NMR spectroscopy.
^{1}H-NMR (C_5D_5N, 300 MHz): δ ppm 10.6 (br s, 1H, N*H*), 8.04, 7.87 (br s, 1H, C*H*Me), 7.74 , 7.45 (s, 1H, NC*H*CHN), 4.66, 2.98 (2H, s, NCH_2), 1.88, 1.03 (s, 3H, CH*Me*), 1.52, 1.12, (s, 9H, CMe_3).

Crystallography

A crystal of **1** was grown by vapour phase diffusion (80 ˚C, 10^{-3} mbar), and was mounted in a film of RS3000 perfluoropolyether on a dual-stage glass fibre and transferred to the diffractometer.

Lactide polymerisation reactions

For **A** and **B**

In a Schlenk flask, to a solution containing the appropriate amount of catalyst (and benzyl alcohol if indicated) (see table in text) in toluene (1.5 ml) was added *D,L*-lactide (50 mg, 0.35 mmol). The solution was allowed to stir for 1 hour, and then quenched with a drop of water. The volatiles were removed under reduced pressure, to afford a solid or oily product according to the degree of oligomerisation or polymerisation. Samples were analysed by ^{1}H

NMR spectroscopy at this point to determine the conversion of monomer to polymer. Each of the crude products was then dissolved in a minimum quantity of dichloromethane, dried with $MgSO_4$, and then filtered. The product was isolated by evaporation of volatiles from the filtrate, and drying. The residue in each case was analysed by NMR spectroscopy and by gel phase chromatography.

For **1** and **1a**

Bulk polymerisation of lactide

An ampoule charged with 2.00g (13.8mmol) of *D,L*-lactide and the appropriate amount (0.05 mmol) of titanium catalyst (see table in text) was stirred at 130 °C for 2 hours. After this time, the reaction was terminated by the addition of 5 ml of methanol. The volatiles were removed under reduced pressure, to afford an oily product according to the degree of oligomerisation or polymerisation. Samples were analysed by ^{1}H NMR spectroscopy at this point to determine the conversion of monomer to polymer. The crude product was then dissolved in a minimum quantity of dichloromethane, dried with $MgSO_4$, and then filtered through a pad of silica gel. The product was isolated by evaporation of volatiles from the filtrate, and drying. The residue was analysed by NMR spectroscopy.

Solution polymerisation.

To a solution containing the appropriate amount of titanium catalyst dissolved in toluene was added *D,L*-lactide (0.500 g, 3.47 mmol) in toluene. The solution was stirred at room temperature for 2 hours (24 hours for **1a)**, with aliquots removed by syringe and quenched (by the addition of one drop of water) at regular intervals. The volatiles were removed under reduced pressure from each aliquot, to afford a solid or oily product according to the degree of oligomerisation or polymerisation. Samples were analysed by ^{1}H NMR spectroscopy at this point to determine the conversion of monomer to polymer. The crude product was then dissolved in a minimum quantity of dichloromethane, dried with $MgSO_4$, and then filtered through a pad of silica gel. The product was isolated by evaporation of volatiles from the filtrate, and drying. The residue in each case was analysed by NMR spectroscopy and by gel phase chromatography.

For **2**

In a Schlenk flask, to a solution containing the appropriate amount of catalyst (and benzyl alcohol if indicated) (see table in text) in toluene (1.5 ml) was added *D,L*-lactide (50 mg, 0.35 mmol). The solution was allowed to stir for a given amount of time between 15 seconds and 1 hour (see table in text), and then quenched with a drop of water. The volatiles were removed under reduced pressure, to afford a solid product. Samples were analysed by

^{1}H NMR spectroscopy at this point to determine the conversion of monomer to polymer. Each of the crude products was then dissolved in a minimum quantity of dichloromethane, dried with $MgSO_4$, and then filtered through a pad of silica gel. The product was isolated by evaporation of volatiles from the filtrate, and drying. The residue in each case was analysed by NMR spectroscopy and by gel phase chromatography (GPC System: ELS-1000, Chloroform, Relative to PS standards).

Entry in manuscript	Complex (+ initiator = I)	Catalyst:I: monomer	Time/ min	yield /%	MW	PDI
1	HL^O (**B**)	5:0:100	5	100	27,100	1.46
	HL^O (**B**)	5:0:100	10	100	13,300	2.73
	HL^O (**B**)	5:0:100	300	100	5,300	3.53
2	HL^N (**C**)	1:0:100	15	100	45,000	1.29
3	1	1:0:100	1	60	1,800	1.19
4	1	1:0:100	2	85	2,300	1.17
	1	1:0:100	5	100	27,200	1.11
					2,700	1.14
	1	1:0:100	10	100	24,100	1.11
					3,000	1.15
5	1	5:0:100	60	65	3,600	1.05
6	1a	5:0:100	24 hours	72	3,500	1.05
	1a	5:0:100	24 hours	75	2,000	1.09
	1	1:0:100	60	<5	~1,000	-
7	2	1:0:10000	15	85	66,000	1.47
8	2	1:0:100	0.18	60	65,000	1.19
9	2	1:0:100	2	75	77,000	1.19
10	2	4:0:100	60	100	28,000	1.53
11	A + I	1:1.5:200	15	85	> 25,000	1.18
12	**C** + I	1:0.5:100	15	100	8,900	1.25
13	2 + I[a]	1:0.5:100	2	75	7,400	1.20

Table ESI 1, expanded to include additional data. Activity of complexes for *D,L*-lactide polymerisation. All reactions at 20 °C under purified N_2 atmosphere, I = $PhCH_2OH$.[a]

It is reasonable that the ligand HL^N is completely displaced, and a mixture of an *in situ* generated species such as $Y(N\{SiMe_3\}_2)_2(OCH_2Ph)(HOCH_2Ph)$, and HL^N are now acting as catalysts. No macrocycles were observed in the mass spectral analysis of polymers made by complex **1**.

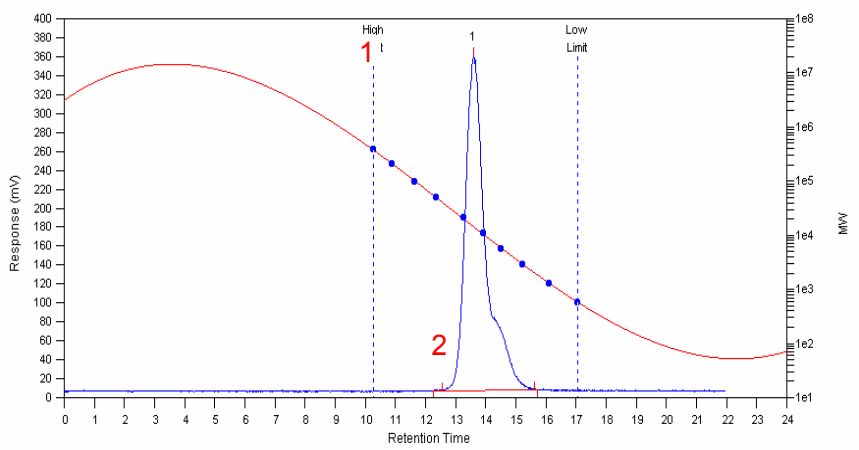


Figure ESI.1: GPC plot for PLA polymer made using 1 mol % of **C** with 0.5 mol% of benzyl alcohol, entry 12

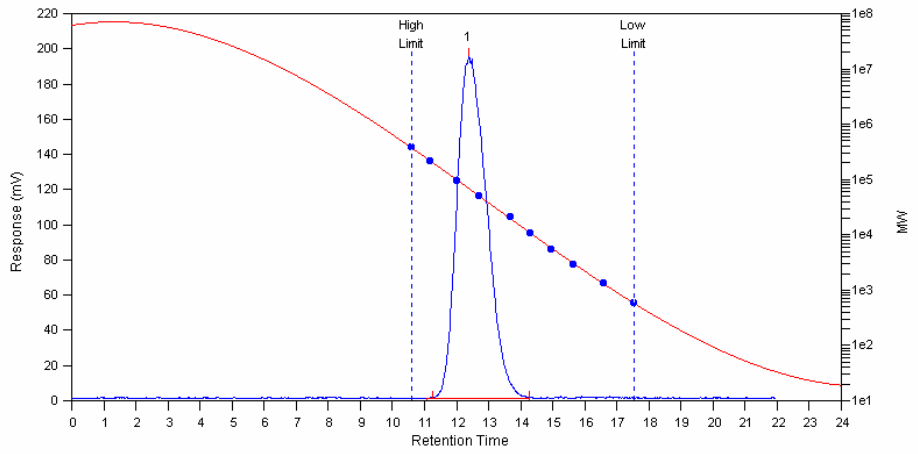


Figure ESI.2: GPC plot for PLA polymer made using 1 mol % of **2** quenched after 10 seconds; entry 8

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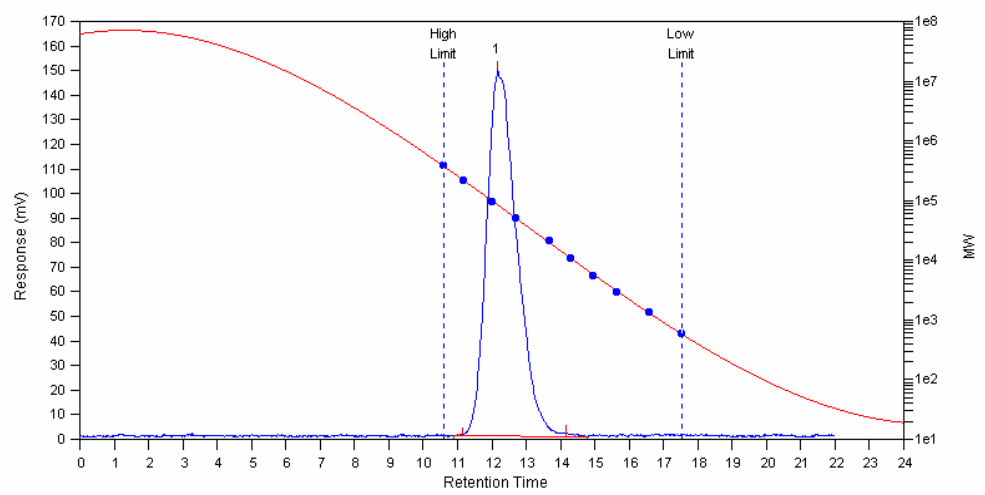
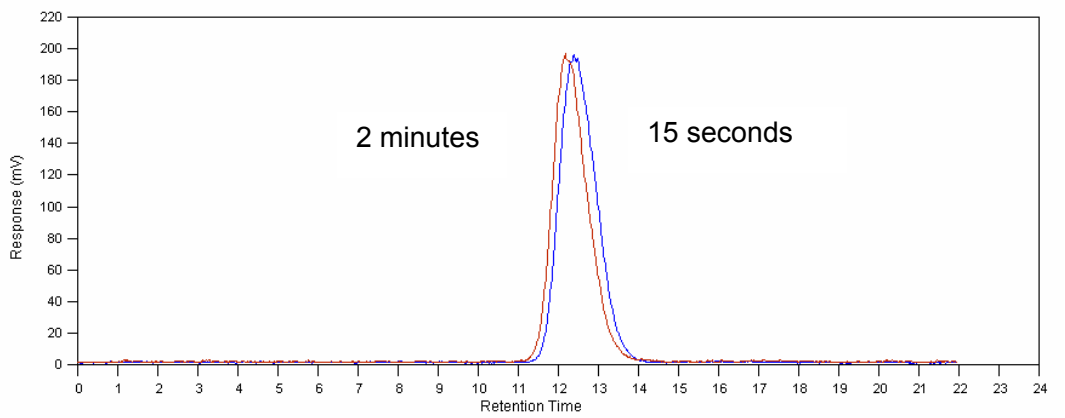


Figure ESI.3: GPC plot for PLA polymer made using 1 mol % of **2** quenched after 2 minutes.; entry 9



Overlay of ESI2 and ESI3

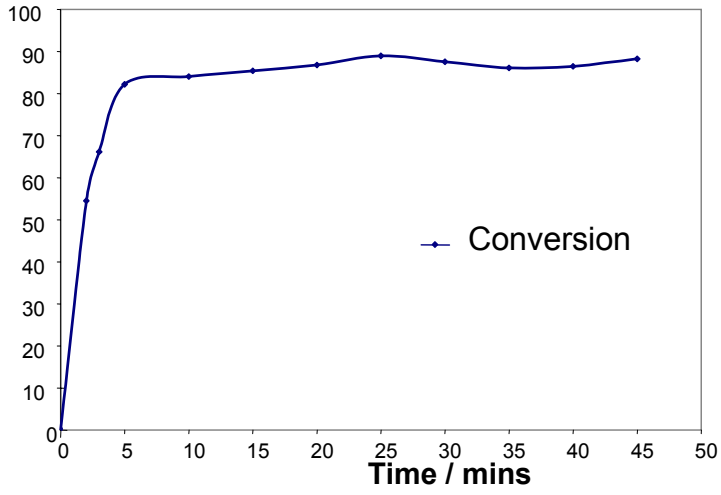


Figure ESI.4: Plot of the conversion of monomer to polymer with 1 mol % of **2**

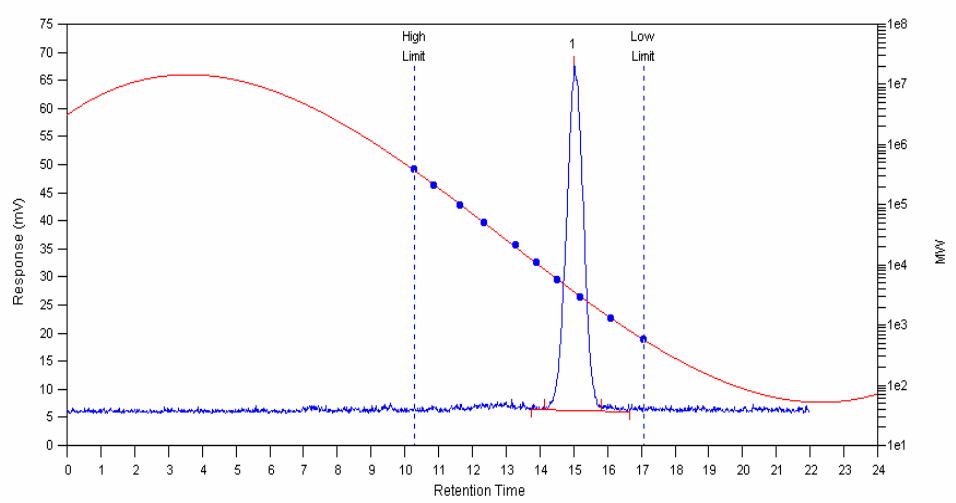


Figure ESI.5:GPC plot for PLA polymer made using **1a**; run 6