Note

Electron deficient zinc complexes: Enhanced lactide polymerization activity achieved through rational ligand design

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1. Introduction

Interest in the use of poly(lactic acid) (PLA) as an eco-friendly commodity polymer has grown substantially over the past decade [1]. This is because lactide (LA) feedstocks are derived from renewable resources, while PLA is biodegradable. This interest has promoted increasingly intensive research in the area of LA polymerization catalysis [2]. While organocatalysts [3] and a wide variety of metal-based catalysts [4] have been developed, much work has been specifically devoted to the preparation of alkoxides of Zn(II) and the alkaline earth metals (most commonly Mg(II) and Ca(II)). Prior to 2009, virtually all such LA polymerization catalysts were neutral complexes stabilized by formally anionic ancillary ligands, and this continues to be the focus of most recent work [5]. Recently, however, we have pursued cationic zinc complexes for LA polymerization catalysis [6].

Since our initial reports, there have been several other accounts of cationic Zn(II), Mg(II) and Ca(II) complexes used for the ROP of LA [7], but these tend to suffer drawbacks ranging from poor activity to poor control to ill-defined polymerization mechanisms. A notable exception is a cationic calcium complex recently reported by Mountford and co-workers, which displays both excellent control and activity for the ROP of rac-lactide at ambient temperature [8].

Herein we report our next generation cationic zinc catalyst, in which the ligand scaffold has been modified by installation of alkyl substituents on the phosphinimine groups (Scheme 1). Specifically, ethyl replaces phenyl at P and benzyl replaces para-iso-propylphenyl (Pipp) at N. This was expected to render the metal center more sterically accessible, while simultaneously providing better moderation of metal center Lewis acidity by enhancing the electron donating capacity of the ligand. Such a less electropositive metal center was targeted in hopes of achieving a level of Lewis acidity somewhere between that of our previous cationic zinc catalysts and the more commonly studied neutral zinc catalysts. The effect of these modifications has been studied, with the major outcome being a marked enhancement in polymerization activity, as discussed below.

2. Results and discussion

Preparation of the bis(phosphine) precursor dbf(PEt₂)₂ was targeted due to its reduced bulk relative to the known dbf(PPr₂)₂ and dbf(PPh₂)₂ analogs. Efficient dilithiation of dibenzofuran was...
Synthesis of zinc-alkyl (1) and zinc-lactate (2) complexes of a bis(phosphinimine) pincer ligand (Ar = m-(CF3)2-C6H4).

Achieved using 2.0 equiv of tBuLi, rather than significant excesses of 18BuLi or 2BuLi employed in previous reports (see ESI [9]). This novel bis(phosphate) compound exhibits one sharp signal in the 31P{1H} NMR spectrum (CD2Cl2) at δ 19.01.

Synthesis of L from dbf[PEt2]2 and benzyl-azide under standard Staudinger conditions [10] was highly exothermic and proceeded to completion within minutes at ambient temperature. Work-up is straightforward and efficient, with high yield of analytically pure crystalline material achieved without the need for further purification. Notably, complex 1 was synthesized in an overall yield of 64% in four steps from dibenzofuran.

Methylzinc complex 1 was effortlessly prepared by reacting [LH] [B(m-(CF3)2-C6H4)] with ZnMe2 at ambient temperature for 1 h, to afford a pure white powder in 90% yield. A single peak in the 31P{1H} NMR spectrum (δ 46.6, CD2Cl2) is indicative of symmetry-related phosphinimines in solution. The ZnCH3 resonates in the 1H NMR spectrum at δ -0.95, which is typical of cationic methylzinc complexes [6].

Synthesis of zinc-lactate complex 2 was performed by reaction of [LH][B(m-(CF3)2-C6H4)] with EtZn(methyl-l-lactate) in toluene solvent at 100 °C for 60 min. This proved much more efficient than the preparation of our previous Zn–lactate complexes [6c], with 95% yield of crystalline material achieved without the need for further purification. Notably, complex 2 was synthesized in an overall yield of 64% in four steps from dibenzofuran. Characteristic peaks of the lactate moiety appear in the 1H NMR spectrum at δ 4.66 (CH), 3.69 (O CH), and 1.41 (C–CH3). Despite the presence of the asymmetric lactate moiety, a single resonance is observed at ambient temperature in the 31P{1H} NMR spectrum (δ 46.8). At −60 °C, the spectrum displays two distinct peaks (δ 46.8, 46.3), indicating a fluxional process which we propose is a simple intramolecular rearrangement involving rotation of the lactate moiety.

Large single crystals of complex 2 suitable for X-ray diffraction were grown from CH2Cl2 solvent, and the solid-state crystal structure was determined (Fig. 2). As expected, the ancillary ligand coordinates to the metal center in a tridentate fashion and the methyl-lactate moiety binds in a bidentate manner, resulting in a 5-coordinate, distorted trigonal bipyramidal geometry. The phosphinimine groups [Zn(1)–N(1) = 2.013(1) Å, Zn(1)–N(2) = 2.009(2) Å] and the formally anionic oxygen atom [Zn(1)–O(2) = 1.923(2) Å] prove to be the strongest donors, occupying the equatorial sites. The sum of angles...
about these positions is 356.5(1). Correspondingly, the neutral oxygen-donors occupy the axial sites, wherein the interaction with the lactate carbonyl lies within the expected range [Zn(1)–O(3) = 2.173(1) Å], while that of the dbf oxygen is relatively long [Zn(1)–O(1) = 2.525(1) Å]. The angle between these groups is distorted somewhat from the ideal 180° [O(1)–Zn(1)–O(2) = 168.57(5)°], presumably due to steric repulsion of a nearby benzyl group. Interestingly, the interaction with the dbf oxygen is 0.189(5) Å longer than that observed in our previous generation catalyst [LPippZnLactate][B(CF$_3$)$_2$C$_6$H$_4$I]$_2$ [6c], which we attribute to decreased Lewis acidity of the metal center.

The efficacy of both complexes for ROP of rac-LA was investigated, and unsurprisingly complex 1 was inactive. However, complex 2 is extremely active for the polymerization of rac-LA, giving 90% conversion of 200 equiv of monomer to atactic PLA (0.189(5) Å longer than that observed in our previous generation complex [rac-ZnLactate][B(CF$_3$)$_2$C$_6$H$_4$I]$_2$ [6c], which we attribute to decreased Lewis acidity of the metal center.

Further reduction of catalyst loading ([LA]$_0$/[2] = 300, 400, and 500) resulted in significantly lower than expected $M_n$ and higher polydispersities (PDI = 1.39–1.43). We attribute this decreased control to appreciable rates of intermolecular transesterification. Catalyst decomposition is an unlikely cause of broadened PDIs at lower catalyst concentration, as we have found 2 to consume additional monomer at a similar rate after complete consumption of the initial portion of rac-LA. Specifically, after polymerization of 200 equiv of rac-LA for a duration of 90 min (~15 half-lives), addition of a further 200 equiv of monomer resulted in continued polymerization, giving PLA with molecular weights similar to those measured for single step polymerization of 400 equiv (Table 1).

In an attempt to improve our understanding of the polymerization process, a variety of samples were prepared under identical conditions ([LA]$_0$ = 1 M, [LA]$_0$/[2] = 200) and quenched at different stages of completion. A plot of $M_n$ versus conversion gives a curve rather than the expected straight line (Fig. 4). During the early stages (40–60% conversion) the polymerization is well controlled (PDI = 1.11–1.13), while in the latter stages, the $M_n$ values begin to drop off relative to the expected values, with a concomitant increase in $M_w$ and PDI (see ESI). An increase in the rate of intermolecular transesterification relative to propagation account for increased PDIs in the later stages of polymerization. The cause of decreasing $M_n$ is less obvious, but most likely attributed to intramolecular transesterification. Such catalyst back-biting would give rise to a lower molecular weight fraction that may be lost upon work-up of the polymer. To verify, GPC studies of an unpurified polymer sample ([LA]$_0$/[2] = 100, [LA]$_0$ = 1 M, CH$_2$Cl$_2$, 25 °C) were undertaken, indicating the presence of a substantial amount of low molecular weight oligomer ($M_n$ = 1.25 kg mol$^{-1}$; PDI = 1.03). The high molecular weight portion closely matched the corresponding purified polymer sample ($M_n$ = 18.9 kg mol$^{-1}$; PDI = 1.16). This observation suggests intramolecular transesterification to be a major cause of lower than expected molecular weights.

3. Conclusions

In summary, a modified bis(phosphinimine) ligand has been prepared, which bears alkyl substituents at both the P and N
positions. From this, cationic zinc-alkyl (1) and zinc-lactate (2) complexes were efficiently prepared. Complex 2 is among the most active yet observed for ROP of lactate by a cationic metal complex. This result further demonstrates the efficacy of cationic zinc species for this process and highlights the necessity of a strongly electron-donating ligand to stabilize the highly electropositive metal. However, relatively poor molecular weight control remains an issue, which future studies will aim to address.

4. Experimental

4.1. Synthesis of compounds

4.1.1. 4-O-Benzyl-azide (177 mg, 1.33 mmol) was added dropwise to a stirring solution of db(PEt2)(2) (218 mg, 0.633 mmol) in benzene (2 ml). The resulting yellow solution was left to stand at ambient temperature for 30 min. The solution was concentrated to a volume of 1 ml, and 10 ml of pentane was added, causing the solution to become cloudy. Cooling to ~35 °C for 19 h resulted in the formation of yellow crystals. The mother liquor was decanted and the crystals were washed with pentane (3 × 1 ml) and dried in vacuo, giving L in 80% yield (279 mg, 0.503 mmol).1H NMR (CD2Cl2): δ 8.24 (dd, 2H, JHH = 11.0 Hz, JHP = 7.6 Hz, 3,7-dbf), 7.78 (d, 4H, JHH = 7.1 Hz, o-CH2Ph), 7.56 (d, 2H, JHH = 7.6 Hz, 1,9-dbf), 7.40 (t, 4H, JHH = 7.7 Hz, m-CH2Ph), 7.22 (t, 2H, JHP = 7.3 Hz, p-CH2Ph), 7.13 (td, 2H, JHH = 7.6 Hz, JHP = 1.1 Hz, 2,6-dbf), 4.73 (d, 4H, JHH = 18.4 Hz, 3,7-dbf), 2.10–1.15 (ov m, 8H, PCH2CH2), 0.95 (dt, 12H, JHH = 16.8 Hz, JHP = 7.6 Hz, PCH2CH2). 31P{1H} NMR (CD2Cl2): δ 4.14. Anal. Calcd. (%) for C34H40N2OP2: C: 73.63; H: 7.27; N: 3.87; P: 19.46. Found: C: 73.72; H: 7.27; N: 3.87; P: 19.46.

4.1.2. [LH][B(m-(CF3)2Ph)] (LH) (320 mg, 0.577 mmol) and [H(OEt)2]3B[m-(CF3)2C6H4]3 (584 mg, 0.577 mmol) were combined in a 20 ml glass vial with 2 ml of benzene. The resulting mixture was stirred briefly, giving a clear red solution, and left to stand for 5 min. Addition of 2 ml of pentane resulted in precipitation of a red oil. The supernatant was decanted, the oil was washed with pentane (3 × 2 ml) and dried in vacuo, affording LH as a pale yellow powder in 96% yield (783 mg, 1.266 mmol).1H NMR (CD2Cl2): δ 8.26 (dd, 2H, JHH = 7.3 Hz, 9,1-dbf), 7.75 (br s, 8H, o-CH2Ph), 7.65–7.50 (ov m, 8H, p-CH2Ph), 3.77–3.28 (br d, 8H, CH2Ph), 2.76–2.58 (ov m, 10H, −CH2−p-C6H4), 2.45 (br s, 1H, NH), 4.03 (d, 4H, JHH = 16.5 Hz, CH2Ph), 2.50–2.15 (ov m, 8H, PCH2CH2), 1.10 (dt, 12H, JHH = 18.9 Hz, JHP = 7.9 Hz, 3,7-dbf, PCH2CH2). 31P{1H} NMR (CD2Cl2): δ 39.53 (s). 1H{31P} (H NMR (CD2Cl2): δ −62.82 (s). 19F{1H} NMR (CD2Cl2): δ −6.60 (s). Anal. Calcd. (%) for C67H55BF24N2OP2Zn: C: 53.71; H: 3.70; N: 1.87; found: C: 53.35; H: 3.54; N: 2.20.

4.1.3. [ZnHCl][B(m-(CF3)2C6H4)] (1)

A 1.2 M solution of dimethylzinc in toluene (177 mg, 1.33 mmol) was added to a solution of LH (200 mg, 141 mmol) in bromobenzene (1 ml). The solution was left to stand for 1 h, then 2 ml of pentane were added, precipitating the product as a red oil. The supernatant was decanted, the material was washed with pentane (3 × 1 ml) and then dried in vacuo, giving 1 as an off-white powder in 90.0% yield (190 mg, 127 mmol).1H NMR (CD2Cl2): δ 8.34 (dt, 2H, JHH = 7.7 Hz, JHP = 1.1 Hz, 9,1-dbf), 7.73 (br s, 8H, o-BAr3), 7.64 (td, 2H, JHH = 7.7 Hz, JHP = 2.4 Hz, 2,8-dbf), 7.56 (br s, 4H, p-BAr3), 7.53 (ddd, 2H, JHH = 10.4 Hz, JHP = 7.7 Hz, JHP 11 Hz, 1,7, J11–14 Hz, JHP = 7.7 Hz, 3,7-dbf, PCH2CH2), 2.10 (dt, 12H, JHH = 18.7 Hz, JHP = 7.6 Hz, PCH2CH2), −0.95 (s, 3H, ZnCH3). 31P{1H} NMR (CD2Cl2): δ 46.60 (s).

4.2. X-ray crystallography data

4.2.1. Crystal data for LH

C34H40N2OP2, FW = 554.62, crystal size 0.32 × 0.32 × 0.12, triclinic, space group P−1, a = 10.863(1) Å, b = 11.262(1) Å, c = 13.923(2) Å, α = 72.388(1)°, β = 88.627(2)°, γ = 69.792(1)°, V = 1499.1(3) Å3, Z = 2, Dcal = 1.229 g cm−3, F(000) = 592, Mo Kα radiation (λ = 0.71073 Å), T = 173(2) K, μ = 0.174 mm−1, 20826 reflections, 6118 unique (Rint = 0.0225) were used in all calculations. R1 (I > 2σ(I)) = 0.0357, wR2 (I > 2σ(I)) = 0.0940.

4.2.2. Crystal data for LH

C34H40N2OP2Zn, FW = 1586.31, crystal size 0.52 × 0.33 × 0.27, triclinic, space group P−1, a = 15.019(2) Å, b = 15.453(2) Å, c = 16.072(2) Å, α = 104.979(1)°, β = 101.291(1)°, γ = 95.363(1)°, V = 3492.5(8) Å3, Z = 2, Dcal = 1.508 g cm−3, F(000) = 1612, Mo Kα radiation (λ = 0.71073 Å), T = 173(2) K, μ = 0.512 mm−1, 47147 reflections, 14,217 unique (Rint = 0.0184) were used in all calculations. R1 (I > 2σ(I)) = 0.0340, wR2 (I > 2σ(I)) = 0.0904.

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Appendix. Supplementary data

Supplementary data related to this article can be found online at doi:10.1016/j.jorgchem.2012.01.004.
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