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Stereochemical studies of the palladium-catalyzed rearrangements of chiral 2-alkynyl sulfinates into chiral allenyl sulfones

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Abstract—Palladium-catalyzed reactions of diastereomerically pure chiral 2-alkynyl *p*-toluenesulfinates under very mild reaction conditions gave both enantiomers of optically active sulfonyl allenes in good yields with high stereospecificity. The stereochemistry of this transformation with the assistance of a palladium catalyst was determined. The conversion rate was measured by the HPLC analysis in accordance with the elapse of the reaction time, and the rather marked difference of the rate was observed between the diastereomeric sulfinates. A novel mechanism for this transformation with palladium catalysts is proposed.

1. Introduction

Allene functionality has been widely used as a three-carbon unit in organic synthesis,[1] being applied to cycloaddition[2] and addition reactions.[3] Furthermore, axial chirality of allenes[4] has received much attention for the high stereospecificity of the reactions with them in asymmetric synthesis. In recent years, in particular, much interest has been focused on the transition metal-catalyzed reactions of allenyl compounds.[5] We have so far investigated asymmetric synthesis by palladium-catalyzed reactions of allenes[6] and palladium-catalyzed enantiospecific reactions of chiral allenes.[7] Hitherto, however, there has appeared no general and efficient synthetic way readily accessible to chiral allenes. Currently, we have been developing a novel method for the easy preparation of both enantiomers of chiral allenes. Previously we achieved successfully asymmetric synthesis of chiral allylic sulfones by thermal[8] or palladium-catalyzed chiral allylic sulfinate–sulfone rearrangements.[9] We have applied this methodology to synthesis of chiral allenes.

We report here details of our stereochemical studies on palladium-catalyzed transformation of chiral 2-alkynyl sulfinates into sulfonyl allenes, and propose a mechanism of the asymmetric transformation on the basis of the stereochemical results obtained.[10]

2. Results and discussion

2.1. Synthesis of chiral 2-alkynyl sulfinates

The 2-alkynyl sulfinates (*S*s,*S*)-**3a** and **4a**, and (*S*s,*R*)-**3b** and **4b** were obtained with 95% stereospecificity in 88% yield of equal amounts of the diasteroisomers by means of our method,[11] namely the $BF_3{\cdot}OEt_2$-mediated alcoholysis of (*S*)-(+)-*N*,*N*-dimethyl-*p*-toluenesulfinamide (**2**) with 2-alkynyl alcohols (±)-**1a,b** in toluene at 0°C for 6 or 7 h (Scheme 1). The diastereomeric sulfinates **3a,b** and **4a,b** were isolated by column chromatography over silica gel. The absolute configuration of the sulfur atom in the chiral sulfinates **3a,b** and **4a,b** obtained above were determined as (*S*) by the highly stereospecific reactions of the sulfinates with phenylmagnesium bromide with inversion of configuration, affording (*R*)-(+)-phenyl tolyl sulfoxide of known absolute configuration.[12] The stereospecificity of the $BF_3{\cdot}OEt_2$-mediated reaction of (*S*)-**2** with **1a,b** was determined on the basis of the enantiomeric excess (e.e.) of (*S*)-**2** used and the optical purity (e.e. of the phenyl tolyl sulfoxide obtained above) of the sulfur atoms in **3a,b** and **4a,b** obtained. The absolute configuration of the chiral carbon centers in **3a,b** and **4a,b** was determined by chemical correlation to 1-butyn-3-yl acetate[13] and 1-ocyn-3-ol[14] of known absolute configuration.

2.2. The palladium-catalyzed reactions of chiral 2-alkynyl sulfinates

The 2-alkynyl sulfinates were thermally transformed into sulfonyl allenes.[15] The transformation was facilitated by the palladium catalysis. The chiral 2-alkynyl sulfinates

Keywords: allenes; asymmetric reactions; palladium and compounds; sulfinic acids and derivatives; sulfonyl compounds.

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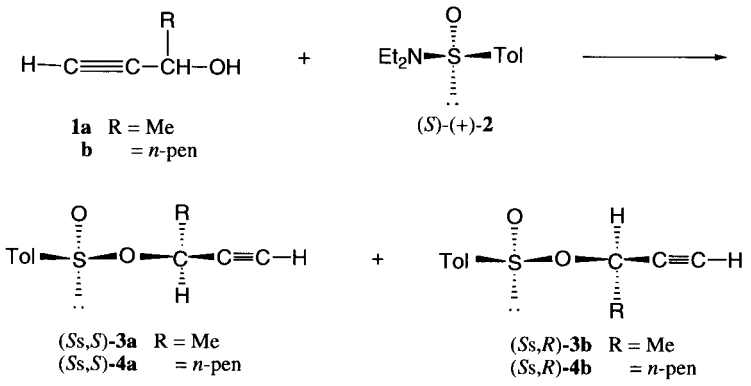
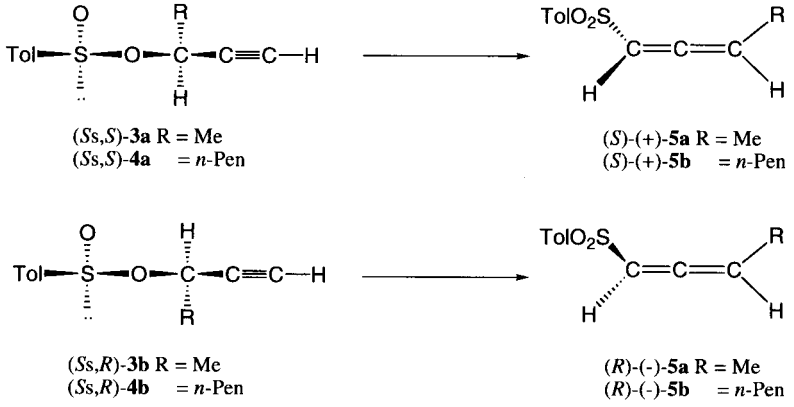


Scheme 1.



Scheme 2.

Table 1. Palladium-catalyzed transformation of chiral sulfinates **3a,b** and **4a,b** into chiral allenes **5a,b**[a]

Sulfinate	Ligand	Reaction time (h)	Isolated yield (%) of **5**	Stereospecificity (%)[b] [absolute configuration]
(*Ss*,*S*)-**3a**	dppe	18	65 (**5a**)	88 (*S*)
(*Ss*,*R*)-**3b**	dppe	18	75 (**5a**)	85 (*R*)
(*Ss*,*S*)-**3a**	dppb	18	72 (**5a**)	82 (*S*)
(*Ss*,*R*)-**3b**	dppb	18	80 (**5a**)	83 (*R*)
(*Ss*,*S*)-**3a**	dpph	18	74 (**5a**)	80 (*S*)
(*Ss*,*R*)-**3b**	dpph	18	89 (**5a**)	89 (*R*)
(*Ss*,*S*)-**3a**	PPh_3	16	65 (**5a**)	79 (*S*)
(*Ss*,*R*)-**3b**	PPh_3	16	64 (**5a**)	77 (*R*)
(*Ss*,*S*)-**4a**	dppb	28	46 (**5b**)	64 (*S*)
(*Ss*,*R*)-**4b**	dppb	18	50 (**5b**)	72 (*R*)
(*Ss*,*S*)-**4a**	dpph	24	39 (**5b**)	69 (*S*)
(*Ss*,*R*)-**4b**	dpph	24	51 (**5b**)	73 (*R*)
(*Ss*,*S*)-**4a**	PPh_3	24	53 (**5b**)	60 (*S*)
(*Ss*,*R*)-**4b**	PPh_3	24	61 (**5b**)	73 (*R*)

[a] The sulfinates (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** or **4b** (87% e.e.) were treated with $Pd(OAc)_2$ (0.05 equiv.) in the prsence of a phosphite ligand [0.075 equiv. except for PPh_3 (0.10 equiv.)] in THF at room temperature; dppe: 1,2-bis(diphenylphosphino)ethane; dppb: 1,3-bis(diphenylphosphino)butane; dpph: 1,6-bis(diphenylphosphino)hexane.

[b] The stereospecificity of the transformation was calculated by the e.e. of the starting sulfinates (87% e.e.) and the products **5a,b** obtained by HPLC analysis with Chiralpack AD.

(*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** obtained above were treated with $Pd(OAc)_2$ (0.05 equiv.) in THF at room temperature in the presence of phosphine ligands (0.075 equiv.) to afford (*S*)-(+)-sulfonyl allenes **5a,b** or (*R*)-(−)-**5a,b**, respectively (Scheme 2). The e.e. of the products was determined by the HPLC analysis with Chiralpak AD. The stereospecificity of the reaction was calculated on the optical purity of the starting sulfinates (87% e.e.) used and the allenes obtained. The results obtained are summarized in Table 1. The palladium-catalyzed reaction of (*Ss*,*S*)-**4a** and (*Ss*,*R*)-**4b** provided slightly lower stereospecificity in comparison to that of the methyl-substituted substrate **3a,b**, as shown in Table 1. The unequivocal effects of phosphine ligands in the palladium-catalyzed reactions were observed. Use of dpph as a ligand provided the highest stereospecificity.

The yields of **5a,b** from (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** were plotted by the HPLC analysis with Chiralpack AD in accordance with the elapse of the reaction time, and depicted in Figs. 1 and 2. The unequivocal difference of the conversion rate between the diastereoisomers was observed as shown in the Figs. 1 and 2; the conversion rate of (*Ss*,*R*)-**3b** and **4b** was greater than that of the corresponding diastereoisomers (*Ss*,*S*)-**3a** and **4a**. The stereospecificity in the transformation of each diastereoisomer was not changeable with the elapse of the reaction time.

Similar results were obtained in the thermal transformation

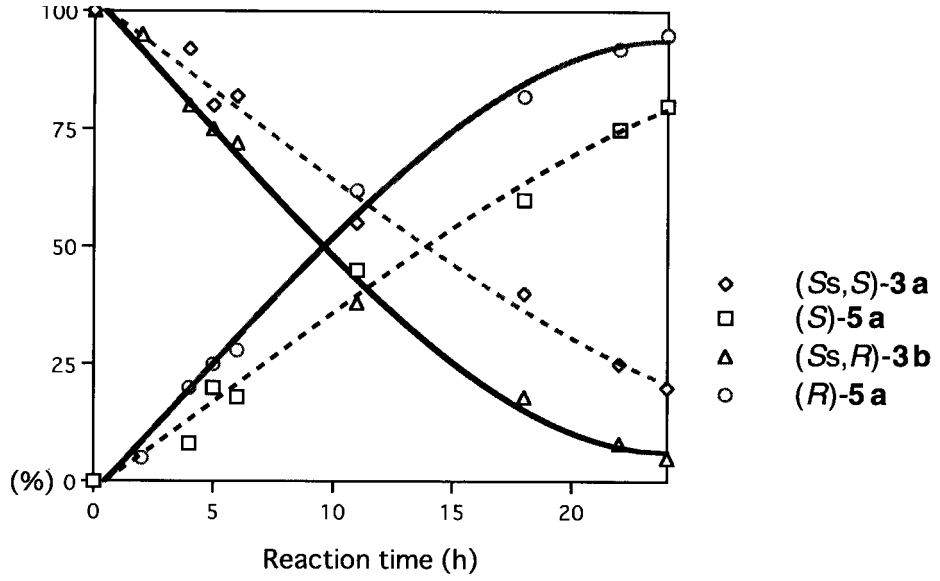


Figure 1. The conversion rate of (*Ss*,*S*)-**3a** and (*Ss*,*R*)-**3b** into (*S*)- or (*R*)-**5a** under palladium-catalyzed reaction conditions [$Pd(OAc)_2$, dppb, in THF, at 22°C].

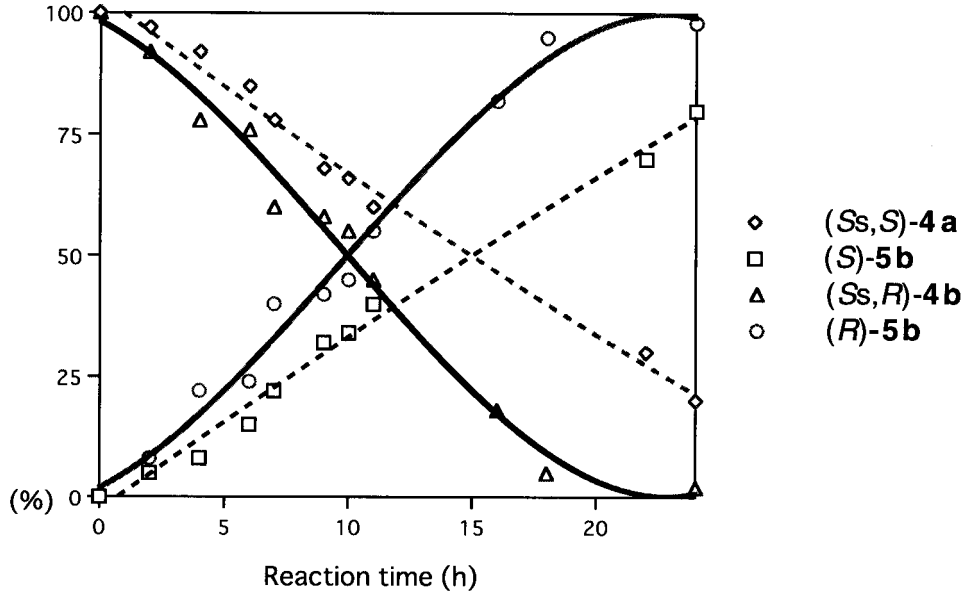


Figure 2. The conversion rate of (*Ss*,*S*)-**4a** and (*Ss*,*R*)-**4b** into (*S*)- or (*R*)-**5b** under palladium-catalyzed reaction conditions [$Pd(OAc)_2$, dppb, in THF, at 22°C].

Table 2. Thermal transformation of chiral sulfinates **3** and **4** into chiral allenes **5**[a]

Alkynyl sulfinates **3** and **4**	Reaction time (h)	Yield of **5** (%)	Stereospecificity (%)[b] [absolute configuration]
(*Ss*,*S*)-**3a**	16	96 (**5a**)	98.6 (*S*)
(*Ss*,*R*)-**3b**	16	94 (**5a**)	99.0 (*R*)
(*Ss*,*S*)-**4a**	15	100 (**5b**)	94.7 (*S*)
(*Ss*,*R*)-**4b**	14	100 (**5b**)	91.8 (*R*)

[a] The reactions of (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** (87% e.e.) were carried out in refluxing toluene.

[b] The stereospecificity of the transformation was calculated by the e.e. of the starting sulfinates (87% e.e.) used and the products **5a,b** obtained by HPLC analysis with Chiralpack AD.

of the chiral 2-alkynyl sulfinates into the sulfonyl allenes under heating at reflux in toluene. The results are summarized in Table 2. The yields of **5a,b** from of (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** were plotted by the HPLC analysis in a similar way in accordance with the elapse of the reaction time. As shown in Figs. 3 and 4, the conversion rate of (*Ss*,*R*)-**3b** and **4b** was greater than that of the corresponding diastereoisomers (*Ss*,*S*)-**3a** and **4a**, similar to the palladium catalysis mentioned above. The greater difference of the conversion rate between each diastereomer was dependent upon the increasing steric bulk of the substituents in the 2-alkynyl groups.

This thermal transformation of (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** proceeds by a [2,3]sigmatropic rearrangement[15] via a five-membered-like cyclic intermediate **6a,b** to give

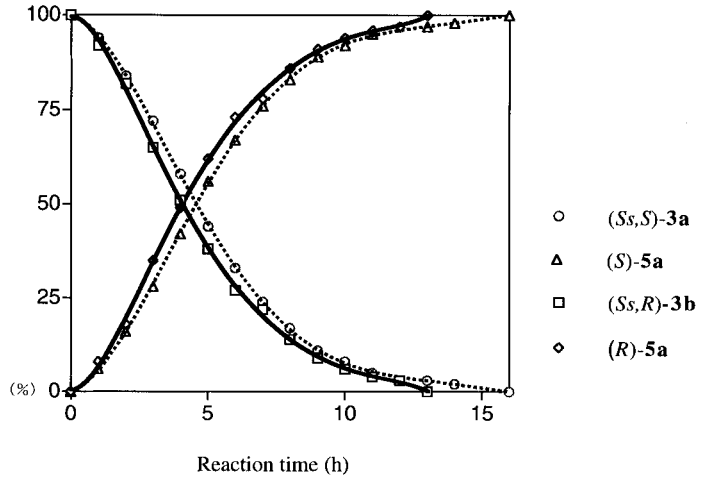


Figure 3. The conversion rate of (*Ss*,*S*)-**3a** and (*Ss*,*R*)-**3b** into (*S*)- or (*R*)-**5a** under thermal reaction conditions [on reflux in toluene].

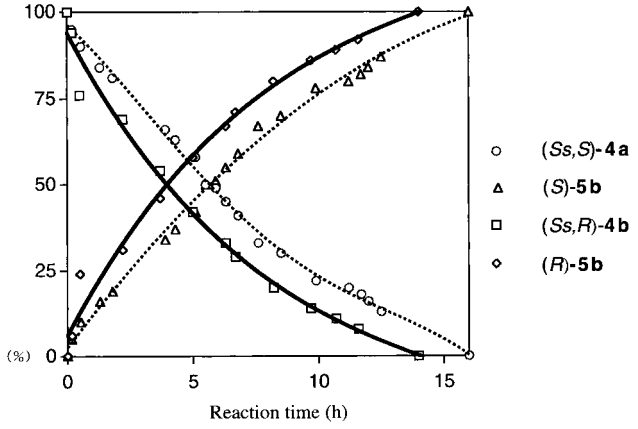
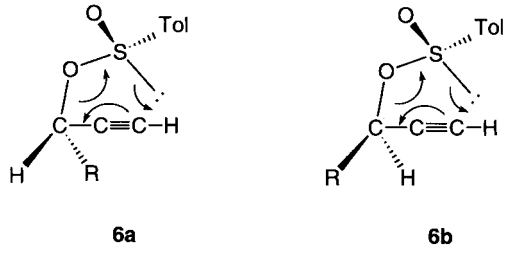


Figure 4. The conversion rate of (*Ss*,*S*)-**4a** and (*Ss*,*R*)-**4b** into (*S*)- or (*R*)-**5b** under thermal reaction conditions [on reflux in toluene].



6a **6b**

Scheme 3.

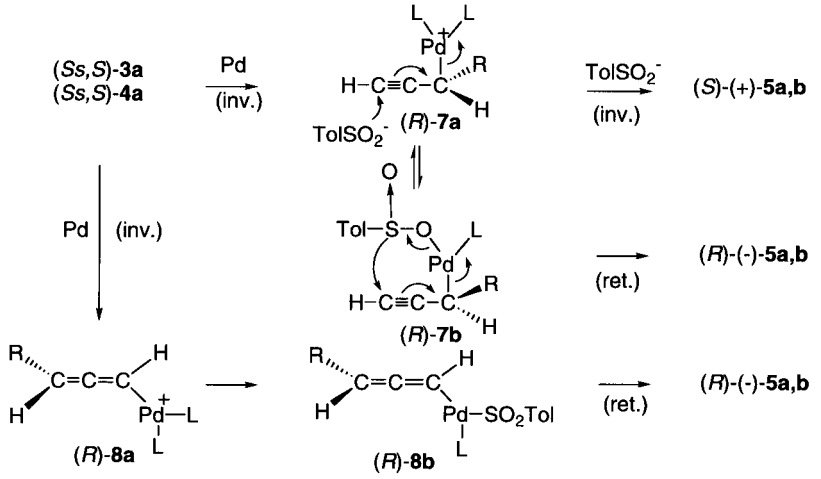
(*S*)-(+)-**5a,b** or (*R*)-(−)-**5a,b** in high stereospecificity, respectively, as shown in Scheme 3. The absolute configuration of the products was also confirmed by the application of the Lowe rule.[16]

2.3. The mechanism of the palladium-catalyzed transformation

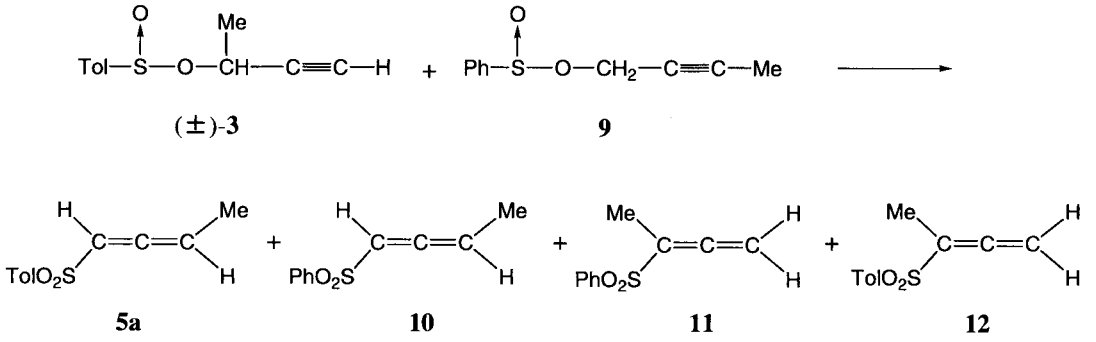
The plausible mechanism of this transformation is presented as follows (see Scheme 4). The conjugate addition of a palladium catalyst to the γ-carbon of the 2-alkynyl group in (*Ss*,*S*)-**3a** and **4a** with inversion of configuration gives (*R*)-**8a**, followed by the sulfonylation with retention of configuration via (*R*)-**8b** to provide (*R*)-**5a,b**. This is not consistent with the result obtained. The substitution of the sulfinate with the palladium catalyst at the α-carbon of the 2-alkynyl group in (*Ss*,*S*)-**3a** and **4a** with inversion of configuration affords (*R*)-**7a**. The intramolecular sulfonylation via (*R*)-**7b** with retention of configuration gives (*R*)-**5a,b**. However, this is not consistent with the experimental result. Therefore, it might be more reasonable that the sulfonylation of (*R*)-**7a** by conjugate addition of the *p*-toluenesulfonyl anion with inversion of configuration gives (*S*)-**5a,b**. However, if (*R*)-**7a** would be the most important key intermediate, the stereospecificity of the reactions, chemical yield of allenes, and the conversion rate of the diastereomeric sulfinates should not be changeable in each diastereomer.

Furthermore, this reaction path to (*S*)-**5a**,**b** via (*R*)-**7a** should be rejected by the following result of the cross-sulfonylation reactions: (1) the palladium-catalyzed reactions of (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** were carried out in the presence of sodium benzenesulfinate to give (*S*)- or (*R*)-**5a**,**b**, respectively, without any formation of the corresponding phenylsulfonyl allenes; (2) the palladium-catalyzed reaction of (±)-**3** (1.0 equiv.) and **9** (1.0 equiv.) in THF at room temperature for 18 h using $Pd(OAc)_2$ (0.05 equiv.) and dpph (0.075 equiv.) gave an equal amount of (±)-**5a** (83% yield) and **11** (86% yield) without any cross-sulfonylation products **10** and **12** (Scheme 5). These results indicate that the aforementioned palladium-catalyzed reactions of the 2-alkynyl sulfinates would proceed, not via an ionic intermediate (*R*)-**7a**, but through an intramolecular transformation mechanism.

Thus, we wish to propose another novel mechanism via palladium-mediated intermediates for this transformation by the direct participation of chirality of the sulfinate in the crucial stage of the transition states (see Scheme 6). The palladium-catalyzed reaction of (*Ss*,*S*)-**3a** and **4a** will take place by the initial formation of **13a** coordinated by the acetylene group and the sulfinate sulfur atom, which has higher potential ability of coordination to palladium rather than the sulfinate oxygen atom.[17] The allenylpalladium



Scheme 4.

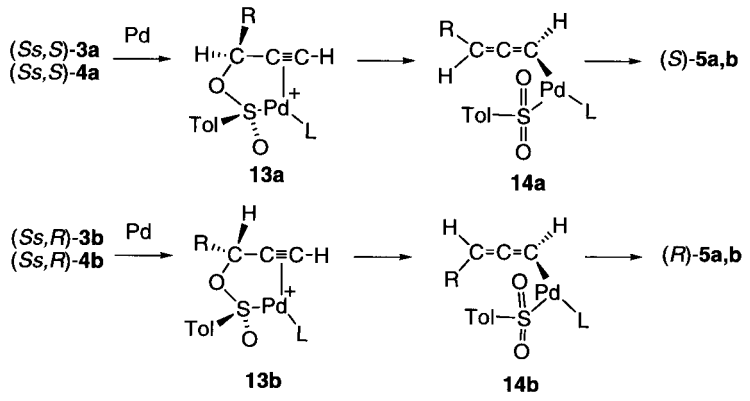


Scheme 5.

complex **14a** would be formed via **13a** with retention of configuration. The intramolecular sulfonylation of **14a** with retention of configuration provides (*S*)-**5a,b**. Similarly, the palladium-catalyzed reaction of another diastereoisomer (*Ss*,*R*)-**3b** or **4b** proceeds via **13b** and **14b** to give (*R*)-**5a,b**. The aforementioned observation of the difference in the transformation rate between both the diastereoisomers (Figs. 1 and 2) should be reasonably understandable. The transition state **13a** has steric hindrance between R and the tolyl group owing to the *cis* configuration in the five-membered-like intermediate. Therefore, the reaction via **13a** could not be accessible with ease, and provided the rather slower conversion rate, as shown in Fig. 1, and the slightly lower stereospecificity, presumably due to proceeding via a somewhat ionized intermediate, compared with that derived from **13b**.

On the other hand, the coordination of the sulfinate oxygen atom to the palladium catalyst, if possible, provides a six-membered-like intermediate, which gives incorrect stereochemical results, due to a similar argument.

Similar observations were detected in the thermal transformation of the chiral sulfinates into allenes, and are



Scheme 6.

rationalized as a result of the formation of the similar cyclic intermediates as mentioned before (Scheme 3).

3. Conclusion

We have found that the palladium-catalyzed reactions of each diastereomer of chiral 2-alkynyl sulfinates resulted in the ready formation of both enantiomers of chiral allenes with considerably high e.e. We proposed a novel mechanism of the intramolecular palladium-catalyzed rearrangement via a five-membered-like cyclic intermediate for this transformation. This is the first example of the synthesis of chiral allenes from propargylic alcohol derivatives bearing chiral leaving groups.

4. Experimental

Infrared (IR) spectra were obtained in the indicated state with a JASCO DR-81 Fourier-transform IR spectrometer. NMR spectra were determined in the indicated solvent with a JEOL EX-270 (^{1}H-NMR; 270 MHz) high-resolution NMR spectrometer; chemical shifts are given in ppm from tetramethylsilane as an internal standard. Splitting patterns are designated as s: singlet, d: doublet, q: quartet, m: multiplet. Mass spectra were taken on a JEOL JMS-DX 303/JMA-DA 5000 system. High performance liquid chromatography (HPLC) was performed with a Tosoh UV-8010 CCPM (column: Daicel Chiralpak AD, *i*-PrOH–hexane 5:95, flow rate 1.0 mL/min, 254 nm). Optical rotations were measured with a JASCO DIP-370 polarimeter. Flash column chromatography was performed with Merck Silica gel 60 (230–400 mesh). Thin layer or thick layer plates (preparative TLC) were made from Merck Silica gel 60PF-254 activated by drying at 140°C for 3.5 h.

4.1. Synthesis of optically active 2-alkynyl *p*-toluenesulfinates. General procedure

A 25 mL two-necked flask equipped with a septum inlet was placed with a stirring bar, flushed with nitrogen, and maintained under a positive pressure of argon.

A solution of (*S*)-(+)-*N*,*N*-dimethyl-*p*-toluenesulfinamide (**2**) ($[\alpha]_D$=+111.5° (acetone, 24°C), 91.6% e.e.[18]) (300 mg, 1.42 mmol) in anhydrous toluene (8 mL) was added to the flask, followed by the addition of a solution of 2-alkynyl alcohols (**1a,b**) (4.27 mmol) in anhydrous toluene (2 mL). A solution of boron trifluoride etherate (0.2 mL, 1.42 mmol) in anhydrous toluene (1 mL) was added to the above flask cooled to 0°C, and the reaction mixture was stirred at 0°C for 6–8 h. The reaction mixture was diluted with ether, and the mixture was washed with a saturated $NaHCO_3$ aqueous solution and a saturated NaCl aqueous solution. The ethereal layer was separated, dried over anhydrous Na_2SO_4, and concentrated under reduced pressure. The residue was submitted to flash column chromatography over silica gel (ether–hexane 1:2) to give a 1:1 diastereomeric mixture of sulfinates (*S*s,*S*)-**3a** and **4a** and (*S*s,*R*)-**3b** and **4b** in good yields with 87% e.e., which was determined by transformation into (*R*)-(+)-phenyl *p*-tolyl sulfoxide as described later.

4.1.1. (*S*)-1-Butyn-3-yl (*S*)-*p*-toluenesulfinate (3a). 50% yield. $[\alpha]_D$=−121.8° (*c* 1.42, EtOH, 28°C) (87% e.e.). IR ν_{max}^{film} cm^{-1}: 3270 (C≡CH), 2120 (C≡C), 1595 (aromatic), 1130 (sulfinate). NMR (CCl_4) δ: 1.53 (3H, d, *J*=7 Hz, CHCH_3), 2.50 (3H, s, $C_6H_4CH_3$), 2.59 (1H, d, *J*=2 Hz, C≡CH), 4.90–5.29 (1H, m, O—CH), 7.38–7.95(4H, m, C_6H_4). MS *m*/*z*: 208 (M^+). Exact mass determination: 208.0378 (Calcd $C_{11}H_{12}O_2S$: 208.0558).

4.1.2. (*R*)-1-Butyn-3-yl (*S*)-*p*-toluenesulfinate (3b). 50% yield. $[\alpha]_D$=−13.2° (*c* 1.59, EtOH, 28°C) (87% e.e.). IR ν_{max}^{film} cm^{-1}: 3300 (C≡CH), 2120 (C≡C), 1590 (aromatic), 1130 (sulfinate). NMR (CCl_4) δ: 1.55 (3H, d, *J*=7 Hz, CHCH_3), 2.17 (1H, d, *J*=2 Hz, C≡CH), 2.46 (3H, s, $C_6H_4CH_3$), 4.73–5.17 (1H, m, O—CH), 7.26–7.90 (4H, m, C_6H_4). MS *m*/*z*: 208 (M^+). Exact mass determination: 208.0012 (Calcd. $C_{11}H_{12}O_2S$: 208.0558).

4.1.3. (*S*)-1-Octyn-3-yl (*S*)-*p*-toluenesulfinate (4a). $[\alpha]_D$=−118.9° (*c* 4.07, EtOH, 22°C) (87% e.e.). IR ν_{max}^{film} cm^{-1}: 3330 (C≡CH), 2125 (C≡C), 1600 (aromatic), 1140 (sulfinate). NMR (CCl_4) δ: 0.56–1.00 (3H, m, $(CH_2)_4CH_3$), 1.05–1.89 (8H, m, $(CH_2)_4CH_3$), 2.35 (3H, s, $C_6H_4CH_3$), 2.41 (1H, d, *J*=7 Hz, C≡CH), 4.45–5.83 (1H, m, O—CH), 6.90–7.49 (4H, m, C_6H_4). MS *m*/*z*: 264 (M^+). Exact mass determination: 264.1056 (Calcd. $C_{15}H_{20}O_2S$: 264.1184).

4.1.4. (*R*)-1-Octyn-3-yl (*S*)-*p*-toluenesulfinate (4b). $[\alpha]_D$=−27.7° (*c* 1.30, EtOH, 28°C) (87% e.e.). IR ν_{max}^{film} cm^{-1}: 3330 (C≡CH), 2130 (C≡C), 1600 (aromatic), 1140 (sulfinate). NMR (CCl_4) δ: 0.68–1.10 (3H, m, $(CH_2)_4CH_3$), 1.15–1.96 (8H, m, $(CH_2)_4CH_3$), 2.15 (1H, d, *J*=2.8 Hz, C≡CH), 2.48 (3H, s, $C_6H_4CH_3$), 4.66–5.00 (1H, m, O—CH), 7.43–7.91 (4H, m, C_6H_4). MS *m*/*z*: 264 (M^+). Exact mass determination: 264.0983 (Calcd. $C_{15}H_{20}O_2S$: 264.1184).

4.2. Reaction of chiral sulfinates 3a,b and 4a,b with phenylmagnesium bromide

A 2 M THF solution of phenylmagnesium bromide (0.8 mL, 0.36 mmol) was added to a solution of chiral sulfinates (*S*s,*S*)-**3a** and **4a** or (*S*s,*R*)-**3b** and **4b** (0.31 mmol) obtained above in THF (5 mL) cooled to −78°C. The reaction mixture was stirred at −78°C for 2 h. After the reaction was completed, the cooling bath was removed, and the reaction solution was quenched with 10% aqueous HCl and extracted with ether. The ethereal layers were combined, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residual oil was submitted to preparative TLC (hexane–ether 1:2) to give almost quantitatively (*R*)-(+)-phenyl *p*-tolyl sulfoxide ($[\alpha]_D$=+22° (acetone)[13]) with high e.e. (95%).

4.3. Hydrolysis of chiral sulfinates 4a,b

A solution of KOH (33mg, 0.60 mmol) in methanol (2 mL) was added to a solution of (*S*s,*S*)-**4a** (79 mg, 0.30 mmol) obtained before in methanol (1 mL), and the reaction mixture was stirred at room temperature for 1 h. The reaction solution was concentrated in vacuo, and the residue was dissolved with chloroform. The chloroform solution was

washed with a saturated aqueous NaCl solution, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was submitted to preparative TLC (hexane–ethyl acetate 6:1) to give (*S*)-(−)-1-octyn-3-ol [32 mg, 84% yield; $[\alpha]_D=-19.6°$ (*c* 2.20, ether, 22°C)] [lit.[15] $[\alpha]_D=-22.3°$ (ether)]. Hydrolysis of (*Ss*,*R*)-**4b** (79 mg, 0.30 mmol) obtained before under the same reaction conditions mentioned above gave (*R*)-(+)-1-octyn-3-ol [30 mg, 79% yield, $[\alpha]_D=+20.6°$ (*c* 1.14, ether, 20°C)].

4.4. Transformation of (*Ss*,*S*)-3a into (*S*)-(−)-1-butyn-3-yl acetate

A solution of KOH (186 mg, 3.33 mmol) in methanol (2 mL) was added to a solution of (*Ss*,*S*)-**3a** (346 mg, 1.66 mmol) obtained before in methanol (1 mL). The reaction mixture was stirred at room temperature for 1 h. The reaction was worked-up in the usual way as described above. The crude product was submitted to an acetylation reaction without further purification. A reaction mixture of the crude alcohol (1-butyn-3-ol) obtained above and acetic anhydride (0.25 mL, 2.49 mmol) in pyridine (1 mL) was stirred at room temperature for 16 h. The reaction mixture was dissolved in ether. The solution was washed with 10% aqueous HCl, saturated aqueous $NaHCO_3$, and saturated aqueous NaCl. The ethereal layer was dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was submitted to preparative TLC (hexane–ethyl acetate 6:1) to give (*S*)-(−)-1-butyn-3-yl acetate[13] [70 mg, 60% yield, $[\alpha]_D=-120.6°$ (*c* 2.57, MeOH, 24°C)]. The reactions of (*Ss*,*R*)-**3b** obtained before under the same reaction conditions described above gave (*R*)-(+)-1-butyn-3-yl acetate (70 mg, 60% yield, $[\alpha]_D=+125.3°$ (*c* 2.25, MeOH, 24°C).

4.5. Palladium-catalyzed transformation of chiral sulfinates (*Ss*,*S*)-3a and 4a and (*Ss*,*R*)-3b and 4b into sulfonyl allenes 5a,b. General procedure

A 25 mL two-necked flask equipped with a septem inlet and containing palladium acetate ($Pd(OAc)_2$) (2.7 mg, 0.01 mmol) and 1,2-bis-(diphenylphosphino)ethane (dppe) (30 mg, 0.02 mmol) was flashed with argon, and maintained under a positive pressure of argon. To the above flask THF (2 mL) was added and the mixture was stirred at room temperature for 30 min. A solution of (*Ss*,*S*)-**3a** or (*Ss*,*R*)-**3b** (50.0 mg, 0.42 mmol) obtained before in THF (1 mL) was added to the above solution, and the reaction mixture was stirred at room temperature for 16–18 h. After the reaction was completed, the reaction mixture was diluted with ether and filtered. The filtrate was concentrated in vacuo and the residue was submitted to preparative TLC (hexane–ether 2:1) to give allenes, (*S*)-(+)- or (*R*)-(−)-**5a**, respectively. The result obtained under various reaction conditions using various phosphine ligands are summarized in Table 1. The conversion rate of **3a,b** into **5a**, when 1,4-bis(diphenylphosphinobutane) (dppb) was used as a ligand, was determined by HPLC analysis with Chiralpak AD (*i*-PrOH–hexane (5:95), flow rate 1.0 mL/min (254 nm), retention time: 16.3 min. [(*S*)-**5a**], 18.1 min [(*R*)-**5a**], 12.1 min [(*S*)-**5b**], and 14.2 min [(*R*)-**5b**)], and plotted in accordance with the elapse of the reaction time, as designated in Fig. 1. Similar reaction conditions and procedure were applied to (*Ss*,*S*)-**4a** and (*Ss*,*R*)-**4b**. The results are summarized in Table 1, and the conversion rate of **4a,b** into **5b** is depicted in Fig. 2. The $[\alpha]_D$ values of **5a,b** obtained above are corrected as for those of the optically pure allenes on the basis of the data by the HPLC analysis.

4.5.1. (*S*)-(+)-1,2-Butadienyl *p*-tolyl sulfone (5a). $[\alpha]_D=+124.6°$(*c* 0.80, EtOH, 24°C). IR ν_{max}^{film} cm^{-1}: 1955 (allene), 1590 (aromatic), 1300, 1140 (sulfone). NMR (CCl_4) δ: 1.74 (3H, q, *J*=4 Hz, C=CHC*H*$_3$), 2.41 (3H, s, $C_6H_4CH_3$), 5.53–6.22 (2H, m, H—C=C=C—H), 7.06–7.86 (4H, m, C_6H_4). MS *m*/*z*: 208 (M^+). Exact mass determination: 208.1390 (Calcd. $C_{11}H_{12}O_2S$: 208.0558).

4.5.2. (*R*)-(−)-1,2-Butadienyl *p*-tolyl sulfone (5a). $[\alpha]_D=-129.9°$ (*c* 1.64, EtOH, 24°C). The IR and NMR spectra of (*R*)-(−)-**5a** obtained were superimposable with those of (*S*)-(+)-**5a** described above. MS *m*/*z*: 208 (M^+). Exact mass determination: 208.0789 (Calcd $C_{11}H_{12}O_2S$: 208.0558).

4.5.3. (*S*)-(+)-1,2-Octadienyl *p*-tolyl sulfone (5b). $[\alpha]_D=+124.5°$ (*c* 0.72, EtOH, 24°C). IR ν_{max}^{film} cm^{-1}: 1960 (allene), 1600 (aromatic), 1330, 1140 (sulfone). NMR (CCl_4) δ: 0.96–1.26 (3H, m, CH_2CH_3), 1.36–1.63 (6H, m, $(CH_2)_3CH_3$), 2.09–2.43 (2H, m, C=CCH_2), 2.55 (3H, s, $C_6H_4CH_3$), 5.71–6.33 (2H, m, H—C=C=C—H), 7.42–8.23 (4H, m, C_6H_4). MS *m*/*z*: 264 (M^+). Exact mass determination: 264.1089 (Calcd. $C_{15}H_{20}O_2S$: 264.1184).

4.5.4. (*R*)-(−)-1,2-Octadienyl *p*-tolyl sulfone (5b). $[\alpha]_D=-130.0°$ (*c* 1.60, EtOH, 24°C). The IR and NMR spectra of (*R*)-(−)-**5b** obtained were superimposable with those of (*S*)-(+)-**5b** described above. MS *m*/*z*: 264 (M^+). Exact mass determination: 264.0721 (Calcd. $C_{15}H_{20}O_2S$: 264.1184).

4.6. Thermal transformation of chiral sulfinates into allenes. General procedure

A solution of chiral sulfinates (*Ss*,*S*)-**3a** and **4a** or (*Ss*,*R*)-**3b** and **4b** (0.372 mmol) (87% e.e.) obtained before in toluene (3.5 mL) was refluxed for 14–16 h. The reaction solution was concentrated in vacuo and the residue was submitted to preparative TLC (ether–hexane 1:4) to give allenes, (*S*)-(+)- or (*R*)-(−)-**5a,b**, respectively. The results are summarized in Tables 2 and 3. The products were identical to those obtained above. The conversion rate was plotted by the HPLC analysis in accordance with the elapse of the reaction time, and depicted in Figs. 3 and 4.

Table 3. Thermal transformation of chiral sulfinates **3** and **4** into chiral allenes **5**[a]

2-Alkynyl sulfinates **3a,b** and **4a,b**	Reaction time (h)	Yield of **5** (%)	$[\alpha]_D$ (*c*, °C, EtOH) of **5**
(*Ss*,*S*)-**3a**	16	96 (**5a**)	+99.4° (1.80, 25)
(*Ss*,*R*)-**3b**	16	94 (**5a**)	−113.0° (1.00, 24)
(*Ss*,*S*)-**4a**	15	100 (**5b**)	+108.3° (0.72, 24)
(*Ss*,*R*)-**4b**	14	40 (**5b**)	−118.5° (1.08, 24)

[a] The reactions were carried out in refluxing toluene.

4.7. Studies on a cross-sulfonylation reaction

4.7.1. 2-Butynyl benzenesulfinate (9). A solution of benzenesulfinyl chloride (2.69 g, 16.8 mmol) (generated from sodium benzenesulfinate and thionyl chloride) in ether (10 mL) was added to a mixture of 2-butynol (806 mg, 11.5 mmol) and pyridine (7 mL) in ether (30 mL) cooled at 0°C. The reaction mixture was stirred at room temperature for 8 h. The reaction mixture was diluted with ether and filtered. The filtrate was washed successively with a 10% aqueous HCl solution, a saturated aqueous $NaHCO_3$ solution, and a saturated NaCl solution, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was submitted to preparative TLC (ether–hexane 1:3) to give **9** (1.65 g, 76% yield).

The reaction of 1-butyn-3-ol (538 mg, 7.70 mmol) with *p*-toluenesulfinyl chloride (1.60 g, 11.20 mmol) was carried out in a similar way to give (±)-**3** (1.50 g, 84% yield), which was identical to that obtained before.

IR ν_{max}^{film} cm^{-1}: 2240 (—C≡C—), 1144 (—SO—O—R). NMR (CCl_4) δ: 1.82 (3H, s, CH_3), 4.27–4.63 (2H, m, CH_2), 7.53–7.76 (5H, m, C_6H_5). MS *m/z*: 195 (M^++1). Exact mass determination: 194.0396 (Calcd $C_{10}H_{10}O_2S$: 194.0402).

4.7.2. 1,2-Butadien-3-yl phenyl sulfone (11). The palladium-catalyzed reaction of sulfinate **9** (50 mg, 0.26 mmol) was carried out in THF (4 mL) at room temperature for 24 h in the presence of $Pd(OAc)_2$ (2.9 mg, 0.013 mmol) and 1,6-bis(diphenylphosphino)hexane (dpph). The usual work-up as described before and purification of the crude product by preparative TLC (ether–hexane 1:2) gave **11** (26 mg, 52% yield).

IR ν_{max}^{film} cm^{-1}: 1968 (allene), 1144 (—SO—O—R). NMR (CCl_4) δ: 1.82 (3H, s, CH_3), 4.27–4.63 (2H, m, CH_2), 7.53–7.76 (5H, m, C_6H_5). MS *m/z*: 195 (M^++1). Exact mass determination: 194.0396 (Calcd $C_{10}H_{10}O_2S$: 194.0402).

4.8. A cross-sulfonylation reaction between (±)-3 and 9

The cross-sulfonylation reaction between (±)-**3** and **9** was studied according to a similar procedure bescribed before. A solution of (±)-**3** (52 mg, 0.25 mmol) and **9** (49 mg, 0.25 mmol) in THF (3 mL) was added to a mixture of $Pd(OAc)_2$ (5.6 mg, 0.025 mmol) and 1,6-bis(diphenylphosphino)hexane (dpph) (17 mg, 0.038 mmol) in THF (5 mL) under argon atmosphere. The reaction mixture was stirred at room temperature for 18 h. The usual work-up as described before, followed by purification with preparative TLC, gave (±)-**5a** (43 mg, 83% yield) and **11** (42 mg, 86% yield). No cross-sulfonylation products **10** and **12** were detected by HPLC analysis (Chiralpak AD, *i*-PrOH–hexane (5:95), flow rate 1.0 mL/min; retention time: 10.8 min (**11**), 16.3 min [(*S*)-**5a**], and 18.1 min [(*R*)-**5a**)]. The products **5a** and **11** were identical to those obtained before.

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References

1. (a) Toylor, D. R. *Chem. Rev.* **1967**, *67*, 317–359. (b) Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805–2827.
2. (a) Okamura, W. H. *Acc. Chem. Res.* **1983**, *16*, 81–88. (b) Okamura, W. H.; Curtin, M. L. *Synlett* **1990**, 1–9. (c) Zimmer, R. *Synthesis* **1993**, 165–178.
3. Smadja, W. *Chem. Rev.* **1983**, *83*, 263–320.
4. Rossi, R.; Diversi, P. *Synthesis* **1973**, 25–36 and references cited therein.
5. (a) Tsuji, J.; Mandai, T. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2589–2612. (b) Hiroi, K.; Kato, F. *Annual Report of Tohoku College of Pharmacy* **1996**, *43*, 1–33. (c) Hiemstra, H.; Beyersbergen van Henegouwen, W. G.; Karstens, W. F.; Moolenaar, M. J.; Rutjes, F. P. J. T. In *Current Trends in Organic Synthesis*, Scolastico, C., Nicotra, F., Eds.; Kluwer Academic/Plenum Publishers: New York, 1999; pp 267–274.
6. Hiroi, K.; Kato, F.; Yamagata, A. *Chem. Lett.* **1998**, 397–398.
7. Kato, F.; Hiratsuka, Y.; Mitsui, T.; Watanabe, T.; Hiroi, K. *Heterocycles* **1999**, *50*, 83–87.
8. Hiroi, K.; Kitayama, R.; Sato, S. *Chem. Pharm. Bull.* **1984**, *32*, 2628–2638.
9. Hiroi, K.; Kitayama, R.; Sato, S. *J. Chem. Soc., Chem. Commun.* **1983**, 1470–1471.
10. For a preliminary report of this work see: Hiroi, K.; Kato, F.; Nakasato, H. *Chem. Lett.* **1998**, 553–554.
11. Hiroi, K.; Kitayama, R.; Sato, S. *Synthesis* **1983**, 1040–1041.
12. Anderson, K. K.; Gaffield, W.; Papanikolau, N. E.; Foley, J. W.; Perins, R. I. *J. Am. Chem. Soc.* **1964**, *86*, 5637–5646.
13. Olsson, L.-I.; Claesson, A. *Acta Chem. Scand.* **1979**, *B33*, 679–684.
14. Sih, C. J.; Price, P.; Sood, R.; Salomon, R. G.; Peruzzotti, G.; Casey, M. *J. Am. Chem. Soc.* **1972**, *94*, 3643–3644.
15. Smith, G.; Stirling, C. J. M. *J. Chem. Soc.* **1971**, 1530–1535.
16. Lowe, G. J. *Chem. Soc., Chem. Commun.* **1965**, 411–413.
17. Hiroi, K.; Suzuki, Y.; Kawagishi, R. *Tetrahedron Lett.* **1999**, *40*, 715–718.
18. (a) Colonna, S.; Giovini, R.; Montanari, F. *J. Chem. Soc., Chem. Commun.* **1968**, 865–866. (b) Mikolajezyk, M.; Drabowicz, J.; Bujnicki, B. *J. Chem. Soc., Chem. Commun.* **1976**, 568–569.