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Romain Ligny, Mikko M. Hänninen, Sophie M. Guillaume, Jean-François Carpentier. Highly Syndiotactic or Isotactic Polyhydroxyalkanoates by Ligand-Controlled Yttrium-Catalyzed Stereoselective Ring-Opening Polymerization of Functional Racemic β -Lactones. *Angewandte Chemie International Edition*, Wiley-VCH Verlag, 2017, 56 (35), pp.10388-10393. 10.1002/anie.201704283 . hal-01579647

HAL Id: hal-01579647

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Submitted on 31 Aug 2017

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Highly Syndiotactic to Isotactic Polyhydroxyalkanoates via Ligand-Controlled Yttrium-Catalyzed Stereoselective Ring-Opening Polymerization of Functional Racemic β -lactones**

Romain Ligny,^a Mikko M. Hänninen,^b Sophie M. Guillaume,^{a,*} and Jean-François Carpentier^{a,*}

Abstract: Reported herein is the first stereoselective controlled ROP of a **specific** family of racemic functional β -lactones, namely 4-alkoxy-methylene- β -propiolactones (BPL^{ORs}), using yttrium catalysts stabilized by nonchiral tetradentate amino-alkoxy-bisphenolate ligands {ONOO^{R'2}}²⁻, combining both a good activity and a high degree of control over the molar masses of the resulting functional poly(3-hydroxyalkanoate)s PHB^{ORs}. The simple modification of ortho,para-R' substituents on the ligand platform allows a complete reversal from virtually pure syndiotactic (P_s up to 0.91 with R' = cumyl) to pure isoselective (P_i up to 0.93 with R' = Cl) ROP, as supported by DFT insights. This is the first example of a highly isoselective ROP of a racemic chiral β -lactone.

Ring-opening polymerization (ROP) of cyclic esters is the method of choice for preparing polyesters with a bespoke architecture. Tremendous efforts have been spent in the past two decades for developing highly effective metal-based or organo-catalysts able to fine-tune the molar mass, terminal groups and the microstructure of the polymers.^[1] A specific point of major interest in this research field is the control of tacticity –and, as a result, of physicochemical properties– when starting from *racemic* mixtures of chiral cyclic monomers. Hence, much work has been devoted to the ROP of *racemic* lactide (*rac*-LA) for the synthesis of biosourced degradable polymer alternatives to regular petrochemical-based plastics. *Heterotactic* polylactide (PLA) is quite commonly obtained, most often as the result of a chain-end stereocontrolled (CEC) mechanism which minimizes steric interactions between the last inserted monomer unit in the growing polymer chain and the new incoming monomer unit, thus resulting in the alternation of monomer units with opposite (*R,R/S,S*) configuration. On the other hand, the preparation of valuable crystalline (sometimes stereocomplexed) *isotactic* PLA from the ROP of *rac*-LA is much more challenging; only a few catalysts/initiators, essentially based on group 13 (Al,^[2] In^[3]), 12 (Zn,^[4] 4 (Zr)^[5] and 3 (rare-earth)^[6] metals, have proved able to do so with probabilities of *isotactic* enchainment (P_i) up to 0.97.

Extension of stereoselective ROP to other chiral cyclic esters is much less documented. In particular, β -lactones such as the prototypical β -butyrolactone (BL), are more reluctant to ring-open and few catalysts are able to perform their ROP, even less in a stereoselective fashion.^[7] We have shown that yttrium catalysts stabilized by nonchiral tetradentate amino-alkoxy-bisphenolate ligands {ONOO^{R'2}}²⁻ offer highly *syndiotactic* poly(3-hydroxybutyrate) (PHB) with a probability of *syndio* enchainment (P_s) up to 0.96, provided sterically bulky aryl-containing substituents are installed on the *ortho*-site of phenolate ligands.^[8] This ROP catalysis has been extended to different *racemic* β -lactones,^[9] in particular to valuable functional ones such as alkyl β -malolactonates (i.e., 4-alkoxycarbonyl- β -lactones, MLA^R; R = allyl, benzyl);^[10] in this latter case, surprisingly, only yttrium catalysts bearing an *ortho,para* (*o,p*)-dichloro-substituted {ONOO^{Cl2}}²⁻ ligand enabled achieving highly *syndiotactic* polymerizations ($P_s > 0.95$). Regular catalysts incorporating sterically crowded R' alkyl/aryl *o,p*-substituents on the {ONOO^{R'2}}²⁻ platform afforded only modest syndiotacticity. All these syndiotactic reactions operated through a CEC mechanism, as revealed by NMR studies and also pinpointed by DFT computations.^[11] On the other hand, the best isoselectivity in the ROP of *racemic* BL was achieved by a Cr catalyst with a modest isotacticity bias (P_i ca. 0.65) and no control over molar masses.^[12]

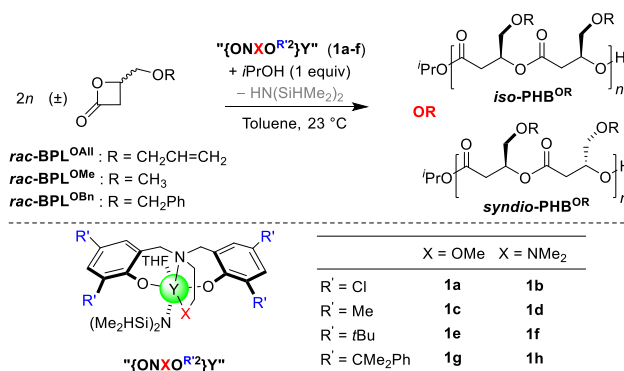
We herein report on the first stereoselective ROP of another class of *racemic functional* β -lactones, namely 4-alkoxymethylene- β -propiolactones (BPL^{ORs}), combining both a good catalytic activity and a high degree of control over the molar masses of the resulting alkoxy-functional poly(3-hydroxyalkanoate)s PHB^{ORs}. It is shown that simple modification of *o,p*-R' substituents on the {ONXO^{R'2}}²⁻ platform of yttrium catalysts allows switching completely from syndiotactic to isoselective polymerization of this specific class of β -lactones; quite unexpectedly and uniquely, catalysts bearing an *o,p*-dichloro-substituted ligand deliver highly *isotactic* polyesters ($P_i > 0.90$). This is the first example of a highly isoselective ROP of a *racemic* chiral β -lactone.

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[**] This research was financially supported in part by the Region Bretagne (Ph.D. grant to R.L.) and by the Academy of Finland (M. H. grant number 274505).

Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/anie.201xxxxx>.



Scheme 1. Stereoselective synthesis of *isotactic* and *syndiotactic* PHB^{ORs} from the ROP of *racemic* BPL^{ORs}.

ROP reactions were performed on three *racemic* BPL^{OR} monomers (R = allyl, benzyl, methyl) (Scheme 1), which were readily prepared by carbonylation of the corresponding *racemic* epoxides following Coates' Co-catalyzed protocol (Figure S1 in the Supporting Information).^[13] As for previous studies,^[8,10] yttrium-isopropoxide catalysts/initiators were conveniently generated in situ from the action of 1 equiv. of *i*PrOH onto the respective amido precursors **1a-g** that were selected with ligands differing by the nature of the R' phenolate substituents.

Catalytic systems with ligands incorporating bulky alkyl *o,p*-substituents (*t*Bu, **1e**, **1f**; cumyl, **1g**, **1h**) revealed quite active at 20 °C in toluene, allowing typically quantitative conversion of ca. 50–100 equiv. of *rac*-BPL^{OR} within 2 h (Tables 1, S1). On the other hand, catalysts based on ligands having small Cl (**1a**, **1b**) or Me (**1c**, **1d**) *o,p*-substituents proved somewhat more sluggish. This observation is peculiar and might appear counterintuitive at first sight, since the approach of the monomer is anticipated to be favored with lower steric hindrance around the metal center; also, the presence of electron-withdrawing substituents (such as Cl) on ligands has been reported to often increase ROP reaction rates.^[2] We also noted that pre-catalyst systems with a NMe₂ cap (X) on the ligand (**1b**, **1d**, **1f**, **1h**) are systematically more active than their OMe-capped counterpart (**1a**, **1c**, **1e**, **1g**), respectively, regardless of the *o,p*-substituents (Tables 1, S1). Hence, the dichloro OMe-capped system (**1a**), poorly active at room temperature (Table S1), can be valuably substituted by the dichloro NMe₂-capped system (**1b**) which offers high BPL^{OR} conversion within reasonable times under the same operating conditions (Table 1, entry 2). Detailed monitoring of NMR-scale reactions performed on *rac*-BPL^{OAll} at 23 °C with the catalyst systems that are not too active, confirmed these kinetic trends derived from batch experiments, and linear semi-logarithmic plots established that the reactions are first-order in monomer (k_{app} (min⁻¹) = 2.43±0.10, **1g**; 2.38±0.10 × 10⁻², **1b**; 1.07±0.09 × 10⁻², **1d**; 0.62±0.03 × 10⁻², **1c**; 0.10±0.01 × 10⁻², **1a**) (Table S2, Figure S2). Reactivity of the catalyst systems in THF was significantly lower,^[14] most likely as the result of competitive coordination of THF vs. monomer onto the metallic center; such a behavior has been previously observed in the ROP of alike polar cyclic ester monomers.^[10,15]

The reactions proceeded with a fair control over the PHB^{ORs} molar masses. This is evidenced by (i) the quite good agreement

between experimental molar mass values ($M_{n,NMR}$) and theoretical ones ($M_{n,theo}$), as determined by ¹H NMR analyses (from the isopropoxycarbonyl end-group and main-chain resonances), and monomer-to-initiator along with BPL^{OR} conversion, respectively, (ii) the linear growth of experimental molar masses (e.g., $M_{n,NMR}$) as a function of monomer conversion as illustrated with BPL^{OAll} (Figure S3), as well as (iii) the rather narrow dispersity values (1.07 ≤ \bar{D}_M ≤ 1.23) as determined by SEC analysis. The analysis of the end-groups was conducted by ¹H and ¹³C{¹H} NMR spectroscopy (Figures S4–S9) as well as by ESI mass spectrometry (Figures S10–S17). The latter MS analyses of PHB^{ORs} (OR = OAll, OMe) showed a major set of peaks assignable to polyester chains with hydroxy and isopropoxycarbonyl end-groups, with peaks separated by 142 and 116 amu, respectively.

The stereoselectivity of the ROP reactions was much affected by the nature of the R' *o,p*-substituents on the phenolate ligand. As a matter of fact, a complete reversal from virtually pure *syndiotactic* (P_s up to 0.91) to pure *isotactic* (P_i up to 0.93) was observed upon switching from dicumyl- (**1g**) to dichloro- (**1a**) substituted ligands in the catalyst/initiator, respectively (Table 1, entries 1,6).^[16] This striking change in stereoselectivity was best assessed by ¹³C{¹H} NMR spectroscopy of the resulting PHB^{ORs} (Figures S5, S7, S9). In line with previous observations on related poly(3-hydroxyalkonates), namely PHB,^[8] and allyl and benzyl β-malolactonates (PMLA^R; R = allyl, benzyl),^[10] we observed that the ¹³C NMR signals of the main chain carbonyl and methine carbons as well as that of the methylene side-chains are diagnostic of the tacticity of PHB^{OR}; the case of PHB^{OAll} is illustrated in Figure 1. Basically, these regions of the NMR spectra show signals at the diad level, enabling a facile determination of the P_s/P_i values (i.e., $P_s = 1 - P_i$).^[17] To ascertain the assignments, pure *isotactic* polymers were independently prepared by ROP of enantiomerically pure (*S*)-BPL^{OAll} and (*R*)-BPL^{OMe} (Table S1). The ¹³C NMR spectra of these two *isotactic* materials each displayed a single sharp resonance for the three aforementioned types of carbons. The polymers prepared from *rac*-BPL^{OAll} with *o,p*-dichloro-substituted catalysts/initiators **1a** and **1b** showed the same strong signals, along with a minor one either downfield (C=O and CH) or upfield (CH₂), assigned to the *syndio* diad. In contrast, the polymers prepared with the dicumyl-substituted catalysts/initiators **1g** and **1h**, exhibited a complete switch in intensity between these two signals for each carbon, indicative of highly *syndiotactic* polymers. Similar observations were made for PHB^{OMe} and PHB^{OBn} (Figures S18, S19).

Table 1. ROP of *rac*-BPL^{OR} mediated by 1/*i*PrOH systems in toluene (refer to Table S1 for further experiments).

Entry	BPL ^{OR}	Catalyst	[BPL ^{OR}] ₀ : ^[1] ₀ : ^[iPrOH] ₀ ^[a]	Temp. (°C)	Time ^[b] (h)	Conv. ^[c] (%)	$M_{n,theo}$ ^[d] (g.mol ⁻¹)	$M_{n,NMR}$ ^[e] (g.mol ⁻¹)	$M_{n,SEC}$ ^[f] (g.mol ⁻¹)	\bar{D}_M ^[g]	P_i ^[g]
1	OAll	1a	53:1:1	60	72	74	7 550	7 150	9 200	1.46	0.07
2	OAll	1b	54:1:1	20	2	94	7 800	7 850	10 500	1.09	0.10
3	OAll	1c	54:1:1	20	2	39	3 050	3 300	4 300	1.12	0.49
4	OAll	1d	50:1:1	20	2	74	5 300	5 600	7 200	1.11	0.51
5	OAll	1g	51:1:1	0	2	100	7 250	7 950	12 150	1.39	0.91
6	OAll	1g	55:1:1	20	2	100	7 850	7 650	11 000	1.19	0.88
7	OAll	1g	108:1:1	20	2	100	15 290	15 150	18 300	1.14	0.84
8	OAll	1h	53:1:1	20	2	100	7 500	7 450	8 600	1.23	0.82
9	OMe	1b	44:1:1	20	2	84	4 350	5 200	5 200	1.06	0.10
10	OMe	1g	49:1:1	20	2	100	5 750	5 750	8 400	1.18	0.81
11	OMe	1h	43:1:1	20	2	100	5 050	4 950	6 850	1.07	0.78
12	OBn	1b	47:1:1	20	2	98	9 100	11 550	11 000	1.08	0.10
13	OBn	1g	52:1:1	20	2	100	10 000	11 400	16 400	1.14	0.88
14	OBn	1h	51:1:1	20	2	100	9 850	10 050	10 500	1.07	0.90

^a Reactions performed at [BPL^{OR}]₀ = 1.0 M. ^b Reaction time was not necessarily optimized. ^c Conversion of BPL^{OR} as determined by ¹H NMR analysis of the crude reaction mixture. ^d Molar mass calculated according to $M_{n,theo} = ([BPL^{OR}]_0/[1]_0 \times \text{conv.}_{BPL^{OR}} \times M_{BPL^{OR}}) + M_{iPrOH}$, with $M_{BPL^{OAll}} = 142$ g.mol⁻¹, $M_{iPrOH} = 60$ g.mol⁻¹. ^e Molar mass determined by ¹H NMR analysis of the isolated polymer, from resonances of the terminal O*i*Pr group. ^f Number-average molar mass and dispersity (M_w/M_n) determined by SEC analysis in THF at 30 °C vs. polystyrene standards (uncorrected values). ^g P_i is the probability of *racemic* linkages between BPL^{OR} units as determined by ¹³C{¹H} NMR analysis of the isolated PHB^{ORs}.

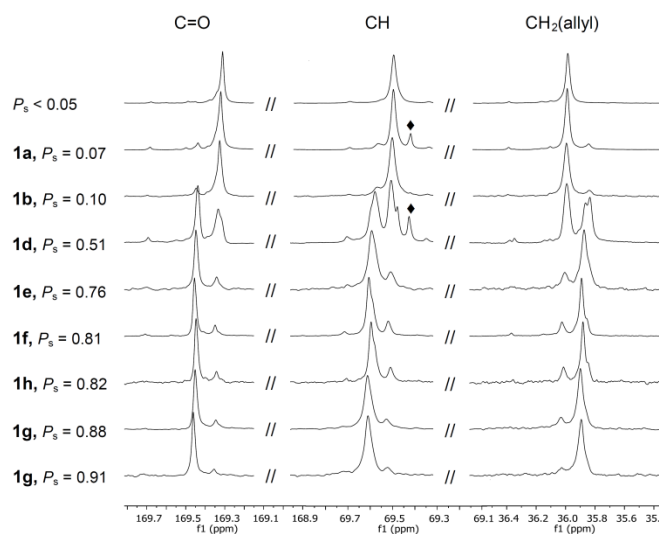


Figure 1. Detailed regions of $^{13}\text{C}\{^1\text{H}\}$ NMR spectra (125 MHz, CDCl_3 , 23 $^\circ\text{C}$) of polymers prepared from the ROP of $\text{rac-BPL}^{\text{OAll}}$ (except top spectrum, from enantiopure (S)- BPL^{OAll}) by 1/*i*PrOH (1:1) systems (Tables 1, S1). ♦ refers to residual monomer.

The *tert*-butyl substituted systems **1e** and **1f** induce a slightly less pronounced syndio-control than their cumyl-substituted analogues **1g** and **1h**, respectively ($P_s = 0.76$ vs. 0.88 and 0.81 vs. 0.82) (Tables 1, S1).^[17] Performing the ROP of $\text{rac-BPL}^{\text{OAll}}$ at lower temperature (0 $^\circ\text{C}$) with the **1g**/*i*PrOH system produced, as anticipated, a polymer with a higher P_s value of 0.91 (Table 1, entry 5). Similar trends were observed for the ROP of $\text{rac-BPL}^{\text{OMe}}$ and $\text{rac-BPL}^{\text{OBn}}$. The formation of highly syndiotactic PHB^{OR} with “{ONOO R^2 }Y” catalysts bearing sterically crowded R' (*t*Bu, CMe_2Ph) substituents follows trends previously established in the ROP of rac-BL ,^[8,11] $\text{rac-MLA}^{\text{R}}$ ($R = \text{allyl, benzyl}$),^[10] and other β -lactones^[9] with related yttrium catalysts. This is consistent with a CEC mechanism where bulky substituents on the ligand platform favor discrimination between enantiomers of opposite configuration in a highly sterically crowded coordination sphere. Accordingly, systems **1c** and **1d** that are based on ligands with much less bulky methyl substituents afforded systematically *atactic* PHB^{OR} materials ($P_s \approx P_i$ ca. 0.50), as clearly illustrated in the ^{13}C NMR spectra (Figure 1).

The most striking feature is the ability of dichloro-substituted systems **1a** and **1b** to give *isotactic* PHB^{OR} materials. This is a completely original behavior since the same systems, when applied to the ROP of rac-LA ,^[8b] rac-BL ^[10] and $\text{rac-PMLA}^{\text{R}}$ s,^[10] formed *atactic* PLA and PHB and highly syndiotactic PMLA R^{S} , respectively. Because Cl has a similar size to methyl, a steric origin of the

isocontrol in the ROP of BPL^{OR} can be ruled out. In this respect, the present phenomenon is quite different from that previously noted by Gibson et al. in the ROP of rac-LA with Al-salan type initiators, since in this latter case, the chloro-substituted systems actually afforded *heterotactic* PLA, just as the methyl-substituted systems did.^[2e] As expected from the achiral nature of our initiators, we checked that both enantiomers of $\text{rac-BPL}^{\text{OAll}}$ are consumed at the same rate (Figures S20, S21), and hence that *racemic* mixtures of homochiral (*S*- and (*R*)- PHB^{OAll} are produced.

DFT studies have been performed to investigate the experimentally observed stereoselectivity of the catalysts. For the sake of computational resources, we have concentrated onto smallest catalysts **1a** and **1c** with BPL^{OAll} as monomer. It should be noted that the mechanism of the elementary steps of ROP (ring-opening of the first monomer) is already well established,^[18] hence our focus was placed on the second step of the reaction determining the stereochemistry of the polymer (Figure 2) (see the Supporting Information for details).^[19]

The free energies (ΔG) of the first two steps (attack of the monomer and formation of the four-membered metallacycle) for both iso- and syndioselective routes are similar. However, the second transition state leading to syndiotactic PHB^{OAll} (**III-SR-TS**) is notably higher in energy ($\Delta G^\ddagger = 11.6 \text{ kcal mol}^{-1}$) compared to the transition state leading to isotactic polymer (**III-SS-TS**, $\Delta G^\ddagger = 6.2 \text{ kcal mol}^{-1}$). The origin of this difference was traced back to strong C–H \cdots Cl interactions between the ring-opened monomer and aromatic chloride substituents of the {ONXO C^{12} } $^{2-}$ ligand (Figures 3 and S22, see the Supporting Information). Because the free energy of **III-SS-TS** is very low, the actual rate limiting step in the *isoselective* route is **II-SS-TS** with $\Delta G^\ddagger = 7.1 \text{ kcal mol}^{-1}$. Hence, the activation energy for the formation of *isotactic* PHB^{OAll} is 4.5 kcal mol $^{-1}$ lower than for the *syndiotactic* polymer, which is in excellent agreement with the experimental result that **1a** and **1b** produce a highly *isotactic* material. It is very important to note that the strongest C–H \cdots Cl interaction exists between a hydrogen from the alkoxymethylene group (–CH $\text{CH}_2\text{OCH}_2\text{CH}=\text{CH}_2$) that is replaced in alkoxycarbonyl- β -lactones (MLA^{R}) by a carbonyl group (–CHC(=O)OCH $_2$ –CH=CH $_2$). Not only this result elucidates the completely inverse behavior of {ONXO C^{12} } $^{2-}$ ligand in the ROP of $\text{rac-MLA}^{\text{R}}$ and $\text{rac-PBL}^{\text{OR}}$ monomers, but it also indicates that the mechanism of MLA^{R} polymerization, producing highly syndiotactic PMLA ($P_s > 0.95$),^[10b] is largely different than the above described route. Furthermore, because the strong interaction between this specific hydrogen and the aryl chloride substituent appears to be the main factor affecting the stereocontrol of the catalyst, it explains why different R-groups in PHB^{OR} ($R = \text{allyl, Me, benzyl}$) do not have a significant impact onto the stereochemistry of the polymer (Tables 1, S1).^[20] The above calculations were repeated for methyl substituted catalyst **1c** to estimate the differences between the substitution pattern of {ONXO R^2 } $^{2-}$ ligand. The ROP of PHB^{OAll} using **1c** as initiator proceeds through a similar route than that with

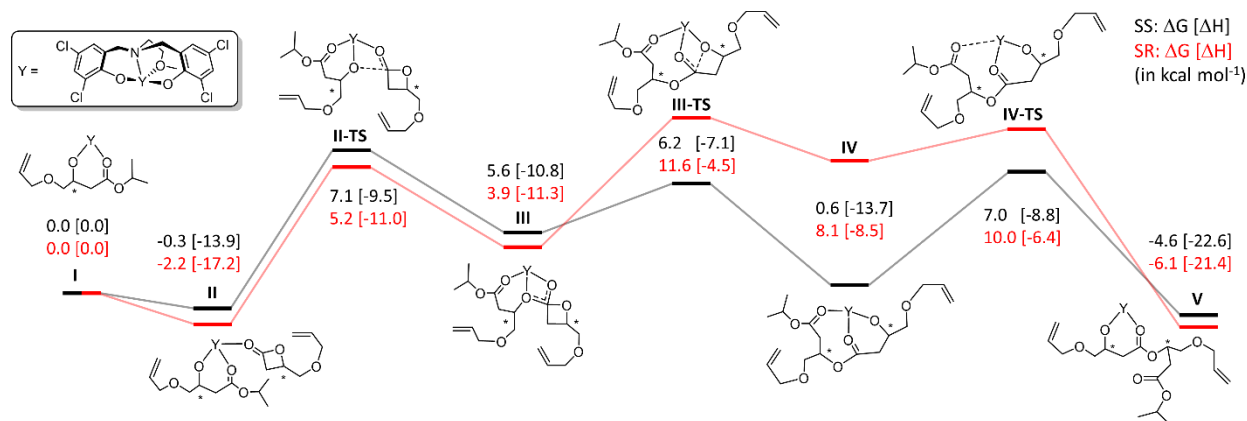


Figure 2. Energy profile of the proposed ROP mechanism for *isotactic* (black) and *syndiotactic* (red) PHB^{OAll} formation with **1a** as initiator.

1a. However, the energy profile of the reaction is significantly different (Figure S23). The free energies of almost all intermediates and transition states on both iso- and syndio-propagation routes are virtually identical. Interestingly, the difference in ΔG^\ddagger of the rate determining step (**III-SS/SR-TS**) is diminishingly small (0.2 kcal mol⁻¹). This result is again in perfect agreement with the experimental observation that methyl substituted catalysts **1c** and **1d** produce practically *atactic* PHB^{ORs}.

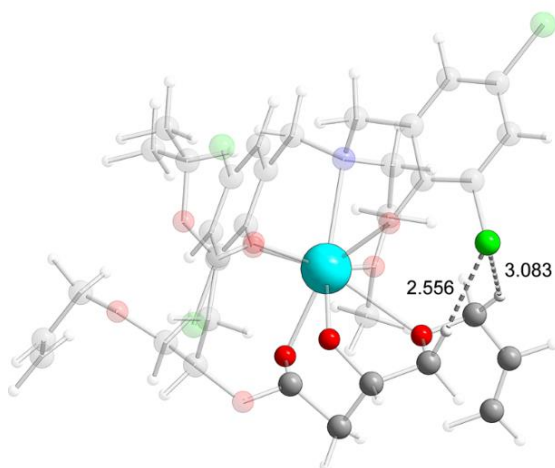


Figure 3. Structure of **III-SS-TS** showing the shortest CH...Cl distances (blue = Y, red = O, green = Cl, dark grey = C, light grey = H) (see also the Supp. Info.).

The thermal properties of the PHB^{ORs} were preliminarily investigated by DSC (Table S3, Figures S24-S29). These analyses revealed that a distinct glass transition temperature between purely *isotactic* ($P_i > 0.95$) and *syndiotactic* ($P_s > 0.90$) polyesters could only be observed for PHB^{OMe} ($T_{g,iso} = -18$ °C vs $T_{g,syndio} = ca. +12$ °C). For *isotactic* PHB^{ORs}, the alkoxyethylene substituent on the repeating unit was found to significantly affect this value ($T_{g,PHBOAll} = -39$ °C, $T_{g,PHBOMe} = -18$ °C, $T_{g,PHBOBn} 0$ °C). Finally, a melting transition temperature was only observed for *syndiotactic* PHB^{ORs} with R = All, Me ($T_{m,PHBOAll} = +85$ °C – a similar value to that reported for PMLA^{All},^[10] – $T_{m,PHBOMe} = +116$ °C).

In conclusion, we have demonstrated for the first time that a **specific class of functional racemic β -lactones** can be polymerized either in a syndioselective, or most originally, in **an** isoselective fashion by simple tuning of a given catalyst. Chloro substituents on the tetradentate bisphenolate ligand have a unique influence. DFT computations hint at the determining role of Cl...H interactions between the ligand and growing polymer chain in enabling the isoselective ROP of BPL^{OR} monomers. Most interestingly, the stereocontrol ability of these *o,p*-dichloro-substituted yttrium catalysts appear to be very different between *rac*-BPL^{OR} and *rac*-MLA^R monomers, leading respectively to *iso*- and *syndiotactic* PHAs. **These unique stereocontrol abilities are prone to be applied to the preparation of original polymer materials derived from various cyclic esters.**

Received: ((will be filled in by the editorial staff))

Published online on ((will be filled in by the editorial staff))

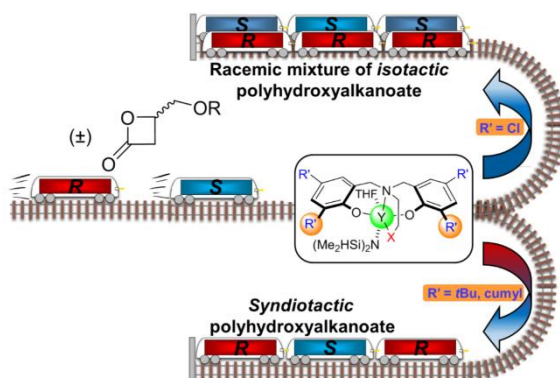
Keywords: β -lactones • stereoselective catalysis • ring-opening polymerization • yttrium

- [1] For recent leading reviews, see: a) *Handbook of Ring-Opening Polymerization*; P. Dubois, O. Coulembier, J.-M. Raquez Eds.; Weinheim: Wiley, **2009**; b) C. M. Thomas, *Chem. Soc. Rev.*, **2010**, *39*, 165–173; c) A. Buchard, C. M. Bakewell, J. Weiner, C. K. Williams, *Top. Organomet. Chem.*, **2012**, *39*, 175–224; d) W. N. Ottou, H. Sardon, Haritz; D. Mecerreyes, J. Vignolle, Joan; D. Taton, *Prog. Polym. Sci.*, **2016**, *56*, 64–115.
- [2] For selected leading references, see: c) T. M. Ovitt, G. W. Coates, *J. Am. Chem. Soc.*, **2002**, *124*, 1316–1326; b) Z. Zhong, P. J. Dijkstra, J. Feijen, *Angew. Chem. Int. Ed.*, **2002**, *41*, 4510–4513; c) N. Nomura, R. Ishii, M. Akakura, K. Aoi, *J. Am. Chem. Soc.*, **2002**, *124*, 5938–5939; d) N. Nomura, R. Ishii, Y. Yamamoto, T. Kondo, *Chem. Eur. J.*, **2007**, *13*, 4433–4451; e) P. Hormnirum, E. L. Marshall, V. C. Gibson, A. J. P. White, D. J. Williams, *J. Am. Chem. Soc.*, **2004**, *126*, 2688–2689; f) P. Hormnirum, E. L. Marshall, V. C. Gibson, R. I. Pugh, A. J. P. White, *Proc. Nat. Acad. Sci.*, **2006**, *103*, 15343–15348; g) P. J. Dijkstra, H. Du, J. Feijen, *Polym. Chem.*, **2011**, *2*, 520–527; h) A. Pilone, K. Press, I. Goldberg, M. Kol, M. Mazzeo, M. Lamberti, *J. Am. Chem. Soc.*, **2014**, *136*, 2940–2943; i) P. McKeown, M. G. Davidson, G. Kociok-Köhn, M. D. Jones, *Chem. Commun.*, **2016**, *52*, 10431–10434.
- [3] a) A. F. Douglas, B. O. Patrick, P. Mehrkhodavandi, *Angew. Chem. Int. Ed.*, **2008**, *120*, 2322–2325; b) D. C. Aluthge, B. O. Patrick, P. Mehrkhodavandi, *Chem. Commun.*, **2013**, *49*, 4295–4297; c) D. C. Aluthge, J. M. Ahn, P. Mehrkhodavandi, *Chem. Sci.*, **2015**, *6*, 5284–5292; d) D. Myers, A. J. P. White, C. M. Forsyth, M. Bown, C. K. Williams, *Angew. Chem. Int. Ed.*, **2017**, DOI: 10.1002/anie.201701745.
- [4] a) H. Wang, H. Ma, *Chem. Commun.* **2013**, *49*, 8686; b) S. Abbina, G. Du, *ACS Macro Lett.*, **2014**, *3*, 689–692; c) Z. Mou, B. Liu, M. Wang, H. Xie, P. Li, L. Li, S. Lia, D. Cui, *Chem. Commun.*, **2014**, *50*, 11411–11414; d) T. Rosen, Y. Popowski, I. Goldberg, M. Kol, *Chem. Eur. J.*, **2016**, *22*, 11533–11536.
- [5] a) M. D. Jones, S. L. Hancock, P. McKeown, P. M. Schäfer, A. Buchard, L. H. Thomas, M. F. Mahon, J. P. Lowe, *Chem. Commun.*, **2014**, *50*, 15967–15970; b) M. D. Jones, L. Brady, P. McKeown, A. Buchard, P. M. Schäfer, L. H. Thomas, M. F. Mahon, T. J. Woodman, J. P. Lowe, *Chem. Sci.*, **2015**, *6*, 5034–5039.
- [6] a) P. L. Arnold, J.-C. Buffet, R. P. Blaudeck, S. Szejcki, A. J. Blake, C. Wilson, *Angew. Chem. Int. Ed.*, **2008**, *47*, 6033–6036; b) C. Bakewell, T. P. Cao, N. Long, X. F. Le Goff, A. Auffrant, C. K. Williams, *J. Am. Chem. Soc.*, **2012**, *134*, 20577–20580; c) C. Bakewell, A. J. P. White, N. J. Long, C. K. Williams, *Angew. Chem. Int. Ed.*, **2014**, *53*, 9226–9230; d) T.-Q. Xu, G.-W. Yang, C. Liu, X.-B. Lu, *Macromolecules*, **2017**, *50*, 515–522.
- [7] J.-F. Carpentier, *Macromol. Rapid Commun.* **2010**, *31*, 1696–1705.
- [8] a) A. Amgoune, C. M. Thomas, S. Ilinca, T. Roisnel, J.-F. Carpentier, *Angew. Chem. Int. Ed.* **2006**, *45*, 2782–2784; b) M. Bouyahy, N. Ajellal, E. Kirillov, C. M. Thomas, J.-F. Carpentier, *Chem. Eur. J.*, **2011**, *17*, 1872–1883; c) J.-F. Carpentier, *Organometallics*, **2015**, *34*, 4175–4189; d) N. Ajellal, M. Bouyahy, A. Amgoune, C. M. Thomas, A. Bondon, I. Pillin, Y. Grohens, J.-F. Carpentier, *Macromolecules*, **2009**, *42*, 987–993.
- [9] J. W. Kramer, D. S. Treitler, E. W. Dunn, P. M. Castro, T. Roisnel, C. M. Thomas, G. W. Coates, *J. Am. Chem. Soc.*, **2009**, *131*, 16042–16044.
- [10] a) C. G. Jaffredo, Y. Chapurina, S. M. Guillaume, J.-F. Carpentier, *Angew. Chem. Int. Ed.*, **2014**, *53*, 2687–2691; b) C. G. Jaffredo, Y. Chapurina, E. Kirillov, J.-F. Carpentier, S. M. Guillaume, *Chem. Eur. J.*, **2016**, *22*, 7629–7641.
- [11] P. T. Altenbuchner, A. Kronast, S. Kissling, S. I. Vagin, E. Herdtweck, A. Pöthig, P. Deglmann, R. Loos, B. Rieger, *Chem. Eur. J.*, **2015**, *21*, 13609–13617.
- [12] a) M. Zintl, F. Molnar, T. Urban, V. Bernhart, P. Preishuber-Pflügl, B. Rieger, *Angew. Chem. Int. Ed.*, **2008**, *47*, 3458–3460; b) R. Reichardt, S. Vagin, R. Reithmeier, A. K. Ott, B. Rieger, *Macromolecules* **2010**, *43*, 9311–9317; c) S. Vagin, M. Winnacker, A. Kronast, P. T. Altenbuchner, P. Deglmann, C. Sinkel, R. Loos, B. Rieger, *ChemCatChem*, **2015**, *7*, 3963–3971.
- [13] a) J. Kramer, E. B. Lobkovsky, G. W. Coates, *Org. Lett.*, **2006**, *8*, 3709–3712; b) J. A. R. Schmidt, E. B. Lobkovsky, G. W. Coates, *J. Am. Chem. Soc.* **2005**, *127*, 11426–11435.
- [14] For the ROP of BPL^{OAll} (similar operating conditions), using **1b**: CONV_{BPL^{OAll}} = traces in THF vs. 94% in toluene (Table 1, entry 2);

- using **1d**: Conv.-BPL_{OAI} = 49% in THF ($P_r = 0.53$) vs. 74% in toluene ($P_r = 0.51$) (Table 1, entry 4); using **1g**: Conv.-BPL_{OAI} = 59% in THF ($P_r = 0.83$) vs. 100% in toluene ($P_r = 0.88$) (Table 1, entry 6).
- [15] C. G. Jaffredo, M. Schmid, I. del Rosal, T. Mevel, P. W. Roesky, L. Maron, S. M. Guillaume, *Chem. Eur. J.* **2014**, *20*, 14387–14402.
- [16] Systems based on a methoxy-capped ligand proved generally to be more stereoselective than their NMe₂-capped analogues; compare e.g. **1a** vs **1b** and **1g** vs **1h**.
- [17] The presence of additional signals/shoulders indicates that there is also information at a larger range (triads) but this could not be further developed due to the poor resolution of these signals.
- [18] J. Fang, M. J. L. Tschan, T. Roisnel, X. Trivelli, R. M. Gauvin, C. M. Thomas, L. Maron, *Polym. Chem.* **2013**, *4*, 360-367.
- [19] The large number of carbonyl and ether oxygens able to coordinate to yttrium center (particularly after the first ring-opening cycle) should favor the mononuclear complexes during the polymerization process. The possibility of dinuclear initiation, evoked earlier in the ROP of *rac*-MLA^R [10b], is most unlikely in the present case, as experiments performed on a 3-fold range of catalyst concentration indicated the apparent rate constants to be first order dependent on the yttrium concentration (see Table S2 and Figure S2 in the Supporting Information); also, the tacticity was not affected within this range of concentration ($P_m = 0.10$).
- [20] The activity of **1a/1b** in ROP of *rac*-BPL^{OR} at room temperature in THF is almost nil and we therefore could not assess whether the stereoselectivity is affected or not when reactions are performed in such a coordinating solvent (see [14]).

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