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# Ring-Opening Polymerization with $Zn(C_6F_5)_2$-Based Lewis Pairs: Original and Efficient Approach to Cyclic Polyesters

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*Supporting Information*

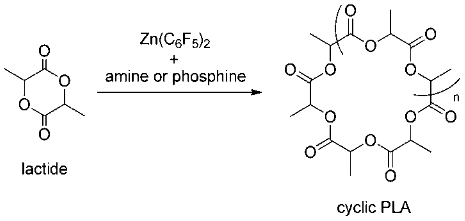
**ABSTRACT:** Dual systems combining $Zn(C_6F_5)_2$ with an organic base (an amine or a phosphine) promote the controlled ring-opening polymerization of lactide and ε-caprolactone. The Lewis pairs cooperate to activate the monomers, affording well-defined high molecular weight cyclic polyesters. Efficient chain-extension gives access to cyclic block copolymers.

The combination of Lewis acids and bases for cooperative activation of small molecules has attracted huge interest since phosphine/borane pairs were discovered to reversibly split $H_2$ under mild conditions.[1] Over the years, this concept has shown remarkable versatility, and a wide range of Lewis pairs have been developed. Not only phosphines but also amines and N-heterocyclic carbenes (NHC)[2] have been associated with perfluoroaryl boranes. Other Lewis acids based on aluminum,[3] carbon,[4] silicon,[5] or transition metals[6] have also been involved. The ability of these Lewis pairs to activate synergistically a broad range of small molecules has been substantiated at the stoichiometric scale.[1] Lewis pairs also give the opportunity to achieve cooperative metal-free catalysis. In this respect, impressive achievements have already been reported in hydrogenation reactions.[7,8] Recently, very promising results have also been reported in polymerization catalysis.[9,10] Indeed, the group of Chen succeeded in polymerizing acrylic monomers using $Al(C_6F_5)_3$ combined with a NHC or a phosphine.[9] These Lewis pairs cooperatively activate the monomer and generate zwiterrionic species that are highly reactive toward propagation.

Ring-opening polymerization (ROP) is a powerful and widespread polymerization technique. It provides efficient access to valuable biodegradable polymers, starting from lactones and related monomers. Here, catalysis plays a pivotal role if polymers of controlled structures are to be obtained under mild conditions.[11,12] Given our interest for ROP catalysis and the potential of dual approaches combining metal acids and organic bases,[13,14] we were keen to explore the use of Lewis pairs to promote ROP. Several recent reports mention such attempts with Al- and B-based Lewis acids but only with limited success so far.[9b] Stephan and co-workers studied the behavior of $B(C_6F_5)_3$/Lewis base combinations but observed only stoichiometric reactions: ring-opening with δ-valerolactone and ring contraction with lactide.[15] The zwitterionic phosphonium/ammonium borate alkoxide formed during these reactions is inactive toward coordination/insertion of lactones. In contrast with boron derivatives, zinc alkoxides are known to efficiently propagate the ROP of cyclic esters and lactones.[12] We thus envisioned to replace $B(C_6F_5)_3$ for a Zn-based Lewis acid and became interested in $Zn(C_6F_5)_2$ that has been scarcely explored in Lewis pair chemistry.[16] Herein, we report that the combination of $Zn(C_6F_5)_2$ and organic bases (amines or phosphines) indeed promotes the controlled ring-opening polymerization of lactide and ε-caprolactone, affording polymers of cyclic architecture.

Cyclic polymers are fascinating macromolecules.[17] The cyclic topology imparts unique properties that significantly differ from those of the corresponding linear polymers. In particular, different degradation and biodistribution profiles have been observed for cyclic and linear polyesters, which open interesting perspectives for material and biomedical applications.[18] However, synthetic issues have so far considerably limited the exploration of the specific properties of cyclic polyesters. Efficient and versatile methods to access cyclic polymers of high and controlled molecular weights are thus highly desirable. Waymouth et al. recently achieved a significant breakthrough in this area, with the NHC-mediated zwitterionic ROP of cyclic esters.[19−22] As shown here, Lewis pair catalysis provides a new method to access cyclic polyesters, and thanks to efficient chain extension, it enlarges the variety of accessible structures to cyclic block copolymers. The combination of 1,2,2,6,6-pentamethylpiperidine (PMP) and $Zn(C_6F_5)_2$ was investigated first. According to $^{19}F$ NMR spectroscopy,[23] the two compounds weakly interact in solution.[24] Nonetheless, lactide (LA) is readily polymerized in the presence of $Zn(C_6F_5)_2$ and PMP to give cyclic polylactides (PLA) (Scheme 1). Under optimal conditions (65 °C, Me-THF as solvent),[25] the polymerization is well-controlled and proceeds to high

**Scheme 1. ROP of Lactide With $Zn(C_6F_5)_2$-Based Lewis Pairs**



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conversion (up to 95%) within a few hours (Table 1). The activity of the $Zn(C_6F_5)_2$/PMP Lewis pair shows a strong solvent dependence.[24] The polymerization proceeds at significantly lower rate in THF (Table S1), and the formed PLA is contaminated by poly(THF), indicating competitive activation of THF by the Lewis pair.[26] $Zn(C_6F_5)_2$ is only sparingly soluble in $CH_2Cl_2$, and no polymerization occurs in this solvent within 24 h. Toluene is more convenient, and polymerization proceeds efficiently, albeit slightly slower than in Me-THF (entries 2 and 3). To assess the cooperativity of the $Zn(C_6F_5)_2$/PMP Lewis pair, control experiments were carried out in Me-THF and toluene. Under the same conditions, no polymerization occurred at all in both solvents when PMP or $Zn(C_6F_5)_2$ was used alone (no polymerization trace detected after 12 h at 65 °C).[24] The combination of $Zn(C_6F_5)_2$ and PMP is thus crucial to observe efficient and controlled polymerization.

**Table 1. Lactide and ε-Caprolactone ROP with $Zn(C_6F_5)_2$-Based Lewis Pairs**[a]

| entry | $[M]_0$:$[Zn]_0$:$[base]_0$ | base | t (h) | conv (%)[b] | $M_w$ (kg/mol)[c] | $M_w/M_n$[c] |
|---|---|---|---|---|---|---|
| 1 | 30:1:1 | PMP | 5 | 95 | 24.3 | 1.3 |
| 2[d,e] | 30:1:1 | PMP | 6.5 | 86 | 16.5 | 1.3 |
| 3[d] | 10:1:1 | PMP | 2 | 27 | 5.0 | 1.1 |
| 4 | 15:1:1 | PMP | 5 | 88 | 21.5 | 1.5 |
| 5 | 70:1:1 | PMP | 8.5 | 90 | 45.8 | 1.6 |
| 6 | 100:1:1 | PMP | 1 | 40 | 16.7 | 1.1 |
| 7 | 100:1:1 | PMP | 7 | 93 | 50.6 | 1.5 |
| 8 | 30:1:1 | DMAP[f] | 2 | 91 | 16.8 | 1.5 |
| 9 | 100:1:1 | DMAP[f] | 3 | 92 | 29.3 | 1.5 |
| 10 | 30:1:1 | $P^nBu_3$ | 2 | 99 | 14.6 | 1.4 |
| 11[g] | 30:1:1 | $P^nBu_3$ | 5.5 | 80 | 9.6 | 1.2 |
| 12 | 30:1:1 | $PPh_3$ | 4 | 93 | 18.1 | 1.2 |
| 13[h] | 30:1:1 | PMP | 3 | 99 | 13.2 | 1.2 |
| 14[h] | 40:1:1 | PMP | 5 | 99 | 18.9 | 1.3 |

[a] Unless otherwise stated, all reactions were carried out with $[LA]_0$ or $[\varepsilon\text{-CL}]_0$ = 0.5 M at 65 °C in MeTHF. [b] Monomer conversion was determined by $^1H$ NMR. [c] Absolute molecular weight and molecular weight distribution determined by SEC using multi-angle light-scattering detector in THF. [d] Polymerization carried out in toluene. [e] $T$ = 80 °C. [f] DMAP = N,N-dimethylaminopyridine. [g] $T$ = 30 °C. [h] Polymerization carried out with ε-caprolactone.

The structure of the obtained PLA was carefully analyzed by several analytical techniques. $^1H$ NMR spectroscopy revealed the absence of end groups, whatever the molecular weight of the PLA. In particular, no methine signal was observed at $\delta \sim 4.3$ ppm (Figure S1), as normally expected for a terminal $CH(CH_3)OH$ moiety, even for a low molecular weight PLA sample ($M_n$ = 4 500 g/mol) deliberately prepared by quenching a polymerization run at low conversion (entry 3). The latter sample was also analyzed by matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry. The corresponding mass spectrum (Figure 1) exhibits signals corresponding to sodium complexed cyclic PLA (molecular mass centered on 4200 m/z), no linear polymers are detected.[27]

The cyclic architecture of the obtained PLA was further corroborated by size-exclusion chromatography (SEC) using multi-angle light scattering (MALS) and viscosimetric detection. The PLA samples prepared with the $Zn(C_6F_5)_2$/PMP elute later and exhibit lower intrinsic viscosities compared to linear PLA of similar molecular weights, as prepared independently.[24] Mark–Houwink plots for a cyclic PLA (entry 1) and a linear PLA of similar molecular weight ($M_n$ = 18 800 g/mol, $M_w/M_n$ = 1.23) are displayed in Figure 2. The obtained $\eta_{cyclic}/\eta_{linear}$ ratios typically range from 0.67 to 0.78. These values are similar to those reported previously for samples prepared with NHC or amidines[19] and clearly indicate that the polymerization of lactide with $Zn(C_6F_5)_2$/PMP gives mostly cyclic PLA.[28]

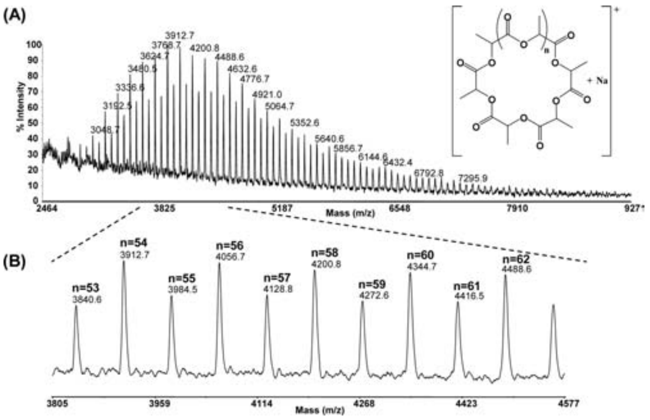


**Figure 1.** (A) Positive ion MALDI-TOF mass spectrum of cyclic PLA (entry 3). (B) Inset shows an expanded zone of this mass spectrum.

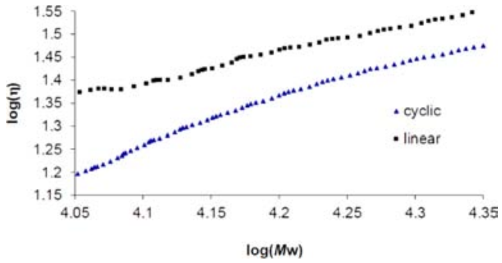


**Figure 2.** Representative Mark–Houwink plot of cyclic (triangles) and linear (squares) PLA of similar molecular weights.

Monitoring the polymerization of 100 equiv of LA over time revealed that the molecular weight of PLA increases linearly with monomer conversion (Figure 3). The molecular weight of PLA also increases with the initial monomer to $[Zn(C_6F_5)_2/PMP]$ ratio, though not linearly (Table 1). The absolute molecular weights determined by SEC exceed those calculated from the $[LA]_0$ to $[Zn(C_6F_5)_2/PMP]$ ratio, as observed with NHC.[19]

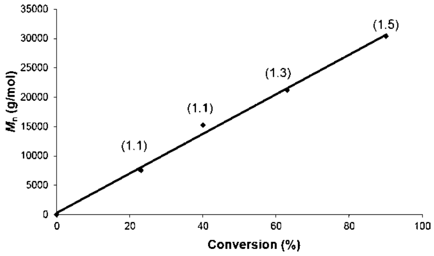


**Figure 3.** Plots of experimental $M_n$ vs monomer conversion (corresponding to entry 7). $M_w/M_n$ values are in parentheses.

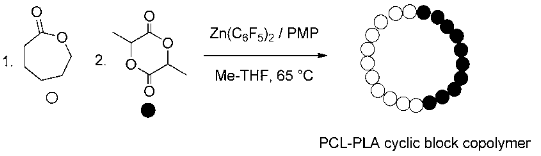
Thus, cyclic PLA of relatively high molecular weights (up to 33 700 g/mol) and narrow distributions ($1.1 < M_w/M_n \leq 1.6$)

can be obtained in a controlled manner with this system. It is also noteworthy that the cyclic PLA are prepared with good control even at $[LA]_0$ concentration of 0.5 M. Alternative synthetic strategies rely on the ring closure of appropriately $\alpha,\omega$-functionalized linear PLA and thus typically require high-dilution techniques.[29] According to homonuclear decoupled $^1H$ NMR spectroscopy (Figure S4), the ROP of L-lactide affords perfectly isotactic PLLA, indicating that the $Zn(C_6F_5)_2$/PMP Lewis pair does not induce epimerization of the monomer or polymer chain to a noticeable extent.

Aiming at extending the scope of such ROP dual catalysis, we then replaced PMP for other organic bases (entries 8–12, Table 1). Remarkably, the combinations of $Zn(C_6F_5)_2$ with more nucleophilic Lewis bases, such as DMAP or phosphines, also promote the controlled ROP of lactide and actually exhibit higher activity. High monomer conversions are now achieved within only 2 h at 65 °C (91% with DMAP and even 99% with $P^nBu_3$), and the $Zn(C_6F_5)_2/P^nBu_3$ Lewis pair proved quite active even at 30 °C (80% after 5.5 h). Note also that only a moderate drop in activity was observed when the electron-rich phosphine $P^nBu_3$ was replaced by $PPh_3$ (entry 12). DMAP and $P^nBu_3$ were among the first organocatalysts to be evaluated for the ROP of lactide, and they are indeed relatively active in the presence of alcohols as initiators, affording end-capped linear PLA.[12] However, they are practically inactive in the absence of protic agent, and as for PMP, their combination with $Zn(C_6F_5)_2$ is essential for cyclic PLA to be obtained. Although the exact polymerization mechanism is not clear at this stage, our results indicate that the Lewis acid and organic base act cooperatively to activate the monomer. By analogy with that proposed by Chen for the polymerization of MMA with $Al(C_6F_5)_3/PR_3$,[9] the propagation of LA ROP most probably involves zwitterionic species. The Lewis acidic $Zn(C_6F_5)_2$ is likely to coordinate the monomer, while amines/phosphines (DMAP, $P^nBu_3$ and $PPh_3$) act as nucleophiles to generate a zinc alkoxide. The good results obtained with PMP (a poorer nucleophile but stronger base) suggest that a basic pathway involving deprotonation of the activated lactide to generate a zinc-enolate may also operate (Figure S5).[30] Another noteworthy feature of these dual systems is that the polymerization of lactide proceeds efficiently despite the formation of adducts between the Lewis bases and $Zn(C_6F_5)_2$,[31] and the two catalyst components can actually be premixed before polymerization.

Finally, we evaluated the ability of $Zn(C_6F_5)_2$/PMP or DMAP combination to achieve chain extension and noticed here a striking difference with the NHC-promoted polymerization developed by Waymouth et al. With NHC, reinitiation of new polymer chains tends to be observed upon addition of a second batch of monomer, while we observed chain extension with $Zn(C_6F_5)_2$/PMP or DMAP.[24,32] Typically, the ROP of a first batch (28 equiv) of monomer was initiated with the $Zn(C_6F_5)_2$-based Lewis pair. After 6 h of reaction, an aliquot was analyzed by $^1H$ NMR and SEC ($M_n$ = 14 000 g/mol, $M_w/M_n$ = 1.25). A second feed of LA (28 equiv) was added to the reaction mixture and reacted for an additional 6 h to give a cyclic PLA with $M_n$ = 24 000 g/mol and $M_w/M_n$ = 1.50. The behavior of $Zn(C_6F_5)_2$/PMP and DMAP toward chain extension prompted us to explore cyclic block copolyesters synthesis. Recently, Waymouth et al. reported the copolymerization of $\varepsilon$-caprolactone ($\varepsilon$-CL) and $\varepsilon$-valerolactone with NHC in batch conditions and obtained thereby cyclic gradient copolymers.[20] Attempts to generate block copolymers were frustrated by the tendency of NHC to promote reinitiation rather than chain extension.[19,33] Preliminarily, the ability of the $Zn(C_6F_5)_2$/PMP Lewis pair to promote efficiently the ROP of other monomers was evaluated using $\varepsilon$-CL (entries 13 and 14, Table 1). The polymerization proceeded to complete conversion (>99%) within 3–5 h in MeTHF at 65 °C, affording cyclic polycaprolactones (PCL). The preparation of several PCL–PLA block copolymers was then targeted by sequential addition of $\varepsilon$-CL and LA in Me-THF at 65 °C (Scheme 2). The monomer conversions were followed by $^1H$ NMR. Again, no signal attributable to a LA or $\varepsilon$-CL chain end was detected. SEC analyses of aliquots taken after consumption of the first and second monomer show monomodal distributions of polymers of increasing molecular weight (from $M_n$ = 14 500 g/mol, $M_w/M_n$ = 1.34 to $M_n$ = 37 000 g/mol, $M_w/M_n$ = 1.39). After complete conversion of the second monomer, the polymer was isolated and further characterized. Similar results were obtained with the $Zn(C_6F_5)_2$/DMAP combination (Table S3).[24]

**Scheme 2. Sequential Polymerization of $\varepsilon$-CL and Lactide Affording PCL–PLA Cyclic Block Copolymer**



The copolymer microstructure was analyzed by NMR spectroscopy. In the $^1H$ and $^{13}C$ NMR spectra (Figures S7 and S8), resonance signals for LA–LA and CL–CL homodyads but not for heterodyads (LA–CL and CL–LA) are observed, indicating the absence of monomer alternation and thus the formation of a perfect diblock copolymer.[34] The cyclic architecture of the copolymer was ascertained by comparing its SEC elution time and intrinsic viscosity with that of a linear PCL-PLA block copolymer of similar molecular weight.[24] The cyclic copolymer elutes later than its linear analogue (Figure S16), consistent with a smaller hydrodynamic volume for the cyclic sample, and displays lower intrinsic viscosities (Figure S17). The $\eta_{cyclic}/\eta_{linear}$ ratio of the block copolymers is calculated to be ~0.8. This value falls in the same range than those reported for cyclic copolymers prepared by NHC-promoted ROP[20,21a] and attests to the formation of mostly cyclic PLA–PCL copolymers.

In conclusion, Lewis pair catalysis has been applied successfully to ring-opening polymerization. Dual systems combining $Zn(C_6F_5)_2$ with organic bases (amines and phosphines) have been shown to promote the ROP of lactide and $\varepsilon$-caprolactone, affording high molecular weight polymers of cyclic architecture. Such systems offer a new route to cyclic polyesters. The polymerization is well-controlled and enables the preparation of cyclic block copolymers, thanks to efficient chain extension. Future work in our laboratory will seek to study the polymerization mechanism and extend the scope of Lewis pair-promoted ROP. The properties of the ensuing (co)polymers will also be investigated to gain better knowledge on the influence of their cyclic topology.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

Experimental details and characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

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### Notes

The authors declare no competing financial interest.

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## REFERENCES

(1) (a) Stephan, D. W.; Erker, G. *Angew. Chem., Int. Ed.* **2010**, *49*, 46. (b) FLP chemistry : *Topics in Current Chemistry*; Stephan, , D. W., Erker, , G., Eds.; Springer: New York, **2013**,; Vols. 332, and 334,.

(2) (a) Holschumacher, D.; Bannenberg, T.; Hrib, C.; Jones, P. G.; Tamm, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 7428. (b) Chase, P. A.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2008**, *47*, 7433.

(3) (a) Dureen, M. A.; Stephan, D. W. *J. Am. Chem. Soc.* **2009**, *131*, 8396. (b) Ménard, G.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2012**, *51*, 8272. (c) Appelt, C.; Westenberg, H.; Bertini, F.; Ehlers, A. W.; Slootweg, J. C.; Lammertsma, K.; Uhl, W. *Angew. Chem., Int. Ed.* **2011**, *50*, 3925.

(4) (a) Inés, B.; Holle, S.; Goddard, R.; Alcarazo, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 8389. (b) Li, H.; Risko, C.; Seo, J. H.; Campbell, C.; Wu, G.; Brédas, J. L.; Bazan, G. C. *J. Am. Chem. Soc.* **2011**, *133*, 12410.

(5) Schäfer, A.; Reissmann, M.; Schäfer, A.; Saak, W.; Haase, D.; Müller, T. *Angew. Chem., Int. Ed.* **2011**, *50*, 12636.

(6) (a) Chapman, A. M.; Haddow, M. F.; Wass, D. F. *J. Am. Chem. Soc.* **2011**, *133*, 18463. (b) Sgro, M. J.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2012**, *51*, 11343.

(7) E.g.: (a) Chase, P. A.; Welch, G. C.; Jurca, T.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 8050. (b) Spies, P.; Schwendemann, S.; Lange, S.; Kehr, G.; Froehlich, R.; Erker, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 7543. (c) Farrell, J. M.; Hatnean, J. A.; Stephan, D. W. *J. Am. Chem. Soc.* **2012**, *134*, 15728. (d) Greb, L.; Ona-Burgos, P.; Schirmer, B.; Grimme, S.; Stephan, D. W.; Paradies, J. *Angew. Chem., Int. Ed.* **2012**, *51*, 10164.

(8) Phosphine-boranes have also been shown to promote Michael addition (CC coupling): Basle, O.; Porcel, S.; Ladeira, S.; Bouhadir, G.; Bourissou, D. *Chem. Commun.* **2012**, *48*, 4495.

(9) (a) Zhang, Y.; Miyake, G. M.; Chen, E. Y. X. *Angew. Chem., Int. Ed.* **2010**, *49*, 10158. (b) Zhang, Y.; Miyake, G. M.; John, M. G.; Falivene, L.; Caporaso, L.; Cavallo, L.; Chen, E. Y. X. *Dalton Trans.* **2012**, *41*, 9119.

(10) Nitroxides derived from phosphine-boranes have been used to promote controlled radical polymerization of styrene: Sajid, M.; Stute, A.; Cardenas, A. J.; Culotta, B. J.; Hepperle, J. A. M.; Warren, T. H.; Schirmer, B.; Grimme, S.; Studer, A.; Daniliuc, C. G.; Fröhlich, R.; Petersen, J. L.; Kehr, G.; Erker, G. *J. Am. Chem. Soc.* **2012**, *134*, 10156.

(11) ROP of lactones with metal-alkoxide initiators reviews: (a) O'Keefe, B. J.; Hillmyer, M. A.; Tolman, W. B. *J. Chem. Soc., Dalton Trans.* **2001**, 2215. (b) Dechy-Cabaret, O.; Martin-Vaca, B.; Bourissou, D. *Chem. Rev.* **2004**, *104*, 6147.

(12) For reviews on the organocatalyzed ROP of lactones, see: (a) Kamber, N. E.; Jeong, W.; Waymouth, R. M.; Pratt, R. C.; Lohmeijer, B. G. G.; Hedrick, J. L. *Chem. Rev.* **2007**, *107*, 5813. (b) Bourissou, D.; Moebs-Sanchez, S.; Martin-Vaca, B. *C. R. Chimie* **2007**, *10*, 775. (c) Dove, A. P. *ACS Macro Lett.* **2012**, *1*, 1409.

(13) Recent contributions: (a) Pietrangelo, A.; Knight, S. C.; Gupta, A. K.; Yao, L. J.; Hillmyer, M. A.; Tolman, W. B. *J. Am. Chem. Soc.* **2010**, *132*, 11649. (b) Piedra-Arroni, E.; Brignou, P.; Amgoune, A.; Guillaume, S. M.; Carpentier, J. F.; Bourissou, D. *Chem. Commun.* **2011**, *47*, 9828.

(14) Recent frontier article: Piedra-Arroni, E.; Amgoune, A.; Bourissou, D. *Dalton Trans.* **2013**, *42*, 9024.

(15) Kreitner, C.; Geier, S. J.; Stanlake, L. J. E.; Caputo, C. B.; Stephan, D. W. *Dalton Trans.* **2011**, *40*, 6771.

(16) Bridging $N_2O$ complexes have been prepared by Lewis acid exchange from phosphine-borane adducts: Neu, R.; Otten, E.; Stephan, D. W. *Angew. Chem., Int. Ed.* **2009**, *48*, 9709.

(17) (a) *Cyclic Polymers*, 2nd ed.; Semlyen, J. A., Ed.; Kluwer Academic Publishers: Dordrecht, 2000. (b) Endo, K. *Adv. Polym. Sci.* **2008**, *217*, 121. (c) Kricheldorf, H. R. *J. Polym. Sci. A Polym. Chem.* **2010**, *48*, 251.

(18) Hoskins, J. N.; Grayson, S. M. *Polym. Chem.* **2011**, *2*, 289.

(19) (a) Culkin, D. A.; Jeong, W.; Csihony, S.; Gomez, E. D.; Balsara, N. P.; Hedrick, J. L.; Waymouth, R. M. *Angew. Chem., Int. Ed.* **2007**, *46*, 2627. (b) Jeong, W.; Shin, E. J.; Culkin, D. A.; Hedrick, J. L.; Waymouth, R. M. *J. Am. Chem. Soc.* **2009**, *131*, 4884. (c) Brown, H. A.; De Crisci, A. G.; Hedrick, J. L.; Waymouth, R. M. *ACS Macro Lett* **2012**, *1*, 1113. (d) Brown, H. A.; Waymouth, R. M. *Acc. Chem. Res.* **2013**, DOI: 10.1021/ar400072z.

(20) Shin, E. J.; Brown, H. A.; Gonzalez, S.; Jeong, W.; Hedrick, J. L.; Waymouth, R. M. *Angew. Chem., Int. Ed.* **2011**, *50*, 6388.

(21) NHC have also been used to mediate the zwitterionic polymerization of N-carboxyanhydrides towards poly($\alpha$-peptoids): (a) Guo, L.; Zhang, D. *J. Am. Chem. Soc.* **2009**, *131*, 18072. (b) Guo, L.; Lahasky, S. H.; Ghale, K.; Zhang, D. *J. Am. Chem. Soc.* **2012**, *134*, 9163.

(22) For ring-expansion polymerization of lactide with Al alkoxides: Weil, J.; Mathers, R. T.; Getzler, Y. D. Y. L. *Macromolecules* **2012**, *45*, 1118.

(23) $\Delta\delta_{m,p}(^{19}F)$ is a sensitive indicator for the coordination of Lewis bases to $Zn(C_6F_5)_2$: (a) Mountford, A. J.; Lancaster, S. J.; Coles, S. J.; Horton, P. N.; Hughes, D. L.; Hursthouse, M. B.; Light, M. E. *Organometallics* **2006**, *25*, 3837. (b) Martin, E.; Spendley, C.; Mountford, A. J.; Coles, S. J.; Horton, P. N.; Hughes, D. L.; Hursthouse, M. B.; Lancaster, S. J. *Organometallics* **2008**, *27*, 1436.

(24) See SI for details.

(25) General discussion of the advantages of MeTHF over THF: Aycock, D. F. *Org. Process Res. Dev.* **2006**, *11*, 156.

(26) Phosphine and pyridine/$B(C_6F_5)_3$ Lewis pairs have been shown to ring-open THF: (a) Welch, G. C.; Prieto, R.; Dureen, M. A.; Lough, A. J.; Labeodan, O. A.; Holtrichter-Rossmann, T.; Stephan, D. W. *Dalton Trans.* **2009**, 1559. (b) Geier, S. J.; Stephan, D. W. *J. Am. Chem. Soc.* **2009**, *131*, 3476.

(27) As with NHC,[19] cyclic PLA with even and odd numbers of lactate units are formed. This can be classically explained by interchain transesterification and/or random back-biting.

(28) Theoretically, the intrinsinc viscosity of a cyclic polymer is predicted to be ideally 0.667 of that of a linear polymer of same molecular weight.[17a]

(29) (a) Stanford, M. J.; Pflughaupt, R. L.; Dove, A. P. *Macromolecules* **2010**, *43*, 6538. (b) Sugai, N.; Yamamoto, T.; Tezuka, Y. *ACS Macro Lett.* **2012**, *1*, 902.

(30) Our working hypothesis is that the key cyclization step occurs at the very end of the polymerization and/or during work up.

(31) According to NMR spectroscopy ($^{19}F$ and eventually $^{31}P$), all bases (DMAP, $PnBu_3$, $PPh_3$) interact weakly with $Zn(C_6F_5)_2$ in solution.[24]

(32) Chain extension is not observed when polymerization of lactide is carried out in the presence of isolated cyclic PLA, instead the Lewis pairs initiate new polymer chains.

(33) Cyclic block copolyamides have been obtained upon sequential polymerization of N-carboxyanhydrides with NHC.[21a]

(34) To enable direct observation of the covalent linkage between the two blocks by NMR, copolymers with a short gradient interface were prepared by adding LA at ~80 to 95% conversion of CL. Sequential copolymerization starting from lactide also gives cyclic PLA−PCL block copolymers with a short gradient interface.[24]