Macromolecules **1994,** *27,* 3139–3146

Polylactones. 28. Syndiotactic Poly(β-D,L-hydroxybutyrate) by Ring-Opening Polymerization of β-D,L-Butyrolactone with Butyltin Methoxides

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Received September 27, 1993; Revised Manuscript Received March 29, 1994[⊛]

ABSTRACT: Predominantly syndiotactic poly(β-D,L-hydroxybutyric acid) was prepared by ring-opening polymerization of β-D,L-butyrolactone with butyltin trimethoxide, dibutyltin dimethoxide, and tributyltin methoxide as initiators. Obviously, due to steric hindrance the reactivity of the catalysts decreases in the given order, whereas the stereoselectivity of the polymerizations increases. The highest yields (up to 92%) were obtained with $Bu_2Sn(OMe)_2$ but the molecular weights were relatively low (≤10 000 g/mol) in all cases. HO and CO_2CH_3 end groups were identified by ^1H and ^{13}C NMR spectroscopy whereas CO_2H end groups were never found. All initiators yielded preferentially syndiotactic polyesters. Variation of the reaction temperature with $Bu_2Sn(OMe)_2$ and Bu_3SnOMe had a strong influence on the stereoselectivity of the polymerization. At 100 °C perfectly atactic amorphous poly(β-D,L-HBu) was obtained, whereas the crystalline sample prepared at −17 °C showed a ratio of isotactic to syndiotactic diads (i/s ratio) of 0.2/1.0. Fractionation of this sample yielded a crystalline poly(β-D,L-HBu) with an i/s ratio of 0.1/1.0 and a melting temperature of 143 °C. The WAXS pattern, IR spectrum, and ^{13}C NMR spectrum of this syndiotactic polyester are quite different from those of the biogenic, isotactic material.

Introduction

Poly(β-D-hydroxybutyric acid), poly(D-HBu) has recently attracted much interest as a biodegradable nontoxic engineering plastic.[1,2] (The abbreviation PHB is misleading because it is often used for poly(4-hydroxybenzoic acid).) Numerous species of bacteria produce this polyester in an isotactic form with all chiral carbons having the D-(*R*)-configuration.[3,4] This poly-D-configuration has several important consequences for the properties of the polyester. Poly(D-HBu) forms a left handed helix in the solid state, is highly crystalline, and has a melting temperature (T_m) around 180 °C. This high T_m in combination with a low thermostability makes processing from the melt a difficult task, because the thermal degradation (yielding crotonate groups) starts immediately above T_m. In addition to neat poly(D-HBu), copolyesters containing small amounts of a hydroxyisovaleric acid which improves the processability were biotechnically produced and commercialized by ICI (BIOPOL). A syndiotactic poly(D,L-HBu) might be a useful alternative as a biodegradable engineering plastic, provided that its melting temperature is lower than that of the isotactic polyester.

Whereas the synthesis of more or less isotactic poly(hydroxybutyric acid) was described by several authors,[5–12] much less is known about syndiotactic poly(D,L-HBu). In a previous symposium report[13] we briefly mentioned that the tributyltin methoxide (Bu_3SnOMe) initiated polymerization of β-D,L-butyrolactone yields a preferentially syndiotactic polyester.

Hocking and Marchessault[14] have extracted a few percent of a similar material from a preferentially isotactic sample initiated with methylaluminoxane. Quite recently, Kemnitzer et al.[15] have also studied tin methoxide initiated polymerizations of β-D,L-butyrolactone. The present paper is an extension of previous studies[13,16] and has the purpose of describing in more detail the synthesis and characterization of syndiotactic poly(D,L-HBu) resulting from butyltin methoxide initiated polymerizations of β-D,L-butyrolactone.

Experimental Section

Materials. β-D,L-Butyrolactone was purchased from Aldrich Co. (Milwaukee, WI) and was distilled over freshly powdered calcium hydride prior to polymerization. Tributyltin methoxide (Bu_3SnOMe), dibutyltin dichloride, and butyltin trichloride were also purchased from Aldrich Co. and distilled in vacuum. Dibutyltin dimethoxide $(Bu_2SnOMe)_2$ and tributyltin trimethoxide ($BuSn(OMe)_3$) were prepared from the corresponding chlorides and sodium methoxide in dry methanol and purified by distillation in vacuo.

Polymerizations. β-D,L-Butyrolactone (50 mmol) and the initiator (1 M solution in dry toluene) were weighed into a 25-mL Erlenmeyer flask with silanized glass walls. The reaction vessel was closed with a glass stopper and steel springs and thermostated at the temperatures given in Tables 1–4. The reaction product was dissolved in CH_2Cl_2 and precipitated into an 1/1 mixture (by volume) of diethyl ether and ligroin. The reaction mixtures were prepared in a glovebox under dry nitrogen.

Fractionation (Table 10). The poly(β-D,L-HBu) samples DB-1 and DB-3 were dissolved in CH_2Cl_2 and precipitated into cold diethyl ether. The material isolated from this first reprecipitation (fraction II) was again dissolved in CH_2Cl_2 and precipitated into cold methanol. The fraction isolated from this precipitation is denoted III in Table 9.

Measurements. The viscosities were measured in an automated Ubbelohde visometer thermostated at 25 °C. The IR spectra (KBr pellets) were recorded on a Nicolet SXB-20 FT-IR spectrometer. The 100-MHz ^1H NMR spectra were recorded with a Bruker AC-100 FT-NMR spectrometer in 5-mm-o.d. sample tubes. The 90.5-MHz ^{13}C NMR spectra were obtained on a Bruker AM-360 FT-NMR spectrometer in 10-mm-o.d. sample tubes. A pulse angle around 30 °C and a pulse interval of 3 s were applied. For Figure 2 and related spectra 15 000 transients were accumulated. The 75.4-MHz ^{13}C NMR CP/MAS spectra were recorded with a Bruker MSL 300 FT-NMR spectrometer in double-bearing ZrO_2 rotors: A contact time of 1 ms, a pulse interval of 4 s, and a spinning rate of 4 kHz were used. The DSC measurements were conducted with a Perkin-Elmer DSC-4 in aluminum pans under nitrogen. The WAXD powder patterns were recorded with a Siemens D-500 diffractometer using Ni-filtered Cu Kα radiation.

Results and Discussion

Optimization of the Reaction Conditions. The previous experiments with β-D,L-butyrolactone and tribu-

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[⊛] Abstract published in *Advance ACS Abstracts,* May 1, 1994.

0024-9297/94/2227-3139$04.50/0

Table 1. Reaction Conditions and Results of $Bu_2Sn(OMe)_2$ Initiated polymerizations of β-D,L-Butyrolactone with M/I = 50

sample no.	temp (°C)	time (days)	yield (%)	η_{inh}[a] (dL/g)
DB-1	-17	30	33	0.04
DB-2	-17	60	52	0.04
DB-3	3	10	53	0.05
DB-4	3	20	81	0.06
DB-5	25	2	70	0.06
DB-6	25	4	90	0.08
DB-7	25	8	92	0.08
DB-8	50	2	72	0.10
DB-9	50	4	68	0.09
DB-10	50	8	61	0.08

[a] Measured at 25 °C with c = 2 g/L in CH_2Cl_2.

Table 2. Reaction Conditions and Results of $Bu_2Sn(OMe)_2$ Initiated polymerizations of β-D,L-Butyrolactone with M/I = 100

sample no.	temp (°C)	time (days)	yield (%)	η_{inh}[a] (dL/g)
DB-11	3	20	56	0.06
DB-12	3	40	92	0.12
DB-13	25	2	81	0.09
DB-14	25	4	85	0.08
DB-15	25	8	33	0.06
DB-16	50	2	88	0.18
DB-17	50	4	85	0.13
DB-18	50	8	74	0.11
DB-19	75	1	77	0.12
DB-20	75	2	90	0.11
DB-21	75	4	78	0.10
DB-22	100	0.5	28	0.11
DB-23	100	1	25	0.13
DB-24	100	2	25	0.08

[a] Measured at 25 °C with c = 2 g/L in CH_2Cl_2.

Table 3. Reaction Conditions and Results of $Bu_2Sn(OMe)_2$ Initiated Polymerizations of β-D,L-Butyrolactone with M/I = 200

sample no.	temp (°C)	time (days)	yield (%)	η_{inh}[a] (dL/g)
DB-25	25	8	0	
DB-26	50	2	89	0.16
DB-27	50	4	95	0.17
DB-28	50	8	83	0.15
DB-29	75	1	86	0.14
DB-30	75	2	88	0.15
DB-31	75	4	88	0.15
DB-32	100	0.5	51	0.14
DB-33	100	1	35	0.16
DB-34	100	2	30	0.13

[a] Measured at 25 °C with c = 2 g/L in CH_2Cl_2.

Table 4. Reaction Conditions and Results of Bu_3SnOMe Initiated polymerizations of β-D,L-Butyrolactone

sample no.	monomer/initiator	temp (°C)	time (days)	yield (%)	η_{inh}[a] (dL/g)
TB-1	50/1	50	8	3	
TB-2	50/1	50	16	45	0.06
TB-3	50/1	75	4	69	0.09
TB-4	50/1	75	8	74	0.11
TB-5	50/1	75	16	83	0.15
TB-6	100/1	75	4	42	0.08
TB-7	100/1	75	8	73	0.13
TB-8	100/1	75	16	76	0.14
TB-9	100/1	100	8	80	0.13

[a] Measured at 25 °C with c = 2 g/L in CH_2Cl_2.

tyltin methoxide as initiator have shown that this monomer–initiator combination reacts sluggishly so that polymerizations at 25 °C or below were not feasible. On the basis of this experience the reaction conditions should be optimized for all three initiators studied in this work. All polymerizations were conducted in bulk, but the initiators were added as 1 M solutions in CH_2Cl_2 to allow an accurate dosage. The Bu_3SnOMe-initiated polymerizations were repeated with an 1 M solution of the initiator in toluene. The results proved to be reproducible, and thus, the CH_2Cl_2 initiator solution was used throughout this work.

Regardless of the initiator three parameters were varied: the monomer/initiator (M/I) ratio, the temperature, and the reaction time. $BuSn(OMe)_3$ gave the poorest results of all four initiators with regard to yields (<70%) and viscosities (η_{inh} < 0.08 dL/g). Therefore the results of the $BuSn(OMe)_3$-initiated polymerizations were not reported in detail. Yet the stereosequences of two samples prepared with $BuSn(OMe)_3$ (MB-1 and MB-2) are discussed in connection with other results summarized in Table 8.

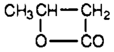
$Bu_2Sn(OMe)_2$ turned out to be the most useful initiator, and the influence of the reaction conditions on yield, viscosity, and stereosequence (see below) were studied in much detail. The M/I ratio had a strong influence on the overall reactivity, and only the low M/I ratio of 50/1 enabled polymerizations at temperatures below 0 °C (Table 1). For M/I = 100 the lowest reaction temperature was +3 °C (Table 2), and for M/I = 200 the minimum temperature was 50 °C (Table 3). Higher M/I ratios have, of course, the advantage of yielding higher molecular weights, and this correlation is illustrated by the results obtained at 50 °C (Tables 1–3). However, at M/I ratios >200/1 low yields (0–50%) were observed, obviously, because side reactions occur which cause termination steps (see below). The data of Tables 1–3 and several results not listed in this table demonstrate that higher temperatures, longer reaction times, and lower M/I ratios favor a reduction of yield and viscosity, most likely due to back-biting degradation.

All attempts to polymerize β-D,L-butyrolactone with Bu_3SnOMe at 0 or 25 °C failed, and even at 50 °C long reaction times were required (Table 4). Kemnitzer et al.[15] reported a minimum reaction temperature of 40 °C for this initiator. At higher temperatures the yields were slightly lower than those obtained with $Bu_2Sn(OMe)_2$, but the viscosities were similar. In summary, it may be said that $Bu_2Sn(OMe)_2$ is the most attractive initiator from a preparative point of view (a) because of a relatively high reactivity, and (b) because the highest yields and molecular weights were obtained with this initiator.

End Group Analyses and Mechanistic Aspects. Two samples of each series (Tables 1–4) were characterized by ^1H and ^{13}C NMR spectroscopy with regard to end groups. The formation of OH, CO_2CH_3, CO_2H, and crotonate end groups was analyzed, and NMR data for poly(β-D,L-butyrolactone) and several model compounds (Table 5) demonstrate that the combination of ^1H and ^{13}C NMR spectroscopy allows an unambiguous identification of these end groups. In agreement with previous results[16] relatively high concentrations of OH and CO_2CH_3 end groups were found in all cases (Figures 1 and 2). Furthermore, crotonate groups were not clearly detectable. The ^1H NMR spectra exhibit a weak doublet around 1.9 ppm with a coupling constant of 7.5–8.0 Hz (signal x in Figure 1) which might originate from the CH_3 group of crotonate units. However, the CH signals of the crotonate group were not clearly identified. If crotonate groups were present at all, their concentration was below 10% of that of CO_2CH_3 end groups. These results confirm the existence of the insertion mechanism outlined in eqs 1 and 2,[15] because anionic polymerizations of β-D,L-butyrolactone involve the formation of high concentrations of crotonate groups regardless of the initiator.[17]

Another interesting result is the absence of CO_2H end groups as evidenced by 90.5-MHz ^{13}C NMR spectra (Figure

Table 5. ^{1}H and ^{13}C NMR Chemical Shifts (δ)[a] of Poly(β-D,L-hydroxybutyric acid) and Related Compounds in $CDCl_3$

	^{13}C NMR				^{1}H NMR			
compd	CO	CH	CH_2	CH_3	CH	CH_2	CH_3	various proton
$[O{-}CH(CH_3){-}CH_2{-}CO{-}]$	169.1	67.5	40.7	19.7	5.25 (m)	2.54	1.28 (d)	
$HO{-}CH(CH_3){-}CH_2{-}CO_2H$	176.1	64.4	42.6	22.2	4.25 (m)	2.44	1.26 (d)	6.59 (2-OH)
$HO{-}CH(CH_3){-}CH_2CO_2CH_3$	172.7	63.9	42.6	22.3 (51.3)	4.17 (m)	2.48	1.23 (d)	3.71 (OCH_3)
	167.9	64.4	43.7	20.1	4.69 (m)	3.59 (d) 3.06 (d)	1.56 (d)	3.17 (OH)
$CH_3{-}CH{=}CH{-}CO_2H$					7.15 (m) 5.79 (m)		1.97 (d)	

[a] Relative to internal TMS.

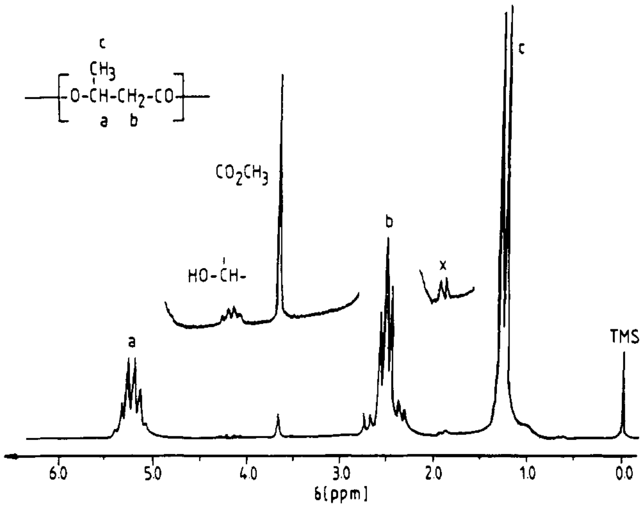


Figure 1. 100-MHz ^{1}H NMR spectrum of poly(β-D,L-HBu) DB-12, dissolved in $CDCl_3$.

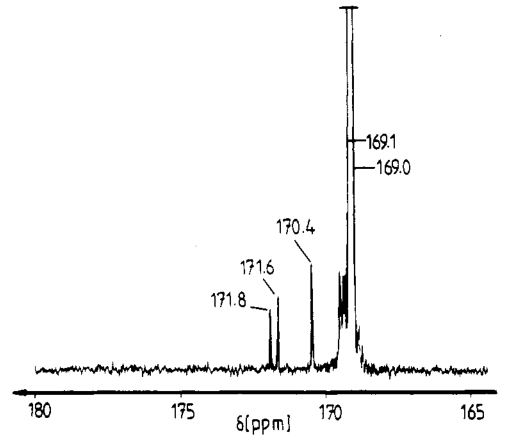
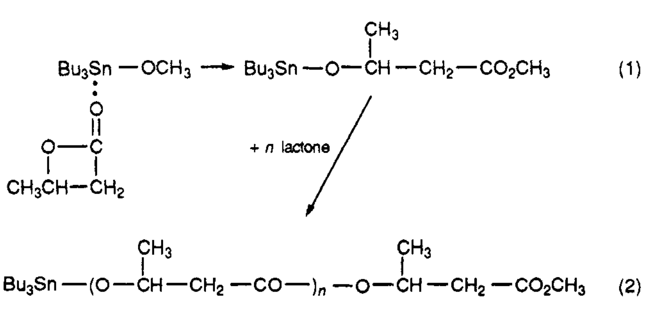


Figure 2. 90.5-MHz ^{13}C NMR spectrum (CO signals) of poly(β-D,L-HBu) DB-10, dissolved in $CDCl_3$.

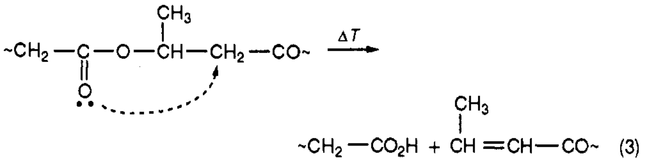


$$\mathrm{Bu_3Sn{-}OCH_3} \longrightarrow \mathrm{Bu_3Sn{-}O{-}CH(CH_3){-}CH_2{-}CO_2CH_3} \quad (1)$$

$$\xrightarrow{+\,n\ \text{lactone}} \mathrm{Bu_3Sn{-}(O{-}CH(CH_3){-}CH_2{-}CO{-})_{\mathit{n}}{-}O{-}CH(CH_3){-}CH_2{-}CO_2CH_3} \quad (2)$$

2). Whereas the signals for CO_2CH_3 end groups are easily detectable at 51 and 171.7 or 171.8 ppm (Figure 2), no signal for CO_2H groups shows up downfield of 173 ppm. This result is important because Kemnitzer et al.[15] reported to have high concentrations of carboxyl end groups in their samples and consequently doubted the validity of the insertion mechanism of eqs 1 and 2. However, those authors worked under somewhat different conditions and determined the CO_2H groups in an indirect way (treatment with diazomethane). Furthermore, they did not explain how their CO_2H groups were formed.

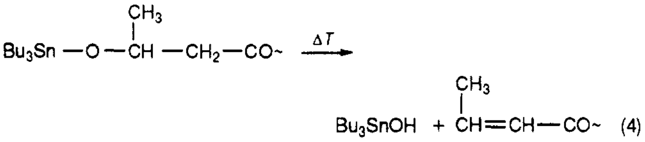
Obviously, carboxyl groups can only result from two side reactions: (A) hydrolysis, (B) elimination according to eq 3. In connection with this it should be noted that



$$\mathrm{\sim CH_2{-}C({=}O){-}O{-}CH(CH_3){-}CH_2{-}CO\sim} \xrightarrow{\Delta T} \mathrm{\sim CH_2{-}CO_2H + CH(CH_3){=}CH{-}CO\sim} \quad (3)$$

the number of HO–CH end groups as determined by ^{1}H NMR spectroscopy (Figure 1) never exceeded that of CO_2CH_3 end groups. This finding excludes a significant influence of hydrolysis in agreement with a careful drying of all reactants. On the other hand, the aforementioned low level of crotonate groups excludes the formation of a significant amount of carboxyl groups by elimination (eq 3). Thus the ^{1}H NMR spectroscopic results perfectly agree with the ^{13}C NMR spectroscopic evidence.

Nonetheless it should be emphasized that the insertion mechanism schematically outlined in eqs 1 and 2 is not necessarily an absolutely clean process. In addition to the hypothetical elimination reaction of eq 4 unknown



$$\mathrm{Bu_3Sn{-}O{-}CH(CH_3){-}CH_2{-}CO\sim} \xrightarrow{\Delta T} \mathrm{Bu_3SnOH + CH(CH_3){=}CH{-}CO\sim} \quad (4)$$

sidereactions may exist. Furthermore, formation of cyclic oligomers is highly likely due to back-biting degradation at least at temperatures above 20 °C. The high transesterifications activity of butyltin methoxides, including back-biting degradation, has been demonstrated for poly(ε-caprolactone).[16] In connection with this the numerous weak CO signals in the ^{13}C NMR spectra of all samples should be mentioned (Figure 2). The two signals of the CO_2CH_3 end group may be due to diastereomeric stereosequences of the chain end. Also other weak signals in the range 169–171 ppm may result from end group effects, because the molecular weights of all samples are low. However, one or two signals may also result from cyclic oligomers.

Molecular Weights. The aforementioned end group analyses suggest that almost all polymer chains were initiated according to eq 1. This result offers the possibility of determining the average degrees of polymerization (DP's) and the number average molecular weights (M_n's) by means of ^{1}H NMR spectroscopic analyses of the CO_2CH_3 end groups. The results determined from a representative selection of samples are listed in Table 6. A

Table 6. Comparison of Inherent Viscosities, Degrees of Polymerization (DP), and GPC Measurements

sample no.	$\eta_{inh}{}^{a}$ (dL/g)	$\overline{DP}^{b}$ (calc)	$\overline{DP}^{c}$ (^{1}H NMR)	$M_n{}^{c}$ (^{1}H NMR)	$M_w{}^{d}$ (GPC)
DB-7	0.08	25	27	2200[e]	3300
DB-12	0.12	50	45	4000	10000
DB-16	0.18	50	40	3500[f]	8000
DB-20	0.11	50	35	3100	7500
DB-27	0.17	100	50	4400	13000
TB-5	0.15	50	35	3100[g]	7500
TB-8	0.14	100	30	2700	5600

[a] Measured at 25 °C with $c = 2$ g/L in CH_2Cl_2. [b] Calculated from the M/I at 100% conversion of monomer and methoxide groups. [c] Determined by ^{1}H NMR spectroscopic end group analyses of the methyl ester group. [d] GPC in tetrahydrofuran using polystyrene standards and the universal calibration. [e] $M_n = 2000$ by VPO. [f] $M_n = 3300$ by VPO. [g] $M_n = 3000$ by VPO.

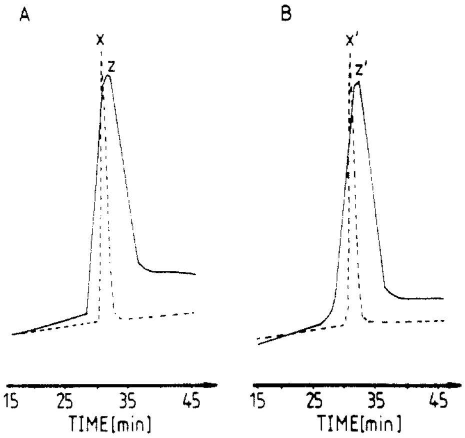


Figure 3. GPC measurements of (A) sample DB-16 and (B) sample TB-5. The dotted curves represent a commercial polystyrene standard with M_w = 21 000 and M_n = 20 000.

comparison with the M/I ratios is not very informative for three reasons. First, the yields are not identical with the conversion. Second, conversion was not complete in many cases, as evidenced by ^{1}H NMR spectroscopy of the reaction mixtures (see chemical shifts in Table 5). Third, precipitation of the dissolved crude polymers leads to fractionation, because a fraction of the linear (and possibly cyclic) oligomers remains in solution. However, comparison with vapor pressure osmometry gave in all three cases a satisfactory agreement (see footnotes of Table 6). Furthermore, it is noteworthy that the VPO measurements of Kemnitzer et al.[15] yielded the same range of M_n's. The end group analyses of Kemnitzer et al.[15] were complicated by the coexistence of CO_2H and CO_2CH_3 end groups. Yet, after derivatization with diazomethane the ^{1}H NMR analyses of the CO_2CH_3 end groups show a satisfactory agreement with their VPO measurements and with the order of magnitude (M_n 2000–5000) found in this work.

The weight average molecular weights (M_w's) found by GPC measurements calibrated with commercial polystyrene standards are higher than the M_n's by a factor of 1.5–3.0 (Table 6). However, it must be kept in mind that such measurements (also reported in ref 15) are not highly accurate because the hydrodynamic properties of poly(β-D,L-butyrolactone) and polystyrene are not necessarily identical. Nonetheless, the existence of broader molecular weight distributions ($M_w/M_n \sim 1.5$–2.0) is confirmed by a direct comparison of the elution curves with those of the polystyrene standards (Figure 3). In this regard the present results deviate from those of Kemnitzer et al.[15] who reported M_w/M_n ratios ≤ 1.12 despite the assumption of a complex polymerization mechanism. However, broader molecular weight distributions agree with the polymerization mechanism where the initiation step is not significantly faster than the propagation step and where back-biting degradation may take place.

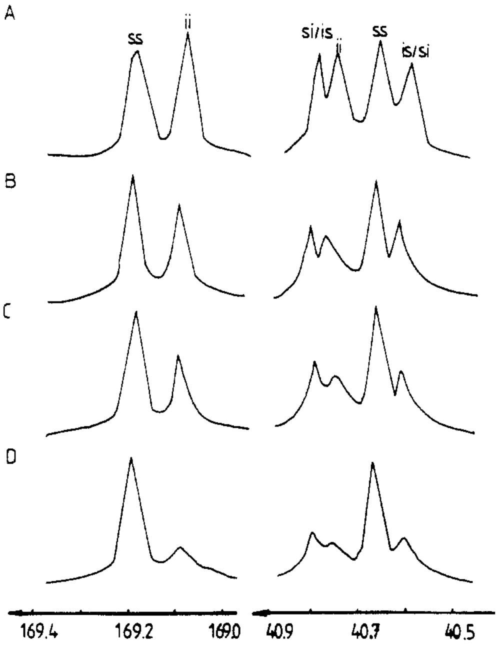


Figure 4. ^{13}C NMR signals of CO and CH groups of poly(β-D,L-HBu) initiated with $Bu_2Sn(OMe)_2$: (A) DB-23; (B) DB-16; (C) DB-14; (D) DB-1.

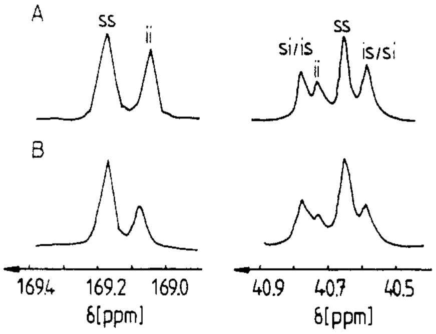


Figure 5. ^{13}C NMR signals of poly(β-D,L-HBu) initiated with Bu_3SnOMe: (A) TB-9; (B) TB-2.

Stereosequence Analyses. It is well-known from previous publications of several authors[5–14] that ^{13}C NMR spectroscopy of poly(β-hydroxybutyric acid)s dissolved in $CDCl_3$ allows a characterization of the stereosequences. Without mathematical refinement the CO signal exhibits a diad splitting and the CH_2 signal even a tetrad splitting (Figures 4 and 5). As illustrated by Kemnitzer et al.,[15] mathematical treatment of the NMR signals (i.e. of the *f*ree-*i*nduction *d*ecay) may improve the resolution to such an extent that tetrad peaks of all signals become detectable. However, the quantification of these tetrad peaks is less accurate than that of the CO diad peaks, and thus, the quantitative characterization of the stereosequences in this work is based on the ratio of isotactic and syndiotactic diads (i/s ratio).

Table 7. Stereosequence Analyses and DSC Measurements of Poly(β-D,L-hydroxybutyrate) Prepared by Means of $Bu_2Sn(OMe)_2$

		stereosequence					
sample no.	monomer/initiator	temp (°C)	i/s	% syn[a]	T_g[b] (°C)	T_m[b] (°C)	T_m[c] (°C)
DB-1	50/1	−17	0.2/1	83		84/127	
DB-3	50/1	3	0.3/1	77	−5	76/124	117
DB-11	100/1	3	0.4/1	72	−1	80/115	114
DB-7	50/1	25	0.4/1	72	5	67/123	100
DB-14	100/1	25	0.4/1	72	8	72/120	98
DB-8	50/1	50	0.5/1	67			
DB-16	100/1	50	0.5/1	67	7	67/114	113
DB-18	100/1	50	0.5/1	67			
DB-27	200/1	50	0.5/1	67	10	71/107	
DB-19	100/1	75	0.8/1	55			
DB-29	200/1	75	0.8/1	55	6	57/72	
DB-23	100/1	100	1.0/1	50	3	58	
DB-34	200/1	100	1.0/1	50			

[a] Percentage of syndiotactic diads, margin of error approximately ±5%. [b] DSC measurements: first heating (heating rate 20 °C/min); most samples show two endotherms (Figures 6A–D and 8A). [c] DSC measurements: second heating (heating rate 20 °C/min).

Table 8. Stereosequence Analyses and DSC Measurements of Poly(β-D,L-hydroxybutyrate) Prepared by $BuSn(OMe)_3$ or Bu_3SnOMe

				stereosequence			
sample no.	initiator	monomer/initiator	temp (°C)	i/s	% syn[a]	T_g[b] (°C)	T_m[b] (°C)
MB-1	$BuSn(OMe)_3$	100/1	50	0.9/1	91		
MB-2	$BuSn(OMe)_3$	200/1	50	0.8/1	83	3	52/74
TB-2	$Bu_3Sn(OMe)$	50/1	50	(0.3–0.4)/1	72–77		
TB-5	$Bu_3Sn(OMe)$	50/1	75	(0.6–0.7)/1	58–63	4	56/72
TB-7	$Bu_3Sn(OMe)$	100/1	75	(0.6–0.7)/1	58–63	4	54/70
TB-9	$Bu_3Sn(OMe)$	100/1	100	(0.8–0.9)/1	55–50		

[a] Percentage of syndiotactic diads, margin of error approximately ±5%. [b] DSC measurements: first heating (heating rate 20 °C/min).

At first it should be mentioned that in several cases not only the insoluble fraction (listed in Tables 1–4) but also the soluble fraction was analyzed with regard to the stereosequence and viscosity. In no case was an excess of isotactic diads found. In other words the stereoselectivity of the butyltin methoxides is homogeneous, favoring syndiotactic diads, in contrast to aluminoxanes.[14] Because synthesis and characterization of highly syndiotactic and high molecular weight poly(β-D,L-HBu) was the purpose of this work, the soluble fractions which possessed a somewhat lower percentage of syndiotactic diads and/or a lower viscosity were not studied and discussed in detail.

The stereosequence analyses of the samples initiated with $Bu_2Sn(OMe)_2$ are compiled in Table 7. The most conspicuous result is the relatively strong influence of the temperature on the i/s ratio. At 100 °C perfectly atactic polyesters with i/s ratios around 1.0/1.0 were obtained, whereas the i/s ratio was as low as 0.2/1 at a polymerization temperature of −17 °C (Figure 4). Unfortunately, such low temperatures require long reaction times and yield low molecular weights (η_{inh} < 0.1 dL/g).

The stereosequence analyses of Bu_3SnOMe revealed a similar trend (Table 8). A nearly atactic polyester was obtained at 100 °C, but an i/s ratio of (0.3–0.4)/1, at 50 °C (Figure 5). The latter result agrees with literature data, because Kemnitzer et al.[15] obtained a nearly 70% syndiotactic poly(β-HBu) with Bu_3SnOMe at 40 °C. However, those authors did not find a significant temperature dependence of the tacticity in contrast to results presented in this work.

When the poly(D,L-HBu) samples were subjected to DSC measurements, another interesting observation was made. It is an obvious result that the atactic sample DB-34 (Table 7) is completely amorphous. It is also reasonable that polyesters with low i/s ratios are semicrystalline. Furthermore, it is reasonable that the melting temperature increases with decreasing i/s ratio. However, it is difficult to understand why several atactic or nearly atactic samples such as DB-23, DB-29, and MB-2 exhibit a weak endotherm in their heating traces (Figure 6A,B). This endotherm is absent in the second heating trace but reappears upon annealing. These surprising observations suggest that the stereosequences are somewhat blocky in nature. This suggestion is supported by the following comparison. Sample TB-2 (i/s = 0.3–0.4) prepared with Bu_3SnOMe shows two endotherms, a weak one 56 °C and a stronger one at 72 °C (Table 8). A similar result was reported by Kemnitzer et al.[15] Four samples prepared with $Bu_2Sn(OMe)$ have similar i/s ratios (DB-3, DB-11, DB-7, DB-14), but their DSC heating curves display two endotherms at higher temperatures, namely the first one at 67–80 °C and the second one at 115–124 °C (analogous to Figure

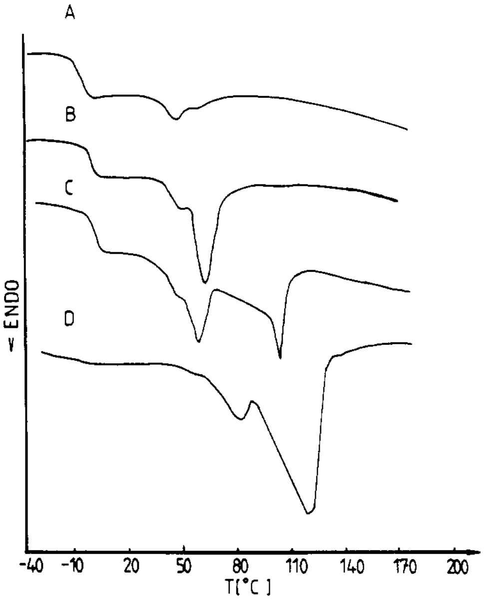


Figure 6. DSC heating curves (first heating) of poly(β-D,L-HBu): (A) DB-23; (B) DB-29; (C) DB-16; (D) DB-1.

Table 9. Results of the Fractionation of Two Samples of Poly(β-D,L-hydroxybutyrate)

sample no.	nonsolvent	yield[a] (%)	stereosequence i/s	stereosequence % syn[b]	T_g[c]	T_m[c]	T_c[d]	T_m[e]
DB-3/I	ligroin/DE[a]	53	0.3/1	77	-5	76/124	30	117
DB-3/II	diethyl ether	34	0.25/1	80	1	131	52	112
DB-3/III	methanol	12	0.2/1	83	-0	133	83	128
DB-1/I	ligroin/DE[a]	33	0.2/1	83		84/127		
DB-1/II	diethyl ether	15	0.2/1	83		137	50	106
DB-1/III	methanol	8	0.1/1	91		113/143	87	123

[a] Relative to the monomer used for the polymerization. [b] Percentage of syndiotactic diads, margin of error approximately ±5%. [c] DSC measurements, first heating (heating rate 20 °C/min). [d] DSC measurements, first cooling (cooling rate 20 °C/min). [e] DSC measurements, second heating (heating rate 20 °C/min).

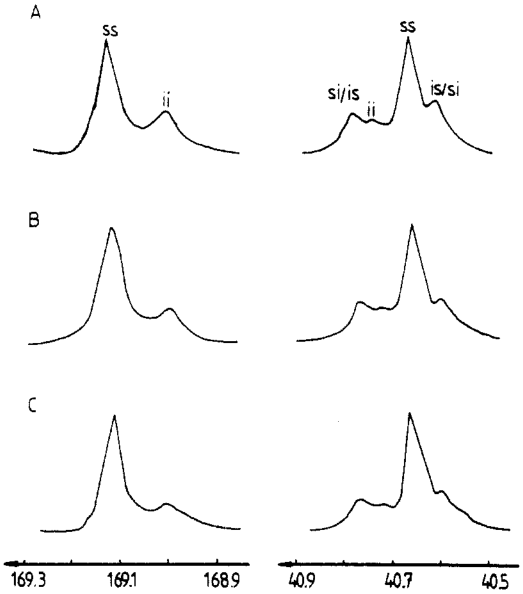


Figure 7. ^{13}C NMR signals of CO and CH groups of poly(β-D,L-HBu) DB-3 fractionated by precipitation into three different nonsolvents: (A) DB-3/I; (B) DB-3/II; (C) DB-3/III (Table 10).

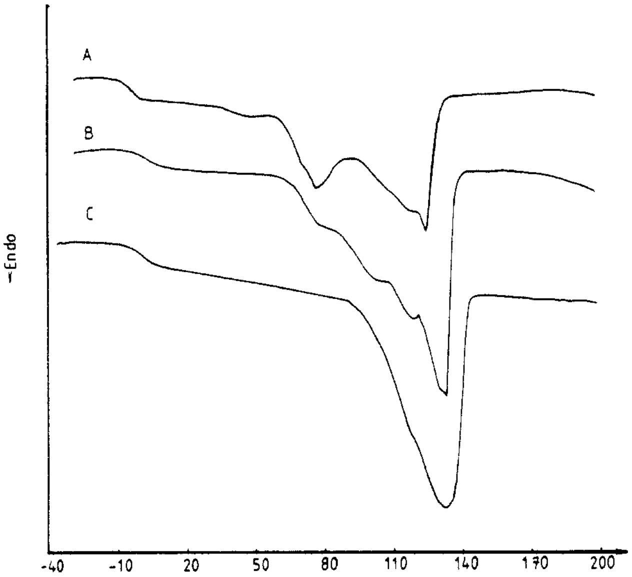


Figure 8. DSC heating curves (first heating) of fractionated poly(β-D,L-HBu) DB-3 (Table 10): (A) DB-3/I; (B) DB-3/II; (C) DB-3/III.

6C). Longer blocks of syndiotactic sequences in the DB samples are the most obvious explanation for this difference. Further confirmation for a somewhat heterogeneous distribution of syndiotactic blocks comes from the fractionation experiments discussed below.

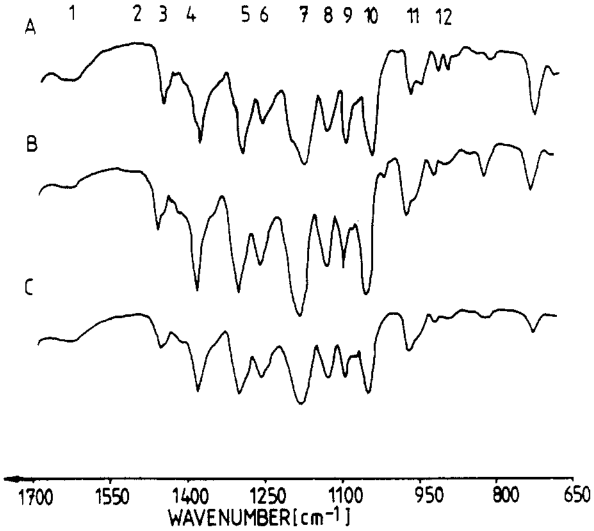


Figure 9. IR spectra (KBr pellets) of poly(β-D,L-HBu): (A) TB-2 (i/s = 0.3/1); (B) TB-5 (i/s = 0.5/1); (C) DB-34 (i/s = 1.0/1).

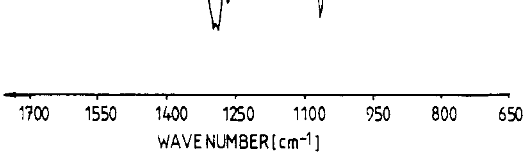


Figure 10. IR spectra (KBr pellets) of (A) poly(β-D,L-HBU) DB-1/III (i/s = 0.1/1) and (B) biogenic poly(β-D-HBu).

Finally, a comparison of the three initiators with regard to their stereoselectivity should be made. Such a comparison is feasible on the basis of polymerizations conducted at 50 °C: DB-8, DB-16, DB-18, DB-27, MB-1, MB-2, and TB-2. Taking into account that the stereosequence of TB-2 is reproducible in this work and agrees with literature data,[15] the three initiators can be arranged in the following order of slightly increasing overall stereoselectivity:

$$BuSn(OMe)_3 < Bu_2Sn(OMe)_2 < Bu_3SnOMe$$

This order of stereoselectivity obviously reflects the increasing steric demands of the butyl groups. The pronounced temperature effect of the stereoselectivity found for $Bu_2Sn(OMe)_2$ and Bu_3SnOMe indicates that

Table 10. Absorption Maxima in the IR Spectra of Various Poly(β-hydroxybutyric acids) in the Range below 1700 cm^{-1}

	IR bands (wavelengths in cm^{-1} numbered according to Figures 9 and 10)											
sample no. (i/s)	1	2	3	4	5	6	7	8	9	10	11	12
TB-2 (0.3/1)			1458	1384		1307 1265	1184	1142	1109	1059	980 962	927 907
TB-5 (0.7/1)			1457	1384		1306 1265	1184	1134	1102	1058	979	927
DB-34 (1/0.1)			1457	1384		1306 1264	1184	1134	1102	1058	978	927
DB-3 (0.1/1)	1655		1458	1395 1384		1307 1265	1212 1180	1144	1102	1052	984 962	926 909
Bio (∞/1)	1652	1537	1457	1385	1358 1347	1290 1280 1262	1230 1184	1132	1102 1045	1057 954	980 911, 895	939, 930

the association of an L monomer with an active D chain end (and vice versa) possesses a lower energy of activation than the association of two identical chiral centers. It is thus plausible that increasing steric demands of the initiator group widen the difference between these activation energies, thereby enhancing the stereoselectivity.

The above order of "overall stereoselectivity" seems to contrast with the relatively long syndiotactic blocks obtained with $Bu_2Sn(OMe)_2$. The hypothesis of two diastereomeric active centers may explain this alleged contradiction, including the following experimental findings.

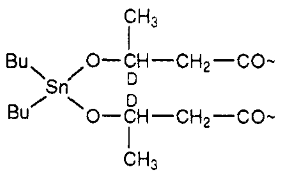
(A) $Bu_2Sn(OMe)_2$ yields longer syndiotactic blocks than Bu_3SnOMe.

(B) The fractionations discussed below indicate a heterogeneous distribution of the stereoblock lengths.

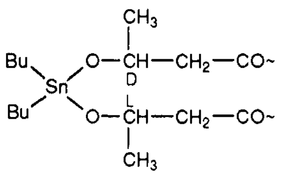
(C) The results obtained with triphenyltin methoxide-initiated polymerizations (reported in the succeeding part of this series) resemble those obtained with Bu_3SnOMe. No poly(β-D,L-HBu) with a T_m above 82 °C was obtained.

(D) In the case of $Bu_2Sn(OMe)_2$ and other metal methoxides all methoxide groups may initiate a chain growth, albeit not simultaneously.[16] The initiation reaction of the second methoxide group may be delayed by the steric hindrance of the polyester chain initiated by the first methoxide group.

When only one methoxide group of $Bu_2Sn(OMe)_2$ reacts with β-D,L-butyrolactone, two enantiomeric active chain ends are formed with a stereoselectivity similar to that of Bu_3SnOMe. These active centers may be responsible for the fraction of poly(β-D,L-HBu) chains with T_m's ≤80 °C. When both methoxide groups have reacted with the monomer, two diastereomeric catalyst centers (1 and 2) exist which will differ in concentration and stereoselectivity.



1



2

A propagation reaction of the insertion mechanism outlined in eq 1 consists of at least two steps: firstly, the association of monomer with catalyst and, secondly, the insertion step. The stereoselectivity of a L,L (or D,D) catalyst center (1) is necessarily connected with the association step, whereas the stereoselectivity of a D,L center (2) is based on the insertion step. When the L,L center reacts with an associated L monomer, it produces an isotactic diad. The reaction with an associated D monomer entails a change to a D,L center. In contrast, the D,L center can maintain its stereochemistry and support a syndiotactic growth at both chain ends, when the associated D monomer reacts with the L chain end and the L monomer with the D chain end. With the reasonable assumption that the stereoselectivity of an insertion step is higher than that of an association step, it is obvious that the reactivity and selectivity of the D,L center are decisive for the formation of long syndiotactic blocks with T_m's >100 °C. This interpretation of our results is still speculative at this time and needs further studies and confirmation.

Fractionation of Poly(β-D,L-hydroxybutyrate). The samples DB-1 and DB-3 were subjected to a simple fractionation for two reasons. Firstly, additional evidence for a heterogeneous distribution of syndiotactic blocks should be elaborated. Secondly, samples with a high percentage of syndiotactic diads (e.g. i/s ratios < 0.2/1) should be prepared and characterized. The fractionation was conducted by repeated precipitation into different nonsolvents. The first precipitation into ligroin was conducted with all samples of this work. DB-1 and DB-3 were subjected to two further reprecipitations, namely into diethyl ether and into methanol (Table 9). Decreasing yields and nearly constant viscosities of the insoluble fractions suggested a fractionation effect based on different tacticities. This conclusion was confirmed by ^{13}C NMR spectroscopy (Table 9 and Figure 7). In the case of DB-1, a fraction (labeled III) with an i/s ratio of 0.1/1 was isolated which represents the highest level of syndiotacticity reported so far.

The DSC measurements (e.g. Figure 8) confirmed the success of the fractionation. Melting temperatures (T_m) above 130 °C were found in the first heating curves of DB-1/III and DB-3/II or -III (Table 9). These results suggest that a 100% syndiotactic poly(β-D,L-hydroxybutyrate) may have a T_m in the range 145–150 °C.

The IR spectrum of DB-1/III (Figure 10A) also demonstrates the higher level of syndiotacticity by slight differences, when compared with the spectrum of TB-2 (Figure 9A) which is in turn almost identical with the spectrum published by Kemnitzer et al.[15] for their 70% syndiotactic material. Not surprising is the significant difference between the IR spectra of DB-1/III and biogenic poly(β-D-HBu) illustrated in Figure 10). The wavenumbers of the skeleton vibrations of both polyesters and further samples (Figure 9B,C) are compiled in Table 10.

These different IR spectra suggest that the chain packing and conformation of solid syndiotactic and isotactic poly(β-hydroxybutyrate) are completely different. This suggestion is confirmed by a comparison of the WAXD patterns, as shown in Figure 11. The sharp reflections at different scattering angles indicate different crystal lattices. The WAXD patterns also prove that the crystallinity of sample DB-1/III is still considerably lower than that of the biogenic isotactic poly(β-D-HBu). Different crystal

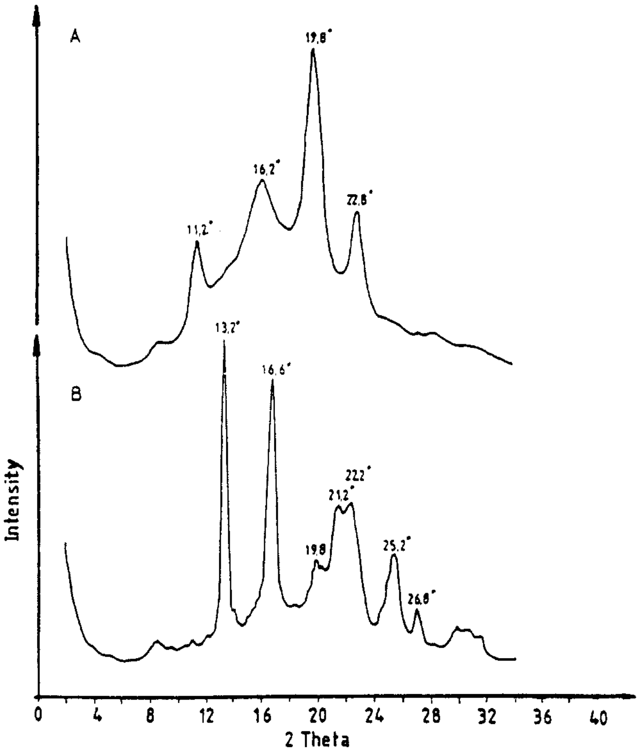


Figure 11. WAXS powder patterns of (A) poly(β-D,L-HBU) DB-1/III (i/s = 0.1/1) and (B) biogenic poly(β-D-HBu).

lattices normally involve different conformations of the repeating units, and this relationship is confirmed by the ^{13}C NMR CP/MAS spectra of Figure 12. The signals of the CO and CH_2 carbons proved to be most sensitive to the conformational change, which obviously involves the ester group.

Conclusion

The comparison of the three *n*-butyltin methoxide initiators revealed that all three enable the synthesis of predominantly syndiotactic poly(β-D,L-HBu) from β-D,L-butyrolactone. The stereoselectivity slightly increases with the number of butyl groups, but the reactivity decreases. $Bu_2Sn(OMe)_2$ represents the optimum initiator from the preparative point of view. It allows polymerizations of β-D,L-butyrolactone even below room temperature, and a decreasing polymerization temperature significantly enhances the percentage of syndiotactic diads. Furthermore, the stereoselectivity of $Bu_2Sn(OMe_2)$ seems to be basically different from that of Bu_3SnOMe, because it favors the formation of relatively long syndiotactic blocks, even when the overall percentage of syndiotactic diads is not particularly high. The heterogeneity of the stereoblock length distribution allows one to improve the level of syndiotacticity by fractionation. The 90% syndiotactic poly(β-D,L-HBu) obtained in this way suggests that a 100% syndiotactic material has a T_m in the range 145–150 °C. Such a T_m in combination with a high degree of crystallinity provides a sufficiently high heat distortion temperature and is low enough for convenient processing from the melt. In other words syndiotactic poly(β-D,L-HBu) should be a useful biodegradable engineering plastic, but the problem of high molecular weights still needs to be solved.

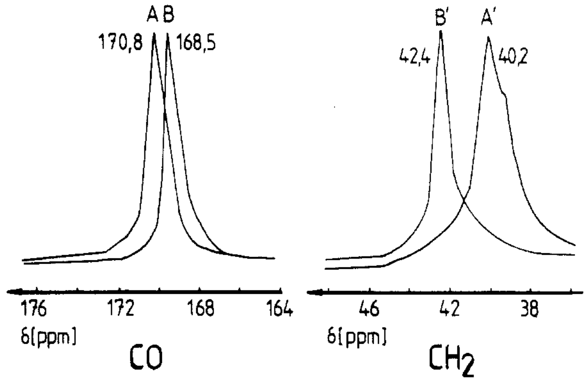


Figure 12. 75.4-MHz ^{13}C NMR CP/MAS spectra of (A) poly-(β-D,L-HBu) DB-1/III (i/s = 0.1/1) and (B) biogenic poly(β-D-HBu).

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