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Tetracrystalline Tetrablock Quarterpolymers: Four Different Crystallites under the Same Roof

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Abstract: Multicrystalline block copolymers having three or more crystalline segments are essential materials for the advancement of physics in the field of crystallinity. Due to the challenging synthesis of multicrystalline polymers only a limited number of tricrystalline terpolymers are reported until now. We report, for the first time, the synthesis of poly(ethylene)-*b*-poly(ethylene oxide)-*b*-poly(ϵ -caprolactone)-*b*-poly(*L*-Lactide) (PE-*b*-PEO-*b*-PCL-*b*-PLLA) tetracrystalline tetrablock quarterpolymer, by combining polyhomologation, ring-opening polymerization, and an organic/metal “catalyst switch” strategy. ¹H NMR spectroscopy and gel-permeation chromatography confirm the formation of the tetrablock quarterpolymer, while differential scanning calorimetry, X-ray diffraction, and wide-line separation solid-state NMR spectroscopy reveal the existence of four different crystalline domains.

Introduction

Crystalline polymers are important materials with myriad applications.^[1] For example, high density polyethylene (HDPE), the most widely used crystalline polymer^[2] is applied in packaging, plumbing, electrical, automotive industry, among others. Other well-known crystalline polymers such as poly(ethylene oxide) (PEO) or poly(ethylene glycol) (PEG), poly(ϵ -caprolactone) (PCL) and poly(*L*-lactide) (PLLA) are generally used for biomedical applications thanks to their biodegradability and biocompatibility.^[3] Moreover, combining two or more crystalline blocks in one polymeric chain will result in a new material with remarkable properties.^[3]

Double-crystalline diblock copolymers containing PCL and/or PLLA block are usually prepared by ring-opening polymerization (ROP) of ϵ -caprolactone (CL) and *L*-Lactide (LLA) in one-pot with primary alcohol as (macro)initiator and tin(II) 2-ethylhexanoate [Sn(Oct)₂] as catalyst.^[4] Sn(Oct)₂ is cheap and commercially available, highly active at a temperature range of

60 – 180 °C, and has good solubility in many organic solvents.^[5] Moreover, Sn(Oct)₂ has been approved as a food additive by the United States Food and Drug Administration.^[5]

Several examples of the double-crystalline diblock copolymers containing PCL and/or PLLA block are PCL-*b*-PLLA^[6] PEG-*b*-PCL^[7] and PEG-*b*-PLLA.^[8] For the synthesis of PE-*b*-PCL^[9] and PE-*b*-PLLA,^[10] two approaches have been reported. In the first approach an ω -hydroxyl 1,4-polybutadiene (PB-OH) was prepared by anionic polymerization of 1,3-butadiene, followed by chain-end functionalization with ethylene oxide (EO).^[11] ROP of CL or LLA was carried out from PB-OH macroinitiator catalyzed by Sn(Oct)₂. Then, the PB block was hydrogenated to obtain PE-*b*-PCL or PE-*b*-PLLA.^[10a, 10b, 11] In the second approach, an ω -hydroxyl polyethylene (PE-OH) was synthesized by the polymerization of ethylene using metallocenes as a catalyst.^[9d, 10f] Subsequently, PE-OH was used to initiate the ROP of lactones to achieve PE-*b*-PCL or PE-*b*-PLLA.^[9d, 10f] Nevertheless, the PE prepared by the first approach is not fully hydrogenated and contain some 1,2 isomer whereas the PE prepared by metallocenes catalyst is not perfectly linear.

A new route to prepare well-defined and perfectly linear polyethylene is the polyhomologation or C1 polymerization. This (alkyl)borane initiated polymerization of ylides was discovered by Shea *et al.*, and proved to be a powerful methodology to synthesize well-defined PE-based materials.^[12] The polymerization is performed in two consecutive steps: (i) formation of an “ate” complex between the ylide (monomer) and the alkylborane (initiator), followed by (ii) intramolecular 1,2-migration of the methylene groups from the ylide into the three alkyl branches of borane with the simultaneous elimination of dimethyl sulfoxide. After quantitative consumption of the ylide, a boron-linked PE 3-arm star is generated, giving three linear PE-OH chains by oxidation/hydrolysis. This methodology enables the synthesis of perfectly linear PE-OH with controlled microstructure.^[13] The PE-OH can be used as a macroinitiator to prepare various complex macromolecular architectures in combination with other living/controlled polymerization techniques.^[13]

A limited number of reports are available in the literature on tricrystalline triblock terpolymers. Abetz *et al.* reported the synthesis of PB-*b*-PEO from PB-OH macroinitiator. PB-*b*-PEO was used as the macroinitiator for the non-catalyzed thermal ROP of CL to afford PB-*b*-PEO-*b*-PCL.^[14] Then, hydrogenation of PB block was performed by Wilkinson catalyst to yield PE-*b*-PEO-*b*-PCL triblock terpolymers. Side reactions have detected that lead to the formation of undesired PCL-*b*-PEO diblock copolymer, which was removed by several purification steps. Kuo *et al.* recently reported the synthesis of PEG-*b*-PCL-*b*-PLLA by a two-pots ROP of CL and LLA from PEG macroinitiator catalyzed by Sn(Oct)₂.^[15] Coulembier *et al.* reported a one-pot two-step process for the synthesis of PEG-*b*-

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PCL-*b*-PLLA amphiphilic triblock terpolymer using organic catalyst.^[16]

Our group have reported the synthesis of PEO-*b*-PCL-*b*-PLLA by ROP of EO, CL and LLA in one-pot catalyzed by phosphazene superbase (PSB) 1-*tert*-butyl-2,2,4,4,4-pentakis(dimethylamino)-2λ⁵,4λ⁵-catenadi(phosphazene) (*t*-BuP₅, p*K*_{a,ACN} = 33.5).^[17] The complex interplay and isothermal crystallization behavior of the terpolymer were also studied extensively.^[18] We also developed an organic/organic catalyst switch strategy from PSB 1-*tert*-butyl-4,4,4-tris(dimethylamino)-2,2-bis[tris(dimethylamino)phosphoranylid-enamino]-2λ⁵,4λ⁵-catenadi(phosphazene) (*t*-BuP₄, p*K*_{a,ACN} = 42.7) to an organic acid (diphenyl phosphate [DPP], p*K*_{a,DMSO} = 3.88), or *t*-BuP₂.^[19] First, an alcohol initiator was activated by *t*-BuP₄ (suitable for polymerizing epoxides [EXs] and macrolactones [MLs]) and promoted the ROP of EXs or MLs to high conversion. Afterward, two strategies were performed. The first strategy was the addition of an excess of DPP to neutralize *t*-BuP₄ and polymerizing small lactones (SLs) or trimethylene carbonate (TMC) from PEXs macroinitiators catalyzed by the excess of DPP to afford PEXs-*b*-PSLs and PEXs-*b*-PTMC.^[19a] The second strategy was the addition of a weaker PSB, *t*-BuP₂, that can act as a catalyst for the ROP of LLA from PEXs macroinitiators towards PEX-*b*-PLLA^[20] or small lactones (SLs) from PMLs macroinitiators towards PMLs-*b*-PSLs.^[19b] To the best of our knowledge, there is no report on one-pot synthesis and properties of tetracrystalline tetrablock quarterpolymer. The absence of the report might be attributed to the challenging synthetic methodology in combining two or more different polymerizations in one-pot.

The interplay between crystallization and phase separation is a complex and fundamental problem in the physics of block copolymers. As the number of crystallizable block increases, their interactions regarding nucleation, crystallization, and morphology becomes very complex and at the same time fascinating. As we reported for the first time in our recent papers,^[18] PCL-*b*-PEO-*b*-PLLA triblock terpolymers crystallized from a melt/mixed melt forming tricrystalline spherulites and axialites, where three different types of lamellae (i.e., PCL, PEO, and PLLA) co-exist in a single superstructure. The addition of a fourth crystallizable block and formation of a tetrablock quarterpolymer increases the complexity even more.

In this article, we report for the first time, the synthesis of a tetracrystalline PE-*b*-PEO-*b*-PCL-*b*-PLLA quarterpolymer, by combining polyhomologation (PE) with sequential block copolymerization (PE-*b*-PEO) and a new organic/metal catalyst-switch (*t*-BuP₄/DPP/Sn[Oct]₂) strategy. The molecular structure of the tetrablock quarterpolymer was confirmed by one-dimensional (1D-) and two-dimensional (2D-) NMR spectroscopy (in liquid and solid-state), as well as by gel-permeation chromatography (GPC). The preliminary results on differential scanning calorimetry (DSC) and X-ray diffraction spectroscopy (XRD) confirms the existence of four crystallites. An in-depth study on the phase structure, crystallization and morphology is being performed and will be reported in the near future.

Results and Discussion

The general reactions for the synthesis of tetracrystalline tetrablock quarterpolymer is presented in Scheme 1. The first attempt was performed by combining polyhomologation (PE-OH-1 as macroinitiator) with organic/organic catalyst-switch (*t*-BuP₄/DPP/*t*-BuP₂) strategy in toluene at 80 °C (the details are given in the Supporting Information [SI], Scheme S1, Table S1, and Figure S1 – S3).^[19b] Under these conditions, *t*-BuP₂ promotes rapid side reactions of LLA, resulting in PE-*b*-PEO-*b*-PCL-*b*-PLLA-1 with amorphous PLLA block (Figure S4, SI).

Scheme 1. Synthesis of tetracrystalline quarterpolymer PE-*b*-PEO-*b*-PCL-*b*-PLLA from PE-OH macroinitiator by a combination of polyhomologation and catalyst-switch strategy.

In order to investigate the origin of side reactions that worsen the thermal properties of PLLA, a systematic experiment was performed. LLA was mixed with *t*-BuP₂ in toluene at 80 °C in the absence of primary alcohol as initiator. The progress of the reaction was followed by ¹H NMR and GPC (Figure S5, SI). ¹H NMR spectrum of an aliquot taken after 10 min of mixing shows that 91.4% of methine proton of LLA shifted downfield from 4.93 ppm to 5.18 ppm, indicating that polymerization occurred without primary alcohol. After 60 min, the conversion of LLA reached 99%. GPC trace of the aliquot taken after 4.5 h confirms that PLLA formed in the reaction mixture but has broad *M*_w (1.65). This *M*_w is broader than in the case of PLLA prepared with primary alcohol (PPA)/*t*-BuP₂ in toluene at 80 °C (*M*_w = 1.35, Figure S6, SI).

¹H NMR analysis on the reaction mixture (Figure S5a) suggested that *t*-BuP₂ triggered racemization through reversible deprotonation of the slightly acidic α-methine group of LLA (Scheme S2, SI). Two types of LA formed after this reaction: (i) (*S,S*) LLA, as a consequence of reversible deprotonation and (ii) (*R,S*) *meso*-LA as the product of tautomerization. Thus, two LA isomers existed in the polymerization mixture. At the same time, self-initiation occurred from O=C(CH₃)C[−]O anion to another LA followed by propagation (Scheme S2, SI). This anion has a lower nucleophilicity than primary alcohol, which leads to a slow initiation as can be seen from the monomodal and broad *M*_w of

Table 1. Synthesis and thermal properties of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 and the corresponding precursor polymers by organic/metal catalyst switch.^[a]

entry	sample	time ^[c] (h)	Conv. ^[d] (%)	M_n ,NMR (kg mol ⁻¹) ^[e]	T_m/T_c (°C) ^[f]			
					PE	PEO	PCL	PLLA
1	PE-OH-2 ^[b]	17	100	7.1	130.0/ 117.3			
2	PE- <i>b</i> -PEO-2	15	100	15.1	120.3/ ^[g] 76.1	63.8/30.9		
3	PE- <i>b</i> -PEO- <i>b</i> -PCL-2	48	92	10.4	120.2/ 75.3	60.6/36.7	60.6/44.1	
4	PE- <i>b</i> -PEO- <i>b</i> -PCL- <i>b</i> -PLLA-2	20	94	7.6	119.5/ 77.3	60.9/41.7	60.9/46.7	148.1/88. 3

^[a] Polymerizations were performed from PE-OH macroinitiator in toluene at 80 °C with *t*-BuP₄/DPP/Sn(Oct)₂ catalyst-switch.

^[b] Prepared by polyhomologation of sulfoxonium methylide in toluene under Ar at 80 °C. ^[c] Polymerization time of the last block.

^[d] Conversion of the monomer on the last block. Determined by 600 MHz ¹H NMR spectrometer from the polymerization mixture (toluene *d*₈, 80 °C). ^[e] M_n of the last block. Determined by 600 MHz ¹H NMR spectrometer from the isolated polymer (toluene *d*₈, 80 °C). ^[f] Determined by DSC (heating and cooling rates are 10 °C min⁻¹ except for PLLA block [cooling rate 1 °C min⁻¹, under N₂].

^[g] Split peak. The value is taken from the highest peak.

Figure 1. a, 1D ¹H NMR spectra of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 and the corresponding precursor polymers (entry 1 – 4, Table 1) and b, 2D COSY spectrum of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 1) prepared by organic/metal catalyst switch (toluene-*d*₈, 80 °C). ° denotes the unknown impurity.

the resulting PLA (Figure S5b, SI). PLA that contained more than 10% of *meso*-LA will become amorphous.^[5] This information is confirmed by the DSC thermogram of the resulting PLA (Figure S5c, SI). T_m and T_c are not observed on the thermogram while a glass-transition temperature appears at 54 °C, corresponds to amorphous PLA. Thus, *t*-BuP₂ is not a suitable catalyst for the ROP of LLA at 80 °C because it triggers side reactions and worsens the thermal properties of PLA.

We envisaged a new strategy, namely, organic/metal catalyst-switch. The basic concept is similar to the organic/organic catalyst switch. Firstly, ROP of EO (Scheme 1) from PE-OH-2 macroinitiator (entry 1, Table 1) to afford PE-*b*-PEO + [*t*-BuP₄H]⁺. Second, neutralization of the base with the addition of an equimolar amount of organic acid (DPP). This process terminates the ROP of EO yielding a hydroxyl terminated PE-*b*-PEO-2 diblock copolymer (entry 2, Table 1) and residual organic salt (phosphazanium diphenyl phosphate). Subsequently, PE-*b*-PEO-2 was utilized as a macroinitiator for the next

Figure 2. 2D ^1H - ^{13}C HETCOR solid-state NMR of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 2); **a**, short-distance and **b**, long distance.

polymerization because the whole system is still under inert and dry conditions. Third, the addition of $\text{Sn}(\text{Oct})_2$ to promote the ROP of CL (PE-*b*-PEO-*b*-PCL-2, entry 3, Table 1), and then LLA in one-pot to produce PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 1).

^1H NMR spectra of the isolated PE-OH-2, PE-*b*-PEO-2, PE-*b*-PEO-*b*-PCL-2, and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 1 - 4, Table 1) are presented in Figure 1a. The $-\text{CH}_2\text{OH}$ protons of PE (a) appear between 3.32 – 3.41 ppm while the CH_2 protons of the main chain (e) observed around 1.17 - 1.46 ppm. The integral ratio of these protons was used to calculate the M_n of PE-OH-2. For PE-*b*-PEO-2 diblock copolymer, a new sharp peak appears around 3.30 – 3.56 ppm (g) corresponds to $-(\text{CH}_2)_2\text{O}-$ of PEO block. After the terpolymerization with CL, six new peaks appear in the spectrum. The peak between 3.91 – 4.01 ppm (k) is assigned as $\text{CH}_2\text{OC}=\text{O}$ protons of CL block. The OCH_2 protons appear between 2.09 – 2.14 ppm (h) while the 4 protons of $-\text{CH}_2-\text{CH}_2\text{O}$ (i) and $-\text{CH}_2-\text{CH}_2-\text{OC}=\text{O}$ (n) appear around 1.49 – 1.56 and 1.40 – 1.48 ppm, respectively. The $-\text{CH}_2-\text{CH}_2-\text{CH}_2$ protons (j) arise from 1.19 – 1.26 ppm. Two new protons emerged after the ROP of LLA from PE-*b*-PEO-*b*-PCL-2 macroinitiator; methine proton ($\text{CH}_3-\text{CHO}-\text{CO}$) and methyl ($-\text{CH}_3$) protons of PLLA block (m and l) around 4.99 – 5.13 ppm and 1.34 – 1.49 ppm, respectively.

It is essential to assign the chemical shift of end-groups protons of each block correctly because these protons are used to determine the M_n of the block. To support the 1D ^1H NMR assignment (Figure 1a), 2D ^1H - ^1H correlation spectroscopy (COSY, Figure 1b), total correlation spectroscopy (TOCSY, Figure S7, SI), ^1H - ^{13}C hetero-nuclear single-bond correlation (HSQC, Figure S8, SI), and hetero-nuclear multiple-bond correlation (HMBC, Figure S9, SI) of PE-*b*-PEO-*b*-PCL-*b*-PLLA-

2 (entry 4, Table 1) were performed in $\text{toluene-}d_8$ at 80 °C. The $-\text{CH}_2-\text{O}-(\text{CH}_2)_2\text{O}$ protons (a) (Figure 1a and 1b) between 3.30 – 3.56 ppm is the ω -end of CH_2 protons of PE (e), covalently linked to $\text{O}-(\text{CH}_2)_2-\text{O}$ (g) protons of PEO as shown by HSQC (Figure S8, ESI). The $-\text{CH}_2-\text{OC}$ end groups of PEO (b), PCL (c) and PLLA (d) (Figure 1a) protons that overlap in the 1D ^1H spectrum could be observed in separate positions by 2D NMR spectroscopy (Figure 1b and Figure S7 – S9, SI) ascertaining our assignment. Protons (b) correlated to (g) (Figure 1b) indicating that it is the CH_2 end group of PEO, and in correlation with $\text{OC}-\text{CH}_2$ (h) of PCL (Figure S7 – S9, SI). All 2D liquid NMR analyses confirm that (b) is covalently bonded to PCL and c is covalently bonded to PLLA block.

Solid-state NMR was also used to characterize the structure of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 1). ^1H and ^{13}C CP-MAS spectra (Figure S10 and S11, SI) show the $-(\text{CH}_2)-$ protons and carbons chemical shifts of PE block (e) at 0.68 ppm and 33.75 ppm, respectively. The 2D ^1H - ^{13}C short distance heteronuclear correlation (HECTOR) spectrum confirms the correlation between ^1H at 0.68 ppm and ^{13}C at 31.84 ppm (Figure 2a) in one bond. A sharp peak at 2.95 ppm is assigned as $-\text{O}-(\text{CH}_2)_2-\text{O}-$ protons of PEO block (g) and pose a strong correlation with ^{13}C at 69.17 ppm. The protons and carbons chemical shifts of PCL block are assigned as follow: $-\text{CH}_2-\text{COO}$ (k) observed at 3.46 ppm and 63.57 ppm, $-\text{CH}_2\text{CO}$ (h) at 1.67 ppm and 33.75 ppm, and three $-\text{CH}_2-$ protons (i, n, and j) merged at 0.98 ppm whereas the ^{13}C peaks of (j) appear at 28.62 ppm and (i and n) at 25.28 ppm, respectively. The carbonyl carbon of PCL ($\text{O}=\text{C}=\text{O}$) at 172.9 ppm (p) reveals a strong correlation on long-distance HETCOR spectrum with methylene protons of PCL (Figure 2b). Similar long-distance correlation is also observed on the carbonyl carbon of PLLA block (170.9 ppm) with methine proton (m) of PLLA at 4.66 ppm

(Figure 2b). A small shoulder around 169.4 ppm is probably triggered by stereoregularity of PLLA chain. The CH_3 protons of PLLA (I) merged with methylene protons of PCL at 0.98 ppm. Due to the broad ^1H peak in solid-state NMR, the end-group protons of each block are not observable.

Because PE-OH-2, PE-*b*-PEO-2, PE-*b*-PEO-*b*-PCL-2, and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 1 – 4, Table 3) are not soluble in tetrahydrofuran (THF) and partially soluble in CHCl_3 , the analysis of molecular weight distribution ($\bar{M}_w$) has to be performed by high-temperature GPC (HT-GPC) in 1,2,4-trichlorobenzene (TCB) at 150 °C. PE-OH-2 (entry 1, Table 1) exhibits a monomodal and narrow GPC trace ($\bar{M}_w = 1.21$) indicating that polyhomologation of sulfoxonium methylide is giving well-defined PE (Figure S12, SI). However, PE-*b*-PEO-2, PE-*b*-PEO-*b*-PCL-2, PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 did not exhibit any peak on HT-GPC traces (Figure S12, SI). This probably due to absorption of PEO block into the columns (2× PLgel 10 μm mixed-B, 7.5 × 300 mm) since we also encountered similar circumstance on our previous work on PE containing PEO molecular co-brush.^[21]

For more in-depth study, we analyzed the GPC traces of PEO, PCL, and PLLA prepared by ROP in toluene at 80 °C (entry 1, Table S2, SI) in both TCB and THF. PEO did not show any peak in TCB at 150 °C, which correlates to strong absorption in the column (Figure S13, SI). The same PEO exhibited a narrow and monomodal peak in THF at 35 °C ($\bar{M}_w = 1.09$) (Figure S13, SI), indicating that the ROP of EO catalyze by *t*-BuP₄ at 80 °C in toluene is controlled. PCL (entry 2, Table S2) also exhibited a narrow and monomodal traces in both GPCs (Figure S14, SI). PLLA shows monomodal GPC traces in both THF and TCB (Figure S15, SI). However, the $\bar{M}_w$ in TCB (1.54) is much broader than the $\bar{M}_w$ in THF (1.13). The reason behind this discrepancy is still unknown.

Figure 3. GPC traces of tetrablock quarterpolymer initiated by low M_n PE-OH macroinitiator (800 g mol^{-1}); PE-OH-3 (black), PE-*b*-PEO-3 (red), PE-*b*-PEO-*b*-PCL-3 (blue) and PE-*b*-PEO-*b*-PCL-*b*-PLLA-3 (green) in THF (50 °C, PS standards).

An ideal approach to tackle the aforementioned challenge is to prepare a PE-OH macroinitiator with low M_n by polyhomologation (entry 1, Table S3, SI). ^1H NMR analysis of the resulting PE-OH-3 gives the $M_n = 800 \text{ g mol}^{-1}$ (Figure S16, SI). This PE-OH-3 is soluble in THF at 50 °C (concentration 2 mg mL^{-1}) and exhibits narrow and monomodal GPC trace (Figure 3, black). Tetrablock quarterpolymer was synthesized from PE-OH-3 macroinitiator via organic/metal catalyst-switch (*t*-BuP₄/DPP/Sn[Oct]₂) strategy (entry 2 – 4, Table S3). The GPC traces of the PE-*b*-PEO-3 (red), PE-*b*-PEO-*b*-PCL-3 (blue) and PE-*b*-PEO-*b*-PCL-*b*-PLLA-3 (green) are monomodal with narrow $\bar{M}_w$ (Figure 3). The result implies that the ROPs are controlled and result in tetrablock quarterpolymer with well-defined microstructure.

Figure 4. DSC thermograms of PE-OH-2, PE-*b*-PEO-2, PE-*b*-PEO-*b*-PCL-2, and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 1 – 4, Table 1) prepared by organic/metal catalyst switch (heating [a] and cooling [b] rates are 10 °C min^{-1} except for PLLA block [cooling rate 1 °C min^{-1}], under N_2).

DSC analysis was performed to evaluate the thermal properties (Figure 4) of PE-OH-2 (black), PE-*b*-PEO-2 (red), and PE-*b*-PEO-*b*-PCL-2 (blue), and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green). A noticeable decrease of the $T_{m,PE}$ (Figure 4a, black) observed from 130.0 °C to 120.3 °C in the PE-*b*-PEO-2 (Figure 4a, red). The decrease of $T_{m,PE}$ might be attributed to the fact that PEO block, covalently linked to PE-OH-2, has a much larger M_n and melted earlier than PE-OH-2 block. The $T_{m,PE}$ on PE-*b*-PEO-*b*-PCL-2 and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (Figure 4a, blue and green) is relatively unchanged ($\sim 120 \text{ °C}$). Little to no deviations were observed on the melting behavior of PEO block ($60.6 \text{ °C} < T_{m,PEO} < 63.8 \text{ °C}$) and PCL block ($60.6 \text{ °C} < T_{m,PCL} < 60.9 \text{ °C}$). The endothermic peaks of PCL and PEO observed as a merged peak due to the close T_m of the two blocks. The $T_{m,PLLA}$ on PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green) observed at 148.0 °C indicating the formation of crystalline PLLA block.

Figure 5. a, 2D ^1H - ^{13}C CP-MAS WISE NMR spectrum of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2, and b, four ^1H slices extracted from specific ^{13}C chemical shifts of each block.

After melting and annealing of the polymers for 3 min, crystallization behavior was observed by applying a cooling scan $10\text{ }^\circ\text{C min}^{-1}$ (Figure 4b for PE-OH-2 (black), PE-*b*-PEO-2 (red), PE-*b*-PEO-*b*-PCL-2 (blue), and $1\text{ }^\circ\text{C min}^{-1}$ for PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green). A slow cooling scan ($1\text{ }^\circ\text{C min}^{-1}$) must be applied to facilitate crystallization of PLLA block.^[18a] A drastic depression of $T_{\text{c,PE}}$ was observed on PE-*b*-PEO-2 ($76.1\text{ }^\circ\text{C}$) relative to PE-OH-2 ($117.3\text{ }^\circ\text{C}$). Such depression is attributed to the existence of large PEO melt-matrix during the crystallization PE-OH-2 block. The T_{cs} of PEO block ($30.9\text{ }^\circ\text{C} < T_{\text{c,PEO}} < 41.7\text{ }^\circ\text{C}$), PCL block ($44.1\text{ }^\circ\text{C} < T_{\text{c,PCL}} < 46.7\text{ }^\circ\text{C}$) and PLLA block ($T_{\text{c,PLLA}} = 88.3\text{ }^\circ\text{C}$) could be observed as the separate peaks on each polymers. Four T_{cs} appear on PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green) confirm the successful synthesis of tetracrystalline quarterpolymer. Details on the thermodynamic and kinetic crystallization of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 as well as its precursor polymers will be discussed in a separate paper.

2D ^1H - ^{13}C cross-polarization (CP) magic angle spinning (MAS) wide-line separation (WISE) solid-state NMR experiments is a powerful technique to assess the relationship between structure and segmental mobility of the polymer chain.^[22] The structure of the polymer is reflected in the ^{13}C chemical shifts, whereas the segmental mobility is reflected in the ^1H line width. For a given ^{13}C resonance, an average broad ^1H line width (typically more than 50 kHz)^[23] corresponds to low segmental mobility (rigid

chain/crystalline domain) whereas an average narrow ^1H line width corresponds to high segmental mobility (mobile chain/amorphous domain). The WISE contour of PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 1) is presented in Figure 5a. In order to find the segmental mobility of each block, four ^1H slices extracted from specific ^{13}C chemical shifts of each block: 33.7 ppm, $-(\text{CH}_2)-$ PE; 69.17 ppm, $-\text{O}-(\text{CH}_2)_2-\text{O}-$ PEO; 25.28 ppm, $-\text{CH}_2-\text{CH}_2-\text{CH}_2-$ PCL; and 16.33 ppm, $-\text{CH}-\text{CH}_3$ PLLA, are analyzed and presented in Figure 5b. All ^{13}C environments at the specified chemical shifts of each block exhibit broad ^1H line widths in the range of 50 – 60 kHz. These broad ^1H line widths correlated to the low average mobility of the chain in each block which formed crystalline domain as a majority over the amorphous domain. This result corroborates the successful synthesis of tetracrystalline PE-*b*-PEO-*b*-PCL-*b*-PLLA-2.

The crystal structures of PE-OH-2 (black), PE-*b*-PEO-2 (red), PE-*b*-PEO-*b*-PCL-2 (blue) and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green) were analyzed using XRD (Figure 6) at room temperature (rt). Samples were deposited on top of a glass substrate and heated up to $180\text{ }^\circ\text{C}$, annealed for 10 min, and cooled down to rt at a roughly $2\text{ }^\circ\text{C min}^{-1}$. PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 shows peaks in the range of $2\theta = 15^\circ - 26^\circ$. The peaks at $2\theta = 24.0^\circ$ and 21.7° correspond to diffraction from (200) and (110) crystallographic planes of PE and PCL blocks. These two blocks are known to form the *orthorhombic* crystal structure. The

peak at $2\theta = 19.5^\circ$ denotes the diffraction from (203) PLLA overlapped with (120) PEO crystallographic planes. Two peaks at $2\theta = 15.2^\circ$ and 16.9° are the diffractions from (010) and (200/110) crystallographic planes of PLLA. Due to the overlap of some of the reflexions, it is not easy to distinguish the separate contribution of each crystalline block in the x-ray diffractograms shown in Figure 6. Measurements as a function of temperature could easily solve this problem, and they will be reported in our next contribution. Moreover, an in-depth study of the phase segregation, crystallization, and morphology of these remarkable tetracrystalline tetrablock quarterpolymers will be presented.

Figure 6. XRD diffractograms of PE-OH-2 (black), PE-*b*-PEO-2 (red), PE-*b*-PEO-*b*-PCL-2 (blue) and PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (green) (entry 1 – 4, Table 2).

Conclusion

For the first time, tetracrystalline tetrablock quarterpolymer PE-*b*-PEO-*b*-PCL-*b*-PLLA was synthesized by combining polyhomologation (PE-OH macroinitiator) with a new organic/metal catalyst-switch (*t*-BuP₄/DPP/Sn[Oct]₂) strategy. The use of Sn(Oct)₂ instead of *t*-BuP₂ in this strategy could overcome the side reactions occurred during the ROP of LLA at 80 °C. The micro structure of PE-*b*-PEO-*b*-PCL-*b*-PLLA was fully characterized by liquid and solid-state NMR as well as GPC. DSC, WISE NMR, and XRD spectroscopies confirm the formation of four crystallites in solid-state. This new strategy opens a broader horizon on the synthesis of complex macromolecular architecture based crystalline polymers in one-pot. Moreover, the tetracrystalline tetrablock quarterpolymer will serve polymer physics in the advancement of crystallinity field.

Experimental Section

PE-*b*-PEO-2 (entry 2, Table 1). In a glove box under Ar atmosphere, 400 mg PE-OH-2 (0.07 mmol), 44 μ L (35 μ mol) *t*-BuP₄ solution and 14 mL dry toluene were charged into a round bottom flask. The flask was quickly sealed by a rotaflo stopcock, removed from the glove box and evacuated through vacuum line for 10 min. Then, 0.69 mL of pre-dried EO (14 mmol) was condensed to the reaction solution at -78°C under vacuum. The temperature was slowly increased to 80 °C, and the ROP of EO was performed for 15 h. The conversion of EO was calculated from the yield of 3 mL polymerization mixture quenched with benzoic acid and precipitated in MeOH/Et₂O (1:1 v/v) mixture. PE-*b*-PEO was isolated by centrifugation and dried under vacuum for 24 h at 40 °C. The rest of the polymerization mixture was neutralized by the addition of 65 μ L DPP (0.0325 mmol) at 80 °C and kept stirring. After 30 min, the reaction mixture was stored inside a glove box under Ar. ¹H NMR (600 MHz, toluene-*d*₈, 80 °C with three drops of TFAA): δ/ppm = 3.32 – 3.41 (PE, [–CH₂–O–PEO]), 1.17 – 1.46 (PE, [–CH₂–]), 0.83 – 1.01 (PE, [–CH₃]), 3.30 – 3.56 (PEO [O–CH₂–CH₂–O]), 3.99 – 4.02 (PEO, [PEO–CH₂–CH₂–O–TFAA]); $M_{n,\text{NMR}}$ PEO = 15100 g mol^{–1}.

PE-*b*-PEO-*b*-PCL-2 (entry 3, Table 1). In a glove box under Ar atmosphere, a dry polymerization flask equipped with a stirrer bar was charged with 3 mg of Sn(Oct)₂ (0.0075 mmol), 0.17 mL CL (0.75 mmol), and 1 mL dry toluene. The flask was sealed and placed in an oil bath at 80 °C outside the glove box. After 15 min, 3 mL of polymerization mixture containing PE-*b*-PEO-2 macroinitiator was withdrawn and transferred to the flask. The ROP of CL was performed for 48 h, and the conversion was monitored by ¹H NMR spectroscopy. After the conversion reached 92 %, 2 mL of the reaction mixture was withdrawn, quenched with benzoic acid, and precipitated in cold MeOH/Et₂O mixture (7:3 v/v). PE-*b*-PEO-*b*-PCL-2 was isolated by centrifugation and dried *in vacuo* for 24 h at 40 °C. ¹H NMR (600 MHz, toluene-*d*₈, 80 °C): δ/ppm = 3.32 – 3.41 (PE, [–CH₂–O–PEO]), 1.17 – 1.46 (PE, [–CH₂–]), 0.83 – 1.01 (PE, [–CH₃]), 3.30 – 3.56 (PEO [O–CH₂–CH₂–O]), 4.09 – 4.14 (PEO, [PEO–CH₂–CH₂–OCO–PCL]), 3.41 – 3.57 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–OH]), 3.91 – 4.01 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 2.09 – 2.14 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.49 – 1.56 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.40 – 1.48 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.19 – 1.26 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]); $M_{n,\text{NMR}}$ PCL = 10400 g mol^{–1}.

PE-*b*-PEO-*b*-PCL-*b*-PLLA-2 (entry 4, Table 1). The flask containing 2 mL PE-*b*-PEO-*b*-PCL-2 solution was transferred into the glove box. Then, 216 mg LLA (1.50 mmol) was added to the flask. The flask was transferred outside the glove box, heated in an oil bath at 80 °C for 20 h. The conversion of LLA measured by ¹H NMR was 96%. The polymerization was quenched by the addition of benzoic acid, and the polymerization mixture was precipitated in cold MeOH/Et₂O (8:2 v/v). The polymer was recovered by centrifugation and decantation of the solvents and dried *in vacuo* at rt for 24 h. ¹H NMR (600 MHz, toluene-*d*₈, 80 °C): δ/ppm = 3.32 – 3.41 (PE, [–CH₂–O–PEO]), 1.17 – 1.46 (PE, [–CH₂–]), 0.83 – 1.01 (PE, [–CH₃]), 3.30 – 3.56 (PEO [O–CH₂–CH₂–O]), 4.09 – 4.14 (PEO, [PEO–CH₂–CH₂–OCO–PCL]), 3.41 – 3.57 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–OH]), 3.91 – 4.01 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 2.09 – 2.14 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.49 – 1.56 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.40 – 1.48 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.19 – 1.26 (PCL, [OCO–CH₂CH₂CH₂CH₂CH₂–]), 1.34 – 1.49 (PLLA, [–CHCH₃]), 4.99 – 5.13 (PLLA, [OCO–CHCH₃–]), 4.17 – 4.25 (PLLA, [OCO–CHCH₃–COOH]); $M_{n,\text{NMR}}$ PLLA = 7600 g mol^{–1}.

The solid-state ^1H - ^{13}C WISE 2D NMR analysis was performed according to the literature.^[24] The spectrum was acquired on Bruker AVANCE III spectrometers operating at 900 MHz resonance frequencies using a 3.2 mm MAS probe. A MAS of 5 KHz was applied in all experiments. The t_1 increment time was set to 5 μs , and the contact time was 1 ms.

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Keywords: polyhomologation • ring-opening polymerization • catalyst switch • tetrablock quarterpolymers • multicrystalline polymers

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Entry for the Table of Contents

RESEARCH ARTICLE

Tetracrystalline tetrablock quarterpolymer, poly(ethylene)-*b*-poly(ethylene oxide)-*b*-poly(ϵ -caprolactone)-*b*-poly(L-Lactide) was synthesized by combining polyhomologation, ring-opening polymerization and an organic/metal “catalyst switch” strategy. The existence of four different crystalline domains in the polymer was confirmed by differential scanning calorimetry, X-ray diffraction, and wide-line separation solid-state NMR spectroscopy.

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Tetracrystalline Tetrablock Quarterpolymers: Four Different Crystallites under the Same Roof