

P-Chiral Phosphine–Sulfonate/Palladium-Catalyzed Asymmetric Copolymerization of Vinyl Acetate with Carbon Monoxide

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S Supporting Information

ABSTRACT: Utilization of palladium catalysts bearing a *P*-chiral phosphine–sulfonate ligand enabled asymmetric copolymerization of vinyl acetate with carbon monoxide. The obtained γ -polyketones have head-to-tail and isotactic polymer structures. The origin of the regio- and stereoregularities was elucidated by stoichiometric reactions of acylpalladium complexes with vinyl acetate. The present report for the first time demonstrates successful asymmetric coordination–insertion (co)polymerization of vinyl acetate.

Synthesis and application of optically active polymers has been an important subject in polymer science because their chiral nature is essential for many well-defined functions and properties, as exemplified by polypeptide and nucleic acid chemistry.^{1,2} Among various artificial polymers, γ -polyketones obtained by the alternating copolymerization of monosubstituted ethenes with carbon monoxide (CO) are endowed with various structural regularities (Figure 1): head-to-tail regio-regularity, syndiotactic or isotactic stereoregularity (tacticity), and in the isotactic structure, enantioselectivity to control the absolute stereochemistry.³ During the last few decades, asymmetric monosubstituted ethenes/CO copolymerization

was achieved using nonpolar olefins such as propylene and vinylarenes.^{1,4,5} Until now, however, there have been no reports of the regulation of tacticity and enantioselectivity by coordination–insertion polymerization of fundamental polar vinyl monomers such as vinyl acetate and methyl acrylate with carbon monoxide.^{6,7} The introduction of polar functional groups into polyketones in a highly controlled manner has been a significant challenge, since it would drastically alter the polymer properties and expand the range of applications. In 2007, we reported the first example of copolymerization of vinyl acetate and carbon monoxide using palladium/phosphine–sulfonate catalysts, but the resulting copolymers showed low regio- and stereoregularities.^{8,9} Here we report the synthesis of the first optically active *P*-chiral phosphine–sulfonate ligands¹⁰ and their application to palladium-catalyzed asymmetric copolymerization of vinyl acetate with carbon monoxide.

A series of *P*-chiral ligand precursors [1b]H–[1d]H were prepared according to literature procedures.^{10a,c,11} The enantiomerically pure ligands 1b and 1d were prepared by HPLC separation of the corresponding racemates with a chiral stationary phase (CHIRALPAK IC). Copolymerization of vinyl acetate with carbon monoxide was performed in the presence of a mixture of Pd₂(dba)₃·CHCl₃ and [1]H (Table 1). The use of achiral ligand 1a resulted in the formation of polyketone A with 71% head-to-tail selectivity (entry 1). The regioselectivity was estimated by the integration ratio of the ketone carbonyl region in ¹³C NMR spectra (Figure 2), assuming that the broad signal at 201.5 ppm corresponds to either head-to-head or tail-to-tail structure and that multiple signals from 202–204 ppm corresponds to all the other regioisomeric structures.^{12,13} In entries 2–4, three types of racemic *P*-chiral ligands 1b–1d were employed for the copolymerization. In entries 2 and 3, the copolymerization produced polyspiroketal B as a major product instead of polyketone A.³ In contrast, higher chemo-, regio- and stereoselectivities were obtained when using ligand 1d, bearing phenyl and 2',6'-dimethoxy(1,1'-biphenyl)-2-yl groups on the phosphorus atom (entry 4), and the ratio of head-to-tail structure was improved to 84%. Furthermore, the resonance at 203.5 ppm became predominant, which suggests higher regio- and stereoregularities.

Encouraged by the result in entry 4, asymmetric copolymerization was examined with enantiomerically pure ligand (S)-(–)-1d (entry 5). Unexpectedly, the regio- and stereo-

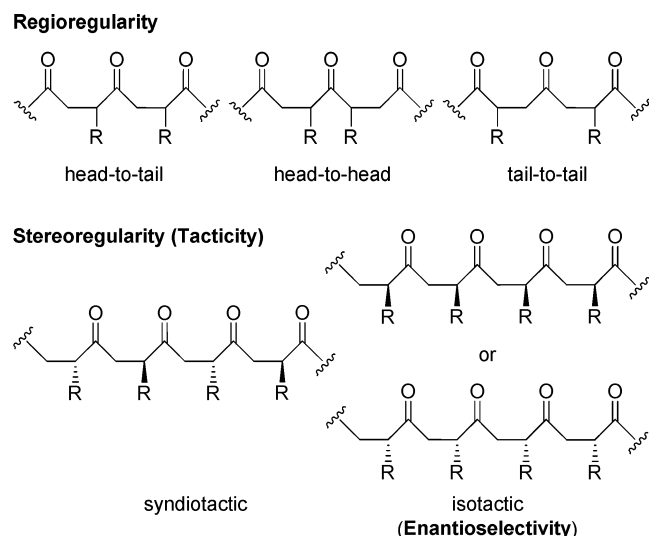


Figure 1. Possible structural regularities in monosubstituted ethene/carbon monoxide copolymers.

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Table 1. Copolymerization of Polar Vinyl Monomers with Carbon Monoxide^a

1a: R¹, R² = 2-MeOC₆H₄
1b: R¹ = Ph, R² = *t*-Bu
1c: R¹ = Ph, R² = 2-PhC₆H₄
1d: R¹ = Ph, R² = 2-{2',6'-(MeO)₂C₆H₃}C₆H₄

entry	ligand	FG	yield (mg)	TOF (h ⁻¹)	M _n (×10 ³) ^b	M _w /M _n ^b	A or B ^c	h-to-t (%) ^c
1	1a	OAc	320	14	65	1.6	A	71
2	(<i>rac</i>)- 1b	OAc	150	6.6	14	1.5	B	
3	(<i>rac</i>)- 1c	OAc	500	22	44	1.5	1:5 (A : B)	
4	(<i>rac</i>)- 1d	OAc	230	10	25	1.2	A	84
5	(<i>S</i>)- 1d	OAc	170	7.4	20	1.8	A	90
6	(<i>S</i>)- 1d	CO ₂ Me	106	4.7	10	1.2	A	>99
7	(<i>S</i>)- 1d	Ph	101	3.8	12	1.1	A	>99

^aConditions: Pd₂(dba)₃·CHCl₃ (5 μmol), ligand **1** (12 μmol), and vinyl monomer (2.5 mL) were stirred under carbon monoxide pressure (6.0 MPa) for 20 h at 70 °C in a 50-mL autoclave. ^bDetermined by SEC analysis using polystyrene standards. ^cDetermined by NMR analysis.

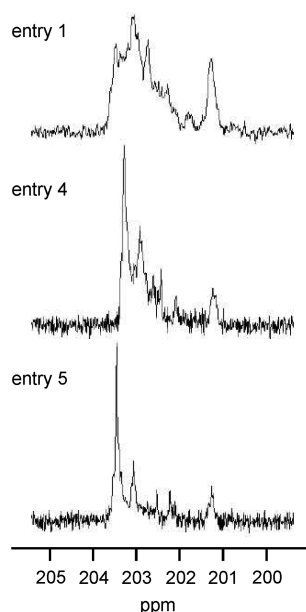


Figure 2. Ketone regions in the ¹³C NMR spectra of the polyketones obtained in entries 1, 4, and 5 in Table 1 (CDCl₃).

regularities were improved compared with the results using (*rac*)-**1d** (Figure 2).¹⁴ The solubility of the resulting polymer in entry 5 was lower than that of entry 4 in CDCl₃, indicating different higher-order structures.^{15,16} Although the reason for the different regio- and stereoregularities between entry 4 and 5 is still unclear, chain transfer between the two enantiomeric palladium complexes may be operating during the polymerization with *rac*-**1d** so that one chain contains segments formed by each enantiomer of the catalyst.¹⁷

The resulting vinyl acetate/carbon monoxide copolymer in entry 5 exhibited moderate optical rotation ([Φ]_D²² = −8.5, *c* = 0.32, CHCl₃), which may correspond to regions of enantio-enriched isotactic structure (Figure 3). The absolute config-

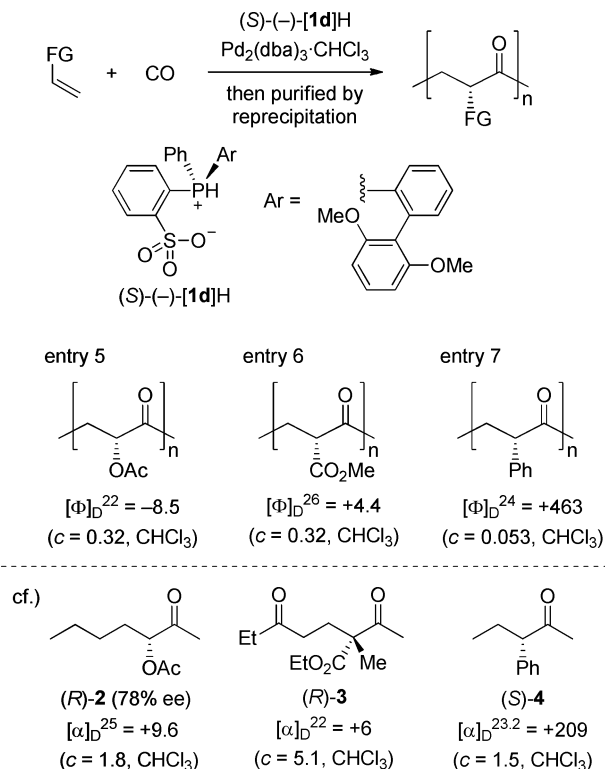
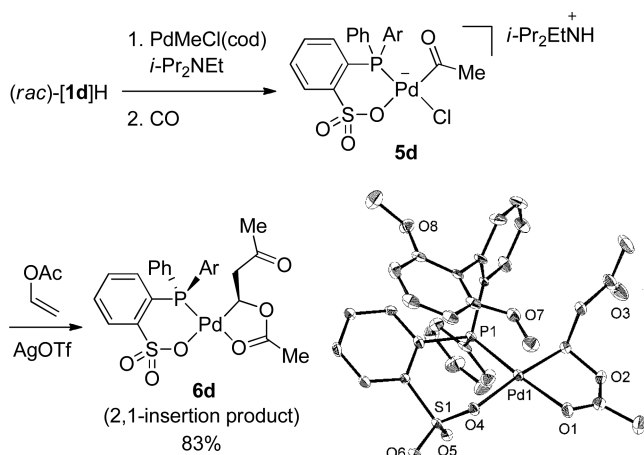


Figure 3. Asymmetric copolymerization of vinyl acetate with carbon monoxide using optically active (*S*)-(-)-**1d**/Pd₂(dba)₃·CHCl₃. Optical rotation values of analogous model compounds are also shown for comparison.¹⁹

uration of the asymmetric center in the polymer main chain was inferred from the results of the reaction shown in Scheme 1 (vide infra).¹⁸ These data represent the first example of the synthesis of an optically active γ-polyketone having ester substituents directly attached to the main chain. Although the absolute value of the specific optical rotation is not high, it does

Scheme 1. Synthesis and Molecular Structure of **6d**^a

^aHydrogen atoms and solvent molecules are omitted for clarity. Ar = 2',6'-dimethoxy(1,1'-biphenyl)-2-yl.

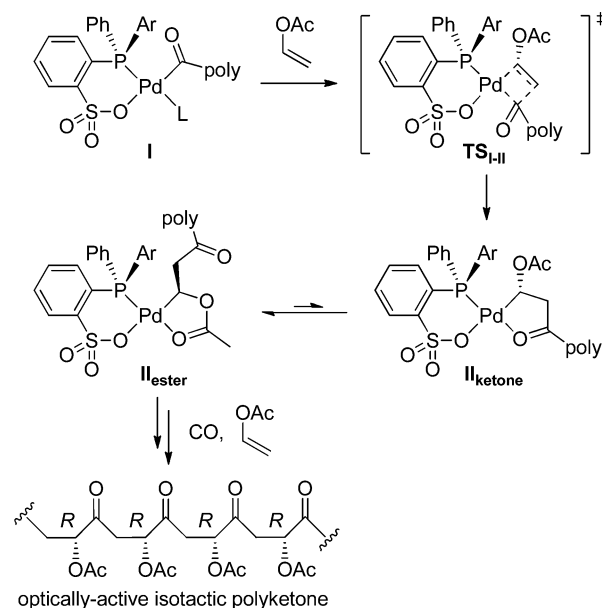
not necessarily indicate low selectivity considering that reported model compounds similar to the repeating unit of the copolymer, such (*S*)-**2**, also exhibit moderate values (Figure 3).^{19a}

Copolymerization reactions of other monosubstituted ethenes with carbon monoxide were also investigated. The use of methyl acrylate as a comonomer produced a regio-controlled alternating copolymer, as confirmed by the observation of a single resonance in the ketone carbonyl region of the ¹³C NMR spectrum (entry 6).⁹ The copolymer exhibited an optical rotation value $[\Phi]_D^{26} = +4.4$ ($c = 0.32$, CHCl₃),²⁰ which is consistent with a small optical rotation value of analogous molecule (*R*)-**3**^{19b} as shown in Figure 3. However, epimerization of the asymmetric center may have occurred, since our previous studies revealed that the methine proton in the methyl acrylate/CO copolymer was exchangeable with deuterium by the treatment with MeOD.^{9b} In contrast, the styrene/CO copolymer obtained in entry 7 exhibited a large optical rotation value $[\Phi]_D^{24} = +463$ ($c = 0.053$, CHCl₃),²⁰ which is one of the highest values reported for styrene/CO copolymers.^{4,5} These results indicate that the introduction of *P*-chirogenic centers into phosphine-sulfonate ligands is an effective strategy for catalyst-controlled asymmetric polymerization.¹¹

The origin of regio- and stereoregularities in the copolymerization of vinyl acetate with carbon monoxide was investigated by the stoichiometric reaction of palladium complexes bearing chiral ligand (*rac*)-**1d** with vinyl acetate (Scheme 1). First, acetylpalladium complex **5d** bearing ligand **1d** was synthesized by the reaction of phosphonium-sulfonate [**1d**]⁺H with PdMeCl(cod) in the presence of Hünig's base followed by treatment with carbon monoxide. Next, reaction of **5d** with an excess amount of vinyl acetate in the presence of AgOTf afforded 2,1-insertion complex **6d** in 83% yield. NMR and X-ray analyses revealed that the major isomer arises from 2,1-insertion of vinyl acetate, and the ester carbonyl coordinates to the palladium center preferentially over the ketone carbonyl. The highly selective 2,1-insertion in this reaction contrasts the corresponding reaction with ligand **1a** where both 2,1- and 1,2-insertion products were detected.²¹ In complex **6d**, the acetylmethyl group lies on the same side of the

metal square plane as the 2',6'-dimethoxy(1,1'-biphenyl)-2-yl moiety of the phosphorus atom.

The relative configuration in **6d** and asymmetric copolymerization can be rationalized by the reaction sequence outlined in Scheme 2. According to density functional theory

Scheme 2. Possible Explanation for the Enantioface Selection in Asymmetric Copolymerization of Vinyl Acetate with Carbon Monoxide^a

^aAr = 2',6'-dimethoxy(1,1'-biphenyl)-2-yl; poly = polymer chain.

calculation, vinyl acetate insertion proceeds via coordination of vinyl acetate at the position *cis* to the phosphine moiety followed by migration of the acetyl group.²² The relative configuration in **6d** can be explained by coordination of vinyl acetate to the metal such that the acetoxy group is located on the same side of the square plane as the smaller phenyl group on the phosphorus atom to avoid steric repulsion with the bulky 2',6'-dimethoxy(1,1'-biphenyl)-2-yl group (TS_{I-II} in Scheme 2). If this stereoselective insertion of vinyl acetate operates in the copolymerization reaction of entry 5 of Table 1, *R*-configuration of the stereocenter would be generated using (*S*)-**1d**, giving an isotactic-rich copolymer with *R*-configuration in the main chain.

In summary, we have developed asymmetric copolymerization of vinyl acetate, methyl acrylate, or styrene with carbon monoxide using palladium complexes ligated by *P*-chiral phosphine-sulfonates to synthesize optically active polyketones. The utilization of *P*-chiral phosphine-sulfonate ligands enables the microstructure regulation of coordination-insertion polymerization of polar vinyl monomers. Further improvement of the selectivity in this copolymerization and application of these chiral palladium/phosphine-sulfonate catalysts to other reactions will be forthcoming.

■ ASSOCIATED CONTENT

S Supporting Information

Experimental procedures, supplementary experiments, NMR spectra, and crystal data for (*rac*)-[**1b**]⁺H, (*S*)-(-)-[**1d**]⁺H, and **6d**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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- (14) In isotactic propylene/CO copolymers in ref 13, the half width of the sharpest ketone signal in the ^{13}C NMR spectra can be estimated to be within 2–6 Hz. Since the width of the sharpest ketone signal of the vinyl acetate/CO copolymer obtained in entry 5 was found to be 5 Hz, we concluded that the stereoregularity of the vinyl acetate/CO copolymer was controlled to be isotactic.
- (15) Differential scanning calorimetry (DSC) analysis revealed that the copolymers obtained using (S)-**1d** showed glass transition temperatures (T_g s) almost identical to those obtained using achiral **1a**. See Supporting Information for details.
- (16) The VAc/CO copolymer obtained using (S)-**1d** more easily isomerizes to form polyspiroketal structure **B** than that obtained using **1a**, also suggesting the presence of regio- and stereoregular structures.
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